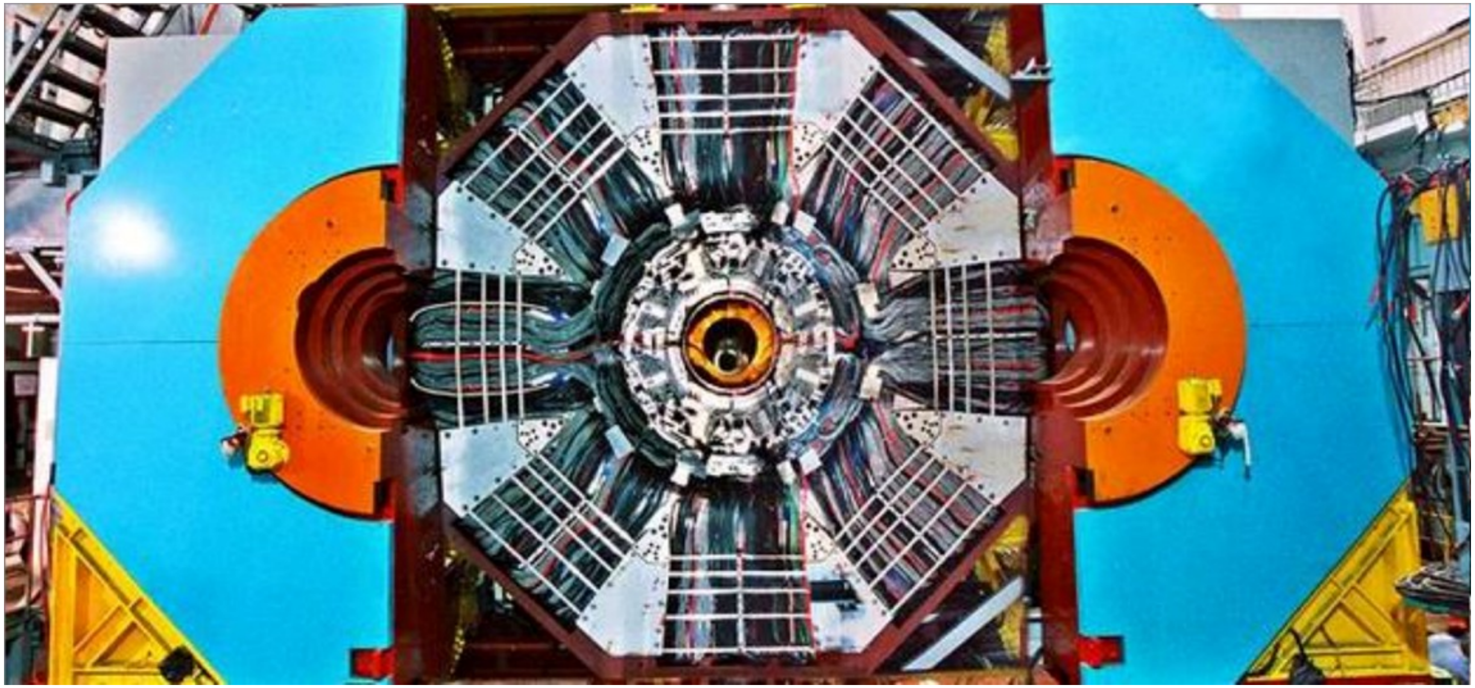


BESIII强子物理前沿进展

吕晓睿
中国科学院大学

BESIII

粒子物理重大科学前沿问题

ATLAS, CMS
CEPC, ILC, Fee

- 标准模型的Higgs粒子反映什么样的相互作用，是否有超出标准模型的新物理？

PandaX, CEDX, DAMPE
LUX, AMSII
ATLAS, CMS

- 暗物质
- 暗能量

Dayabay, JUNO, T2K, SK…DUNE

- 中微子的属性
- 引力量子化

CSR, CJPL

- 宇宙起源及铁以上重元素的形成

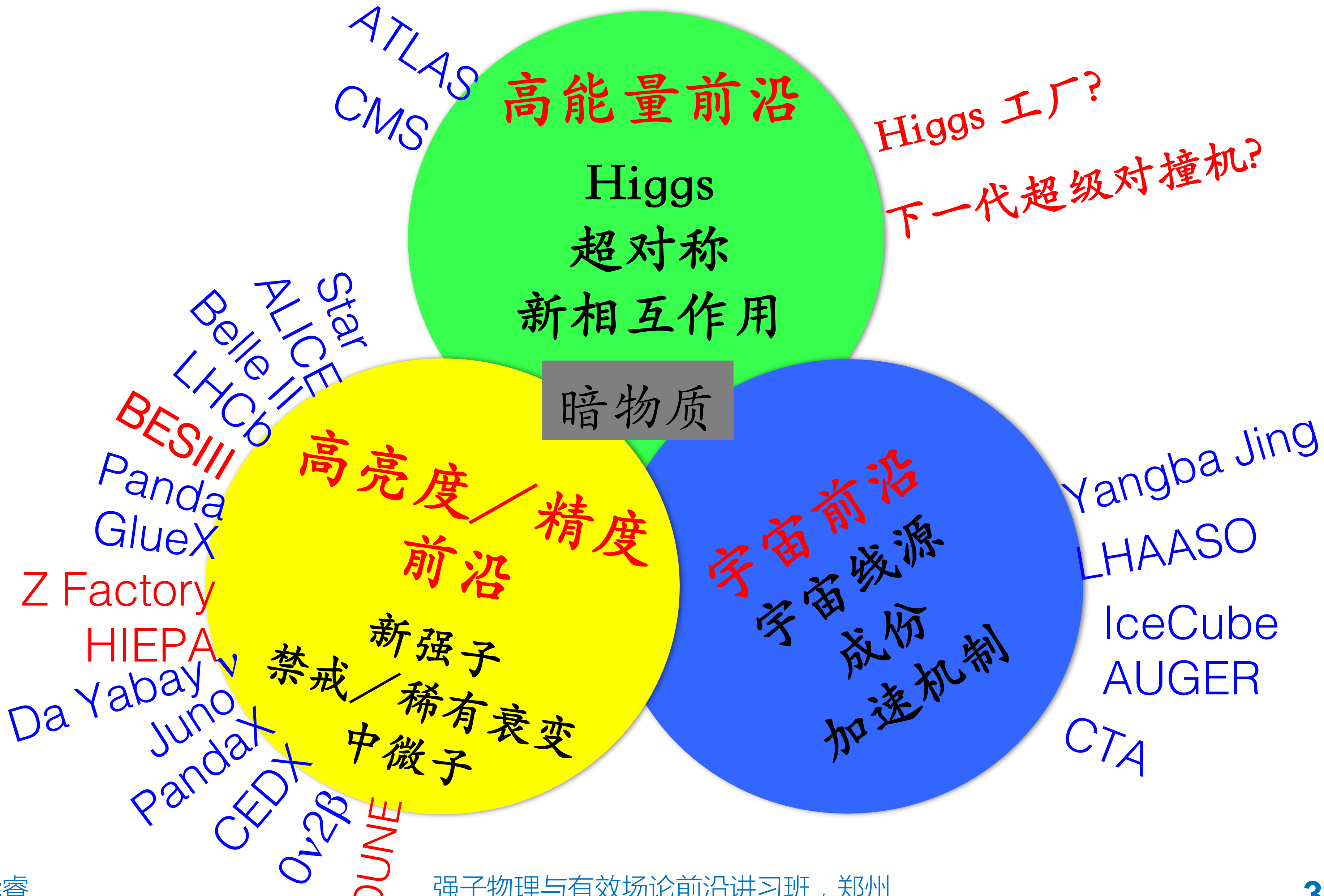
Yangbajing,
CTA, LHASSO

- 宇宙线粒子给我们带来的信息

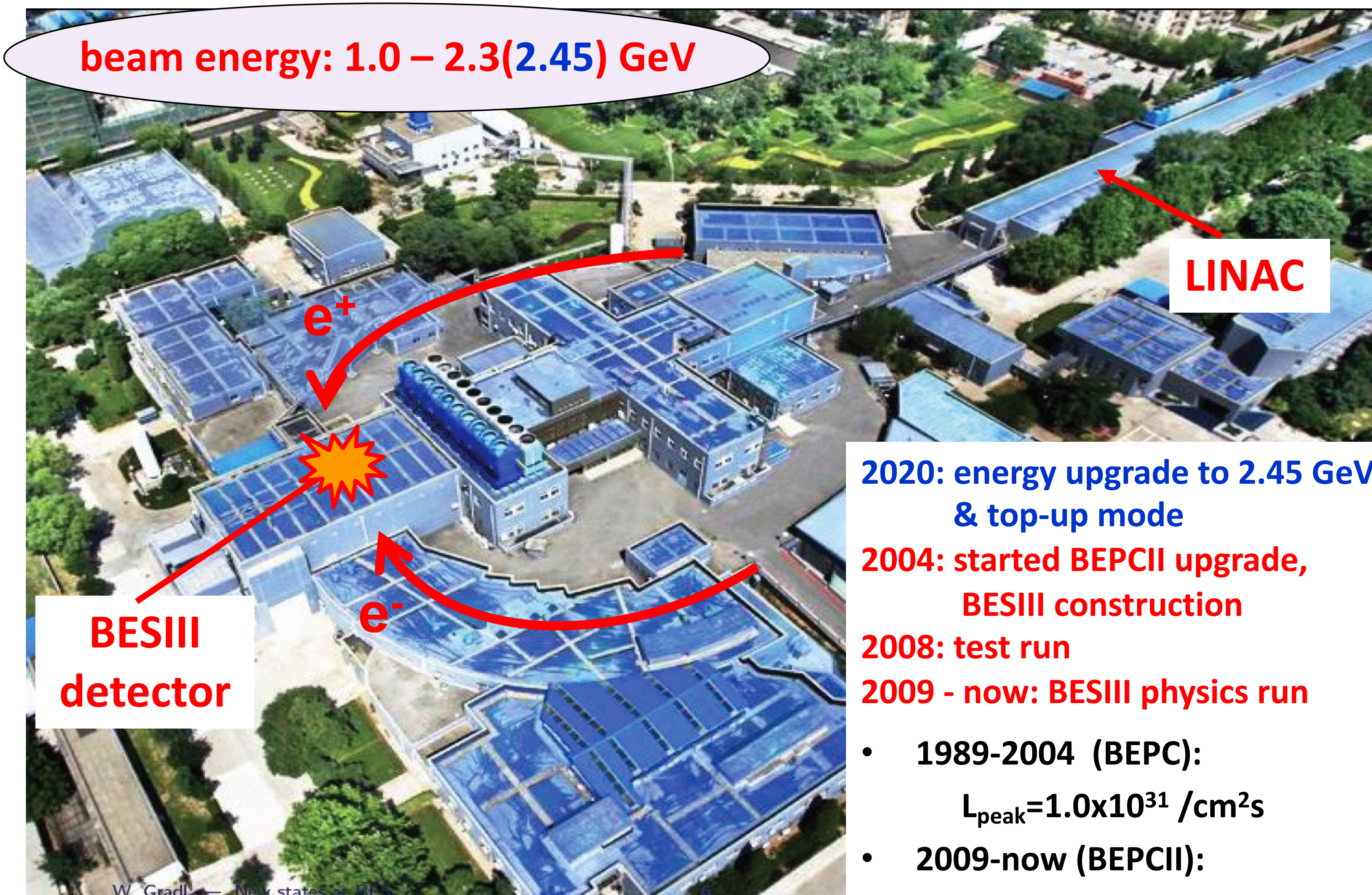
STAR, ALICE, LHCb, BELLE(II), BESIII, ATLAS, CMS, AMSII, CBM, CEE

- 极端条件下的物质形态及奇异物质
- 宇宙中正反物质不对称
- 万有引力与弱电及强相互作用的统一

粒子物理前沿


高能量前沿
Higgs
超对称
新相互作用
ATLAS
CMS
Higgs 工厂?
下一代超级对撞机?
暗物质
高亮度／精度前沿
新强子
禁戒／稀有衰变
中微子
Star
ALICE
Belle II
LHCb
BESIII
Panda
GlueX
Z Factory
HIEPA
Da Yabay
Juno
PandaX
CEDX
0ν2β
DUNE
宇宙前沿
宇宙线源
成份
加速机制
Yangba Jing
LHAASO
IceCube
AUGER
CTA

Beijing Electron Positron Collider (BEPCII)



2020: energy upgrade to 2.45 GeV & top-up mode

2004: started BEPCII upgrade, BESIII construction

2008: test run

2009 - now: BESIII physics run

- 1989-2004 (BEPC): L_{peak}=1.0x10^{31} /cm^{2}s
- 2009-now (BEPCII): L_{peak}= 1.0 x10^{33}/cm^2(4/5/2016)

BEPC/BES关键科学问题

物质的基本结构和物质间的相互作用

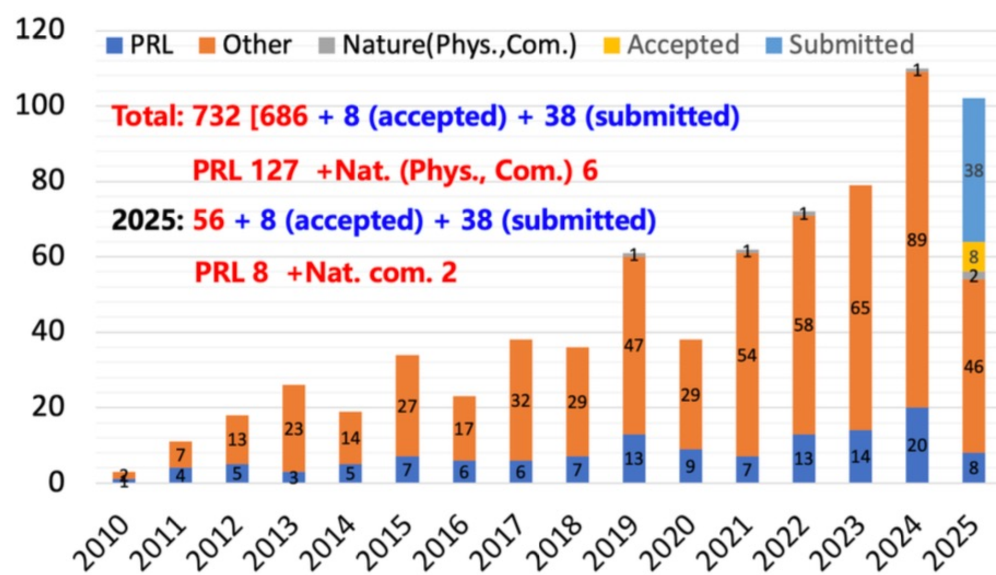
- 研究强子的结构，回答自然界中是否存在超出夸克模型的新型强子这一基本问题。

- 精确检验弱电统一理论，精确检验量子色动力学理论，寻找超出标准模型的新物理。

BESIII data sample

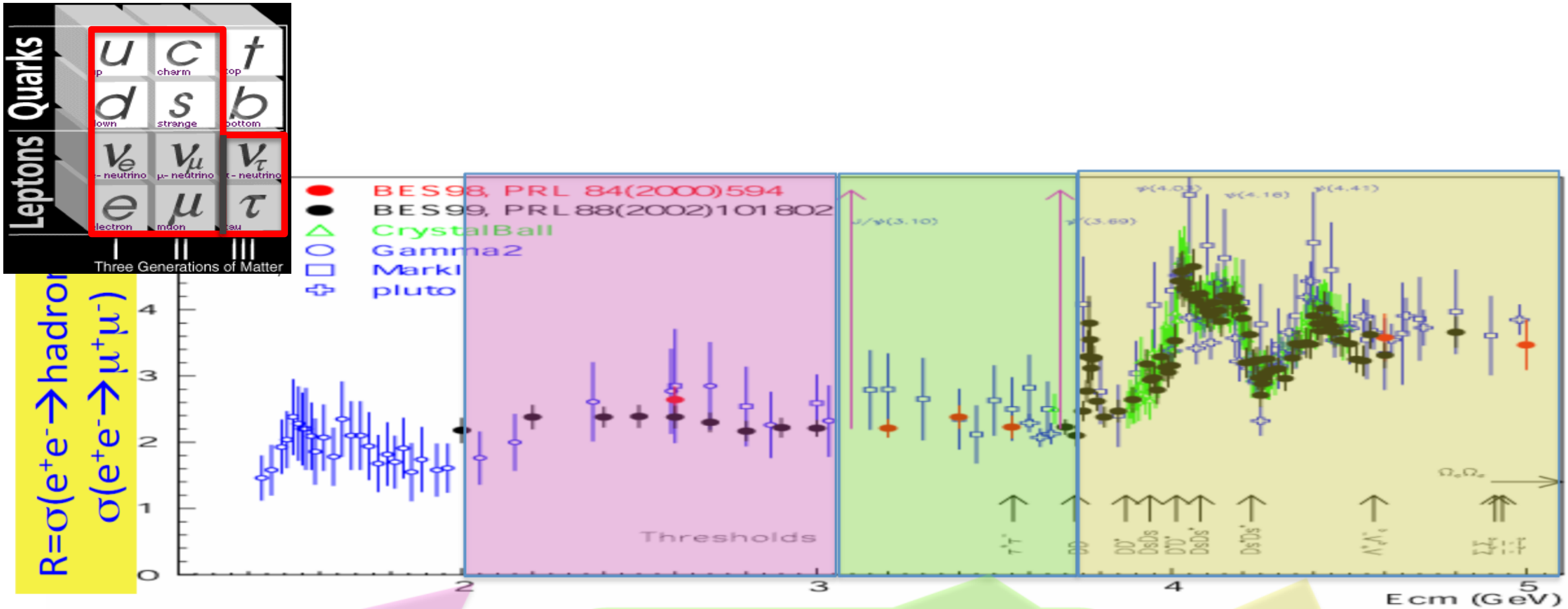
2009: 106M $\psi(2S)$
225M J/ψ
2010: 975 pb^{-1} at $\psi(3770)$
2011: 2.9 fb^{-1} *(total)* at $\psi(3770)$
482 pb^{-1} at 4.01 GeV
2012: 0.45B *(total)* $\psi(2S)$
1.3B *(total)* J/ψ
2013: 1092 pb^{-1} at 4.23 GeV
826 pb^{-1} at 4.26 GeV
540 pb^{-1} at 4.36 GeV
10×50 pb^{-1} scan 3.81 — 4.42 GeV
2014: 1029 pb^{-1} at 4.42 GeV
110 pb^{-1} at 4.47 GeV
110 pb^{-1} at 4.53 GeV
48 pb^{-1} at 4.575 GeV
567 pb^{-1} at 4.6 GeV
0.8 fb^{-1} R-scan 3.85 — 4.59 GeV

2015: R-scan 2 — 3 GeV + 2.175 GeV
2016: ~3fb^{-1} at 4.18 GeV (for D_s)
2017: 7×500 pb^{-1} scan 4.19 — 4.27 GeV
2018: more J/ψ *(and tuning new RF cavity)*
2019: 10B *(total)* J/ψ
8×500 pb^{-1} scan 4.13, 4.16, 4.29 — 4.44 GeV
2020: 3.8 fb^{-1} scan **4.61-4.7 GeV**
2021: 2 fb^{-1} scan **4.74-4.95 GeV**; 2.55B $\psi(2S)$
2022: 5 fb^{-1} at $\psi(3770)$
2023: 8.2 fb^{-1} at $\psi(3770)$
2024: ~5 fb^{-1} at $\psi(3770)$; $\psi(3770)$ scan data



in total ~55/fb

Physics at tau-charm Energy Region



- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

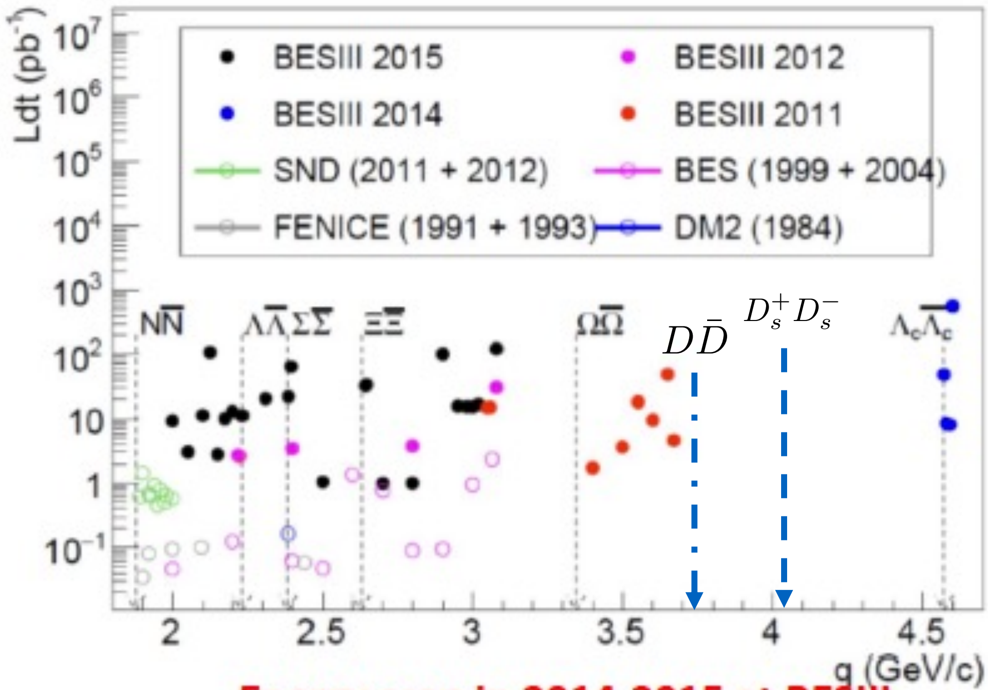
- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- D mesons
- f_D and f_{Ds}
- D_0-D_0 mixing
- Charm baryons

Unique data sets near thresholds

e^+e^- symmetric collision:
energy scan data sets at open charm thresholds

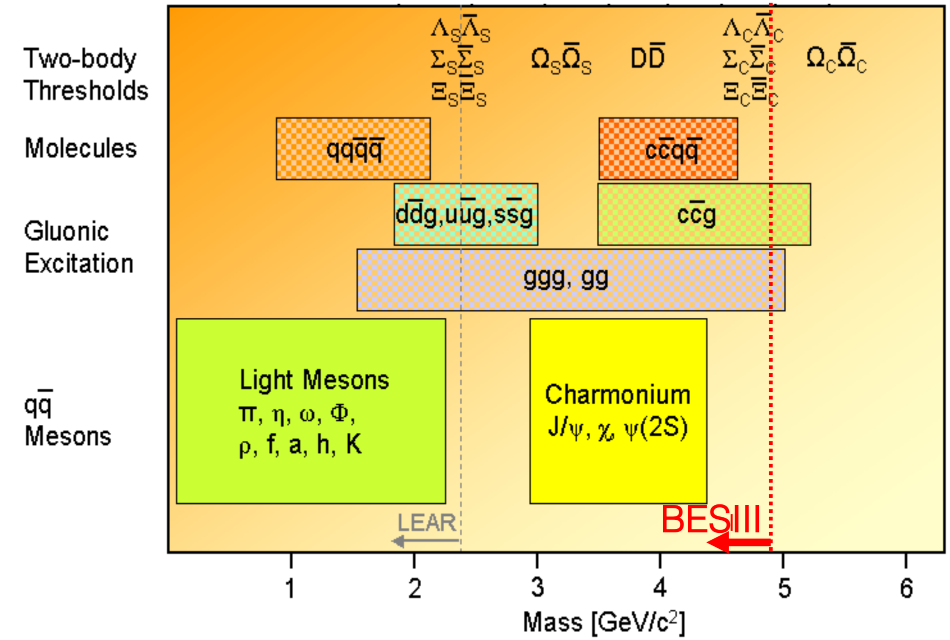
3.773 GeV, ~8 fb^{-1}, $D\bar{D}$
4.008 GeV, 0.48 fb^{-1}, $D_s\bar{D}_s$
4.18-4.23 GeV, 6.32 fb^{-1}, $D_s\bar{D}_s^*$
4.6-4.7 GeV, 4.4 fb^{-1}, $\Lambda_c\bar{\Lambda}_c$



Energy scan in 2014-2015 at BESIII

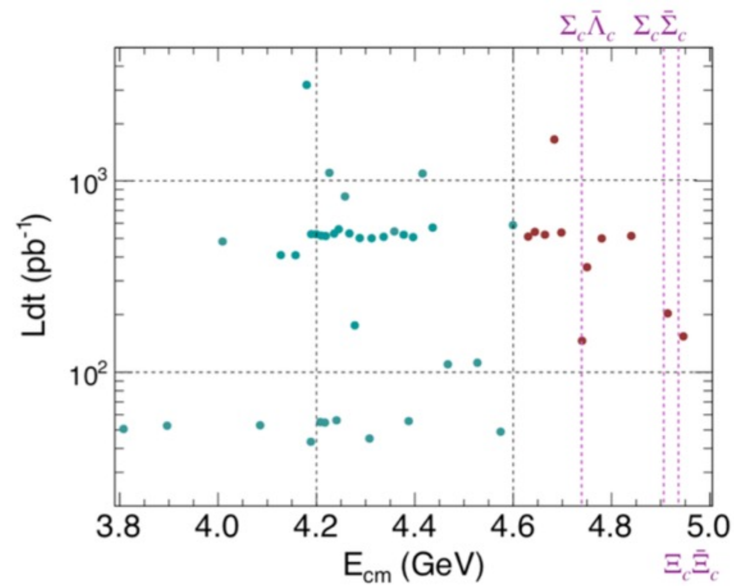
- **Meson and Baryon pair-productions near thresholds:**
  form-factors in the time-like production, precision branching fractions, relative phase;
- **Quantum-entangled pair productions of charmed mesons**
- **Hyperon and charmed baryon spin polarization in quantum entangled productions;**

Hadron Landscape



Hadron-physics challenges:

- Understanding of established states: precision spectroscopy
- Nature of exotic states: search and spectroscopy of unexpected states

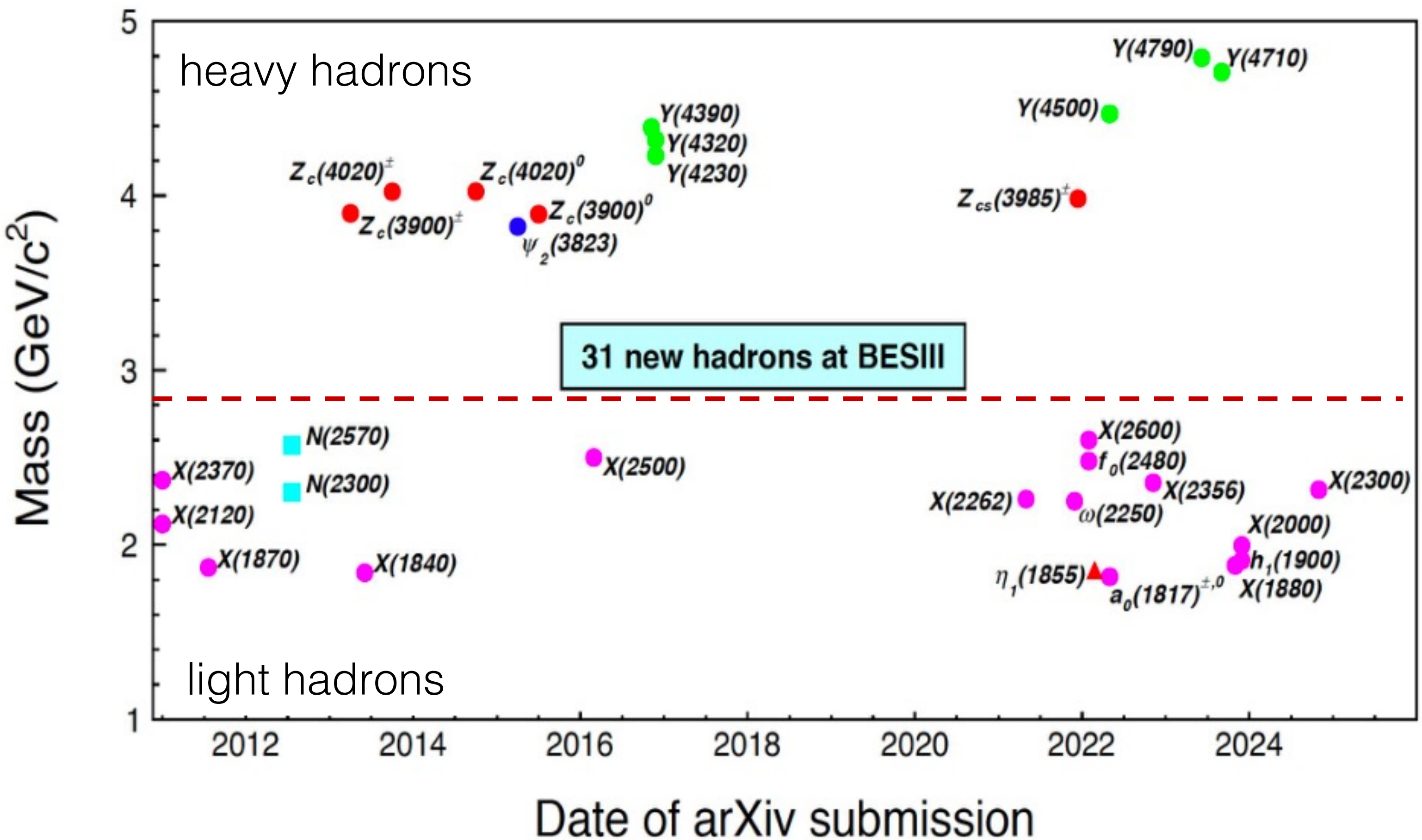


XYZ studies: about 23 /fb data above 3.8 GeV

At BESIII, two golden measures to study hadron spectroscopy, *esp*., to search for exotics

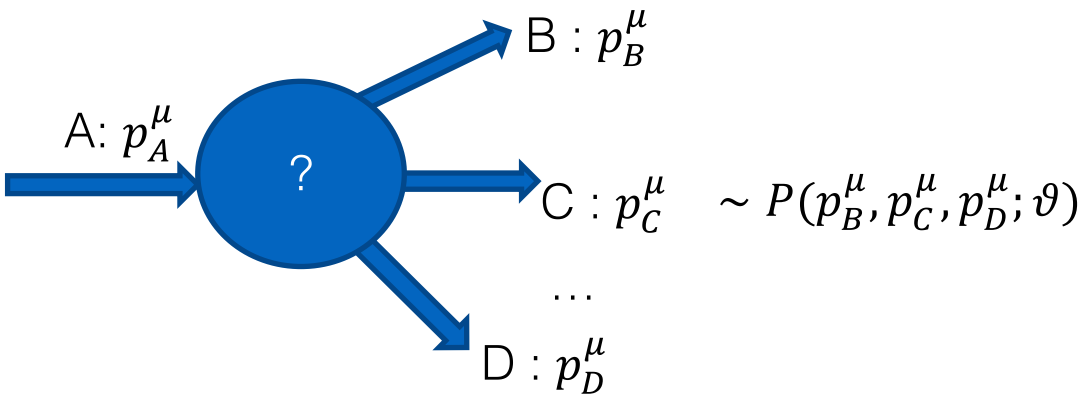
- Light hadrons: charmonium radiative decays (act as spin filter) (**10 B J/ψ and 2.7 B $\psi(2S)$**)
- Heavy hadrons: direct production, radiative and hadronic transitions (**data above 3.8 GeV**)

BESIII discoveries of new hadrons



Partial wave analysis

- Amplitude analysis / Partial wave analysis (PWA) is a powerful method to study multi-body decay processes, e.g.
  - to search for (exotic) resonances and measure their properties
  - to understand CP violation over phase space



- Most of previous fitters are designed for special processes or are time-consuming.

- A general PWA framework using modern acceleration technology (such as GPU, AD, …) is eagerly needed.

Partial wave analysis tools

- Closed source / hand coded
  - Tensor formulism: most of charm decays. [$D^+ \to K_S^0 \pi^+ \pi^0 \pi^0$: JHEP09, 077(2023)]
  - Helicity formulism: [$e^+ e^- \to \omega \pi^+ \pi^-$: JHEP08,159(2023)]
- GPUPWA:
  - First PWA tool based on GPU
  - Used in many PWA of light mesons: [$J/\psi \to \gamma\eta\eta$: PRD87, 092009(2013); $J/\psi \to \gamma\eta\eta'$: PRD106, 072012(2022)]
- FDC-PWA:
  - Feynman Diagram Calculation
  - Used in some baryon final states [$\psi' \to p\bar{p}\eta$:PRD88, 032010(2013); $e^+ e^- \to pK^-\bar{\Lambda}$: PRL131, 151901 (2023)]
- TF-PWA:
  - TensorFlow-based, configurable, GPU acceleration, AD
  - as an example: [$\Lambda_c^+ \to \Lambda\pi^+\pi^0$:JHEP12, 033(2022)]
- Other tools:
  - Amptools: [$\chi_{c1} \to \eta\pi^+\pi^-$: PRD95,032002(2017)]
  - PAWIAN: [$e^+ e^- \to \phi K^+ K^-$: PRD108, 032004 (2023)]
  - ComPWA: [$D^0 \to K_S K^+ K^-$: arXiv:2006.02800]

Properties and requirements of PWA tools

- Complex formula
  - Avoid hard coding, automatic formula generation
  - Rule-based amplitude evaluation
  - Constraints in special process
- Multiple dimension.
  - Study relation between many variables, e.g., masses and angles.
  - Proper way to consider resolution
  - Large size MC sample for integration to normalize the PDF.
- Large size of data (e.g.,10B J/ψ decays)
  - Fast calculation to reduce time cost.
  - Distribute the calculation into multi devices.

Configurable

High performance calculation

Configuration

- Why configurable?
  - Global representation for automation and transportability
  - General way to support more decays
- Different level
  - No configuration: hand coding / code templates
  - Decay card like:
    - key-value / command-parameters / structured
    - specify all possible decays (interactions)
    - with addition simplification rules
  - Auto search:
    - provide a large particle database
    - use rules to find all possible intermediate states
    - filter with requirement.

balance

GPUPWA
TensorFlowAnalysis

TF-PWA
PAWIAN
AmpGen

Automatic,
Simple

Controllable

FDC-PWA series
ComPWA series

Symbolic and numerical approaches

- Symbolic approach
  - require a Computer Algebra System (CAS) to simplify formulae
  - write/generate code from CAS outputs
  - procedure: configuration → CAS → formula → generated code → function → amplitude
  - simplifying the formula is difficult and time-consuming
- Numerical approach
  - combine function directly
  - rule based evaluation
  - procedure:
    configuration → function call → amplitude
  - w/o simplified formula, more computation might be required
  - allow caching rule to reduce computation

FDC-PWA series (REDUCE)
ComPWA series (SymPy)

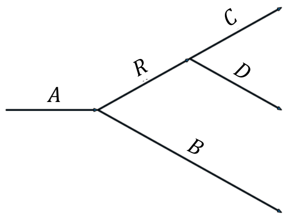
AmpGen
GPUPWA
Self hold tensor library

TF-PWA
PAWIAN
TensorFlowAnalysis

TF-PWA: Partial Wave Analysis with

- Fast
  - GPU based
  - Vectorized calculation
  - Automatic differentiation
    Quasi-Newton Method: scipy.optimize
- General
  - Model customization support
- Easy to use
  - Simple configuration file (example provided)
  - Most processing is automatic
  - All necessary functions implemented
  - Rich function support
- Open access
  - https://github.com/jiangyi15/tf-pwa

TF-PWA: amplitude factorization



$$A^R_{\lambda_A,\lambda'_B,\lambda'_C,\lambda'_D}$$

$$\sum_{\lambda} H_{\lambda_R\lambda_B} D^{j_A\star}_{\lambda_A,\lambda_R-\lambda_B}(\varphi_1,\theta_1,0) R(M) H_{\lambda_C,\lambda_D} D^{j_R\star}_{\lambda_R,\lambda_C-\lambda_D}(\varphi_2,\theta_2,0)$$

$$D^{j_B\star}_{\lambda_B,\lambda_B'}(\alpha_B,\beta_B,\gamma_B) D^{j_C\star}_{\lambda_C,\lambda_C'}(\alpha_C,\beta_C,\gamma_C) D^{j_D\star}_{\lambda_D,\lambda_D'}(\alpha_D,\beta_D,\gamma_D)$$

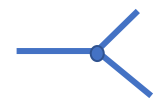
$$\frac{d\sigma}{d\Phi} \propto \sum_{\lambda_A} \sum_{\lambda_B,\lambda_C,\lambda_D} \left| \sum_R A^R_{\lambda_A,\lambda_B,\lambda_C,\lambda_D} \right|^2$$

Automatically calculated from decay structure

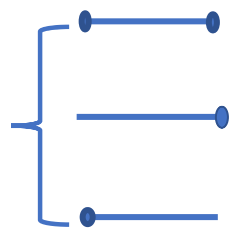
- automatic factorization of amplitude, as combination of summation and production
- automatic differentiation in likelihood minimization and error propagation
- optional optimization for better performances
  - amplitude caching (eg, resonance lineshape, …)
  - mixed likelihood for simultaneous fit

Feynman rules

Decay



Particle



user defined

$$A^{0\to1+2} = H_{\lambda_1,\lambda_2} D^{j_0\star}_{\lambda_0,\lambda_1-\lambda_2}(\varphi,\theta,0)$$

Wigner-D matrix

$$R(M) = \frac{1}{m_0^2 - M^2 - i m_0 \Gamma}, \cdots$$

1 or $\rho = 1 + \vec{p}\cdot\vec{\sigma}$

$D^{j_1\star}_{\lambda_1,\lambda_1'}(\alpha,\beta,\gamma)$ alignment

probability: $|\mathcal{A}|^2$

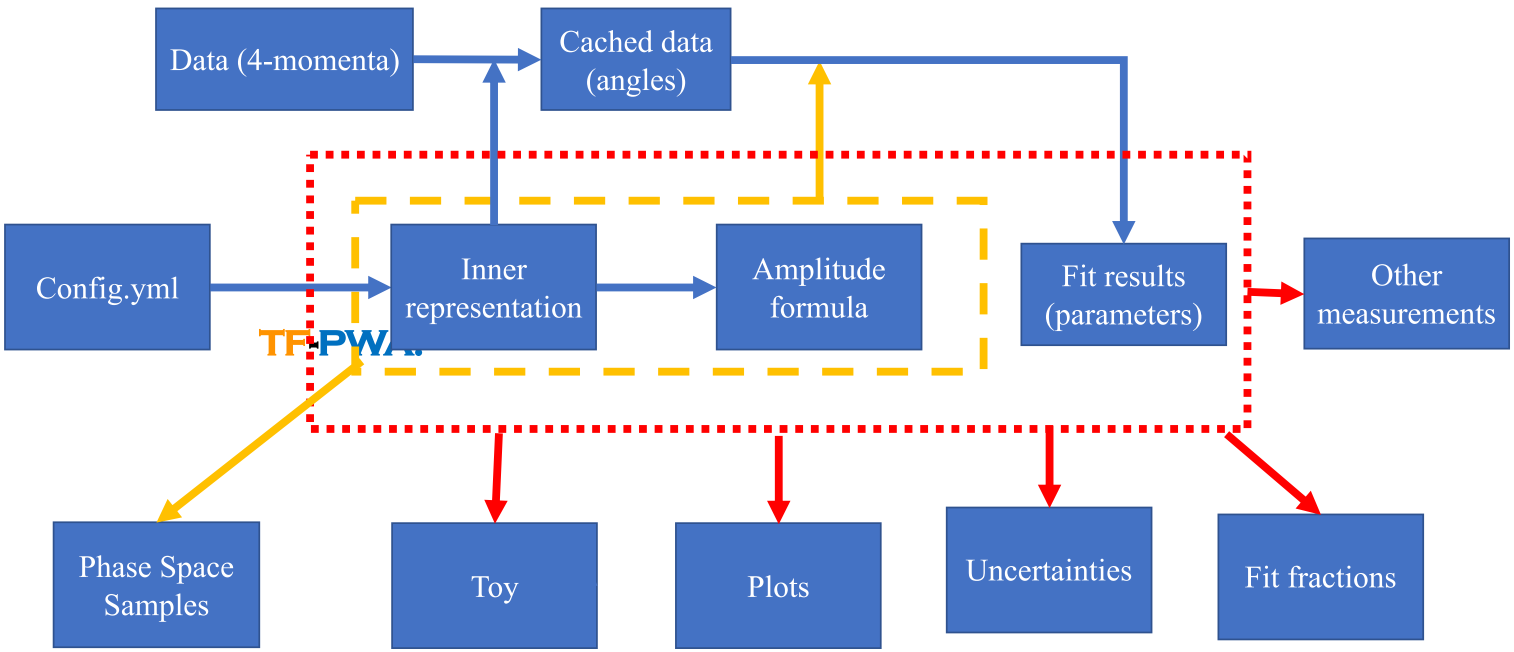
Decay Group: $\mathcal{A} = \tilde{A}_1 + \tilde{A}_2 + \cdots$

Decay Chain: $\tilde{A} = A_1 R A_2 \cdots$

Decay: Wigner D-matrix, $A = HD^{*J}(\phi,\theta,0)$

Particle: Breit-Wigner: $R(m)$, user defined

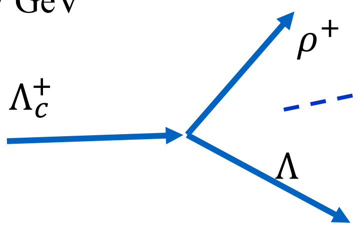
TF-PWA architecture

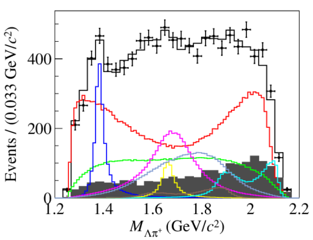


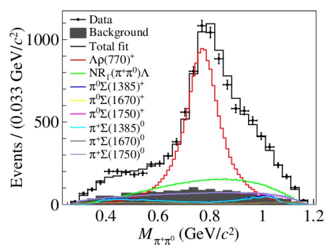
Example fit of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

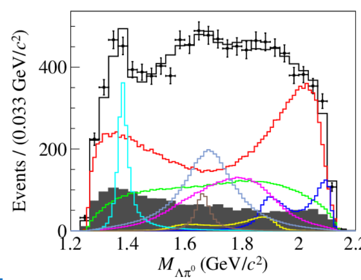
JHEP12, 033(2022)

- Simultaneous fit to 7 energy points from 4.6 to 4.7 GeV
  - ✓ in total around 10k events and 854k MC
  - ✓ 38 free parameters
  - ✓ dominated by $\Lambda_c^+ \to \Lambda\rho$: 57.2 ± 4.2%
  - ✓ clear peak for $\Lambda_c^+ \to \pi\Sigma(1385)$










```python
with config.params_trans() as pt:
    # g1 is fixed to 1
    g2_r = pt["L_c->Sigma1385p.pi0_g_ls_1r"]
    g2_phi = pt["L_c->Sigma1385p.pi0_g_ls_1i"]
    alpha = 2*g2_r*tf.cos(g2_phi) / (1+g2_r*g2_r)
print(alpha, pt.get_error(alpha))
```

$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^+(\Sigma(1385)^+) + 0^-(\pi^0)$

Amplitude	Magnitude	Phase ϕ (rad)
$g_{1,\frac{3}{2}}^{\Sigma(1385)^+}$	1.0 (fixed)	0.0 (fixed)
$g_{2,\frac{3}{2}}^{\Sigma(1385)^+}$	1.29 ± 0.25	2.82 ± 0.18

$$\alpha_{\Sigma(1385)\pi} = \frac{|H_{0,\frac{1}{2}}^{\Sigma(1385)}|^2 - |H_{0,\frac{-1}{2}}^{\Sigma(1385)}|^2}{|H_{0,\frac{1}{2}}^{\Sigma(1385)}|^2 + |H_{0,\frac{-1}{2}}^{\Sigma(1385)}|^2} = \frac{2\Re\left(g_{1,\frac{3}{2}}^{\Sigma(1385)} \cdot \bar{g}_{2,\frac{3}{2}}^{\Sigma(1385)}\right)}{|g_{1,\frac{3}{2}}^{\Sigma(1385)}|^2 + |g_{2,\frac{3}{2}}^{\Sigma(1385)}|^2}$$

$-0.789 \pm 0.098 \pm 0.056$

Listing 1: Full view of *config.yml* for $\Lambda_c^+ \to \Lambda\pi^+\pi^0$.

```yaml
decay:
    L_c:
        - [rho, L, p_break: True]
        - [S_p, pi0, p_break: True]
        - [S_0, pip, p_break: True]
    rho: [pip, pi0]
    S_0: [L, pi0]
    S_p: [L, pip]
particle:
    $top: L_c              # initial particle
    $finals: [L, pip, pi0] # final particles
    # rules for replacement
    rho: [ rho(770), NR ]
    S_0: [ Sigma1385z, Sigma1670z, Sigma1750z ]
    S_p: [ Sigma1385p, Sigma1670p, Sigma1750p ]
    # particle proporities
    rho(770):
        J: 1
        P: -1
        mass: 0.77511
        width: 0.1491
        model: GS_rho
    # or import from file
    $include: Resonances.yml
data:
    # particle order in data files
    dat_order: [L, pip, pi0]
    # path of data files
    data: ["data.dat"]
    phsp: ["mc.dat"]
# additional configuration, plot
plot:
    mass:
        S_0: {display: "$M(\\Lambda \\pi^{0})$"}
        S_p: {display: "$M(\\Lambda \\pi^{+})$"}
        rho: {display: "$M(\\pi^{+} \\pi^{0})$"}
```

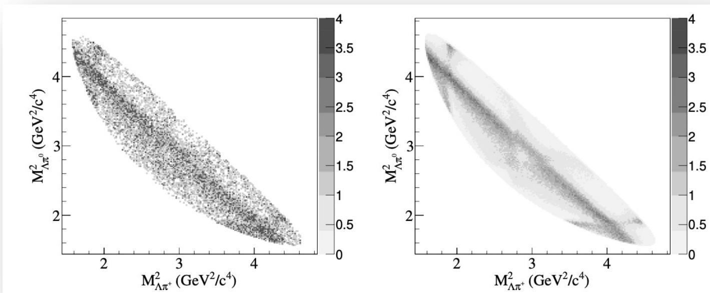
all decay chains added automatically

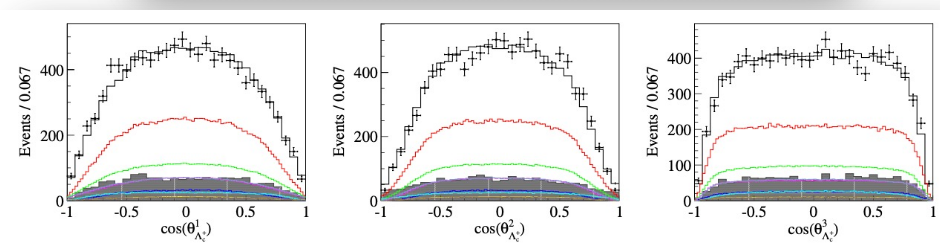
settings of properties of particles and resonances

datasets

plotting

Various outputs of the fitting results





Process	Magnitude	Phase ϕ (rad)	FF (%)	Significance
$\Lambda\rho(770)^+$	1.0 (fixed)	0.0 (fixed)	57.2 ± 4.2	$36.9\,\sigma$
$\Sigma(1385)^+\pi^0$	0.43 ± 0.06	-0.23 ± 0.18	7.18 ± 0.60	$14.8\,\sigma$
$\Sigma(1385)^0\pi^+$	0.37 ± 0.07	2.84 ± 0.23	7.92 ± 0.72	$16.0\,\sigma$
$\Sigma(1670)^+\pi^0$	0.31 ± 0.08	-0.77 ± 0.23	2.90 ± 0.63	$5.1\,\sigma$
$\Sigma(1670)^0\pi^+$	0.41 ± 0.07	2.77 ± 0.20	2.65 ± 0.58	$5.2\,\sigma$
$\Sigma(1750)^+\pi^0$	1.75 ± 0.21	-1.73 ± 0.11	16.6 ± 2.2	$10.1\,\sigma$
$\Sigma(1750)^0\pi^+$	1.83 ± 0.21	1.34 ± 0.11	17.5 ± 2.3	$10.2\,\sigma$
$\Lambda + NR_{1^-}$	4.05 ± 0.47	2.16 ± 0.13	29.7 ± 4.5	$10.5\,\sigma$

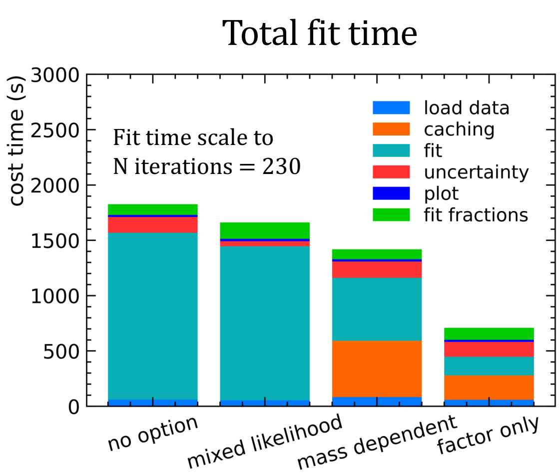
	Result
$\frac{\mathcal{B}(\Lambda_c^+\to\Lambda\rho(770)^+)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)}$	$(57.2 \pm 4.2 \pm 4.9)\%$
$\frac{\mathcal{B}(\Lambda_c^+\to\Sigma(1385)^+\pi^0)\cdot\mathcal{B}(\Sigma(1385)^+\to\Lambda\pi^+)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)}$	$(7.18 \pm 0.60 \pm 0.64)\%$
$\frac{\mathcal{B}(\Lambda_c^+\to\Sigma(1385)^0\pi^+)\cdot\mathcal{B}(\Sigma(1385)^0\to\Lambda\pi^0)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)}$	$(7.92 \pm 0.72 \pm 0.80)\%$
$\mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	$(4.06 \pm 0.30 \pm 0.35 \pm 0.23) \times 10^{-2}$
$\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	$(5.86 \pm 0.49 \pm 0.52 \pm 0.35) \times 10^{-3}$
$\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$	$(6.47 \pm 0.59 \pm 0.66 \pm 0.38) \times 10^{-3}$
$\alpha_{\Lambda\rho(770)^+}$	$-0.763 \pm 0.053 \pm 0.045$
$\alpha_{\Sigma(1385)^+\pi^0}$	$-0.917 \pm 0.069 \pm 0.056$
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.789 \pm 0.098 \pm 0.056$

I.F.	$\Lambda + NR_{1^-}$	$\Sigma(1385)^0\pi^+$	$\Sigma(1385)^+\pi^0$	$\Sigma(1670)^0\pi^+$	$\Sigma(1670)^+\pi^0$	$\Sigma(1750)^0\pi^+$	$\Sigma(1750)^+\pi^0$
$\Sigma(1385)^0\pi^+$	-0.50 ± 0.38						
$\Sigma(1385)^+\pi^0$	-0.76 ± 0.36	-0.05 ± 0.04					
$\Sigma(1670)^0\pi^+$	-0.36 ± 0.17	-0.00 ± 0.00	-0.66 ± 0.09				
$\Sigma(1670)^+\pi^0$	-0.34 ± 0.15	-0.58 ± 0.12	0.00 ± 0.00	0.04 ± 0.02			
$\Sigma(1750)^0\pi^+$	-8.1 ± 3.1	-0.03 ± 0.00	0.43 ± 0.07	-0.01 ± 0.00	0.08 ± 0.05		
$\Sigma(1750)^+\pi^0$	-7.2 ± 3.1	0.35 ± 0.08	-0.02 ± 0.00	0.23 ± 0.05	-0.00 ± 0.00	-6.23 ± 0.92	
$\Lambda\rho(770)^+$	-2.7 ± 4.4	-5.94 ± 0.56	-6.01 ± 0.46	0.72 ± 0.29	1.29 ± 0.26	-2.1 ± 1.3	-3.1 ± 1.3

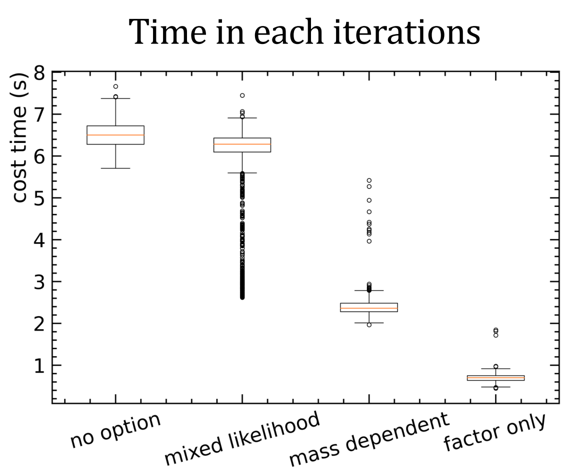
Real analysis performance

- Optimized method in Factor System page
  - Caching method (in Page 14)
    - Large time for caching
    - required more memory
    - limited to special cases
  - All the process is automatic (from config.yml to all basic results)

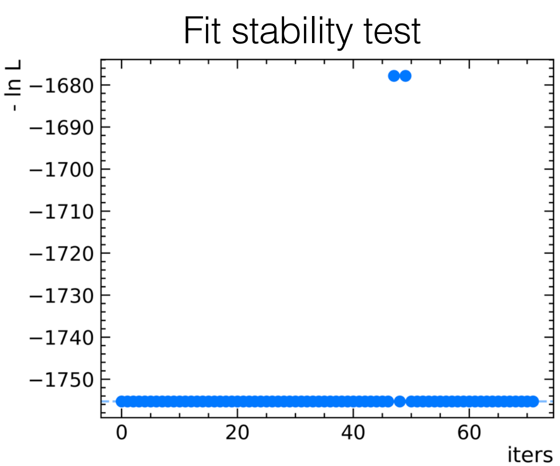
Environment:
NVIDIA RTX 3080
TensorFlow 2.2
CUDA 10.1



Only half of hours
for ALL the process



Caching provide 8 times speed up
for fit parts



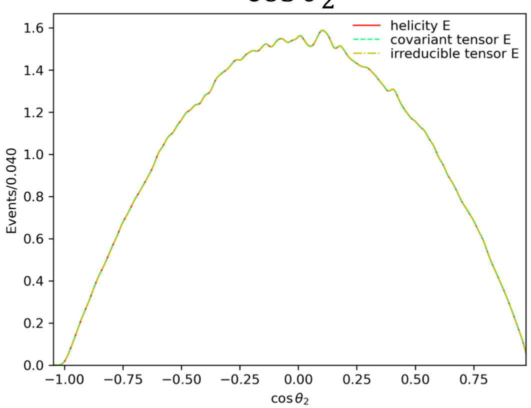
Fit stability looks well
in random initial parameters

Implement of Covariant tensor formula

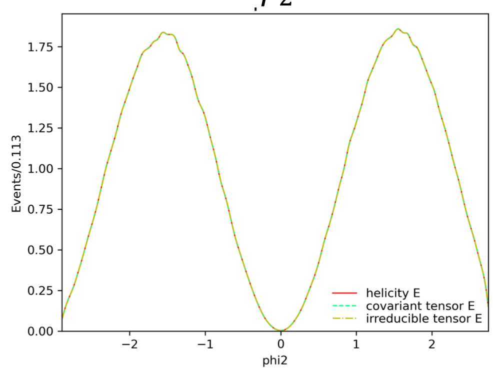
arxiv:2301.01575

- Covariant tensor formula
  - Covariant orbital-spin scheme for any spin based on irreducible tensor
  - Traditional covariant tensor formula
- Include some symbolic method for automation.
- Angular distribution consist in simple cases: Eur. Phys. J. A 16 537-547(2003) Zou, Hugg
  - $0^- \to R_1(1^+)0^-, R_1(1^+) \to R_2(1^-)0^-, R_2(1^-) \to 0^-0^-$
- Preliminary implement, working in process.

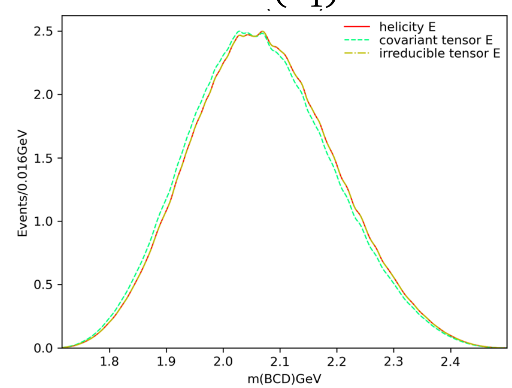
$\cos\theta_2$



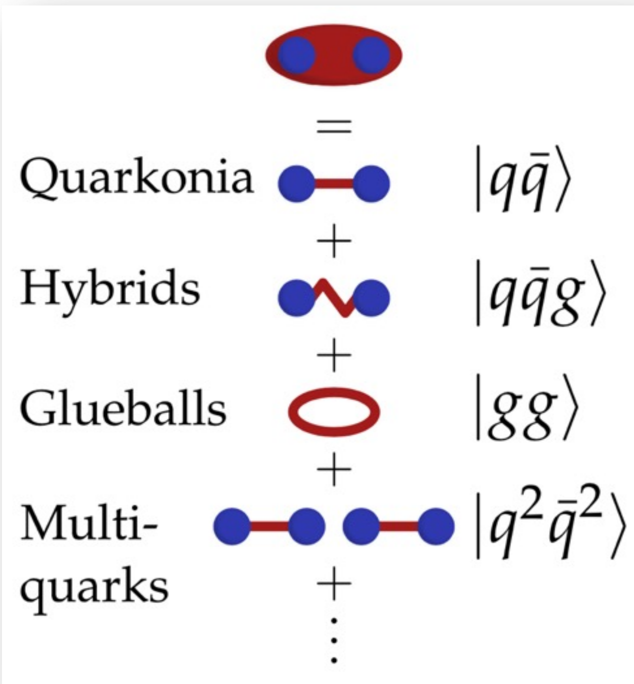
ϕ_2



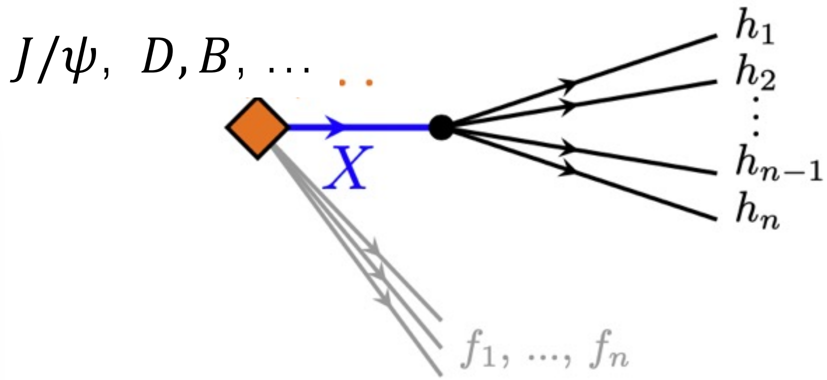
Fluctuations due to MC sample size $M(R_1)$



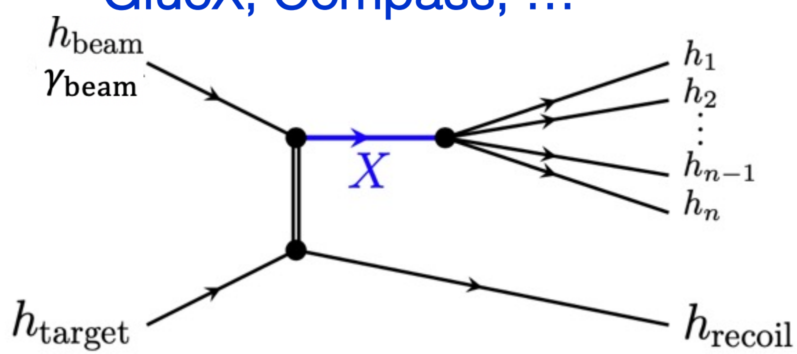
Light hadron spectroscopy



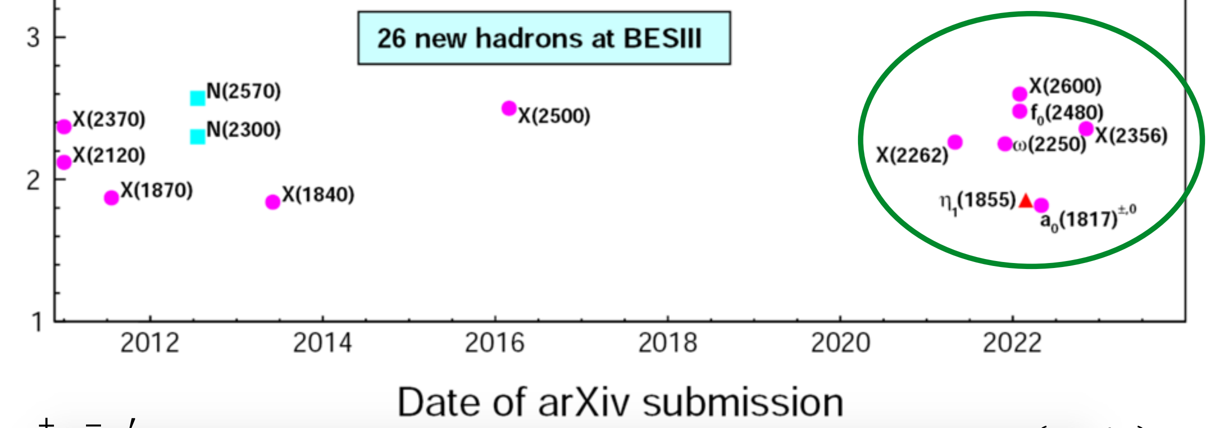
BESIII, LHCb, Belle (II) …



GlueX, Compass, …

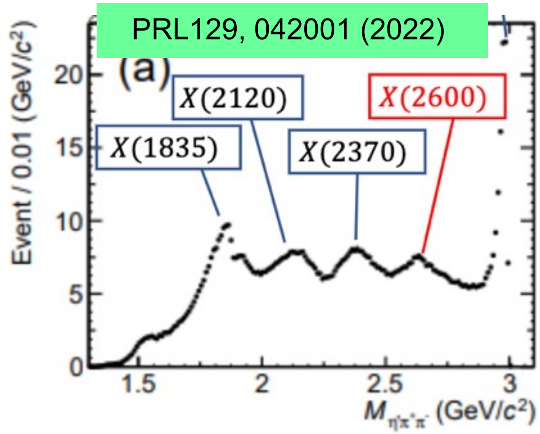


BESIII



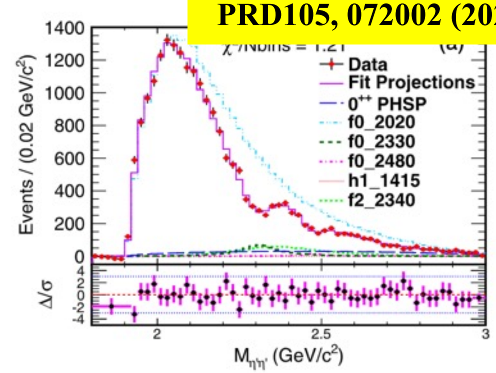
$X(2600)$ in $J/\psi \to \gamma\pi^+\pi^-\eta'$

PRL129, 042001 (2022)



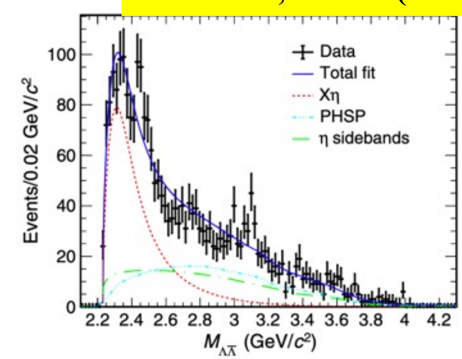
$f_0(2480)$ in $J/\psi \to \gamma\eta'\eta'$

PRD105, 072002 (2022)



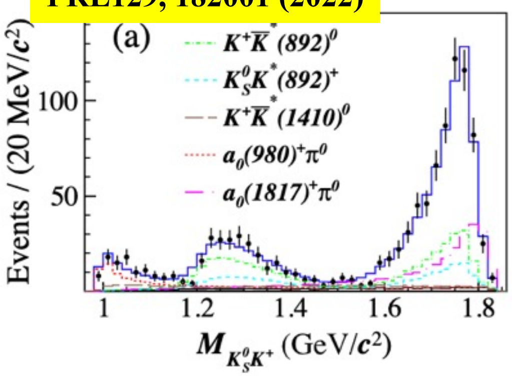
$X(2356) \to \Lambda\bar{\Lambda}$ in $e^+e^- \to \eta\Lambda\bar{\Lambda}$

PRD 107, 112001 (2023)



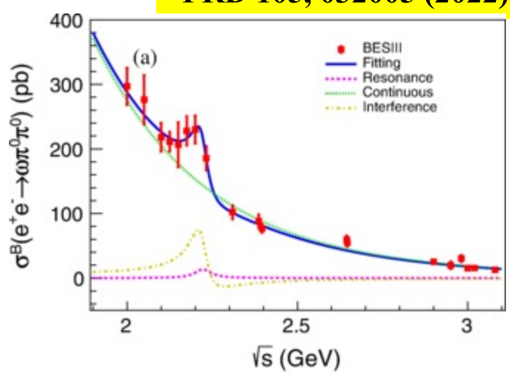
$a_0(1817)$ in $D_s^+ \to K_S K^+\pi^0$

PRL129, 182001 (2022)



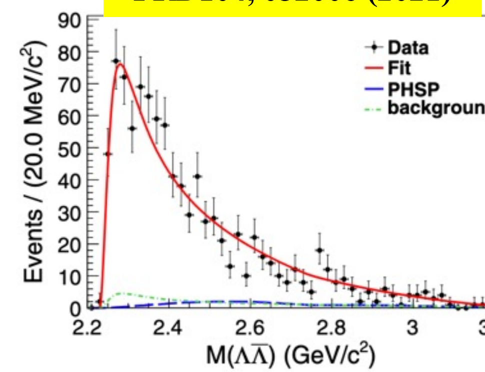
$\omega(2250)$ in $e^+e^- \to \omega\pi^0\pi^0$

PRD 105, 032005 (2022)

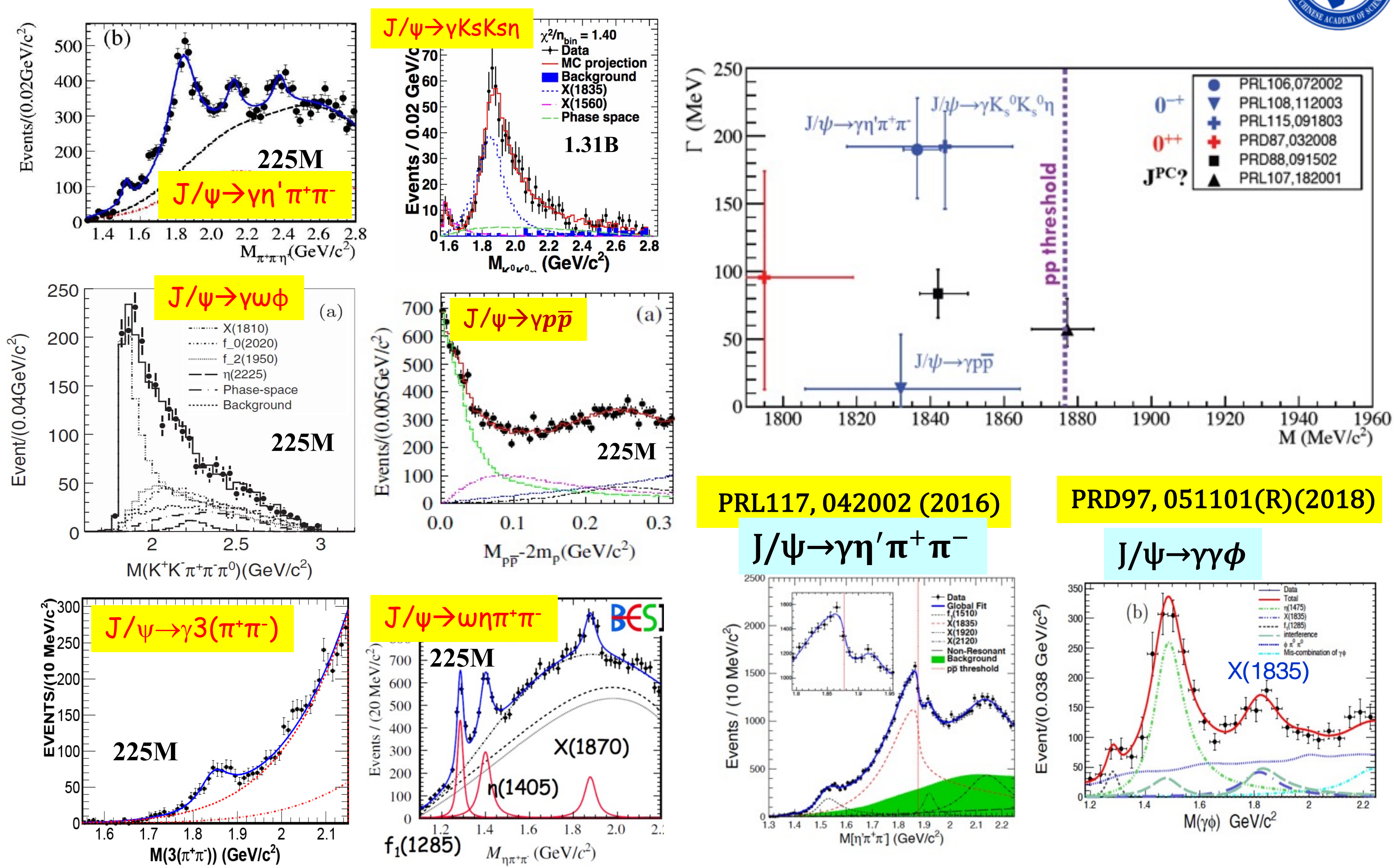


$X(2262) \to \Lambda\bar{\Lambda}$ in $e^+e^- \to \phi\Lambda\bar{\Lambda}$

PRD104, 052006 (2021)



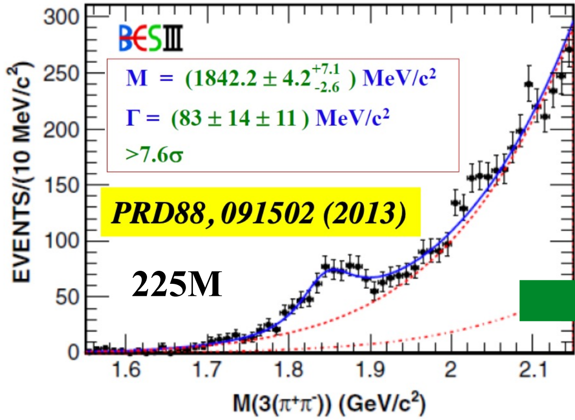
X($p\bar{p}$)/X(18??) from J/ψ radiative decays



Are they the same state? It is crucial to understand their connections.

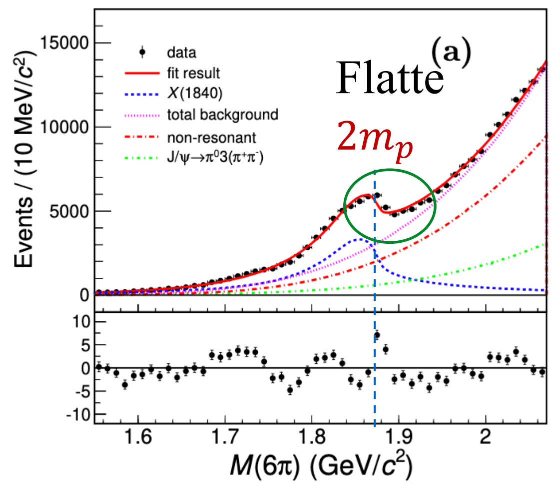
Anomolous lineshape of X(1840) in $J/\psi \to \gamma 3(\pi^+\pi^-)$

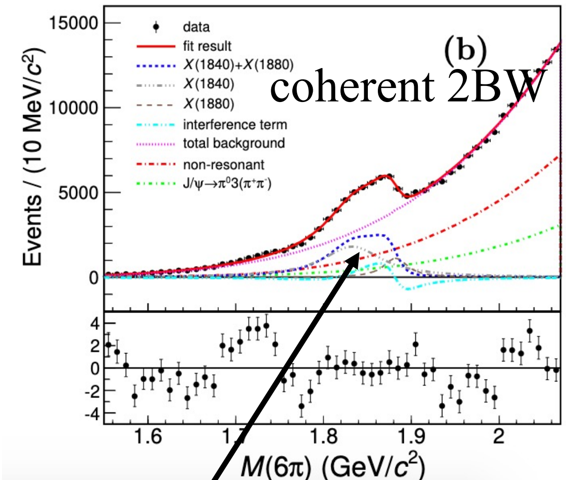
PRL132, 151901 (2024)



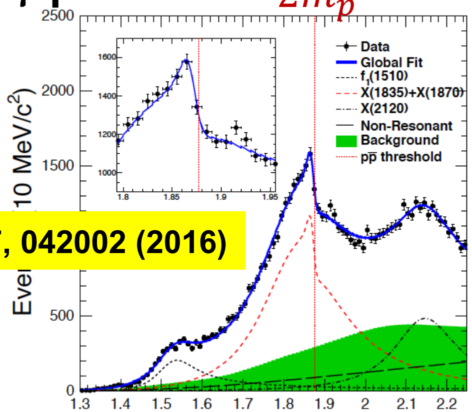
10B J/ψ events are analyzed:

50x more than the previous BESIII work





$J/\psi \to \gamma \eta' \pi^+\pi^-$



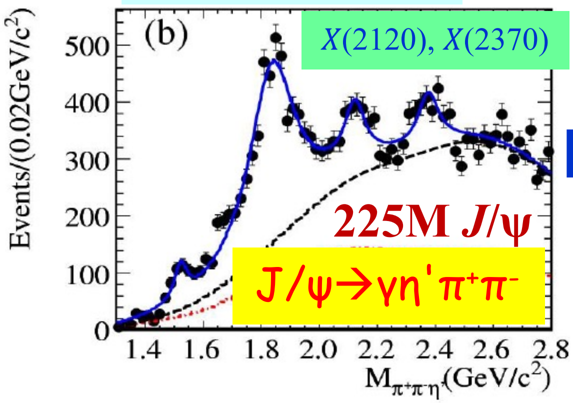
PRL 117, 042002 (2016)

$X(1835)$	
Mass (MeV/c^2)	$1825.3 \pm 2.4^{+17.3}_{-2.4}$
Width (MeV/c^2)	$245.2 \pm 13.1^{+4.6}_{-9.6}$
$X(1870)$	
Mass (MeV/c^2)	$1870.2 \pm 2.2^{+2.3}_{-0.7}$
Width (MeV/c^2)	$13.0 \pm 6.1^{+2.1}_{-3.8}$

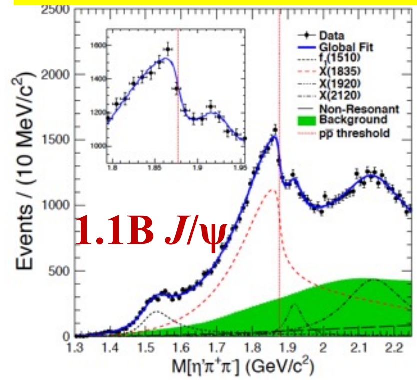
Parameters	Solution I	Solution II
$M_{X(1840)}$ (MeV/c^2)	$1832.5 \pm 3.1 \pm 2.5$	
$\Gamma_{X(1840)}$ (MeV)	$80.7 \pm 5.2 \pm 7.7$	
$\mathcal{B}_{X(1840)}$ ($\times 10^{-5}$)	$1.19 \pm 0.30 \pm 0.15$	$2.07 \pm 0.50 \pm 0.36$
$M_{X(1880)}$ (MeV/c^2)	$1882.1 \pm 1.7 \pm 0.7$	
$\Gamma_{X(1880)}$ (MeV)	$30.7 \pm 5.5 \pm 2.4$	
$\mathcal{B}_{X(1880)}$ ($\times 10^{-5}$)	$0.29 \pm 0.20 \pm 0.09$	$1.19 \pm 0.31 \pm 0.18$

The X(2120), X(2370) and X(2600)

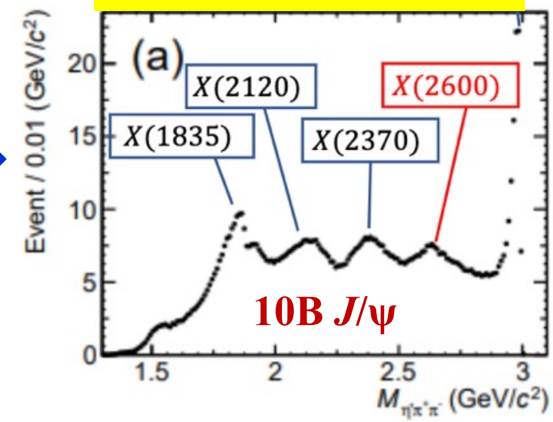
$J/\psi \to \gamma\eta'\pi^+\pi^-$



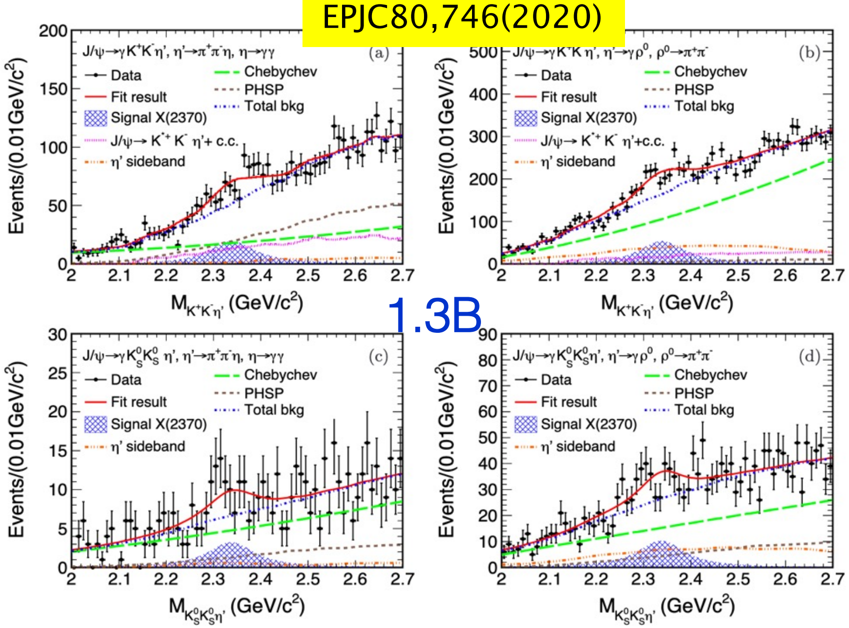
PRL117, 042002 (2016)



PRL129, 042001 (2022)



EPJC80,746(2020)



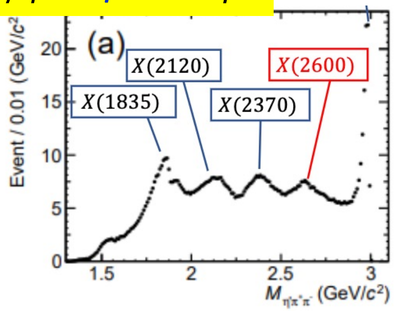
- Candidates of glueball states
- Combined analysis of $J/\psi \to \gamma K^+K^-\eta'$ and $\gamma K_S K_S \eta'$

$$M_{X(2370)} = 2341.6 \pm 6.5(\text{stat.}) \pm 5.7(\text{syst.})\ \text{MeV}/c^2,$$
$$\Gamma_{X(2370)} = 117 \pm 10(\text{stat.}) \pm 8(\text{syst.})\ \text{MeV},$$

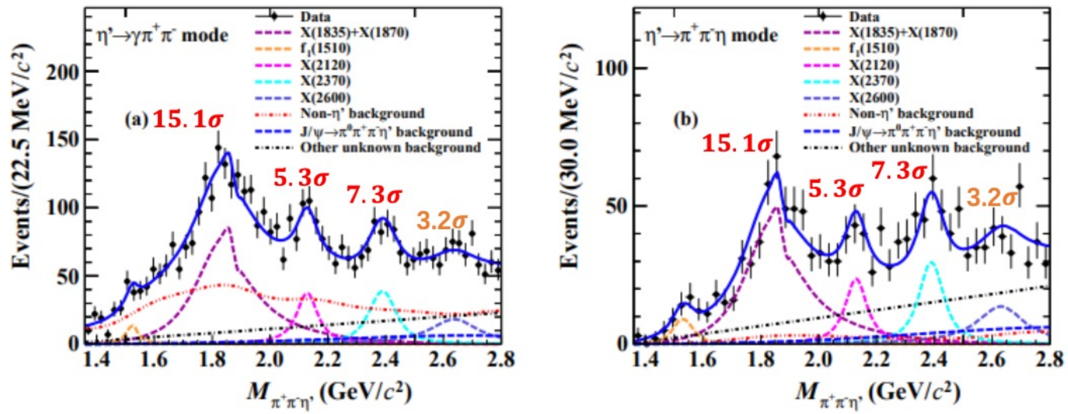
Observation of $X(2370) \to K\bar{K}\eta'$ with stat. significance of 8.3σ

BESIII EM Dalitz decay of $J/\psi \to e^+e^-\pi^+\pi^-\eta'$

$J/\psi \to \gamma\pi^+\pi^-\eta'$



PRL129, 022002(2022)

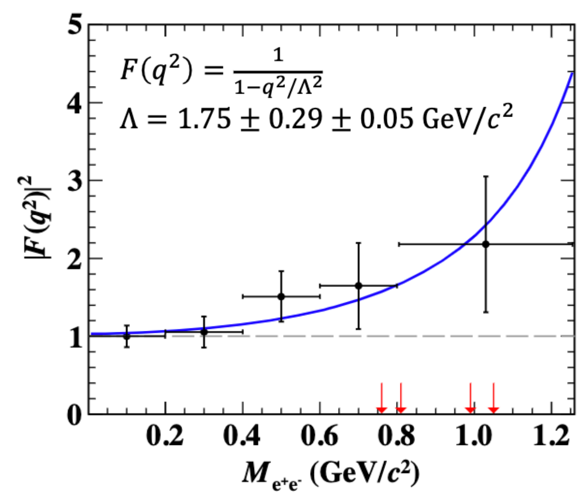


reconstruct η' from $\gamma\pi^+\pi^-$ (left) & $\eta(\to\gamma\gamma)\pi^+\pi^-$ (right)

- Observation of X(1835), X(2120), and X(2370) in EM Dalitz decays
- First measurement of the TFF between J/ψ and X(1835)

Branching fractions of $J/\psi \to e^+e^-X$, $X \to \pi^+\pi^-\eta'$		
$X = X(1835)$	(solution I)	$(3.58 \pm 0.19 \pm 0.16) \times 10^{-6}$
	(solution II)	$(4.43 \pm 0.23 \pm 0.19) \times 10^{-6}$
$X = X(2120)$		$(0.82 \pm 0.12 \pm 0.06) \times 10^{-6}$
$X = X(2370)$		$(1.08 \pm 0.14 \pm 0.10) \times 10^{-6}$

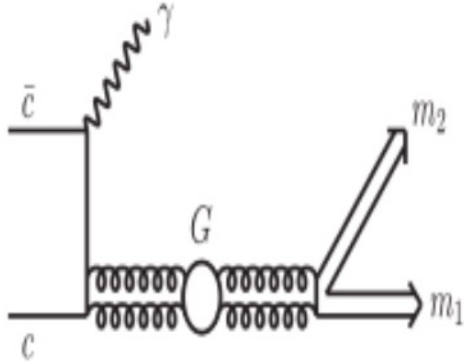
$$\frac{d\Gamma(J/\psi \to X(1835)e^+e^-)}{dq^2\Gamma(J/\psi \to X(1835)\gamma)} = |F(q^2)|^2 \times [\text{QED}(q^2)],$$

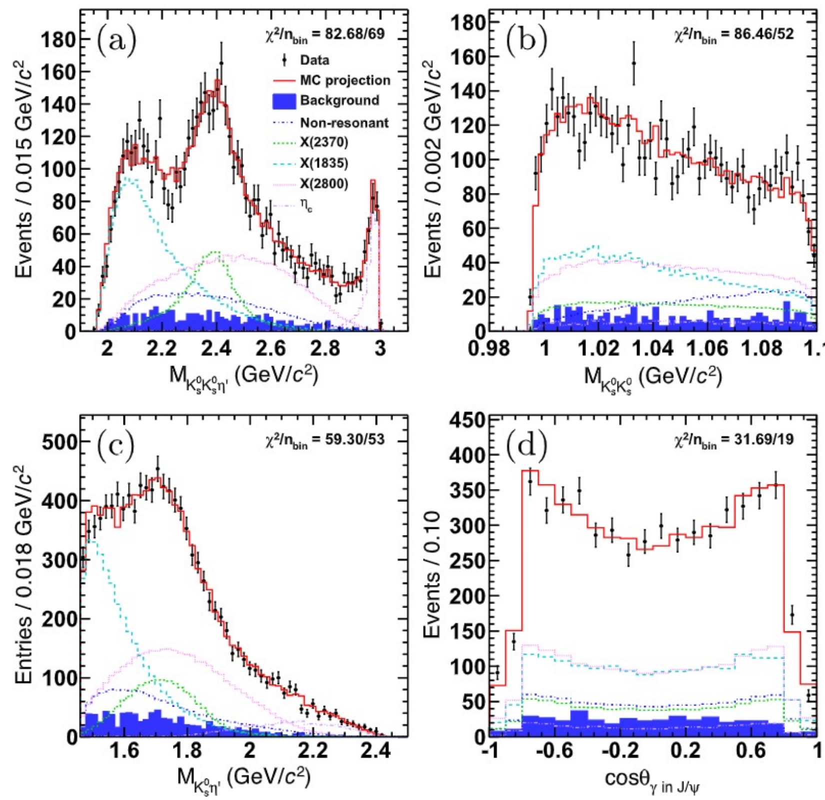


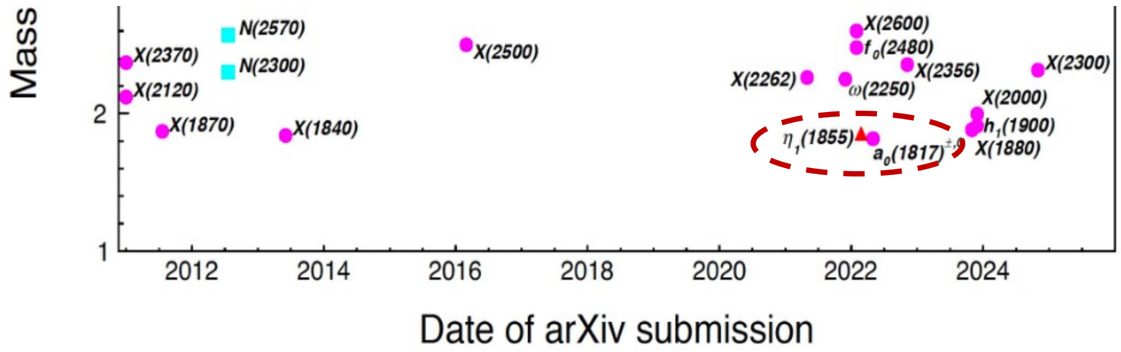
X(2370) in $J/\psi \to \gamma K_S K_S \eta'$

- Partial wave analysis $J/\psi \to \gamma K_S K_S \eta'$ in 10B J/ψ decays **PRL 132.181901 (2024)**
- $X(2370) \to K_S K_S \eta'$ significance larger than 14 σ
- mass $2395 \pm 11^{+26}_{-94}$ MeV$/c^2$; width $188^{+18}_{-17}{}^{+124}_{-33}$ MeV
- spin-parity is determined to be 0^{-+}
- candidate for lightest pseudoscalar glueball predicted by LQCD

J/ψ radiative decays are gluon-rich processes

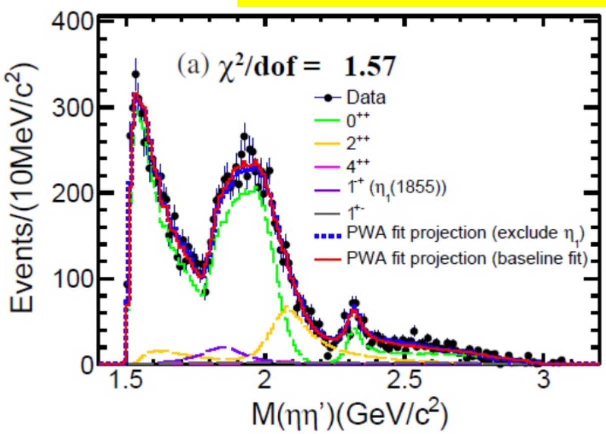






Observation of $\eta_1(1855)(1^{-+})$ with exotic quantum number

PRL129, 192002 (2022)
PRD106, 072012 (2022)

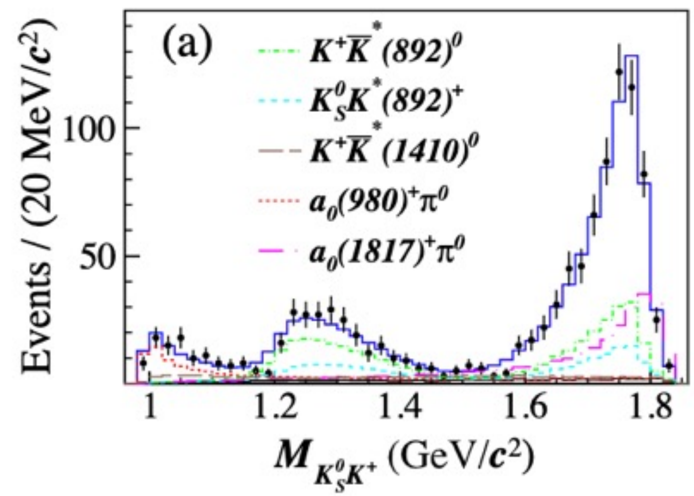


PWA of $J/\psi \to \gamma\eta\eta'$ in 10B J/ψ events

Must be exotic state!
Hybrid? Molecule? Tetraquark?

Observation of $a_0(1817)^+$ in $D_s^+ \to K_S K^+ \pi^0$

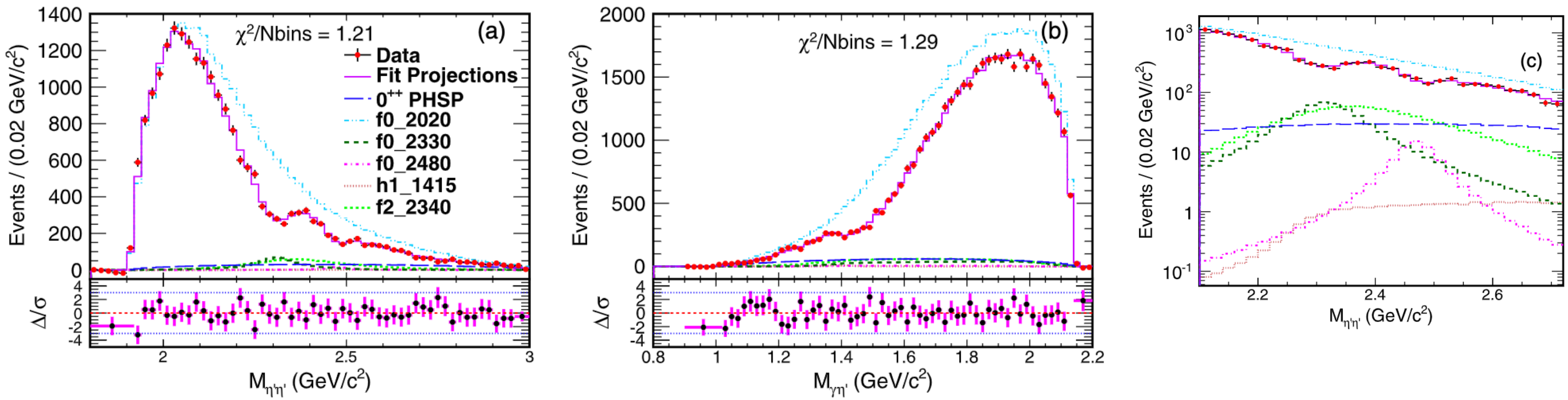
PRL129, 182001 (2022)



A new a_0 isospin triplet!

PWA of $J/\psi \to \gamma\eta'\eta'$

PRD105, 072002 (2022)



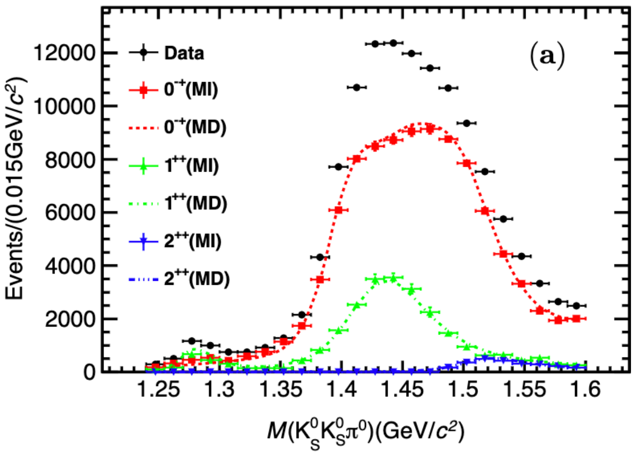
Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV})$	B.F.	Significance (σ)
$f_0(2020)$	$1982 \pm 3^{+54}_{-0}$	$436 \pm 4^{+46}_{-49}$	$(2.63 \pm 0.06^{+0.31}_{-0.46}) \times 10^{-4}$	$\gg 25$
$f_0(2330)$	$2312 \pm 2^{+10}_{-0}$	$134 \pm 5^{+30}_{-9}$	$(6.09 \pm 0.64^{+4.00}_{-1.68}) \times 10^{-6}$	16.3
$f_0(2480)$	$2470 \pm 4^{+4}_{-6}$	$75 \pm 9^{+11}_{-8}$	$(8.18 \pm 1.77^{+3.73}_{-2.23}) \times 10^{-7}$	5.2
$h_1(1415)$	$1384 \pm 6^{+9}_{-0}$	$66 \pm 10^{+12}_{-10}$	$(4.69 \pm 0.80^{+0.74}_{-1.82}) \times 10^{-7}$	5.3
$f_2(2340)$	$2346 \pm 8^{+22}_{-6}$	$332 \pm 14^{+26}_{-12}$	$(8.67 \pm 0.70^{+0.61}_{-1.67}) \times 10^{-6}$	16.1
0^{++} PHSP	⋯	⋯	$(1.17 \pm 0.23^{+4.09}_{-0.70}) \times 10^{-5}$	15.7

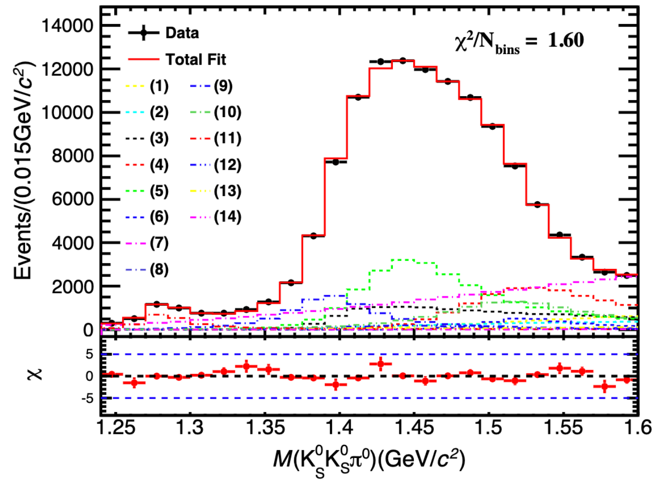
- new decay modes for $f_0(2020)$, $f_0(2330)$, and $f_0(2340)$
- new state $f_0(2480)$ firstly observed
- $f_0(2020)$ a scalar glueball? $\frac{\Gamma(f_0(2020) \to \eta\eta')}{\Gamma(f_0(2020) \to \eta'\eta')} = 0.0148$

PWA of $J/\psi \to \gamma K_S K_S \pi^0$

JHEP03, 121 (2023)

- To explore the nature of $\eta(1405)$ and $\eta(1475)$: radial ex-citations of the η and η′? non-$q\bar{q}$ exotic state?
- A clean channel with negligible background





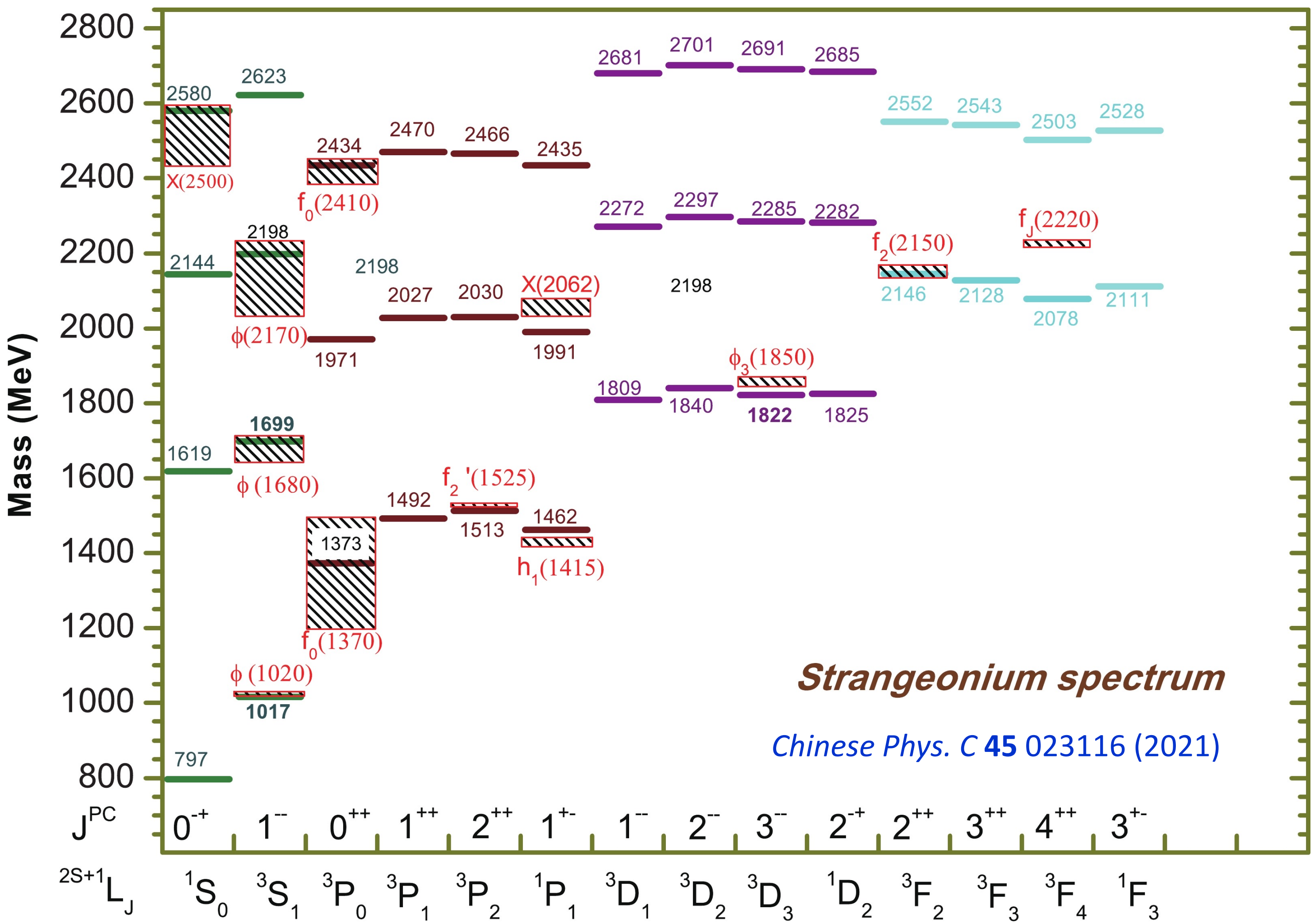
Components
(1). $J/\psi \to \gamma \text{PHSP}(0^{-+}) \to \gamma K^*(892)^0 K_S^0 \to \gamma K_S^0 K_S^0 \pi^0$
(2). $J/\psi \to \gamma \text{PHSP}(1^{++}) \to \gamma K^*(892)^0 K_S^0 \to \gamma K_S^0 K_S^0 \pi^0$
(3). $J/\psi \to \gamma \eta(1405) \to \gamma K_S^0 (K_S^0 \pi^0)_{\text{P-wave}} \to \gamma K_S^0 K_S^0 \pi^0$
(4). $J/\psi \to \gamma \eta(1475) \to \gamma K_S^0 (K_S^0 \pi^0)_{\text{P-wave}} \to \gamma K_S^0 K_S^0 \pi^0$
(5). $J/\psi \to \gamma f_1(1420) \to \gamma K^*(892)^0 K_S^0 \to \gamma K_S^0 K_S^0 \pi^0$
(6). $J/\psi \to \gamma f_2(1525) \to \gamma K^*(892)^0 K_S^0 \to \gamma K_S^0 K_S^0 \pi^0$
(7). $J/\psi \to \gamma \text{PHSP}(0^{-+}) \to \gamma a_0(980)^0 \pi^0 \to \gamma K_S^0 K_S^0 \pi^0$
(8). $J/\psi \to \gamma \text{PHSP}(2^{-+}) \to \gamma a_0(980)^0 \pi^0 \to \gamma K_S^0 K_S^0 \pi^0$
(9). $J/\psi \to \gamma \eta(1405) \to \gamma (K_S^0 K_S^0)_{\text{S-wave}} \pi^0 \to \gamma K_S^0 K_S^0 \pi^0$
(10). $J/\psi \to \gamma \eta(1475) \to \gamma (K_S^0 K_S^0)_{\text{S-wave}} \pi^0 \to \gamma K_S^0 K_S^0 \pi^0$
(11). $J/\psi \to \gamma f_1(1285) \to \gamma a_0(980)^0 \pi^0 \to \gamma K_S^0 K_S^0 \pi^0$
(12). $J/\psi \to \gamma f_1(1420) \to \gamma a_0(980)^0 \pi^0 \to \gamma K_S^0 K_S^0 \pi^0$
(13). $J/\psi \to \gamma \eta(1405) \to \gamma a_2(1320)^0 \pi^0 \to \gamma K_S^0 K_S^0 \pi^0$
(14). $J/\psi \to \gamma \eta(1475) \to \gamma a_2(1320)^0 \pi^0 \to \gamma K_S^0 K_S^0 \pi^0$

In MI-PWA, large flat 0^{-+} components between 1.4-1.5 GeV

Resonance	M(MeV/c^2)	Γ(MeV)	Decay Mode	B.F.	Sig.(σ)
$\eta(1405)$	$1391.7 \pm 0.7^{+11.3}_{-0.3}$	$60.8 \pm 1.2^{+5.5}_{-12.0}$	$J/\psi \to \gamma \eta(1405) \to \gamma K_S^0 (K_S^0 \pi^0)_{\text{P-wave}} \to \gamma K_S^0 K_S^0 \pi^0$	$(5.84 \pm 0.12^{+2.03}_{-3.36}) \times 10^{-5}$	$\gg 35$
			$J/\psi \to \gamma \eta(1405) \to \gamma (K_S^0 K_S^0)_{\text{S-wave}} \pi^0 \to \gamma K_S^0 K_S^0 \pi^0$	$(2.88 \pm 0.04^{+1.64}_{-0.38}) \times 10^{-5}$	18.4
$\eta(1475)$	$1507.6 \pm 1.6^{+15.5}_{-32.2}$	$115.8 \pm 2.4^{+14.8}_{-10.9}$	$J/\psi \to \gamma \eta(1475) \to \gamma K_S^0 (K_S^0 \pi^0)_{\text{P-wave}} \to \gamma K_S^0 K_S^0 \pi^0$	$(6.58 \pm 0.12^{+3.98}_{-2.82}) \times 10^{-5}$	$\gg 35$
			$J/\psi \to \gamma \eta(1475) \to \gamma (K_S^0 K_S^0)_{\text{S-wave}} \pi^0 \to \gamma K_S^0 K_S^0 \pi^0$	$(3.99 \pm 0.09^{+0.41}_{-0.66}) \times 10^{-5}$	$\gg 35$
$f_1(1285)$	$1280.2 \pm 0.6^{+1.2}_{-1.5}$	$28.2 \pm 1.1^{+5.5}_{-2.9}$	$J/\psi \to \gamma f_1(1285) \to \gamma a_0(980)^0 \pi^0 \to \gamma K_S^0 K_S^0 \pi^0$	$(8.55 \pm 0.41^{+3.42}_{-1.04}) \times 10^{-6}$	$\gg 35$
$f_1(1420)$	$1433.5 \pm 1.1^{+27.9}_{-0.7}$	$95.9 \pm 2.3^{+13.6}_{-10.9}$	$J/\psi \to \gamma f_1(1420) \to \gamma K^*(892)^0 K_S^0 \to \gamma K_S^0 K_S^0 \pi^0$	$(7.25 \pm 0.12^{+0.73}_{-1.25}) \times 10^{-5}$	$\gg 35$
			$J/\psi \to \gamma f_1(1420) \to \gamma a_0(980)^0 \pi^0 \to \gamma K_S^0 K_S^0 \pi^0$	$(4.62 \pm 0.36^{+2.36}_{-1.94}) \times 10^{-6}$	17.8
$f_2(1525)$	$1515.4 \pm 2.5^{+3.2}_{-7.6}$	$64.0 \pm 4.3^{+2.0}_{-6.1}$	$J/\psi \to \gamma f_2(1525) \to \gamma K^*(892)^0 K_S^0 \to \gamma K_S^0 K_S^0 \pi^0$	$(9.47 \pm 0.43^{+1.51}_{-0.66}) \times 10^{-6}$	23.8

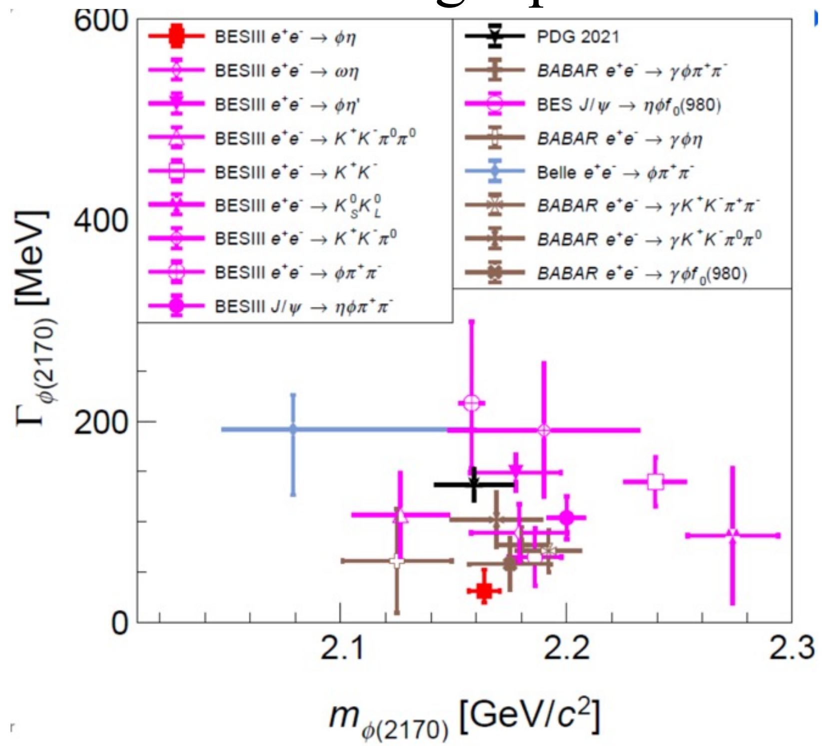
- Resonance parameters of the involved pseudoscalar, axial vector, and tensor states
- Data can be used for further investigations of the properties of the $\eta(1405)$ and $\eta(1475)$ mesons

Strangeonium [$s\bar{s}$] spectroscopy

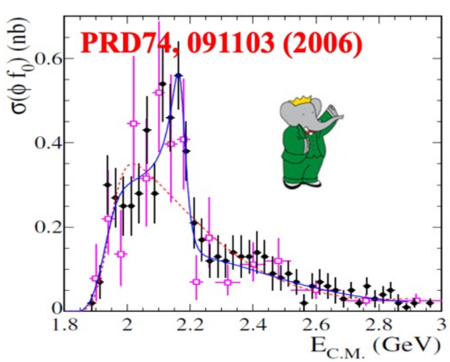


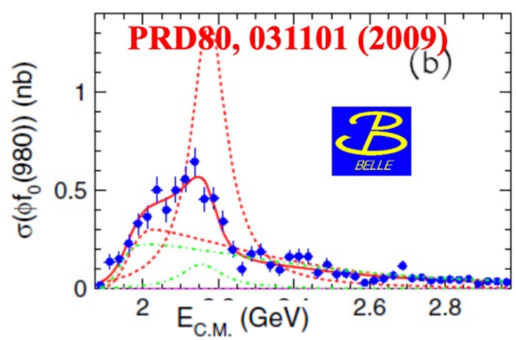
Studies on the $\phi(2170)$/Y(2175)

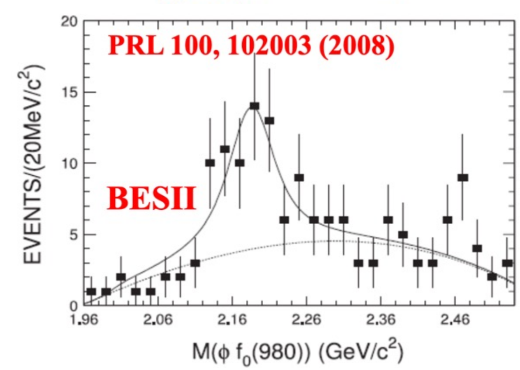
- A strangenium(-like) state: Y-particle with strange quark



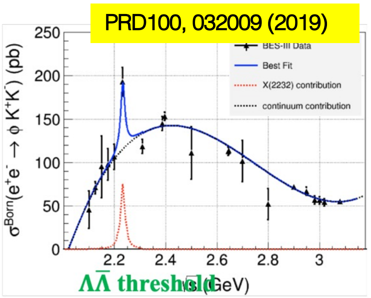
➢ **Theorists explain $\phi(2170)$ as**
- ✓ **$s\bar{s}g$ hybrid**
- ✓ **2^3D_1 or 3^3S_1 $s\bar{s}$**
- ✓ **tetraquark**
- ✓ **Molecular state $\Lambda\bar{\Lambda}$**
- ✓ **$\phi f_0(980)$ resonance with FSI**
- ✓ **Three body system ϕKK**

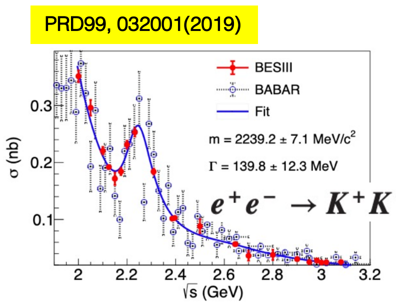


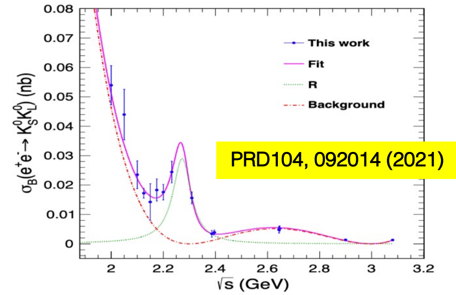


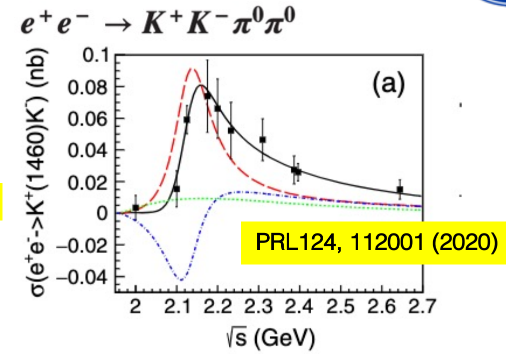


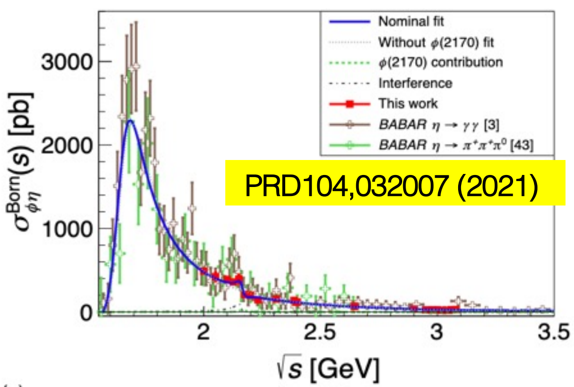
More results on the $\phi(2170)$/Y(2175)

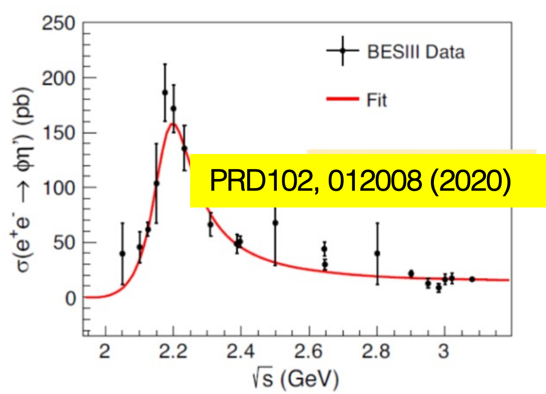


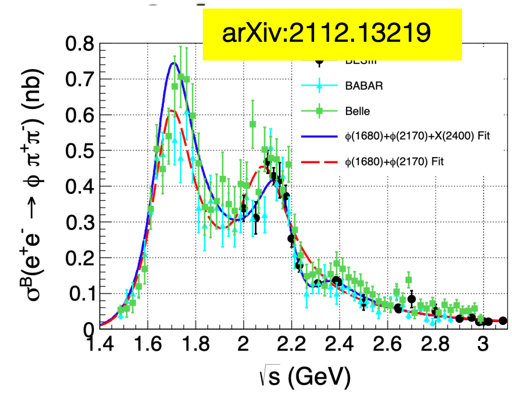


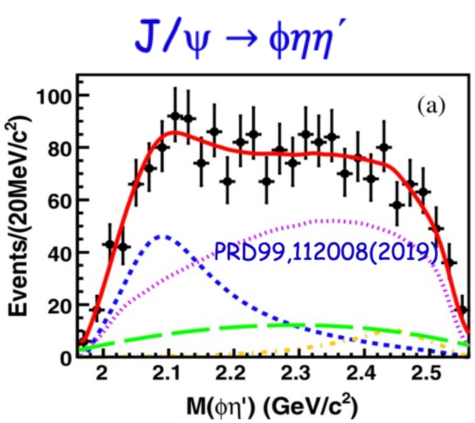


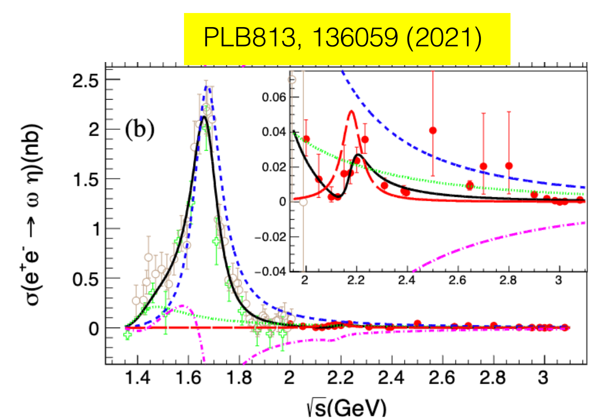


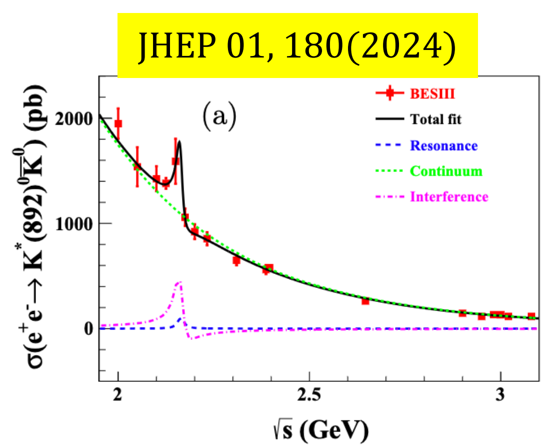










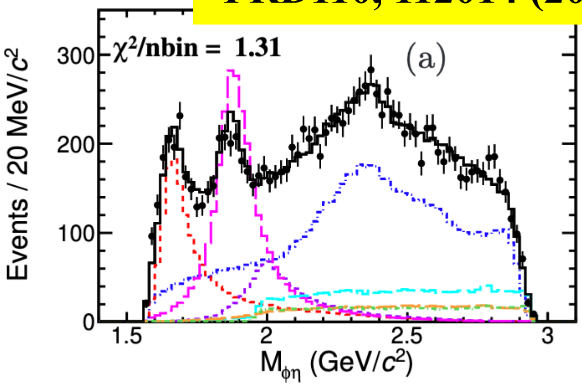


$\phi(2170)$/Y(2175) is still a mystery

BESIII New axial-Vector strangeonia

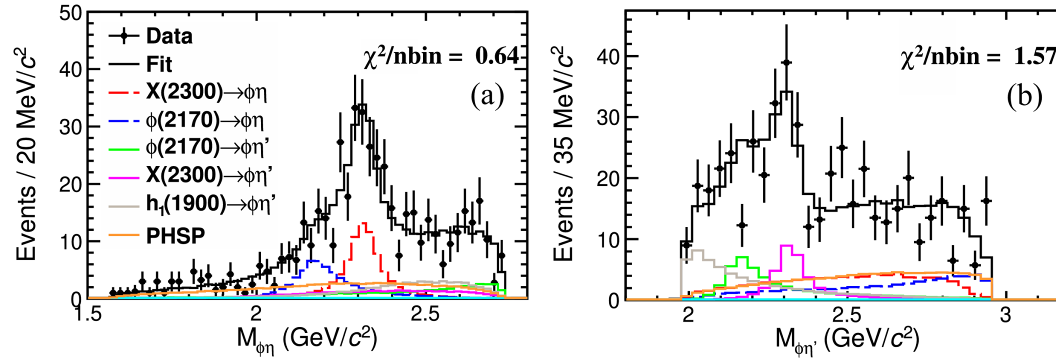
Based on 10B J/ψ events, a PWA fit to $J/\psi \to \phi\eta\pi^0$

PRD110, 112014 (2024)



Based on 2.7B $\psi(3686)$ events, a PWA fit to $\psi(3686) \to \phi\eta\eta'$

PRL134, 191901 (2025)



	Process	M (MeV/c^2)	Γ (MeV)
	$\phi(1680)\pi^0$	$1668 \pm 7 \pm 25$	$147 \pm 14 \pm 35$
$J^{PC} = 1^{--}$	$X(2000)\pi^0$	$1996 \pm 11 \pm 30$	$148 \pm 16 \pm 66$
$J^{PC} = 1^{+-}$	$h_1(1900)\pi^0$	$1911 \pm 6 \pm 14$	$149 \pm 12 \pm 23$
	$\phi a_0(980)_{\mathrm{EM}}$	–	–
	$\phi a_0(980)_{\mathrm{mix}}$	–	–

observations!

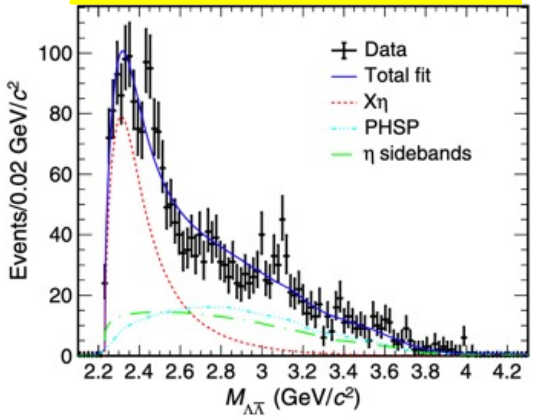
$h_1(2300)$ $J^{PC} = 1^{+-}$ *observations!*

$M = 2316 \pm 9 \pm 30 \mathrm{MeV}/c^2$
$\Gamma = 89 \pm 15 \pm 26$ MeV

- $h_1(1900)$: candidate for $h_1(2P)$ strangeonium state
- X(2000): candidate for $\phi(3S)$ or for $\phi(3D)$ strangeonium state
- $h_1(2300)$: mass lower than the predicted mass of $h_1(3P)$. Full strange [$s\bar{s}s\bar{s}$] tetraquark candidate?

The $X(2356) \to \Lambda\bar{\Lambda}$ in $e^+e^- \to \eta\Lambda\bar{\Lambda}$

PRD 107, 112001 (2023)

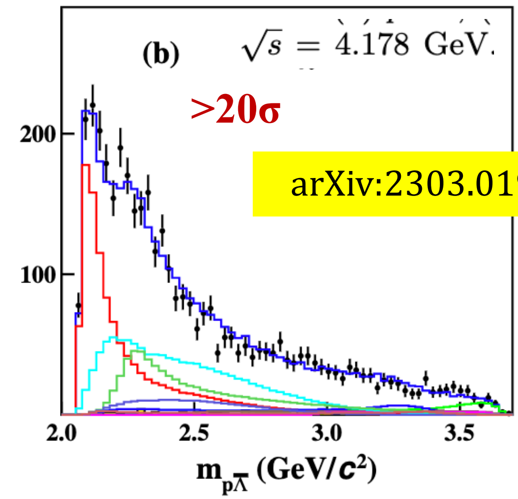


- Clear enhancement is seen near the $\Lambda\bar{\Lambda}$ mass threshold combining 31 datasets
- Simultaneous 1D fit to the $\Lambda\bar{\Lambda}$ mass spectra assuming a 1^{--} state:
  mass: $2536 \pm 7 \pm 15$ MeV/c^2
  width: $304 \pm 28 \pm 54$ MeV

hexaquark? baryonium?

The X(2085) in $e^+e^- \to pK^-\bar{\Lambda}$

arXiv:2303.01989

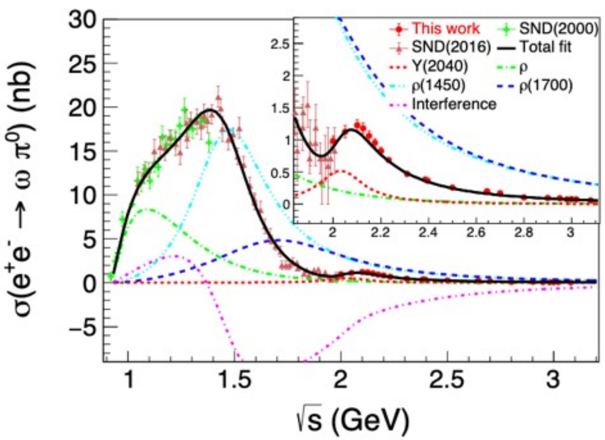


- $p\bar{\Lambda}$ resonance parameters and spin-parity:
  - pole mass: (2086±4±6) MeV/c^2
  - pole width: (56±5±16) MeV
  - favor 1^+
- no corresponding excited kaon candidates in experiment or in quark model prediction
- could be an exotic state

The isovector states

$e^+e^- \to \omega\pi^0$

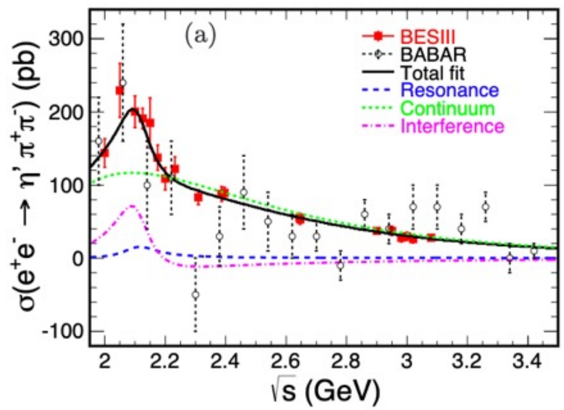
PLB 813, 136059 (2021)



- a structure Y(2040) with stat. significance $>10\sigma$
  $M = 2034 \pm 14 \pm 9\ \text{MeV}/c^2$
  $\Gamma = 234 \pm 30 \pm 25\ \text{MeV}$
- close to the isovector state $\rho(2000)$ or $\rho(2150)$

$e^+e^- \to \eta'\pi^+\pi^-$

PRD 103, 072007 (2021)



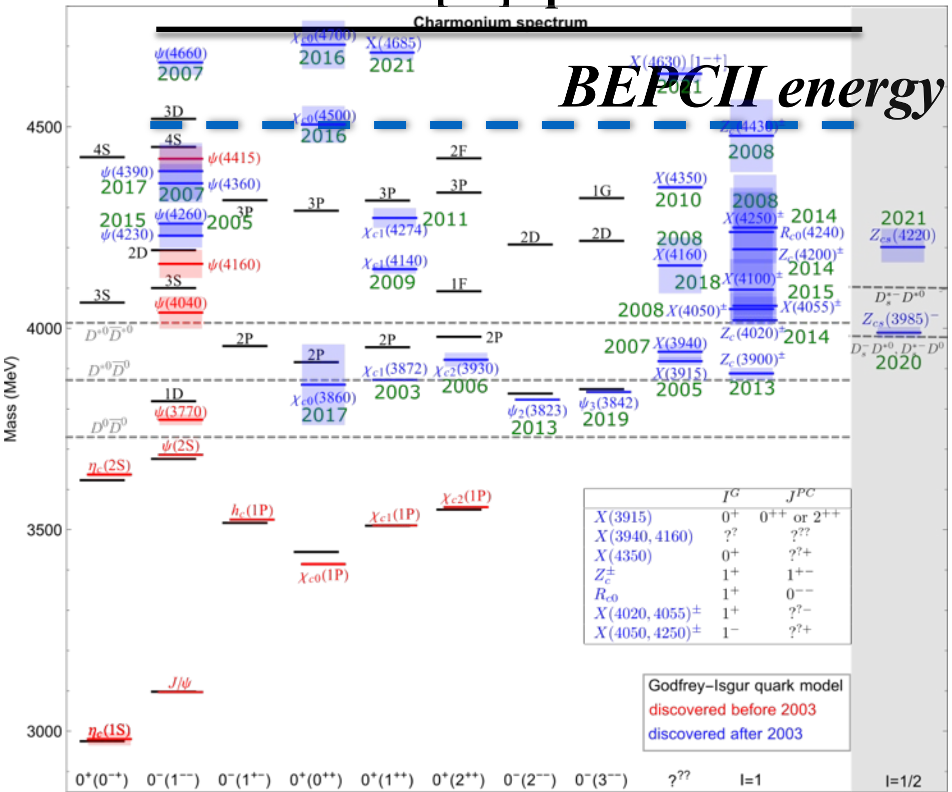
- a structure around 2.1 GeV: stat. significance $>6.3\sigma$
  $M = 2111 \pm 43 \pm 25\ \text{MeV}/c^2$
  $\Gamma = 135 \pm 34 \pm 30\ \text{MeV}$
- consistent with the Y(2040) in $e^+e^- \to \omega\pi^0$

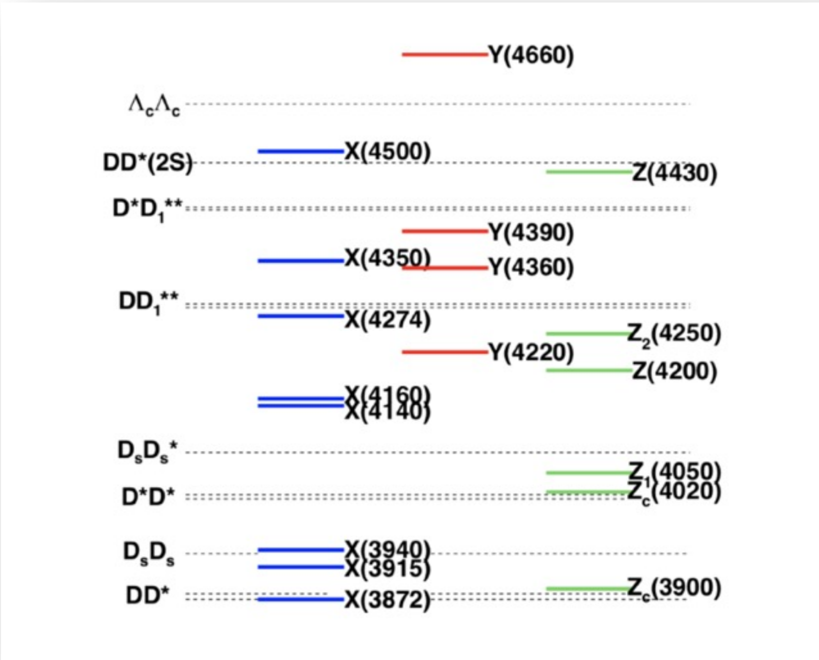
(类)粲偶素谱学

Overpopulated charmonium spectrum

Charmonium-like [$c\bar{c}$] spectrum *from F-K. Guo*

arXiv:1511.01589, arXiv:1812.10947





Overpopulated observed new charmonium-like states, i.e. "XYZ":

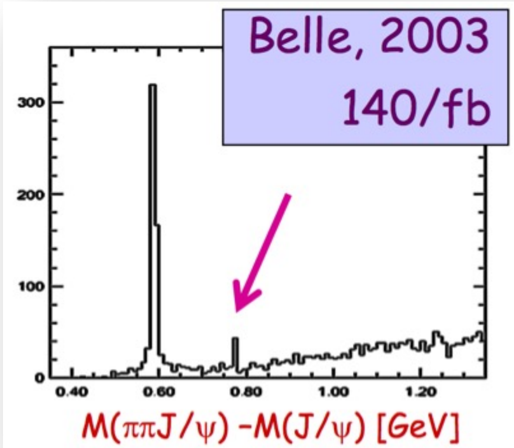
- Most of them are close to the mass thresholds of charmed meson pairs
- Some are not accommodated as conventional meson
  ==> candidate of exotic hadron states
- More efforts are needed to pin down their nature

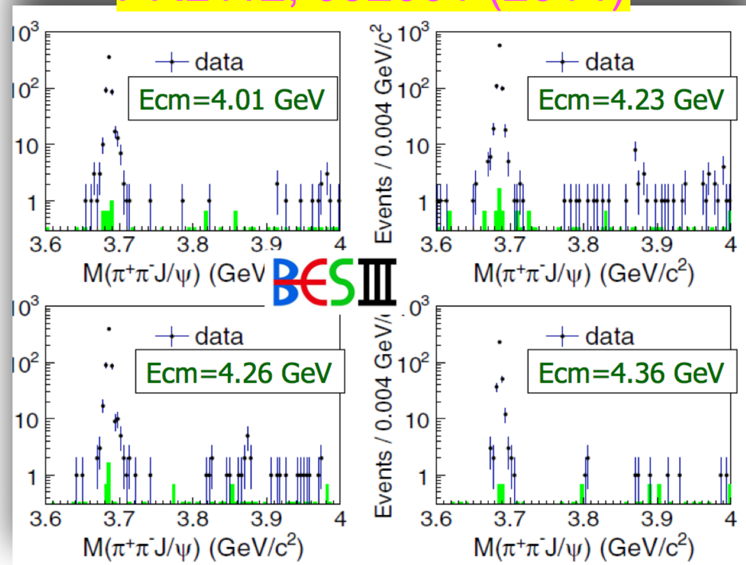
The X states

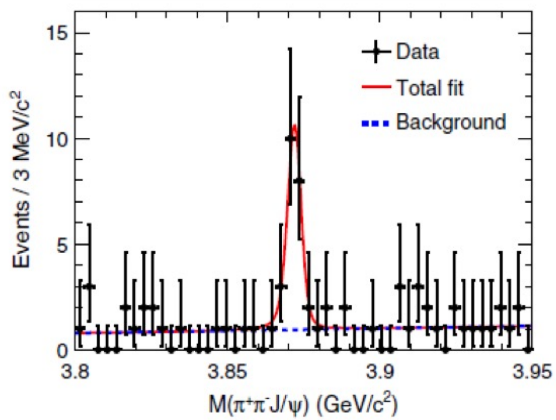
The X(3872) state

- Discovered in $B \to K\pi\pi J/\psi$ at Belle
- The first XYZ states

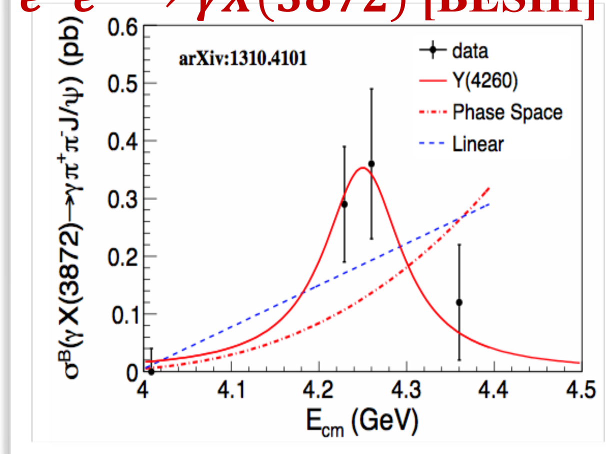
PRL112, 092001 (2014)







$e^+e^- \to \gamma X(3872)$ [BESIII]



- Clear ISR $\psi(3686)$ signal for data validation
- X(3872) signal at around 4.23-4.26 GeV

What have we learnt about $X(3872)$

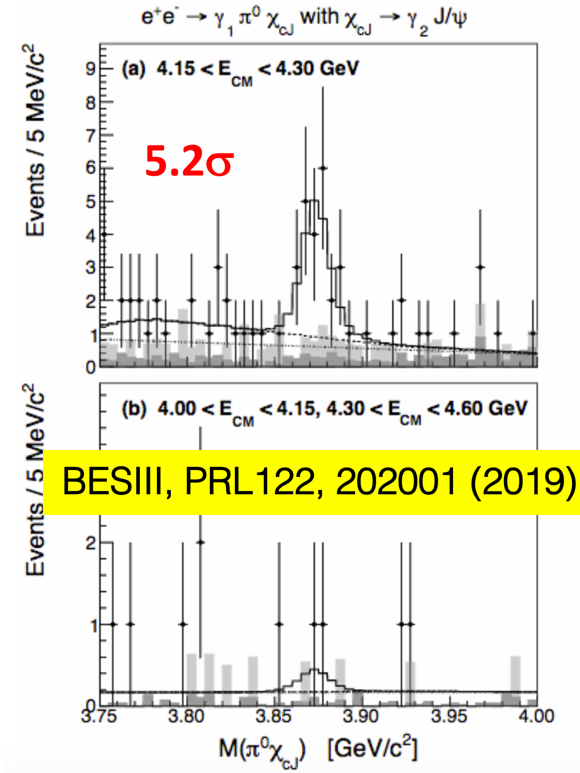
- $X(3872)$ nature is still uncertain, although many studies are performed since 2003
  - **$J^{PC} = 1^{++}$**
  - **Mass = 3871.69 ± 0.17 MeV**
  - **Width < 1.2 MeV** @90% CL

  $\delta E = (m_{D^{*0}} + m_{D^0}) - m_{X(3872)} = 0.01 \pm 0.20$ MeV
- Production
  - In e^+e^- collision, see strong connection of Y(4260) resonance decays [BESIII, PRL 112. 092001 (2014); 122, 202001 (2019)]
  - In b-hadron decays: B, Bs, Λ_b, …
  - Prompt production in $pp/p\bar{p}$ and heavy ion collision
- What is it?
  - **Loosely $D^0\bar{D}^{0*}$ bound state?**
  - **Mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{0*}$?**
- Important to fully explore its production and decay properties

Mode			Fraction (Γ_i/Γ)
Γ_1		e^+e^-	$< 2.8 \times 10^{-6}$
Γ_2		$\pi^+\pi^- J/\psi(1S)$	$(3.8 \pm 1.2)\%$
Γ_3		$\pi^+\pi^-\pi^0 J/\psi(1S)$	not seen
Γ_4		$\omega\eta_c(1S)$	$< 33\%$
Γ_5	★	$\omega J/\psi(1S)$	$(4.3 \pm 2.1)\%$
Γ_6		$\phi\phi$	not seen
Γ_7		$D^0\bar{D}^0\pi^0$	$(49^{+18}_{-20})\%$
Γ_8	★	$\bar{D}^{*0}D^0$	$(37 \pm 9)\%$
Γ_9		$\gamma\gamma$	$< 11\%$
Γ_{10}		$D^0\bar{D}^0$	$< 29\%$
Γ_{11}		D^+D^-	$< 19\%$
Γ_{12}		$\pi^0\chi_{c2}$	$< 4\%$
Γ_{13}	★	$\pi^0\chi_{c1}$	$(3.4 \pm 1.6)\%$
Γ_{14}		$\pi^0\chi_{c0}$	$< 70\%$
Γ_{15}		$\pi^+\pi^-\eta_c(1S)$	$< 14\%$
Γ_{16}		$\pi^+\pi^-\chi_{c1}$	$< 7 \times 10^{-3}$
Γ_{17}		$p\bar{p}$	$< 2.4 \times 10^{-5}$
Radiative decays			
Γ_{18}		γD^+D^-	$< 4\%$
Γ_{19}		$\gamma\bar{D}^0D^0$	$< 6\%$
Γ_{20}	★	$\gamma J/\psi$	$(8 \pm 4) \times 10^{-3}$
Γ_{21}		$\gamma\chi_{c1}$	$< 9 \times 10^{-3}$
Γ_{22}		$\gamma\chi_{c2}$	$< 3.2\%$
Γ_{23}	★	$\gamma\psi(2S)$	$(4.5 \pm 2.0)\%$

More X(3872) decay information

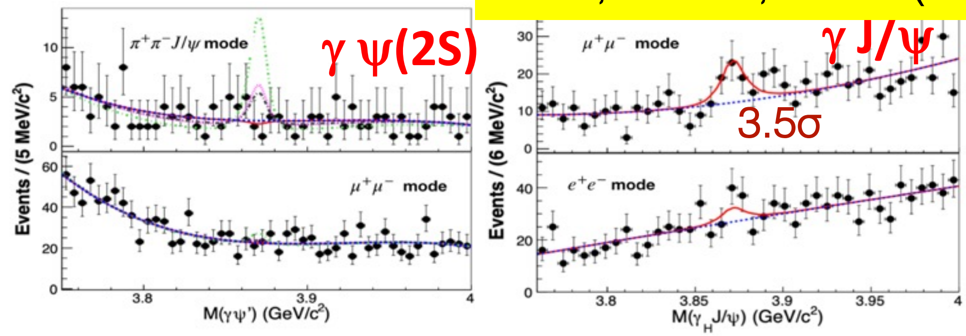
- Observation of X(3872) $\rightarrow \pi^0 \chi_{c1}$



BESIII, PRL122, 202001 (2019)

- Transition of $X(3872) \rightarrow \gamma J/\psi$, $\gamma\psi(2S)$

BESIII, PRL 124, 242001 (2020)



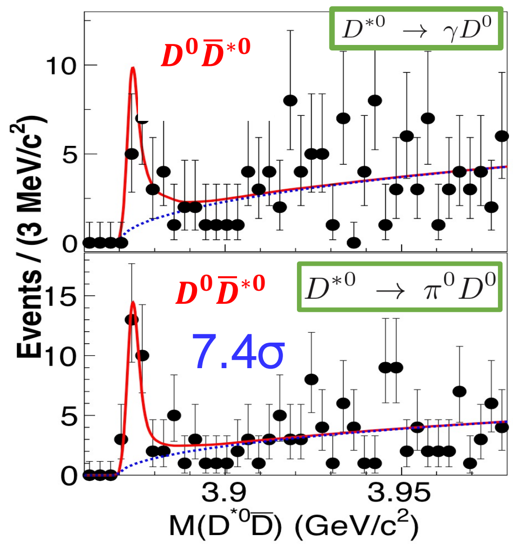
$R = \frac{BF(X(3872)\rightarrow\gamma\psi(2S))}{BF(X(3872)\rightarrow\gamma J/\psi)} < 0.59$ at 90% C.L. , agrees with Belle(<2.1), while challenges Babar(3.4±1.1) and LHCb results (2.46± 0.70)

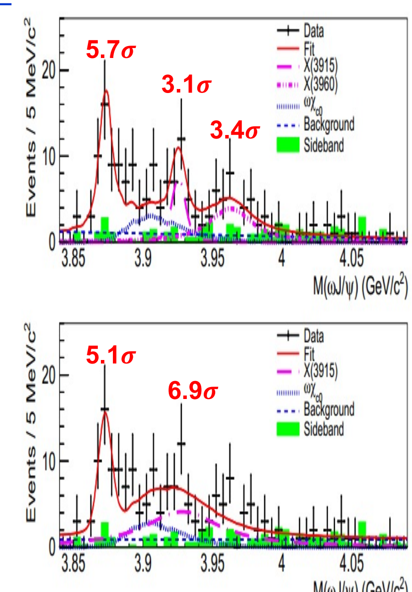
- Observation of X(3872) → ωJ/ψ

BESIII, PRL 122, 232002 (2019)

- Observation of X(3872) $\rightarrow D^0\bar{D}^{*0}$

BESIII, PRL 124, 242001 (2020)



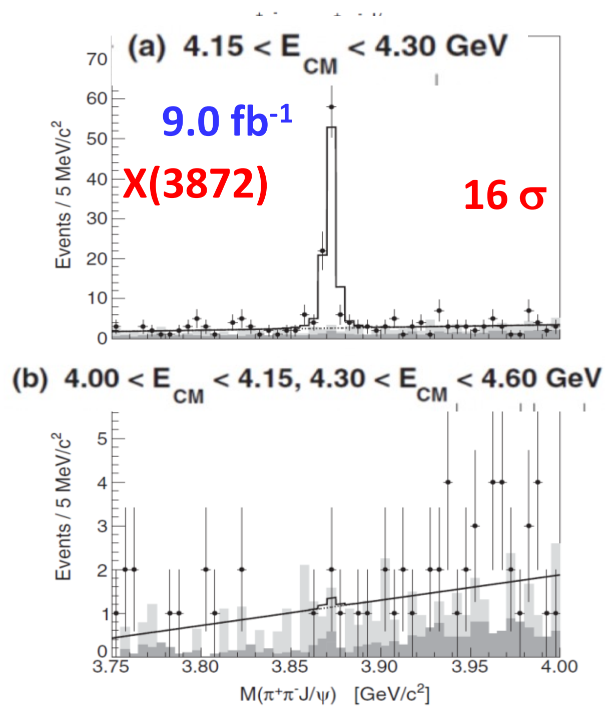


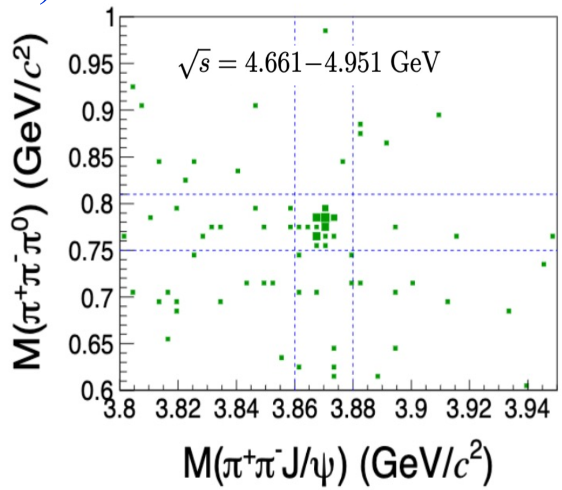
A new X(3872) production process $e^+e^- \to \omega X(3872)$

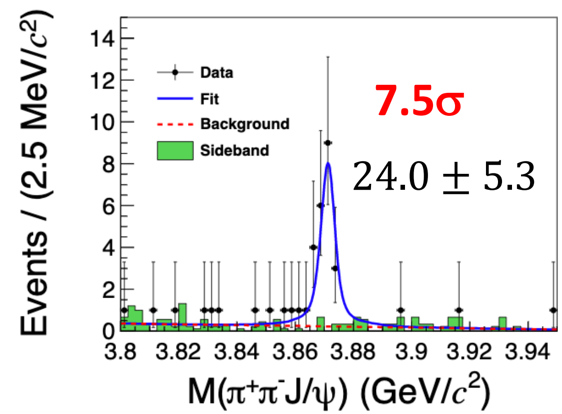
PRL130, 151904 (2023)

Radiative production in $e^+e^- \to \gamma X(3872)$

BESIII, PRL122, 202001 (2019)



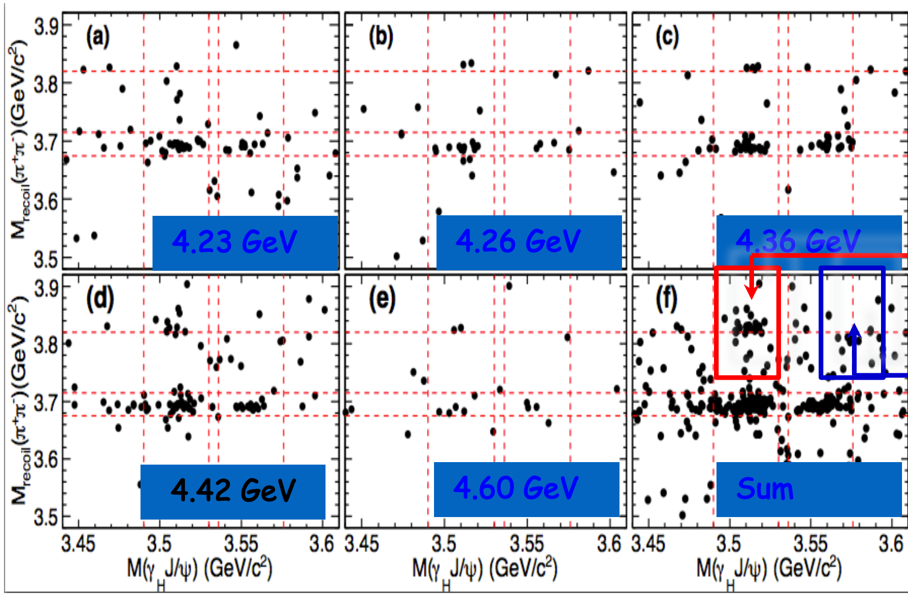


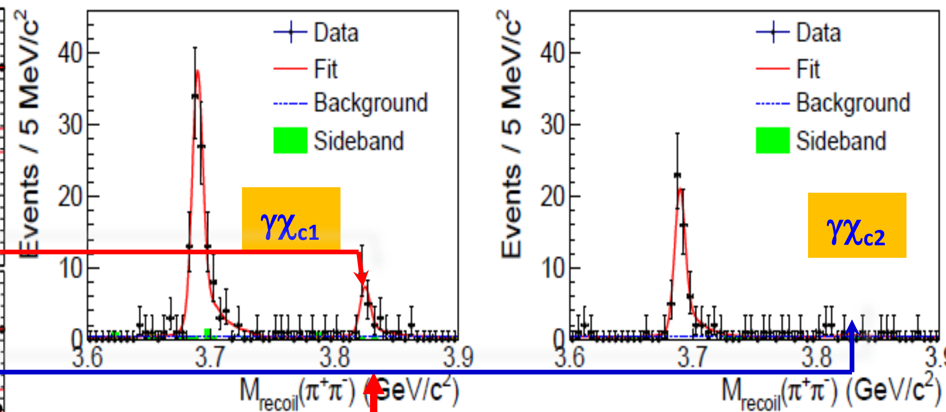


$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}(\rm pb^{-1})$	$N_{\rm sig}$	$\epsilon(1+\delta)$ (%)	$\sigma^{\rm B}$(pb)	$\sigma^{\rm B}_{\rm up}$(pb)	Significance
4.661	529.63	$0.33^{+1.36}_{-0.33}$	28.25	$0.523^{+2.128}_{-0.523} \pm 0.051 \pm 0.165$	5.64	-
4.682	1669.31	$8.00^{+3.34}_{-2.68}$	24.62	$4.567^{+1.908}_{-1.528} \pm 0.393 \pm 1.442$	11.49	3.4σ
4.699	536.45	$0.00^{+0.95}_{-0.00}$	26.96	$0.000^{+1.541}_{-0.000} \pm 0.000 \pm 0.000$	3.32	-
4.740	164.27	$1.67^{+1.77}_{-1.10}$	21.83	$10.906^{+11.551}_{-7.213} \pm 1.025 \pm 3.444$	40.58	1.0σ
4.750	367.21	$5.00^{+2.58}_{-1.92}$	22.43	$14.239^{+7.349}_{-5.455} \pm 1.424 \pm 4.497$	38.17	3.1σ
4.781	512.78	$1.00^{+1.36}_{-0.70}$	31.60	$1.448^{+1.965}_{-1.011} \pm 0.216 \pm 0.457$	6.51	0.7σ
4.843	527.29	$4.67^{+2.58}_{-1.92}$	26.73	$7.768^{+4.295}_{-3.189} \pm 0.668 \pm 2.453$	21.14	2.6σ
4.918	208.11	$1.00^{+1.36}_{-0.70}$	22.64	$4.980^{+6.760}_{-3.477} \pm 0.433 \pm 1.573$	21.69	0.7σ
4.951	160.37	$0.00^{+0.95}_{-0.00}$	20.42	$0.000^{+6.802}_{-0.000} \pm 0.000 \pm 0.000$	14.67	-

a new X(3872) production process $e^+e^- \to \omega X(3872)$ is observed for the first time

$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^-\gamma\chi_{c1}$

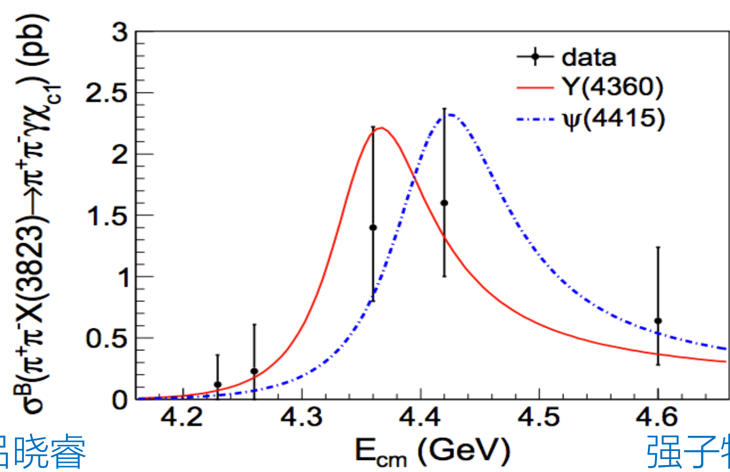




Fit: M=3821.7±1.3±0.7 MeV;

Significance: 6.7σ, observation!

Phys. Rev. Lett. 91, 112015 (2015)

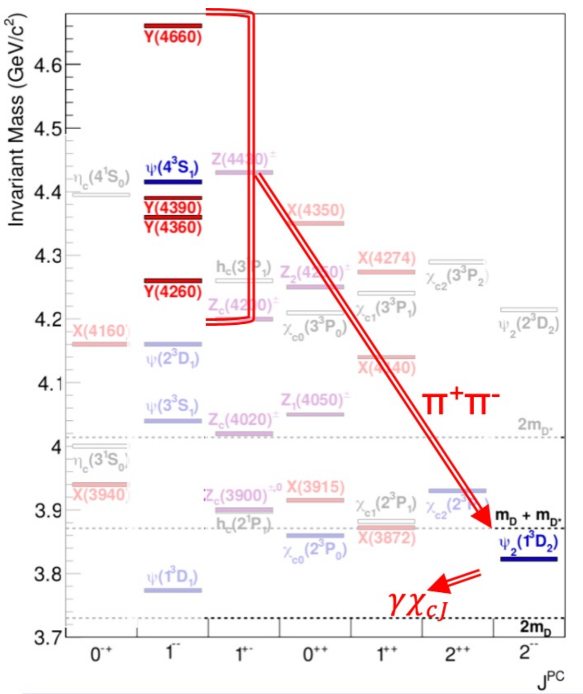


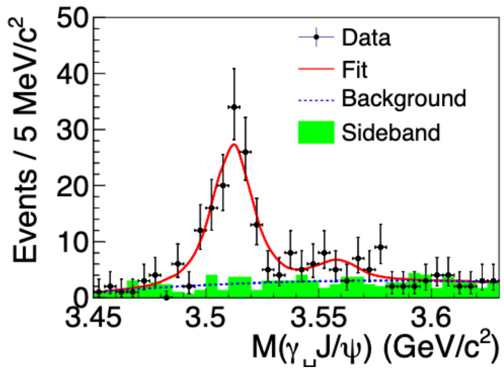
- Whether from Y(4360) or ψ(4415) decay
- Favor the Y(4360) ? [M. B. Voloshin, PRD 91, 114029 (2015)]
- Y(4360)→$\pi^+\pi^-$X(3823)? New decay model of Y(4360)?

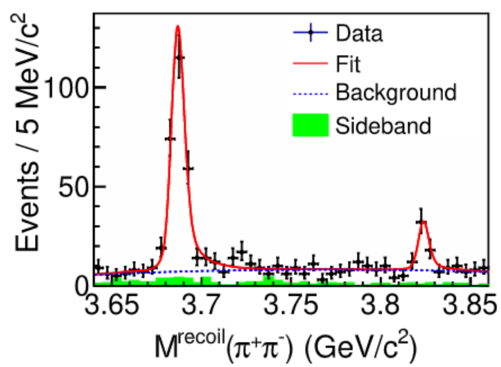
Cross sections of $e^+e^- \to \pi^+\pi^-\psi(3823)$

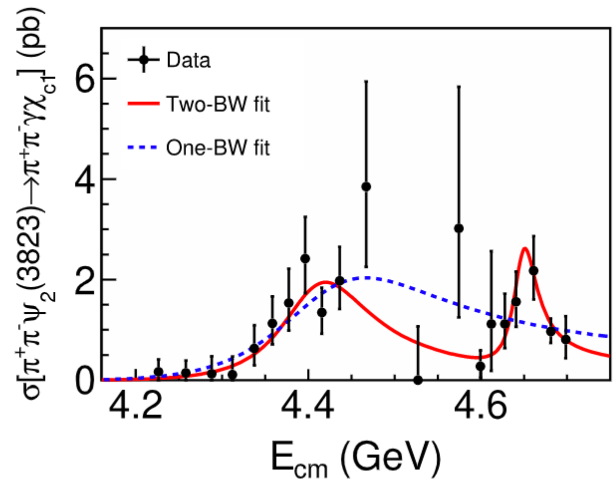
PRL129, 102003 (2022)

first observation of vector Y states
decaying to D-wave charmonium state









Parameters	Solution I	Solution II
$M[R_1]$	$4406.9 \pm 17.2 \pm 4.5$	
$\Gamma_{\rm tot}[R_1]$	$128.1 \pm 37.2 \pm 2.3$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_1}\mathcal{B}_2$	$0.36 \pm 0.10 \pm 0.03$	$0.30 \pm 0.09 \pm 0.03$
$M[R_2]$	$4647.9 \pm 8.6 \pm 0.8$	
$\Gamma_{\rm tot}[R_2]$	$33.1 \pm 18.6 \pm 4.1$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_2}\mathcal{B}_2$	$0.24 \pm 0.07 \pm 0.02$	$0.06 \pm 0.03 \pm 0.01$
ϕ	$267.1 \pm 16.2 \pm 3.2$	$-324.8 \pm 43.0 \pm 5.7$

Most precise measurement

mass and width of $\psi_2(3823)$:
$m = 3823.12 \pm 0.43 \pm 0.13$ MeV/c^2
$\Gamma < 2.9$ MeV (at 90% CL)

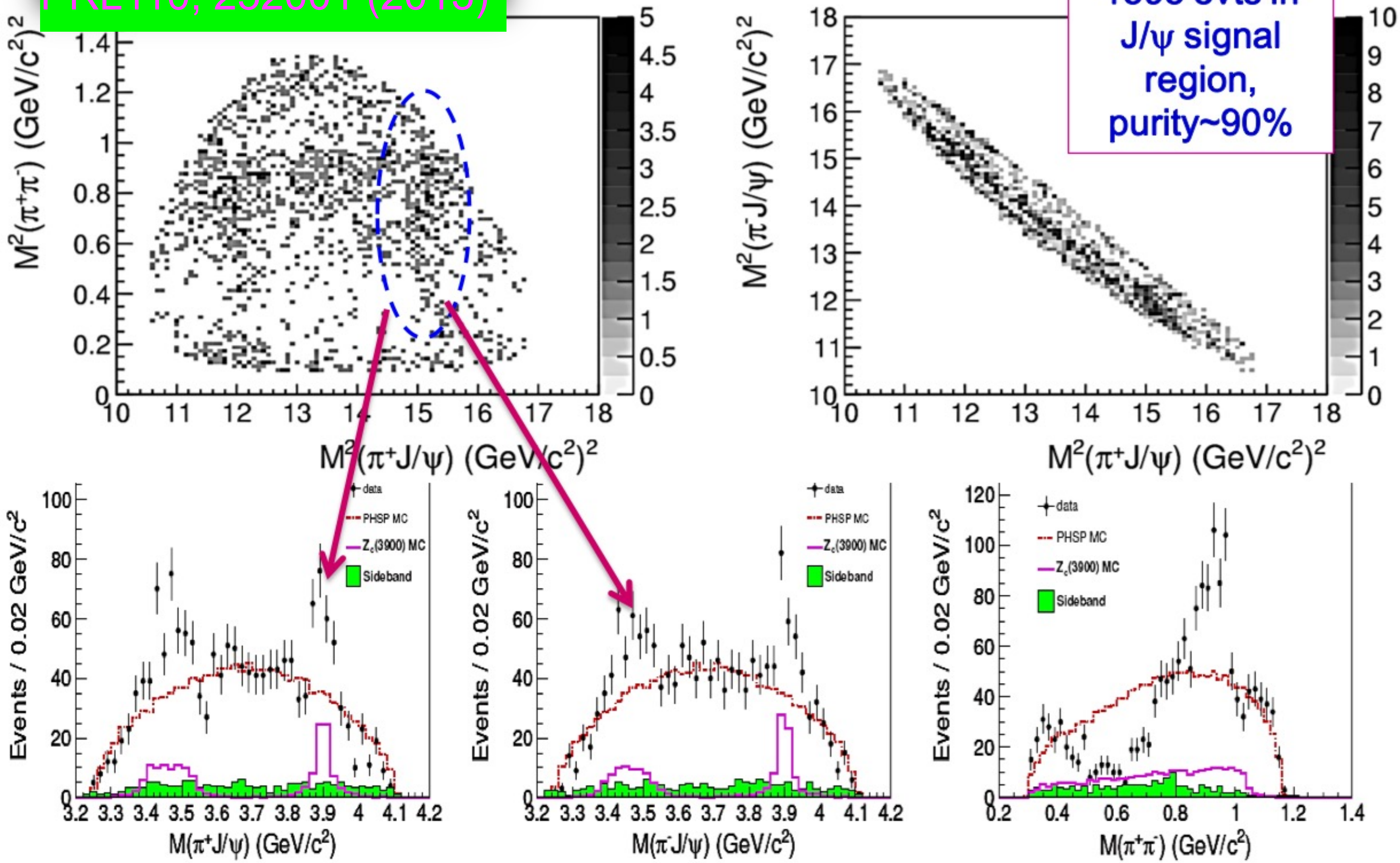
$$\frac{\mathcal{B}[\psi_2(3823)\to\gamma\chi_{c2}]}{\mathcal{B}[\psi_2(3823)\to\gamma\chi_{c1}]} = 0.33 \pm 0.12 (< 0.51)$$

- R_1 and R_2 consistent with Y(4360) and Y(4660)
- BESIII also observes $e^+e^- \to \pi^0\pi^0\psi(3823)$ [JHEP02, 171 (2023)], consistent with isospin symmetry

The Z states

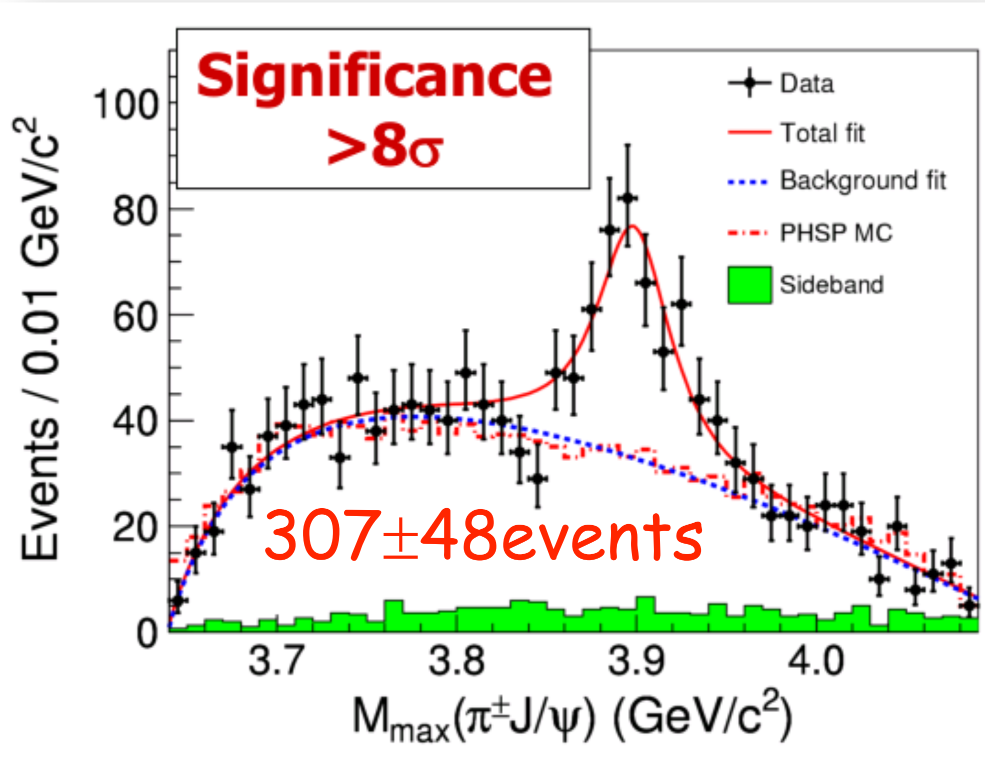
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at 4.26GeV

PRL110, 252001 (2013)

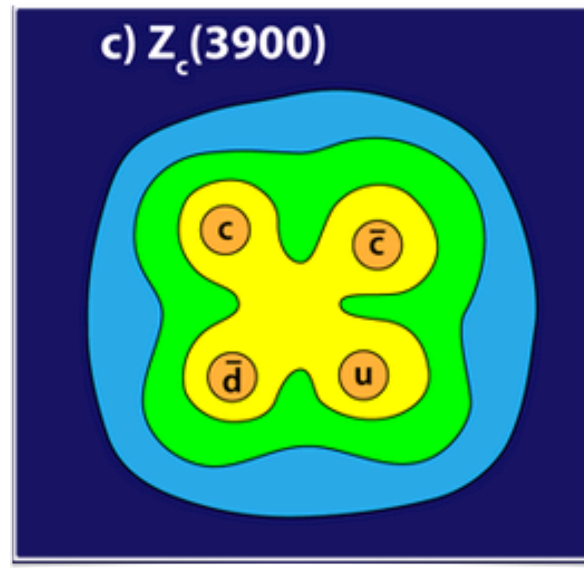


$Z_c^+(3900)$ discovered

PRL110, 252001 (2013)



Mass = (3899.0±3.6±4.9) MeV
Width = (46±10±20) MeV



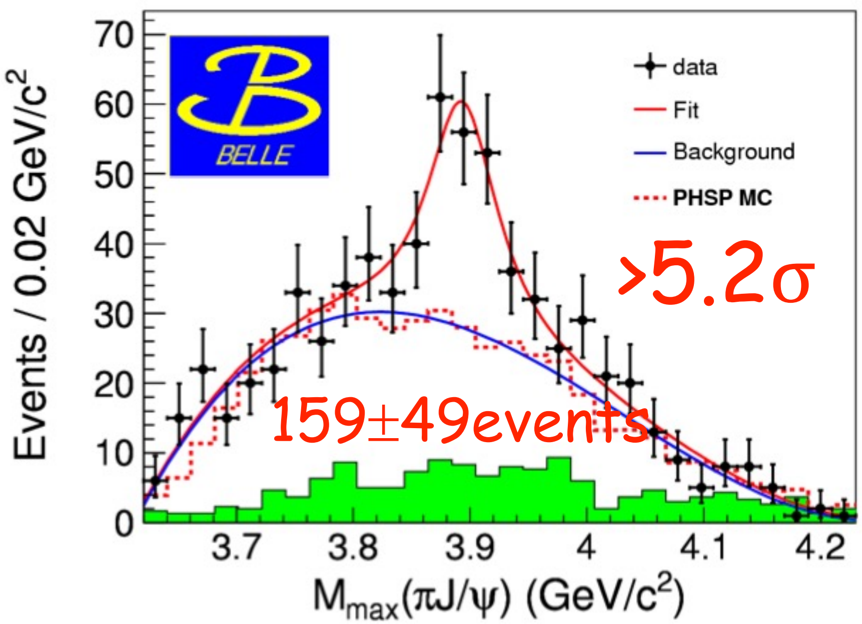
from APS/Alan Stonebraker

- Couples to $c\bar{c}$
- Has electric charge **1**

➔ consists of at least four quarks of $c\bar{c}u\bar{d}$

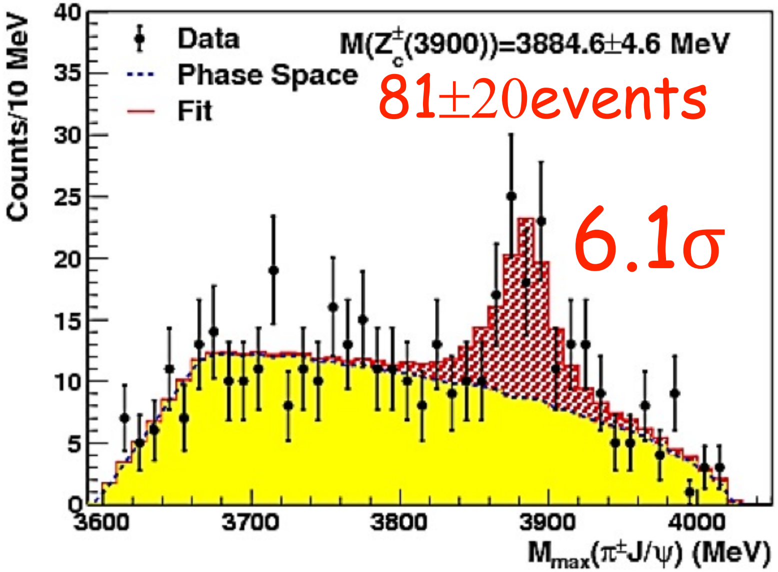
Confirmations from other experiments

Belle with ISR: PRL110, 252002 (2013)



Mass = (3894.5±6.6±4.5) MeV
Width = (63±24±26) MeV

CLEOc data at 4.17 GeV: PLB 727, 366 (201



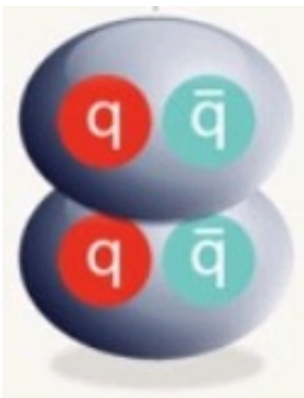
Mass = (3885±5±1) MeV
Width = (34±12±4) MeV

Consistent results from other electron-positron annihilation experiments!

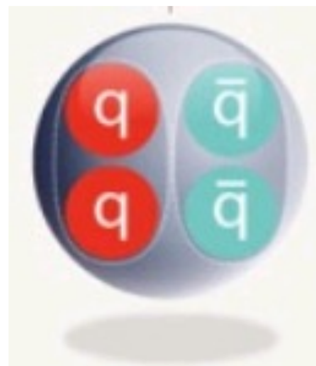
Nature of the exotic Zc^{+}(3900)

- ➢ Its mass lies close to the threshold of m(D)+m(D*)

DD* molecule?



tetraquark?



and other scenarios:

- Cusp?
- Threshold effect?
- ...

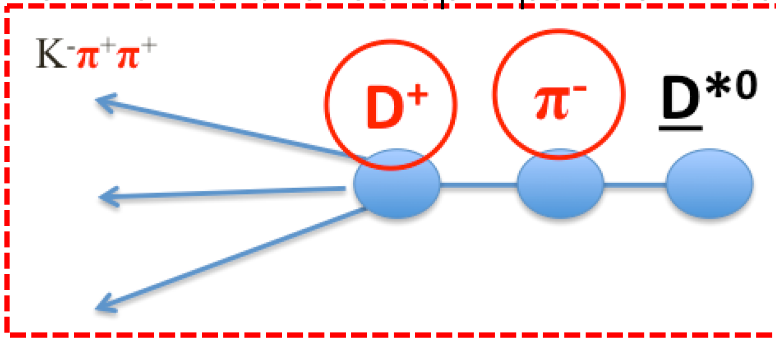
- ➢ Other decay mode of the Zc(3900)?
- ➢ Partner(s) of the Zc?

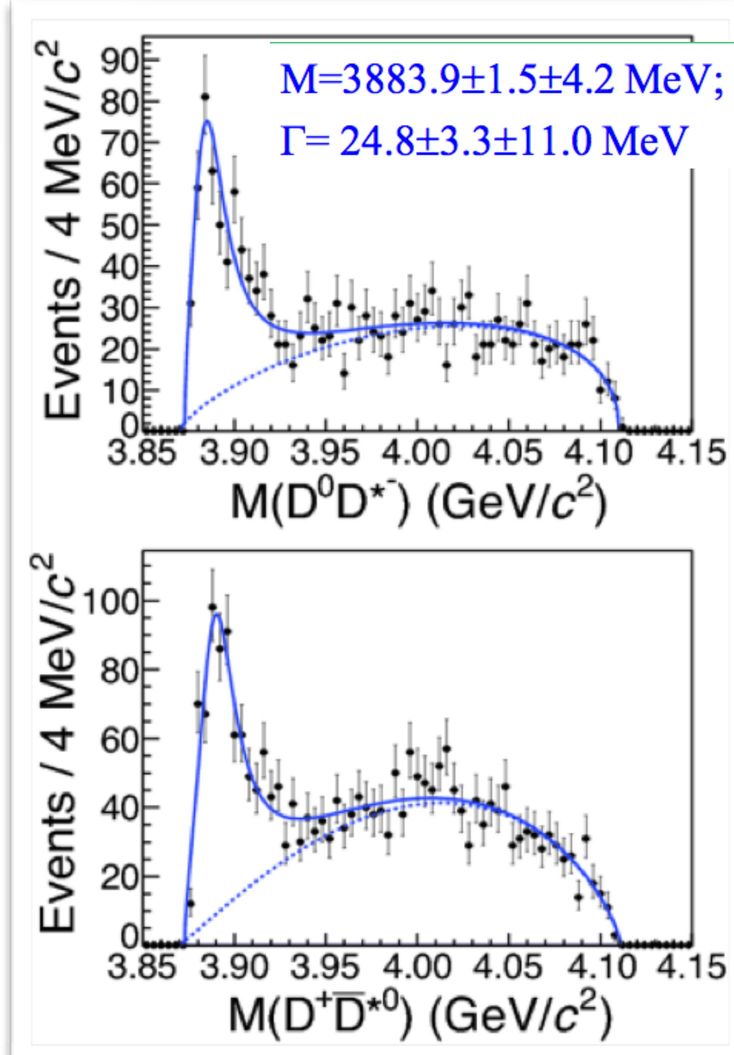
Evidence for neutral isospin partner! *[T. Xiao et al., PLB 727, 366 (2013)]*

$e^+e^- \to \pi^- Z^+_c(3885) \to \pi^-(D\bar{D}^*)^+$ at 4.26GeV

PRL110, 252001 (2013)

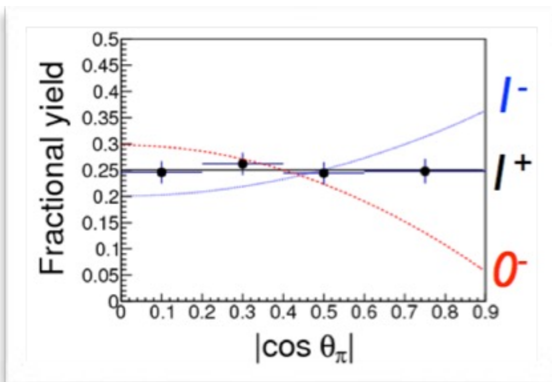
similar for the iso-spin partner mode





If $Z_c(3885)$ is $Z_c(3900)$:

$$R = \frac{\Gamma(Z_c(3885) \to D^*\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = (6.2 \pm 1.1 \pm 2.7)$$

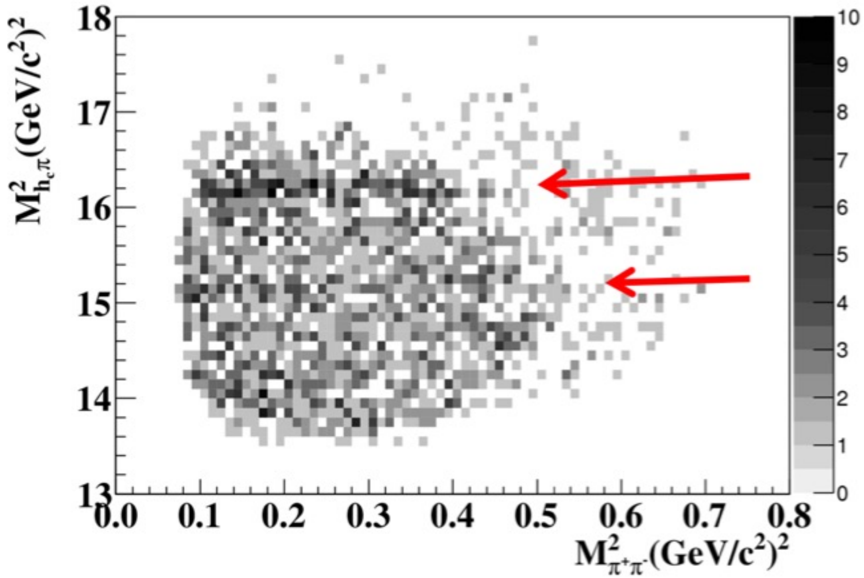


Angular distribution favors 1+ and disfavors 1^- or 0^-

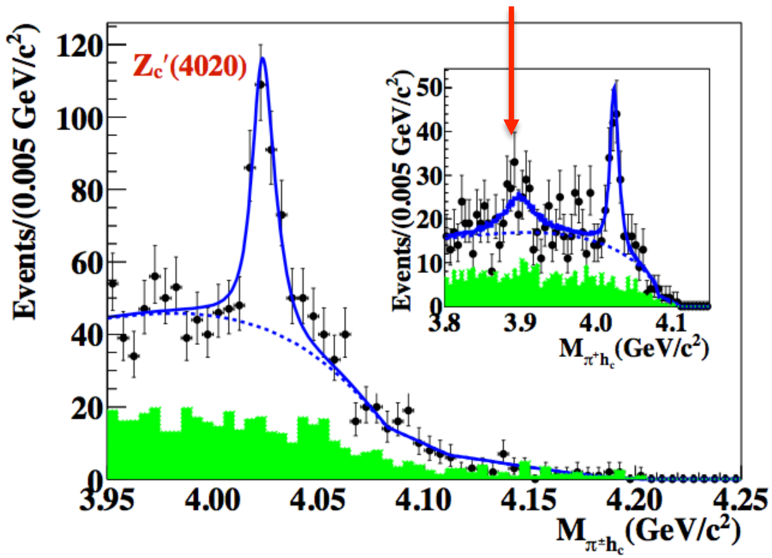
$$\sigma(e^+e^- \to \pi^- Z_c(3885)^+,\ Z_c(3885)^+ \to (D\bar{D}^*)^+ + c.c.) = (83.5 \pm 6.6 \pm 22.0)\ \text{pb}$$

Structures in $e^+e^- \to \pi^+\pi^- h_c(1P)$

PRL111, 242001 (2013)



Reflection and possible $Z_c(3900)$ signal

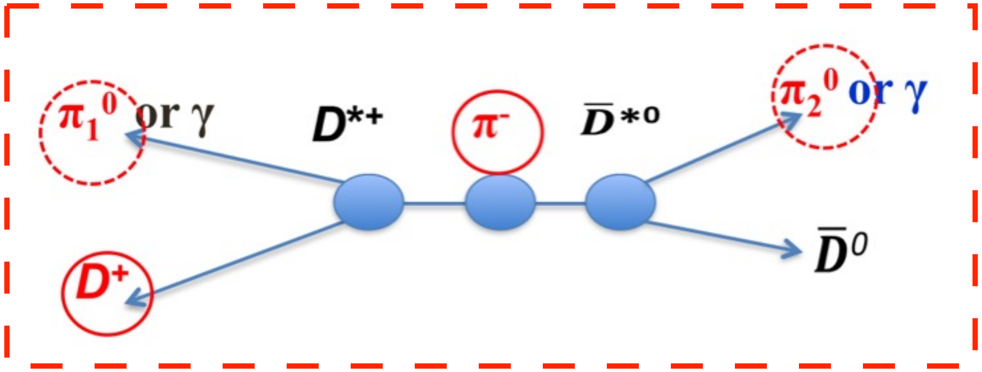


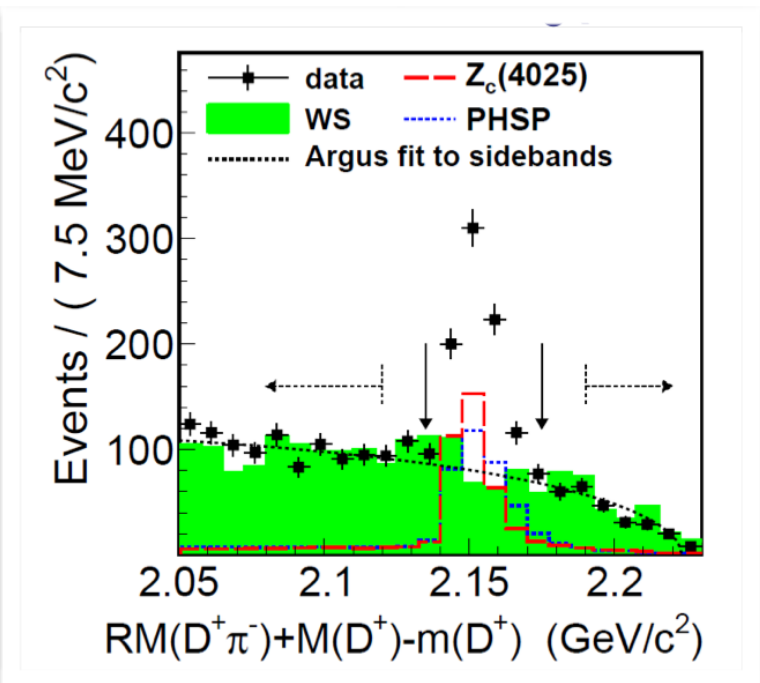
Simultaneous fit to 4.23/4.26/4.36 GeV data and 16 η_c decay modes: 8.9σ

$M(Z_c(4020)) = 4022.9 \pm 0.8 \pm 2.7$ MeV; $\Gamma(Z_c(4020)) = 7.9 \pm 2.7 \pm 2.6$ MeV

$e^+e^- \to \pi^- Z_c^+(4025) \to \pi^-(D^*D^*)^+$

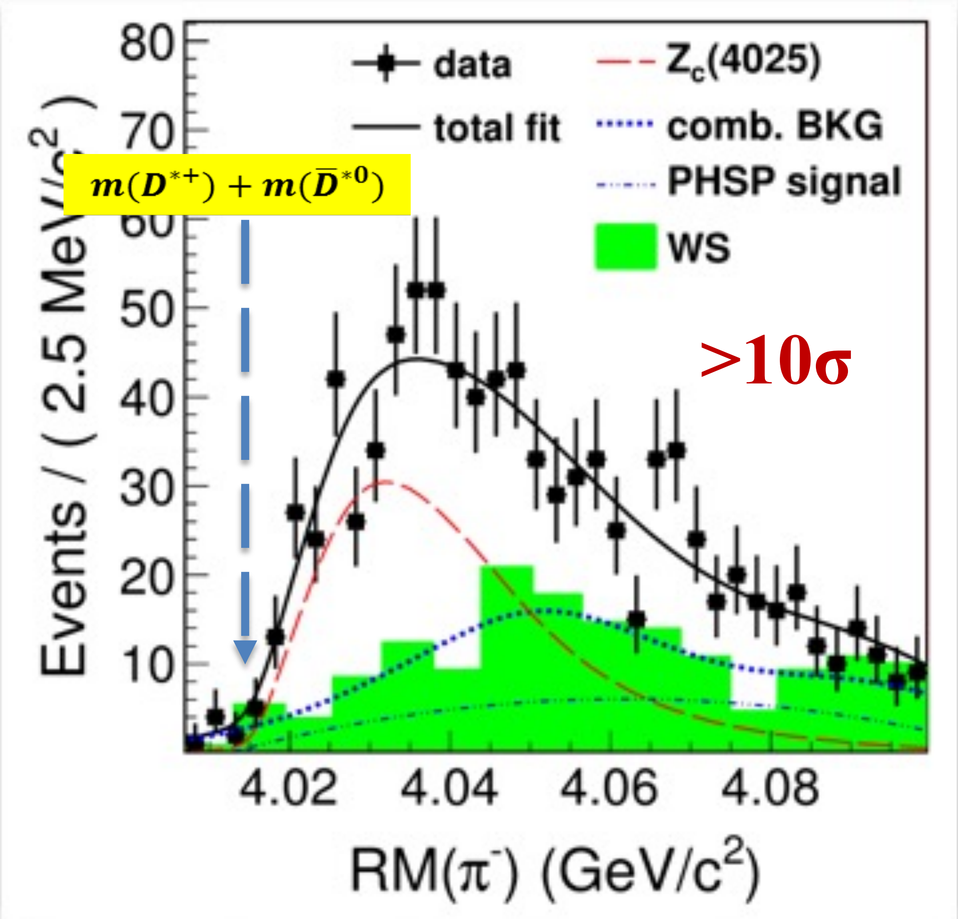
PRL113, 132001 (2014)





- Partial reconstruction of the process $e^+e^- \to \pi^\pm (D^*D^*)$
  - tag a D^+ meson in an event
  - find an additional charged π^-
  - reject backgrounds from $e^+e^- \to D^{(*)}D^{(*)}$
  - use signature in the recoil mass spectrum of $D^+\pi^-$ to identify the process of $e^+e^- \to \pi^- D^{*+}\underline{D}^{*0}$
  - to improve the significance, at least one of the π_1^0/π_2^0 is detected
  - study the mass spectrum of recoil π^-

Measurement of the $Z^{+}_{c}(4025)$



assume it as a particle, Zc(4025), and fit to the π^- recoil mass distribution

resonance parameter:

$$m(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7\,\text{MeV}/c^2,$$
$$\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7\,\text{MeV}.$$

401±47 $Z_c(4025)$ events

$$\sigma(e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}) = (137 \pm 9 \pm 15)\,\text{pb}$$

$$\frac{\sigma(e^+e^- \to Z_c^{\pm}(4025)\pi^{\mp} \to (D^*\bar{D}^*)^{\pm}\pi^{\mp})}{\sigma(e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp})} = 0.65 \pm 0.09 \pm 0.06$$

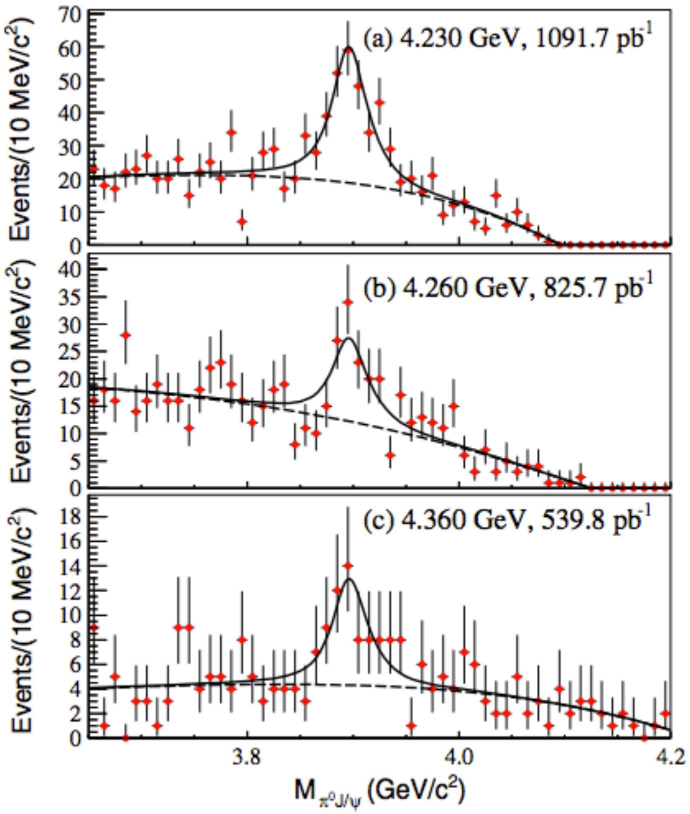
$Z_c(4020)=Z_c(4025)$?

Coupling to D*D* is much larger than to $\pi^- h_c$ if they are the same state

Search for $Z_c(3900)^0$ in $e^+e^- \to \pi^0\pi^0 J/\psi$

PRL 115, 112003 (2015)

$M = 3894.8 \pm 2.3 \pm 3.2$ MeV/c²
$\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV

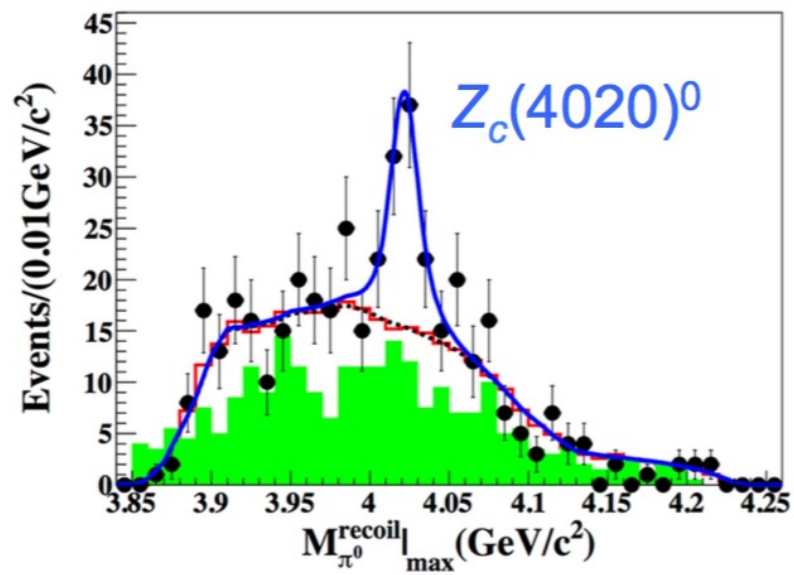


Search for $Z_c(4020)^0$ in $e^+e^- \to \pi^0\pi^0 h_c$

PRL113, 212002 (2014)

h_c reconstructed through E1 transition $h_c \to \gamma\eta_c$, η_c reconstructed from 16 exclusive hadronic modes.

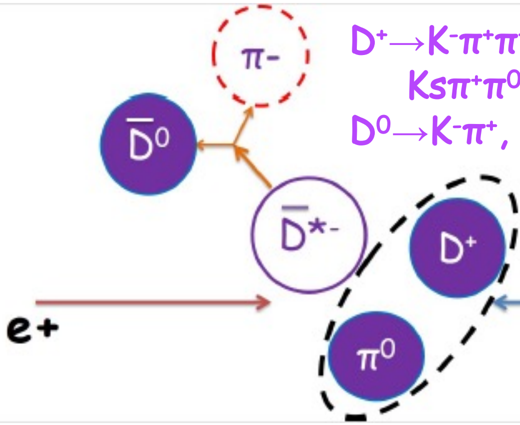
$M = (4023.6 \pm 2.2 \pm 3.9)$ MeV/c²
Width fixed to the $Zc(4020)^+$



Isospin triplet is established: $Z_c(3900)^{\pm/0}$ & $Z_c(4020)^{\pm/0}$

Search for $Z_c(3885)^0$ in $e^+e^- \to \pi^0(D\bar{D}^*)^0$

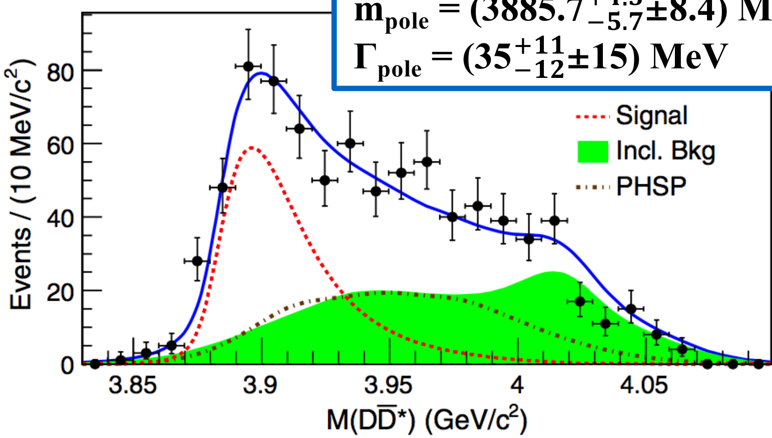
PRL 115, 222002 (2015)



$D^+ \to K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K_S\pi^+$, $K_S\pi^+\pi^0$, $K_S\pi^+\pi^+\pi^-$
$D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^-\pi^+\pi^+$

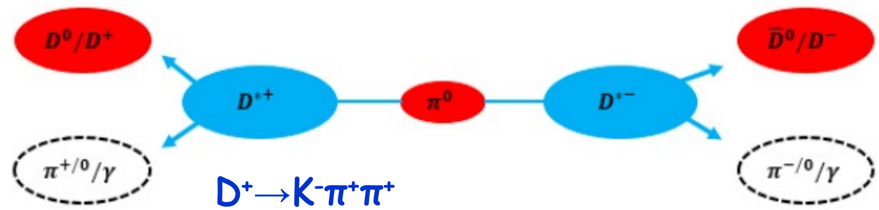
$e^+e^- \to D^+D^{*-}\pi^0 \to D^+\bar{D}^0\pi^-\pi^0$

$m_{pole} = (3885.7^{+4.3}_{-5.7} \pm 8.4)$ MeV/c²
$\Gamma_{pole} = (35^{+11}_{-12} \pm 15)$ MeV

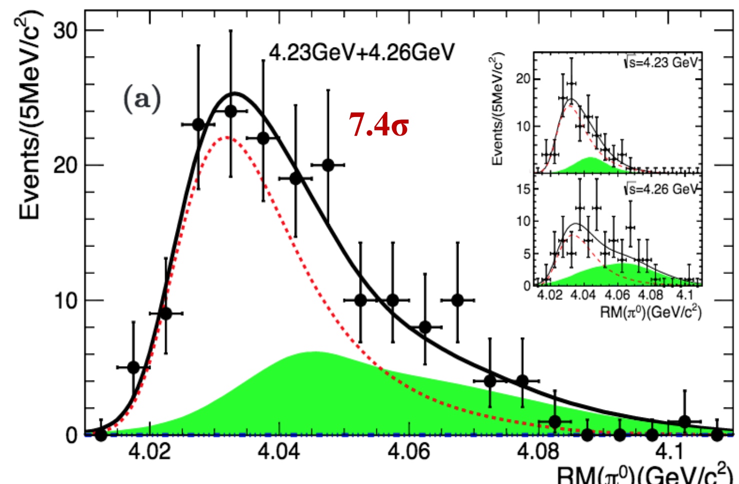


Search for $Z_c(4025)^0$ in $e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

PRL115, 182002 (2015)



$D^+ \to K^-\pi^+\pi^+$
$D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^-\pi^+\pi^+$

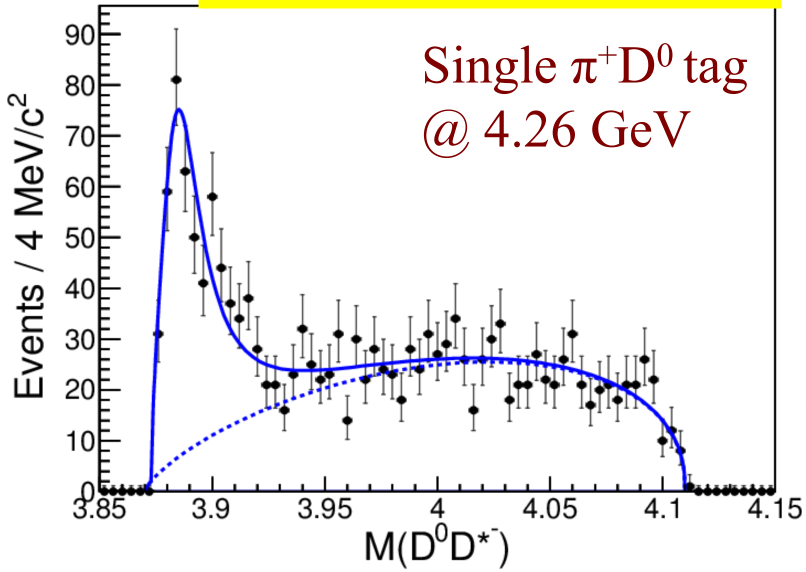


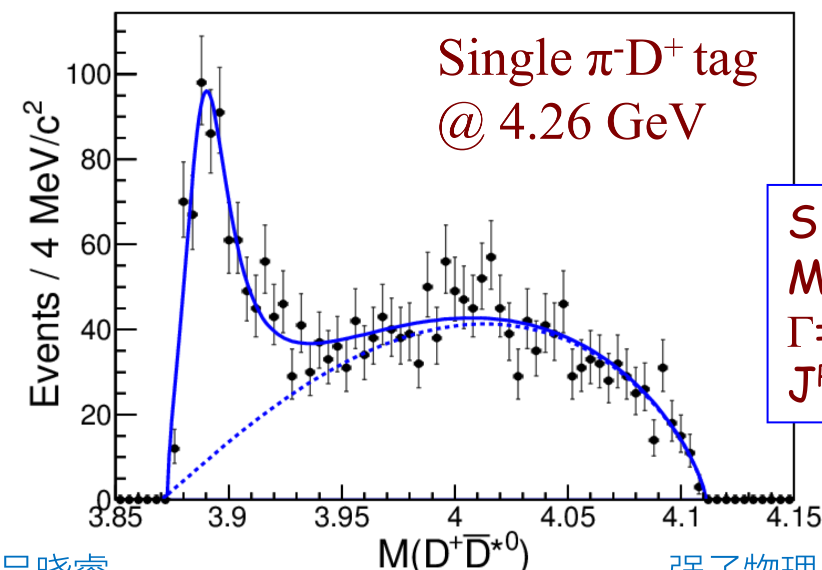
$m_{pole} = (4025.5^{+2.0}_{-4.7} \pm 3.1)$ MeV/c²
$\Gamma_{pole} = (23.0 \pm 6.0 \pm 1.0)$ MeV

Isospin triplet is established: $Z_c(3885)^{\pm/0}$ & $Z_c(4025)^{\pm/0}$

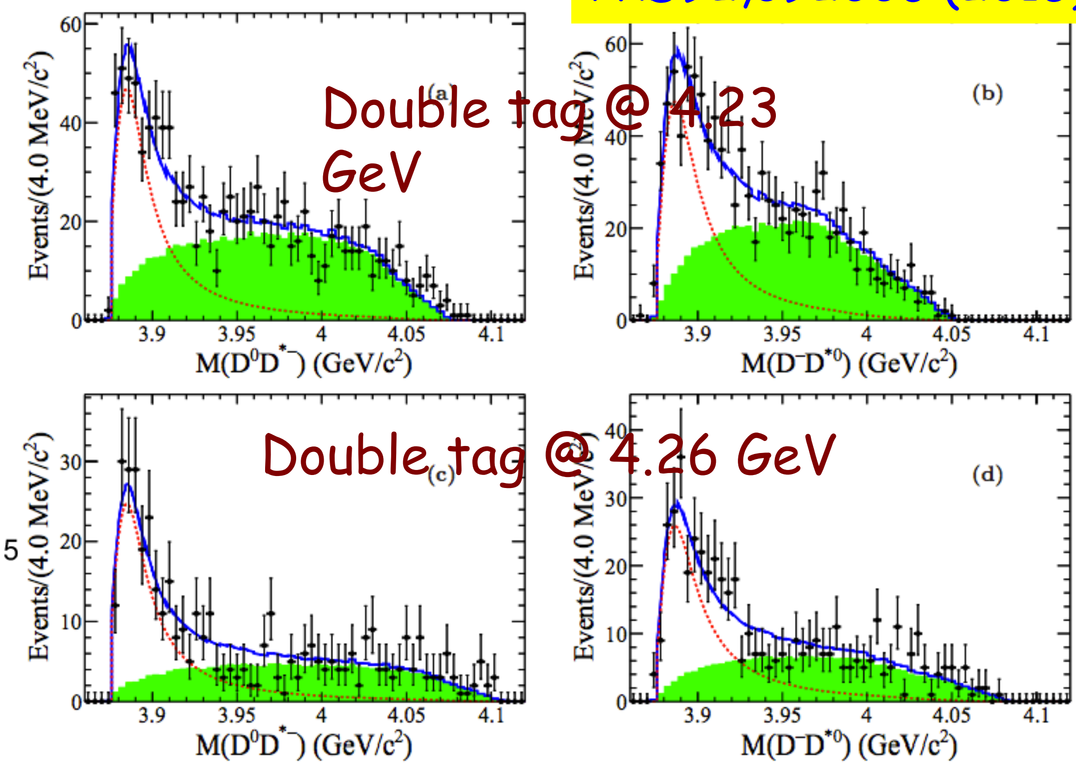
$e^+e^- \rightarrow (DD^*)^+\pi^- + c.c.$ (DT method)

PRL 112, 022001 (2014)





PRD92,092006 (2015)

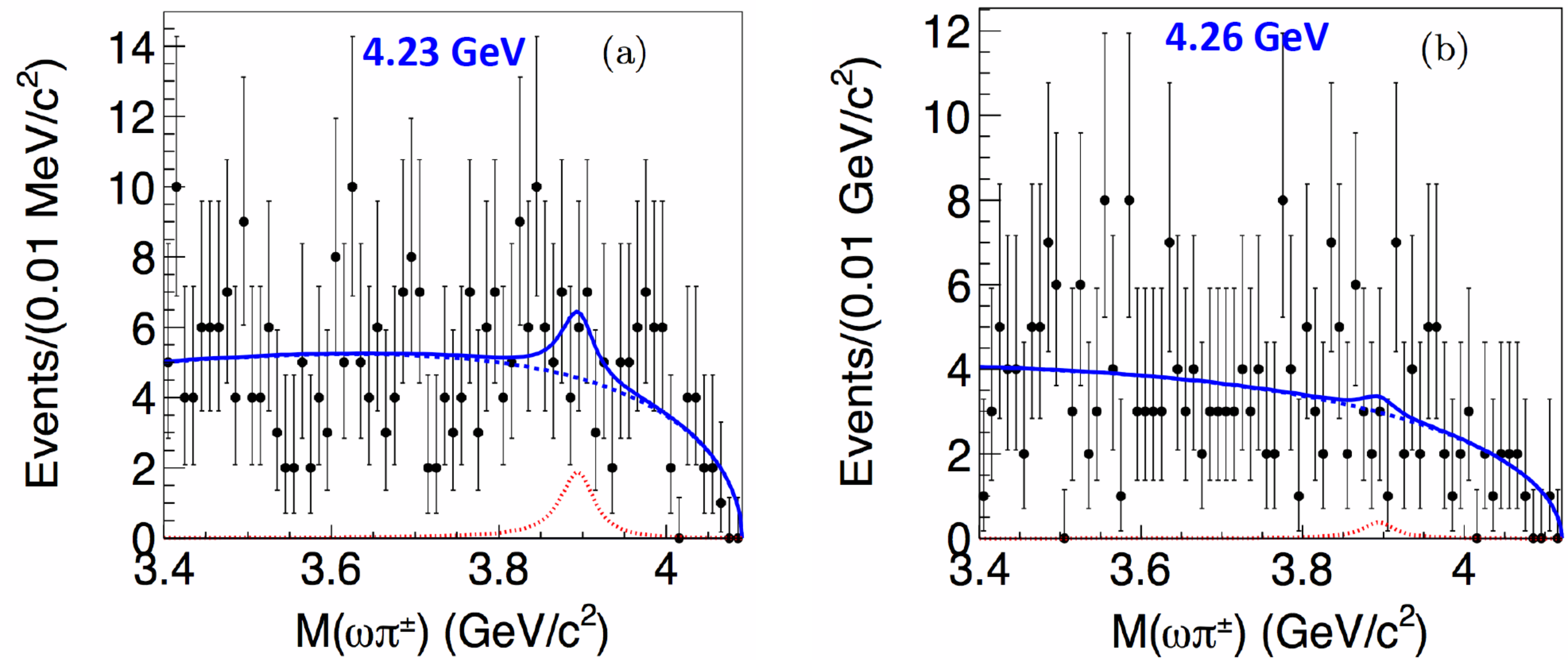


Single tag	Double tag
M=3883.9±1.5±4.2 MeV	M=3881.7±1.6±2.1 MeV
Γ=24.8±3.3±11.0 MeV	Γ=26.6±2.0±2.3 MeV
$J^P=1^+$	$J^P=1^+$

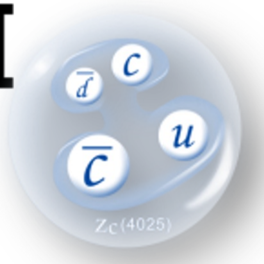
Good agreement between ST & DT method

Search for light hadron decays of Zc in $e^+e^- \to \pi Z_c(3900) \to \pi(\omega\pi)$

PRD 92, 032009(2015)



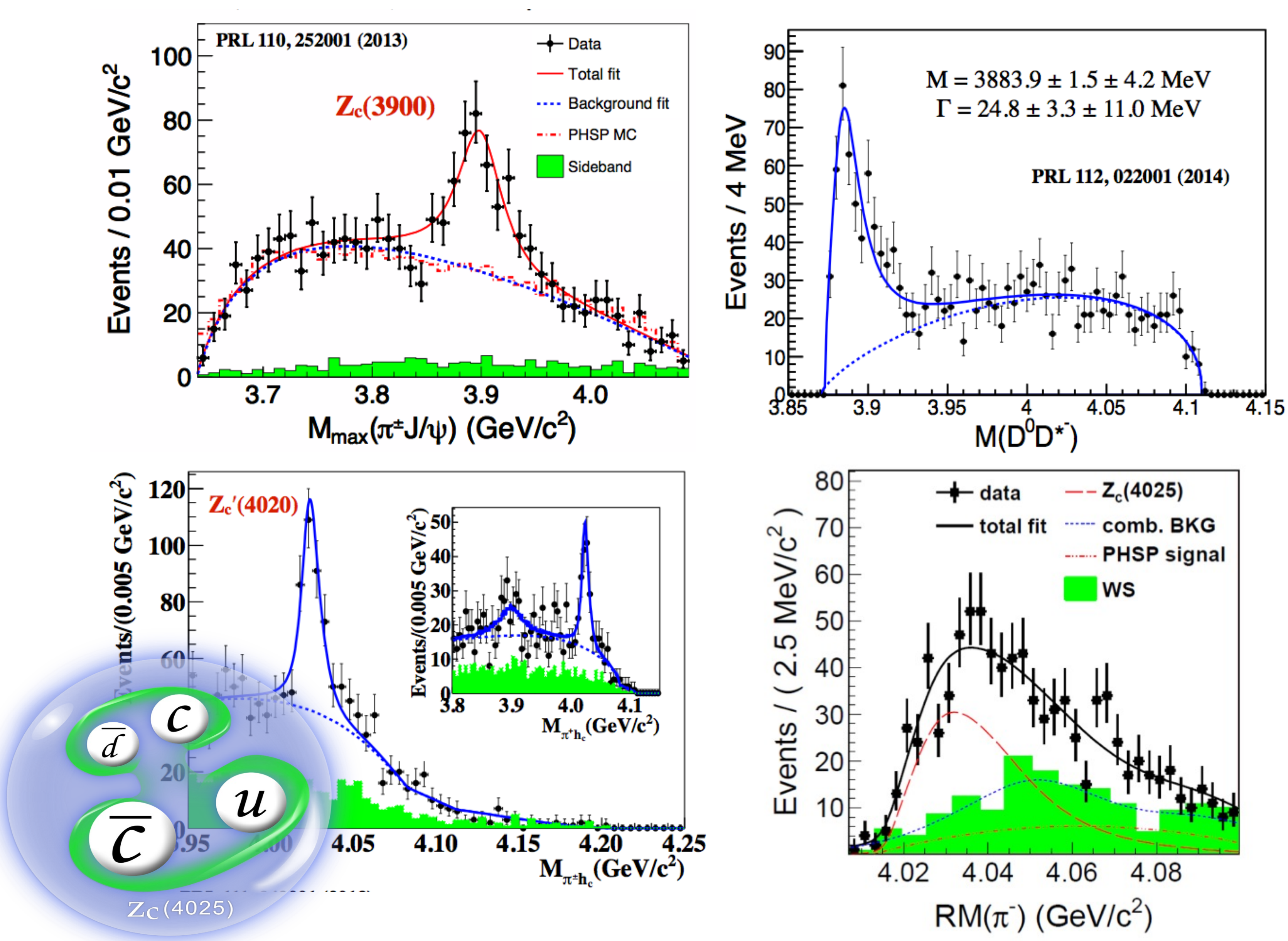
- **Searching for new decays of Zc(3900) to light hadrons: distinguish a resonance from threshold effects**
- **No significant Zc→ωπ is observed:**
  σ(e+e-→Zcπ, Zc →ωπ) < 0.26 pb @ 4.23 GeV
  σ(e+e-→Zcπ, Zc →ωπ) < 0.18 pb @ 4.26 GeV



The Zc Family at BESIII

State	Mass (MeV/c²)	Width (MeV)	Decay	Process
$Z_c(3900)^{\pm}$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	$\pi^{\pm} J/\psi$	$e^+e^- \to \pi^+\pi^- J/\psi$
$Z_c(3900)^0$	$3894.8 \pm 2.3 \pm 2.7$	$29.6 \pm 8.2 \pm 8.2$	$\pi^0 J/\psi$	$e^+e^- \to \pi^0\pi^0 J/\psi$
$Z_c(3885)^{\pm}$	$3883.9 \pm 1.5 \pm 4.2$ Single D tag	$24.8 \pm 3.3 \pm 11.0$ Single D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$
	$3881.7 \pm 1.6 \pm 2.1$ Double D tag	$26.6 \pm 2.0 \pm 2.3$ Double D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$	$(D\bar{D}^*)^0$	$e^+e^- \to (D\bar{D}^*)^0\pi^0$
$Z_c(4020)^{\pm}$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$\pi^{\pm} h_c$	$e^+e^- \to \pi^+\pi^- h_c$
$Z_c(4020)^0$	$4023.9 \pm 2.2 \pm 3.8$	fixed	$\pi^0 h_c$	$e^+e^- \to \pi^0\pi^0 h_c$
$Z_c(4025)^{\pm}$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^0\pi^0$

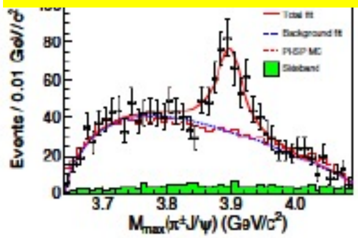
Charged Zc's found at BESIII



The Zc Family

Zc(3900)$^+$

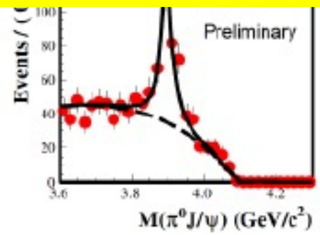
PRL 110, 252001 (2013)



$e^+e^- \to \pi^-\pi^+ J/\psi$

Zc(3900)^0

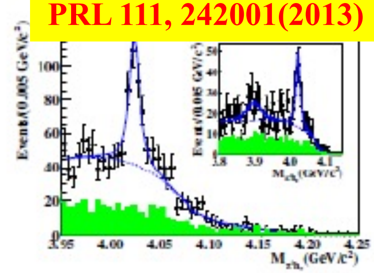
PRL 115, 112003 (2015)



$e^+e^- \to \pi^0\pi^0 J/\psi$

Zc(4020)$^+$

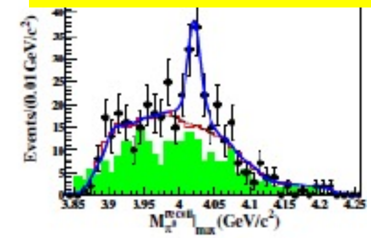
PRL 111, 242001(2013)



$e^+e^- \to \pi^-\pi^+ h_c$

Zc(4020)^0

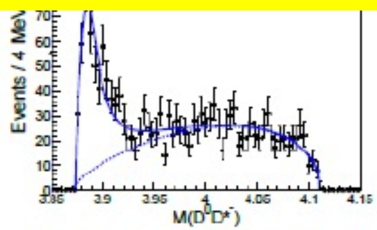
PRL113,212002 (2014)



$e^+e^- \to \pi^0\pi^0 h_c$

Zc(3885)$^+$

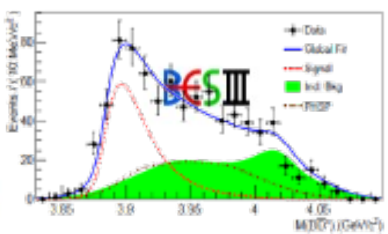
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



$e^+e^- \to \pi^-(D\bar{D}^*)^+$

Zc(3885)^0

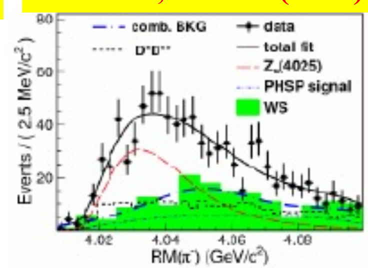
PRL 115, 222002 (2015)



$e^+e^- \to \pi^0(D^*\bar{D})^0$

Zc(4025)$^+$

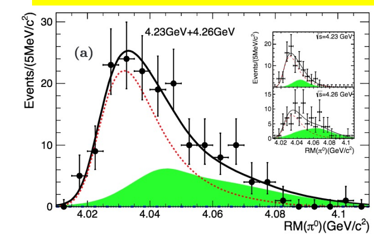
PRL 112, 132001 (2014)



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

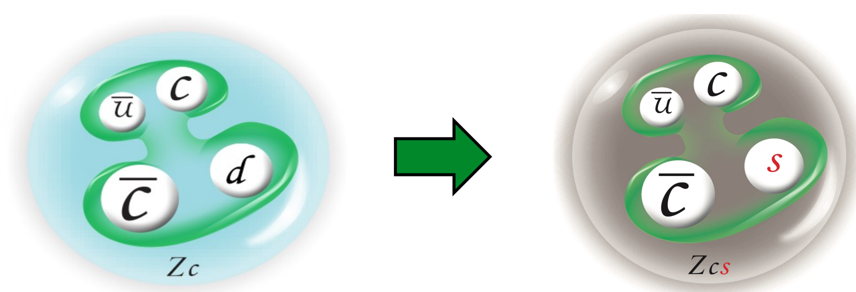
Zc(4025)^0

PRL115, 182002 (2015)



$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

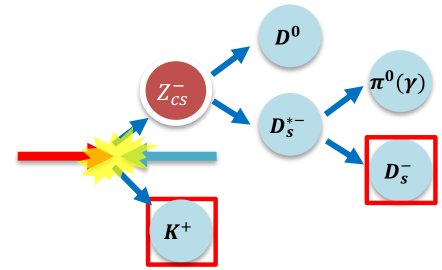
Which is the nature of these states?
If exists, there should be SU(3) counter-part Zcs state with strangeness



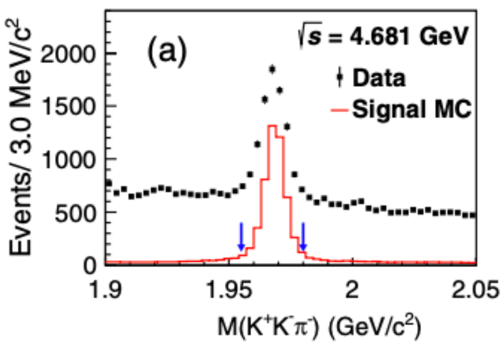
Observation of the $Z_{cs}(3985)^{\pm}$

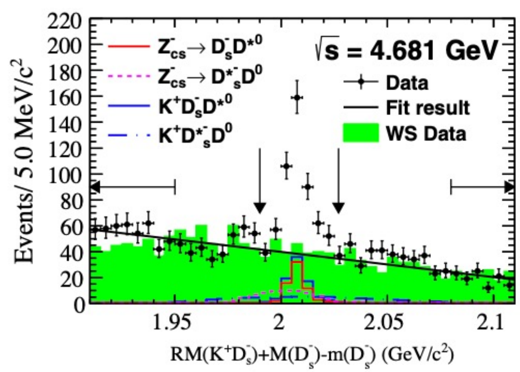
PRL126, 102001 (2021)

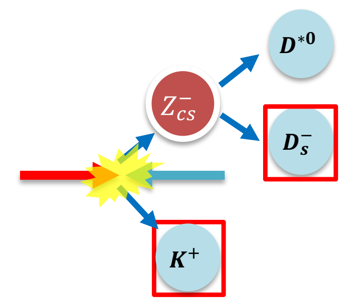
- 3.7fb^{-1} data accumulated at 4.628-4.698 GeV
- **Partial reconstruction of K^+ and D_s^-**
- Signature in the **recoil mass spectrum of $K^+D_s^-$** to identify the process of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$



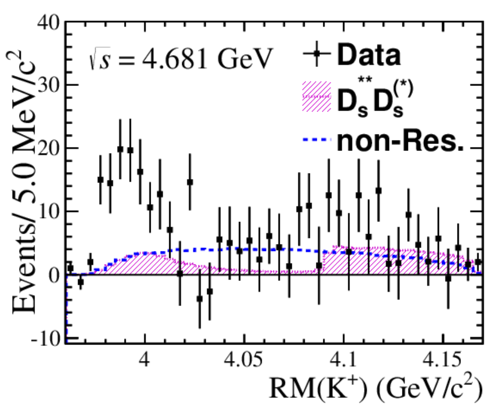
$e^+e^- \to K^+ D_s^{*-} D^0$

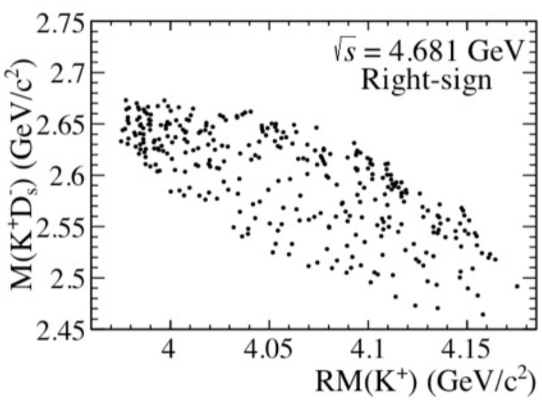


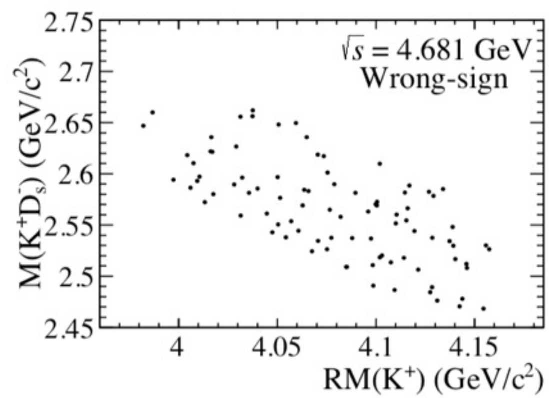




$e^+e^- \to K^+ D_s^- D^{*0}$

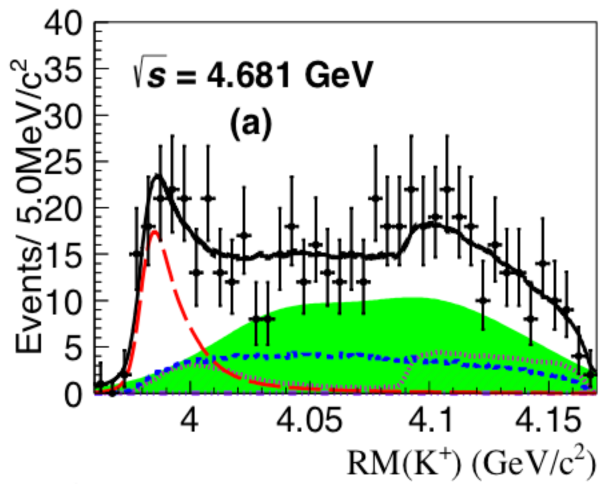


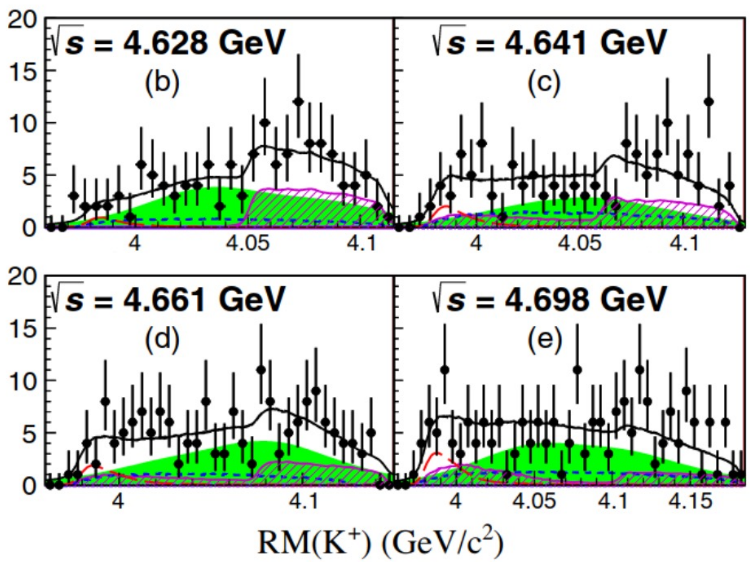




Observation of the $Z_{cs}(3985)^{\pm}$

PRL126, 102001 (2021)

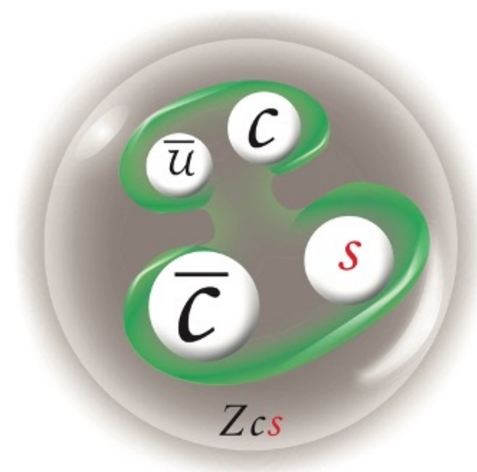




- Assume the structure as a $D_s^- D^{*0}/D_s^{*-} D^0$ resonance, denoting it as the $Z_{cs}(3985)^-$.
- A fit of J^P=1^+ S-wave Breit-Wigner with mass dependent width returns:

$$\boldsymbol{m} = 3985.2^{+2.1}_{-2.0} \pm 1.7\ \mathrm{MeV/c^2}$$
$$\boldsymbol{\Gamma} = 13.8^{+8.1}_{-5.2} \pm 4.9\ \mathrm{MeV}$$

- Global significance: >5.3 $\boldsymbol{\sigma}$



First candidate of the hidden-charm tetraquark with strangeness

The Zcs (3985)$^{\pm}$ and Zc(3885)$^{\pm}$

1643/pb data @4.681 GeV

525/pb data @4.26 GeV

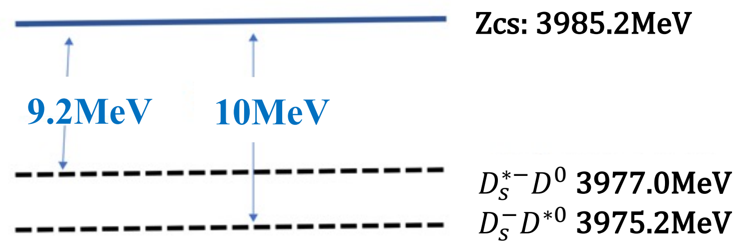
	$Z_{cs}(3985)^{\pm}$	$Z_c(3900)^{\pm}$	$Z_c(3885)^{\pm}$
Mass (MeV/c^2)	$3985.2^{+2.1}_{-2.0} \pm 1.7$	3899.0±3.6±4.9	3883.9±1.5±4.2
Width (MeV)	$13.8^{+8.1}_{-5.2} \pm 4.9$	46±10±26	24.8±3.3±11.0
$\sigma^{Born} \cdot \mathcal{B}$ (pb)	$4.4^{+0.9}_{-0.8} \pm 1.4$	13.5±2.1±4.8	83.5±6.6±22.0

~10 MeV above D_sD^*/D_sD thresholds
similar to $Z_c(3900)$ & $Z_b(10,610)$
(DD*) (BB*)

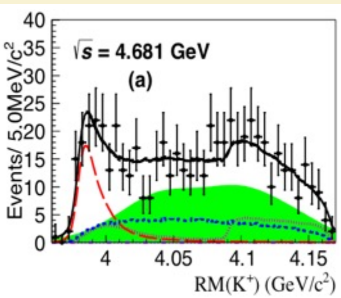
from Marek Karliner in Nov. 2020

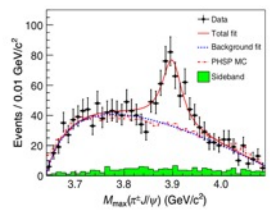
two general comments about
charm-tau factory program

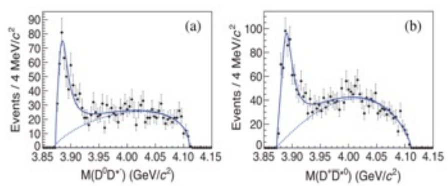
- $J/\psi\, K^{\pm}$ resonances:
  $Z_c(3900)$ analogue?
  $Z_c(3900)^+ = (c\bar{c}u\bar{d})$; $d \to s$: $(c\bar{c}u\bar{s}) \sim D_s\bar{D}^*$
  no natural molecular binding,
  so if discovered, would indicate
  Tq or a novel mechanism



SU(3) partner of Zc(3900)?







$Z_{cs}(3985)$

$K^- Z_{cs}^+$	$\bar{K}^0 Z_{cs}^0$	$K^0 \bar{Z}_{cs}^0$	$K^+ Z_{cs}^-$
1/4	1/4	1/4	1/4

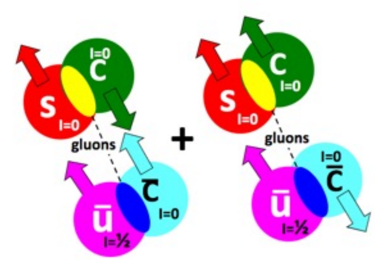
neutral/charged = 1

$Z_c(3900)$

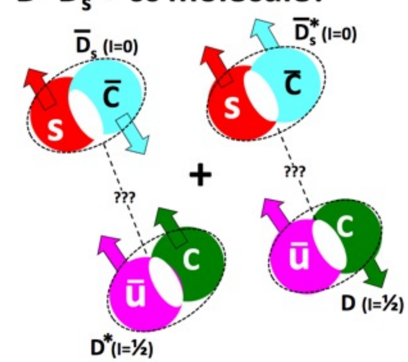
$\pi^- Z_c^+$	$\pi^0 Z_c^0$	$\pi^+ Z_c^-$
1/3	1/3	1/3

neutral/charged = 1/2

diquark-antidiquark?



$D^*\bar{D}_s$ + cc molecule?



Evidence for the neutral $Z_{cs}(3985)^0$

arXiv 2204.13703, accepted by PRL

3.7fb[-1] data accumulated at 4.628-4.698 GeV

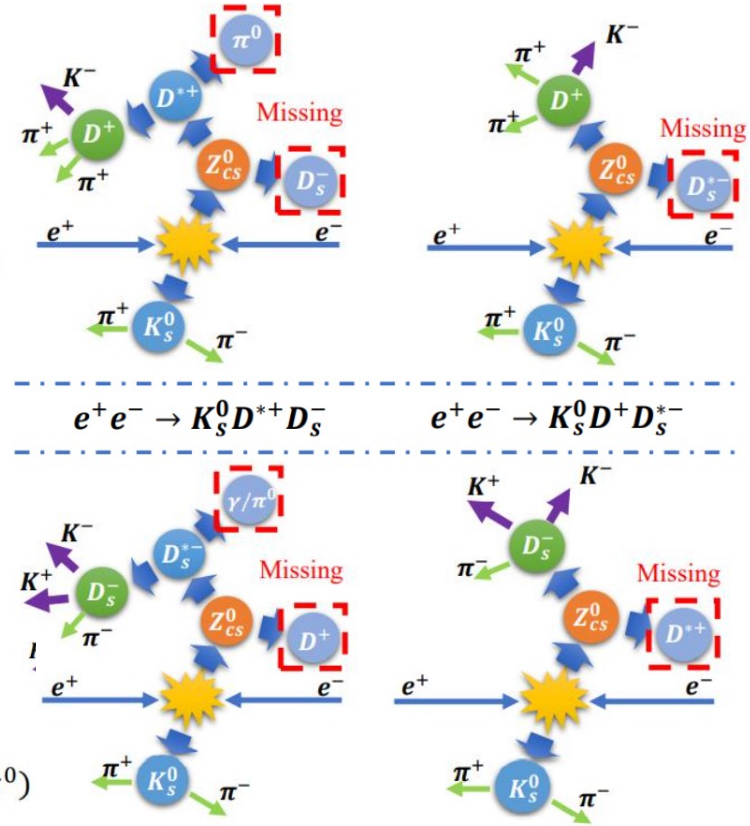
Partial reconstruction

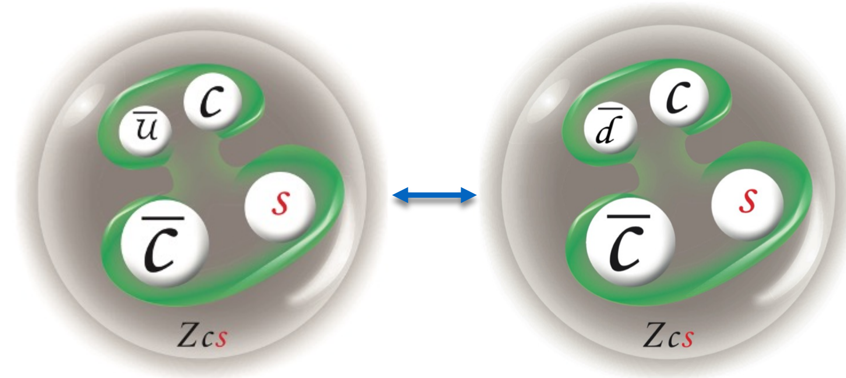
Tag: K_S^0, D^+

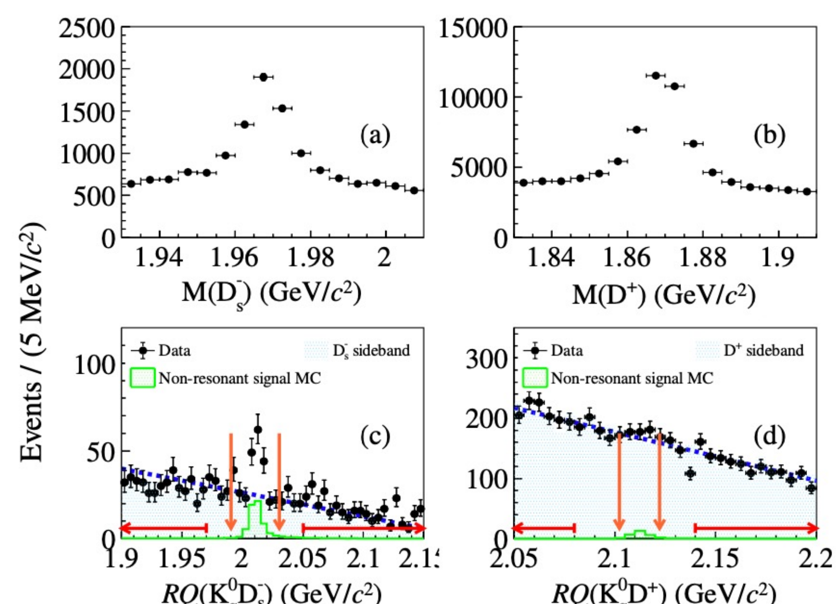
Missing: D_s^{*-} or D_s^- and π^0

Tag: K_S^0, D_s^-

Missing: D^{*+} or D^+ and $\gamma(\pi^0)$



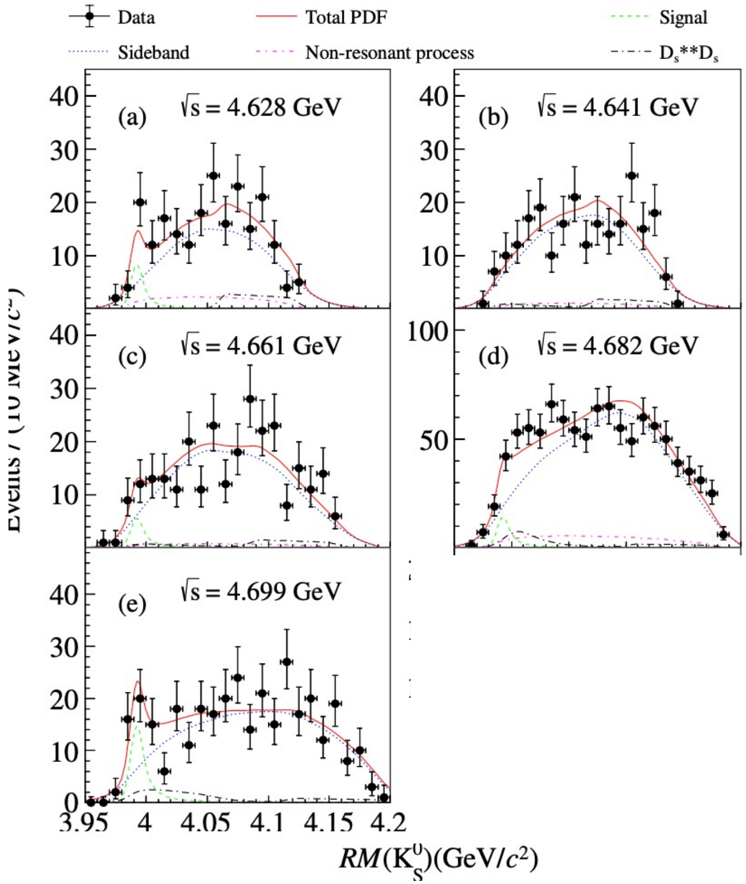


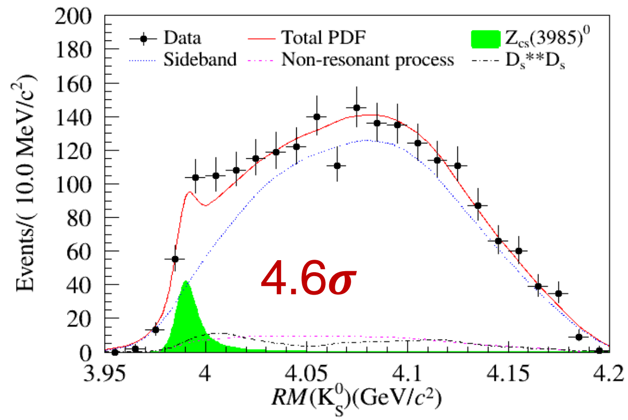


- The D_s^+ and D^+ are reconstructed through
  - $D_s^- \to K^+K^-\pi^-$, $K^+K^-\pi^-\pi^0$, $K_s^0K^-$, $K_s^0K^+\pi^-\pi^-$, $\eta'\pi^-$
  - $D^+ \to K^-\pi^+\pi^+$, $K_s^0\pi^+$, $K_s^0\pi^+\pi^+\pi^-$

Evidence for the neutral $Z_{cs}(3985)^0$

arXiv 2204.13703 accepted by PRL





$\sqrt{s}$ (MeV)	$\sigma^{Born}\times\mathcal{B}$ (pb) $\bar{K}^0 Z_{cs}(3985)^0$	$K^- Z_{cs}(3985)^+$	χ^2	χ^2_{total}/ndf
4628	$4.4^{+2.6}_{-2.2}\pm2.0$	$0.8^{+1.2}_{-0.8}\pm0.6$	1.2	
4641	$0.0^{+1.6}_{-0.0}\pm0.2$	$1.6^{+1.2}_{-1.1}\pm1.3$	0.5	
4661	$2.8^{+1.8}_{-1.6}\pm0.6$	$1.6^{+1.3}_{-1.1}\pm0.8$	0.3	5.1/5
4682	$2.2^{+1.2}_{-1.0}\pm0.8$	$4.4^{+0.9}_{-0.8}\pm1.4$	1.0	
4699	$7.0^{+2.2}_{-2.0}\pm1.8$	$2.4^{+1.1}_{-1.0}\pm1.2$	2.1	

	Mass (MeV/c^2)	Width (MeV)
$Z_{cs}(3985)^0$	$3992.2\pm1.7\pm1.6$	$7.7^{+4.1}_{-3.8}\pm4.3$
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0}\pm1.7$	$13.8^{+8.1}_{-5.2}\pm4.9$

- Mass and width consistent with the charged Zcs: $m(Zcs^+)<m(Zcs^0)$
- Cross sections are consistent under isospin symmetry

➔ they are isospin partners

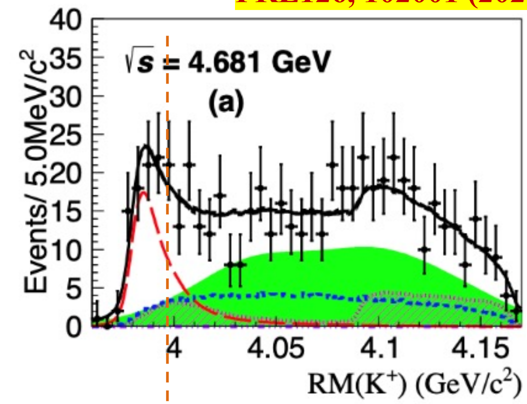
Discussions on the nature of $Z_{cs}(3985)$

- Various interpretations are possible for the structure
  - Tetraquark state
  - Molecule
  - $D_{s2}^{*}(2573)^{+}D_{s}^{*-}$ threshold kinematic effects (Re-scattering , Reflection, Triangle singularity)
  - Mixture of molecular and tetraquark
  - …

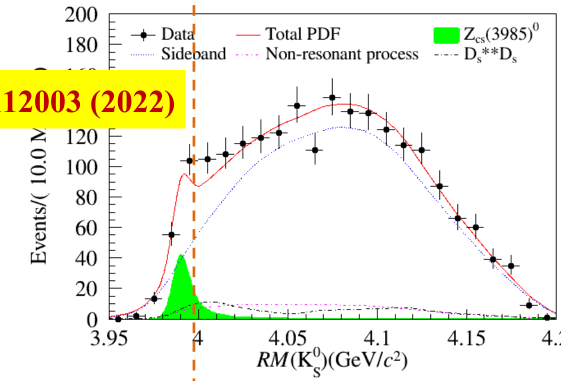
$Z_{cs}(3985)$ from e^+e^- annihilations and $Z_{cs}(4000)$ from B decays

- their masses are close, but widths are different
- If they are same, why width so different?
- If they are not same, is there the corresponding wide Zc(3900)?
- Looking for more channels will be useful

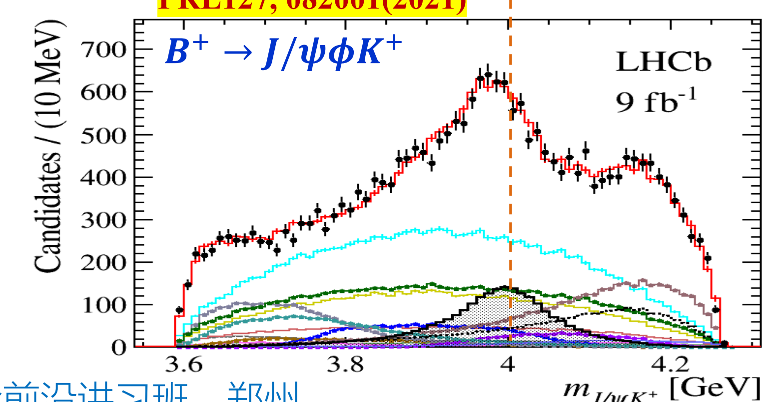
PRL126, 102001 (2021)



PRL 129, 112003 (2022)



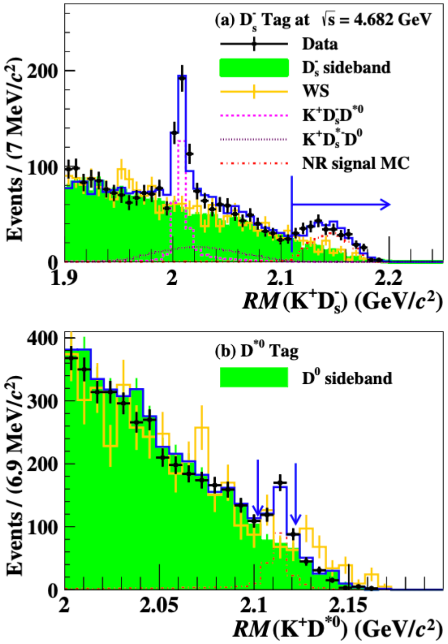
PRL127, 082001(2021)

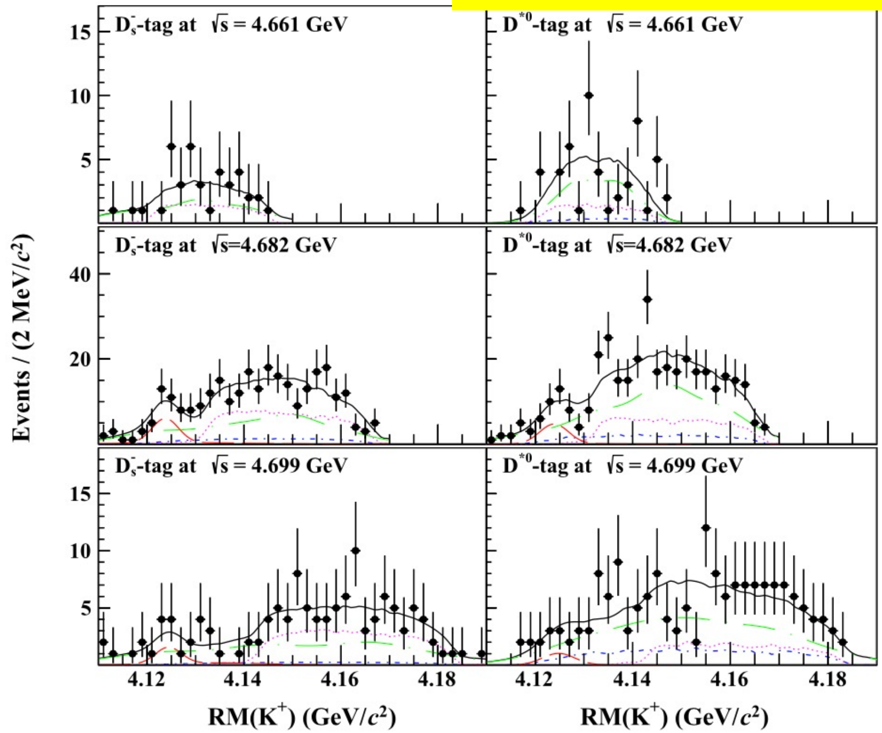


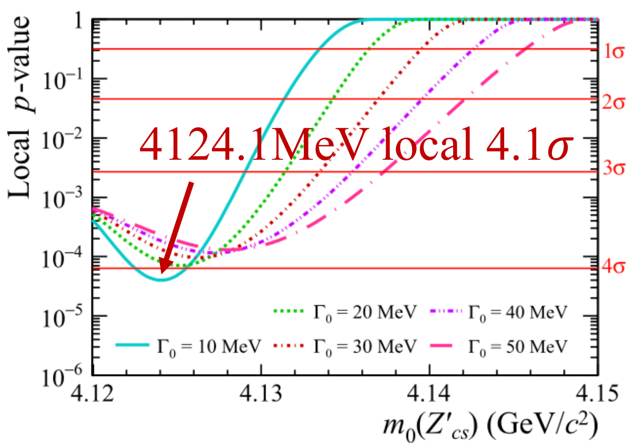
Search for the charged Z'_{cs}

CPC47, 033001 (2023)

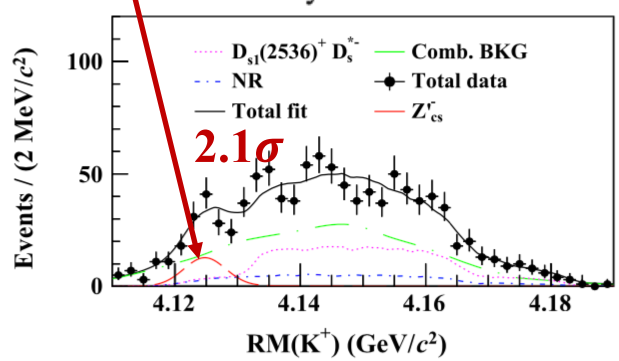
signal channel: $e^+e^- \to K^+D^{*0}D_s^{*-}$



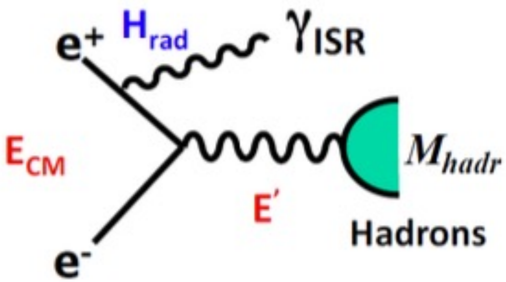




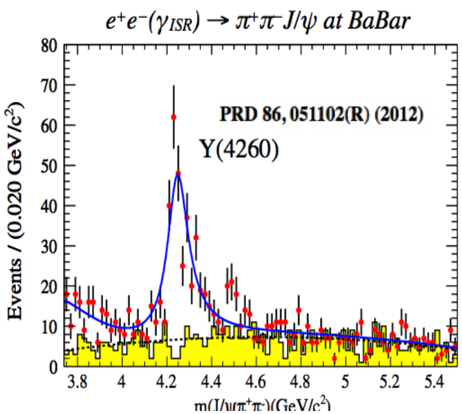
$(4123.5 \pm 0.7_{\text{stat.}} \pm 4.7_{\text{syst.}})\,\text{MeV}/c^2$

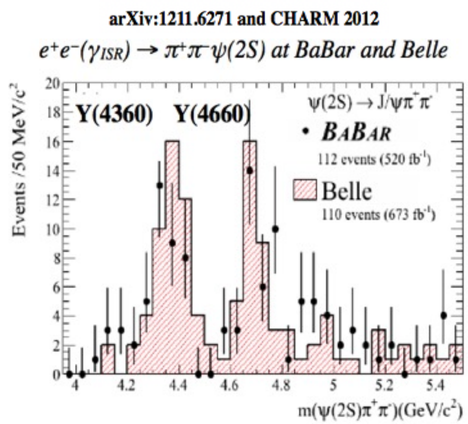


The Y states



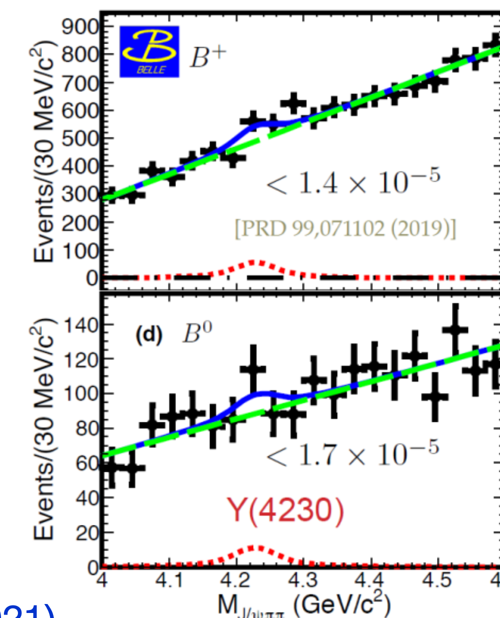
Y states: charmonium-like states with $J^{PC}=1^{--}$; Observed in direct e+e- annihilation or initial state radiation (ISR).



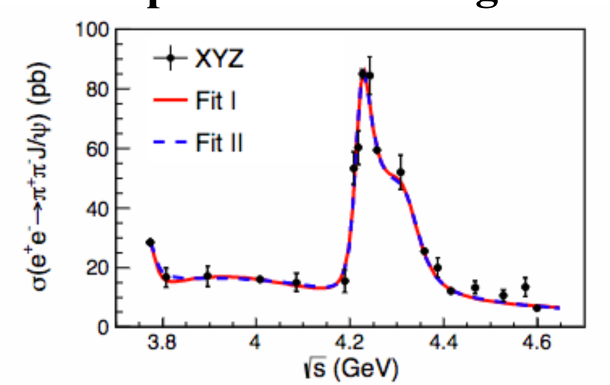


- **While not seen yet in B decays**

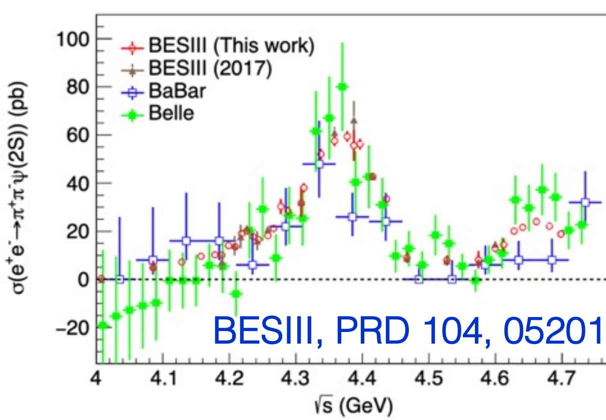
$$B^{\pm,0} \to K^{\pm,0}\pi^+\pi^- J/\psi$$



- **Improved knowledges from BESIII**



BESIII, PRL118, 092001 (2017)



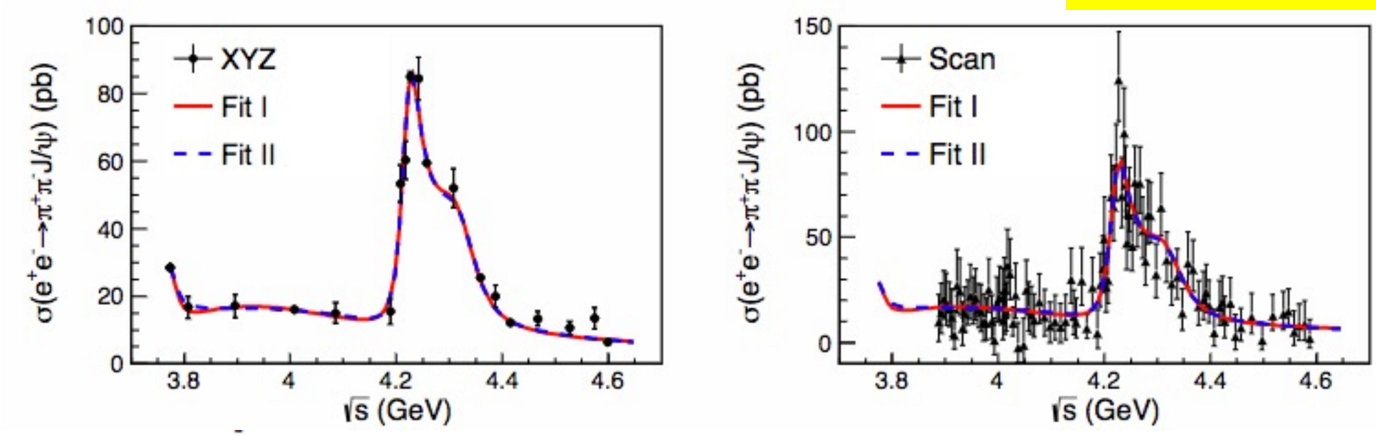
BESIII, PRD 104, 052012 (2021)

Cross sections of $e^+e^-\to\pi^+\pi^-J/\psi$

$e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII (direct)

Inconsistent with a single BW of Y(4260)

PRL118, 092001 (2017)



Parameters	Fit result
$M(R_1)$	$3812.6^{+61.9}_{-96.6}$ $(\cdots)$
$\Gamma_{tot}(R_1)$	$476.9^{+78.4}_{-64.8}$ $(\cdots)$
$M(R_2)$	4222.0 ± 3.1 (4220.9 ± 2.9)
$\Gamma_{tot}(R_2)$	44.1 ± 4.3 (44.1 ± 3.8)
$M(R_3)$	4320.0 ± 10.4 (4326.8 ± 10.0)
$\Gamma_{tot}(R_3)$	$101.4^{+25.3}_{-19.7}$ $(98.2^{+25.4}_{-19.6})$

Structure at 4260 is not a simple BW, but rather two:

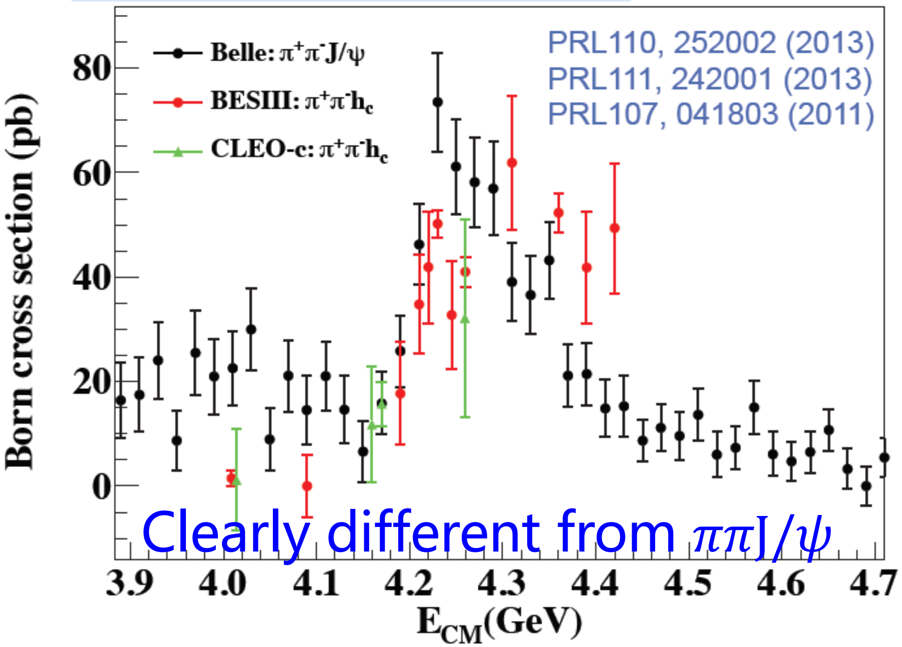
- Significance > 7.6σ
- R_2: consistent with the Y(4260), however narrower
- R_3: comparable to the Y(4360)

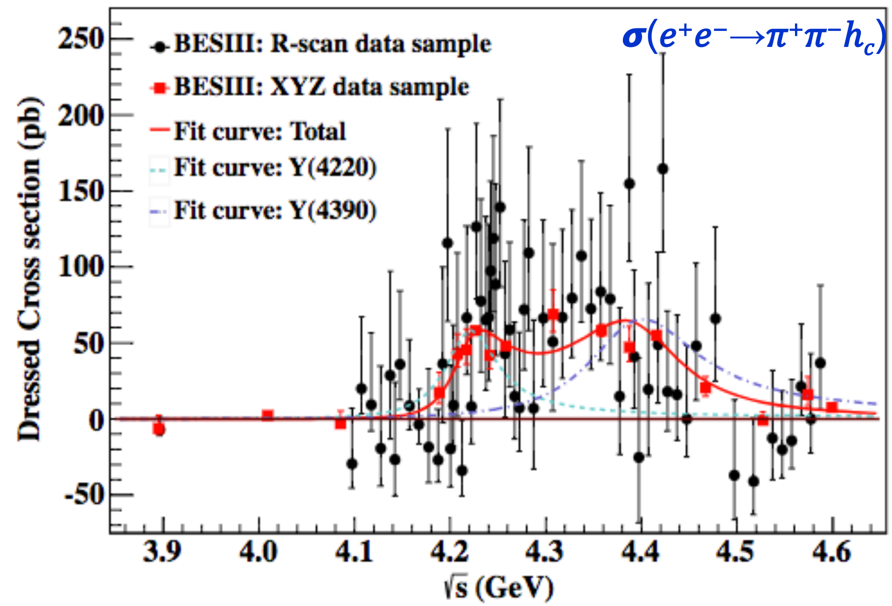
Y(4260) ➔ Y(4230) and Y(4320)

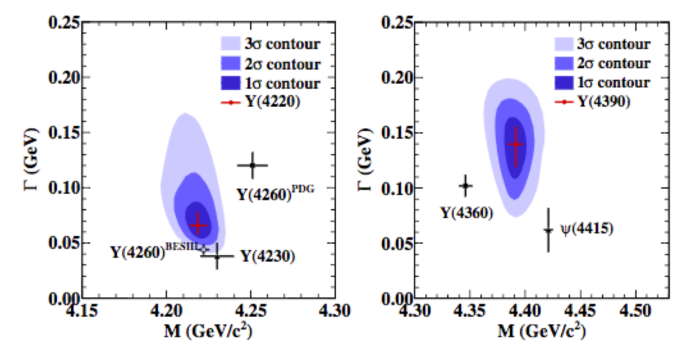
Cross sections of $e^+e^-\to\pi^+\pi^-h_c$

PRL118, 092002 (2017)

$e^+e^- \to \pi^+\pi^- h_c$ at BESIII (direct)

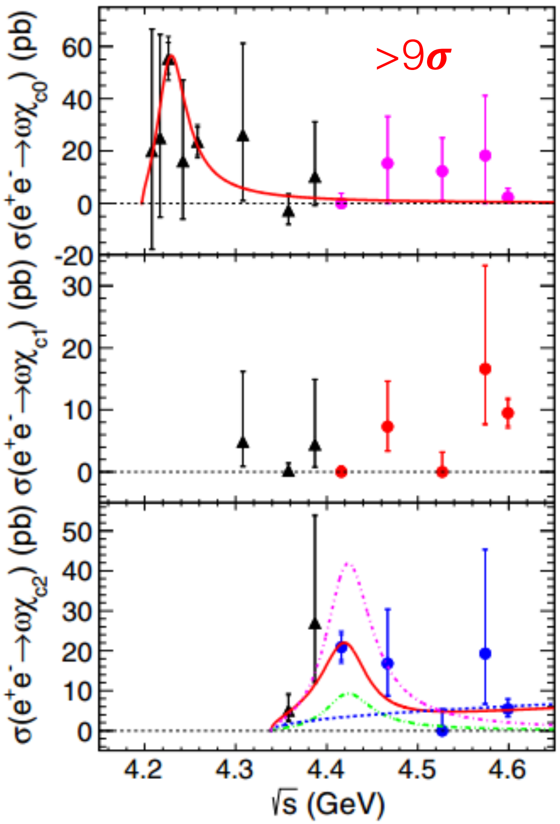






- h_c reconstructed in $h_c\to\gamma\eta_c$, $\eta_c\to$ 16 exclusive hadronic final states
- Coherent sum of two BWs
  - $M_1=(4218.4^{+5.5}_{-4.5}\pm0.9)$ MeV, $\Gamma_1=(66.0^{+12.3}_{-8.3}\pm0.4)$ MeV
    $M_2=(4391.5^{+6.3}_{-6.8}\pm1.0)$ MeV, $\Gamma_2=(139.5^{+16.2}_{-20.6}\pm0.6)$ MeV
- First one has consistent mass with $\pi^+\pi^-J/\psi$ state at 4222 MeV
- Significance of double BW vs. single BW is 10 σ

Cross sections of $e^+e^-\to\omega/\phi\chi_{cJ}$ (J=0,1,2)



The triangle black data points are from

Phys. Rev. Lett. 114,092003(2015)

Other data points are from

Phys. Rev. D 93, 011102 (2016)

$e^+e^-\to\omega\chi_{c0}$:

Fit with a single BW

Mass = 4226±8±6 MeV

Width = 39±12±2 MeV

Significance > 9**σ**

$e^+e^-\to\omega\chi_{c2}$:

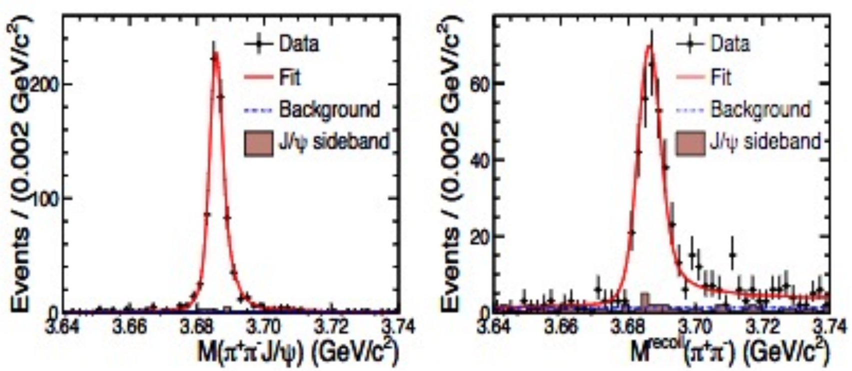
Agree with from ψ(4415) with
BR=(1.4±0.5)×10^{-3} (sol. I), or
BR=(6±1)×10^{-3} (sol. II)

While BESIII measures $e^+e^-\to\phi\chi_{cJ}$ at 4.6GeV *PRD97, 032008 (2018)*

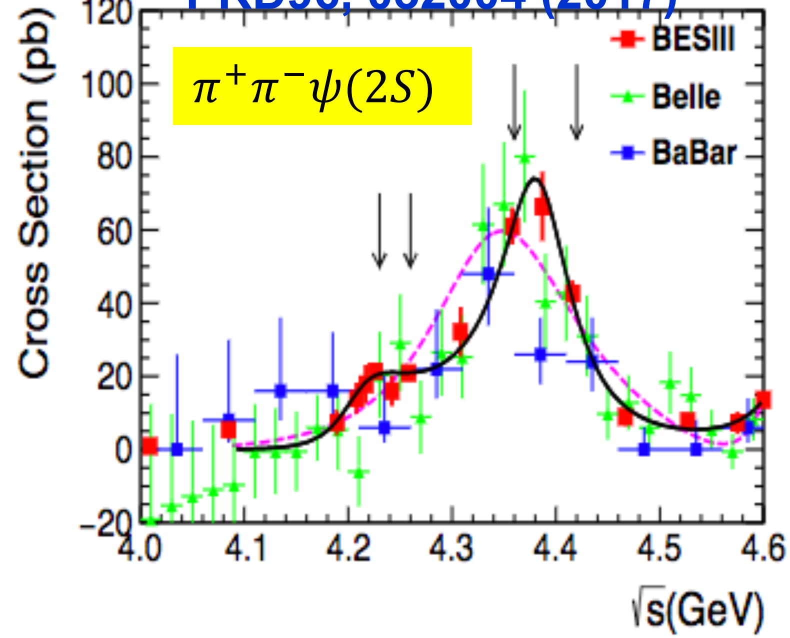
- $\sigma(e^+e^-\to\phi\chi_{c0}) < 5.4$ pb
- $\sigma(e^+e^-\to\phi\chi_{c1}) < (4.2^{+1.7}_{-1.0}\pm0.3)$ pb
- $\sigma(e^+e^-\to\phi\chi_{c2}) < (6.7^{+3.4}_{-1.7}\pm0.5)$ pb

Need data beyond 4.6 GeV to check structure in $\omega\chi_{c1}$ and $\phi\chi_{cJ}$

Cross sections of $e^+e^-\to\pi\pi\psi(2S)$

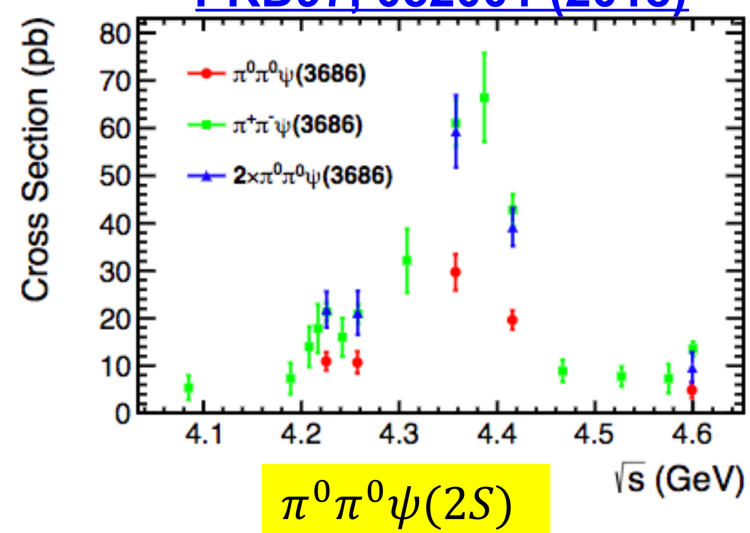


PRD96, 032004 (2017)



Parameters	Solution I	Solution II
$M(Y4220)$ (MeV/c^2)	4209.5 ± 7.4	
$\Gamma(Y(4220))$ (MeV)	80.1 ± 24.6	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4220))$ (eV)	0.8 ± 0.7	0.4 ± 0.3
$M(Y4390)$ (MeV/c^2)	4383.8 ± 4.2	
$\Gamma(Y(4390))$ (MeV)	84.2 ± 12.5	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4390))$ (eV)	3.6 ± 1.5	2.7 ± 1.0
ϕ_1 (rad)	3.3 ± 1.0	2.8 ± 0.4
ϕ_2 (rad)	0.8 ± 0.9	4.7 ± 0.1

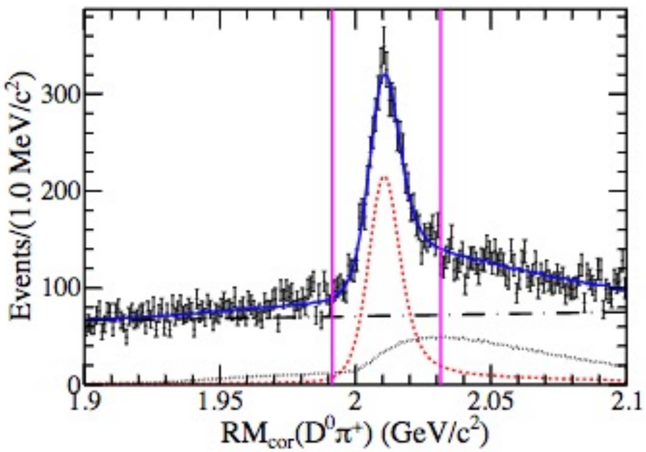
PRD97, 052001 (2018)



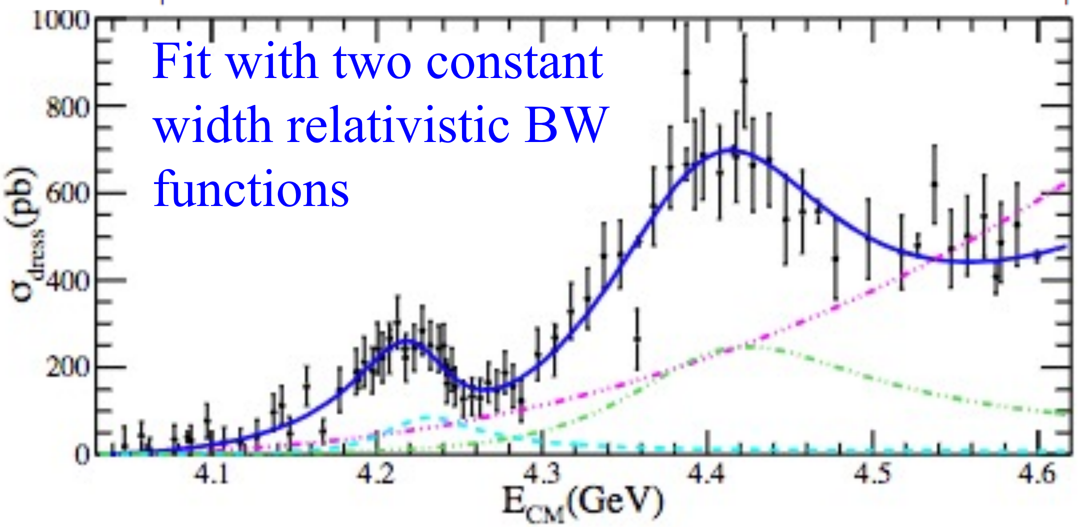
- Confirm the lineshape of the Y(4360)
- Y(4220) and Y(4390) are confirmed

$e^+e^- \to \pi^+ D^0 D^{*-}$ cross section

- Detect $D^0 \to K^-\pi^+$ and bachelor π^+, and reconstruct D^{*-} in the missing mass spectrum



$$\sigma_{\text{dress}}(m) = \left| c \cdot \sqrt{P(m)} + e^{i\phi_1} B_1(m) \sqrt{P(m)/P(M_1)} + e^{i\phi_2} B_2(m) \sqrt{P(m)/P(M_2)} \right|^2$$



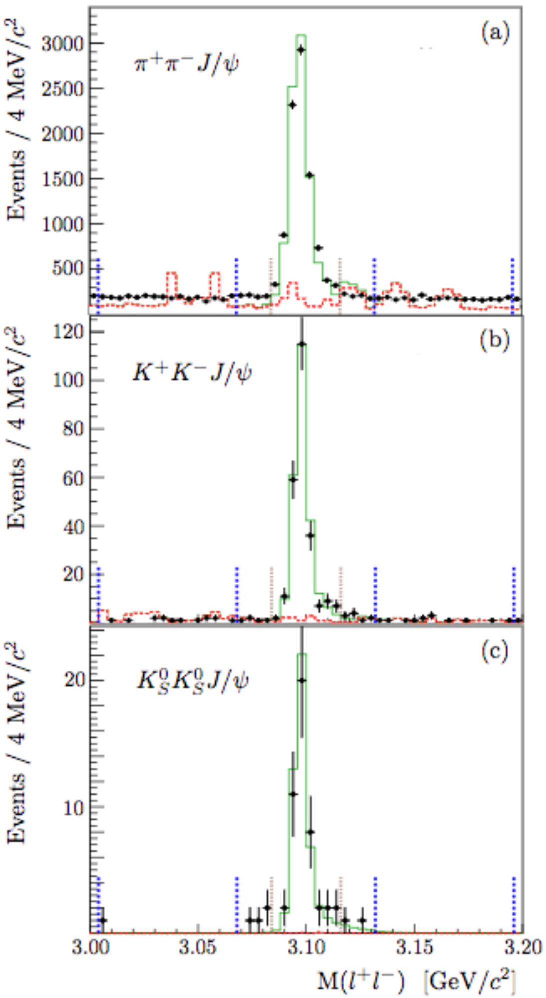
PRL 122, 102002 (2019)

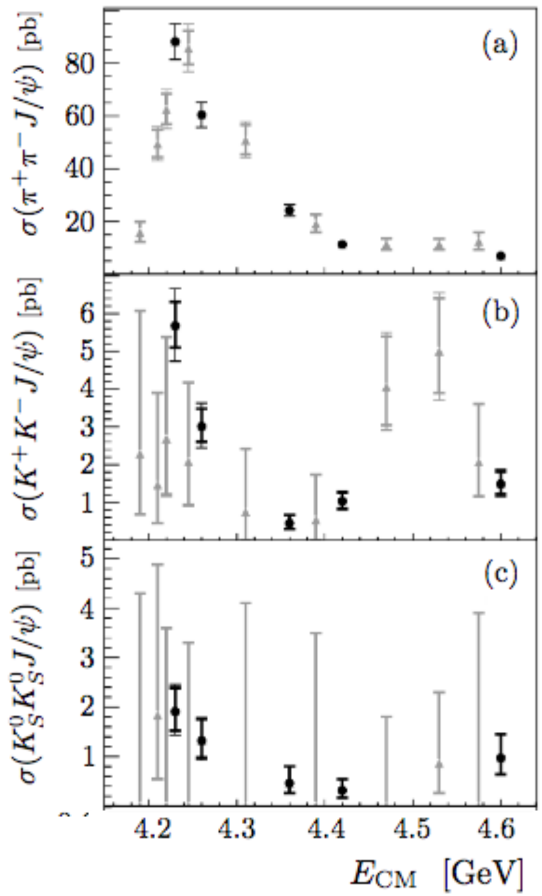
- Two enhancements are evident
- Many ψ and Y states are adopted to fit the bumps
- The lower bump consistently corresponds to the Y(4220) $M = (4228.6 \pm 4.1 \pm 5.9)$ MeV $\Gamma = (77.1 \pm 6.8 \pm 6.9)$ MeV
- The higher bump around 4.4GeV can not be described by either single resonance of the Y(4260), Y(4320), Y(4360) or $\psi(4415)$. Further more data set is required to better understand this.

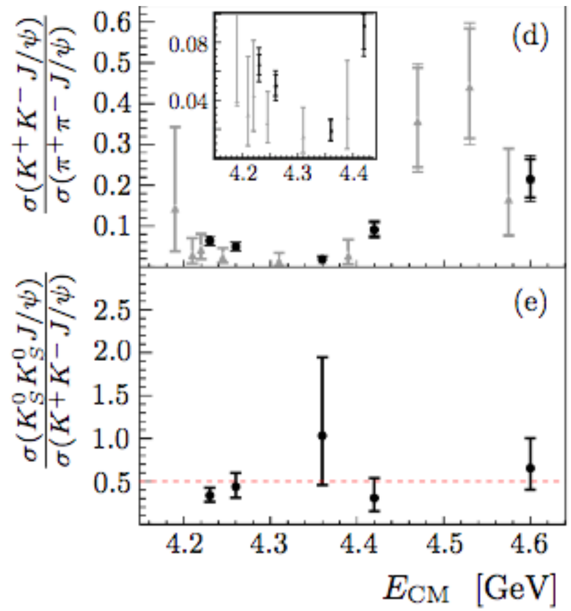
First observation of the Y(4260) decays to open charm states

$e^+e^- \to K^+K^-J/\psi$

[PRD 97, 071101 (2018)]

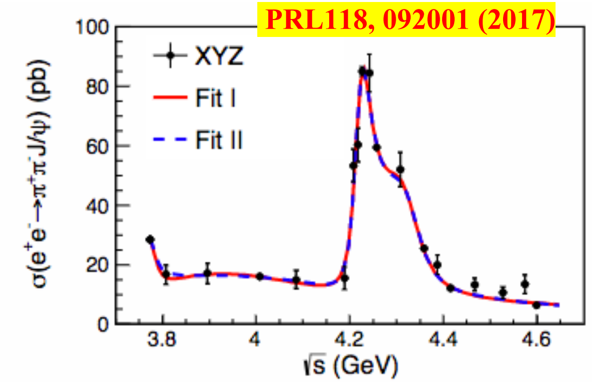


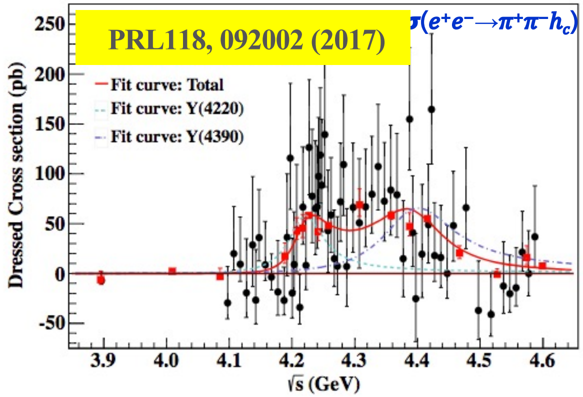


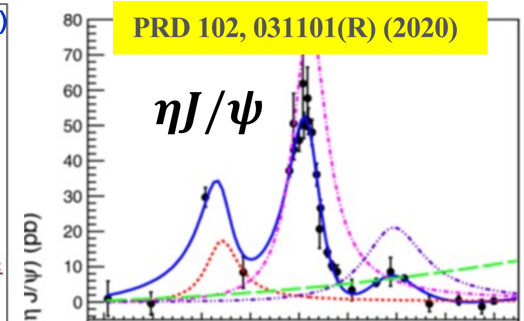


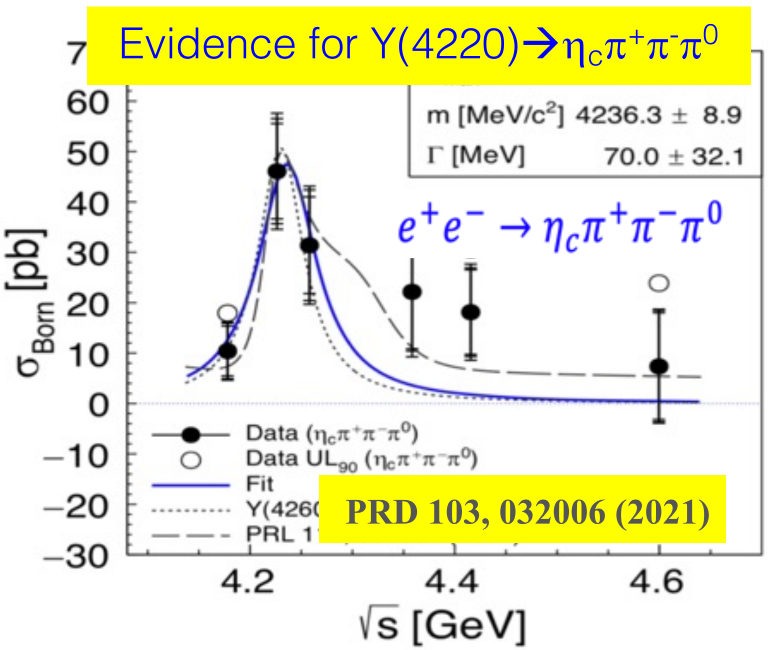
- $\sigma\,(KKJ/\psi)$ lineshape is quite different from $\sigma\,(\pi^+\pi^-J/\psi)$ around Y(4220)/Y(4260)
- Higher bump around 4.5GeV is clear and need further investigation

Y(4260) ➔ Y(4230) and new Y's

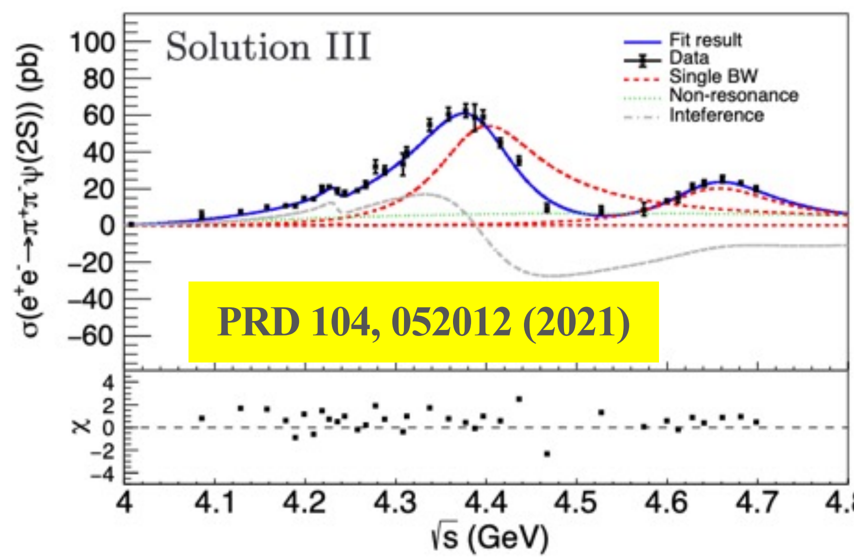


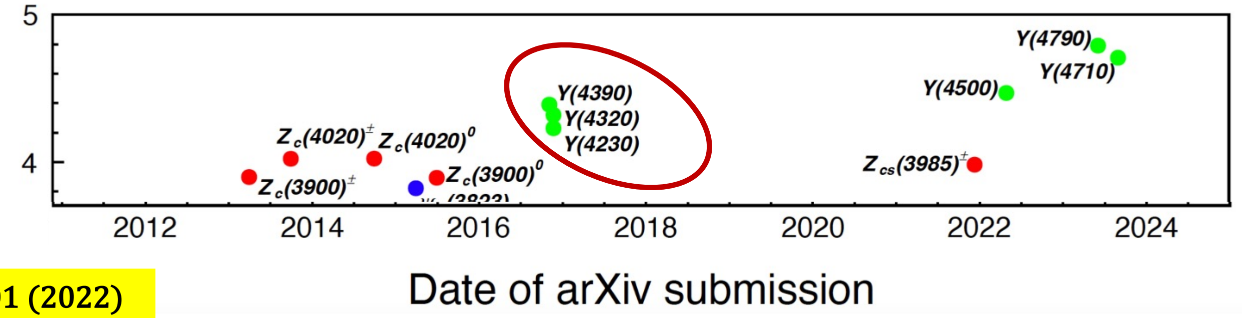




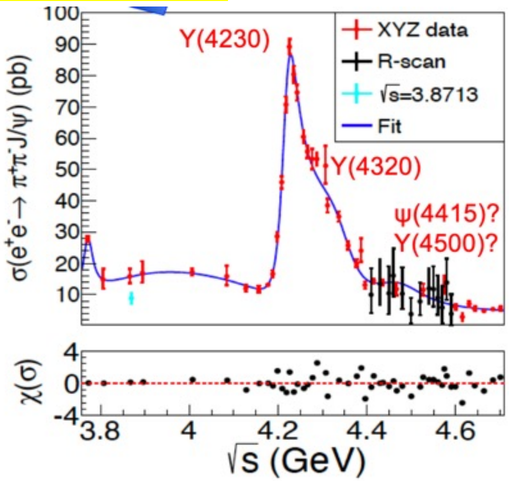


confirmed Y(4220), Y(4390) and Y(4660)





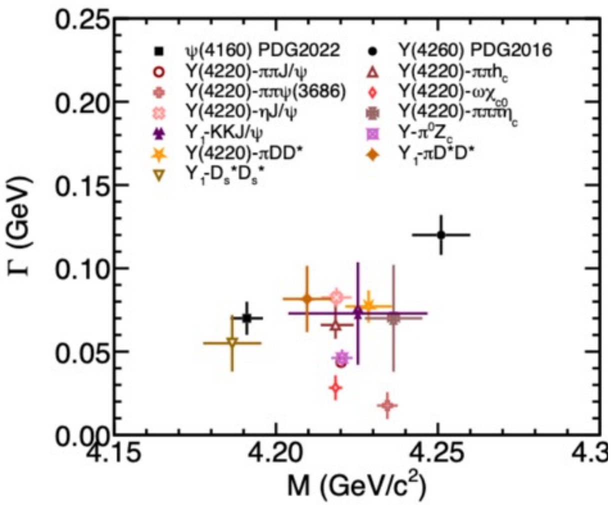
PRD106, 072001 (2022)



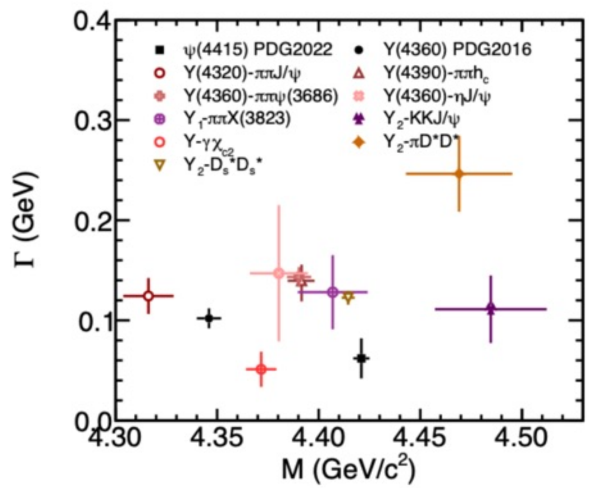
Y(4260) ➔ Y(4230) & Y(4320)

$M_{Y(4230)}$ = 4221.4 ± 1.5 ± 2.0 MeV/c²
$\Gamma_{Y(4230)}$ = 41.8 ± 2.9 ± 2.7MeV

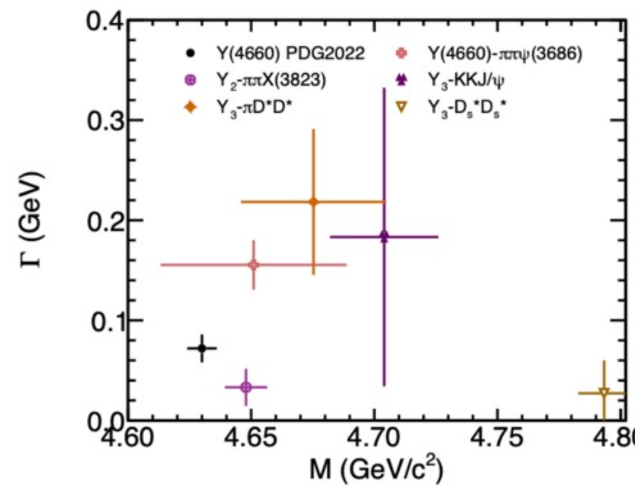
$M_{Y(4320)}$ = 4298 ± 12± 26 MeV/c²
$\Gamma_{Y(4320)}$ = 127 ± 17± 10 MeV



Y(42XX)



Y(43XX), ψ(4415), Y(4500)

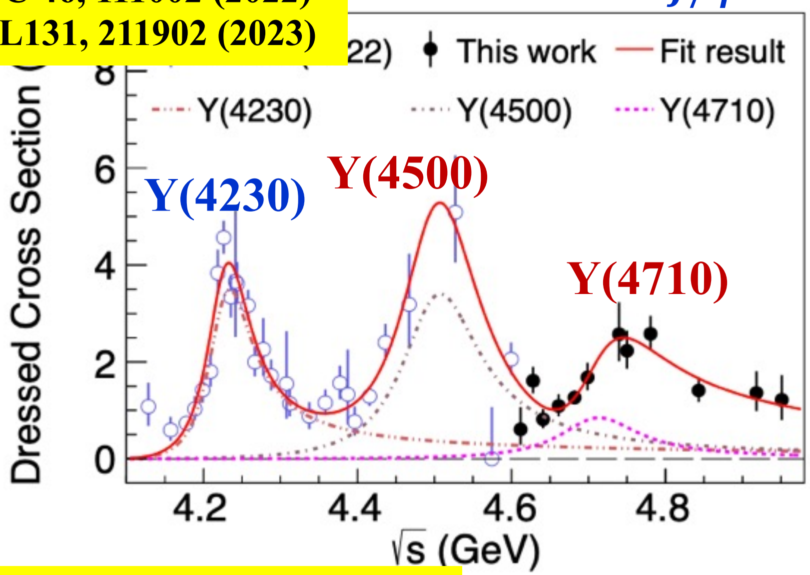


Y(46XX), Y(47XX)

Observations of three heavy Y(4500), Y(4710) and Y(4790) states

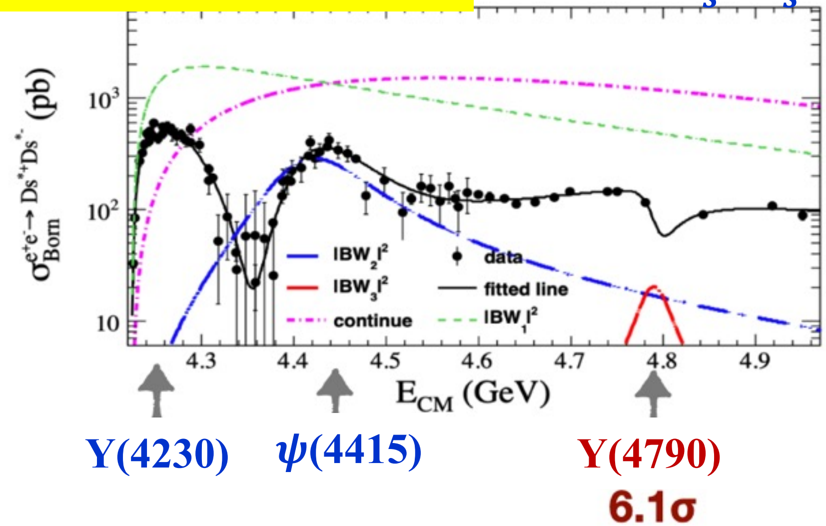
CPC 46, 111002 (2022)
PRL131, 211902 (2023)

$e^+e^- \to K^+K^-J/\psi$



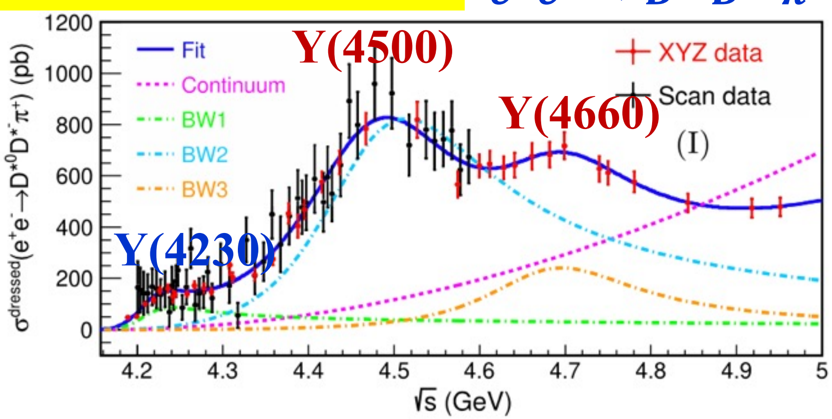
PRL131, 151903 (2023)

$e^+e^- \to D_s^{*+}D_s^{*-}$



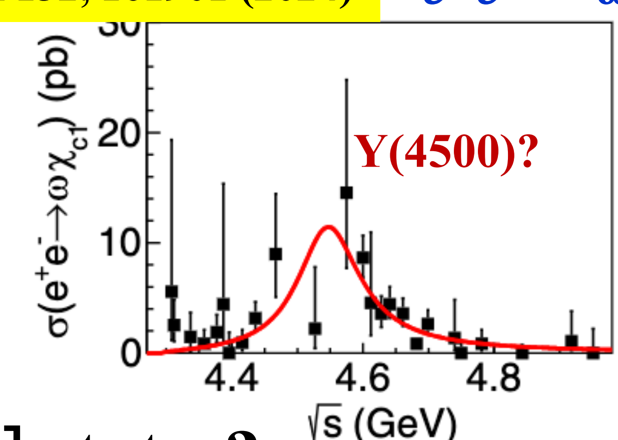
PRL130, 121901 (2023)

$e^+e^- \to D^{*0}D^{*-}\pi^+$



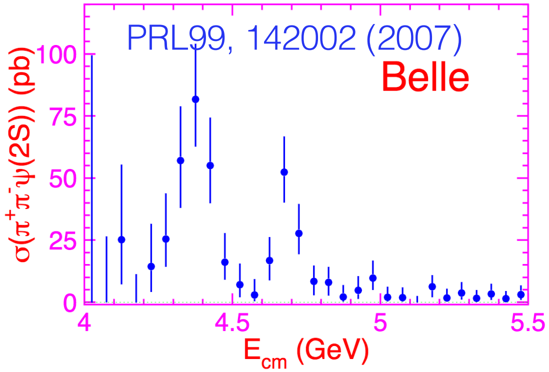
PRL 132, 161901 (2024)

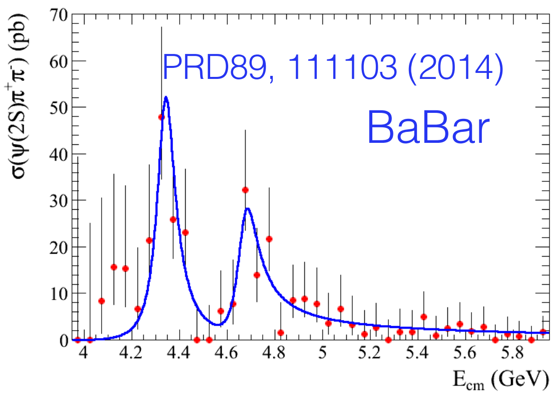
$e^+e^- \to \omega\chi_{c1}$

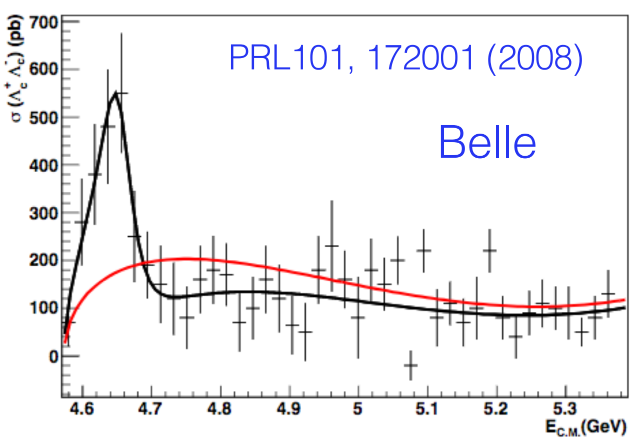


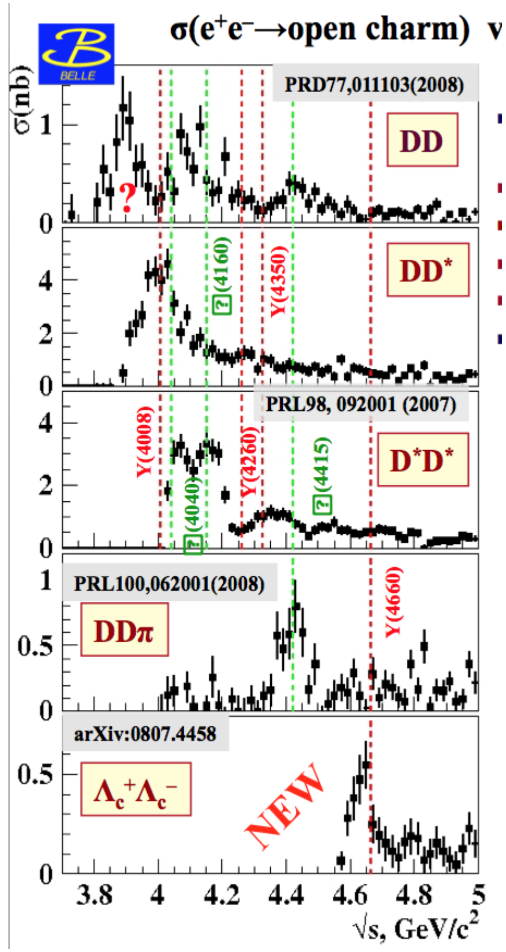
Are they $[c\bar{c}s\bar{s}]$ states?

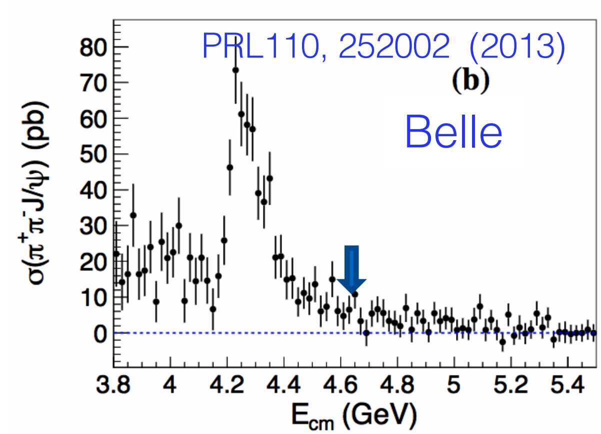
The Y(4630)/Y(4660)











$$\frac{\mathcal{B}(Y_B \to \Lambda_c \bar{\Lambda}_c)}{\mathcal{B}(Y_B \to \psi(2S)\pi^+\pi^-)} = 25 \pm 7,$$

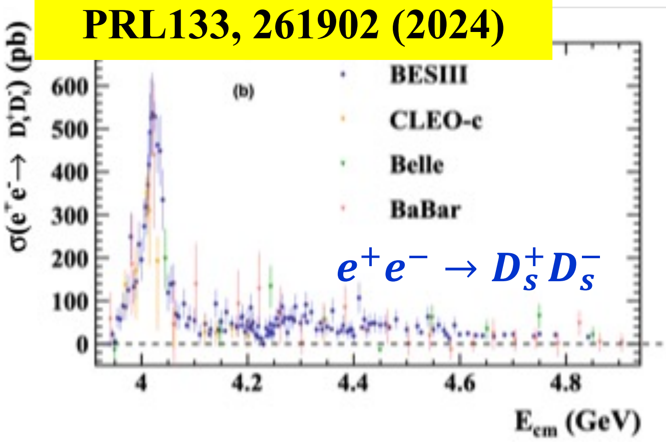
Phys.Rev.Lett. 104 (2010) 132005

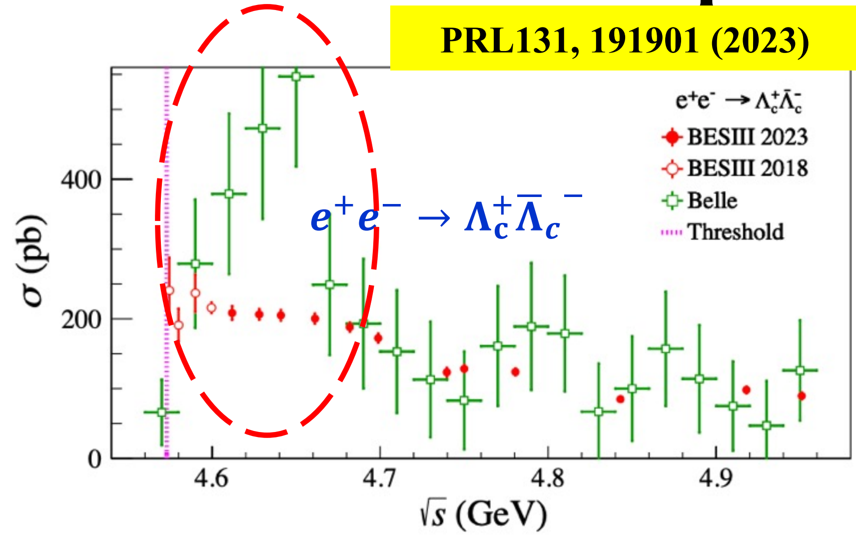
$$\frac{B(Y_B \to D^0 D^{*-}\pi^+)}{B(Y_B \to \psi(2S)\pi^+\pi^-)} < 10$$

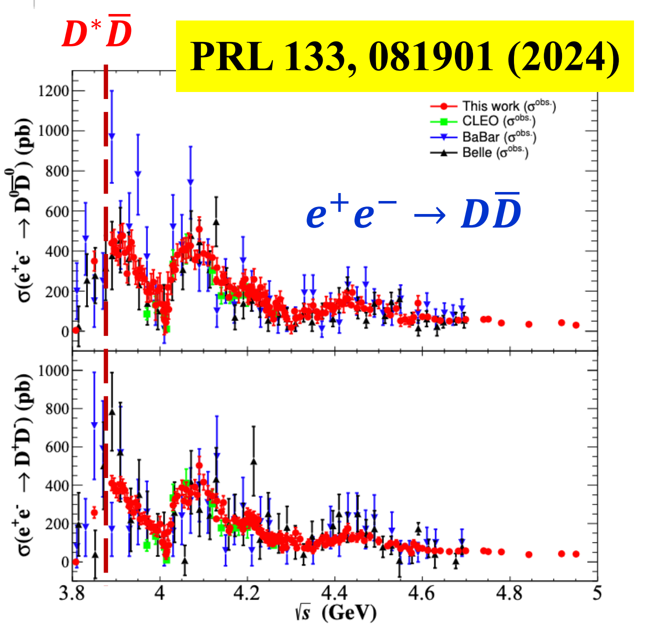
PDG

- Y(4660) baryonic coupling $\geq$ 10 mesonic coupling (unexpected!)
- Another missing large mesonic decay? Or Y(4660) is a charmed baryonium?

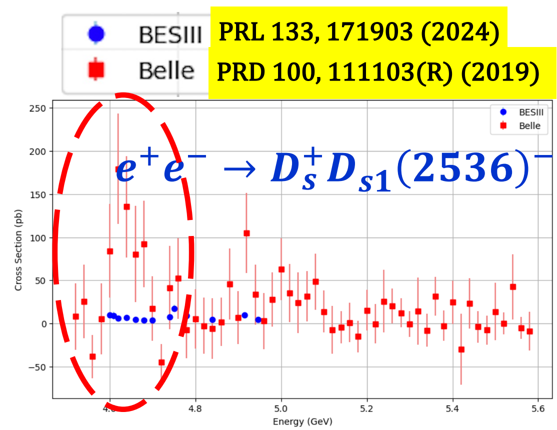
Cross sections of charmed hadron pairs

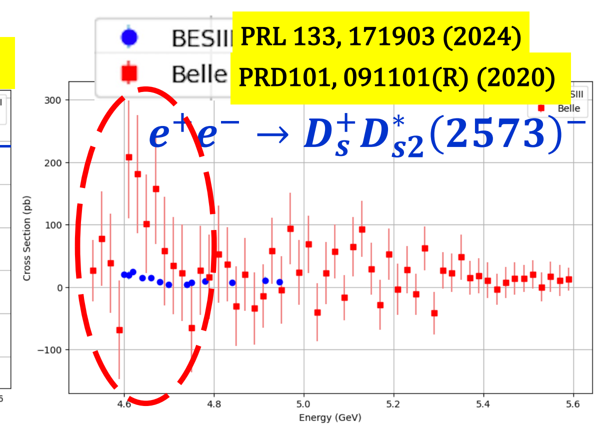






Rich ψ/Y resonances in the final states of the charmed hadron pairs.

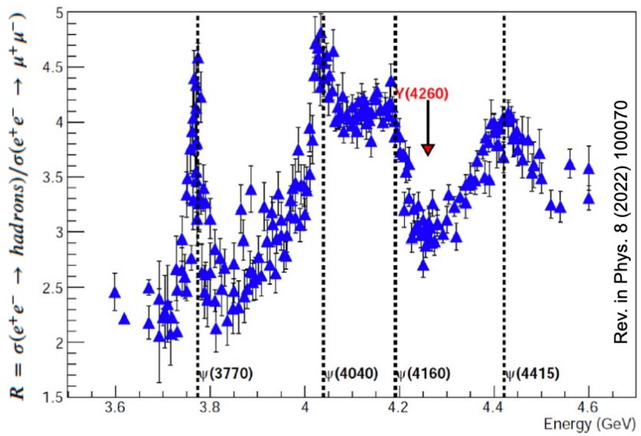




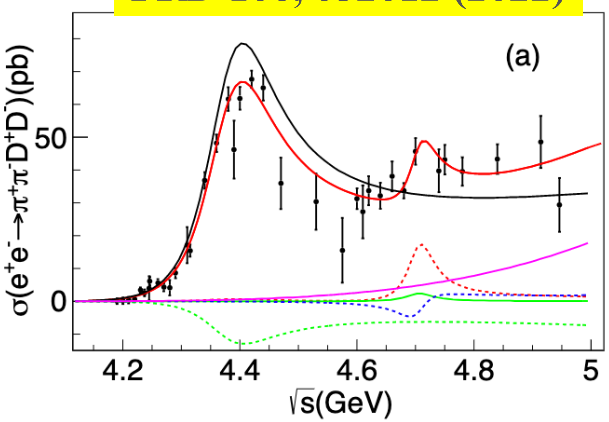
- **Mind**: Tension of cross sections near threshold between direct (BESIII) and ISR(Belle) methods
- BESIII negates the $Y(4630)$ reported by Belle

Open charm cross sections

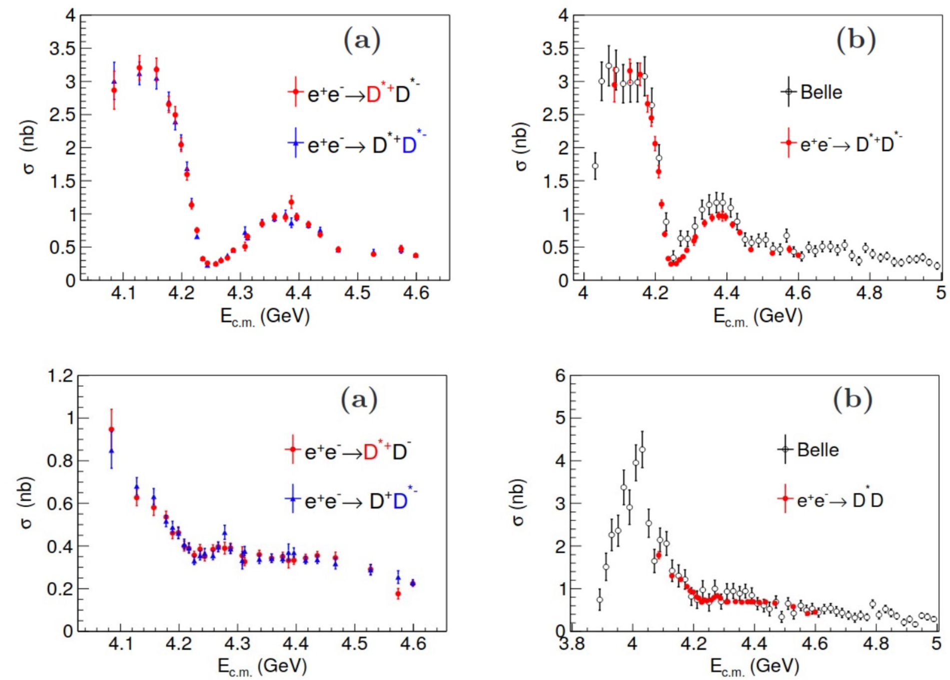
- essential to fully understand the XYZ states
- Important input for coupled-channel analysis



PRD 106, 052012 (2022)



JHEP2022, 55 (2022)

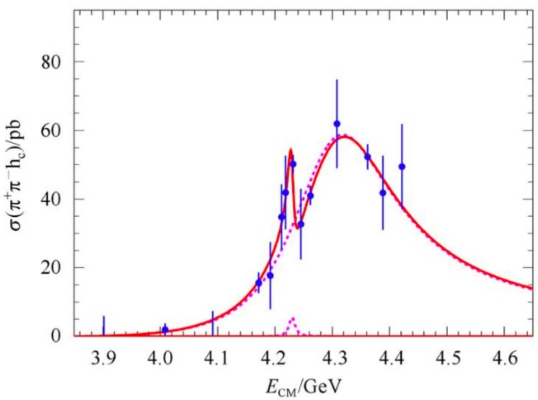


- Good agreement with existing measurements, with best precisions
- Structure at 4.39 GeV in D^*D^*?

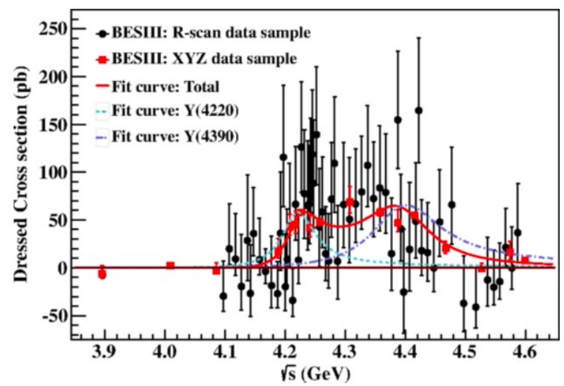
Improved measurement of $\sigma(e^+e^- \to \pi^+\pi^- h_c)$

PRL135, 071901 (2025)

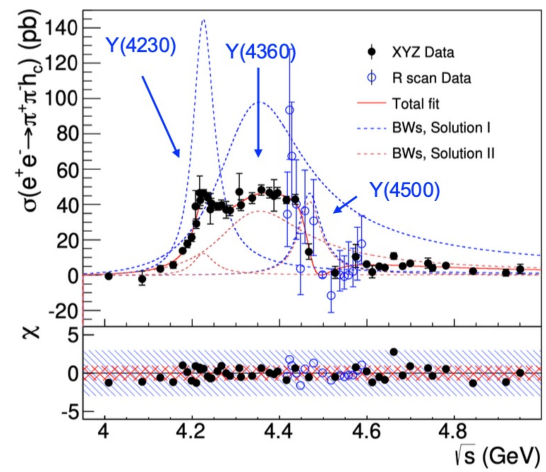
- Initially observed by CLEO-c at √s=4.17 GeV [PRL107, 041803 (2011)]
- Cross sections of $e^+e^- \to \pi^+\pi^- h_c$ obtained by BESIII at 3.9-4.6 GeV, found two structures [PRL118, 092002 (2017)]
- New data collected by BESIII between 4.18-4.95 GeV (27 data samples)



PRL107, 041803 (2011) – CLEO-c
PRL111, 242001 (2013) – BESIII
CPC 38, 043001 (2014)



PRL118, 092002 (2017) - BESIII



PRL135, 071901 (2025)

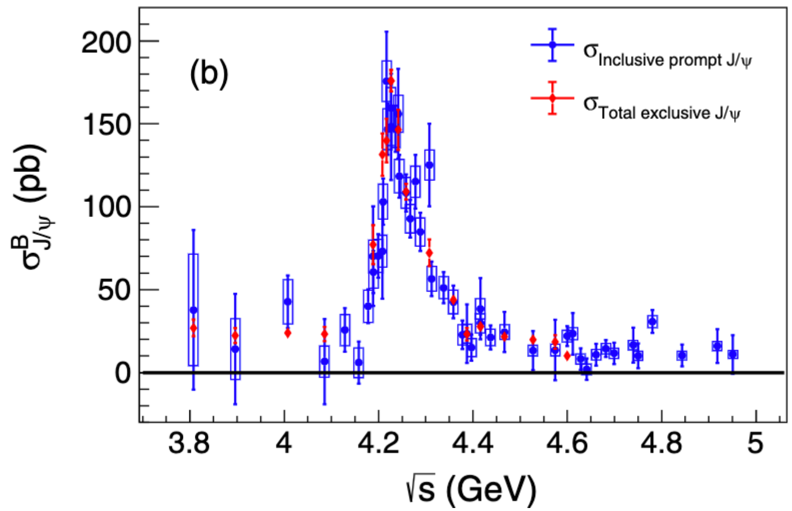
Y(4230) Y(4360) >5σ Y(4500)

Parameter	R_1	R_2	R_3
M (MeV/c^2)	$4223.6^{+3.6+2.6}_{-3.7-2.9}$	$4327.4^{+20.1+10.7}_{-18.8-9.3}$	$4467.4^{+7.2+3.2}_{-5.4-2.7}$
Γ (MeV)	$58.5^{+10.8+6.7}_{-11.4-6.5}$	$244.1^{+34.0+24.2}_{-27.1-18.3}$	$62.8^{+19.2+9.9}_{-14.4-7.0}$

a bit larger width
$\Gamma_{Y(4360)}$= 120±21 MeV

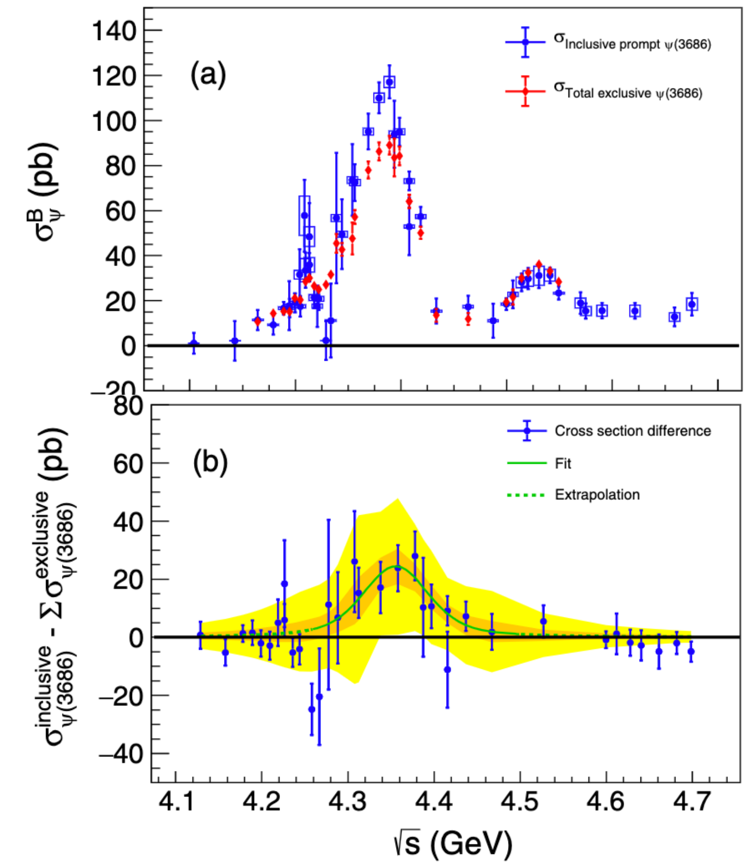
Inclusive and exclusive J/ψ and $\psi(3686)$ production

PRD111, 052007 (2025)



no evidence of hidden decays involving the J/ψ meson

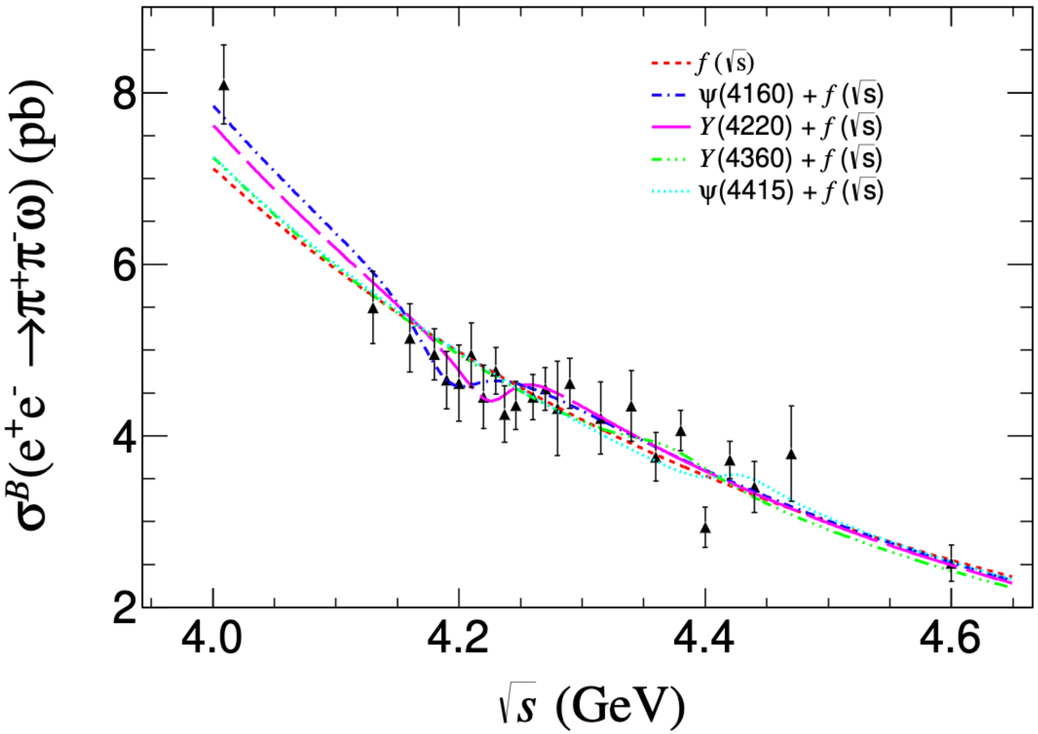
$c\bar{c}$ Meson	Decays into J/ψ	Decays into $\psi(3686)$
$\chi_{c1}(3872)$	$\pi^+\pi^- J/\psi, \omega J/\psi, \gamma J/\psi$	$\gamma\psi(3686)$
$Z_c(3900)$	$\pi J/\psi$	...
$\chi_{c0}(3915)$	$\omega J/\psi$	...
$\psi(4040)$	$\eta J/\psi$	...
$X(4160)$	$\phi J/\psi$	...
$\psi(4230)$	$\pi\pi J/\psi, KKJ/\psi, \eta J/\psi$	$\pi^+\pi^-\psi(3686)$
$X(4350)$	$\phi J/\psi$	...
$\psi(4360)$	$\pi^+\pi^- J/\psi, \eta J/\psi$	$\pi^+\pi^-\psi(3686)$
$Y(4500)$	$K^+K^- J/\psi$	...
$\psi(4660)$	...	$\pi^+\pi^-\psi(3686)$
$Y(4710)$	$K^0K^0 J/\psi$	...



- Missing exclusive processes around the Y(4360) region
- Excess ~ 23% of the $Y(4360)_{\text{prompt}}$ inclusive cross section

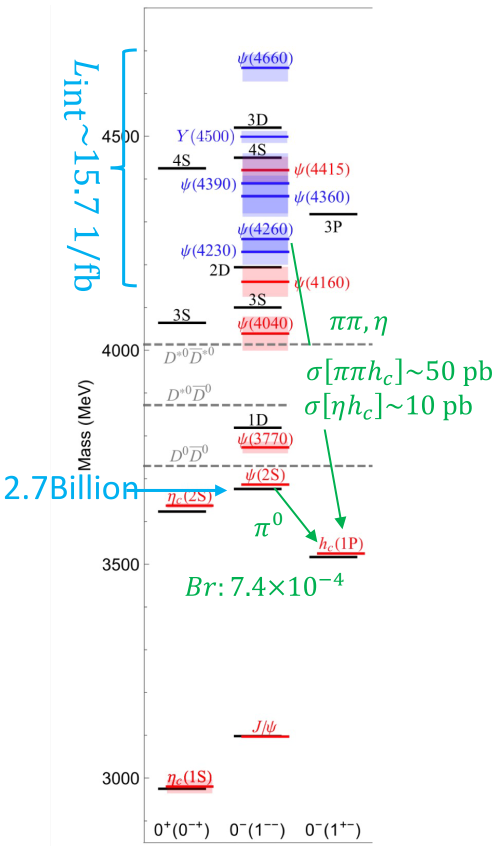
Y states in $e^+e^- \to \omega\pi^+\pi^-$

arXiv:2303.09718

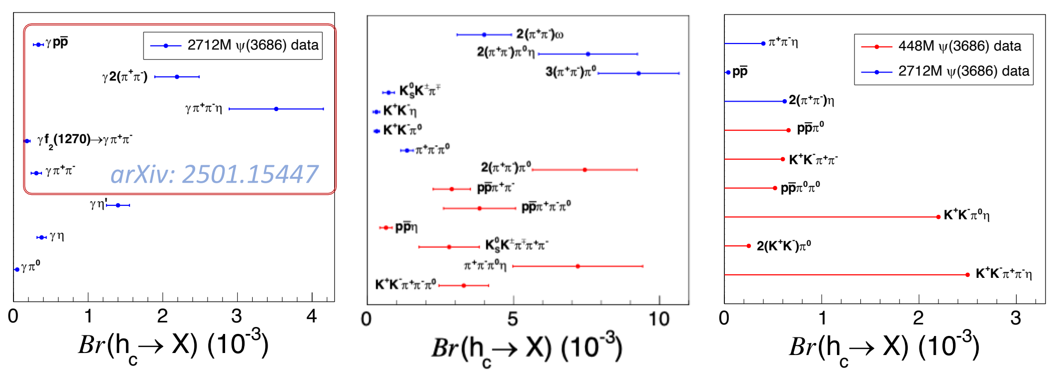


Parameter	$\psi(4160)$		$Y(4220)$	
	Solution I	Solution II	Solution I	Solution II
$12\pi\Gamma_{ee}Br$ (eV)	0.03 ± 0.02	24.57 ± 0.47	18.29 ± 0.32	0.02 ± 0.02
$\Gamma_{\rm tot}$ (GeV)	0.070		0.055	
M (GeV/c^2)	4.191		4.23	
ϕ (rad)	4.61 ± 0.34	4.68 ± 0.01	4.70 ± 0.01	5.38 ± 0.31
Significance (σ)	3.6		3.1	

Highlight: Production and decay properties of h_c



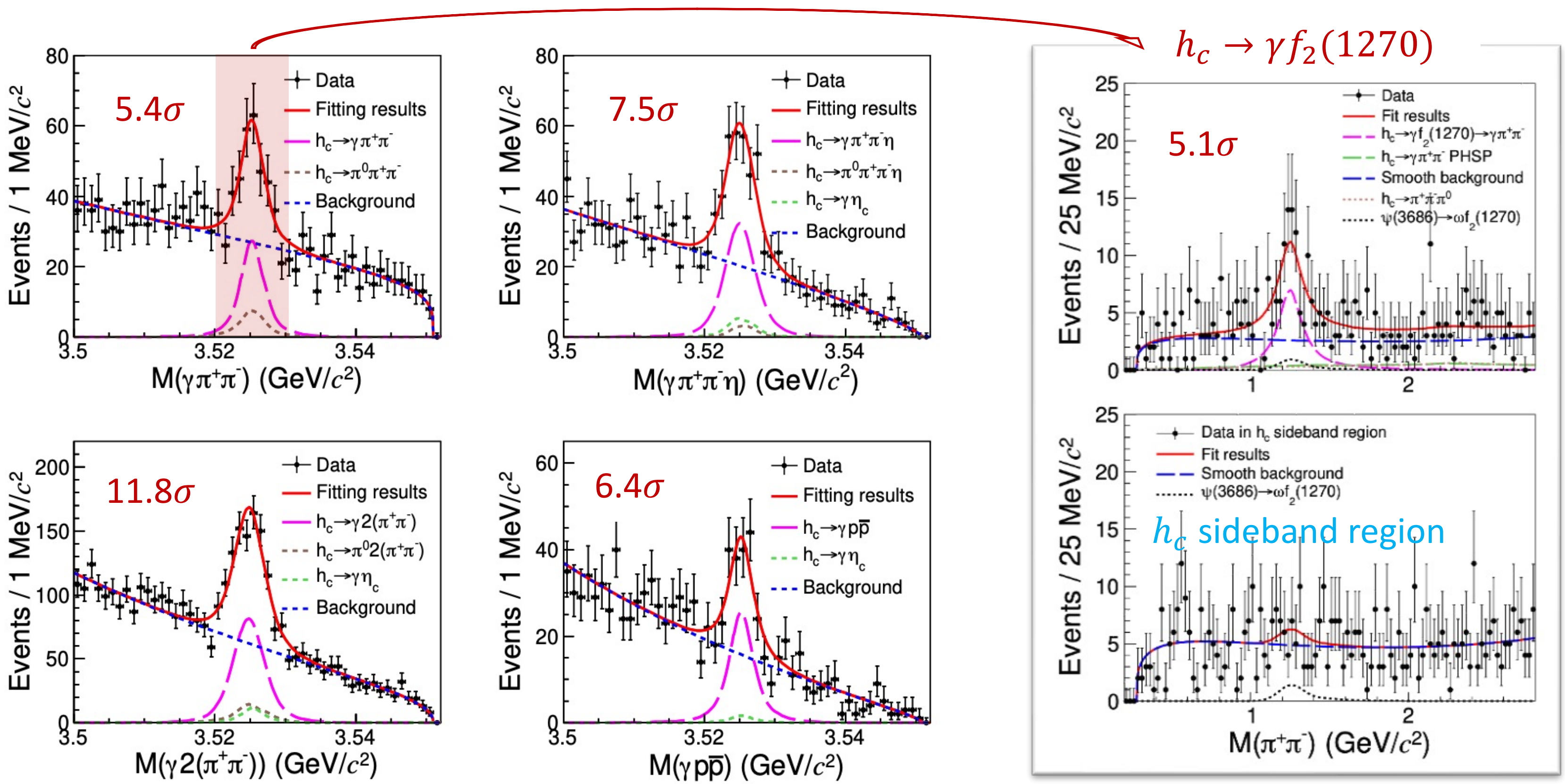
- *P*-wave singlet charmonium state, first observed by CLEO
- First measurement of $B[\psi' \to \pi^0 h_c]$ by BESIII PRL95, 102003 (2005) PRL104, 132002 (2010)
- 2M h_c particle in 2.7B ψ' events, possible to explore h_c decay mode with Br~10^{-4}; 0.7M h_c particle from XYZ scan sample
- Decay of h_c:
  - pQCD prediction: $h_c \to \gamma gg$~5.5% PRD 66, 014012 (2002)
  - pQCD and NRQCD predictions of h_c →light hadrons: 48% and 8% PRD 65, 094024 (2002)



Highlight: Production and decay properties of h_c

Observation of h_c radiative decays and $h_c \to \gamma f_2(1270)$

arXiv: 2501.15447

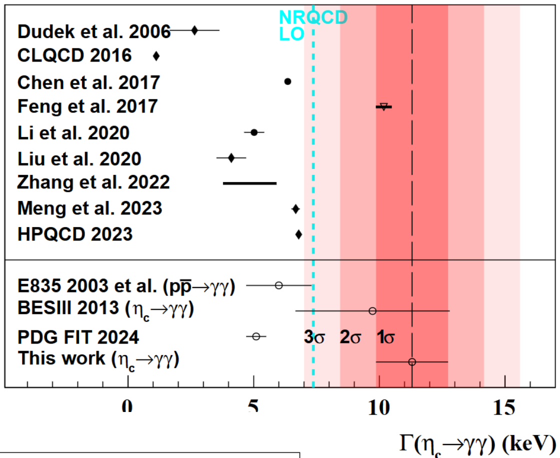


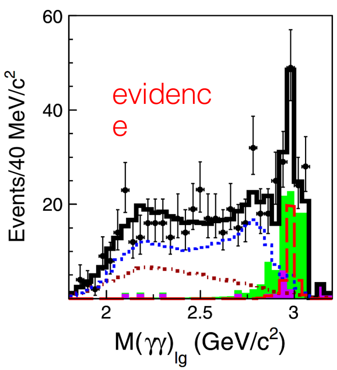
Highlight: measurements of $\eta_c \to \gamma\gamma$

PRL 134, 181901 (2025)

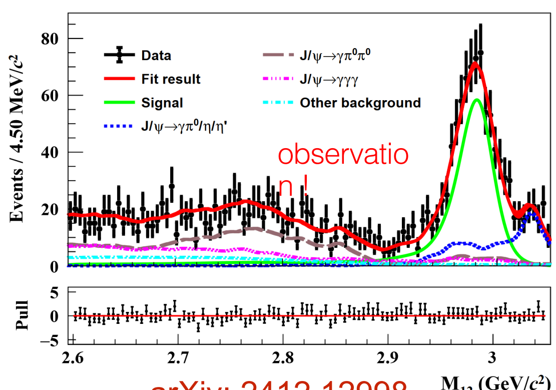
- As the simplest decay of η_c , $\eta_c \to \gamma\gamma$ serves as a benchmark for QCD calculation.
- Most measurements come from the time reversal process $\gamma\gamma^{(*)} \to \eta_c$
- BESIII has the unique opportunity to directly measure $\eta_c \to \gamma\gamma$ via $J/\psi \to \gamma\eta_c$ (first observation)
- The absolute branching fraction *of* $B(\eta_c \to \gamma\gamma)$ *can be obtained through the* ψ(2S)→ $\pi^0 hc$ ($h_c \to \gamma\eta_c$)
- Measured $B(J/\psi \to \gamma\eta_c)\times B(\eta_c \to \gamma\gamma)$ is consistent with theoretical predictions, while the individual $\Gamma(\eta_c \to \gamma\gamma)$ deviates from the most recent LQCD prediction by more than 3σ.

$$\Gamma(\eta_c \to \gamma\gamma) = (11.30 \pm 0.56_{\text{stat.}} \pm 0.66_{\text{syst.}} \pm 1.14_{\text{ref.}})\ \text{keV}$$



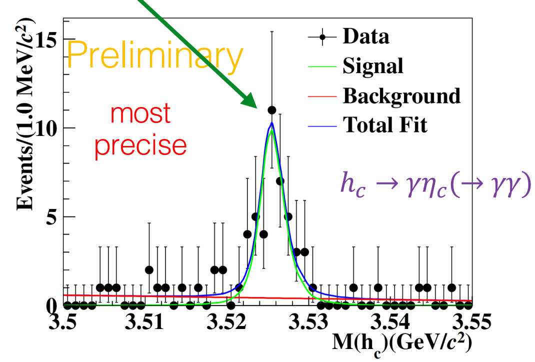


Phys. Rev. D 87 (2013) 3, 032003



arXiv: 2412.12998

$J/\psi \to \gamma\eta_c(\to \gamma\gamma)$



The first measurement of absolute branching fraction via $h_c \to \gamma\eta_c$ will provide a brand new reference

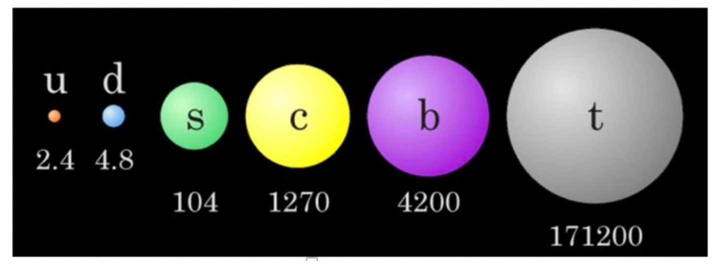
in preparation

Precise test of LQCD: hyperfine mass splitting

粲强子物理

Charm is charming

- **Over-constrain the SM, probe for new physics**
  - ✓ Precision CKM physics in B sector needs input from charm
- **CPV and mixing**
  - ✓ The only up-type quark to form weakly decaying hadrons, complementary to K and B systems
- **Unique to test QCD in low energy**



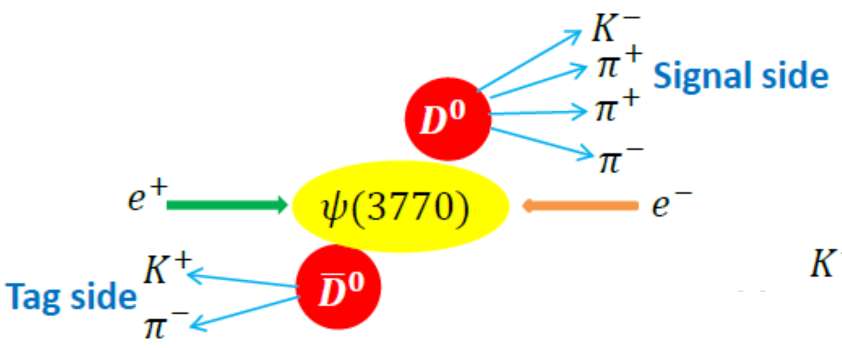
Charm is challenging

- **Intermediate mass, compared to Λ_{QCD} -- not heavy, not light**
- **Do methods like Heavy Quark Expansion and Factorization work?**

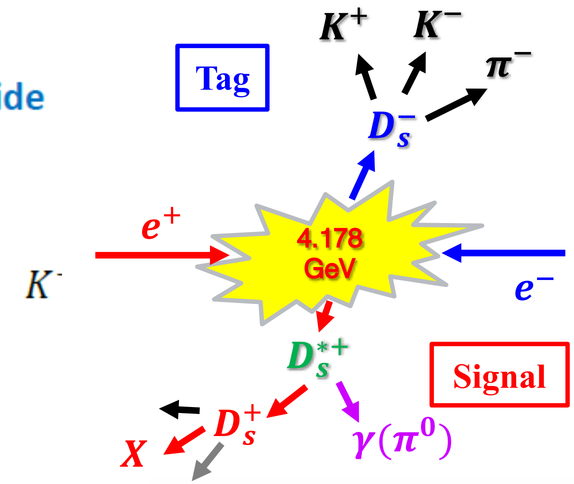
] → **Theory**

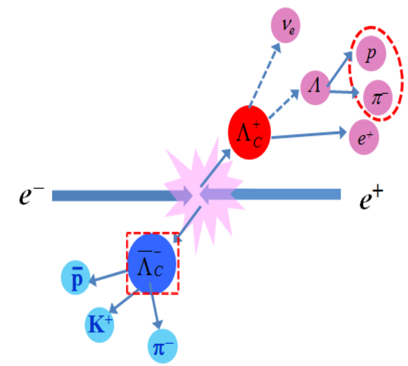
- **CKM and GIM suppression can be strong – low rates** → **Large data sample**

Charm hadron decays



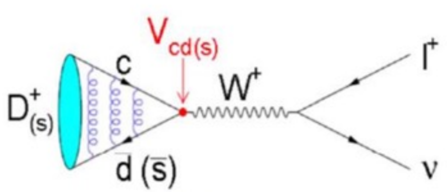
2.93/fb at $\psi(3770)$



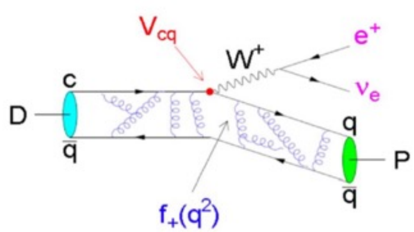


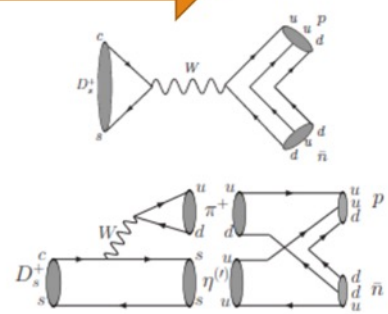
0.567/fb at 4.6 GeV

COMPLEXITY



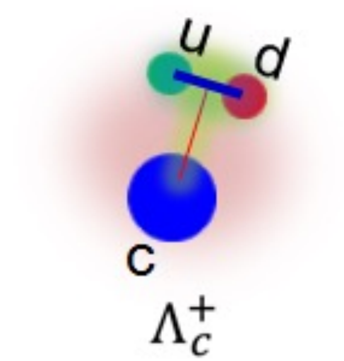
$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2 f_{D_{(s)}}^2}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D_{(s)}^+} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}^+}^2}\right)^2$$





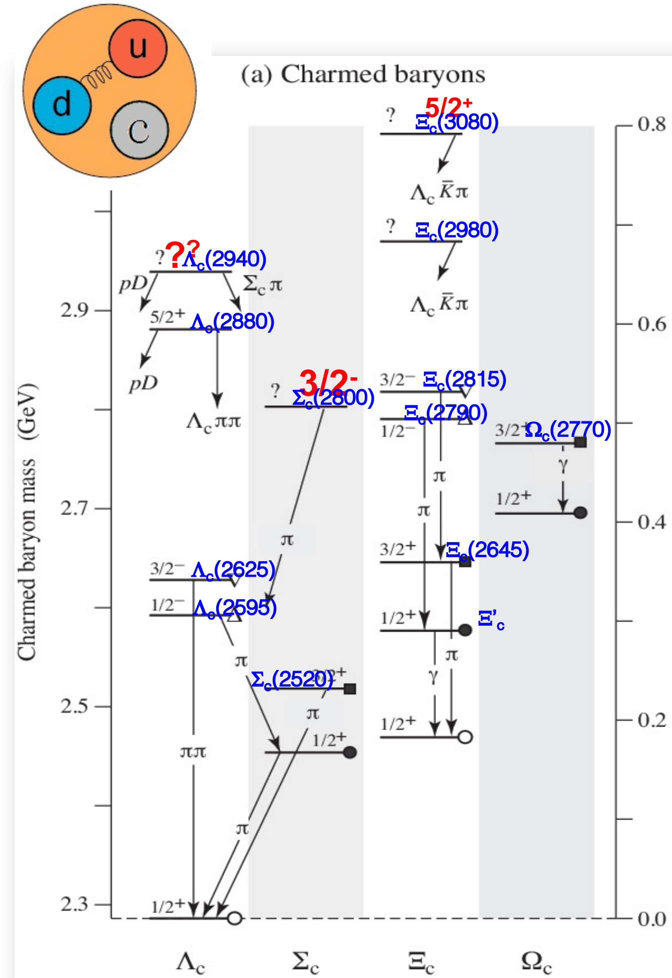
Purely Leptonic	Semi Leptonic	Hadronic
Take V_{cx} from fits to CKM assuming unitarity and measure f Precise test of lattice QCD in charm and extrapolate to beauty	Similar to leptonic decay but now q (= four-momentum of W) dependent Test QCD models of the form factor	Models of hadronic decay • Isospin • SU(3) flavour • Different amplitudes T, P, A, E • Long and short distance effects

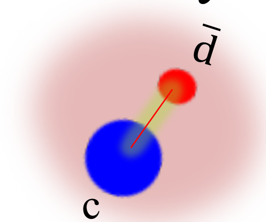
粲重子物理



Why Λ_c^+ is interesting

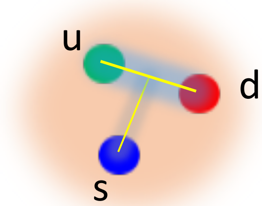
- An important intermediate particle:
  - corner stone of the charmed baryon spectra
  - many b-baryon decays to Λ_c
- Its decays reveal information of strong- and weak-interactions in charm region, complementary to D/Ds





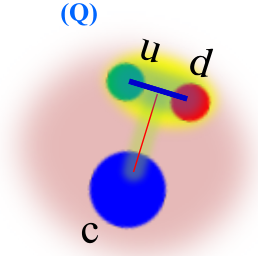
→ Charmed meson ($D^+[c\bar{d}]$)

$m_d << m_c$ → **quark + heavy quark** **(q)** **(Q)**



→ Strange baryons ($\Lambda[uds]$)

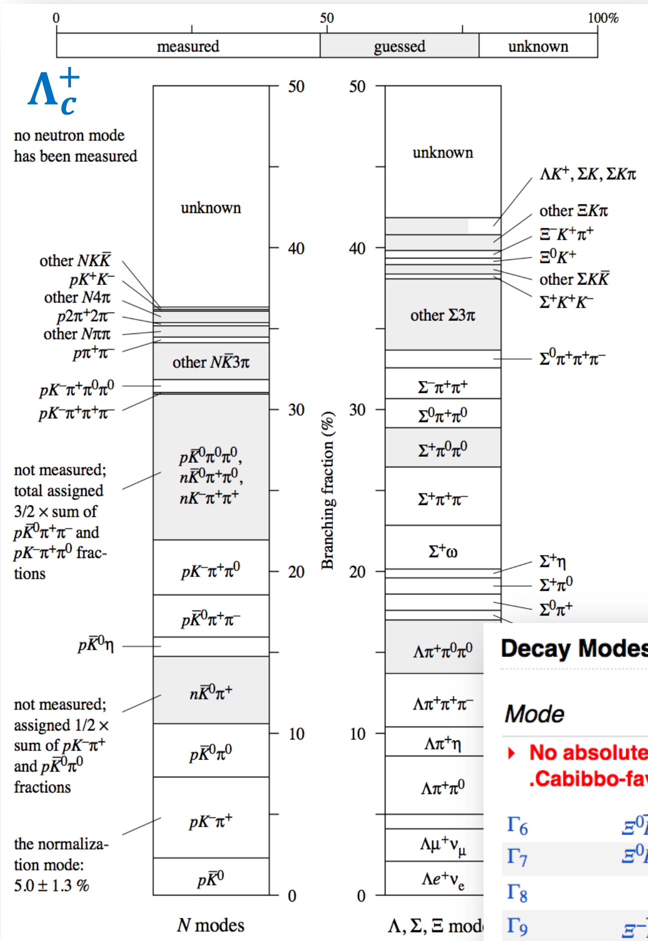
$m_u, m_d \approx m_s$ → **(qqq)** uniform



→ Charmed baryon ($\Lambda_c[udc]$)

$m_u, m_d << m_c$ → **diquark + quark** **(qq)** **(Q)**

Knowledge of charmed baryon decays before 2014



Ξ_c^+: relative to the decay of $\Xi^-2\pi^+$

	Mode	Fraction (Γ_i/Γ)
No absolute branching fractions have been measured. The following are branching to $\Xi^-\pi^+$. Cabibbo-favored ($S=-2$) decays – relative to $\Xi^-\pi^+$		
Γ_1	$p2K_S^0$	0.087 ± 0.021
Γ_2	$\Lambda\bar{K}^0\pi^+$	
Γ_3	$\Sigma(1385)^+\bar{K}^0$	1.0 ± 0.5
Γ_4	$\Lambda K^-2\pi^+$	0.323 ± 0.033
Γ_5	$\Lambda\bar{K}^*(892)^0\pi^+$	< 0.16
Γ_6	$\Sigma(1385)^+K^-\pi^+$	< 0.23
Γ_7	$\Sigma^+K^-\pi^+$	0.94 ± 0.10
Γ_8	$\Sigma^+\bar{K}^*(892)^0$	0.81 ± 0.15
Γ_9	$\Sigma^0K^-2\pi^+$	0.27 ± 0.12
Γ_{10}	$\Xi^0\pi^+$	0.55 ± 0.16
Γ_{11}	$\Xi^-2\pi^+$	**DEFINEDAS1**
		< 0.10
		2.3 ± 0.7
		1.7 ± 0.5
		$2.3^{+0.7}_{-0.8}$
		0.07 ± 0.04
ative to $\Xi^-\pi^+$		
		0.21 ± 0.04
		0.116 ± 0.030
		0.48 ± 0.20
		0.18 ± 0.09
		0.15 ± 0.06

Decay Modes Ω_c^0

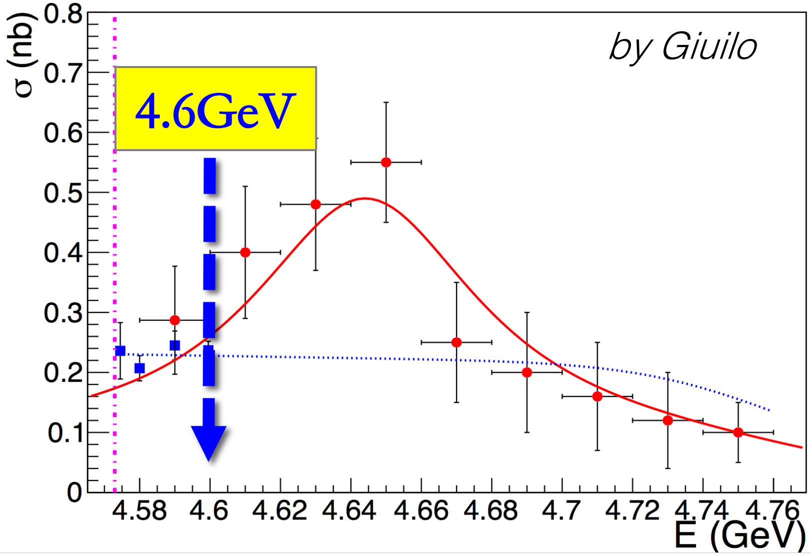
	Mode	Fraction (Γ_i/Γ)
No absolute branching fractions have been measured. The following are branching ra .Cabibbo-favored ($S=-3$) decays – relative to $\Omega^-\pi^+$		
Γ_6	$\Xi^0\bar{K}^0$	1.64 ± 0.29
Γ_7	$\Xi^0K^-\pi^+$	1.20 ± 0.18
Γ_8	$\Xi^0\bar{K}^{*0}$, $\bar{K}^{*0} \to K^-\pi^+$	0.68 ± 0.16
Γ_9	$\Xi^-\bar{K}^0\pi^+$	2.12 ± 0.28
Γ_{10}	$\Xi^-K^-2\pi^+$	0.63 ± 0.09
Γ_{11}	$\Xi(1530)^0K^-\pi^+$, $\Xi^{*0} \to \Xi^-\pi^+$	0.21 ± 0.06
Γ_{12}	$\Xi^-\bar{K}^{*0}\pi^+$	0.34 ± 0.11
Γ_{13}	$\Sigma^+K^-K^-\pi^+$	< 0.32
Γ_{14}	$\Lambda\bar{K}^0\bar{K}^0$	1.72 ± 0.35

Near threshold production at BESIII

In 2014, BESIII took (only!) 35 days to run at 4.6GeV and collected ~500/pb data.

Energy(GeV)	lum.(1/pb)
4.575	47.67
4.580	8.54
4.590	8.16
4.600	566.93

Corresponds to 0.1M Λ_c pairs

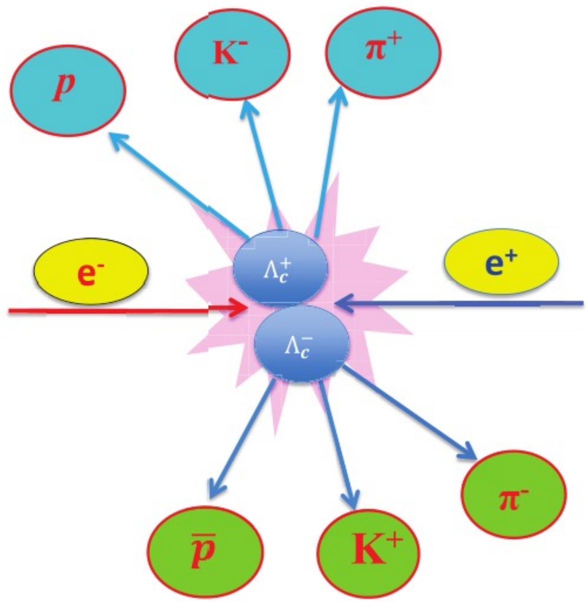


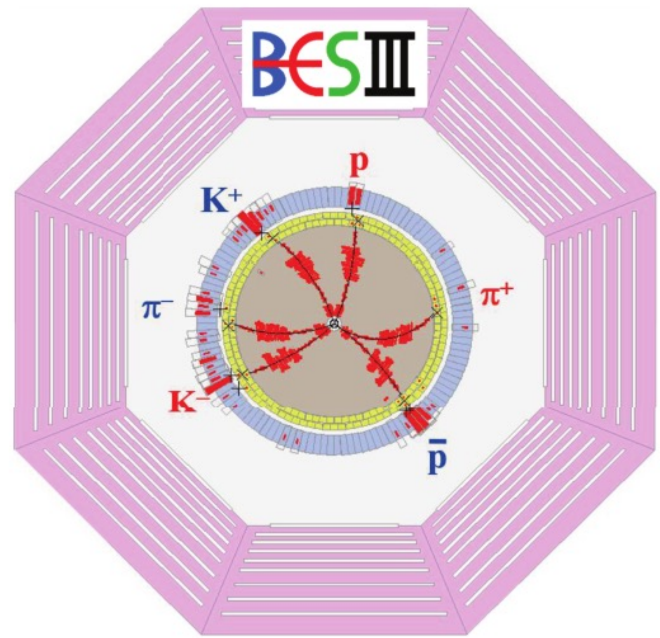
Measurement using the threshold pair-productions via e^+e^- annihilations is unique: *the most simple and straightforward*

First time to systematically study charmed baryon at threshold!

Single Tag (ST) and Double Tag (DT) method at Threshold

The absolute BF can be obtained by the ratio of DT yields to ST yields





- High efficiency and clean background
- Absolute measurement with many systematics cancel out
- Missing-mass technique: K_L/neutron, neutrino, …
- Good photon resolution: Σ, Ξ, π^0, …

$$\mathcal{B}_i = \frac{N_{ij}^{\mathrm{DT}}}{N_j^{\mathrm{ST}}} \frac{\varepsilon_j}{\varepsilon_{ij}}$$

Physics publications on the Λ_c^+

Published 17 papers
(7 PRLs)

- A series of precise absolute BF measurements: hadronic, semi-leptonic and inclusive decays
- Observation of decays into neutron $\Lambda_c^+ \to nK_s\pi^+, \Sigma^-\pi^+\pi^+\pi^0$
- Observation of Cabbibo-suppressed decay $\Lambda_c^+ \to p\pi^+\pi^-$
- First evidence of Cabbibo-suppressed decay $\Lambda_c^+ \to p\eta$
- First measurements of many decay asymmetries
- Determination of Λ_c^+ spin
- Threshold cross section and form factors of Λ_c^+ pairs

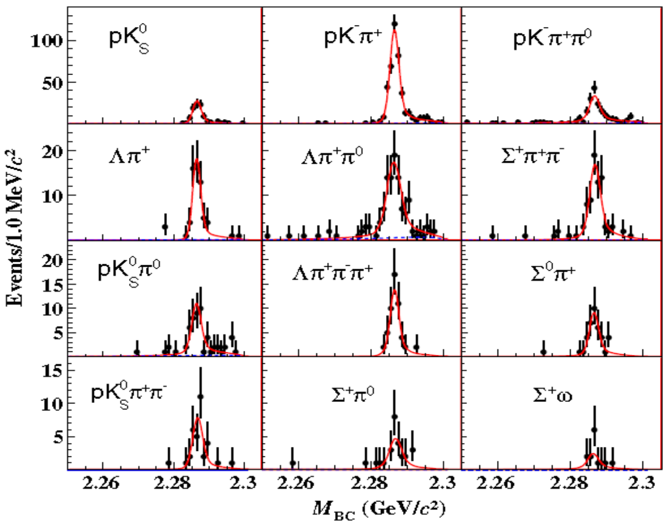
Very productive for the data set taken in 35 days!

Hadronic decay — **2014：0.567 fb^{-1} at 4.6 GeV**

$\Lambda_c^+ \to pK^-\pi^+$ + 11 CF modes	**PRL 116, 052001 (2016)**
$\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-$	**PRL 117, 232002 (2016)**
$\Lambda_c^+ \to nK_s\pi^+$	**PRL 118, 12001 (2017)**
$\Lambda_c^+ \to p\eta, p\pi^0$	PRD 95, 111102(R) (2017)
$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$	PLB 772, 388 (2017)
$\Lambda_c^+ \to \Xi^{0(*)}K^+$	PLB 783, 200 (2018)
$\Lambda_c^+ \to \Lambda\eta\pi^+$	PRD 99, 032010 (2019)
$\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta'$	CPC 43, 083002 (2019)
$\Lambda_c^+ \to$ BP decay asymmetries	PRD 100, 072004 (2019)
$\Lambda_c^+ \to pK_s\eta$	PLB 817, 136327 (2021)
Λ_c^+ spin determination	PRD 103, L091101(2021)
Semi-leptonic decay	
$\Lambda_c^+ \to \Lambda e^+\nu_e$	**PRL 115, 221805(2015)**
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	PLB 767, 42 (2017)
Inclusive decay	
$\Lambda_c^+ \to \Lambda X$	**PRL121, 062003 (2018)**
$\Lambda_c^+ \to e^+X$	**PRL 121 251801(2018)**
$\Lambda_c^+ \to K_s^0X$	EPJC 80, 935 (2020)
Production	
$\Lambda_c^+\bar{\Lambda}_c^-$ cross section	**PRL 120,132001(2018)**

Absolute BFs of Λ_c^+ hadronic decays

- Absolute BF of Λ_c^+ decays are still not well determined since its discovery 30 years ago. PDG2014: δB/B~26%; BELLE2014: δB/B~5.3%
- Double tag technique is applied to control systematics



PRL 116, 052001 (2016)

Mode	This work (%)	PDG (%)	BELLE $\mathcal{B}$
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50	
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0	
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28	
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3	
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7	
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28	
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34	
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0	
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0	

- a global least square fit to 12 hadronic modes [Chin. Phys. C37(2013)106201]

✓ **First direct measurement on Λc BFs at threshold**

✓ **$B(pK^-\pi^+)$: BESIII precision comparable with Belle's**

✓ **Improved precisions of the other 11 modes significantly**

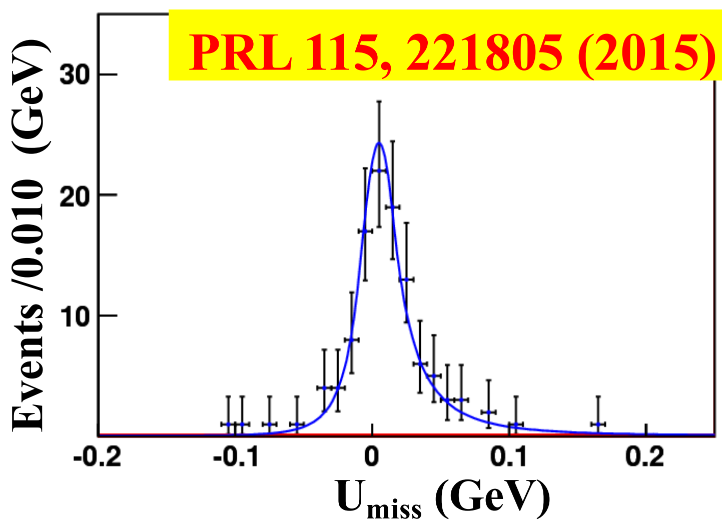
So far, the mostly cited BESIII charm paper

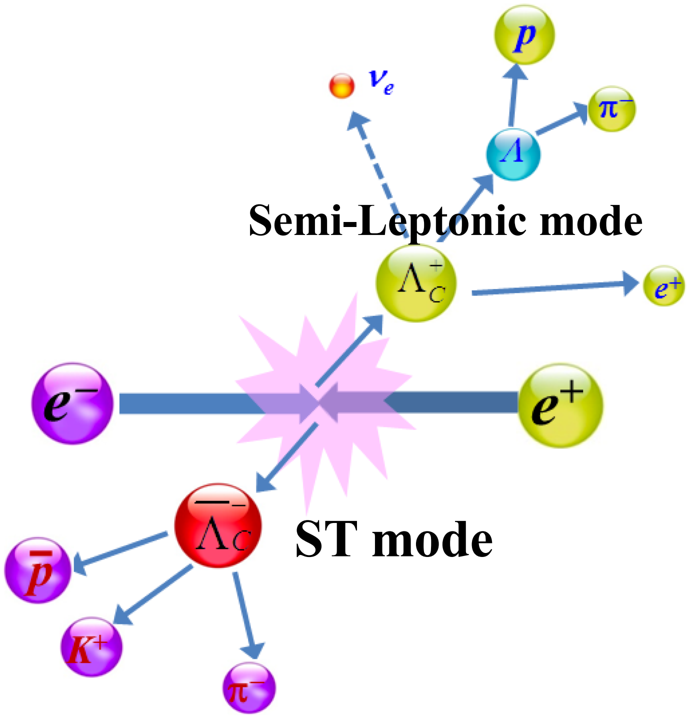
BF for $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$

- $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$ is a $c \rightarrow s l^+ \nu_l$ dominated process.
- Urgently needed for LQCD calculations.
- No direct absolute measurement for $\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e)$ available.

$$\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e) = (2.1 \pm 0.6)\% \qquad \text{PDG 2014}$$

11 hadronic single tag modes are used





$$B(\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\%$$

- First absolute measurement of the semi-leptonic decay
- Statistics limited
- Best precision to date: twofold improvement

First Lattice calculation on charmed baryon SL decays

PRL **118**, 082001 (2017) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2017

$\Lambda_c \to \Lambda l^+ \nu_l$ Form Factors and Decay Rates from Lattice QCD with Physical Quark Masses

Stefan Meinel
Department of Physics, University of Arizona, Tucson, Arizona 85721, USA and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA

(Received 1 December 2016; published 21 February 2017)

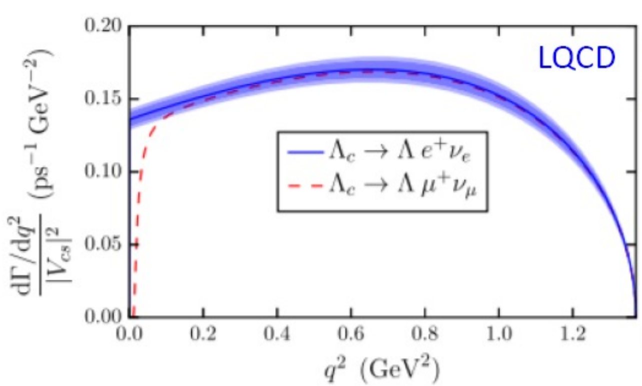
- Input the measured BFs from BESIII

Triggered by BESIII

$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell) = \begin{cases} 0.0363(38)(20), & \ell = e, \\ 0.0349(46)(27), & \ell = \mu. \end{cases}$$

- The first LQCD calculations on BFs and form factors

$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell) = \begin{cases} 0.0380(19)_{\mathrm{LQCD}}(11)_{\tau_{\Lambda_c}}, & \ell = e, \\ 0.0369(19)_{\mathrm{LQCD}}(11)_{\tau_{\Lambda_c}}, & \ell = \mu, \end{cases}$$



✓ The first determination of $|V_{cs}|$ based on BFs of $\Lambda_c^+ \to \Lambda l^+ \nu_l$ measured by BESIII

$$|V_{cs}| = \begin{cases} 0.951(24)_{\mathrm{LQCD}}(14)_{\tau_{\Lambda_c}}(56)_{\mathcal{B}}, & \ell = e, \\ 0.947(24)_{\mathrm{LQCD}}(14)_{\tau_{\Lambda_c}}(72)_{\mathcal{B}}, & \ell = \mu, \\ 0.949(24)_{\mathrm{LQCD}}(14)_{\tau_{\Lambda_c}}(49)_{\mathcal{B}}, & \ell = e, \mu, \end{cases}$$

✓ More data on Λ_c^+ will be collected at BESIII

BESIII

PDG2015

Λ_c^+ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Hadronic modes with a p: $S=-1$ final states			
Γ_1	$p\overline{K}^0$		(3.21 ± 0.30) %	
Γ_2	$pK^-\pi^+$		$(6.84^{+0.32}_{-0.40})$ %	
Γ_3	$p\overline{K}^*(892)^0$	[a]	(2.13 ± 0.30) %	
Γ_4	$\Delta(1232)^{++}K^-$		(1.18 ± 0.27) %	
Γ_5	$\Lambda(1520)\pi^+$	[a]	(2.4 ± 0.6) %	
Γ_6	$pK^-\pi^+$ nonresonant		(3.8 ± 0.4) %	
Γ_7	$p\overline{K}^0\pi^0$		(4.5 ± 0.6) %	
Γ_8	$p\overline{K}^0\eta$		(1.7 ± 0.4) %	
Γ_9	$p\overline{K}^0\pi^+\pi^-$		(3.5 ± 0.4) %	
Γ_{10}	$pK^-\pi^+\pi^0$		(4.6 ± 0.8) %	
Γ_{11}	$pK^*(892)^-\pi^+$	[a]	(1.5 ± 0.5) %	
Γ_{12}	$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(5.0 ± 0.9) %	
Γ_{13}	$\Delta(1232)\overline{K}^*(892)$		seen	
Γ_{14}	$pK^-\pi^+\pi^+\pi^-$		$(1.5\pm1.0)\times10^{-3}$	
Γ_{15}	$pK^-\pi^+\pi^0\pi^0$		(1.1 ± 0.5) %	
Γ_{16}	$pK^-\pi^+3\pi^0$			
	Hadronic modes with a p: $S=0$ final states			
Γ_{17}	$p\pi^+\pi^-$		$(4.7\pm2.5)\times10^{-3}$	
Γ_{18}	$pf_0(980)$	[a]	$(3.8\pm2.5)\times10^{-3}$	
Γ_{19}	$p\pi^+\pi^+\pi^-\pi^-$		$(2.5\pm1.6)\times10^{-3}$	
Γ_{20}	pK^+K^-		$(1.1\pm0.4)\times10^{-3}$	
Γ_{21}	$p\phi$	[a]	$(1.12\pm0.23)\times10^{-3}$	
Γ_{22}	pK^+K^- non-ϕ		$(4.8\pm1.9)\times10^{-4}$	
	Hadronic modes with a hyperon: $S=-1$ final states			
Γ_{23}	$\Lambda\pi^+$		(1.46 ± 0.13) %	
Γ_{24}	$\Lambda\pi^+\pi^0$		(5.0 ± 1.3) %	
Γ_{25}	$\Lambda\rho^+$		<6 %	CL=95%
Γ_{26}	$\Lambda\pi^+\pi^+\pi^-$		(3.59 ± 0.28) %	
Γ_{27}	$\Sigma(1385)^+\pi^+\pi^-$, $\Sigma^{*+}\to\Lambda\pi^+$		(1.0 ± 0.5) %	
Γ_{28}	$\Sigma(1385)^-\pi^+\pi^+$, $\Sigma^{*-}\to\Lambda\pi^-$		$(7.5\pm1.4)\times10^{-3}$	
Γ_{29}	$\Lambda\pi^+\rho^0$		(1.4 ± 0.6) %	
Γ_{30}	$\Sigma(1385)^+\rho^0$, $\Sigma^{*+}\to\Lambda\pi^+$		$(5\pm4)\times10^{-3}$	
Γ_{31}	$\Lambda\pi^+\pi^+\pi^-$ nonresonant		<1.1 %	CL=90%
Γ_{32}	$\Lambda\pi^+\pi^+\pi^-\pi^0$ total		(2.5 ± 0.9) %	
Γ_{33}	$\Lambda\pi^+\eta$	[a]	(2.4 ± 0.5) %	
Γ_{34}	$\Sigma(1385)^+\eta$	[a]	(1.16 ± 0.35) %	
Γ_{35}	$\Lambda\pi^+\omega$	[a]	(1.6 ± 0.6) %	
Γ_{36}	$\Lambda\pi^+\pi^+\pi^-\pi^0$, no η or ω		$<9\times10^{-3}$	CL=90%
Γ_{37}	$\Lambda K^+\overline{K}^0$		$(6.4\pm1.3)\times10^{-3}$	S=1.6
Γ_{38}	$\Xi(1690)^0K^+$, $\Xi^{*0}\to\Lambda\overline{K}^0$		$(1.8\pm0.6)\times10^{-3}$	
Γ_{39}	$\Sigma^0\pi^+$		(1.43 ± 0.14) %	
Γ_{40}	$\Sigma^+\pi^0$		(1.37 ± 0.30) %	
Γ_{41}	$\Sigma^+\eta$		$(7.5\pm2.5)\times10^{-3}$	
Γ_{42}	$\Sigma^+\pi^+\pi^-$		(4.9 ± 0.5) %	
Γ_{43}	$\Sigma^+\rho^0$		<1.8 %	CL=95%
Γ_{44}	$\Sigma^-\pi^+\pi^+$		(2.3 ± 0.4) %	
Γ_{45}	$\Sigma^0\pi^+\pi^0$		(2.5 ± 0.9) %	
	Semileptonic modes			
Γ_{64}	$\Lambda\ell^+\nu_\ell$	[b]	(2.8 ± 0.4) %	
Γ_{65}	$\Lambda e^+\nu_e$		(2.9 ± 0.5) %	
Γ_{66}	$\Lambda\mu^+\nu_\mu$		(2.7 ± 0.6) %	

PDG2020

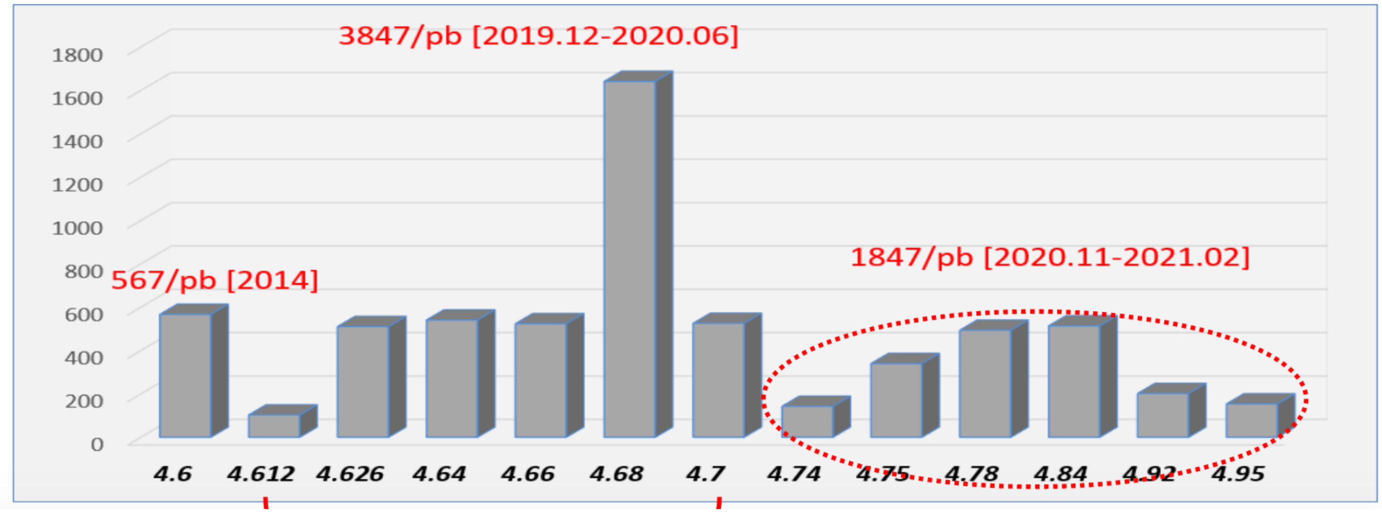
	Mode		Fraction		Change
	Hadronic modes with a p or n: $S=-1$ final states				
Γ_1	pK^0_S		(1.59 ± 0.08) %	S=1.1	↓44%
Γ_2	$pK^-\pi^+$		(6.28 ± 0.32) %	S=1.4	
Γ_3	$p\overline{K}^*(892)^0$	[a]	(1.96 ± 0.27) %		
Γ_4	$\Delta(1232)^{++}K^-$		(1.08 ± 0.25) %		
Γ_5	$\Lambda(1520)\pi^+$	[a]	(2.2 ± 0.5) %		
Γ_6	$pK^-\pi^+$ nonresonant		(3.5 ± 0.4) %		
Γ_7	$pK^0_S\pi^0$		(1.97 ± 0.13) %	S=1.1	↓50%
Γ_8	$nK^0_S\pi^+$		(1.82 ± 0.25) %		**First**
Γ_9	$p\overline{K}^0\eta$		(1.6 ± 0.4) %		
Γ_{10}	$pK^0_S\pi^+\pi^-$		(1.60 ± 0.12) %	S=1.1	↓28%
Γ_{11}	$pK^-\pi^+\pi^0$		(4.46 ± 0.30) %	S=1.5	↓61%
Γ_{12}	$pK^*(892)^-\pi^+$	[a]	(1.4 ± 0.5) %		
Γ_{13}	$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(4.6 ± 0.8) %		
Γ_{14}	$\Delta(1232)\overline{K}^*(892)$		seen		
Γ_{15}	$pK^-2\pi^+\pi^-$		$(1.4\pm0.9)\times10^{-3}$		
Γ_{16}	$pK^-\pi^+2\pi^0$		(1.0 ± 0.5) %		
	Hadronic modes with a p: $S=0$ final states				
Γ_{17}	$p\pi^0$		$<2.7\times10^{-4}$	CL=90%	
Γ_{18}	$p\eta$		$(1.24\pm0.30)\times10^{-3}$		**First**
Γ_{19}	$p\omega(782)^0$		$(9\pm4)\times10^{-4}$		
Γ_{20}	$p\pi^+\pi^-$		$(4.61\pm0.28)\times10^{-3}$		**First**
Γ_{21}	$pf_0(980)$	[a]	$(3.5\pm2.3)\times10^{-3}$		
Γ_{22}	$p2\pi^+2\pi^-$		$(2.3\pm1.4)\times10^{-3}$		
Γ_{23}	pK^+K^-		$(1.06\pm0.06)\times10^{-3}$		
Γ_{24}	$p\phi$	[a]	$(1.06\pm0.14)\times10^{-3}$		↓36%
Γ_{25}	pK^+K^- non-ϕ		$(5.3\pm1.2)\times10^{-4}$		
Γ_{26}	$p\phi\pi^0$		$(10\pm4)\times10^{-5}$		
Γ_{27}	$pK^+K^-\pi^0$ nonresonant		$<6.3\times10^{-5}$	CL=90%	
	Hadronic modes with a hyperon: $S=-1$ final states				
Γ_{28}	$\Lambda\pi^+$		(1.30 ± 0.07) %	S=1.1	
Γ_{29}	$\Lambda\pi^+\pi^0$		(7.1 ± 0.4) %	S=1.1	↓78%
Γ_{30}	$\Lambda\rho^+$		<6 %	CL=95%	
Γ_{31}	$\Lambda\pi^-2\pi^+$		(3.64 ± 0.29) %	S=1.4	
Γ_{44}	$\Sigma^0\pi^+$		(1.29 ± 0.07) %	S=1.1	↓45%
Γ_{45}	$\Sigma^+\pi^0$		(1.25 ± 0.10) %		↓33%
Γ_{46}	$\Sigma^+\eta$		$(4.4\pm2.0)\times10^{-3}$		
Γ_{47}	$\Sigma^+\eta'$		(1.5 ± 0.6) %		
Γ_{48}	$\Sigma^+\pi^+\pi^-$		(4.50 ± 0.25) %	S=1.3	↓46%
Γ_{49}	$\Sigma^+\rho^0$		<1.7 %	CL=95%	
Γ_{50}	$\Sigma^-2\pi^+$		(1.87 ± 0.18) %		
Γ_{51}	$\Sigma^0\pi^+\pi^0$		(3.5 ± 0.4) %		
Γ_{52}	$\Sigma^+\pi^0\pi^0$		(1.55 ± 0.15) %		
Γ_{53}	$\Sigma^0\pi^-2\pi^+$		(1.11 ± 0.30) %		
	Semileptonic modes				
Γ_{72}	$\Lambda e^+\nu_e$		(3.6 ± 0.4) %		↓35%
Γ_{73}	$\Lambda\mu^+\nu_\mu$		(3.5 ± 0.5) %		

Experimental precision reaches of the charmed hadrons

	Golden hadronic mode	δB/B	Golden SL mode	δB/B
D^0	B(Kπ)=(3.88±0.05)%	1.3%	B(Keν)=(3.55±0.05)%	1.4%
D^+	B(Kππ)=(9.13±0.19)%	2.1%	B(K^0eν)=(8.83±0.22)%	2.5%
D_s	B(KKpi)=(5.39±0.21)%	3.9%	B(ϕeν)=(2.49±0.14)%	5.6%
Λ_c	B(pKπ)=(5.0±1.3)%(PDG2014) =(6.8±0.36)% (BELLE) =(5.84±0.35)% (BESIII) =(6.46±0.24)% (HFLAV)	26% 5.3% 6.0% 3.7%	B(Λeν)=(2.1±0.6)%(PDG2014) =(3.63±0.43)% (BESIII) =(3.18±0.32)% (HFLAV)	29% 12% 10%

- The precisions of Λc decay rates reaches to the level of charmed mesons!
- However, search for more unknown modes, especially Cabbibo-suppressed mode, are important

New Λ_c^+ data in 2020-2021



in total, 6.4 fb^{-1} data above Λ_c^+ threshold (~8x times more Λ_c^+ statistics)

- First measurement of absolute form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$
- Observation of second SL decay $\Lambda_c^+ \to pK^- e^+ \nu_e$
- Many observations and improved precisions of Cabbibo-Suppressed modes
- First partial wave analysis of Λ_c^+ decays
- More studies of neutron-involved decay modes
- Search for rare decay $\Lambda_c^+ \to \gamma \Sigma^+$

Based on Phase II data

Semi-leptonic decay

- ✓ Form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ and $\Lambda \mu^+ \nu_\mu$ — ***PRL129, 231803 (2022);*** *PRD108, L031105 (2023)*
- ✓ $\Lambda_c^+ \to pK^- e^+ \nu_e$ — *PRD106, 112010 (2022)*
- ✓ Search for $\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e$ and $pK_s \pi^- e^+ \nu_e$ — *PLB843, 137993 (2023)*
- ✓ $\Lambda_c^+ \to n e^+ \nu_e$ — ***Nature Commun. 16, 681 (2025)***

Neutron-involved decay

- ✓ $\Lambda_c^+ \to n \pi^+$ — ***PRL 128, 142001 (2022)***
- ✓ $\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^+\pi^-, nK^-\pi^+\pi^+$ — *CPC 47, 023001 (2023) (Cover Story)*
- ✓ $\Lambda_c^+ \to nK_sK^+$ — *PRD 109, 072010 (2024)*
- ✓ $\Lambda_c^+ \to \Sigma^- K^+ \pi^+$ — *PRD 109, L071103 (2024)*
- ✓ $\Lambda_c^+ \to nK_s\pi^+\pi^0$ — *PRD 109, 053005 (2024)*

Hadronic CS decays

- ✓ $\Lambda_c^+ \to p\pi^0, p\eta, p\omega$ — *JHEP11, 137 (2023); PRD09, L091101 (2024); PRD111, L051101 (2025)*
- ✓ $\Lambda_c^+ \to p\eta'$ — *PRD106, 072002 (2022)*
- ✓ $\Lambda_c^+ \to \Lambda K^+, \Lambda K^+\pi^0, \Lambda K_s\pi^+$ — *PRD106, L111101 (2022); PRD109, 032003 (2024); PRD111, 012014 (2025)*
- ✓ $\Lambda_c^+ \to \Sigma^+ K_s, \Sigma^0 K^+ (\pi^0, \pi^+\pi^-), \Sigma^+ K^+ \pi^-$ — *PRD106, 052003 (2022); JHEP09, 125 (2023);arXiv:2502.11047*
- ✓ ***Hadronic CF decays***
- ✓ PWA of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ and $\Lambda\pi^+\eta$ — *JHEP 12, 033(2022);* ***PRL134, 021901 (2025)***
- ✓ W-exchange-only process $\Xi^0 K^+$ — ***PRL132, 031801 (2024)***
- ✓ $\Lambda_c^+ \to \Xi^0 K^+ \pi^0$ — *PRD109, 052001 (2024)*
- ✓ $\Lambda_c^+ \to pK_L,\ pK_L\pi^0, pK_L\pi^+\pi^-$ — *JHEP09, 007 (2024)*

>33 papers are published

Inclusive decay

- ✓ Improved BF of $\Lambda_c^+ \to e^+ X$ — *PRD107, 052005 (2023)*
- ✓ First BF of $\bar{\Lambda}_c^- \to \bar{n} X$ — *PRD108, L031101 (2023)*
- ✓ First BF of $\bar{\Lambda}_c^- \to K_S^0 X$ — *arXiv:2502.20821*

Rare decay

- ✓ $\Lambda_c^+ \to \gamma \Sigma^+$ — *PRD107, 052002 (2023)*

Production and excited Λ_c^+

- ✓ $\Lambda_c^+ \bar{\Lambda}_c^-$ *lineshape and form factor* — ***PRL107, 052002 (2023)***
- ✓ $\Lambda_c(2595)^+$ *and* $\Lambda_c(2625)^+$ — *PRD109, L071104 (2024); PRD109, 112007 (2024); arXiv:2503.21413*

Λ_c^+ Mode	BF($\times10^{-3}$)	Experiment	Λ_c^+ Mode	BF($\times10^{-3}$)	Experiment
$\Lambda_c^+ \to \Lambda e^+ \nu_e$	$23.7\pm5.1(37\%)^\dagger$	ARGUS(1991)[24]	$\Lambda_c^+ \to pK^- e^+ \nu_e$	$0.88\pm0.18(20\%)$	BESIII(2022)[29]
	$26.8\pm5.1(19\%)^\dagger$	CELO(1994)[25]	$\Lambda_c^+ \to \Lambda(1405)e^+\nu_e$, $\Lambda(1405)\to pK^-$	$0.42\pm0.19(45\%)$	BESIII(2022)[29]
	$36.3\pm4.3(12\%)$	BESIII(2015)[30]			
	$35.6\pm1.3(3.6\%)$	BESIII(2022)[31]	$\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$	$1.0\pm0.5(50\%)$	BESIII(2022)[29]
$\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$	$34.9\pm5.3(15\%)$	BESIII(2017)[32]	$\Lambda_c^+ \to pK_S^0\pi^- e^+\nu_e$	<0.33	BESIII(2023)[33]
	$34.8\pm1.7(4.9\%)$	BESIII(2023)[34]	$\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e$	<0.39	BESIII(2023)[33]
$\Lambda_c^+ \to e^+ X$	$39.5\pm3.5(8.9\%)$	BESIII(2018)[35]	$\Lambda_c^+ \to n e^+\nu_e$	3.57 ± 0.37 (10%)	BESIII(2025)[36]
	$40.6\pm1.3(3.2\%)$	BESIII(2023)[37]			
Ξ_c Mode	BF($\times10^{-3}$)	Experiment	Ξ_c Mode	BF($\times10^{-3}$)	Experiment
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	$13.7\pm7.7(56\%)^\dagger$	ARGUS(1993)[26]	$\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$	$10.1\pm2.1(21\%)^\dagger$	Belle(2021)[38]
	$44.3^{+16.6}_{-17.8}(40\%)^\dagger$	CLEO(1995)[27]	$\Xi_c^+ \to \Xi^0 e^+ \nu_e$	$67\pm39(58\%)^\dagger$	CLEO(1995)[27]
	$19.7\pm5.3(27\%)^\dagger$	ALICE(2021)[39]			
	$10.4\pm2.1(20\%)^\dagger$	Belle(2021)[38]			
Ω_c^0 Mode	Ratio	Experiment	Ω_c^0 Mode	Ratio	Experiment
$\Omega_c^0 \to \Omega^0 e^+ \nu_e$	$2.4\pm1.1(47\%)$	CLEO(2002)[28]	$\Omega_c^0 \to \Omega^0 \mu^+ \nu_\mu$	$1.94\pm0.21(11\%)$	Belle(2022)[40]
	$1.98\pm0.15(7.7\%)$	Belle(2022)[40]			

Table 3. The determined BFs for the CS decays of the Λ_c^+ (in units of 10^{-3}). Upper limits are set at 90% confidence level.

Mode	BF	Experiment	Mode	BF	Experiment
Nucleon-involved					
$\Lambda_c^+ \to n\pi^+$	0.66 ± 0.13	BESIII(2022)[126]	$\Lambda_c^+ \to nK^+\pi^0$	<0.71	BESIII(2024)[107]
$\Lambda_c^+ \to p\pi^0$	<0.27	BESIII(2017)[117]	$\Lambda_c^+ \to n\pi^+\pi^0$	0.64 ± 0.09	BESIII(2023)[129]
	<0.08	Belle(2021)[109]	$\Lambda_c^+ \to nK_S^0K^+$	$0.39^{+0.17}_{-0.14}$	BESIII(2024)[91]
	$0.16^{+0.07}_{-0.06}$	BESIII(2024)[118]	$\Lambda_c^+ \to n\pi^+\pi^-\pi^+$	0.45 ± 0.08	BESIII(2023)[129]
	0.18 ± 0.04	BESIII(2025)[119]	$\Lambda_c^+ \to p\pi^+\pi^-$	3.91 ± 0.40	BESIII(2016)[127]
$\Lambda_c^+ \to p\eta$	1.24 ± 0.30	BESIII(2017)[117]		4.72 ± 0.28	LHCb(2018)[138]
	1.42 ± 0.12	Belle(2021)[109]	$\Lambda_c^+ \to pK^+K^-$	1.08 ± 0.07	LHCb(2018)[138]
	1.57 ± 0.12	BESIII(2023)[120]	$\Lambda_c^+ \to p(K^+K^-)_{\text{non-}\phi}$	0.55 ± 0.14	BESIII(2016)[127]
	1.63 ± 0.33	BESIII(2024)[118]	$\Lambda_c^+ \to pK_S^0K_S^0$	0.24 ± 0.02	Belle(2023)[146]
	1.67 ± 0.80	LHCb(2024)[121]	$\Lambda_c^+ \to p\phi\pi^0$	<0.15	Belle(2017)[147]
$\Lambda_c^+ \to p\eta'$	$0.56^{+0.25}_{-0.21}$	BESIII(2022)[123]	$\Lambda_c^+ \to (pK^+K^-\pi^0)_{\text{NR}}$	<0.06	Belle(2017)[147]
	0.47 ± 0.10	Belle(2022)[122]	$\Lambda_c^+ \to pK^+\pi^-$	0.16 ± 0.02	Belle(2016)[137]
$\Lambda_c^+ \to p\rho$	1.52 ± 0.44	LHCb(2024)[121]		0.10 ± 0.01	LHCb(2018)[138]
$\Lambda_c^+ \to p\omega$	0.94 ± 0.39	LHCb(2018)[124]			
	0.83 ± 0.11	Belle(2021)[125]			
	1.11 ± 0.21	BESIII(2023)[120]			
	0.98 ± 0.31	LHCb(2024)[121]			
$\Lambda_c^+ \to p\phi$	1.06 ± 0.22	BESIII(2016)[127]			
Λ-involved					
$\Lambda_c^+ \to \Lambda K^+$	0.62 ± 0.06	BESIII(2022)[131]	$\Lambda_c^+ \to \Lambda K^+\pi^0$	<2.0	BESIII(2024)[107]
	0.66 ± 0.04	Belle(2023)[132]		1.49 ± 0.29	BESIII(2024)[135]
$\Lambda_c^+ \to \Lambda K^{*+}$	$2.40\pm0.59(\theta_0=0^\circ)$	BESIII(2025)[134]	$\Lambda_c^+ \to \Lambda K_S^0\pi^+$	1.73 ± 0.29	BESIII(2025)[134]
	$5.21\pm0.75(\theta_0=109^\circ)$	BESIII(2025)[134]	$\Lambda_c^+ \to \Lambda K^+\pi^+\pi^-$	0.41 ± 0.15	BESIII(2024)[135]
	$1.29\pm0.44(\theta_0=221^\circ)$	BESIII(2025)[134]			
Σ-involved					
$\Lambda_c^+ \to \Sigma^0K^+$	0.47 ± 0.10	BESIII(2022)[133]	$\Lambda_c^+ \to \Sigma^+K^+\pi^-$	2.00 ± 0.28	BESIII(2023)[150]
	0.36 ± 0.03	Belle(2023)[132]	$\Lambda_c^+ \to \Sigma^+K^+\pi^-\pi^0$	<0.01	BESIII(2023)[150]
$\Lambda_c^+ \to \Sigma^+K_S^0$	0.48 ± 0.14	BESIII(2022)[133]	$\Lambda_c^+ \to \Sigma^0K^+\pi^0$	<1.8	BESIII(2024)[107]
				<0.50	BESIII(2024)[151]
			$\Lambda_c^+ \to \Sigma^0K^+\pi^+\pi^-$	<0.65	BESIII(2024)[151]
			$\Lambda_c^+ \to \Sigma^-K^+\pi^+$	0.38 ± 0.12	BESIII(2024)[136]

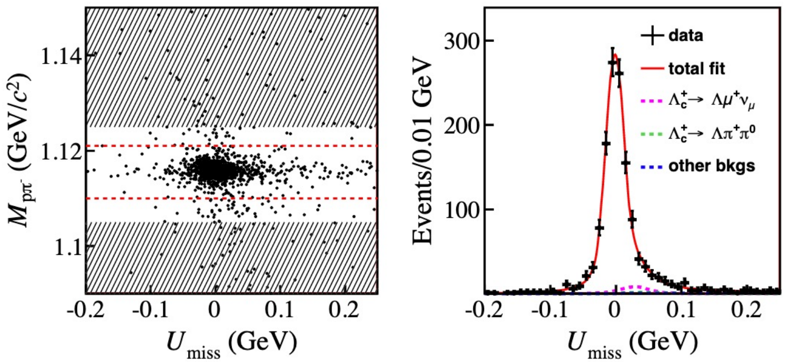
Table 2. Measurements of the BFs for the CF decays of the Λ_c^+ (in units of %).

Mode	BF	Experiment	Mode	BF	Experiment
Nucleon-involved					
$\Lambda_c^+ \to pK_S^0$	1.52 ± 0.09	BESIII(2016)[80]	$\Lambda_c^+ \to nK_S^0\pi^+$	1.82 ± 0.25	BESIII(2017)[90]
$\Lambda_c^+ \to pK_L^0$	1.67 ± 0.07	BESIII(2024)[89]		1.86 ± 0.09	BESIII(2024)[91]
$\Lambda_c^+ \to p\bar{K}_0^*(700)^0 \to pK^-\pi^+$	0.19 ± 0.06	LHCb(2023)[86]	$\Lambda_c^+ \to nK_S^0\pi^+\pi^0$	0.85 ± 0.13	BESIII(2024)[92]
$\Lambda_c^+ \to p\bar{K}_0^*(892)^0 \to pK^-\pi^+$	1.38 ± 0.08	LHCb(2023)[86]	$\Lambda_c^+ \to nK^-\pi^+\pi^+$	1.90 ± 0.12	BESIII(2023)[129]
$\Lambda_c^+ \to p\bar{K}_0^*(1430)^0 \to pK^-\pi^+$	0.92 ± 0.18	LHCb(2023)[86]	$\Lambda_c^+ \to pK_S^0\pi^0$	1.87 ± 0.14	BESIII(2016)[80]
$\Lambda_c^+ \to \Delta(1232)^{++}K^- \to p\pi^+K^-$	1.78 ± 0.05	LHCb(2023)[86]		2.12 ± 0.11	Belle(II)(2025)[144]
$\Lambda_c^+ \to \Delta(1600)^{++}K^- \to p\pi^+K^-$	0.28 ± 0.10	LHCb(2023)[86]	$\Lambda_c^+ \to pK_L^0\pi^0$	2.02 ± 0.14	BESIII(2024)[89]
$\Lambda_c^+ \to \Delta(1700)^{++}K^- \to p\pi^+K^-$	0.24 ± 0.06	LHCb(2023)[86]	$\Lambda_c^+ \to pK_S^0\eta$	0.41 ± 0.09	BESIII(2021)[145]
				0.44 ± 0.03	Belle(2023)[146]
			$\Lambda_c^+ \to pK_S^0\pi^+\pi^-$	1.53 ± 0.14	BESIII(2016)[80]
			$\Lambda_c^+ \to pK_L^0\pi^+\pi^-$	1.69 ± 0.11	BESIII(2024)[89]
			$\Lambda_c^+ \to pK^-\pi^+$	$6.84^{+0.32}_{-0.36}$	Belle(2014)[81]
				5.84 ± 0.35	BESIII(2016)[80]
			$\Lambda_c^+ \to pK^-\pi^+\pi^0$	4.53 ± 0.38	BESIII(2016)[80]
				4.42 ± 0.21	Belle(2017)[147]
Λ-involved					
$\Lambda_c^+ \to \Lambda\pi^+$	1.24 ± 0.08	BESIII(2016)[80]	$\Lambda_c^+ \to \Lambda\pi^+\pi^0$	7.01 ± 0.42	BESIII(2016)[80]
	1.31 ± 0.09	BESIII(2023)[126]	$\Lambda_c^+ \to \Lambda\pi^+\eta$	1.84 ± 0.26	BESIII(2019)[94]
$\Lambda_c^+ \to \Lambda\rho(770)^+$	4.06 ± 0.52	BESIII(2022)[93]		1.84 ± 0.13	Belle(2021)[95]
$\Lambda_c^+ \to \Lambda a_0(980)^+$	1.23 ± 0.21	BESIII(2025)[94]		1.94 ± 0.13	BESIII(2025)[148]
$\Lambda_c^+ \to \Lambda(1405)\pi^+ \to pK^-\pi^+$	0.48 ± 0.19	LHCb(2023)[86]	$\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$	3.81 ± 0.30	BESIII(2016)[80]
$\Lambda_c^+ \to \Lambda(1520)\pi^+ \to pK^-\pi^+$	0.12 ± 0.02	LHCb(2023)[86]	$\Lambda_c^+ \to \Lambda K_S^0K^+$	0.30 ± 0.03	BESIII(2025)[134]
$\Lambda_c^+ \to \Lambda(1600)\pi^+ \to pK^-\pi^+$	0.32 ± 0.12	LHCb(2023)[86]		0.31 ± 0.05	BESIII(2025)[108]
$\Lambda_c^+ \to \Lambda(1670)\pi^+ \to pK^-\pi^+$	0.07 ± 0.02	LHCb(2023)[86]			
$\Lambda_c^+ \to \Lambda(1670)\pi^+ \to \Lambda\eta\pi^+$	0.27 ± 0.06	Belle(2021)[95]			
	0.27 ± 0.06	BESIII(2025)[148]			
$\Lambda_c^+ \to \Lambda(1690)\pi^+ \to pK^-\pi^+$	0.07 ± 0.02	LHCb(2023)[86]			
$\Lambda_c^+ \to \Lambda(2000)\pi^+ \to pK^-\pi^+$	0.60 ± 0.07	LHCb(2023)[86]			
Σ-involved					
$\Lambda_c^+ \to \Sigma^+\pi^0$	1.18 ± 0.10	BESIII(2016)[80]	$\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$	4.25 ± 0.31	BESIII(2016)[80]
$\Lambda_c^+ \to \Sigma^+\eta$	0.41 ± 0.20	BESIII(2018)[96]		4.57 ± 0.28	Belle(2018)[149]
	0.31 ± 0.05	Belle(2023)[98]	$\Lambda_c^+ \to \Sigma^+\pi^0\pi^0$	1.57 ± 0.15	Belle(2018)[149]
	0.38 ± 0.06	BESIII(2025)[97]	$\Lambda_c^+ \to \Sigma^0\pi^+\pi^0$	3.65 ± 0.30	Belle(2018)[149]
$\Lambda_c^+ \to \Sigma^+\eta'$	1.34 ± 0.56	BESIII(2018)[96]	$\Lambda_c^+ \to \Sigma^0\pi^+\eta$	0.76 ± 0.08	Belle(2021)[95]
	0.42 ± 0.09	Belle(2023)[98]	$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$	1.81 ± 0.19	BESIII(2017)[105]
	0.57 ± 0.18	BESIII(2025)[97]	$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$	2.11 ± 0.36	BESIII(2017)[105]
$\Lambda_c^+ \to \Sigma^+\omega$	1.56 ± 0.21	BESIII(2016)[80]	$\Lambda_c^+ \to \Sigma^+K^+K^-$	0.38 ± 0.05	BESIII(2023)[150]
$\Lambda_c^+ \to \Sigma^+\phi$	0.41 ± 0.09	BESIII(2023)[150]	$\Lambda_c^+ \to \Sigma^+K^+K^-_{\text{non-}\phi}$	0.20 ± 0.04	BESIII(2023)[150]
$\Lambda_c^+ \to \Sigma^0\pi^+$	1.27 ± 0.09	BESIII(2016)[80]	$\Lambda_c^+ \to \Sigma^0K_S^0K^+$	0.08 ± 0.03	BESIII(2025)[108]
	1.22 ± 0.11	BESIII(2023)[126]			
$\Lambda_c^+ \to \Sigma(1385)^+\pi^0$	0.59 ± 0.08	BESIII(2022)[93]			
$\Lambda_c^+ \to \Sigma(1385)^+\eta$	0.91 ± 0.20	BESIII(2019)[94]			
	1.21 ± 0.12	Belle(2021)[95]			
	0.68 ± 0.08	BESIII(2025)[148]			
$\Lambda_c^+ \to \Sigma(1385)^0\pi^+$	0.65 ± 0.10	BESIII(2022)[93]			
Ξ-involved					
$\Lambda_c^+ \to \Xi^0K^+$	0.59 ± 0.09	BESIII(2018)[106]	$\Lambda_c^+ \to \Xi^0K^+\pi^0$	0.78 ± 0.17	BESIII(2024)[107]
$\Lambda_c^+ \to \Xi(1530)^0K^+$	0.50 ± 0.10	BESIII(2018)[106]	$\Lambda_c^+ \to \Xi^0K_S^0\pi^+$	0.37 ± 0.06	BESIII(2025)[108]
	0.60 ± 0.11	BESIII(2024)[107]			

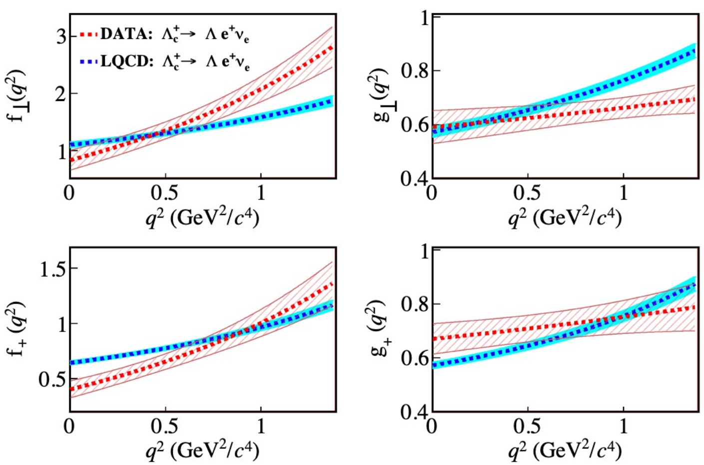
Recent results on Λ_c^+ leptonic decays

Determination of form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$

PRL129, 231803 (2022)



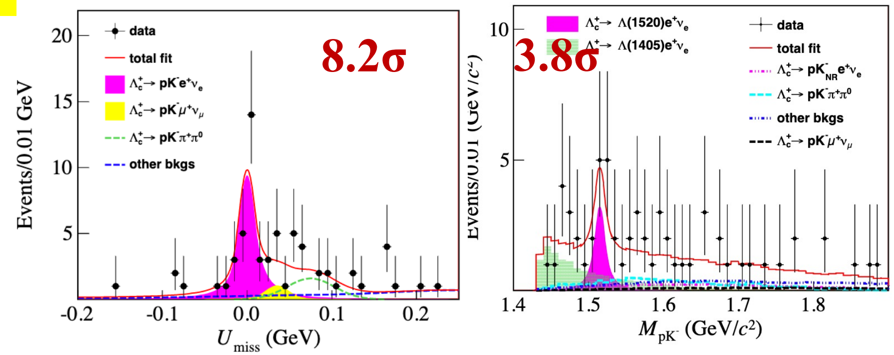
$B(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11 \pm 0.07)\%$



First direct comparisons on the differential decay rates and form factors with LQCD calculations

Observation of $\Lambda_c^+ \to pK^- e^+ \nu$

PRD106, 112010 (2022)



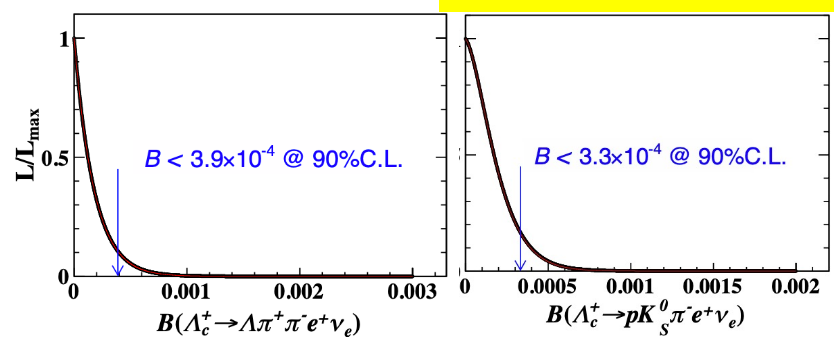
$B(\Lambda_c^+ \to pK^- e^+ \nu) = (0.88 \pm 0.17 \pm 0.07) \times 10^{-3}$

$B(\Lambda_c^+ \to \Lambda(1405) e^+ \nu) = (1.69 \pm 0.76 \pm 0.16) \times 10^{-3}$

$B(\Lambda_c^+ \to \Lambda(1520) e^+ \nu) = (0.99 \pm 0.51 \pm 0.10) \times 10^{-3}$

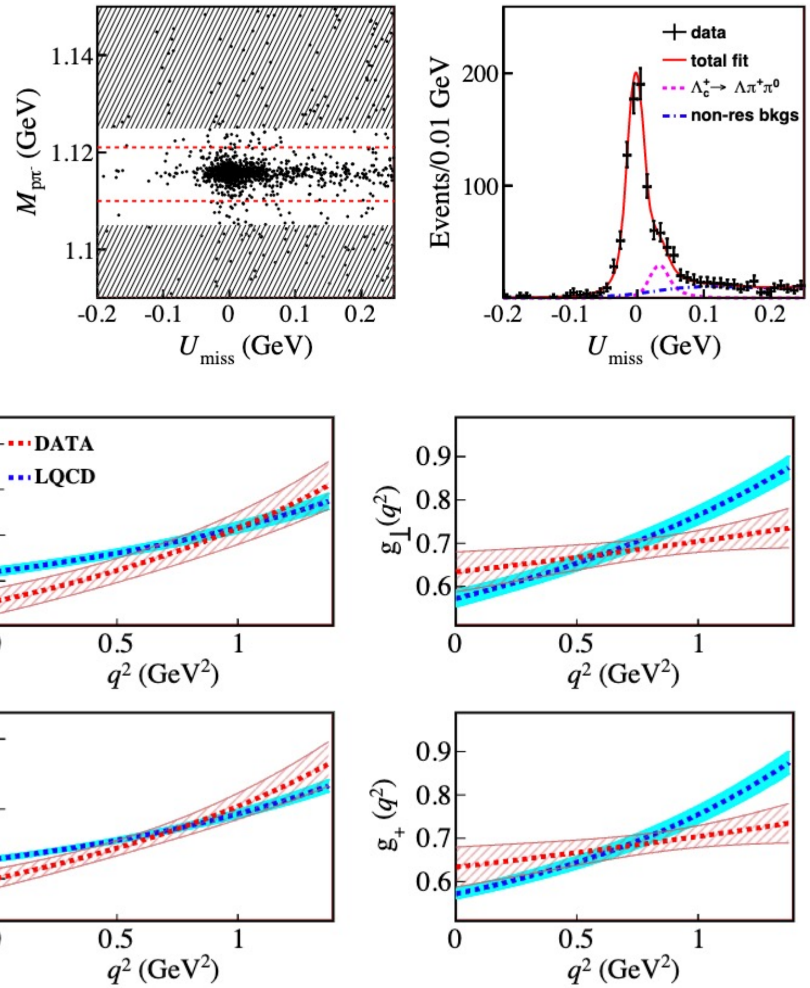
- Second leptonic decay of Λ_c^+ is observed!
- Good channel to study Λ excited states, such as $\Lambda(1405)$ and $\Lambda(1520)$

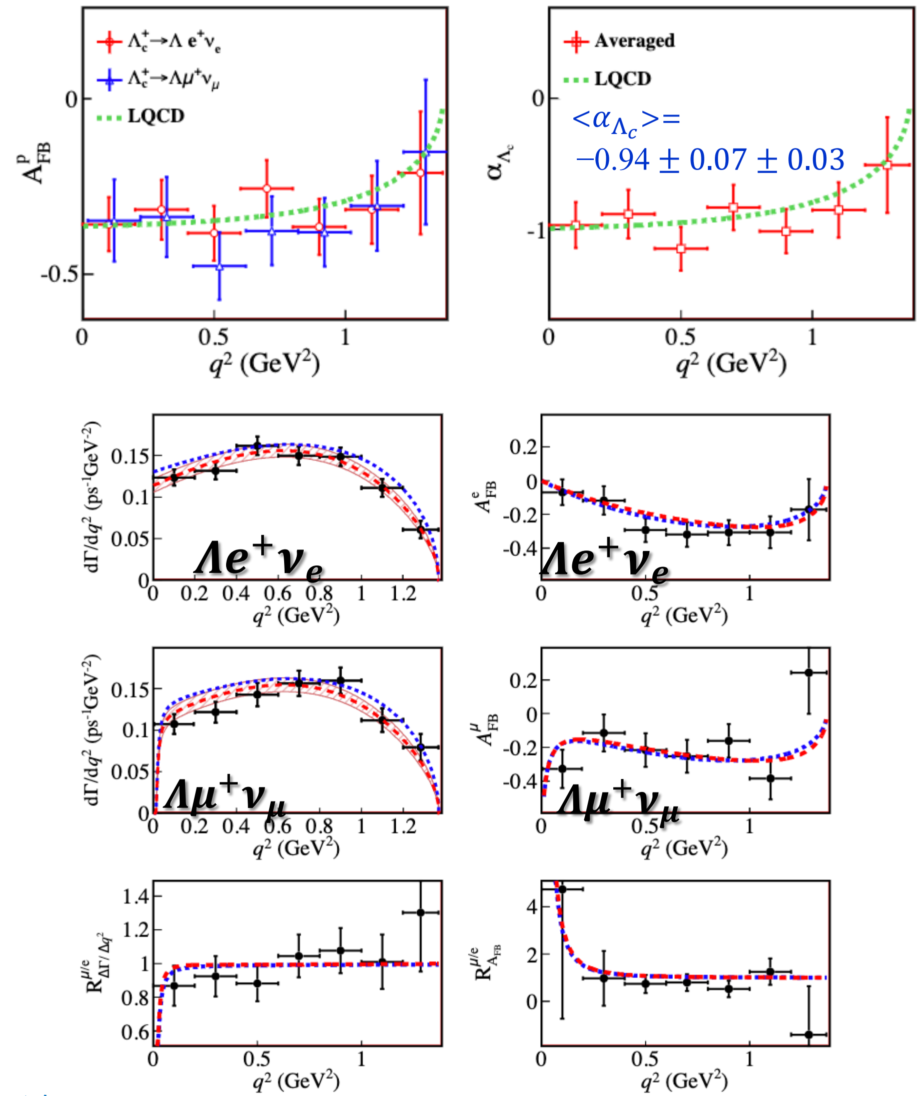
PLB 843, 137993 (2023)



Combined form factor fits to $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$ and $\Lambda e^+\nu_e$

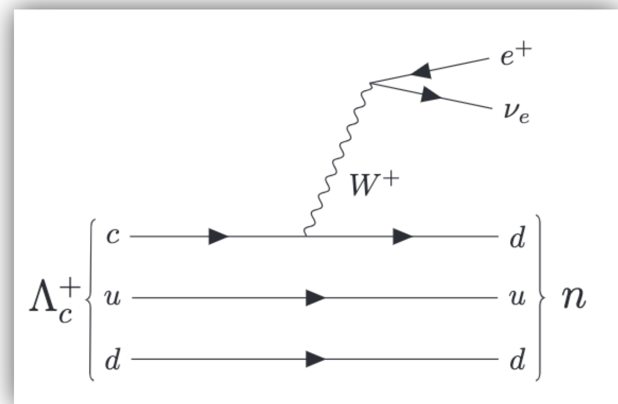
PRD 108, L031105 (2023)

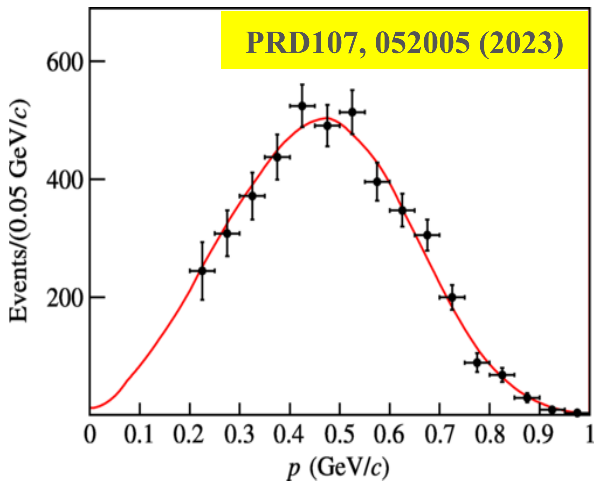




Cabibbo-suppressed SL decays

- There is still room of 0.5% for un-seen SL decay of the Λ_c^+
- The Cabibbo-Suppressed SL decays have not been studied in experiment
- $\Lambda_c^+ \to n e^+ \nu_e$ is the most promising channel for the experimental observation



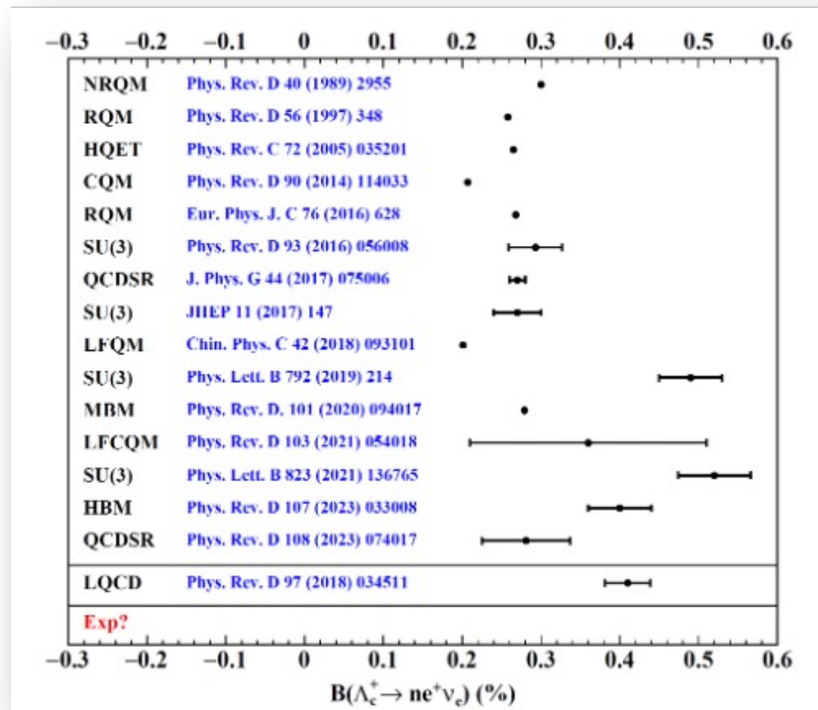


$\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (4.06 \pm 0.10_{\rm stat} \pm 0.09_{\rm syst})\%.$

$B(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11 \pm 0.07)\%$

$B(\Lambda_c^+ \to p K^- e^+ \nu_e) = (8.8 \pm 1.1 \pm 0.7) \times 10^{-4}$

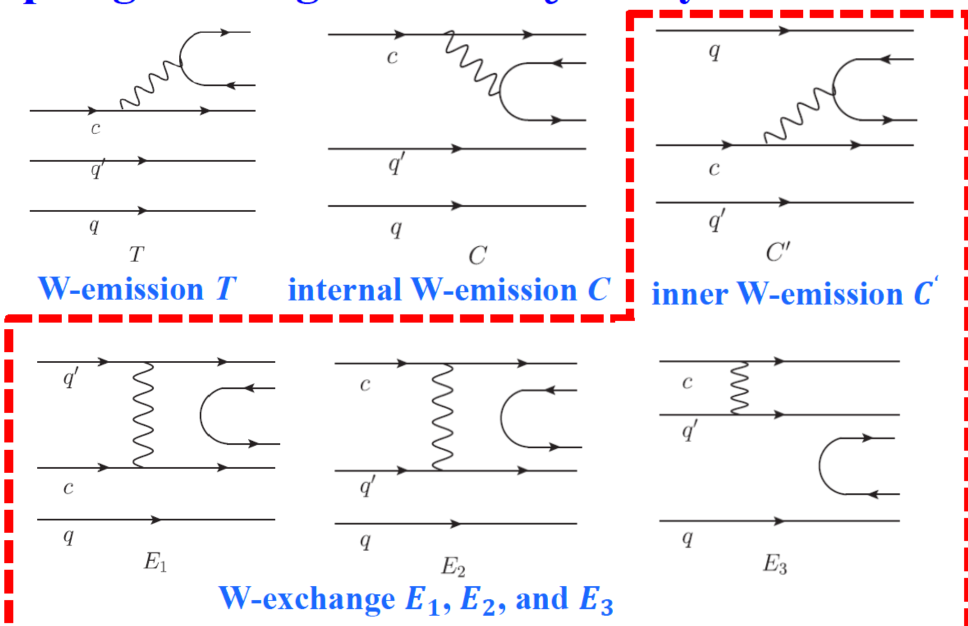
$B(\Lambda_c^+ \to \Lambda(1520) e^+ \nu_e) = (10.2 \pm 5.2 \pm 1.1) \times 10^{-4}$



Charmed baryon decay

- Λ_c^+ may reveal more information of strong- and weak-interactions in charm region, complementary to D/D_s
  → Most charmed baryons eventually decay to Λ_c^+

Topological Diagrams for Λ_c^+ decays:



H.-Y. Cheng *et al.*, *Chinese Journal of Physics*, 78(2022) 324-362

Non-factorization amplitude
→ Calculation is not reliable, need exp. input

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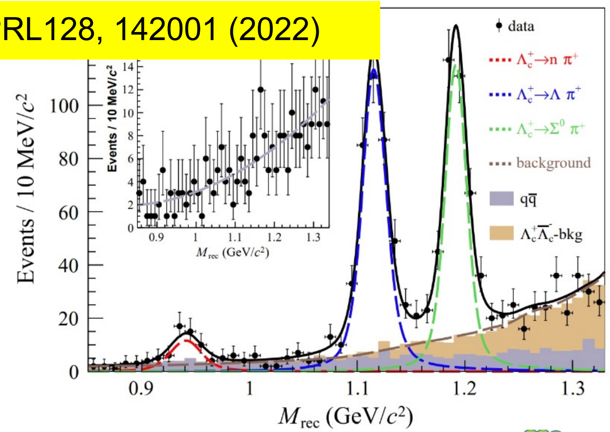
Recent results on Λ_c hadronic decays

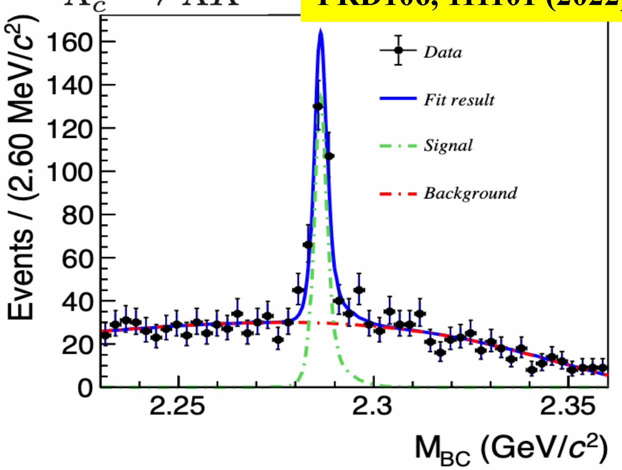
Observation of $\Lambda_c^+ \to n\pi^+$

PRL128, 142001 (2022)



$\Lambda_c^+ \to \Lambda K^+$

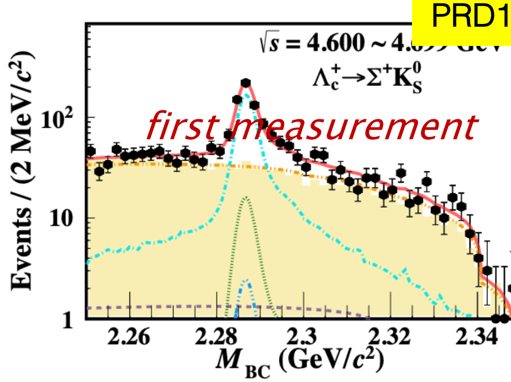
PRD106, 111101 (2022)

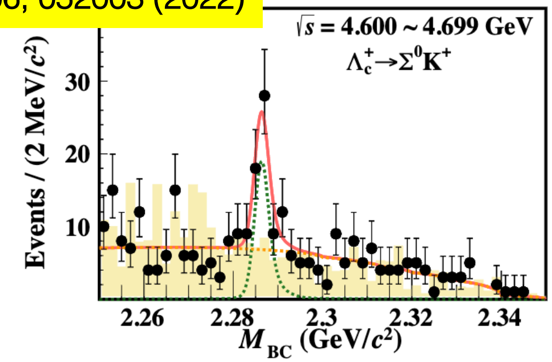


Many CS modes are explored.

Determination of the BF for $\Lambda_c^+ \to \Sigma^+ K_S$ and $\Sigma^0 K^+$

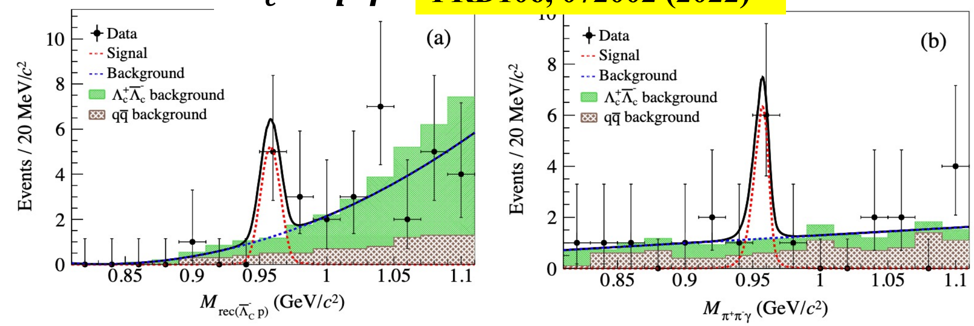
PRD106, 052003 (2022)



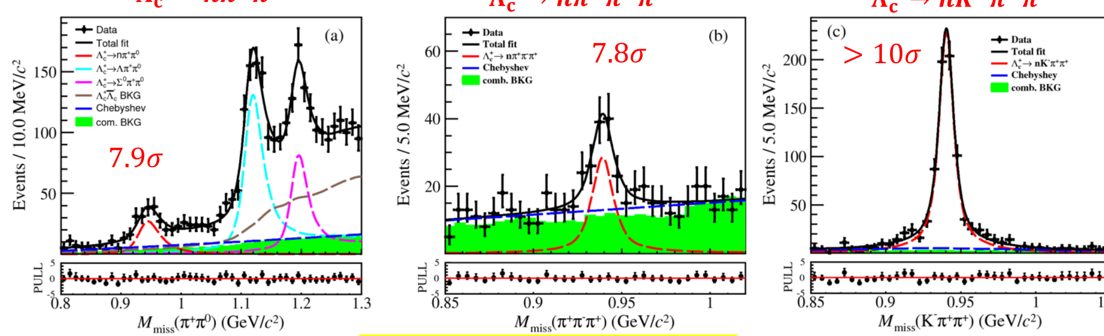


$\Lambda_c^+ \to p\eta'$

PRD106, 072002 (2022)



$\Lambda_c^+ \to n\pi^+\pi^0$ $\Lambda_c^+ \to n\pi^+\pi^-\pi^+$ $\Lambda_c^+ \to nK^-\pi^+\pi^+$



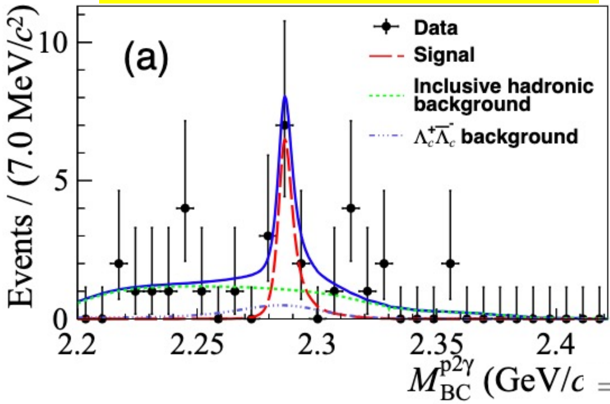
CPC47, 023001 (2023)

SCS decays of $\Lambda_c^+ \to p\pi^0$ and $p\eta$

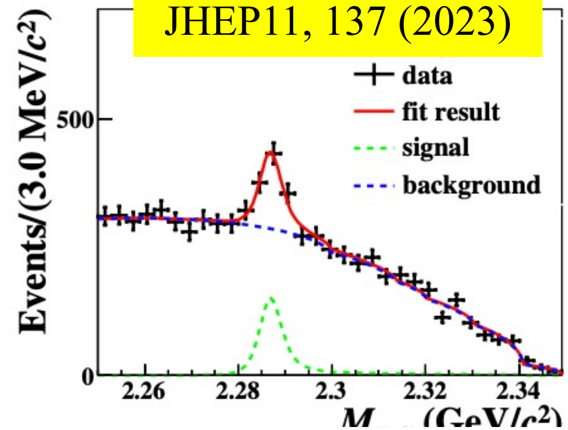
First evidence of $\Lambda_c^+ \to p\pi^0$

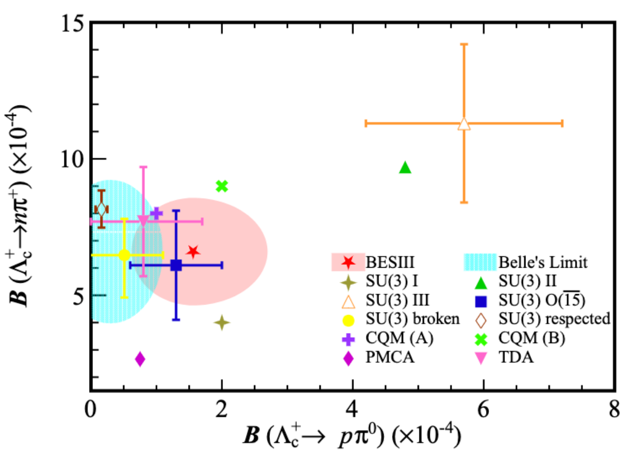
Most precise measurement of $\Lambda_c^+ \to p\eta$

PRD109, L091101 (2024)



JHEP11, 137 (2023)





Model	$\mathcal{B}(\Lambda_c^+ \to p\pi^0)\times 10^4$	$\mathcal{B}(\Lambda_c^+ \to p\eta)\times 10^4$	$\mathcal{B}(\Lambda_c^+ \to n\pi^+)\times 10^4$
Constituent quark model [7]	(1, 2)	3	(8, 9)
Heavy quark effective theory [8]	1.1 - 3.6	-	1.0 - 2.1
Dynamic calculation [9, 10]	(0.75, 1.3)	12.8	2.66
Topological diagram [11]	$0.8^{+0.9}_{-0.8}$	11.4 ± 3.5	7.7 ± 2.0
Topological diagram [12]	$(0.3^{+1.0}_{-0.3},\ 0.4^{+1.7}_{-0.4})$	$(14.2 \pm 2.3,\ 14.7 \pm 2.8)$	$(7.6 \pm 1.7,\ 8.3 \pm 2.6)$
SU(3) flavor symmetry [13]	2	-	4
SU(3) flavor symmetry [14]	4.8	-	9.7
SU(3) flavor symmetry [15]	5.7 ± 1.5	-	11.3 ± 2.9
SU(3) flavor symmetry [16]	1.3 ± 0.7	13.0 ± 1.0	6.1 ± 2.0
SU(3) flavor symmetry [17]	$1.1^{+1.3}_{-1.1}$	11.2 ± 2.8	7.6 ± 1.1
SU(3) flavor symmetry [18]	2.1 ± 1.0	14.1 ± 1.1	6.5 ± 2.3
BESIII experiment	< 2.7 [19] $1.57^{+0.74}_{-0.60}$ [23]	12.4 ± 3.0 [19] 15.8 ± 1.2 [20]	6.6 ± 1.3 [22]
Belle experiment	< 0.8 [21]	14.2 ± 1.2 [21]	-

BESIII

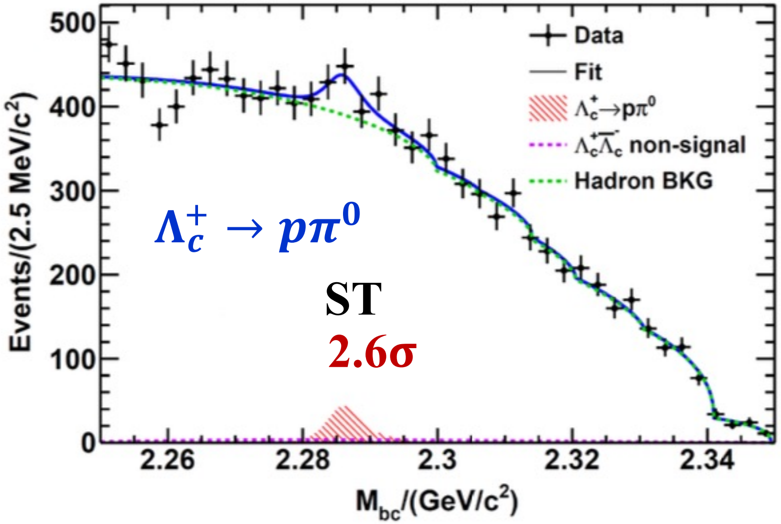
Singly Cabibbo-suppressed decays of $\Lambda_c^+ \to p\pi^0$

$\Lambda_c^+ \to p\pi^0$:

- conflicts with BELLE (BF <8.0×10^{-5})
- need better precision to discriminate different theoretical calculations

Experimental challenge

- neither ST nor DT can achieve sufficient signal sensitivity!



- Use Deep Neural Network (DNN) to identify $\Lambda_c^+(\to p\pi^0)\bar{\Lambda}_c^-(\to anything)$ **after ST selections**
  - ✓ Form point clouds with all recorded tracks & showers
  - ✓ Train Transformer model with MC samples covering all $\bar{\Lambda}_c^-$ final states
  - ✓ Randomly shuffle signal & background MC samples with equal statistics
- Take $\Lambda_c^+ \to p\eta, \eta \to \gamma\gamma$ as reference channel

ML-boosted observation of $\Lambda_c^+ \to p\pi^0$

PRD111, L051101 (2025)

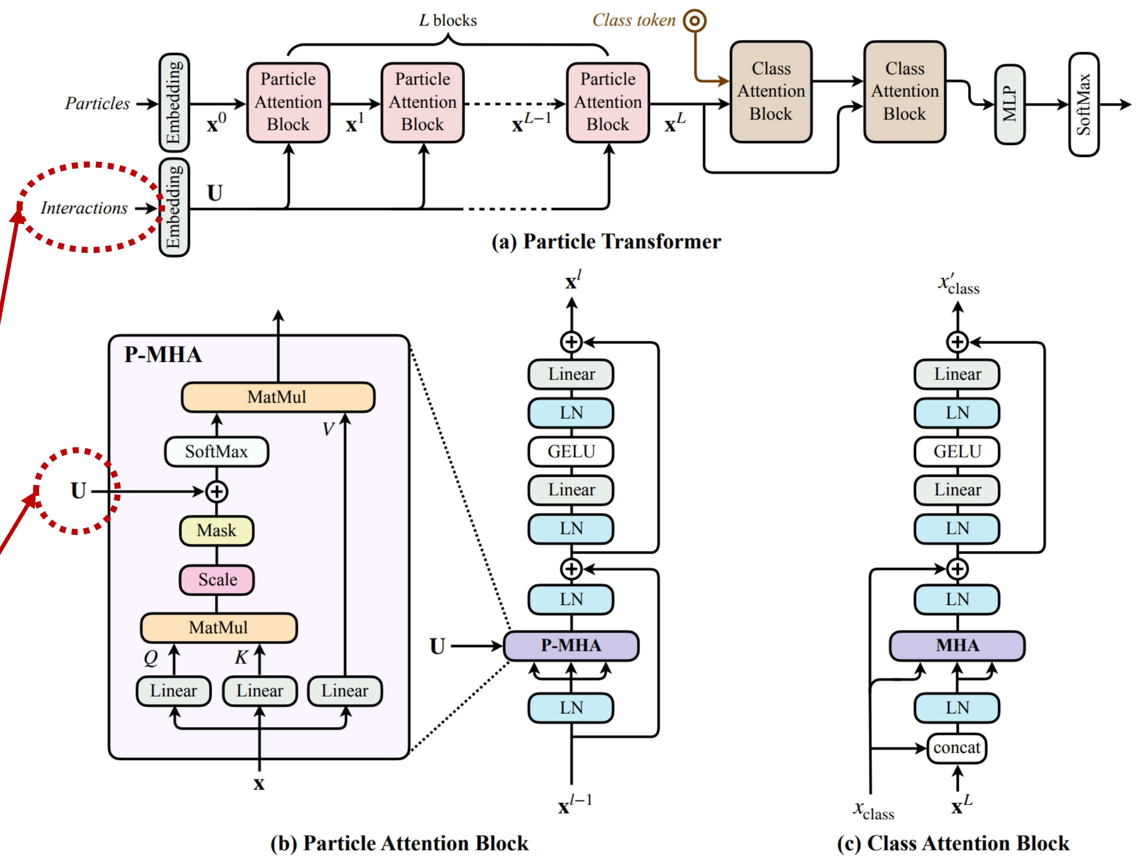
Model architecture – Transformer

- Foundation of Large Language Models like GPT
- Core concept: self-attention mechanism
- Particle Transformer: arXiv:2202.03772

✓ A transformer model tailored for particle physics

✓ Inject physics-inspired pairwise features as “bias” to the self-attention block

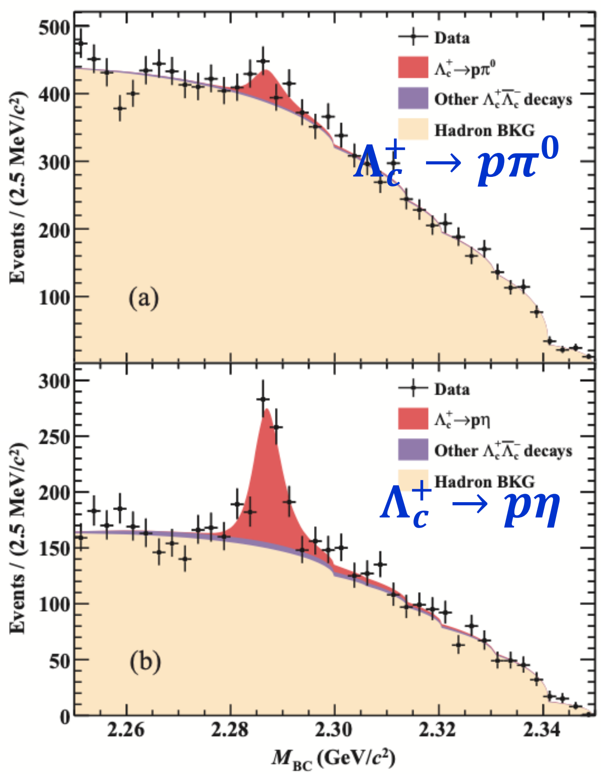
$$\Delta = \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2},$$
$$k_T = \min(p_{T,a}, p_{T,b})\Delta,$$
$$z = \min(p_{T,a}, p_{T,b})/(p_{T,a} + p_{T,b}),$$
$$m^2 = (E_a + E_b)^2 - \left\|\mathbf{p}_a + \mathbf{p}_b\right\|^2.$$



ML-boosted observation of $\Lambda_c^+ \to p\pi^0$

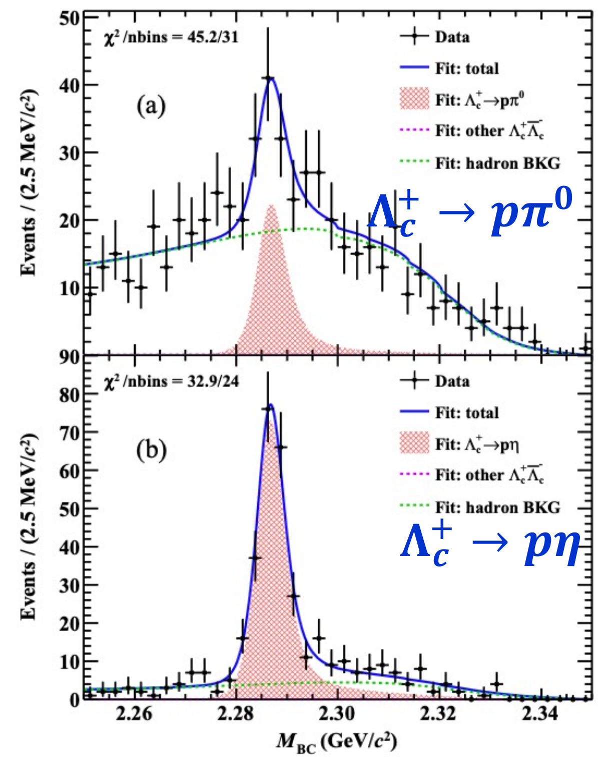
PRD111, L051101 (2025)

2.6σ



DNN training

5.4σ

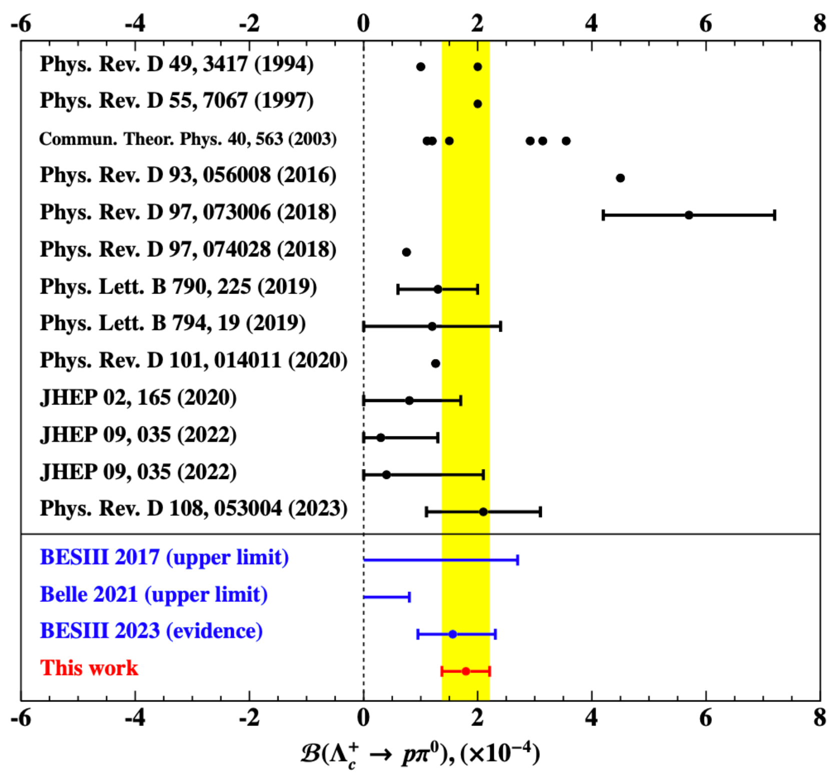


- **20 times of background suppression with 50% of signal efficiency**
- **validation samples of $\Lambda_c^+ \to pK_S\pi^0$ and $pK_S\eta$**

SCS decays of $\Lambda_c^+ \to p\pi^0$

PRD111, L051101 (2025)

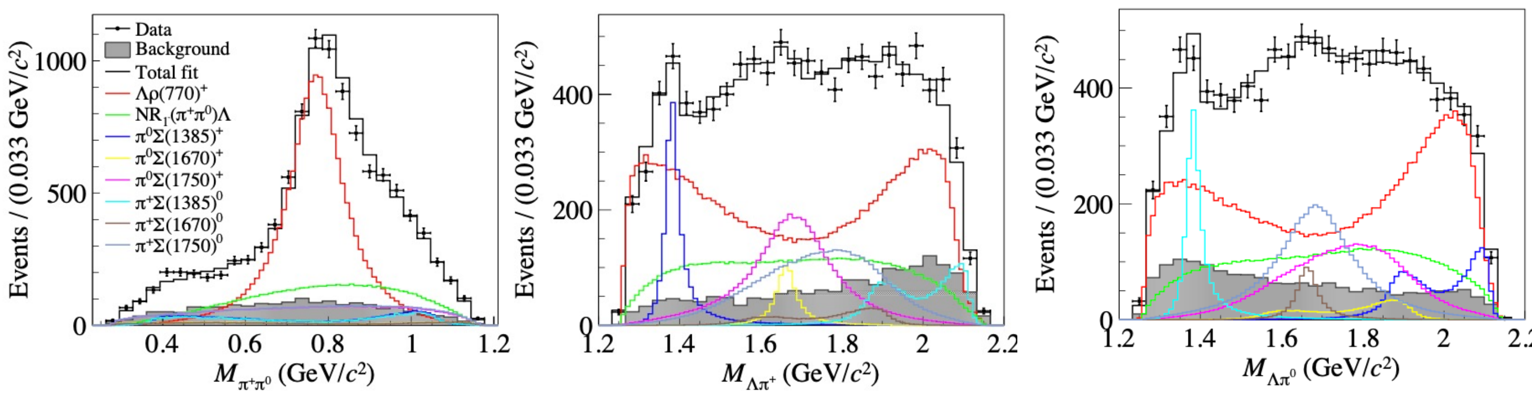
- The ratio is directly measured to be $\frac{B(\Lambda_c^+ \to p\pi^0)}{B(\Lambda_c^+ \to p\eta)} = 0.120 \pm 0.026 \pm 0.007$
- The branching fraction is obtained to be $B(\Lambda_c^+ \to p\pi^0) = (1.79 \pm 0.39 \pm 0.11 \pm 0.08) \times 10^{-4}$, by adopting the average value of $B(\Lambda_c^+ \to p\eta)$ from BESIII and BELLE.
- Agree with previous BESIII measurements and exceeds the upper limit set by BELLE



Amplitude analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP12, 033 (2022)

- First Amplitude analysis of charmed baryon multi-hadronic decays
- Based on **TF-PWA** package: ***https://gitlab.com/jiangyi15/tf-pwa***



	Theoretical calculation		This work	PDG
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14, 15]	4.06 ± 0.52	< 6
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	5.86 ± 0.80	—
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	6.47 ± 0.96	—
$\alpha_{\Lambda\rho(770)^+}$	-0.27 ± 0.04 [13]	-0.32 [14, 15]	-0.763 ± 0.066	—
$\alpha_{\Sigma(1385)^+\pi^0}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.917 ± 0.083	—
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.79 ± 0.11	—

Many first measurements of intermediate states!

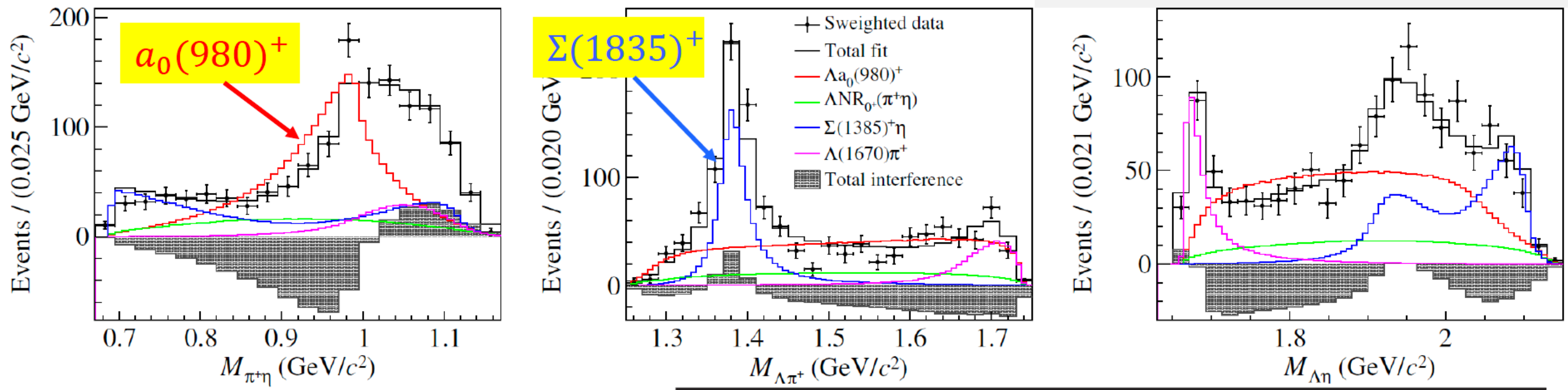
Observation $a_0(980)^+$ in $\Lambda_c^+ \to \Lambda\pi^+\eta$

BESIII

$6.1\ \mathrm{fb}^{-1}@E_{cm} = 4.600 - 4.843\mathrm{GeV}$, PRL 134, 021901(2025)

Observation of $\Lambda_c^+ \to \Lambda a_0(980)^+$

1312 ± 45 signal events with 80% purity



$$\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\eta) = (1.94 \pm 0.07_{stat} \pm 0.11_{syst})\%$$

Process	FF (%)	significance	decay asymmetry α
$\Lambda a_0(980)^+$	$54.0 \pm 8.4 \pm 2.6$	13.1σ	$-0.91^{+0.18}_{-0.09} \pm 0.08$
$\Sigma(1385)^+\eta$	$30.4 \pm 2.6 \pm 0.7$	22.5σ	$-0.61 \pm 0.15 \pm 0.04$
$\Lambda(1670)\pi^+$	$14.1 \pm 2.8 \pm 1.2$	11.7σ	$0.21 \pm 0.27 \pm 0.33$
ΛNR_{0^+}	15.4 ± 5.3	6.7σ	···

$$\mathcal{B}(\Lambda_c^+ \to \Lambda a_0(980)^+, a_0(980)^+ \to \pi^+\eta) = (1.05 \pm 0.16_{stat} \pm 0.05_{syst} \pm 0.07_{ext})\%$$

$\to$ $\mathcal{B}(\Lambda_c^+ \to \Lambda a_0(980)^+) = (1.23 \pm 0.21)\%$ Larger than theoretical calculations by 1-2 orders.

$\Lambda(1670)$ decay rates

Comparing the fraction of the $\Lambda(1670)$ in $\Lambda_c^+ \to \Lambda\pi^+\eta$ and that in $\Lambda_c^+ \to pK^-\pi^+$:

$$\mathcal{B}(\Lambda_c^+ \to \Lambda(1670)\pi^+, \Lambda(1670) \to \Lambda\eta) = (2.74 \pm 0.62)\times 10^{-3} \text{ [BESIII2025]}$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda(1670)\pi^+,\ \Lambda(1670) \to pK^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.18 \pm 0.33)\% \text{ [LHCb 2023]}$$

$$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.24 \pm 0.28)\% \text{ [PDG2024]}$$

We have $$\frac{\mathcal{B}(\Lambda(1670) \to pK^-)}{\mathcal{B}(\Lambda(1670) \to \Lambda\eta)} = (26.9 \pm 9.7)\%$$

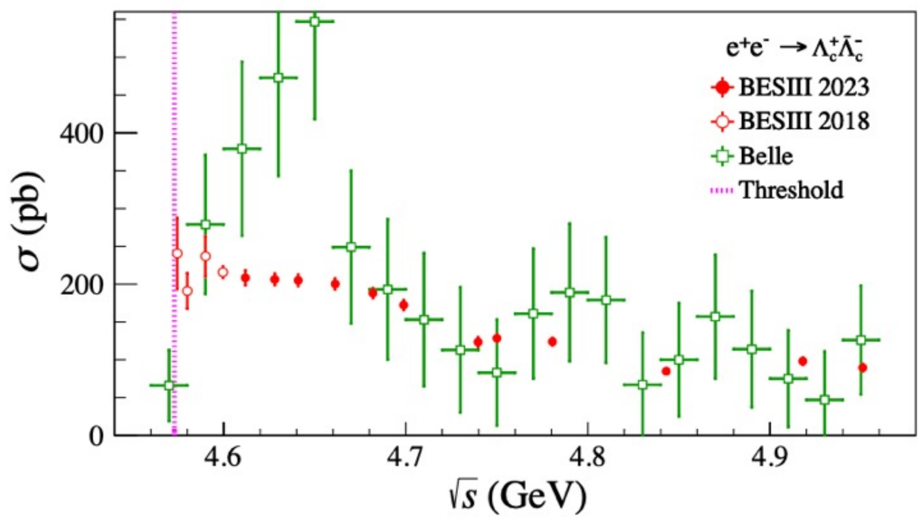
$\Lambda(1670)$ **DECAY MODES**

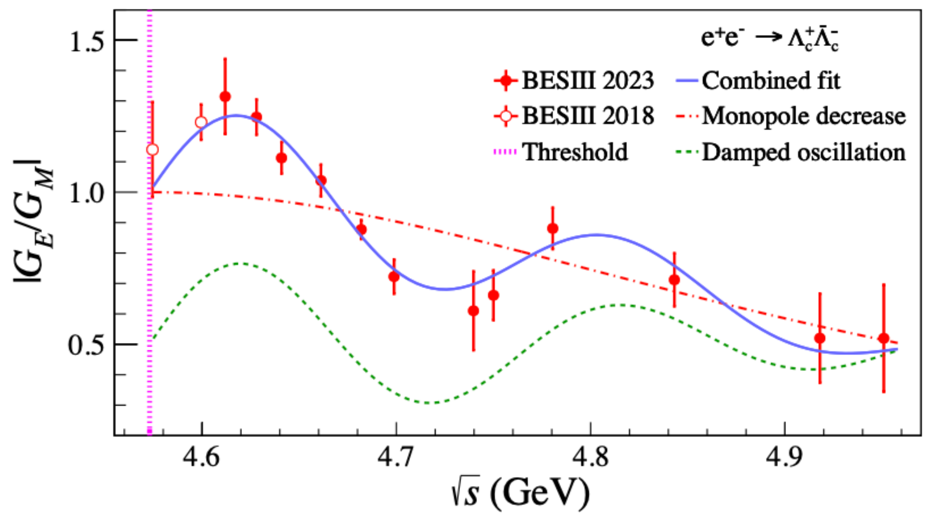
Mode		Fraction (Γ_i / Γ)
Γ_1	$N\bar{K}$	20–30%
Γ_2	$\Sigma\pi$	25–55%
Γ_3	$\Lambda\eta$	10–25%

The rate of $N\bar{K}$ from the previous measurement seems too large!

Cross sections of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$

PRL131, 191901 (2023)



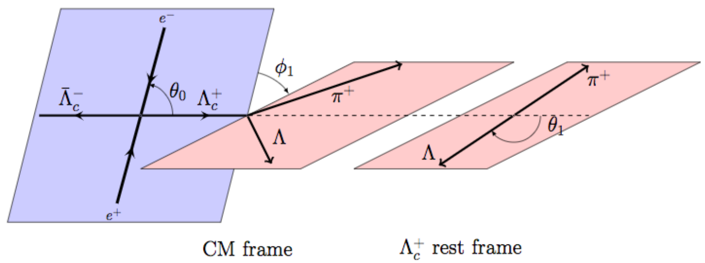


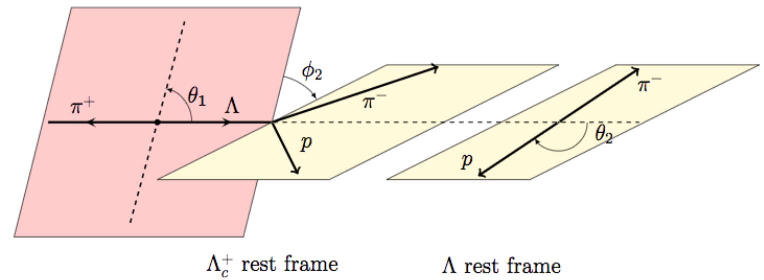
- Negate the $Y(4630)$ in decaying into $\Lambda_c^+\Lambda_c^-$ reported by BELLE
- Energy-dependence of $|G_E/G_M|$ reveals an oscillation feature, which may imply a non-trivial structure of the lightest charmed baryon.

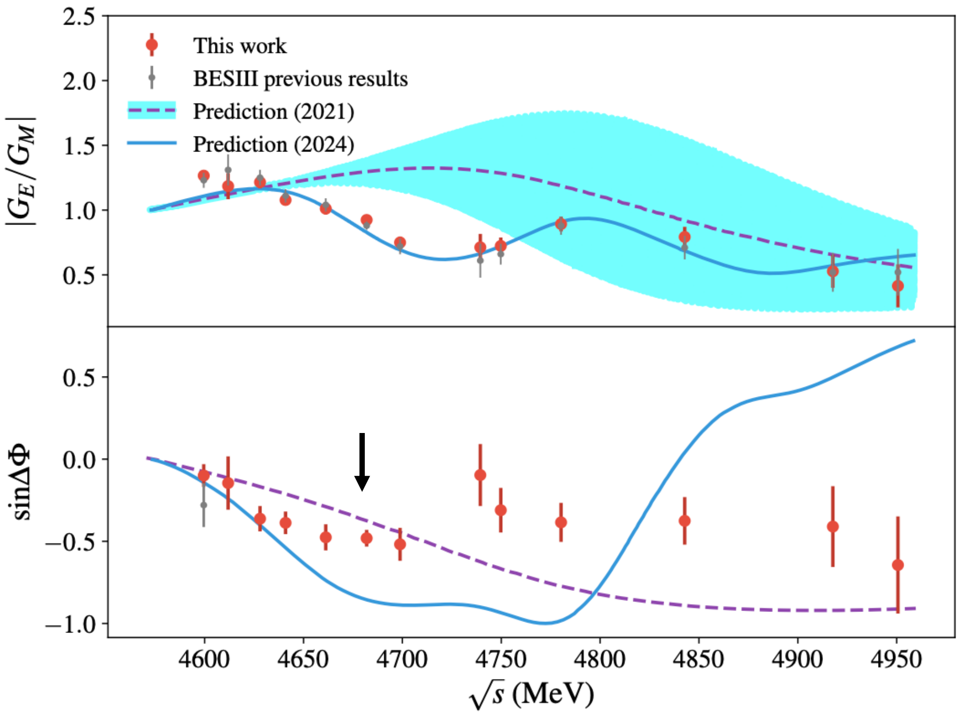
Observation of transverse polarization of the Λ_c^+

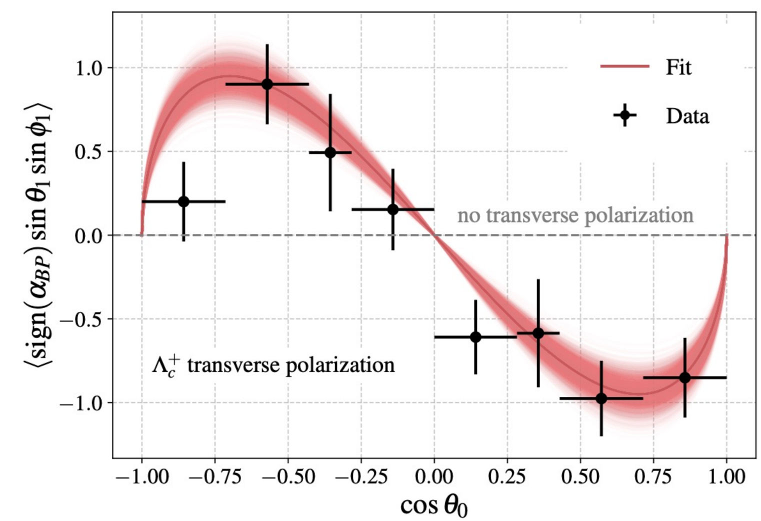
arXiv:2508.11400

Joint angular analyses of the cascade decays of $\Lambda_c \to pK_s, \Lambda\pi^+, \Sigma^+\pi^0$ and $\Sigma^0\pi^+$ and amplitude analysis of $\Lambda_c \to pK^-\pi^+$







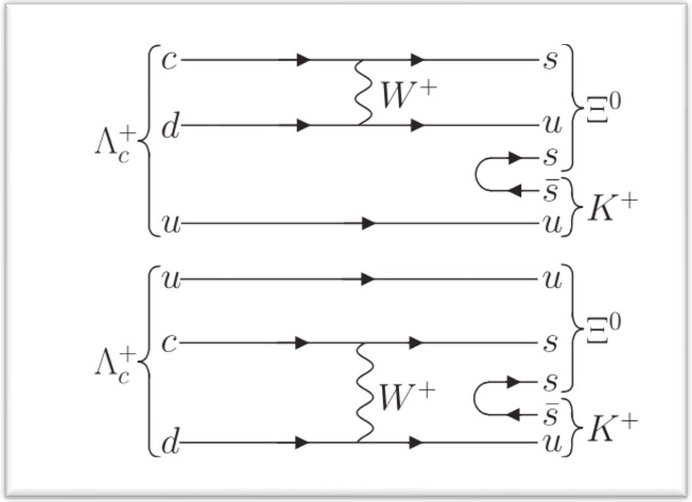


Decay asymmetry in W-exchange-only process $\Lambda_c^+ \to \Xi^0 K^+$

- Previous theoretical calculation on the BF lower than exp. measurement, which all predicted zero decay asymmetry
- BESIII confirmed the exp. result of BF in 2018 [PLB 783, 200 (2018)]
- In theory, BF is enhanced by enhancing the decay asymmetry close to 1

$$\alpha_{\Xi^0 K^+} = 2\mathrm{Re}(s^* p)/(|s|^2 + |p|^2),$$

$$\delta_p - \delta_s = \arctan\left(\sqrt{1-\alpha^2_{\Xi^0 K^+}} \sin\Delta_{\Xi^0 K^+} / \alpha_{\Xi^0 K^+}\right)$$



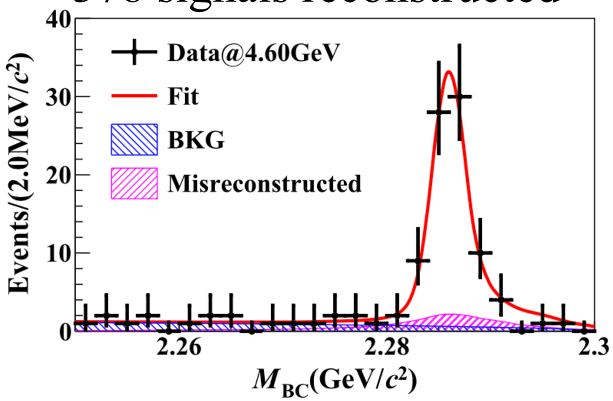
Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ $(\times 10^{-3})$	$\alpha_{\Xi^0 K^+}$	$\lvert A\rvert$ $(\times 10^{-2} G_F\ \mathrm{GeV}^2)$	$\lvert B\rvert$ $(\times 10^{-2} G_F\ \mathrm{GeV}^2)$	$\delta_p - \delta_s$ (rad)
Körner (1992), CCQM [7]	2.6	0	...	...	...
Xu (1992), Pole [8]	1.0	0	0	7.94	...
Źencaykowski (1994), Pole [9]	3.6	0	...	...	...
Ivanov (1998), CCQM [10]	3.1	0	...	...	...
Sharma (1999), CA [11]	1.3	0	...	...	...
Geng (2019), SU(3) [12]	5.7 ± 0.9	$0.94^{+0.06}_{-0.11}$	2.7 ± 0.6	16.1 ± 2.6	...
Zou (2020), CA [6]	7.1	0.90	4.48	12.10	...
Zhong (2022), SU(3)[a] [13]	$3.8^{+0.4}_{-0.5}$	$0.91^{+0.03}_{-0.04}$	3.2 ± 0.2	$8.7^{+0.6}_{-0.8}$	...
Zhong (2022), SU(3)[b] [13]	$5.0^{+0.6}_{-0.9}$	0.99 ± 0.01	$3.3^{+0.5}_{-0.7}$	$12.3^{+1.2}_{-1.8}$	...
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	...	...	...	...
PDG fit (2022) [2]	5.5 ± 0.7	...	...	...	...

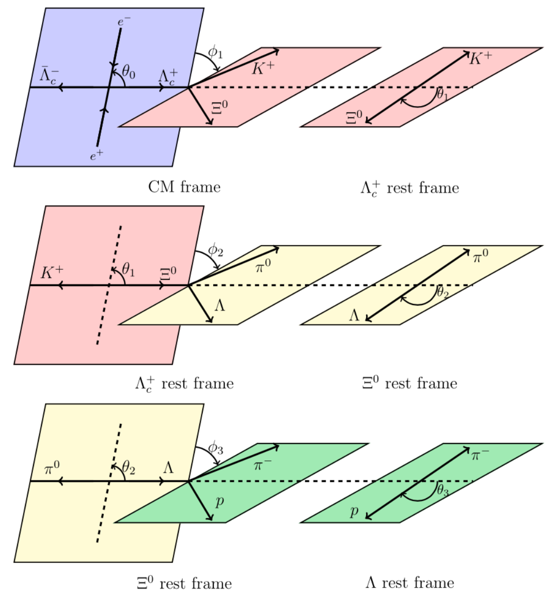
Decay asymmetry in W-exchange-only process $\Lambda_c^+ \to \Xi^0 K^+$

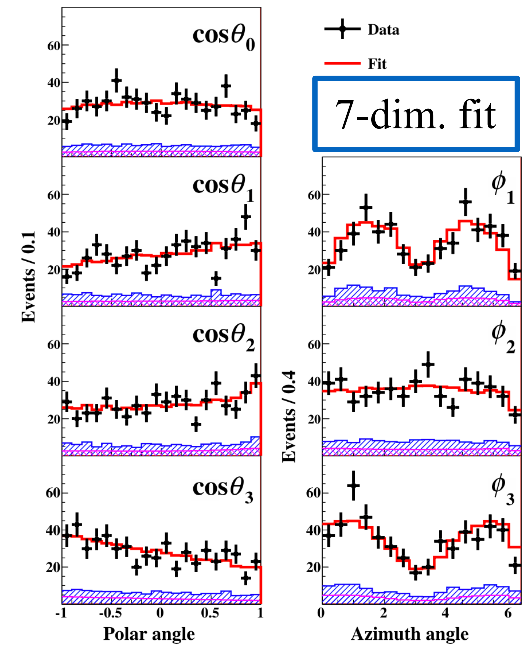
three-level cascade decay $\Lambda_c^+ \to \Xi^0 K^+, \Xi^0 \to \Lambda\pi^0, \Lambda \to p\pi^-$

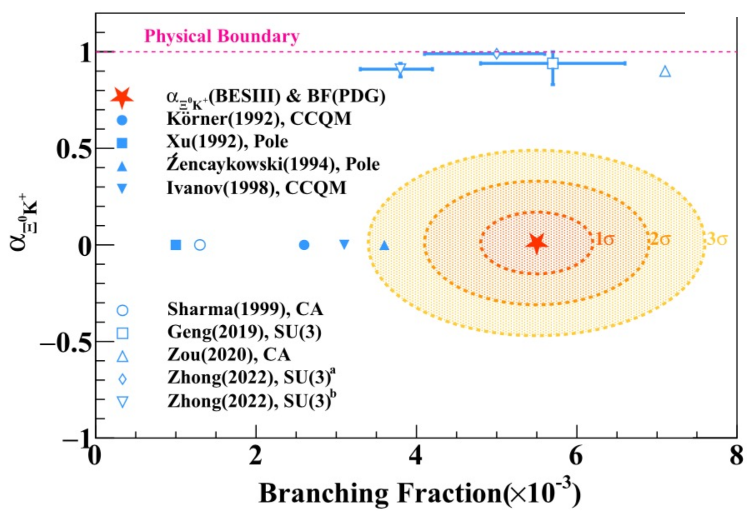
PRL132, 031801(2024)

~378 signals reconstructed









- First determination of decay asymmetry $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16 \pm 0.03$, consistent with zero
- No theoretical model explains the current results
- First determination on phase difference $\delta_p - \delta_s$, with two solutions of $\pi/2$ and $-\pi/2$

Λ_c^+ decay asymmetries

Predictions and measurements	$\alpha_{\Lambda_c^+}^{pK_S^0}$	$\alpha_{\Lambda_c^+}^{\Lambda\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^0\pi^+}$	$\alpha_{\Lambda_c^+}^{\Sigma^+\pi^0}$	$\alpha_{\Lambda_c^+}^{\Xi^0K^+}$
CLEO(1990) [1]	-	$-1.0^{+0.4}_{-0.1}$	-	-	-
ARGUS(1992) [2]	-	-0.96 ± 0.42	-	-	-
Körner(1992), CCQM [3]					0
Xu(1992), Pole [4]					0
Cheng, Tseng(1992), Pole [5]					-
Cheng, Tseng(1993), Pole [6]					-
Żencaykowski(1994), Pole [7]					0
Żencaykowski(1994), Pole [8]					0
CLEO(1995) [9]					-
Alakabha Datta(1995), CA [10]					-
Ivanov(1998), CCQM [11]					0
Sharma(1999), CA [12]					0
FOCUS(2006) [13]					-
BESIII(2018) [14]	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.73 \pm 0.17 \pm 0.07$	$-0.57 \pm 0.10 \pm 0.07$	-
Geng(2019), SU(3) [15]	$-0.89^{+0.26}_{-0.11}$	-0.87 ± 0.10	-0.35 ± 0.27	-0.35 ± 0.27	$0.94^{+0.06}_{-0.11}$
Zou(2020), CA [16]	-0.75	-0.93	-0.76	-0.76	0.90
BELLE(2022) [17, 18]	-	$-0.755 \pm 0.005 \pm 0.003$	$-0.463 \pm 0.016 \pm 0.008$	$-0.48 \pm 0.02 \pm 0.02$	-
Zhong(2022), SU(3)[a] [19]	-0.57 ± 0.21	-0.75 ± 0.01	-0.47 ± 0.03	-0.47 ± 0.03	$0.91^{+0.03}_{-0.04}$
Zhong(2022), SU(3)[b] [19]	-0.29 ± 0.24	-0.75 ± 0.01	-0.47 ± 0.03	-0.47 ± 0.03	0.99 ± 0.01
Liu(2023), Pole [20]	-0.81 ± 0.05	-0.75 ± 0.01	-0.47 ± 0.01	-0.45 ± 0.04	0.95 ± 0.02
Liu(2023), LP [20]	-0.68 ± 0.01	-0.75 ± 0.01	-0.47 ± 0.01	-0.45 ± 0.04	0.92
BESIII(2023) [21]	-	-	-	-	0.01 ± 0.16
Geng(2023), SU(3) [22]	-0.40 ± 0.49	-0.75 ± 0.01	-0.47 ± 0.02	-0.47 ± 0.02	-0.15 ± 0.14
Zhong(2024), TDA [23]	0.01 ± 0.24	-0.76 ± 0.01	-0.48 ± 0.02	-0.48 ± 0.02	-0.16 ± 0.13
Zhong(2024), IRA [23]	0.03 ± 0.24	-0.76 ± 0.01	-0.48 ± 0.02	-0.48 ± 0.02	-0.19 ± 0.12
PDG(for now) [24]	0.20 ± 0.50 (only BESIII)	-0.84 ± 0.09	-0.73 ± 0.18 (only BESIII)	-0.55 ± 0.11	-

Parameter	$\Lambda_c^+ \to pK_S^0$	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Sigma^0\pi^+$	$\Lambda_c^+ \to \Sigma^+\pi^0$
$\langle\alpha_{BP}\rangle$	$-0.918^{+0.133}_{-0.082} \pm 0.031$	$-0.790 \pm 0.032 \pm 0.009$	$-0.502 \pm 0.080 \pm 0.009$	$-0.590 \pm 0.049 \pm 0.022$
$\langle\Delta_{BP}\rangle$	$\cdots$	$0.637 \pm 0.444 \pm 0.014$	$2.190 \pm 0.730 \pm 0.029$	$1.901 \pm 0.603 \pm 0.040$
$\langle\beta_{BP}\rangle$	$\cdots$	$0.365^{+0.173}_{-0.246} \pm 0.010$	$0.704^{+0.143}_{-0.480} \pm 0.015$	$0.764^{+0.051}_{-0.237} \pm 0.018$
$\langle\gamma_{BP}\rangle$	$\cdots$	$0.637^{+0.103}_{-0.202} \pm 0.011$	$-0.502^{+0.591}_{-0.303} \pm 0.021$	$-0.262^{+0.478}_{-0.383} \pm 0.031$
$\delta_p - \delta_s$	$\cdots$	$2.71^{+0.28}_{-0.17} \pm 0.02$	$2.19^{+0.49}_{-0.13} \pm 0.02$	$2.23^{+0.19}_{-0.06} \pm 0.03$
$A_{CP}^{\alpha_{BP}}$	$0.079^{+0.115}_{-0.101} \pm 0.019$	$0.002 \pm 0.047 \pm 0.017$	$0.206^{+0.188}_{-0.156} \pm 0.028$	$-0.086 \pm 0.081 \pm 0.085$
$\tan\phi_{CP}$	$\cdots$	$0.232 \pm 0.242 \pm 0.025$	$0.393 \pm 0.651 \pm 0.042$	$-0.007 \pm 0.474 \pm 0.034$
$\tan\Delta_s$	$\cdots$	$-0.475 \pm 0.242 \pm 0.029$	$-1.411 \pm 0.672 \pm 0.062$	$-1.297 \pm 0.478 \pm 0.068$

BESIII

Strong phase convention in baryon decays

ScienceBulletin 02.030(2025)

$$\alpha = \frac{2\,\mathrm{Re}(S^*P)}{|S|^2+|P|^2},\quad \beta = \frac{2\,\mathrm{Im}(S^*P)}{|S|^2+|P|^2},\quad \gamma = \frac{|S|^2-|P|^2}{|S|^2+|P|^2}$$

$$\delta_P - \delta_S = 2\arctan\frac{\beta\times sign}{\sqrt{\alpha^2+\beta^2}+\alpha\times sign},$$

$$\alpha_1 = \frac{2|S||P|\cos(\delta_P-\delta_S)}{|S|^2+|P|^2},\quad \beta_1 = \frac{2|S||P|\sin(\delta_P-\delta_S)}{|S|^2+|P|^2}.$$

$$S_1 = |S|e^{i\delta_S},\qquad P_1 = |P|e^{i\delta_P},$$

$$\alpha_2 = \frac{2\widetilde{S}\widetilde{P}\cos(\delta_P-\delta_S)}{|\widetilde{S}|^2+|\widetilde{P}|^2},\ \beta_2 = \frac{2\widetilde{S}\widetilde{P}\sin(\delta_P-\delta_S)}{|\widetilde{S}|^2+|\widetilde{P}|^2},$$

$$S_2 = \widetilde{S}e^{i\delta_S},\ P_2 = \widetilde{P}e^{i\delta_P},$$

$$\alpha_3 = \sin(2\zeta)\cos(\delta_P-\delta_S),\ \beta_3 = \sin(2\zeta)\sin(\delta_P-\delta_S).$$

$$S_3 = |\mathcal{A}|\sin\zeta\, e^{i\delta_S},\ P_3 = |\mathcal{A}|\cos\zeta\, e^{i\delta_P}.$$

Table 1
Summary of experimental data on the parameters α, β, and ϕ and the phase shift, $\delta_P-\delta_S$, in various two-body nonleptonic decays of the Λ and Ξ hyperons and singly charmed baryon Λ_c^+.

Experiment	Process	α or $\langle\alpha\rangle$	β or $\langle\beta\rangle$	ϕ or $\langle\phi\rangle$ (rad)	$\delta_P-\delta_S$ (rad)	Value of *sign*	$\delta_P-\delta_S$ (rad) Eq. (10) with *sign*=1	Eq. (10) with *sign*=−1
Λ from π^-p (1963) [14]	$\Lambda\to p\pi^-$	0.62 ± 0.07	-0.18 ± 0.24	...	-0.26 ± 0.35[a]	Unknown	-0.28 ± 0.36	2.86 ± 0.36
Λ from π^-p (1967) [15]		0.645 ± 0.017	-0.103 ± 0.065	-0.14 ± 0.10	-0.16 ± 0.10[a]	Unknown	-0.16 ± 0.10	2.98 ± 0.10
E756 (2003) [18]	$\Xi^-\to\Lambda\pi^-$	-0.458 ± 0.012	-0.03 ± 0.04	-0.03 ± 0.05	0.06 ± 0.09	$+1$	-3.08 ± 0.09	0.06 ± 0.09
HyperCP (2004) [19]		-0.458 ± 0.012	-0.037 ± 0.015	-0.041 ± 0.016	0.080 ± 0.032	Unknown	-3.062 ± 0.031	0.079 ± 0.031
BESIII (2022) [20]		-0.373 ± 0.006	Positive	0.016 ± 0.016	-0.040 ± 0.037	Unknown	3.102 ± 0.036	-0.040 ± 0.036
BESIII (2022) [21]		-0.350 ± 0.018	Positive	0.073 ± 0.052	-0.20 ± 0.13	Unknown	2.95 ± 0.13	-0.19 ± 0.13
BESIII (2024) [22]		-0.371 ± 0.004	Negative	-0.013 ± 0.008	0.033 ± 0.023	Unknown	-3.109 ± 0.025	0.033 ± 0.025
BESIII (2023) [23]	$\Xi^0\to\Lambda\pi^0$	-0.377 ± 0.003	Positive	0.005 ± 0.007	-0.013 ± 0.017	Unknown	3.129 ± 0.017	-0.012 ± 0.017
LHCb (2024) [24]	$\Lambda_c^+\to\Lambda\pi^+$	-0.785 ± 0.007	0.378 ± 0.015	0.656 ± 0.027	2.693 ± 0.017	Unknown	2.693 ± 0.015	-0.449 ± 0.015
LHCb (2024) [24]	$\Lambda_c^+\to\Lambda K^+$	-0.516 ± 0.046	0.33 ± 0.08	2.75 ± 0.11	2.57 ± 0.19	Unknown	2.58 ± 0.12	-0.56 ± 0.12
BESIII (2024) [13]	$\Lambda_c^+\to\Xi^0K^+$	0.01 ± 0.16	-0.64 ± 0.70	3.84 ± 0.90	$-1.55(1.59)\pm0.25$[b]	$+1$	$-1.55(1.59)\pm0.25$	$1.59(-1.55)\pm0.25$

Determination on the phase differences

- Based on the angular fit, the phase angle $\Delta_{\Xi^0 K^+} = (3.84 \pm 0.90 \pm 0.17)$ rad

$$\beta_{\Xi^0 K^+} = \sqrt{1-(\alpha_{\Xi^0 K^+})^2}\sin\Delta_{\Xi^0 K^+},$$
$$\gamma_{\Xi^0 K^+} = \sqrt{1-(\alpha_{\Xi^0 K^+})^2}\cos\Delta_{\Xi^0 K^+}.$$

$$\beta_{\Xi^0 K^+} = -0.64 \pm 0.69 \pm 0.13$$
$$\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58 \pm 0.11$$

- First determination on phase difference $\delta_p - \delta_s$, with two solutions of $\pi/2$ and $-\pi/2$

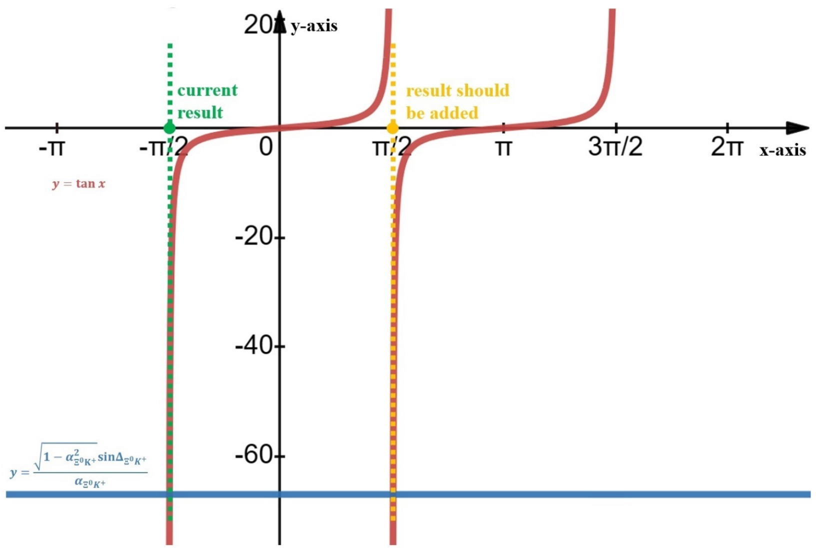
$$\Gamma_{\Xi^0 K^+} = \frac{\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)}{\tau_{\Lambda_c^+}} = \frac{|\vec{p}_c|}{8\pi}\left[\frac{(m_{\Lambda_c^+}+m_{\Xi^0})^2 - m_{K^+}^2}{m_{\Lambda_c^+}^2}|A|^2 + \frac{(m_{\Lambda_c^+}-m_{\Xi^0})^2 - m_{K^+}^2}{m_{\Lambda_c^+}^2}|B|^2\right],$$

$$\alpha_{\Xi^0 K^+} = \frac{2\kappa|A||B|\cos(\delta_p-\delta_s)}{|A|^2+\kappa^2|B|^2},$$

$$\Delta_{\Xi^0 K^+} = \arctan\frac{2\kappa|A||B|\sin(\delta_p-\delta_s)}{|A|^2-\kappa^2|B|^2}$$

$$\delta_p - \delta_s = \arctan\left(\sqrt{1-\alpha_{\Xi^0 K^+}^2}\sin\Delta_{\Xi^0 K^+}/\alpha_{\Xi^0 K^+}\right)$$

1st sol.: $(-1.55 \pm 0.25 \pm 0.05)$ rad
2nd sol.: $(1.59 \pm 0.25 \pm 0.05)$ rad



Λ_c^+ decay asymmetries

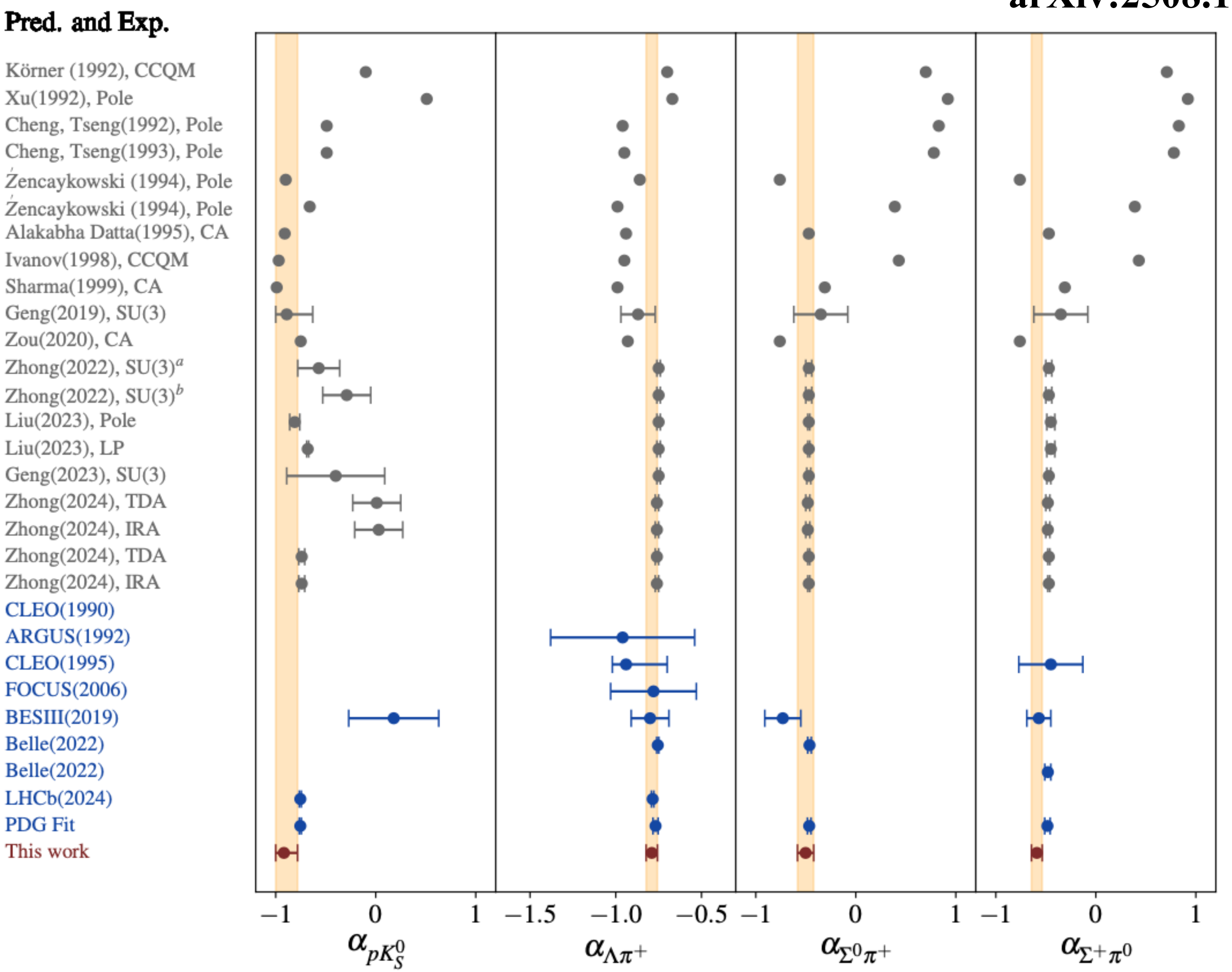
Table 4. The determined polarization parameters of various Λ_c^+ decay modes.

Mode	α	Experiment	Mode	α	Experiment
Nucleon-involved			$\Lambda_c^+ \to \Lambda(1600)\pi^+$	0.2 ± 0.5	LHCb(2023)[86]
$\Lambda_c^+ \to pK_S^0$	0.18 ± 0.45	BESIII(2019)[153]	$\Lambda_c^+ \to \Lambda(1670)\pi^+$	0.82 ± 0.08	LHCb(2023)[86]
	-0.75 ± 0.10	LHCb(2024)[154]		0.21 ± 0.43	BESIII(2025)[148]
$\Lambda_c^+ \to p\bar{K}_0^*(700)^0$	-0.1 ± 0.7	LHCb(2023)[86]	$\Lambda_c^+ \to \Lambda(1690)\pi^+$	0.958 ± 0.034	LHCb(2023)[86]
$\Lambda_c^+ \to p\bar{K}_0^*(892)^0$	0.87 ± 0.03	LHCb(2023)[86]	$\Lambda_c^+ \to \Lambda(2000)\pi^+$	-0.57 ± 0.19	LHCb(2023)[86]
$\Lambda_c^+ \to p\bar{K}_0^*(1430)^0$	0.34 ± 0.14	LHCb(2023)[86]	**Σ-involved**		
$\Lambda_c^+ \to \Delta(1232)^{++}K^-$	0.55 ± 0.04	LHCb(2023)[86]	$\Lambda_c^+ \to \Sigma^+\pi^0$	-0.57 ± 0.12	BESIII(2019)[153]
$\Lambda_c^+ \to \Delta(1600)^{++}K^-$	-0.50 ± 0.18	LHCb(2023)[86]		-0.48 ± 0.03	Belle(2023)[98]
$\Lambda_c^+ \to \Delta(1700)^{++}K^-$	0.22 ± 0.08	LHCb(2023)[86]	$\Lambda_c^+ \to \Sigma^+\eta$	-0.99 ± 0.06	Belle(2023)[98]
Λ-involved			$\Lambda_c^+ \to \Sigma^+\eta'$	-0.46 ± 0.07	Belle(2023)[98]
$\Lambda_c^+ \to \Lambda\pi^+$	-0.80 ± 0.11	BESIII(2019)[153]	$\Lambda_c^+ \to \Sigma^0\pi^+$	-0.73 ± 0.18	BESIII(2019)[153]
	-0.755 ± 0.006	Belle(2023)[132]		-0.46 ± 0.02	Belle(2023)[132]
	-0.785 ± 0.007	LHCb(2024)[154]	$\Lambda_c^+ \to \Sigma(1385)^+\pi^0$	-0.917 ± 0.089	BESIII(2022)[93]
$\Lambda_c^+ \to \Lambda K^+$	-0.59 ± 0.05	Belle(2023)[132]	$\Lambda_c^+ \to \Sigma(1385)^+\eta$	-0.61 ± 0.16	BESIII(2025)[148]
	-0.52 ± 0.05	LHCb(2024)[154]	$\Lambda_c^+ \to \Sigma(1385)^0\pi^+$	-0.789 ± 0.113	BESIII(2022)[93]
$\Lambda_c^+ \to \Lambda\rho(770)^+$	-0.763 ± 0.070	BESIII(2022)[93]	$\Lambda_c^+ \to \Sigma^0K^+$	-0.54 ± 0.20	Belle(2023)[132]
$\Lambda_c^+ \to \Lambda a(980)^+$	$-0.91^{+0.20}_{-0.12}$	BESIII(2025)[148]	**Ξ-involved**		
$\Lambda_c^+ \to \Lambda(1405)\pi^+$	0.58 ± 0.28	LHCb(2023)[86]	$\Lambda_c^+ \to \Xi^0K^+$	0.01 ± 0.16	BESIII(2024)[155]
$\Lambda_c^+ \to \Lambda(1520)\pi^+$	0.93 ± 0.09	LHCb(2023)[86]			

Mode	β	Experiment	Mode	γ	Experiment
$\Lambda_c^+ \to \Lambda\pi^+$	$0.06^{+0.58}_{-0.47}$	BESIII(2019)[153]	$\Lambda_c^+ \to \Lambda\pi^+$	$-0.60^{+0.97}_{-0.06}$	BESIII(2019)[153]
	0.378 ± 0.015	LHCb(2024)[154]		0.491 ± 0.012	LHCb(2024)[154]
$\Lambda_c^+ \to \Sigma^0\pi^+$	$0.48^{+0.36}_{-0.58}$	BESIII(2019)[153]	$\Lambda_c^+ \to \Sigma^0\pi^+$	$0.49^{+0.36}_{-0.57}$	BESIII(2019)[153]
$\Lambda_c^+ \to \Sigma^+\pi^0$	$-0.66^{+0.51}_{-0.25}$	BESIII(2019)[153]	$\Lambda_c^+ \to \Sigma^+\pi^0$	$-0.48^{+0.50}_{-0.42}$	BESIII(2019)[153]
$\Lambda_c^+ \to \Xi^0K^+$	-0.64 ± 0.70	BESIII(2024)[155]	$\Lambda_c^+ \to \Xi^0K^+$	-0.77 ± 0.59	BESIII(2024)[155]
$\Lambda_c^+ \to \Lambda K^+$	0.33 ± 0.08	LHCb(2024)[154]	$\Lambda_c^+ \to \Lambda K^+$	-0.799 ± 0.041	LHCb(2024)[154]

New Λ_c^+ decay asymmetry measurement

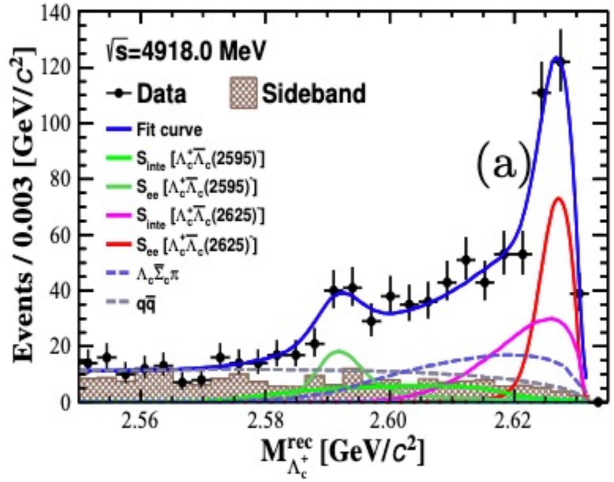
arXiv:2508.11400

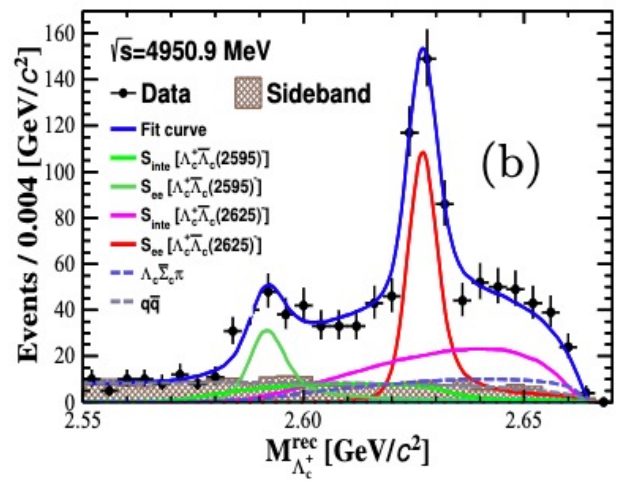


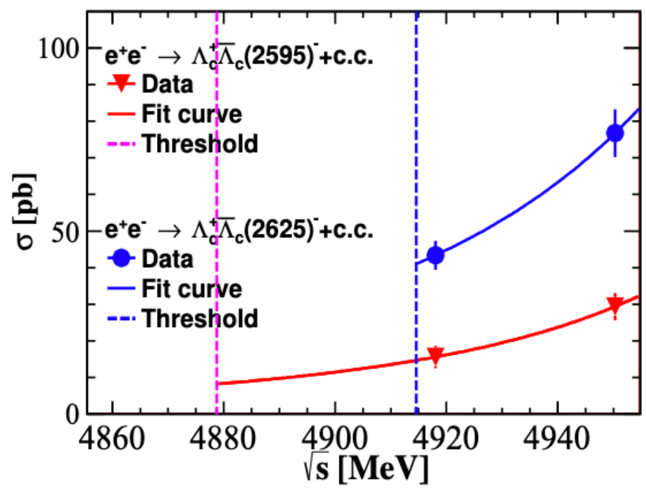
Observation of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2595)^-$ and $\Lambda_c^+\bar{\Lambda}_c(2625)^-$

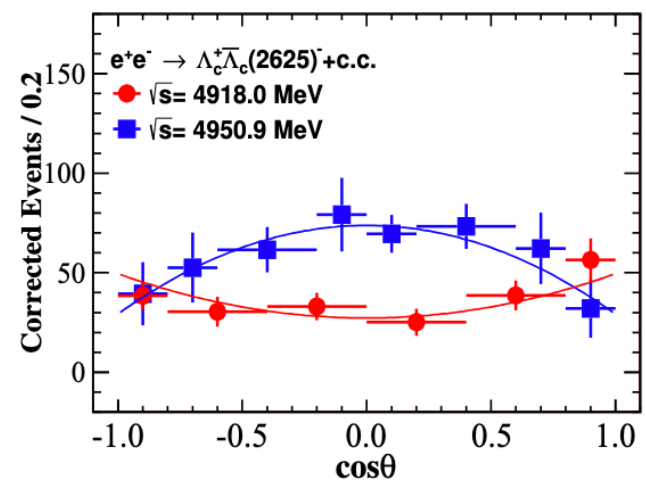
arXiv:2312.08414

Datasets of 208/pb at 4.92 GeV and 159/pb at 4.95 GeV









$$\frac{d\sigma}{d\cos\theta} \propto (1+\cos^2\theta)(|G_E|^2+3|G_M|^2)+\frac{1}{\tau}|G_C|^2\sin^2\theta$$

粲介子物理衰变

Charmed mesons hadronic decays

BESIII

Measurements of the BFs

- → Are important component of heavy-flavor physics program.
- → Probe and calibrate non-perturbative QCD
- → Understand SU(3) flavor symmetry and its breaking effect
- → Test theoretical calculations of BFs and improve theoretical predictions of CP violation

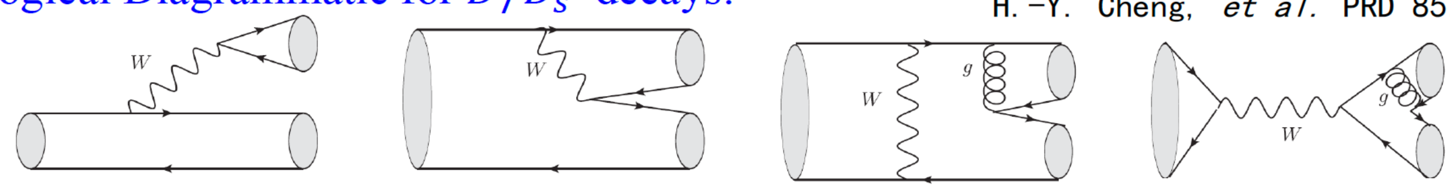
Amplitude analysis of multi-body decays

- → Information of $D \to VP, PP, SP, SV, VV, AP, AV, TP$ ...
- → Light hadron spectroscopy

P: pseudo-scalar
V: vector
S: scalar
A: axial-vector
T: tensor

Topological Diagrammatic for D/D_s^+ decays:

H. -Y. Cheng, *et al.* PRD 85, 034036



Color-allowed tree T | Color-suppressed tree C | W-exchange E | W-annihilation A

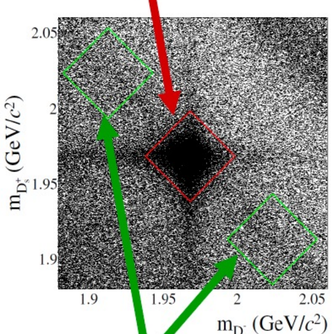
Calculation is not reliable, need exp. input

BF of D_s^+ hadronic decays

$7.33\ \text{fb}^{-1}$ @4.178 – 4.226 GeV, **JHEP05(2024)335**

Global fit to ST and DT yields and obtain:

42965 events in signal region



14728 events in combined sideband

Mode	$\mathcal{B}$ (%)	$\mathcal{A}_{CP}$ (%)
$D_s^+ \to K_S^0 K^+$	$1.502 \pm 0.012 \pm 0.009$	$0.29 \pm 0.50 \pm 0.21$
$D_s^+ \to K^+ K^- \pi^+$	$5.49 \pm 0.04 \pm 0.07$	$0.48 \pm 0.26 \pm 0.24$
$D_s^+ \to K_S^0 K^+ \pi^0$	$1.47 \pm 0.02 \pm 0.02$	$-0.85 \pm 1.97 \pm 0.46$
$D_s^+ \to K_S^0 K_S^0 \pi^+$	$0.73 \pm 0.01 \pm 0.01$	$1.14 \pm 1.58 \pm 0.44$
$D_s^+ \to K^+ K^- \pi^+ \pi^0$	$5.50 \pm 0.05 \pm 0.11$	$-0.66 \pm 0.91 \pm 0.33$
$D_s^+ \to K_S^0 K^+ \pi^+ \pi^-$	$0.93 \pm 0.02 \pm 0.01$	$2.00 \pm 2.37 \pm 0.70$
$D_s^+ \to K_S^0 K^- \pi^+ \pi^+$	$1.56 \pm 0.02 \pm 0.02$	$-0.24 \pm 1.05 \pm 1.07$
$D_s^+ \to \pi^+ \pi^+ \pi^-$	$1.09 \pm 0.01 \pm 0.01$	$-0.88 \pm 1.17 \pm 0.38$
$D_s^+ \to \pi^+ \eta$	$1.69 \pm 0.02 \pm 0.02$	$-0.44 \pm 0.89 \pm 0.19$
$D_s^+ \to \pi^+ \pi^0 \eta$	$9.10 \pm 0.09 \pm 0.15$	$1.05 \pm 1.45 \pm 0.62$
$D_s^+ \to \pi^+ \pi^+ \pi^- \eta$	$3.08 \pm 0.06 \pm 0.05$	$2.42 \pm 2.85 \pm 0.78$
$D_s^+ \to \pi^+ \eta'$	$3.95 \pm 0.04 \pm 0.07$	$-0.59 \pm 0.76 \pm 0.20$
$D_s^+ \to \pi^+ \pi^0 \eta'$	$6.17 \pm 0.12 \pm 0.14$	$-1.60 \pm 2.57 \pm 0.64$
$D_s^+ \to K_S^0 \pi^+ \pi^0$	$0.51 \pm 0.02 \pm 0.01$	$-2.17 \pm 4.65 \pm 1.10$
$D_s^+ \to K^+ \pi^+ \pi^-$	$0.620 \pm 0.009 \pm 0.006$	$1.81 \pm 2.01 \pm 0.45$

Agree with PDG with much improved precision

Multi-body decays based on amplitude models

17 Amplitude analyses published/submitted

$D_s^+ \to K^+ K^- \pi^+$	Phys. Rev. D **104** (2021) 012016
$D_s^+ \to K_S^0 K^+ \pi^0$	Phys. Rev. Lett. **129** (2022) 182001
$D_s^+ \to \pi^+ \pi^+ \pi^-$	Phys. Rev. D **106** (2022) 112006
$D_s^+ \to \pi^+ \pi^+ \pi^- \eta$	Phys. Rev. D **104** (2021) L071101
$D_s^+ \to \pi^+ \pi^0 \eta'$	**JHEP 04** (2022) 058
$D_s^+ \to \pi^+ \pi^0 \pi^0$	**JHEP 01** (2022) 052
$D_s^+ \to K^+ \pi^+ \pi^-$	**JHEP 08** (2022) 196
$D_s^+ \to K^+ \pi^+ \pi^- \pi^0$	**JHEP 09** (2022) 242
$D_s^+ \to K_S^0 K_S^0 \pi^+$	Phys. Rev. D **105** (2022) L051103
$D_s^+ \to K_S^0 K^- \pi^+ \pi^+$	Phys. Rev. D **103** (2021) 092006
$D_s^+ \to K^+ K^- \pi^+ \pi^0$	Phys. Rev. D **104** (2021) 032011
$D_s^+ \to K^+ K^- \pi^+ \pi^+ \pi^-$	**JHEP 07** (2022) 051
$D_s^+ \to K_S^0 \pi^+ \pi^0$	**JHEP 06** (2021) 181
$D_s^+ \to \pi^+ \pi^0 \eta$	Phys. Rev. Lett. **123** (2019) 112001
$D_s^+ \to \pi^+ \pi^+ \pi^- \pi^0$	Phys. Rev. Lett. **134** (2025) 011904
$D_s^+ \to \pi^+ \pi^+ \pi^- \pi^0 \pi^0$	Phys. Rev. Lett. **134** (2025) 201902
$D_s^+ \to K_S^0 K_L^0 \pi^+$	arXiv:2503.11383
$D_s^+ \to \pi^+ \pi^0 \pi^0 \eta$	to be submitted soon

Amplitude analysis of $D_s^+ \to \pi^+\pi^+\pi^-\pi^0$

BESIII

7.33fb^{-1} @ 4.178 – 4.226GeV , PRL 134, 011904 (2025)

1552 candidates with >75% purity

Observation of $D_s^+ \to f_0(980)\rho(770)^+$

(Mainly involves W-external-emission diagram)

$\mathcal{B}(D_s^+ \to \pi^+\pi^+\pi^-\pi^0|_{\text{non}-\eta}) = (2.04 \pm 0.08_{\text{stat.}} \pm 0.05_{\text{syst.}})\%$

$\mathcal{B}(D_s^+ \to \eta\pi^+) = (1.56 \pm 0.09_{\text{stat.}} \pm 0.04_{\text{syst.}})\%$

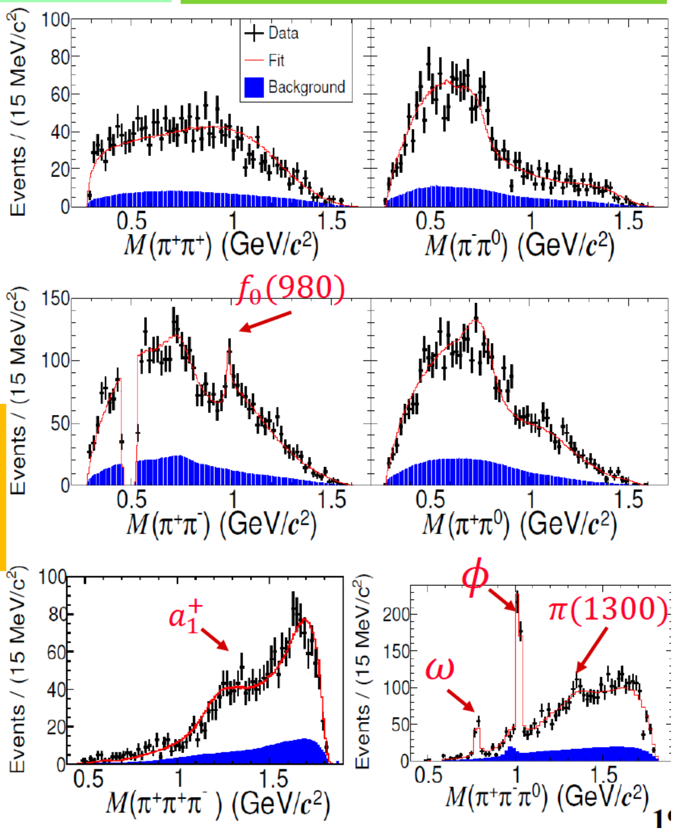
$$\frac{\mathcal{B}(\phi(1020) \to \pi^+\pi^-\pi^0)}{\mathcal{B}(\phi(1020) \to K^+K^-)} = 0.230 \pm 0.014_{\text{stat.}} \pm 0.010_{\text{syst.}}$$

Taking from $D_s^+ \to K^+K^-\pi^+$
BESIII, PRD 104, 012016 (2021)

Deviates from PDG value (0.313±0.010) by >4σ

Component	Phase (rad)	BF (10^{-3})
$f_0(1370)\rho^+$	0.0(fixed)	$5.08 \pm 0.80 \pm 0.43$
$f_0(980)\rho^+$	$3.99 \pm 0.13 \pm 0.07$	$2.57 \pm 0.44 \pm 0.20$
$f_2(1270)\rho^+$	$1.11 \pm 0.10 \pm 0.10$	$1.94 \pm 0.36 \pm 0.12$
$(\rho^+\rho^0)_S$	$1.10 \pm 0.18 \pm 0.10$	$0.71 \pm 0.25 \pm 0.12$
$(\rho(1450)^+\rho^0)_S$	$0.43 \pm 0.18 \pm 0.17$	$0.94 \pm 0.27 \pm 0.16$
$(\rho^+\rho(1450)^0)_P$	$4.58 \pm 0.16 \pm 0.09$	$1.75 \pm 0.27 \pm 0.08$
$\phi((\rho\pi) \to \pi^+\pi^-\pi^0)\pi^+$	$2.90 \pm 0.15 \pm 0.18$	$5.08 \pm 0.32 \pm 0.10$
$\omega((\rho\pi) \to \pi^+\pi^-\pi^0)\pi^+$	$3.22 \pm 0.21 \pm 0.09$	$1.41 \pm 0.17 \pm 0.06$
$a_1^+(\rho^0\pi^+)_S\pi^0$	$3.78 \pm 0.16 \pm 0.12$	$2.55 \pm 0.34 \pm 0.20$
$a_1^0((\rho\pi)_S \to \pi^+\pi^-\pi^0)\pi^+$	$4.82 \pm 0.15 \pm 0.12$	$1.29 \pm 0.39 \pm 0.24$
$\pi(1300)^0((\rho\pi)_P \to \pi^+\pi^-\pi^0)\pi^+$	$2.22 \pm 0.14 \pm 0.08$	$2.39 \pm 0.48 \pm 0.45$

W-annihilation decay
$BF = (1.92 \pm 0.30) \times 10^{-3}$ **(PDG)**

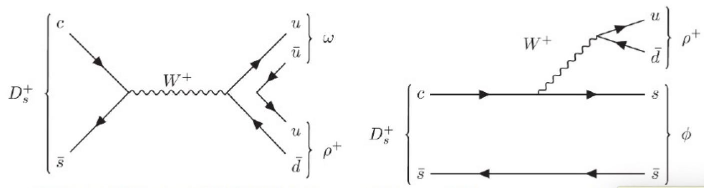


Amplitude analysis of $D_s^+ \to \pi^+\pi^+\pi^-\pi^0\pi^0$

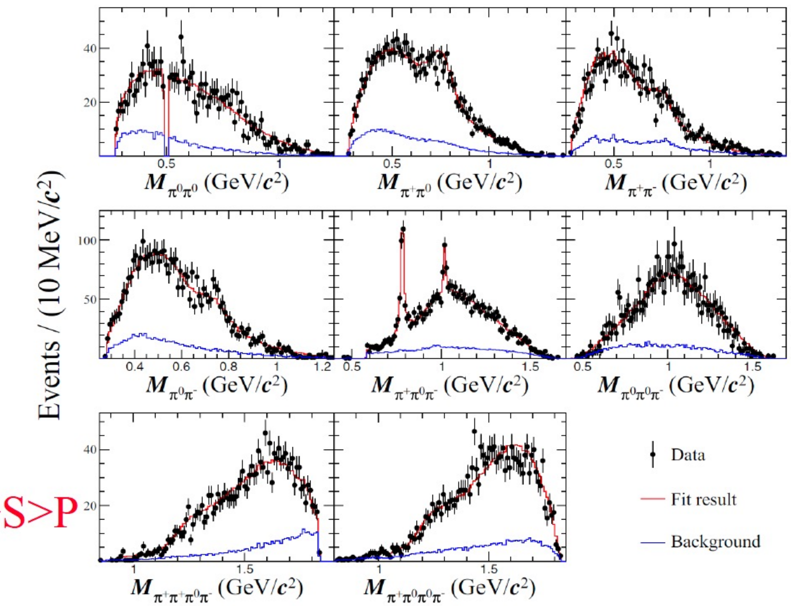
7.33fb^{-1} @ 4.178 – 4.226GeV , PRL 134, 201902 (2025)

1888 candidates with >79% purity

First observation of $D_s^+ \to \omega\rho(770)^+$



Pure W-annihilation   Pure W-external e mailto:1@4.178–4.226GeV



Amplitude	BF (%)
$D_s^+ \to \rho(1450)^+\pi^0,\ \rho(1450)^+ \to \omega\pi^+$	$0.39 \pm 0.04\ ^{+0.03}_{-0.03}$
$D_s^+[S] \to a_1(1260)^0\rho^+,\ a_1(1260)^0[S] \to \rho^+\pi^-$	$0.23 \pm 0.02\ ^{+0.01}_{-0.01}$
$D_s^+[P] \to a_1(1260)^0\rho^+,\ a_1(1260)^0[S] \to \rho^+\pi^-$	$0.50 \pm 0.04\ ^{+0.02}_{-0.02}$
$D_s^+ \to a_1(1260)^0\rho^+,\ a_1(1260)^0 \to \rho^+\pi^-$	$0.50 \pm 0.04\ ^{+0.02}_{-0.02}$
$D_s^+[S] \to a_1(1260)^0\rho^+,\ a_1(1260)^0[S] \to \rho^-\pi^+$	$0.16 \pm 0.02\ ^{+0.01}_{-0.01}$
$D_s^+[P] \to a_1(1260)^0\rho^+,\ a_1(1260)^0[S] \to \rho^-\pi^+$	$0.17 \pm 0.01\ ^{+0.01}_{-0.01}$
$D_s^+ \to a_1(1260)^0\rho^+,\ a_1(1260)^0 \to \rho^-\pi^+$	$0.33 \pm 0.02\ ^{+0.02}_{-0.02}$
$D_s^+[S] \to a_1(1260)^+\rho^0,\ a_1(1260)^+[S] \to \rho^+\pi^0$	$0.41 \pm 0.05\ ^{+0.05}_{-0.05}$
$D_s^+[P] \to a_1(1260)^+\rho^0,\ a_1(1260)^+[S] \to \rho^+\pi^0$	$0.31 \pm 0.04\ ^{+0.02}_{-0.02}$
$D_s^+ \to a_1(1260)^+\rho^0,\ a_1(1260)^+ \to \rho^+\pi^0$	$0.73 \pm 0.07\ ^{+0.07}_{-0.07}$
$D_s^+ \to b_1(1235)^+\pi^0,\ b_1(1235)^+[S] \to \omega\pi^+$	$0.53 \pm 0.05\ ^{+0.03}_{-0.03}$
$D_s^+ \to b_1(1235)^0\pi^+,\ b_1(1235)^0[S] \to \omega\pi^0$	$0.72 \pm 0.06\ ^{+0.05}_{-0.05}$

Polarization puzzle

Amplitude	BF (%)
$D_s^+[S] \to \omega\rho^+$	$0.30 \pm 0.07\ ^{+0.02}_{-0.03}$
$D_s^+[P] \to \omega\rho^+$	$0.25 \pm 0.04\ ^{+0.04}_{-0.04}$
$D_s^+[D] \to \omega\rho^+$	$0.52 \pm 0.07\ ^{+0.04}_{-0.07}$
$D_s^+ \to \omega\rho^+$	$0.99 \pm 0.08\ ^{+0.05}_{-0.07}$
$D_s^+[S] \to \phi\rho^+$	$3.32 \pm 0.29\ ^{+0.19}_{-0.17}$
$D_s^+[P] \to \phi\rho^+$	$0.63 \pm 0.12\ ^{+0.05}_{-0.06}$
$D_s^+ \to \phi\rho^+$	$3.98 \pm 0.33\ ^{+0.21}_{-0.19}$

D>S>P

S>P>D

$$\frac{\mathcal{B}(\phi(1020) \to \pi^+\pi^-\pi^0)}{\mathcal{B}(\phi(1020) \to K^+K^-)} = 0.222 \pm 0.019_{\text{stat}} \pm 0.016_{\text{syst}}$$

Naive prediction: PRL 128,011803

transverse dominates than longitudinal in charm decays

Deviates from PDG value (0.313±0.010) by $>3\sigma$

20

Amplitude analysis of $D_s^+ \to K_S^0 K_L^0 \pi^+$

BESIII

7.33fb^{-1} @ 4.178 – 4.226GeV, arXiv:2503.11383

2310 candidates with >78% purity

Measurement of $\phi \to K_S^0 K_L^0$

$$\mathcal{B}_{D_s^+ \to K_S^0 K_L^0 \pi^+} = (1.86 \pm 0.06_{\rm stat} \pm 0.003_{\rm syst})\%$$

Amplitude	Phase (rad)	BF (%)
$D_s^+ \to \phi\pi^+$	0.0(fixed)	$1.32 \pm 0.05 \pm 0.04$
$D_s^+ \to K_L^0 K^*(892)^+$	$0.68 \pm 0.17 \pm 0.21$	$0.42 \pm 0.03 \pm 0.03$
$D_s^+ \to K_S^0 K^*(892)^+$	$-2.40 \pm 0.18 \pm 0.31$	$0.31 \pm 0.02 \pm 0.02$

$$\frac{\mathcal{B}(\phi(1020) \to K_S^0 K_L^0)}{\mathcal{B}(\phi(1020) \to K^+ K^-)} = 0.597 \pm 0.023_{\rm stat} \pm 0.018_{\rm syst} \pm 0.016_{\rm PDG}$$

Taking from PDG

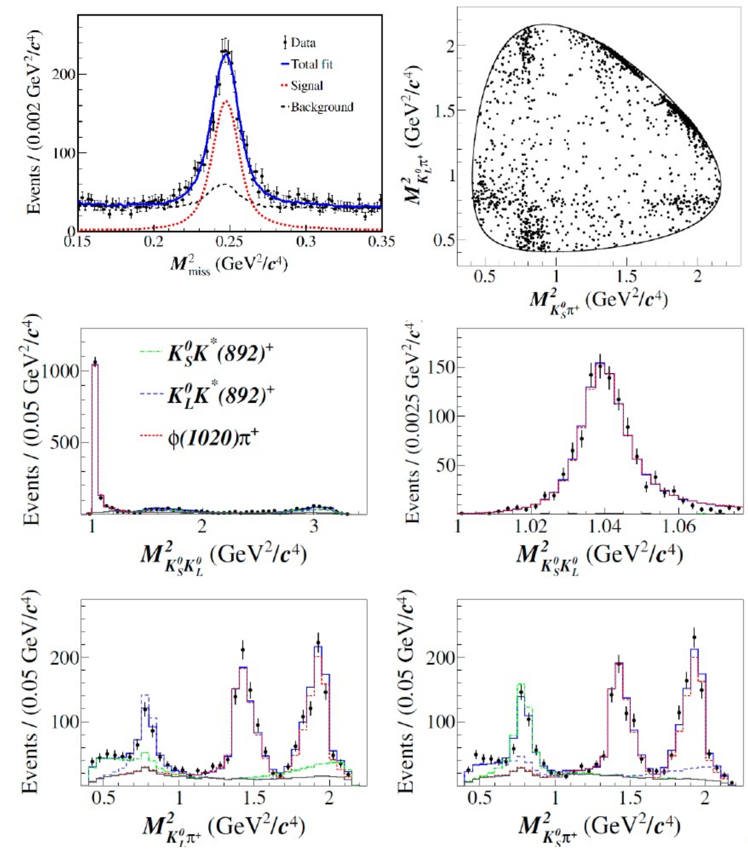
Deviates from PDG value (0.740±0.031) by >3σ

First observation of $K_S^0 - K_L^0$ asymmetry

$$\frac{\mathcal{B}(D_s^+ \to K_S^0 K^*(892)^+) - \mathcal{B}(D_s^+ \to K_L^0 K^*(892)^+)}{\mathcal{B}(D_s^+ \to K_S^0 K^*(892)^+) + \mathcal{B}(D_s^+ \to K_L^0 K^*(892)^+)} = (-13.4 \pm 5.0_{\rm stat} \pm 3.4_{\rm syst})\%$$

Model	DAT(F4)	DAT(F1′)
$D_s^+ \to \bar{K}^0 K^{*+}$	-0.164 ± 0.032	-0.159 ± 0.028

Predictions by H.-Y. Cheng *et al.*, PRD109, 073008（2024）

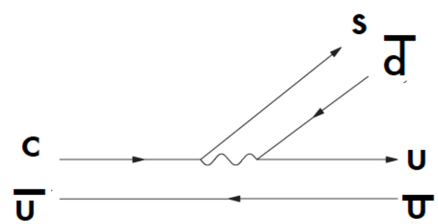


U-spin and Ks-KL asymmetry

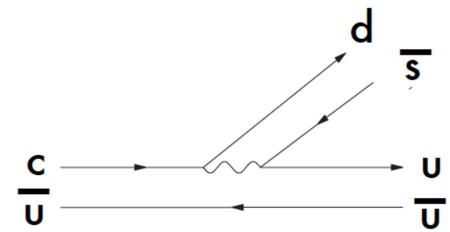
I. Bigi and H. Yamamoto, Physics Letters 349 (1995) 363-366

- $\Gamma(D^o \to K_S\pi^o) \neq \Gamma(D^o \to K_L\pi^o)$
- $A(D^o \to K_{S,L}\pi^o) = A(D \to \bar{K}^o\pi^o) \quad \pm \quad A(D \to K^o\pi^o)$

CF



±



DCS

U-spin* prediction

*U-spin: swap d↔s quarks, important e.g. for extracting γ from $B_S \to KK$, $B_d \to \pi\pi$

- $$\frac{\Gamma\left(D^0 \to K_S\pi^0\right) - \Gamma\left(D^0 \to K_L\pi^0\right)}{\Gamma\left(D^0 \to K_S\pi^0\right) + \Gamma\left(D^0 \to K_L\pi^0\right)} = -2\frac{A_{DCS}}{A_{CF}} = 2\tan^2\theta_C = 0.109$$

CLEO result: $0.108 \pm 0.025 \pm 0.024$ 281/pb at CLEO: PRL **100**, 091801 (2008)

$$\frac{\Gamma\left(D^+ \to K_S\pi^+\right) - \Gamma\left(D^+ \to K_L\pi^+\right)}{\Gamma\left(D^+ \to K_S\pi^+\right) + \Gamma\left(D^+ \to K_L\pi^+\right)} \approx 0.04$$

CLEO result: $0.022 \pm 0.016 \pm 0.018$

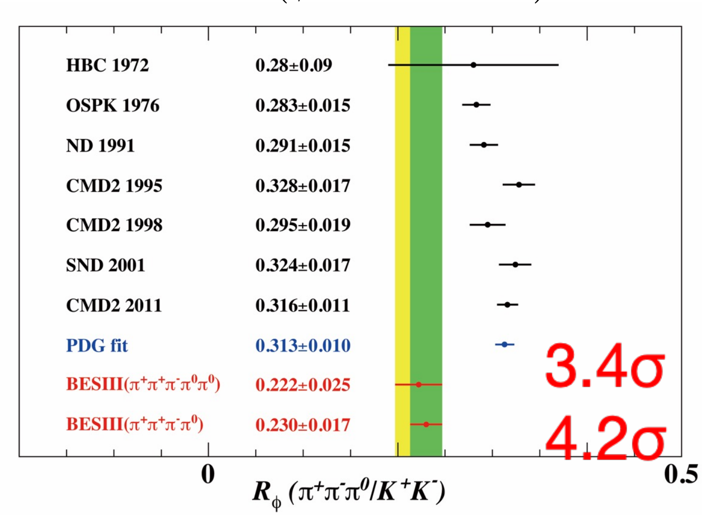
281/pb at CLEO: PRL **100**, 091801 (2008)

D.-N. Gao, Phys. Lett. B **645**, 59 (2007)

Puzzle of ϕ decays in charm

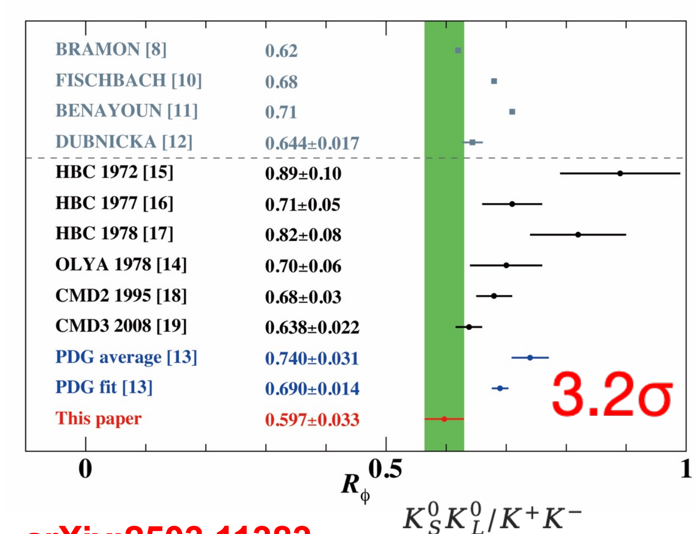
- In $D_s^+ \to \pi^+\pi^+\pi^-\pi^0$, $D_s^+ \to \pi^+\pi^+\pi^-\pi^0\pi^0$ and $K_S^0K_L^0\pi^+$ decays, relative Branching Fraction of ϕ meson deviate from PDG;
- More results are coming. New mechanism?

$$R_\phi = \frac{\mathcal{B}(\phi \to \pi^+\pi^-\pi^0)}{\mathcal{B}(\phi \to K^+K^-)}$$



Phys. Rev. Lett. 134, 011904 (2025)
arXiv:2501.04451

$$R_\phi = \frac{\mathcal{B}(\phi \to K_S K_L)}{\mathcal{B}(\phi \to K^+K^-)}$$



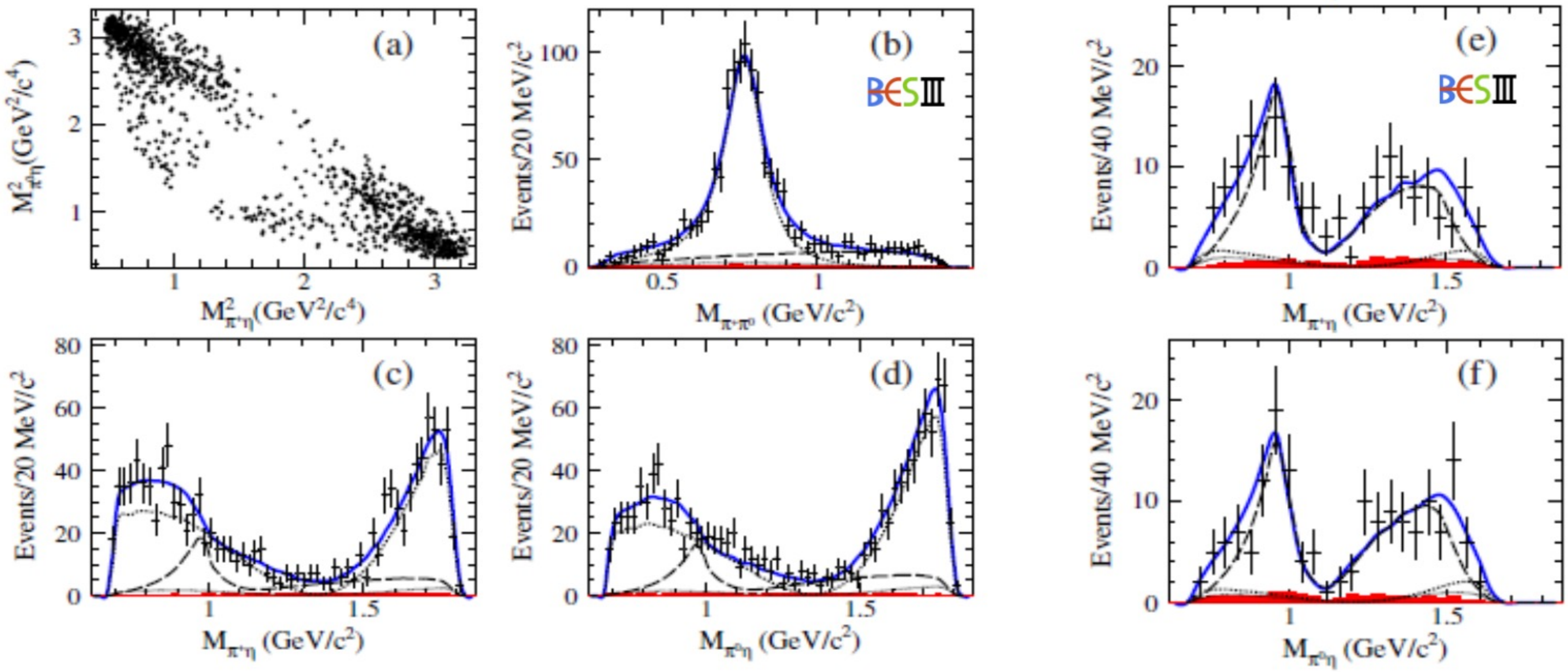
arXiv:2503.11383

Amplitude analysis of $D_s^+ \to \pi^+\pi^0\eta$
- Observation of $D_s^+ \to a_0(980)\pi$

PRL123, 112001 (2019)

$D_s^+ \to \pi^+\pi^0\eta$ Full sample

Sub-sample with $M_{\pi^+\pi^0} > 1.0$ GeV/c^2



Dots with error bar: data; solid: total fit; dotted: $D_s^+ \to \rho^+\eta$; dashed: $D_s^+ \to a_0(980)\pi$ (**with a stat. significance of 16.2σ**).

Branching Fraction Results of $D_s^+ \to \pi^+\pi^0\eta$

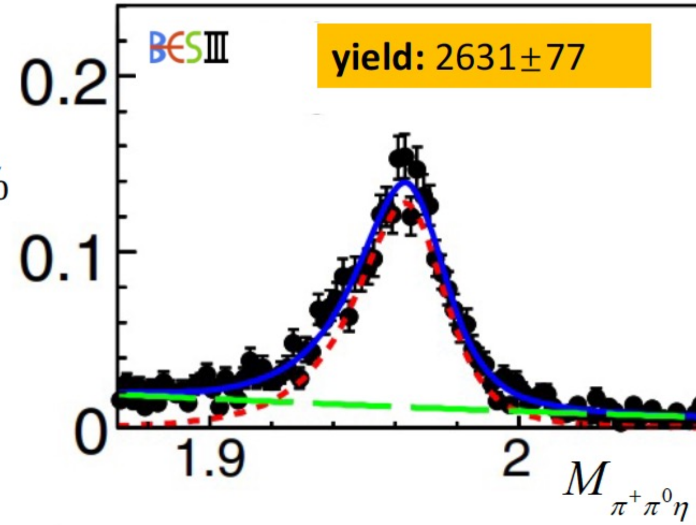
PRL123， 112001 （2019）

Fit to the invariant mass $M_{\pi^+\pi^0\eta}$ to get the yield.

$$\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta) = (9.50 \pm 0.28_{stat.} \pm 0.41_{syst.})\%$$

PDG value = $(9.2 \pm 1.2)\%$

BF(sub-mode n) = $\mathcal{B}(D_s^+ \to \pi^+\pi^0\eta)FF(n)$



Branching fraction (%) BESIII
$\mathcal{B}(D_s^+ \to \rho^+\eta) = 7.44 \pm 0.52_{stat.} \pm 0.38_{sys.}$
$\mathcal{B}(D_s^+ \to a_0(980)^+\pi^0)^* = 1.46 \pm 0.15_{stat.} \pm 0.23_{sys.}$
$\mathcal{B}(D_s^+ \to a_0(980)^0\pi^+)^* = 1.46 \pm 0.15_{stat.} \pm 0.23_{sys.}$

*here, $a_0(980) \to \pi\eta$

PDG value = $(8.9 \pm 0.9)\%$

First observation !

- $\mathcal{B}(D_s^+ \to a_0(980)^+\pi^0$ is larger than other measured pure W-annihilation decays ($D_s^+ \to p\bar{n}$, $D_s^+ \to \omega\pi^+$) by one order.

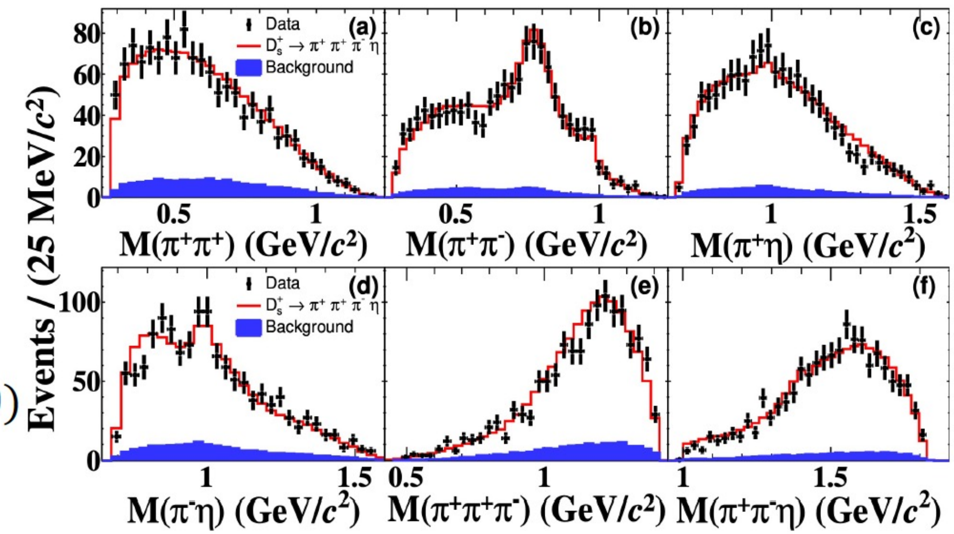
Amplitude analysis of $D_s^+ \to \pi^+\pi^+\pi^-\eta$

2139 events with purity > 85%

PRD 104, L071101 (2021)

$\mathcal{B}(D_s^+ \to \pi^+\pi^+\pi^-\eta)$
$=(3.12\pm0.13\pm0.09)\%$

$\mathcal{B}(D_s^+ \to a_0^+(980)\rho^0,\ a_0^+(980) \to \pi^+\eta)$
$=(0.21\pm0.08\pm0.05)\%$



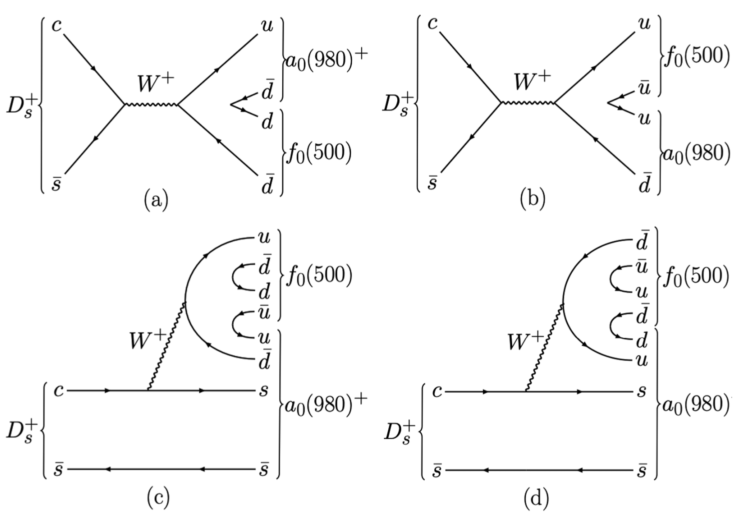
Amplitude	Phase	FF(%)
$a_1(1260)^+(\rho(770)^0\pi^+)\eta$	0.0(fixed)	$55.4\pm3.9\pm2.0$
$a_1(1260)^+(f_0(500)\pi^+)\eta$	$5.0\pm0.1\pm0.1$	$8.1\pm1.9\pm2.1$
$a_0(980)^+\rho(770)^0$	$2.5\pm0.1\pm0.1$	$6.7\pm2.5\pm1.5$
$\eta(1405)(a_0(980)^-\pi^+)\pi^+$	$0.2\pm0.2\pm0.1$	$0.7\pm0.2\pm0.1$
$\eta(1405)(a_0(980)^+\pi^-)\pi^+$	$0.2\pm0.2\pm0.1$	$0.7\pm0.2\pm0.1$
$f_1(1420)(a_0(980)^-\pi^+)\pi^+$	$4.3\pm0.2\pm0.4$	$1.9\pm0.5\pm0.3$
$f_1(1420)(a_0(980)^+\pi^-)\pi^+$	$4.3\pm0.2\pm0.4$	$1.7\pm0.5\pm0.3$
$[a_0(980)^-\pi^+]_S\pi^+$	$0.1\pm0.2\pm0.2$	$5.1\pm1.2\pm0.9$
$[a_0(980)^+\pi^-]_S\pi^+$	$0.1\pm0.2\pm0.2$	$3.4\pm0.8\pm0.6$
$[f_0(980)\eta]_S\pi^+$	$1.4\pm0.2\pm0.3$	$6.2\pm1.7\pm0.9$
$[f_0(500)\eta]_S\pi^+$	$2.5\pm0.2\pm0.3$	$12.7\pm2.6\pm2.0$

Larger than other w-annihilation decays.

How about $D_s^+ \to a_0^0(980)\rho^+$? Does it have the same branching fraction?

$D_s^+ \to \pi^+\pi^0\pi^0\eta$

- The $D_s^+ \to a_0(980)^+ f_0(500)$ decay is expected to proceed through the **pure WA** under the assumption of $a_0(980)$ as a conventional $q\bar{q}$ mesons. Thus, this study will uniquely determine the non-perturbative WA amplitudes.
- The study of $D_s^+ \to a_0(980)^+ f_0(500)$ can provide crucial information on the **tetraquark structure** of the $a_0(980)$ or significant contribution from **FSI effect**.
- Moreover, similar to $D_s^+ \to a_0(980)^+\rho^0$ in $D_s^+ \to \pi^+\pi^+\pi^-\eta$, we can search for $D_s^+ \to a_0(980)^0\rho^+$.



✓ $D_s^+ \to \pi^+\pi^0\pi^0\eta$

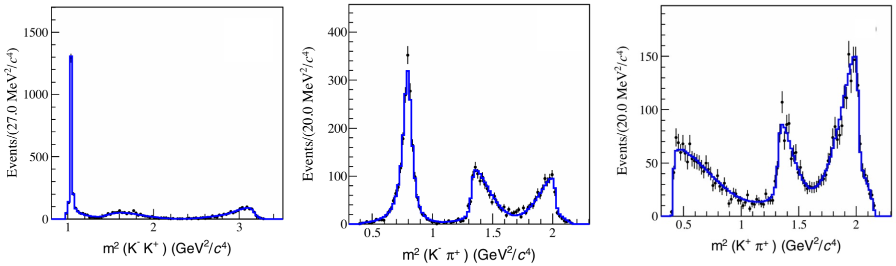
Amplitude
$D_s^+ \to a_1(1260)^+\eta, a_1(1260)^+ \to \rho(770)^+\pi^0$
$D_s^+ \to a_0(980)^+ f_0(500)$
$D_s^+ \to \pi^+(\pi^0\pi^0)_{S-\text{wave}}\eta$

BESIII internal review
内部结果

Scalars from Ds hadronic decays

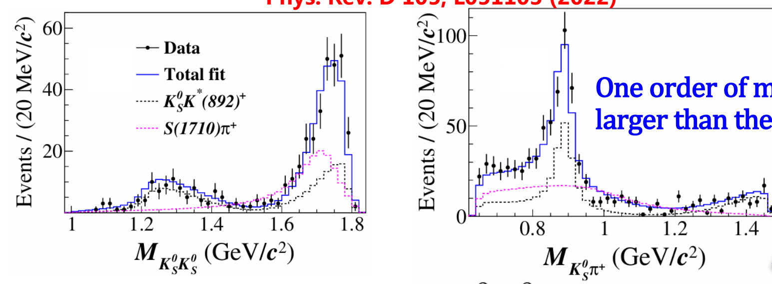
- $a_0(1817)$ and $f_0(1710)$

Phys. Rev. D 104, 012016



$B(D_s^+ \to f_0(1710)\pi^+, f_0 \to K^+K^-) = (0.10 \pm 0.04)\%$

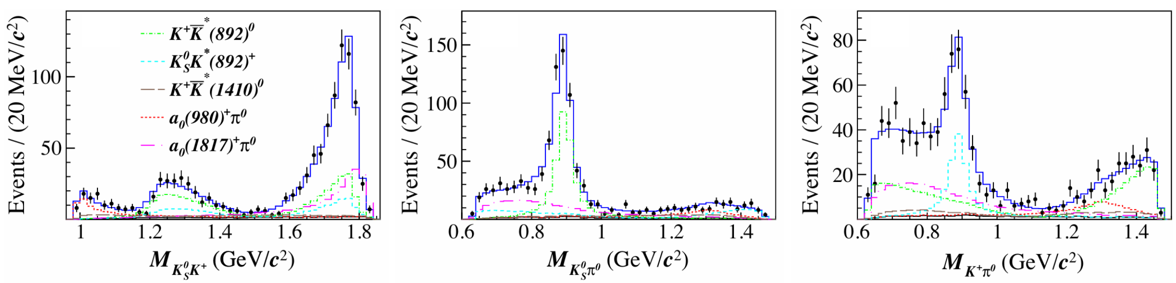
Phys. Rev. D 105, L051103 (2022)



One order of magnitude larger than the expectation!

$B(D_s^+ \to f_0(1710)\pi^+, f_0 \to K_S^0K_S^0) = (0.31 \pm 0.03)\%$

Phys. Rev. Lett. 129, 182001 (2022)



Isospin-one partner of $f_0(1710)$ or $X(1812)$?

$B(D_s^+ \to a_0(1817)^+\pi^0, a_0 \to K_S^0K^+) = (3.44 \pm 0.61) \times 10^{-3}$

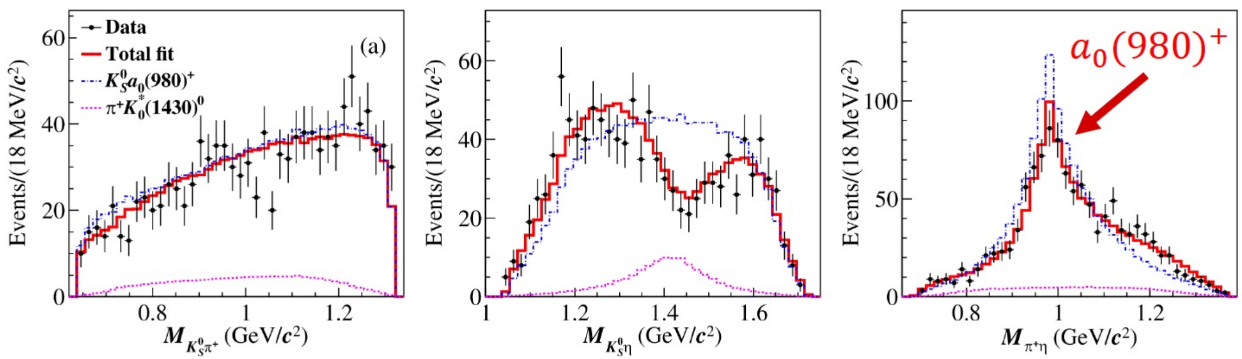
Mass: $(1.817 \pm 0.02)\mathrm{GeV}/c^2$ Width: $(0.097 \pm 0.027)\mathrm{GeV}/c^2$

Amplitude analysis of $D^+ \to K_S^0 \pi^+ \eta$

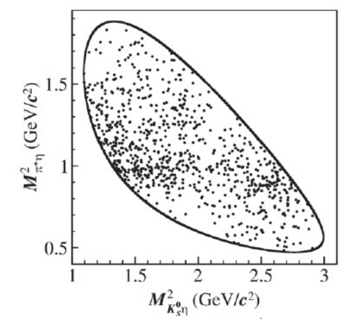
PRL 132, 131903 (2024)

$2.93\mathrm{fb}^{-1}$ @3.773GeV

Observation of *W*-annihilation-free decay $D^+ \to K_S^0 a_0(980)^+$



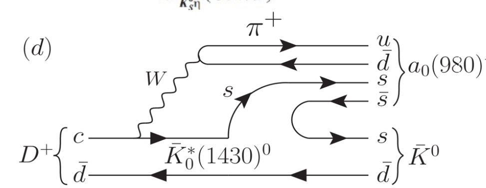
1113 candidates with 98% purity



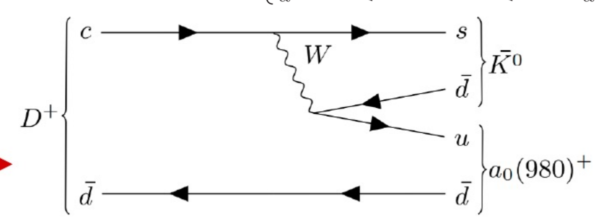
$$\mathcal{B}(D^+ \to K_S^0 a_0(980)^+, a_0(980)^+ \to \pi^+\eta) = (1.33 \pm 0.05_{\rm stat} \pm 0.04_{\rm syst})\%$$

$$\mathcal{B}(D^+ \to \bar{K}_0^*(1430)^0 \pi^+,\ \bar{K}_0^*(1430)^0 \to K_S^0\eta) = (0.14 \pm 0.02_{\rm stat} \pm 0.02_{\rm syst})\%$$

$$\mathcal{B}(D^+ \to K_S^0 \pi^+ \eta) = (1.27 \pm 0.04_{\rm stat} \pm 0.03_{\rm syst})\%$$



Provide sensitive constraints in the extraction of contributions from internal W-emission diagrams →



Amplitude analysis of $D^0 \to \pi^+\pi^-\eta$, $D^+ \to \pi^+\pi^0\eta$

BESIII

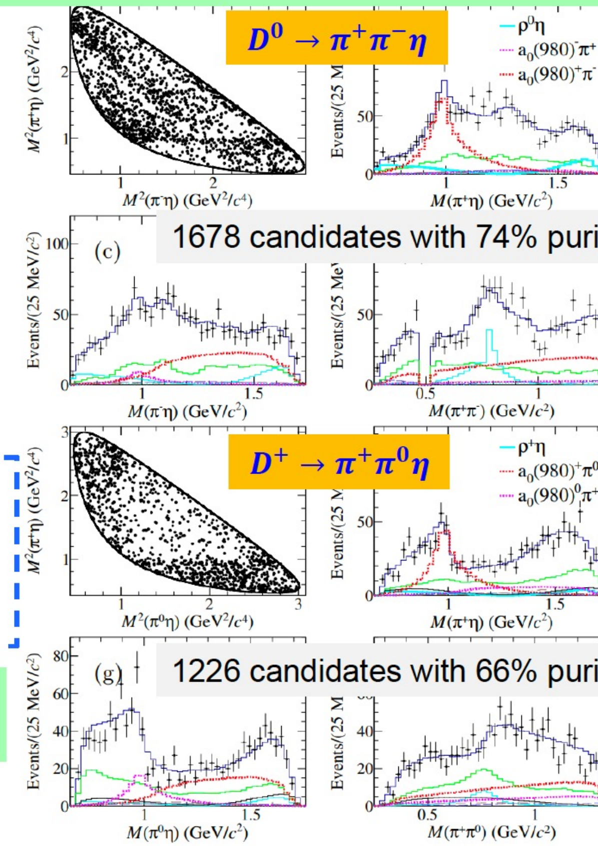
7.9 fb^{-1}@E_{cm} = 3.773GeV, PRD 110, L111102 (2024)

Observation of $D \to a_0(980)\pi$

$\mathcal{B}(D^0 \to \pi^+\pi^-\eta) = (1.24 \pm 0.04 \pm 0.03)\%$

$\mathcal{B}(D^+ \to \pi^+\pi^0\eta) = (2.18 \pm 0.12 \pm 0.03)\%$

Amplitude	Phase (in unit rad)	BF ($\times 10^{-3}$)
$D^0 \to \rho^0\eta$	0 (fixed)	$0.19 \pm 0.02 \pm 0.01$
$D^0 \to a_0(980)^-\pi^+$	$0.06 \pm 0.16 \pm 0.12$	$0.07 \pm 0.02 \pm 0.01$
$D^0 \to a_0(980)^+\pi^-$	$-1.06 \pm 0.12 \pm 0.10$	$0.55 \pm 0.05 \pm 0.07$
$D^0 \to a_2(1320)^+\pi^-$	$-1.16 \pm 0.25 \pm 0.23$	$0.03 \pm 0.01 \pm 0.01$
$D^0 \to a_2(1700)^+\pi^-$	$0.08 \pm 0.17 \pm 0.23$	$0.07 \pm 0.02 \pm 0.03$
$D^0 \to (\pi^+\pi^-)_{S-\mathrm{wave}}\eta$	$-0.92 \pm 0.29 \pm 0.14$	$0.05 \pm 0.02 \pm 0.03$
$D^+ \to \rho^+\eta$	$-4.03 \pm 0.19 \pm 0.13$	$0.20 \pm 0.07 \pm 0.05$
$D^+ \to (\pi^+\pi^0)_V\eta$	$-0.64 \pm 0.22 \pm 0.19$	$0.34 \pm 0.11 \pm 0.11$
$D^+ \to a_0(980)^+\pi^0$	0 (fixed)	$0.95 \pm 0.12 \pm 0.05$
$D^+ \to a_0(980)^0\pi^+$	$2.44 \pm 0.20 \pm 0.10$	$0.37 \pm 0.10 \pm 0.04$
$D^+ \to a_2(1700)^+\pi^0$	$0.92 \pm 0.20 \pm 0.14$	$0.09 \pm 0.05 \pm 0.02$
$D^+ \to a_0(1450)^+\pi^0$	$0.63 \pm 0.41 \pm 0.30$	$0.15 \pm 0.06 \pm 0.02$



$\mathcal{B}(D^0 \to a_0(980)^+\pi^-)/\mathcal{B}(D^0 \to a_0(980)^-\pi^+)$ $7.5^{+2.5}_{-0.8\,\mathrm{stat.}} \pm 1.7_{\mathrm{syst.}}$

$\mathcal{B}(D^+ \to a_0(980)^+\pi^0)/\mathcal{B}(D^+ \to a_0(980)^0\pi^+)$ $2.6 \pm 0.6_{\mathrm{stat.}} \pm 0.3_{\mathrm{syst.}}$

→ **Disagrees with theoretical predictions by orders of magnitude**

Observation of $D_s^+ \to a_0(980)\pi$

3.19 fb^{-1}@E_{cm} = 4.176GeV
PRL123, 112001(2019)

$\mathcal{B}(D_s^+ \to a_0(980)^+\pi^0) = \mathcal{B}(D_s^+ \to a_0(980)^0\pi^+) = (1.46 \pm 0.15 \pm 0.23)\%$

→ **Larger than pure W-annihilation decays $D_s^+ \to \omega\pi^+$, $D_s^+ \to \rho\pi^+$ by one order of magnitude**

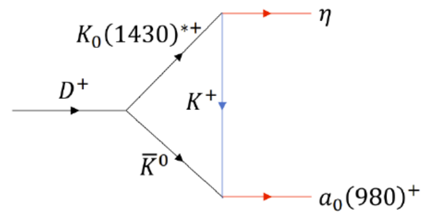
24

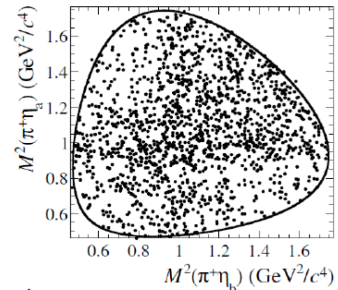
Amplitude analysis of $D^+ \to \pi^+\eta\eta$

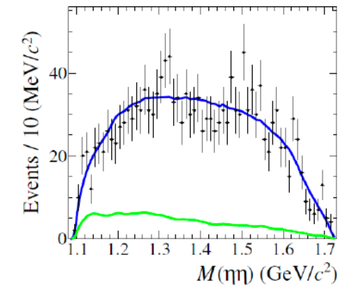
20.3fb^{-1} @3.773GeV

1624 candidates with 85% purity

- First observation of an altered $a_0(980)$ line-shape due to triangle loop rescattering







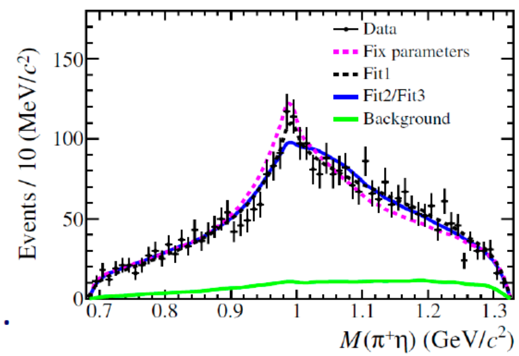
Fit1: $P_{a_0(980)}$ three-channel coupled Flatte formulae, the fitted pole position is inconsistent with previous measurement.

To consider the rescattering process $D^+ \to \bar{K}_0^*(1430)^0 K^+ \to a_0(980)^+\eta$ we perform Fit2 and Fit3

Fit2: $(1 + |C|e^{i\phi_C} A_{\rm loop})P_{a_0(980)}$

Fit3: $(1 + |C|A_{\rm loop})P_{a_0(980)}$ with ϕ_C fixed to zero.

$$|C| = 0.113 \pm 0.015_{\rm stat.} \pm 0.048_{\rm syst.}$$



Fit2 and Fit3 give good descriptions of the altered $a_0(980)$ line-shape.

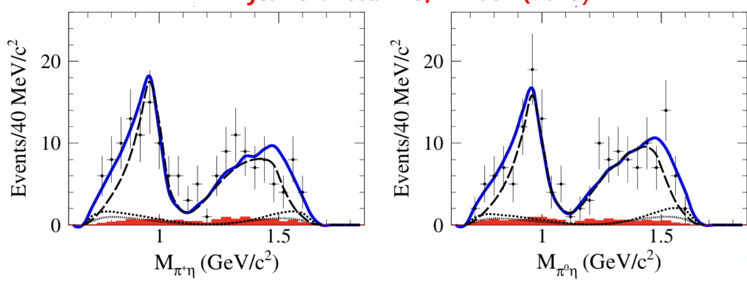
- **BF measurement**

$$\left.\begin{array}{r}\mathcal{B}(D^+ \to \pi^+\eta\eta) \\ \mathcal{B}(D^+ \to a_0(980)^+\eta)\ \mathcal{B}(a_0(980)^+ \to \pi^+\eta)\end{array}\right\} = (3.67 \pm 0.12_{\rm stat.} \pm 0.06_{\rm syst.}) \times 10^{-3}$$

$a_0(980)$ from charmed hadron decays

➤ **$a_0(980)$ and $f_0(980)$: two-quark $q\bar{q}$ or tetraquark $q^2\bar{q}^2$?**

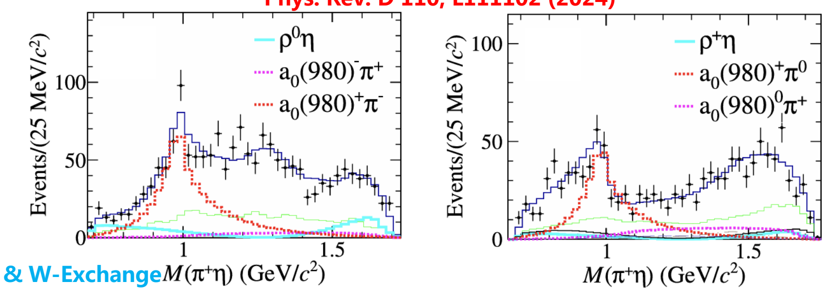
Phys. Rev. Lett. 123, 112001 (2019)



W-Annihilation

$$B(D_s^+ \to a_0\pi, a_0 \to \pi\eta) = (1.46 \pm 0.27)\%$$

Phys. Rev. D 110, L111102 (2024)

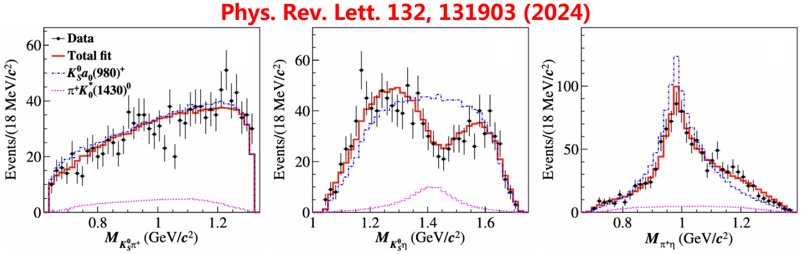


W-Emission & W-Exchange

$$\mathcal{B}(D^0 \to a_0(980)^+\pi^-)/\mathcal{B}(D^0 \to a_0(980)^-\pi^+) \quad 7.5^{+2.5}_{-0.8\,\text{stat.}} \pm 1.7_{\text{syst.}}$$

$$\mathcal{B}(D^+ \to a_0(980)^+\pi^0)/\mathcal{B}(D^+ \to a_0(980)^0\pi^+) \quad 2.6 \pm 0.6_{\text{stat.}} \pm 0.3_{\text{syst.}}$$

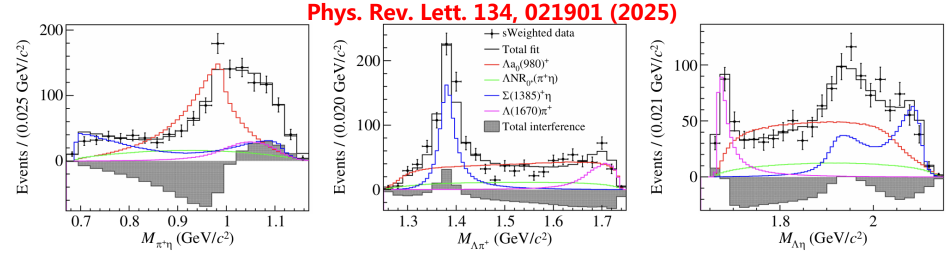
Phys. Rev. Lett. 132, 131903 (2024)



W-Emission

$$B(D^+ \to a_0^+ K_S^0, a_0 \to \pi\eta) = (1.33 \pm 0.06)\%$$

Phys. Rev. Lett. 134, 021901 (2025)



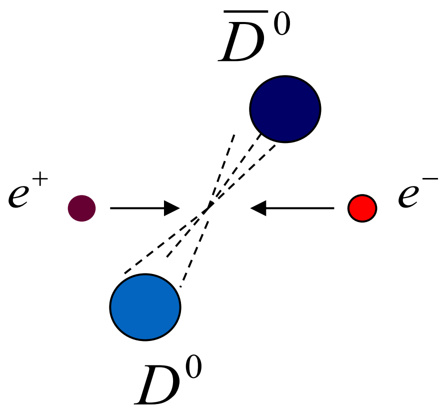
W-Emission & W-Exchange

$$B(\Lambda_c^+ \to a_0^+\Lambda, a_0 \to \pi\eta) = (1.05 \pm 0.18)\%$$

All of the measured branching fractions deviate from the predictions made by $q\bar{q}$ model ⇒ $q^2\bar{q}^2$ and Final State Interaction?

The quantum-correlated state

For a physical process producing $D^0\bar{D}^0$ such as



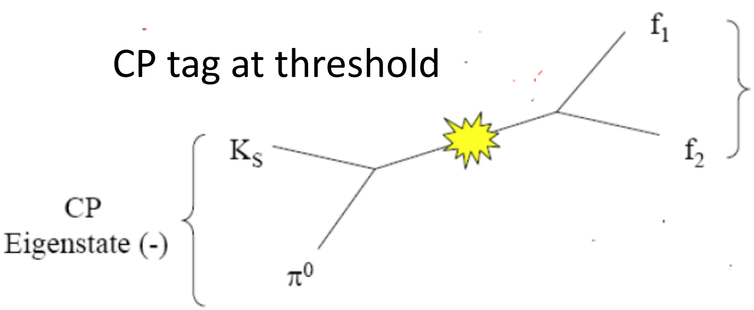
$$e^+e^- \to \psi'' \to D^0\bar{D}^0$$

The $D^0\bar{D}^0$ pair will be a quantum-correlated state

For a correlated state with $C = -$

$$\hat{C}\left|D^0\right\rangle = \left|\bar{D}^0\right\rangle \qquad \hat{C}\left|\bar{D}^0\right\rangle = \left|D^0\right\rangle$$

$$\psi_- = \frac{1}{\sqrt{2}}\left(\left|D^0\right\rangle\left|\bar{D}^0\right\rangle - \left|\bar{D}^0\right\rangle\left|D^0\right\rangle\right)$$



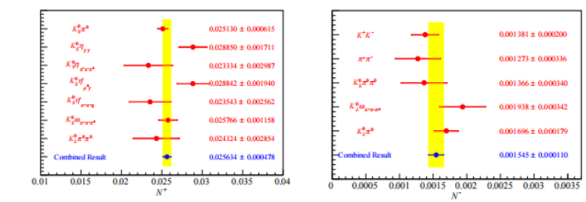
$$\frac{\left\langle K^-\pi^+ \middle| \bar{D}^0\right\rangle^{DCS}}{\left\langle K^-\pi^+ \middle| D^0\right\rangle^{CF}} \equiv -r_{K\pi}e^{-i\delta_{K\pi}}$$

$$\left|D_{CP\pm}\right\rangle = \frac{1}{\sqrt{2}}\left[\left|D^0\right\rangle \pm \left|\bar{D}^0\right\rangle\right]$$

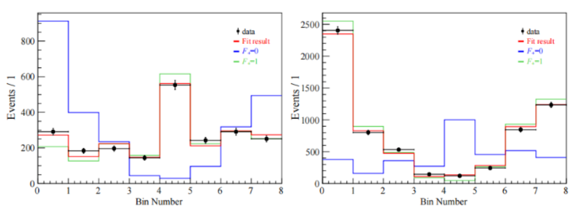
$$\sqrt{2}\,A\left(D_{CP\pm} \to K^-\pi^+\right) = A\left(D^0 \to K^-\pi^+\right) \pm A\left(\bar{D}^0 \to K^-\pi^+\right)$$

CP-even fraction measurements

Phys.Rev.D 111 (2025) 1. 012007, Phys.Rev.D 107 (2023) 3, 032009



(a) N^+ for $\pi^+\pi^-\pi^0$ (b) N^- for $\pi^+\pi^-\pi^0$



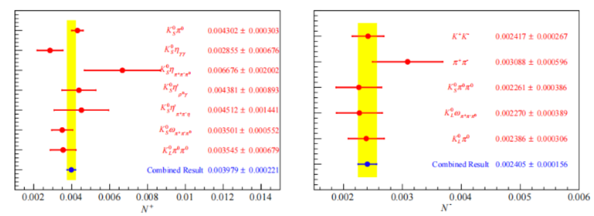
(a) $K_S^0\pi^+\pi^-$ versus $\pi^+\pi^-\pi^0$ (b) $K_L^0\pi^+\pi^-$ versus $\pi^+\pi^-\pi^0$

7.9fb[-1]@3.773GeV

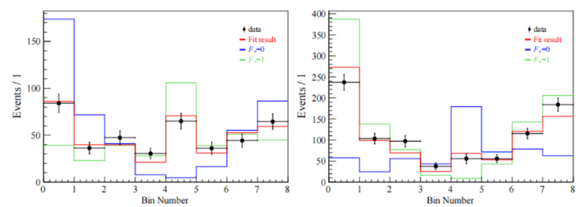
$D^0 \to \pi^+\pi^-\pi^0$

$F_+ = 0.941 \pm 0.006_{stat} \pm 0.003_{syst}$

2.6 times more precise !



(c) N^+ for $K^+K^-\pi^0$ (d) N^- for $K^+K^-\pi^0$



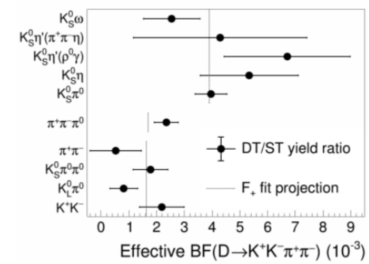
(c) $K_S^0\pi^+\pi^-$ versus $K^+K^-\pi^0$ (d) $K_L^0\pi^+\pi^-$ versus $K^+K^-\pi^0$

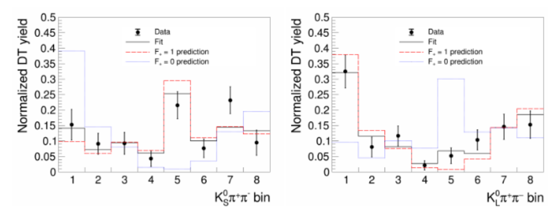
7.9fb[-1]@3.773GeV

$D^0 \to K^+K^-\pi^0$

$F_+ = 0.631 \pm 0.014_{stat} \pm 0.011_{syst}$

2.6 times more precise !





2.93fb[-1]@3.773GeV

$D^0 \to K^+K^-\pi^+\pi^-$

$F_+ = 0.730 \pm 0.037_{stat} \pm 0.021_{syst}$

first model-independent mesurement !

δ and γ/ϕ_3 input

- D hadronic parameters for a final state

$$f: \ \frac{A(\bar{D}^0 \to f)}{A(D^0 \to f)} \equiv -r_D e^{-i\delta_D}$$

- Charm mixing parameters: $x = \frac{\Delta M}{\Gamma}$, $y = \frac{\Delta\Gamma}{2\Gamma}$
  - Time-dependent WS $D^0 \to K^+\pi^-$ rate ⇒
    $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$ (LHCb)
  - $\delta_{K\pi}$: QC measurements from Charm factory
- γ/ϕ_3 measurements from $B \to D^0 K$
  - b→u : $\gamma/\phi_3 = \arg V^*_{ub}$
    - most sensitive method to constrain γ/ϕ_3 at present
  - GLW, ADS method
    - r_D, δ_D : QC measurements from Charm factory
  - GGSZ method
    - c_i, s_i : QC measurements from Charm factory

(c_i, s_i) in $D^0 \to K_{S,L}\pi^+\pi^-$ Dalitz analysis

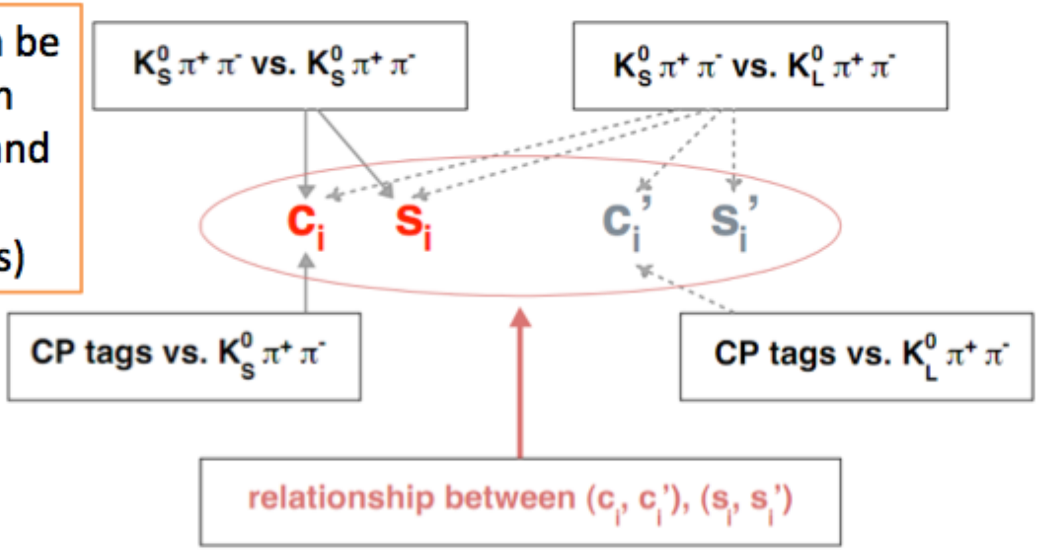
GGSZ (Dalitz) method

$$N_i^{\pm} = h_B\left[K_{\pm i} + r_b^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}\,(x_\pm c_i \pm y_\pm s_i)\right]$$

- $N_i^{\pm}$: $B^{\pm} \to DK^{\pm}$ yields
- $K_{\pm i}$: from flav.-tagged $D \to K_S\pi\pi$
- $x_\pm$, $y_\pm$: extracted from fit to the $B^{\pm}$ yields
- c_i, s_i: measured by CLEO [PRD82, 112006 (2010)]

We can calculate c_i and s_i from double tags of $D^0 \to K_S\pi^+\pi^-$ vs $D^0 \to (K_{S,L}\pi^+\pi^-$ or CP eigenstates)

A relationship can be shown between Dalitz bin yields and c_i and s_i (in backup slides)



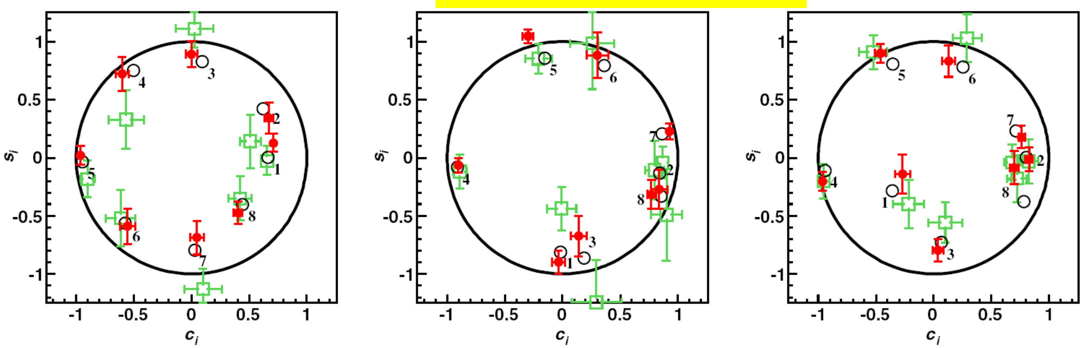
Only c_i, s_i from $K_s\pi^+\pi^-$ is used to calculate γ.
However adding in $D^0 \to K_L\pi^+\pi^-$ we can calculate c'_i, s'_i and use how they relate to c_i, s_i to further constrain our results in a Global fit.

Quantum entangled $D^0\bar{D}^0$ Strong phase measurements

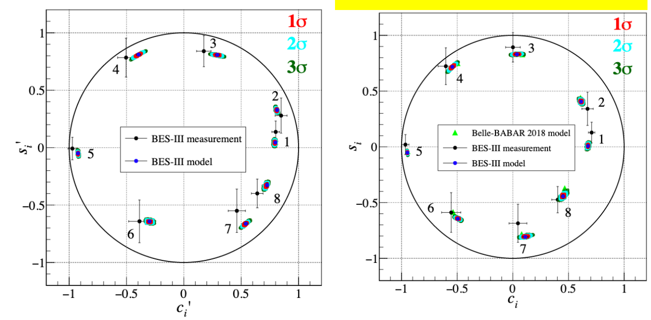
$2.93\ \mathrm{fb}^{-1}@E_{cm} = 3.773$ GeV
$e^+e^- \to \psi(3770) \to D\bar{D}$

- **MI** $D \to K^0_{S/L}\pi^+\pi^-$ PRL 124 (2020)241802

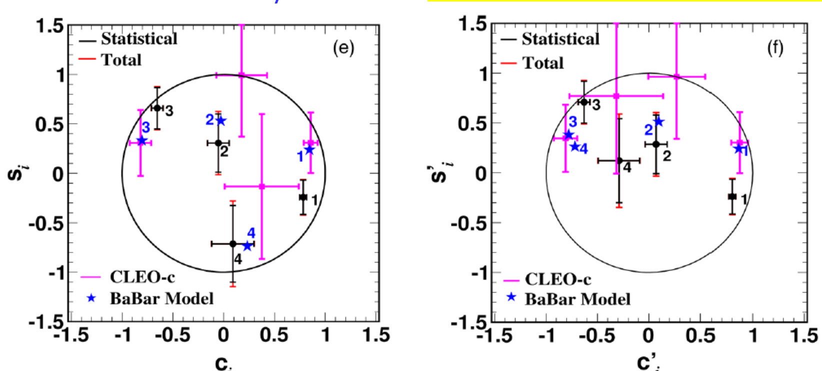
Constraint on γ measurement ~ 0.9^0



- **MD** $D \to K^0_{S/L}\pi^+\pi^-$ arXiv:2212.09048

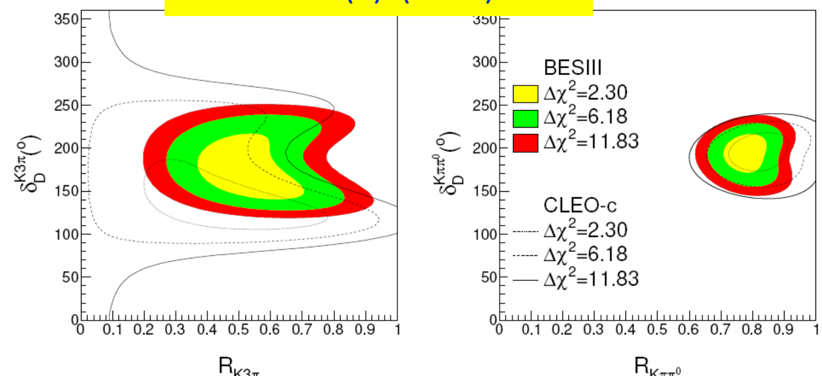


- **MI** $D \to K^0_{S/L}K^+K^-$ PRD102(2020)052008



Constraint on γ measurement ~ 1.3^0

- $D \to K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^0$ JHEP 2021 (5) (2021) 164



Constraint on γ measurement ~ 6^0

- $D \to K^-\pi^+$ EPJC82, 1009 (2022)

$$\delta_D^{K\pi} = (187.6^{+8.9+5.4}_{-9.7-6.4})^\circ$$

the most precise measurement using quantum-entangled $D^0\bar{D}^0$

BESIII data @3770 MeV (20 fb^{-1})

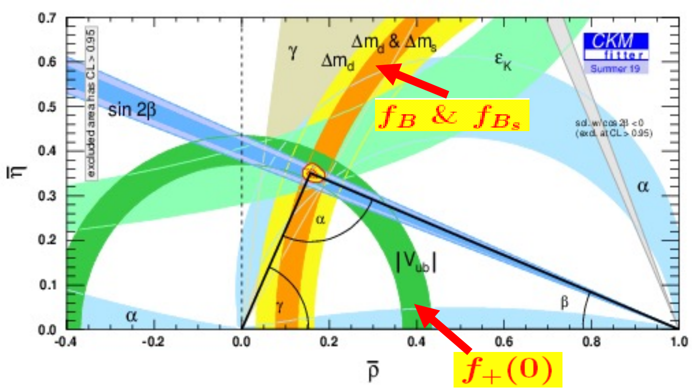
ψ(3770)→$D^0\overline{D^0}$ quantum correlation→strong phase parameters between D^0 and $\overline{D}^0$ decays

→inputs to LHCb measurement of γ

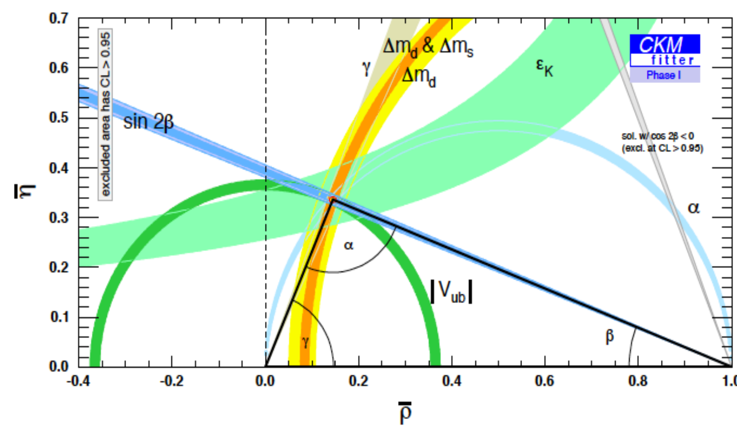
Belle II (arXiv:1808.10567): 1.5^0 with 50 ab^{-1}

LHCb (arXiv:1808.08865v2): < 1^o, 50 fb^{-1}, phase-1 upgrade (2030),

< 0.4^o, 300 fb^{-1}, phase-2 upgrade (> 2035)



2019



>year of 2030 (BESIII 20 fb^{-1} data as inputs)

BESIII White Paper, Chinese Phys. C 44 (2020) 040001

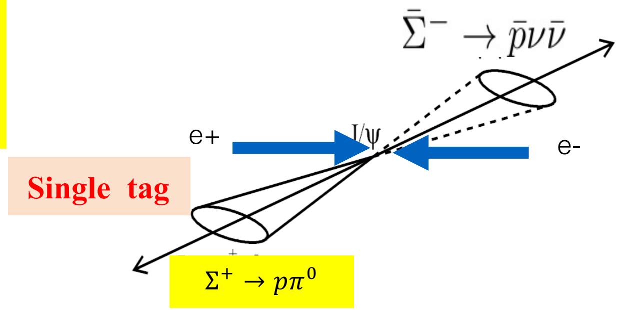
BESIII: a hyperon factory

10 billion J/ψ and 2.7 billion $\psi(2S)$events collected

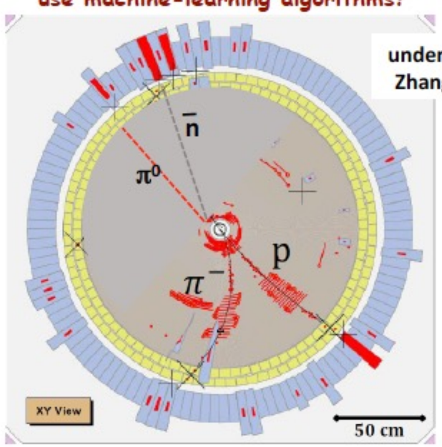
- Large BRs in J/ψ decays : 10^7 **entangled hyperon pairs**
- Quantum entangled pair productions
- Background free

Hai-Bo Li, arXiv:1612.01775

Decay mode	$\mathcal{B}(\times 10^{-3})$	$N_B\ (\times 10^6)$
$J/\psi \to \Lambda\bar{\Lambda}$	1.61 ± 0.15	16.1 ± 1.5
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.29 ± 0.09	12.9 ± 0.9
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.50 ± 0.24	15.0 ± 2.4
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$ (or c.c.)	0.31 ± 0.05	3.1 ± 0.5
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$ (or c.c.)	1.10 ± 0.12	11.0 ± 1.2
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.20 ± 0.24	12.0 ± 2.4
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.86 ± 0.11	8.6 ± 1.0
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	0.32 ± 0.14	3.2 ± 1.4
$J/\psi \to \Xi(1530)^-\bar{\Xi}^+$	0.59 ± 0.15	5.9 ± 1.5
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.05 ± 0.01	0.15 ± 0.03



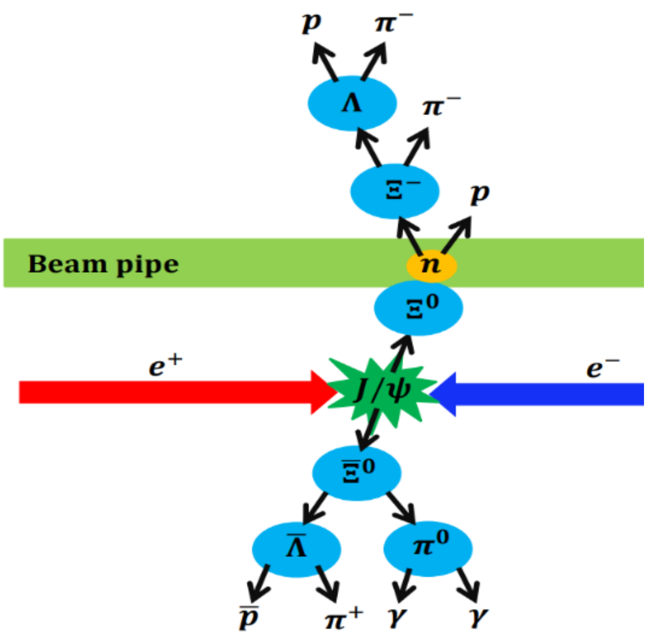
use machine-learning algorithms?



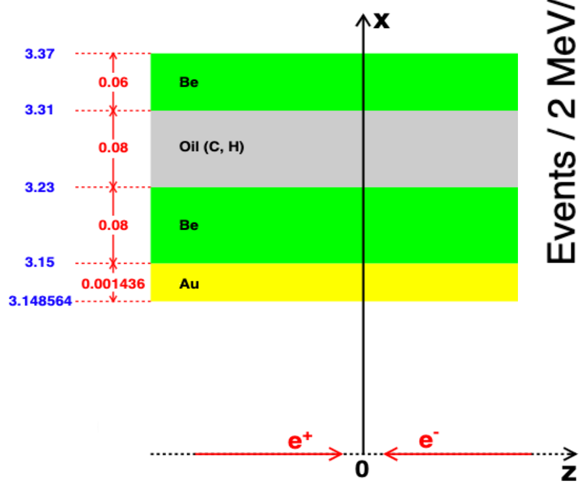
A hyperon beam bombarding beam-pipe target

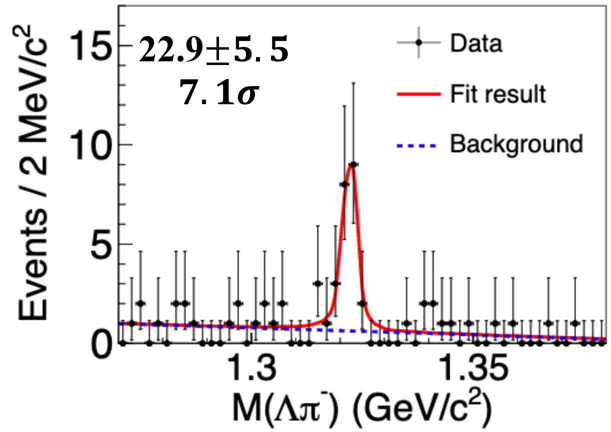
PRL130, 251902 (2023)

- Stable hyperon beam with well-known kinematics is challenging
- Hyperon-nucleon interactions have been studied both theoretically and experimentally. Among them, the knowledge about the Ξ-nucleon are very limited.
- Useful input to study *H*-dibaryon ($uuddss$) with S=-2



intense monoenergetic Ξ⁰ baryon





$\Xi^0 n \to \Xi^- p$ is observed for the first time

For Ξ^0 momentum is 0.818 GeV/c

$$\sigma(\Xi^0 n \to \Xi^- p) = (7.4 \pm 1.8_{\rm stat} \pm 1.5_{\rm sys})\ {\rm mb}$$

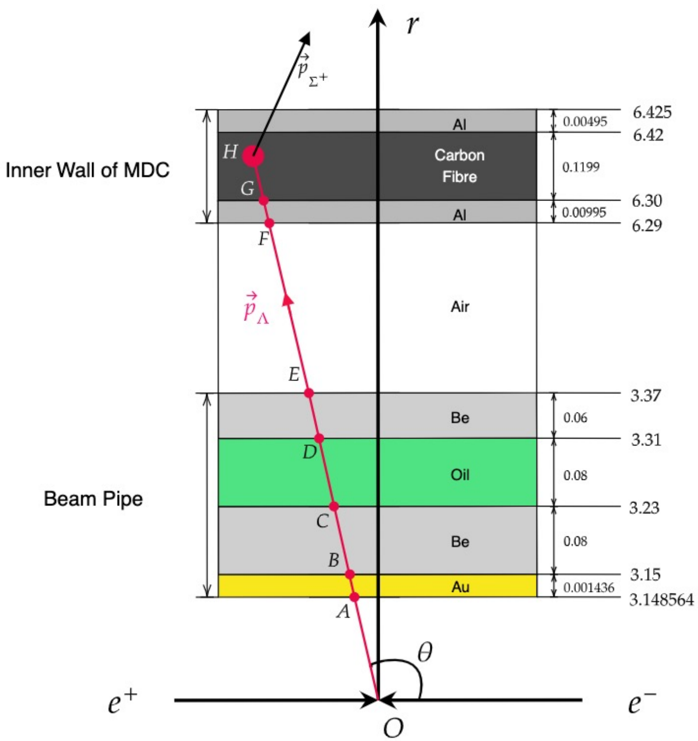
(assuming effective number of reaction neutrons in ^{9}Be is 3)

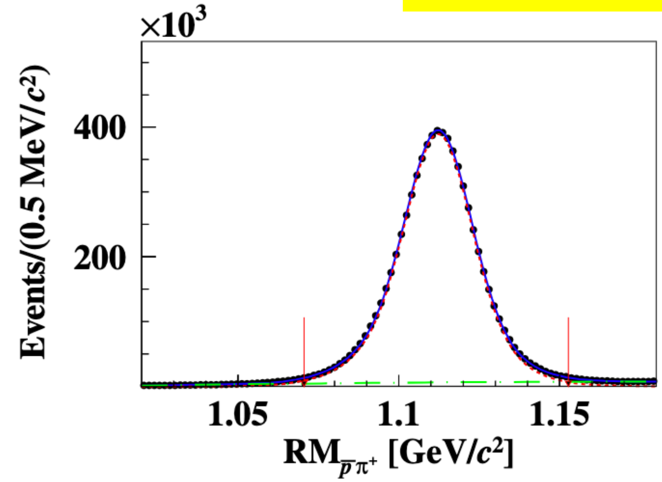
$$\sigma(\Xi^0 + {}^9{\rm Be} \to \Xi^- + p + {}^8{\rm Be}) = (22.1 \pm 5.3_{\rm stat} \pm 4.5_{\rm sys})\ {\rm mb},$$

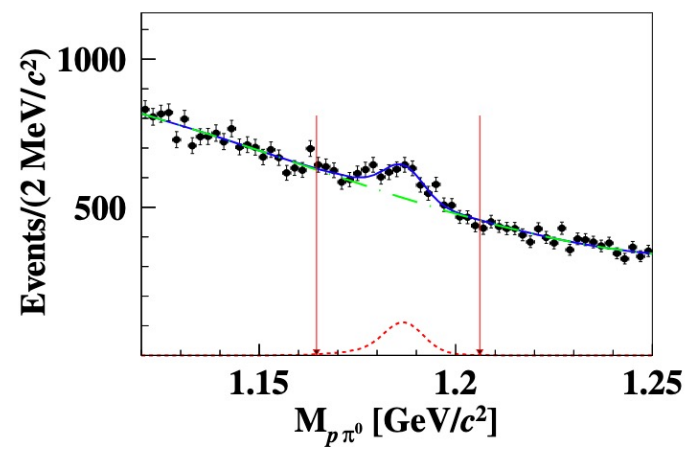
The first study of hyperon–nucleon interaction in electron–positron collisions!

Observation of $\Lambda N \rightarrow \Sigma^{+}X$

arXiv:2310.00720







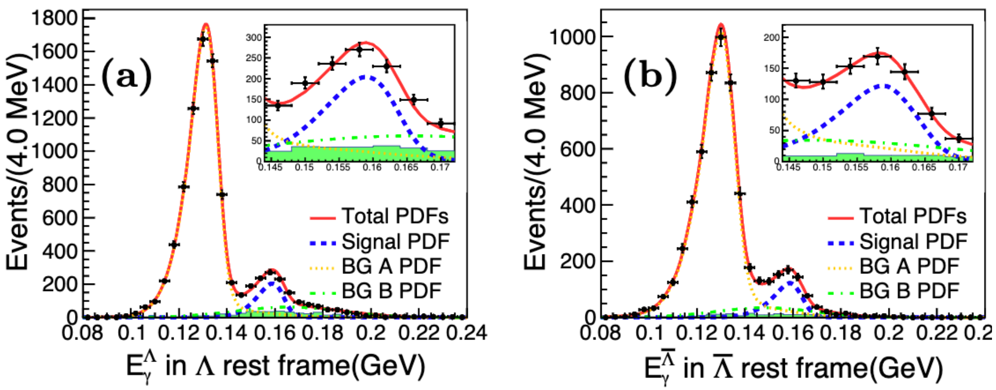
$$\sigma(\Lambda^{9}\mathrm{B_e} \rightarrow \Sigma^{+}\mathrm{X}) = (37.3 \pm 4.7 \pm 3.5)\ \mathrm{mb}$$

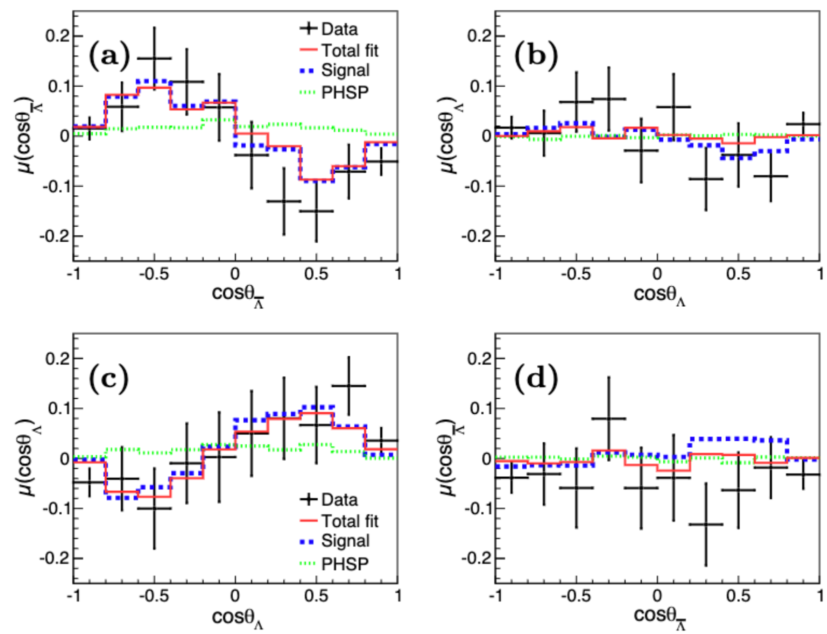
$$p_{\Lambda} \in [1.057, 1.091]\ \mathrm{GeV/c},$$

Radiative hyperon decay $\Lambda \to \gamma n$ in $J/\psi \to \Lambda\bar{\Lambda}$ decays

PRL129, 212002 (2022)

- To access the information on parity violating and parity conserving amplitudes in hyperon decays
- Previous measurements are from fixed target experiments and 30 years old!





Decay Mode	$\Lambda \to n\gamma$	$\bar{\Lambda} \to \bar{n}\gamma$
BF ($\times 10^{-3}$)	$0.820 \pm 0.045 \pm 0.066$	$0.862 \pm 0.071 \pm 0.084$
	$0.832 \pm 0.038 \pm 0.054$	
α_γ	$-0.13 \pm 0.13 \pm 0.03$	$0.21 \pm 0.15 \pm 0.06$
	$-0.16 \pm 0.10 \pm 0.05$	

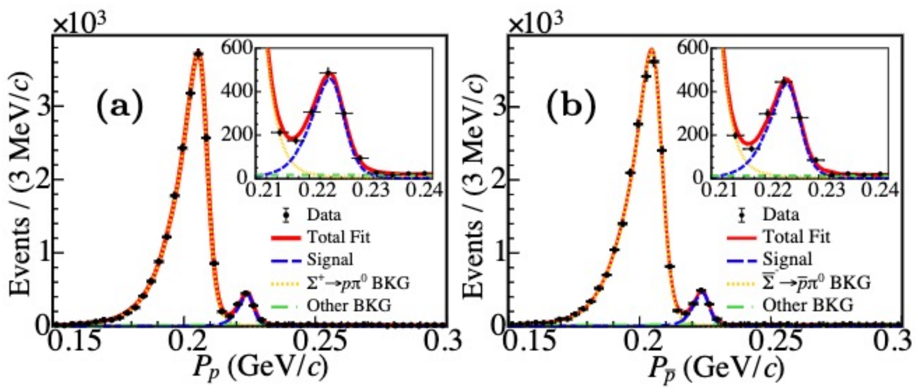
- A factor of two smaller than the previous measurement
- Obtained asymmetry does not agree well with existing theoretical predictions

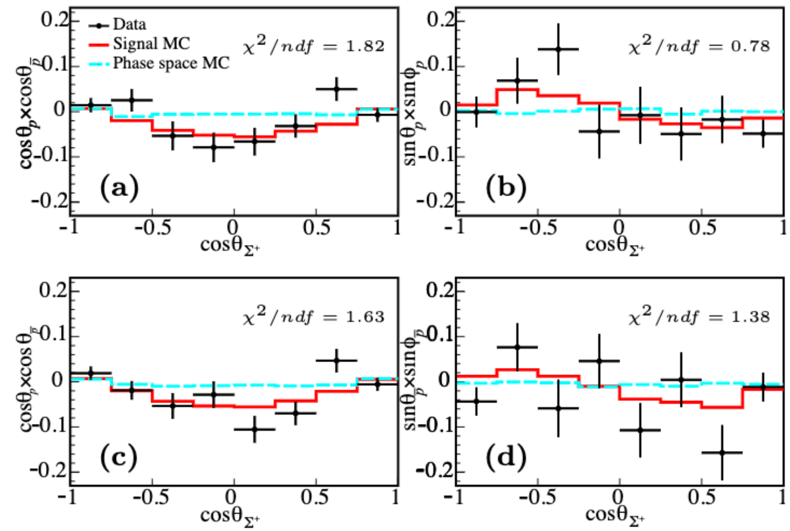
Precise study of $\Sigma^+ \to \gamma p$ from J/ψ decays

arXiv:2302.13568

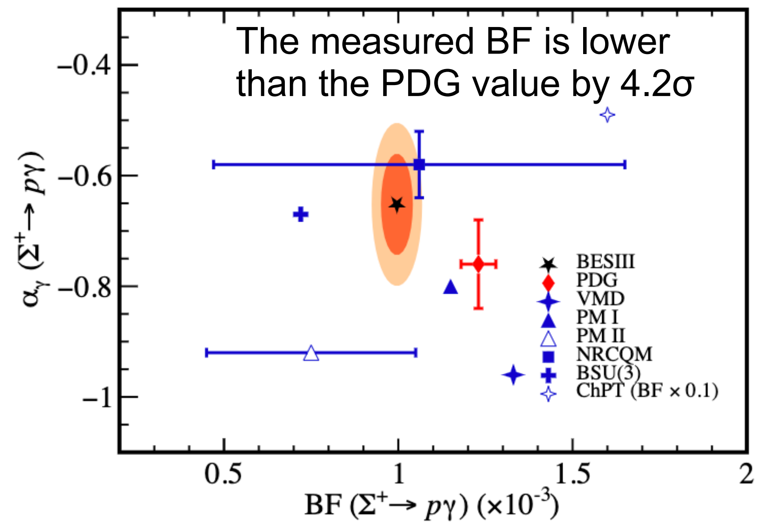
- 10B from J/ψ decays are explored
- Σ^+ tagged from $J/\psi \to \Sigma^+\bar{\Sigma}^-$
- Amplitude fit to obtain decay asymmetry

$$\begin{aligned}\mathcal{W}(\xi) =& \mathcal{F}_0(\xi) + \alpha_\psi \mathcal{F}_5(\xi) + \alpha_\gamma \bar{\alpha}_0 \\ & \times \left(\mathcal{F}_1(\xi) + \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\mathcal{F}_2(\xi) + \alpha_\psi \mathcal{F}_6(\xi)\right) \\ & + \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)(\alpha_\gamma \mathcal{F}_3(\xi) + \bar{\alpha}_0 \mathcal{F}_4(\xi)),\end{aligned}$$

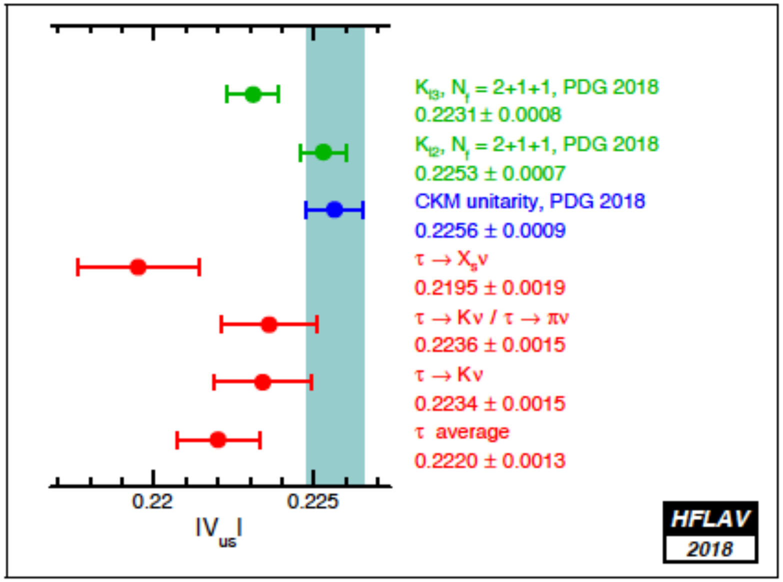




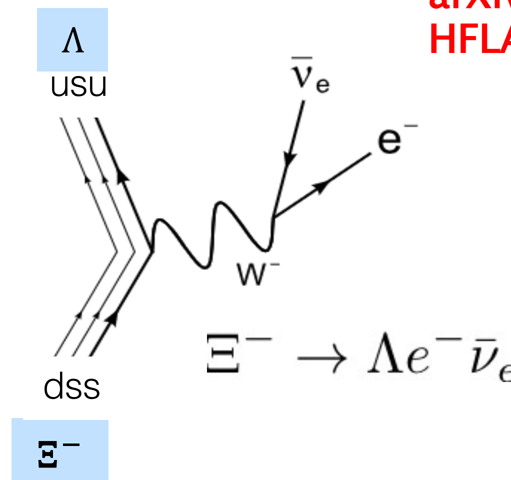
Mode	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
$N_{\rm ST}^{\rm obs}$	2 177 771±2285	2 509 380±2301
$\varepsilon_{\rm ST}$ (%)	39.00±0.04	44.31±0.04
$N_{\rm DT}^{\rm obs}$	1189±38	1306±39
$\varepsilon_{\rm DT}$ (%)	21.16±0.03	23.20±0.03
Individual BF (10^{-3})	1.005±0.032	0.993±0.030
Simultaneous BF (10^{-3})	0.996 ± 0.021 ± 0.018	
Individual α_γ	−0.587±0.082	0.710±0.076
Simultaneous α_γ	−0.651 ± 0.056 ± 0.020	



Semileptonic decays: $|V_{us}|$



arXiv:1909.12524
HFLAV group 2018



$|V_{us}|$ measurements are inconsistent:

between Kl3 and Kl2 decays and tau decays.

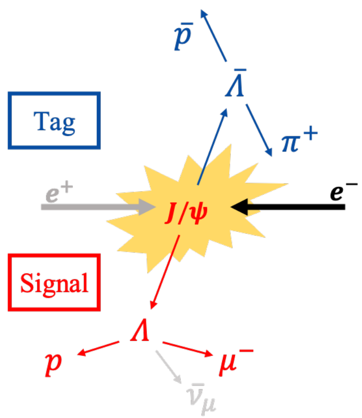
Table 5: Results from V_{us} analysis using measured g_1/f_1 values

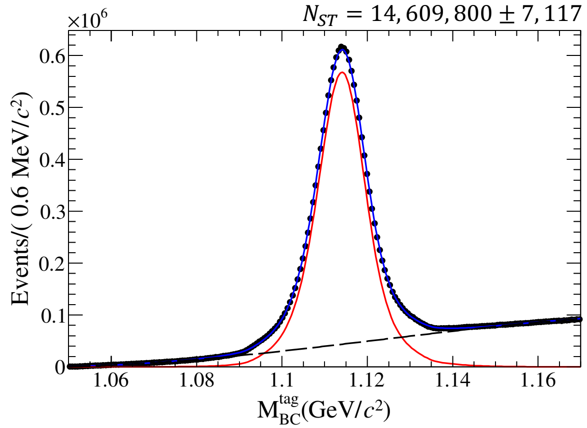
Decay Process	Rate (μsec^{-1})	g_1/f_1	V_{us}
$\Lambda \to p e^- \overline{\nu}$	3.161(58)	0.718(15)	0.2224 ± 0.0034
$\Sigma^- \to n e^- \overline{\nu}$	6.88(24)	−0.340(17)	0.2282 ± 0.0049
$\Xi^- \to \Lambda e^- \overline{\nu}$	3.44(19)	0.25(5)	0.2367 ± 0.0099
$\Xi^0 \to \Sigma^+ e^- \overline{\nu}$	0.876(71)	1.32(+.22/ − .18)	0.209 ± 0.027
Combined	—	—	0.2250 ± 0.0027

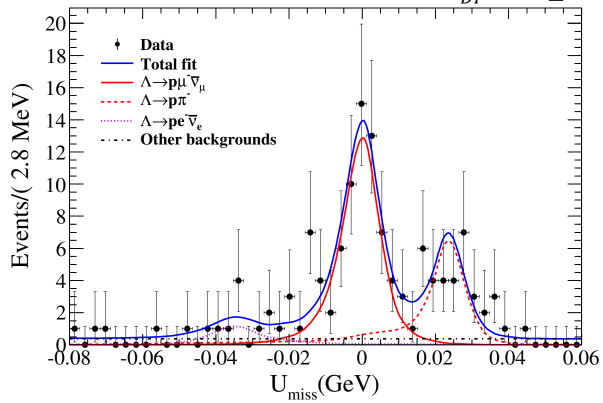
N. Cabibbo, E. Swallon, R. Winston
Ann.Rev.Nucl.Part.Sci. 53:39-75,2003

BF measurement of $\Lambda \to p\mu^-\bar{\nu}_\mu$

Phys. Rev. Lett. 127, 121802 (2021)







First absolute BF measurement

$$\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu) = (1.48 \pm 0.21 \pm 0.08)\times 10^{-4}$$

- ✓ Update measurement after a 50-year hiatus
- ✓ The first study of its absolute BF
- ✓ The most precise result to date

Test lepton flavor universality

$$R^{\mu e} = \frac{\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda \to pe^-\bar{\nu}_e)_{PDG}} = 0.178 \pm 0.028$$

Consistent with LFU

0.153 ± 0.008

Search for CP violation

$$\Delta_{CP} = \frac{\mathcal{B}_{\Lambda \to p\mu^-\bar{\nu}_\mu} - \mathcal{B}_{\bar{\Lambda} \to \bar{p}\mu^+\nu_\mu}}{\mathcal{B}_{\Lambda \to p\mu^-\bar{\nu}_\mu} + \mathcal{B}_{\bar{\Lambda} \to \bar{p}\mu^+\nu_\mu}} = 0.02 \pm 0.14 \pm 0.02$$

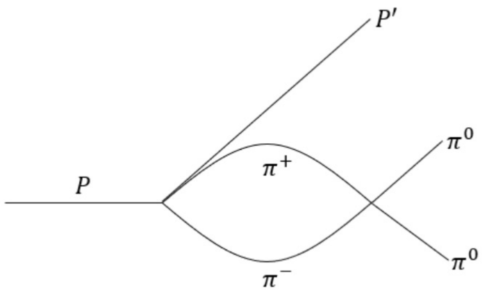
Consistent with CP symmetry

The results for $\Lambda \to pe^-\nu e$ will come soon.

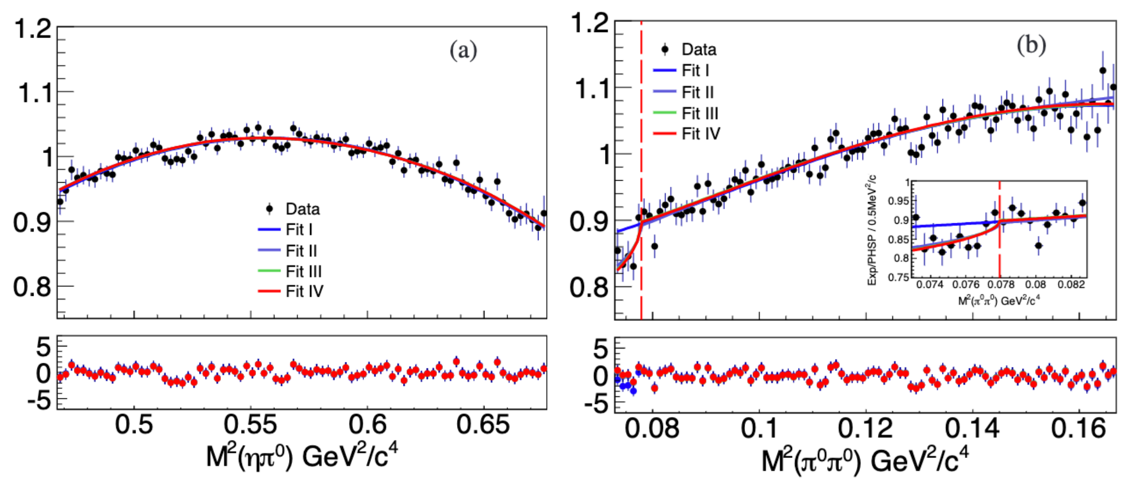
Evidence for the cusp effect in $\eta' \to \eta\pi^0\pi^0$

PRL130, 081901 (2023)

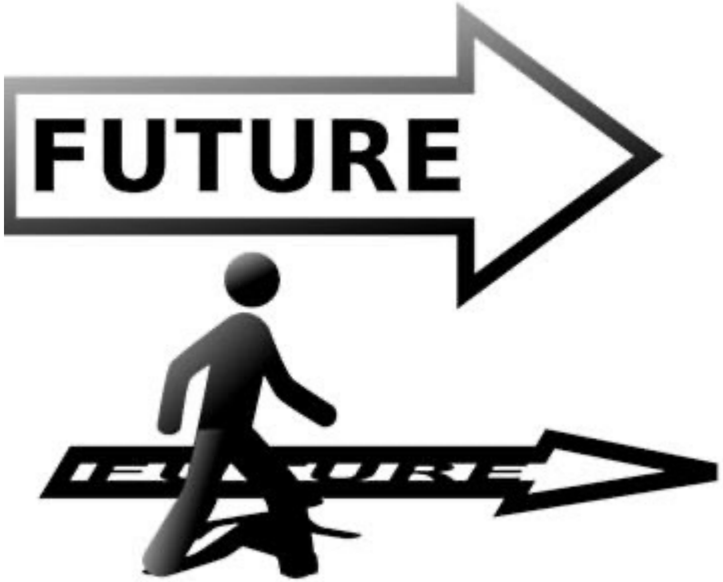
- Based on 10B J/ψ events: ~0.43M signals of $\eta' \to \eta\pi^0\pi^0$
- A Dalitz plot analysis within the framework of non-relativistic effective field theory (NREFT)



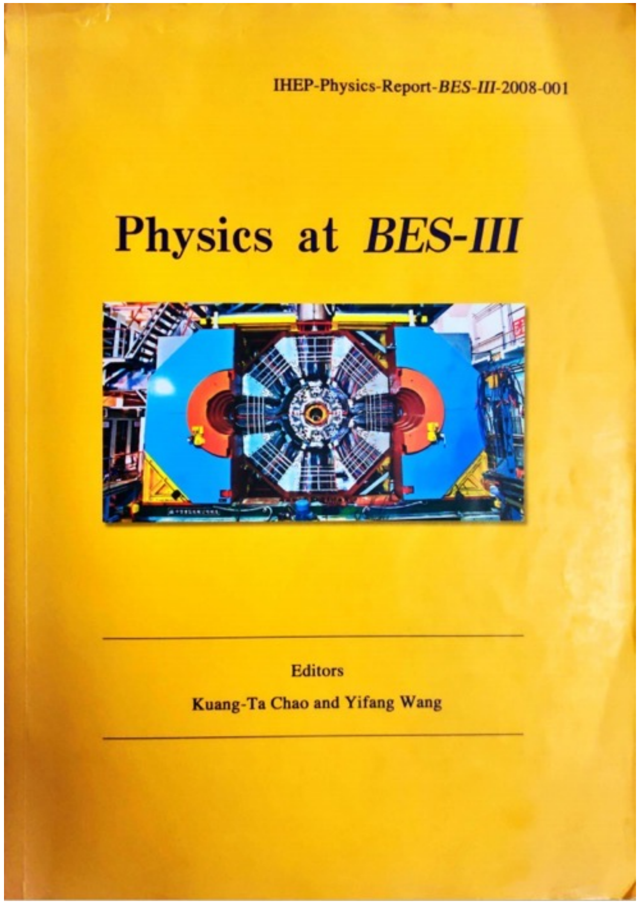
$$C_{00} = \frac{16\pi}{3}(a_0 + 2a_2)(1 - \xi),$$
$$C_x = \frac{16\pi}{3}(a_2 - a_0)(1 + \frac{\xi}{3}),$$
$$C_{+-} = \frac{8\pi}{3}(2a_0 + a_2)(1 + \xi),$$
$$\xi = \frac{M_{\pi^\pm}^2 - M_{\pi^0}^2}{M_{\pi^\pm}^2}.$$



- Evidence for a structure at $\pi^+\pi^-$ mass threshold is observed in the $\pi^0\pi^0$ mass spectrum with a statistical significance of around 3.5σ
  ➔ consistent with the cusp effect as predicted by the non-relativistic effective field theory
- Scattering length combination $a_0 - a_2$ determined to be $0.226 \pm 0.060 \pm 0.012$
  ➔ in good agreement with theoretical calculation of 0.2644 ± 0.0051


FUTURE

BESIII Physics



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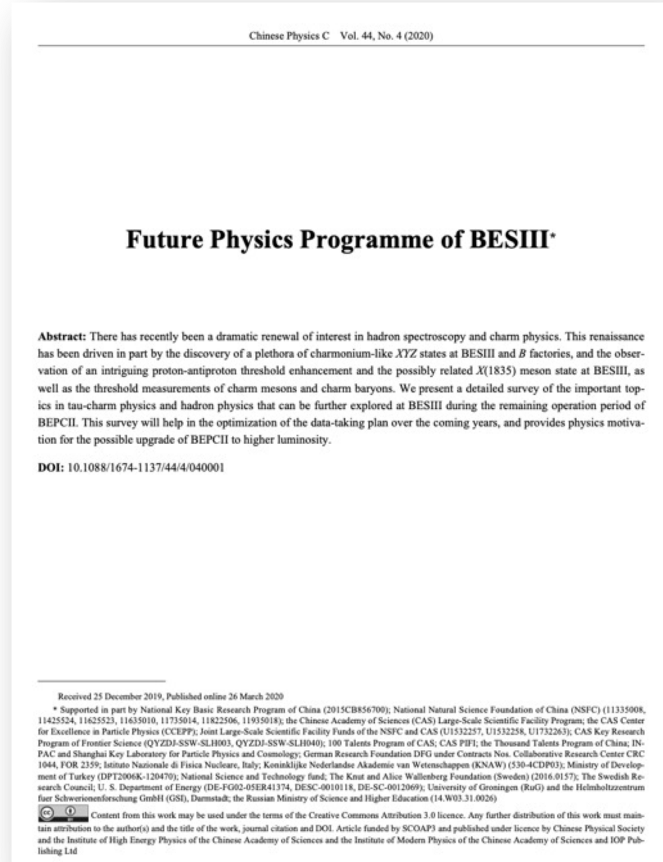

Chinese Physics C Vol. 44, No. 4 (2020)

Future Physics Programme of BESIII*

Abstract: There has recently been a dramatic renewal of interest in hadron spectroscopy and charm physics. This renaissance has been driven in part by the discovery of a plethora of charmonium-like *XYZ* states at BESIII and *B* factories, and the observation of an intriguing proton-antiproton threshold enhancement and the possibly related *X*(1835) meson state at BESIII, as well as the threshold measurements of charm mesons and charm baryons. We present a detailed survey of the important topics in tau-charm physics and hadron physics that can be further explored at BESIII during the remaining operation period of BEPCII. This survey will help in the optimization of the data-taking plan over the coming years, and provides physics motivation for the possible upgrade of BEPCII to higher luminosity.

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Chin. Phys. C 44, 040001 (2020) doi:10.1088/1674-1137/44/4/040001 [arXiv:1912.05983 [hep-ex]].

BESIII

Planned future data set

Table 7.1: List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the remainder of the physics program. The most right column shows the number of required data taking days in current (T_C) or upgraded (T_U) machine. The machine upgrades include top-up implementation and beam current increase.

Energy	Physics motivations	Current data	Expected final data	T_C / T_U
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A	0.1 fb^{-1} (fine scan)	60/50 days
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)	250/180 days
✓ J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)	3.2 fb^{-1} (10 billion)	N/A
✓ $\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (0.45 billion)	4.5 fb^{-1} (3.0 billion)	150/90 days
$\psi(3770)$ peak	$D^0/D^\pm$ decays	2.9 fb^{-1}	20.0 fb^{-1}	610/360 days
3.8 - 4.6 GeV	R values XYZ/Open charm	Fine scan (105 energy points)	No requirement	N/A
4.180 GeV	D_s decay XYZ/Open charm	3.2 fb^{-1}	6 fb^{-1}	140/50 days
4.0 - 4.6 GeV	XYZ/Open charm Higher charmonia cross-sections	16.0 fb^{-1} at different $\sqrt{s}$	30 fb^{-1} at different $\sqrt{s}$	770/310 days
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

to be complete in 2022-23

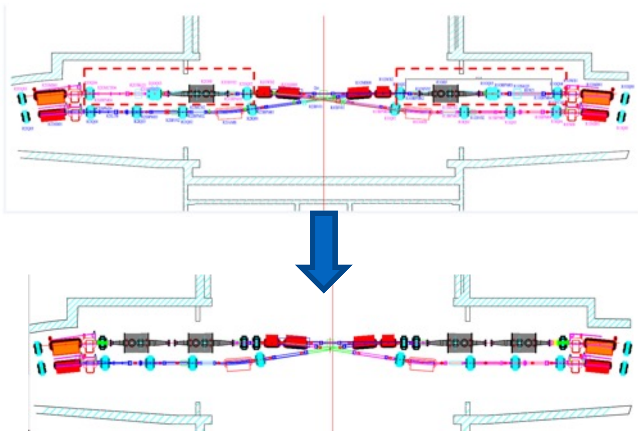
~55 fb^{-1}

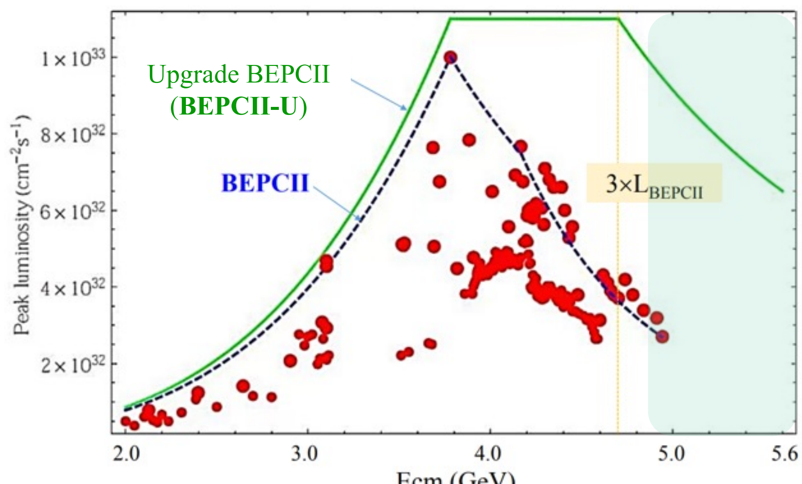
Proposal of the upgrade BEPCII

✓ An upgrade of BEPCII (**BEPCII-U**) has been approved in July 2021:
the optimized energy is 2.35 GeV with luminosity 3 times higher than current BEPCII and extend the maximum energy to 5.6 GeV

- Add another cavity per beam to improve the RF power
- Change optics slightly, increase number of bunches
- Challenges: high beam intensities, backgrounds and aging effect in the detector
- Small risk: can continue running with better performance than BEPCII
- Timescale: 2.5 years construction + 0.5 year installation
- Installation: July – December 2024 and the upgraded machine ready in Jan. 2025

	BEPCII	BEPCII-U
Lum [10^{32}cm^{-2}s^{-1}]	3.5	11
β_y^* [cm]	1.5	1.35
Bunch Current [mA]	7.1	7.5
Bunch Num	56	120
SR Power [kW]	110	250
$\xi_{y,\mathrm{lum}}$	0.029	0.033
Emittance [nmrad]	147	152
Coupling [%]	0.53	0.35
Bucket Height	0.0069	0.011
$\sigma_{z,0}$ [cm]	1.54	1.07
σ_z [cm]	1.69	1.22
RF Voltage [MV]	1.6	3.3

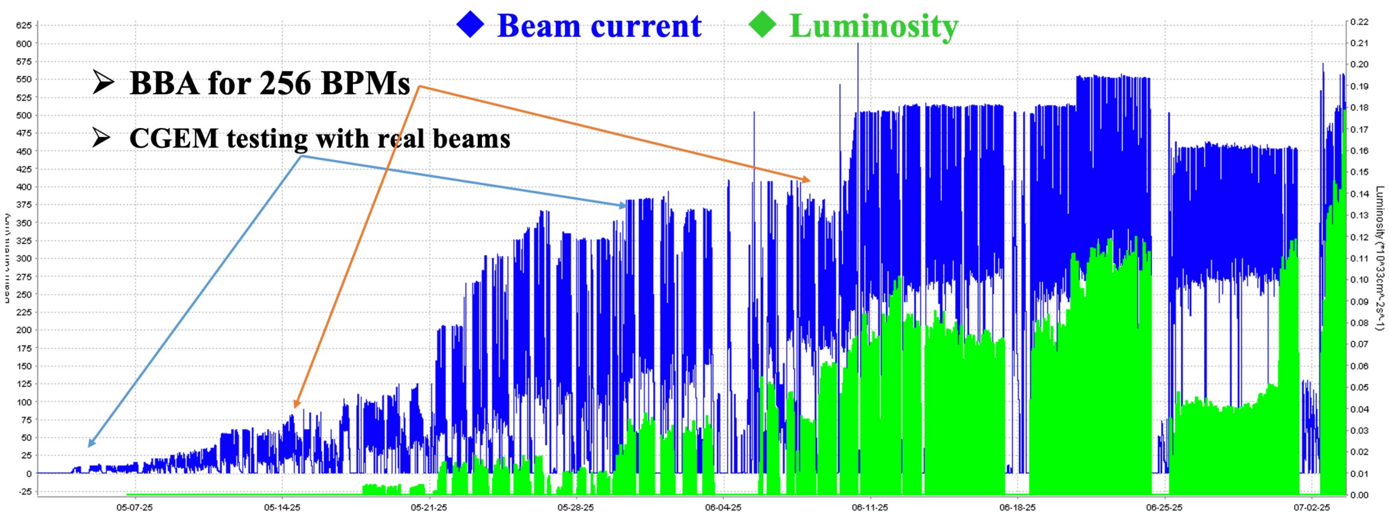




Status of BEPCII-U

from Chenghui YU

The storage ring operation began @ ψ(3686) on May 2nd, 2025, following the successful completion of all system readiness checks.



Beam current 560mA/480mA & Peak luminosity $2\times10^{32}cm^{-2}s^{-1}$

Vacuum of BEPCII-U, a new machine, is getting recovered slowly.
The vacuum of BER(7×10^{-9} torr@560mA) is better than BPR(1×10^{-8} torr@480mA)
→ final target: 4×10^{-9} torr
Further luminosity optimizations are needed!

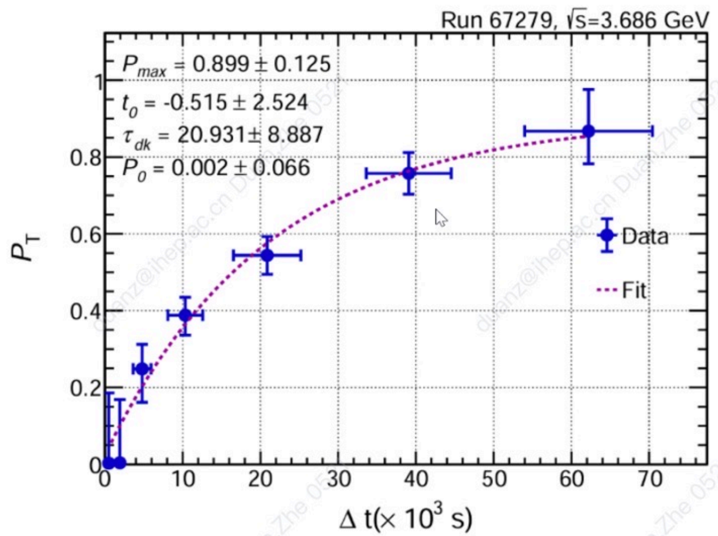
Status of BEPCII-U

Chenghui Yu
Yutie Liang
Zhe Duan

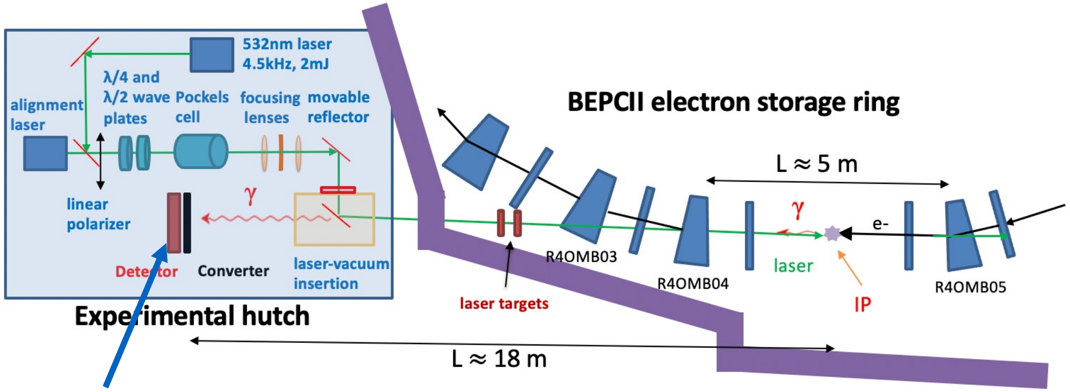
Measurements of beam polarization

➢**Transverse (vertical) polarization has been observed by BESIII at BEPCII**

➢**Laser Compton Polarimeter is being implemented in BEPCII for precise polarization measurement**



Total cost: 4.0 M CNY

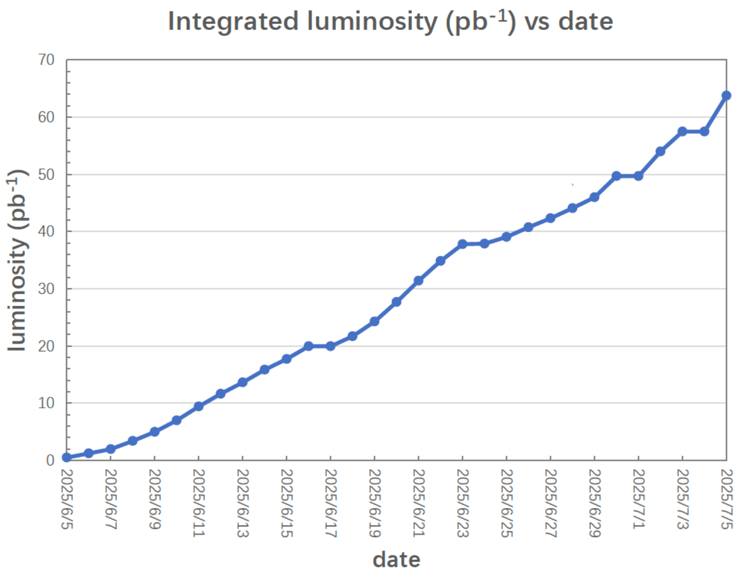


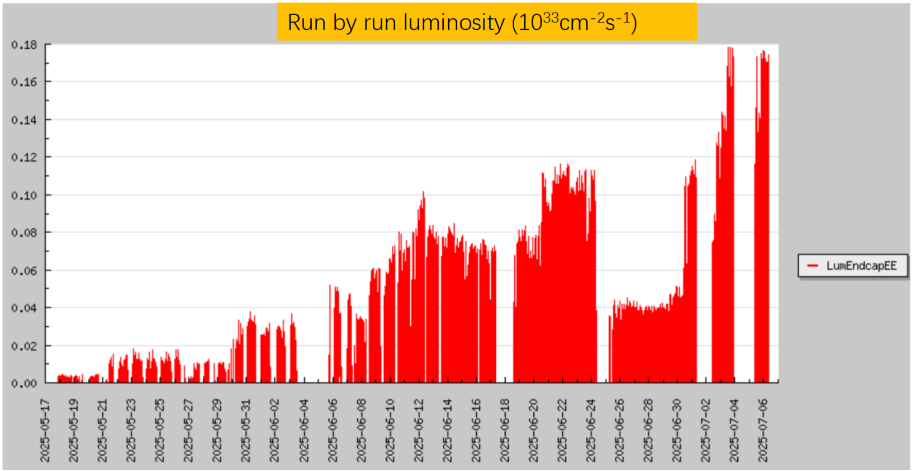
Taichu Pix detector

Providing polarization measurements bunch by bunch!
Spin related physics could be available in the future.

Status of BESIII: data-taking

Mingyi Dong



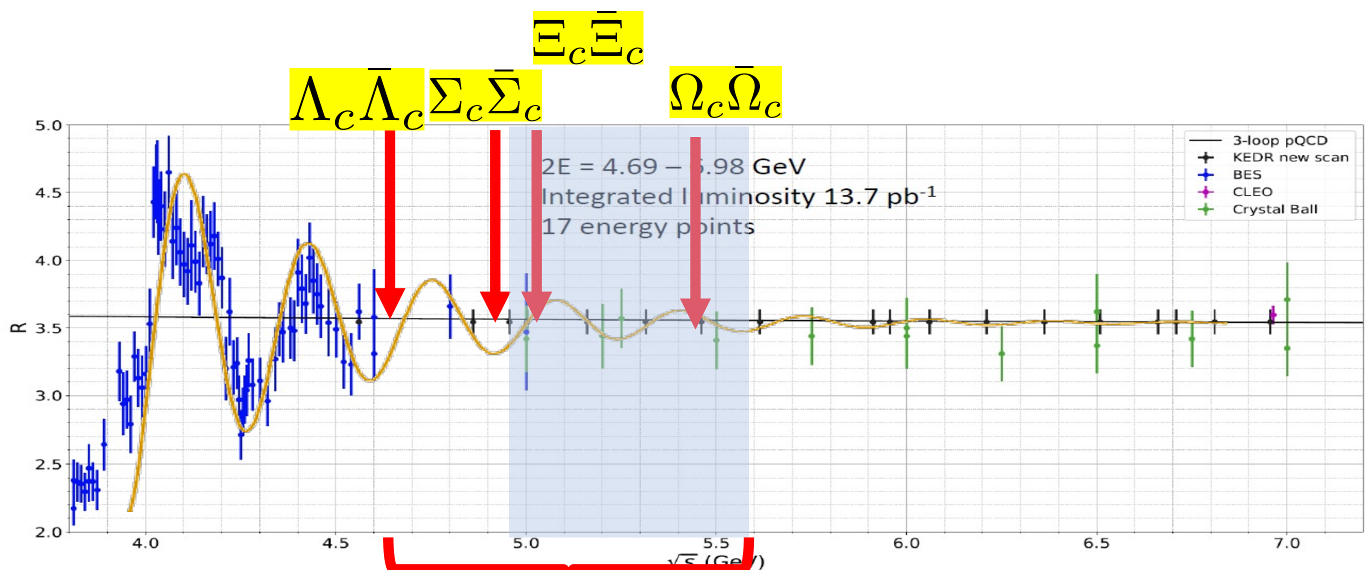


- Collision beam started from May 17, 2025
- Scan of *ψ*(3686) peak position was finished on June 3rd, 2025
- The on-peak data taking started beam energy on June 5th, 2025
- About 65 fb^{-1} integrated luminosity has been collected until July 6th , 2025

Need about 600 pb^{-1}, only 65 pb^{-1} integrated luminosity (40 M ψ') collected.

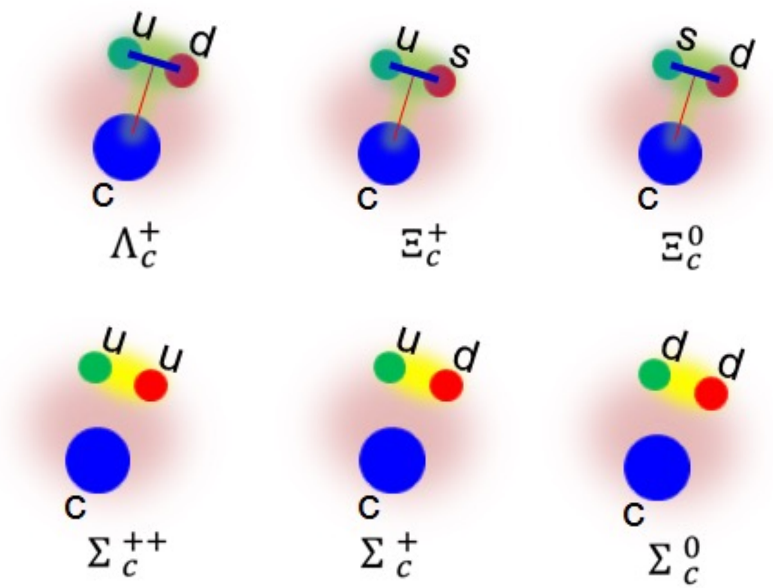
Potential physics with BEPCII-U

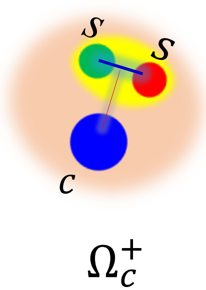
- ✓ Detailed studies of the known $Z_{c(s)}$ states and search for `black swans` in the higher energy region within a considerable amount of data sets.
- ✓ Cover all the ground-state charmed baryons: production & decays, CPV search



Few data and potential physics for XYZ and charmed baryons

Heavier charmed baryons



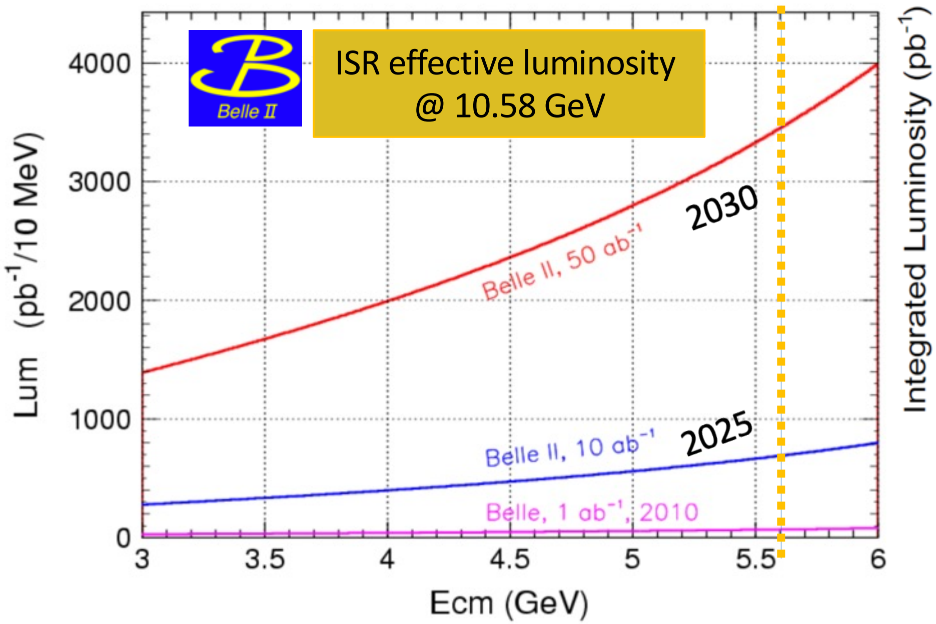


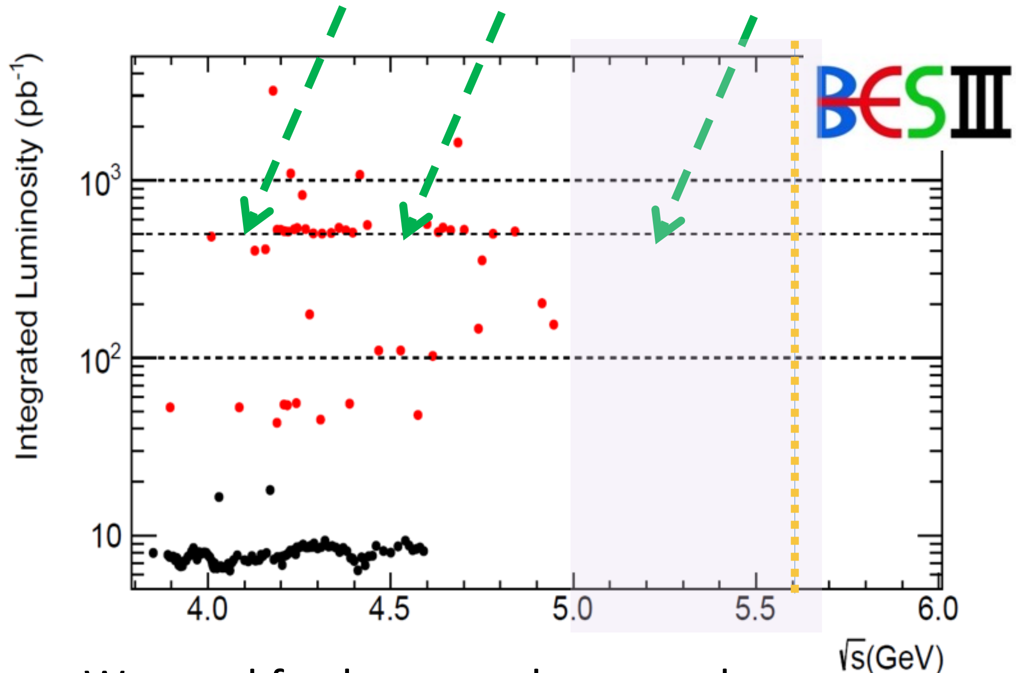
	Structure	J^P	Mass, MeV	Width,MeV	Decay
Λ_c^+	udc	$(1/2)^+$	2286.46 ± 0.14	(200 ± 6) fs	weak
Ξ_c^+	usc	$(1/2)^+$	$2467.8^{+0.4}_{-0.6}$	(442 ± 26) fs	weak
Ξ_c^0	dsc	$(1/2)^+$	$2470.88^{+0.34}_{-0.8}$	112^{+13}_{-10} fs	weak
Σ_c^{++}	uuc	$(1/2)^+$	2454.02 ± 0.18	2.23 ± 0.30	$\Lambda_c^+\pi^+$
Σ_c^+	udc	$(1/2)^+$	2452.9 ± 0.4	< 4.6	$\Lambda_c^+\pi^0$
Σ_c^0	ddc	$(1/2)^+$	2453.76 ± 0.18	2.2 ± 0.4	$\Lambda_c^+\pi^-$
$\Xi_c^{\prime +}$	usc	$(1/2)^+$	2575.6 ± 3.1	—	$\Xi_c^+\gamma$
$\Xi_c^{\prime 0}$	dsc	$(1/2)^+$	2577.9 ± 2.9	—	$\Xi_c^0\gamma$
Ω_c^0	ssc	$(1/2)^+$	2695.2 ± 1.7	(69 ± 12) fs	weak
Σ_c^{*++}	uuc	$(3/2)^+$	2518.4 ± 0.6	14.9 ± 1.9	$\Lambda_c^+\pi^+$
Σ_c^{*+}	udc	$(3/2)^+$	2517.5 ± 2.3	< 17	$\Lambda_c^+\pi^0$
Σ_c^{*0}	ddc	$(3/2)^+$	2518.0 ± 0.5	16.1 ± 2.1	$\Lambda_c^+\pi^-$
Ξ_c^{*+}	usc	$(3/2)^+$	$2645.9^{+0.5}_{-0.6}$	< 3.1	$\Xi_c\pi$
Ξ_c^{*0}	dsc	$(3/2)^+$	2645.9 ± 0.5	< 5.5	$\Xi_c\pi$
Ω_c^{*0}	ssc	$(3/2)^+$	2765.9 ± 2.0	—	$\Omega_c^0\gamma$

Energy thresholds

- ✓ $\Lambda_c^+\bar{\Sigma}_c^-$ 4.74 GeV
- ✓ $\Lambda_c^+\bar{\Sigma}_c\ \pi$ 4.88 GeV
- ✓ $\Sigma_c\ \bar{\Sigma}_c$ 4.91 GeV
- ✓ $\Xi_c\ \bar{\Xi}_c$ 4.95 GeV
- ✓ $\Omega_c^0\bar{\Omega}_c^0$ 5.4 GeV

Some (personal) thoughts for future data taking



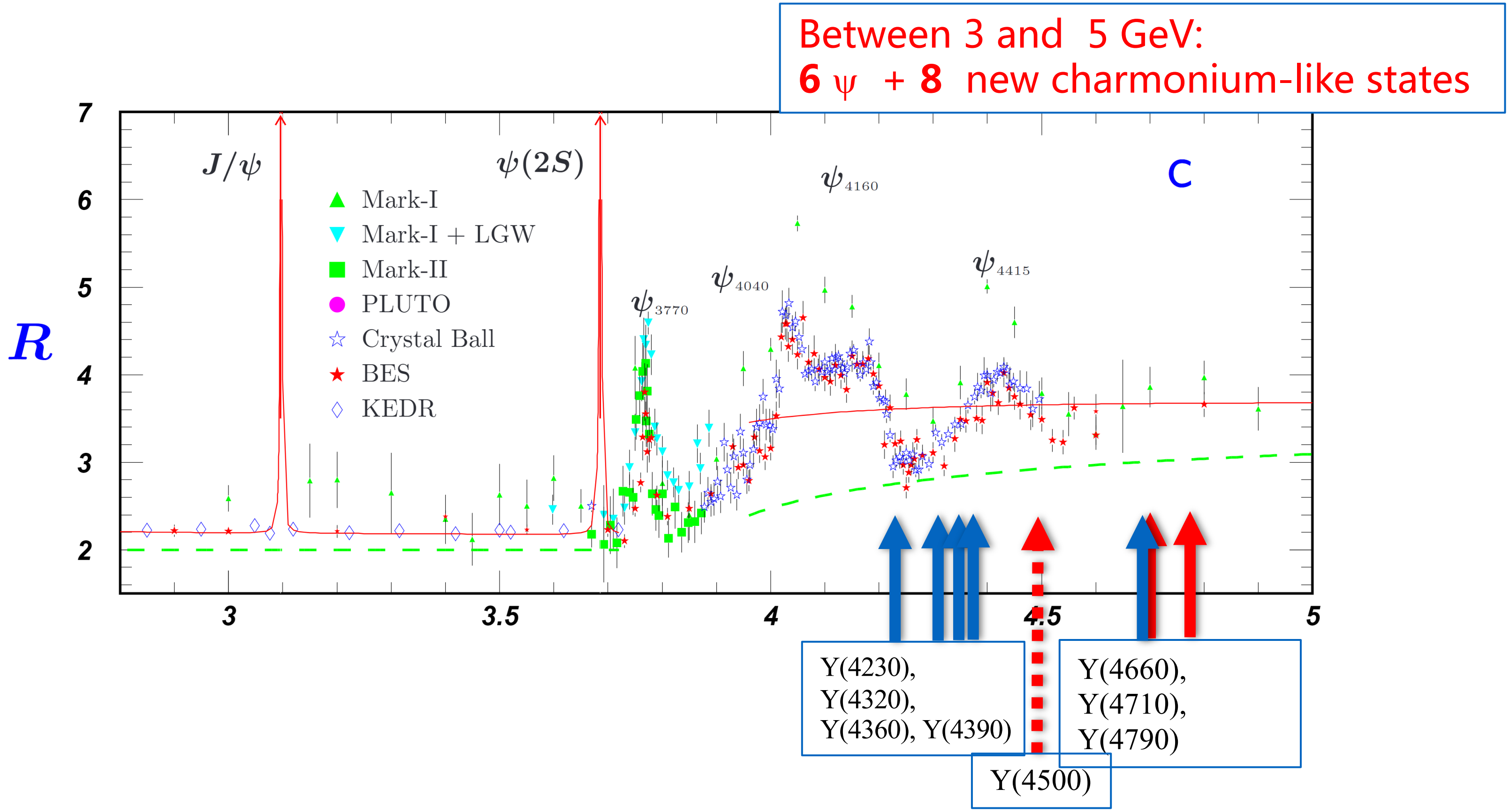


Competition with Belle II exists, and the scan energy points between 4.0 and 5.6 GeV need to be optimized

We need further scan data samples for Ecm=4.00-4.15, 4.43-4.59, 4.90-5.60 GeV, and some other energy points around charmed baryon threshold, such as

- ✓ 4.01 GeV: DsDs
- ✓ 4.6-4.7 GeV: $\Lambda_c\,\overline{\Lambda}_c$
- ✓ 4.95 -4.97GeV: $\Xi_c\ \overline{\Xi}_c$
  5.4 -5.6 GeV: $\Omega_c^0\overline{\Omega}_c^0$

How many vectors in charmonium energy region?



Besides vector charmonium ($c\bar{c}$) states, we also expect $c\bar{c}g$ hybrids, and $c\bar{c}q\bar{q}$ tetraquark states. Have they already been observed?

➔ More theoretical/experimental efforts necessary!

Joint efforts among experiments and theories

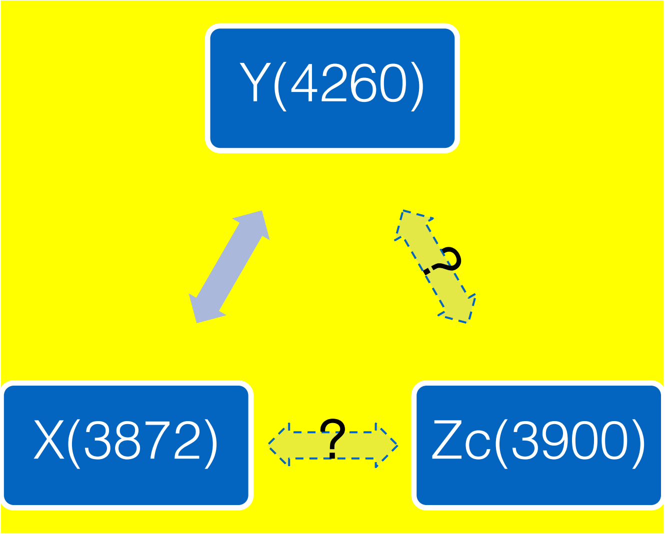
- It is crucial that different experiments, such as BESIII, LHCb and Belle II, exchange information in the efforts of amplitude analyses
  - ✓ Sharing the knowledge on analysis tools
    eg, **TF-PWA** (talks given inside BESIII and LHCb) https://github.com/jiangyi15/tf-pwa
  - ✓ Constraints on properties of the hadronic states
- A few cases:
  - Zc/Zcs productions (e^+e^- annihilations or b-hadron decays) and decays (to open or hidden charm states)

State	Decay modes	Seen by
$Z_c(3900)^{\pm,0}$	$\pi^{\mp}J/\psi$, $(D^*\bar{D})^{\mp}$	BESIII, Belle CLEO
$Z_c(4020)^{\pm,0}$	$\pi^{\mp}h_c$, $(D^*\bar{D}^*)^{\mp}$	BESIII
$Z_c(4430)^{\pm}$	$\pi^{\mp}\psi(2S)$ $\pi^{\pm}J/\psi$	Belle, ~~BaBar,~~ LHCb

in $e^+e^- \to \pi^- Zc$

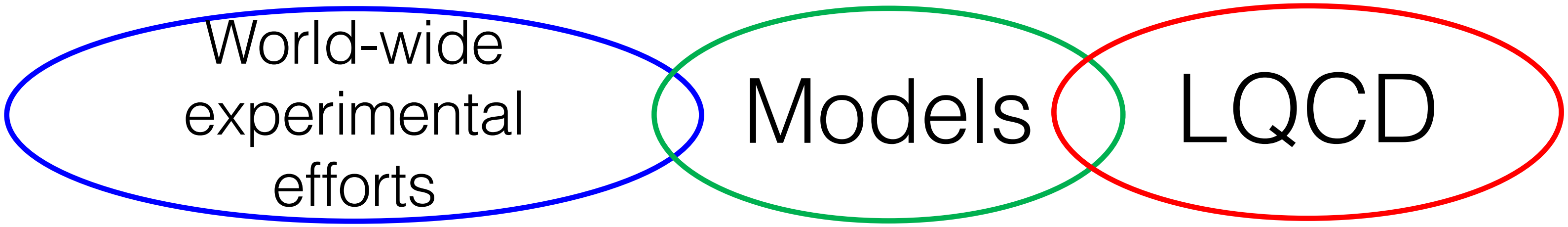
in $e^+e^- \to \pi^- Zc$

in $B \to KZc$



- Energy-dependence
- Patterns in productions and decays

Pole properties



Summary

- BESIII is successfully operating since 2008, and will continue to run for 5–10 years
  – collected large data samples in the energy range 2.0~4.95 GeV
- A large varieties of physics topics
  - ✓ Charmed mesons and baryons
  - ✓ hadron spectroscopy and XYZ states
  - ✓ Form factors of the nucleon and hyperons, hyperon CPV search
  - ✓ Low-Q^2 QCD studies: R value, multi-meson production, fragmentation function, …
  - ✓ Light hadron decays
  - ✓ Rare decays and new physics search
  - ✓ tau physics
  - ✓ …
- **Future goals:**
  50M D0, 50M D+, 15M Ds, 2M Λc , high-lumi. fine scan between 3.8 GeV and 5.6 GeV
  ➔ BEPCII-U: 3x upgrade on luminosity

Thank you!

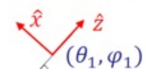
谢谢！

Relative phase of Form Factors(FFs)

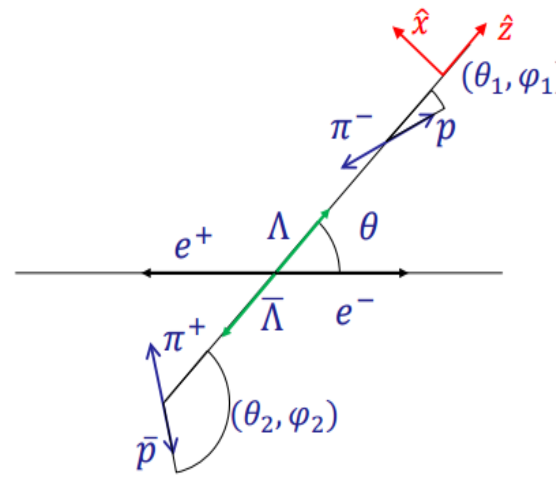
- Through the weak decay of hyperons, we could probe its polarization. Hence more information of the EFF can be studied
- $\Delta\phi$ is the phase angle difference of G_E and G_M: can be explored via angular analysis of the spin-coherent hyperon-pair weak decays

Unpolarized part　　Polarized part　　Spin correlated part

$$W(\xi) = F_0(\xi) + \eta F_5(\xi) + \alpha\bar{\alpha}\left(F_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)F_2(\xi) + \eta F_6(\xi)\right) + \sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\alpha F_3(\xi) + \bar{\alpha}F_4(\xi)\right)$$



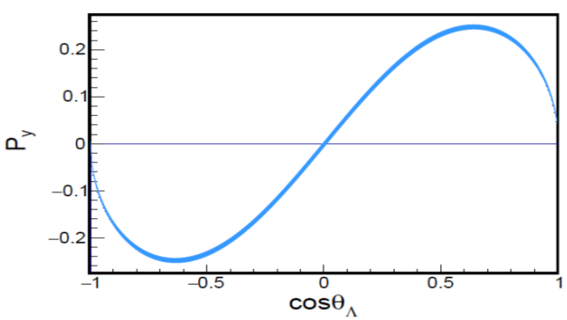
$$R = |G_E/G_M|,\ \Delta\Phi = \Phi_E - \Phi_M,\ \eta = \frac{\tau - R^2}{\tau + R^2}$$



polarization-term

independent α_- and α_+ dependence

$$P_y(\cos\theta_\Lambda) = \frac{\sqrt{1-\alpha_\psi^2}\,\sin(\Delta\Phi)\cos\theta_\Lambda\sin\theta_\Lambda}{1+\alpha_\psi\cos^2\theta_\Lambda}$$



$$\alpha = \frac{2\,\mathrm{Re}(S^*P)}{|S|^2+|P|^2}$$

$$\beta = \frac{2\,\mathrm{Im}(S^*P)}{|S|^2+|P|^2}$$

$$\gamma = \frac{|S|^2-|P|^2}{|S|^2+|P|^2}$$

$$\alpha^2+\beta^2+\gamma^2=1$$

CP asymmetry:

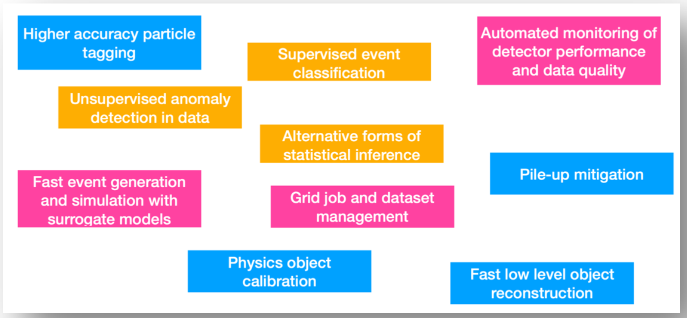
$$A = \frac{\alpha+\overline{\alpha}}{\alpha-\overline{\alpha}}\,,\qquad B = \frac{\beta+\overline{\beta}}{\beta-\overline{\beta}}\,.$$

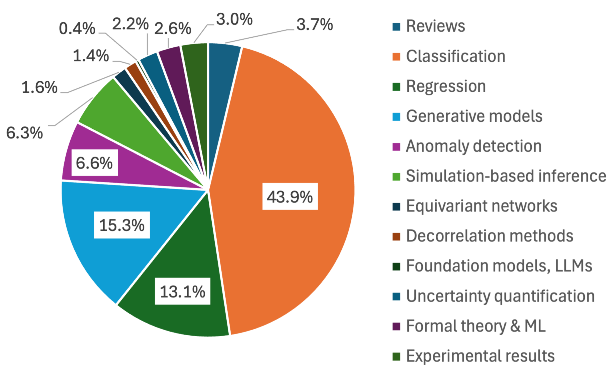
Facilities for Charm Study

- LHCb: huge x-sec, 9 fb^{-1} now (x40 current B-factories); excellent lifetime resolution due to the boost; large combinatorial BKG, difficult with neutral and missing particles
- B-factories (Belle(-II), BaBar): more kinematic constrains, clean environment, ~100% trigger efficiency, good to detect neutral particles; lower boost, poorer lifetime resolution
- τ-charm factory : Low backgrounds and high efficiency; missing technique; Quantum correlations and CP-tagging are unique;
  - BESIII: 20 fb^{-1} at 3.77 GeV; 6 fb^{-1} at 4.18 GeV; 15 fb^{-1} @ 4.6-4.9 GeV
  - STCF : 4×10^9 pairs of $D^{\pm,0}$ and 10^8 Ds pairs per year
  - Highlighted Physics programs
    - Precise measurement of (semi-)leptonic decay (f_D, f_{Ds}, CKM matrix…)
    - $D^0 - \bar{D}^0$ mixing, CPV
    - Rear decay (FCNC, LFV, LNV….)
    - Excite charm meson states D_J, D_{sJ} (mass, width, J^{PC}, decay modes)
    - Charmed baryons (J^{PC}, Decay modes, absolute BF)
    - Light meson and hyperon spectroscopy studied in charmed hadron decays

Active directions in HEP Machine Learning

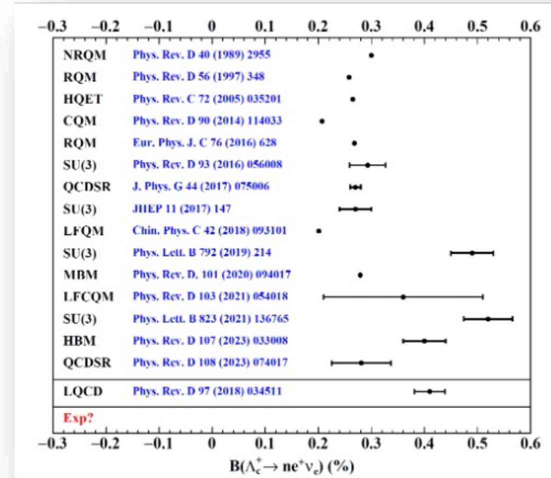
- **Machine Learning (ML) is an increasingly important in many aspects of HEP studies**
- **Ideal platform of BESIII in ML studies:**
  - ✓ large labeled background-free training samples: e.g., 10B J/ψ events
  - ✓ high-quality fully simulated MC samples
  - ✓ rich topology: low-level detector response ➔ particle 4-momentum ➔ full decay tree
  - ✓ energy-momentum conservation in event: hidden symmetry can inspire new ML structures

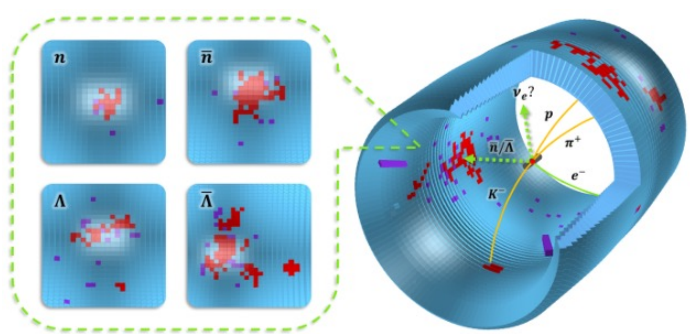


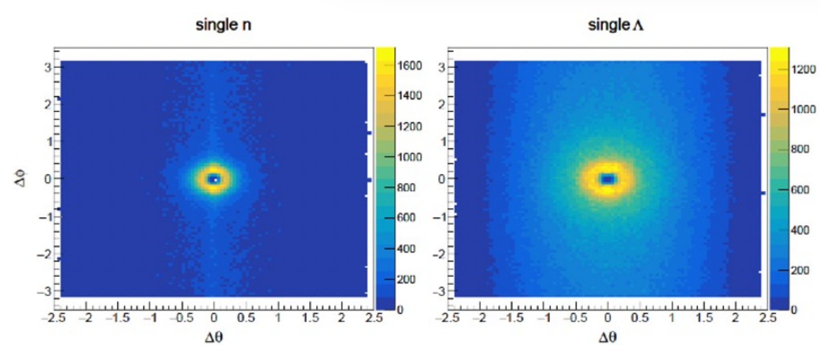


Example: hunting for $\Lambda_c^+ \to ne^+\nu$

- **Important process of semi-leptonic Λ_c^+ decay to probe strong dynamics in charmed baryon**
- **Challenges:**
  - ✓ neutrino is missing in detection
  - ✓ dominant backgrounds from $\Lambda_c^+ \to \Lambda(\to n\pi^0)e^+\nu$, with ~10x yields than that of the pursuing signals
  - ✓ elusive neutron detection due to neutral charge and contaminations from the photon showers (& noises) in electro-magnetic calorimeter (EMC)
- **Need advanced ML tool to identify neutron showers in EMC**

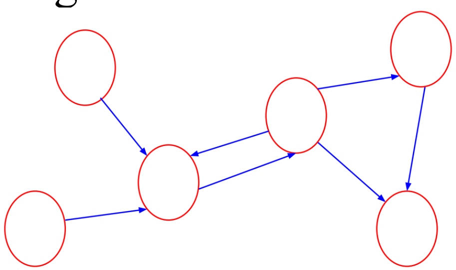




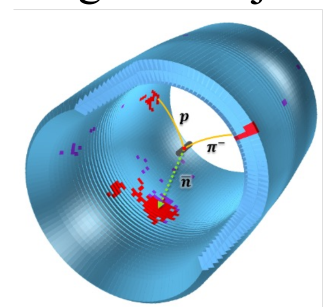


Why Graph Neural Networks (GNN)

- Many neural network architectures are specialized for sequential and image-like data such as RNNs, transformers and CNNs.
- GNN can model more arbitrary relations among data objects by treating them as edges between nodes in a graph.



- Sharing of parameters across node and edge updates in the graph.
- Permutation invariance

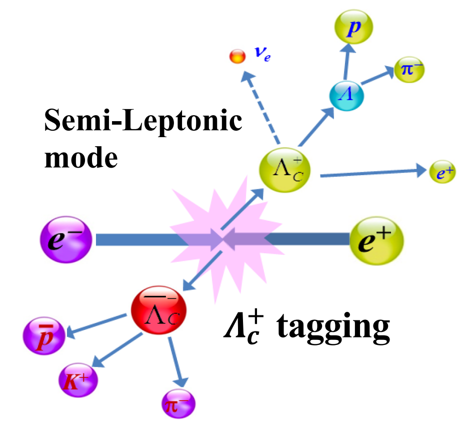


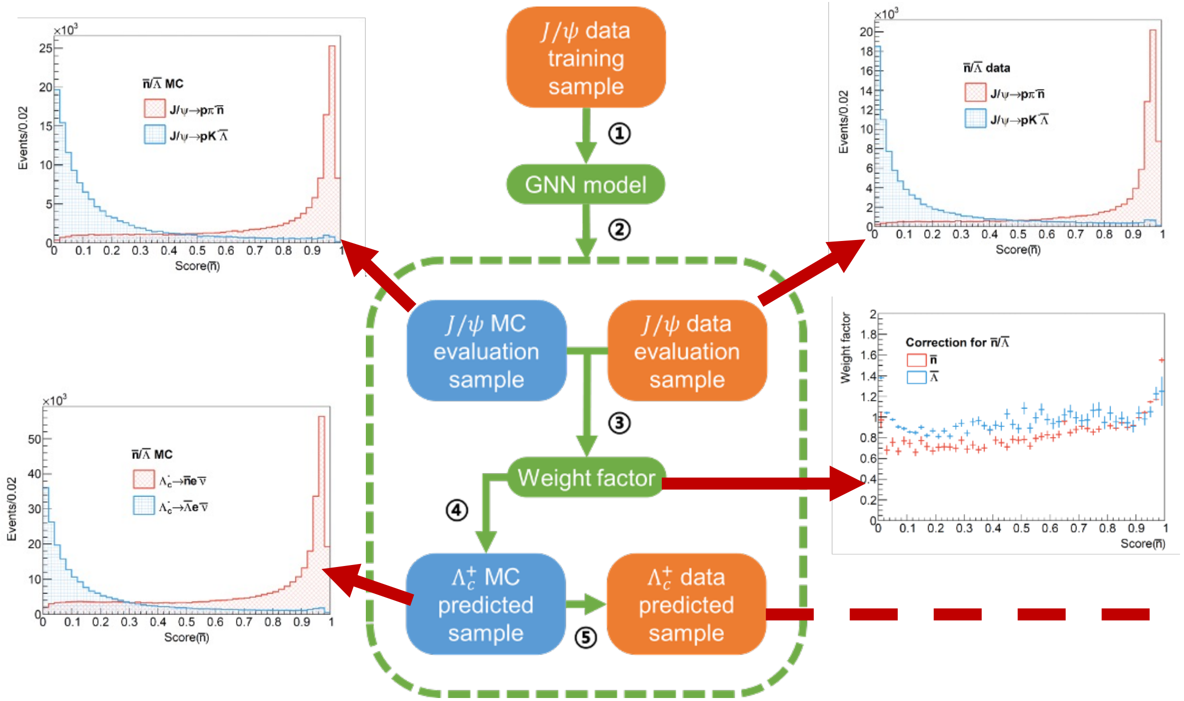
- Nearly unlimited labeled samples
- Structured data
- Clear training objectives

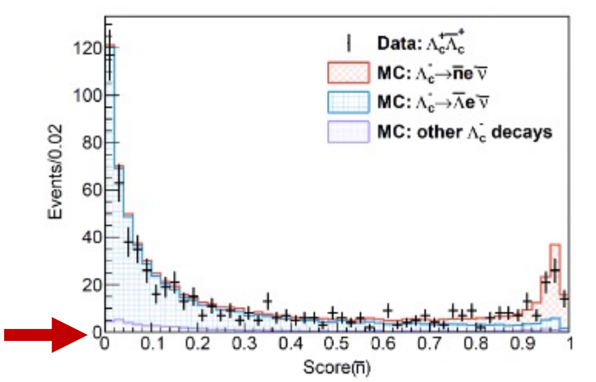
This fits well to the final state particles in physics collisions, where we deal with various objects like tracks/showers and their kinematic relations.

Analysis strategy

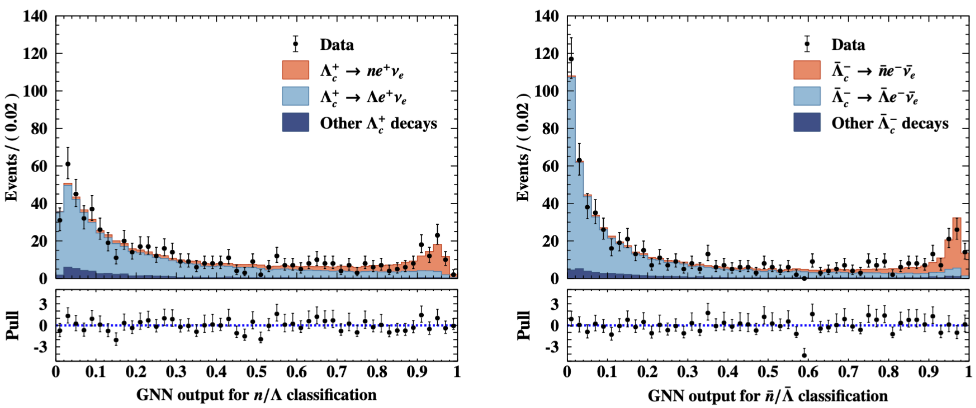
- Threshold Λ_c^+ production: clean environment and Λ_c^+ tagging
- Train GNN with **ParticleNet** using control data from $J/\psi \rightarrow \bar{p}n\pi^+, \bar{p}\Lambda K^+$ and c.c. modes based on 10B J/ψ decays



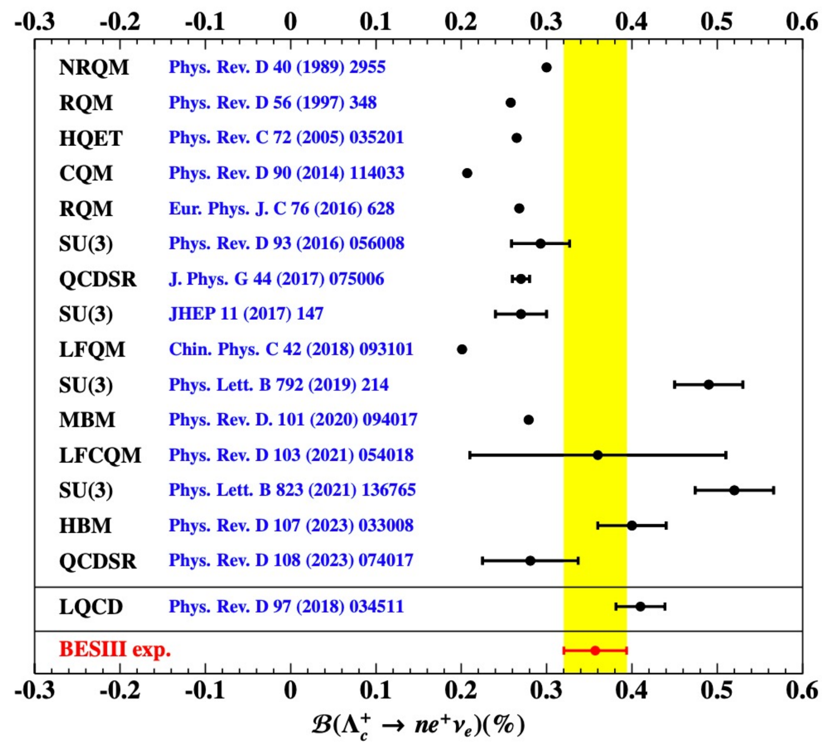




Observation of $\Lambda_c^+ \to ne^+\nu$



$\mathcal{B}(\Lambda_c^+ \to ne^+\nu_e) = (0.357 \pm 0.034_{\text{stat.}} \pm 0.014_{\text{syst.}})\%$, **(>10 σ)**



good control of systematics on GNN training

- **Model settings**: network weight initialization, batch processing sequence and dropout layer are randomly varied
- **Domain shift**: validation of independent control sample via $J/\psi \to \Sigma^+(n\pi^+)\bar{\Sigma}^-(\bar{p}\pi^0)$ and $J/\psi \to \Xi^-(\Lambda\pi^-)\bar{\Xi}^+(\bar{\Lambda}\pi^+)$