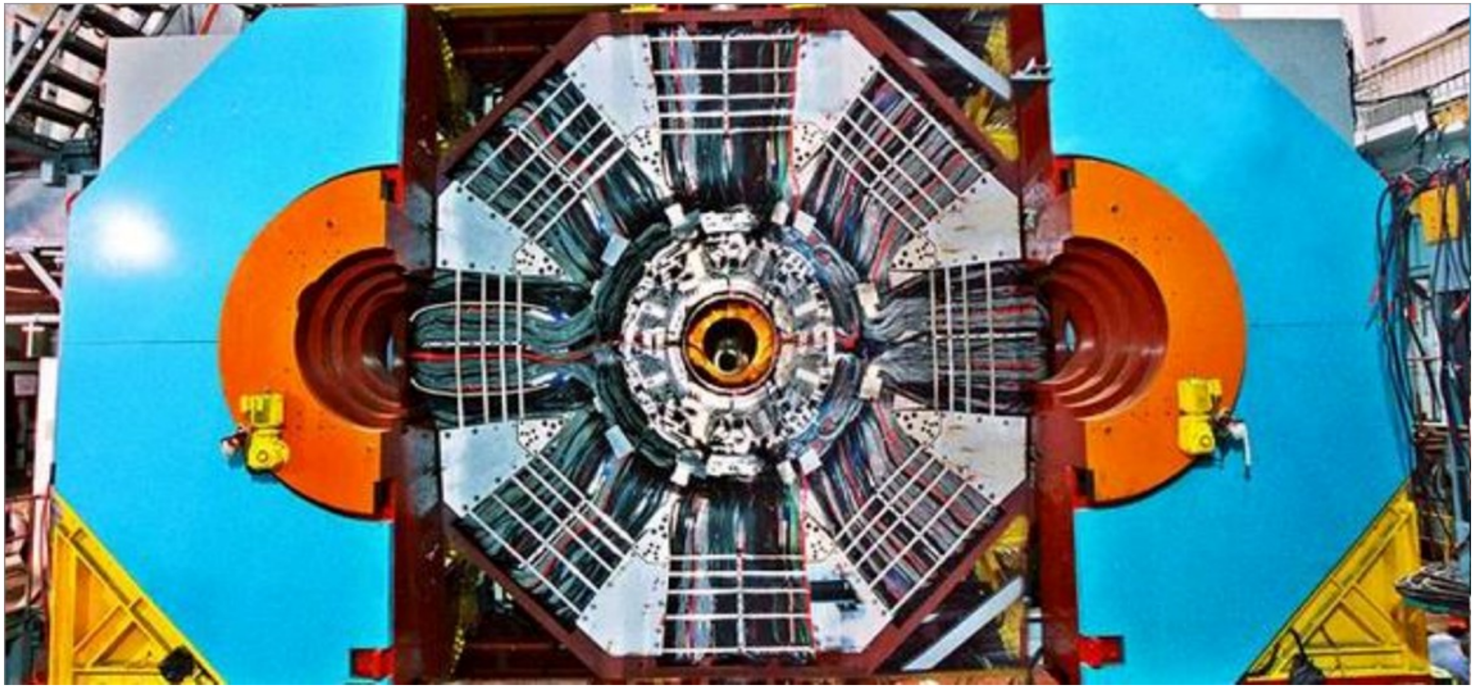

Physics progress and prospects in the BESIII experiment

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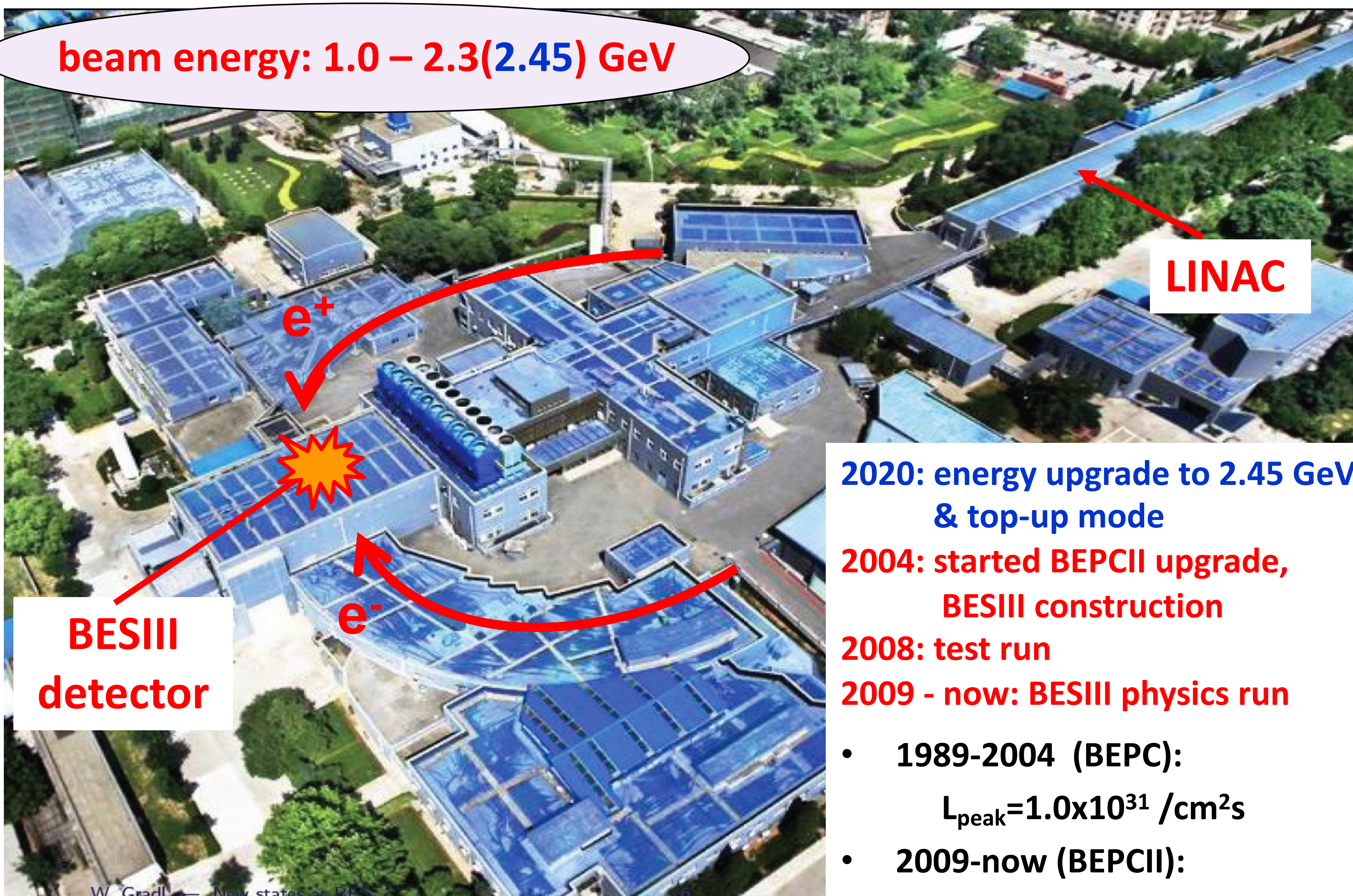
University of Chinese Academy of Sciences (UCAS)

(On behalf of the BESIII collaboration)

Outline

- Introduction
- Highlight on the recent results
- Prospects for the future
- Summary

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

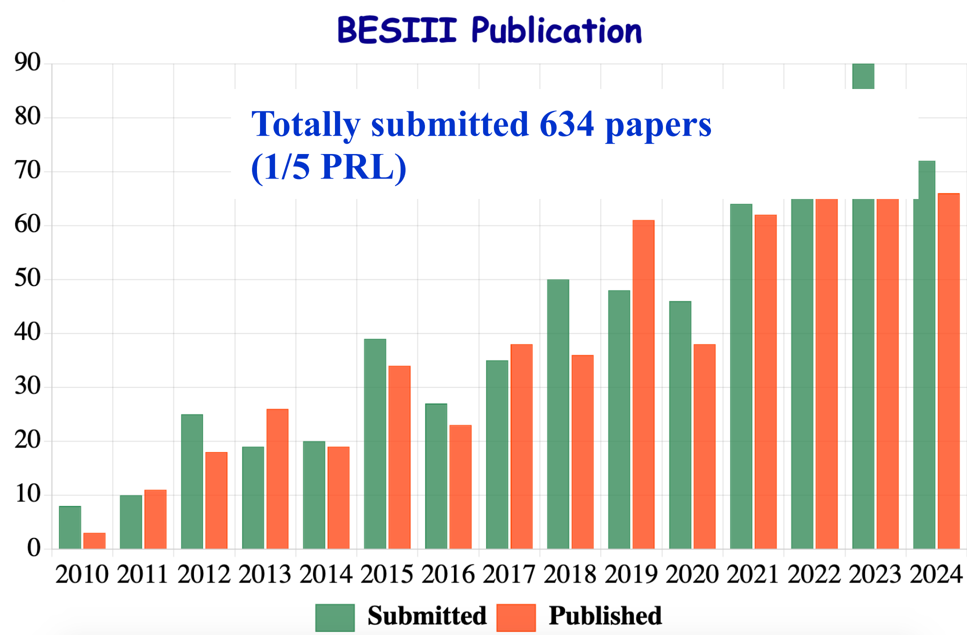
- **1989-2004 (BEPC):** L_{peak}=1.0x10^{31} /cm^2s
- **2009-now (BEPCII):** L_{peak}= 1.0 x10^{33}/cm^2(4/5/2016)

BESIII data sample

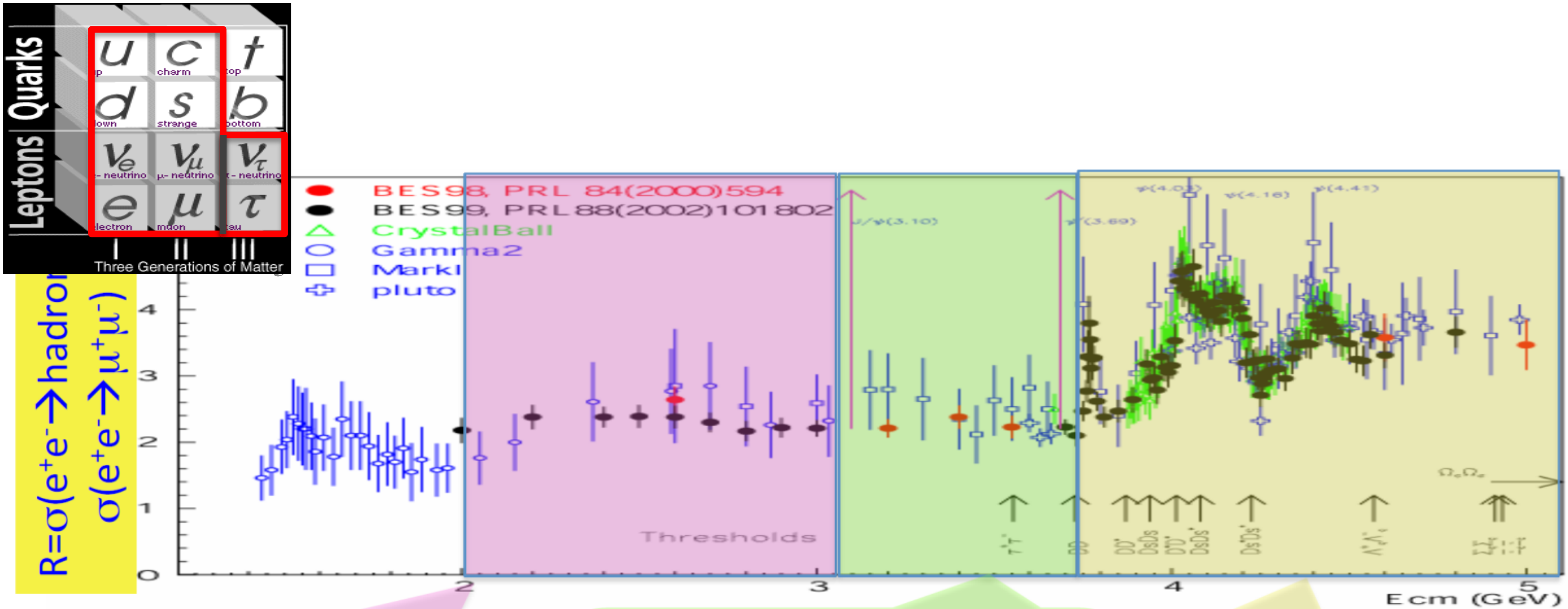
2009: 106M $\psi(2S)$
225M J/ψ
2010: 975 pb^{-1} at $\psi(3770)$
2011: 2.9 fb^{-1} *(total)* at $\psi(3770)$
482 pb^{-1} at 4.01 GeV
2012: 0.45B *(total)* $\psi(2S)$
1.3B *(total)* J/ψ
2013: 1092 pb^{-1} at 4.23 GeV
826 pb^{-1} at 4.26 GeV
540 pb^{-1} at 4.36 GeV
10×50 pb^{-1} scan 3.81 — 4.42 GeV
2014: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

in total ~55/fb

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



Physics at tau-charm Energy Region



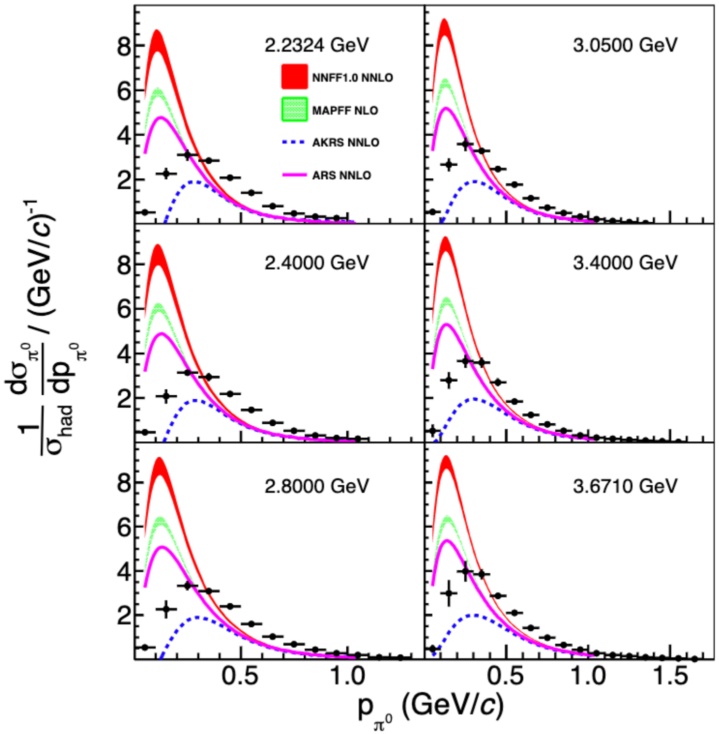
- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

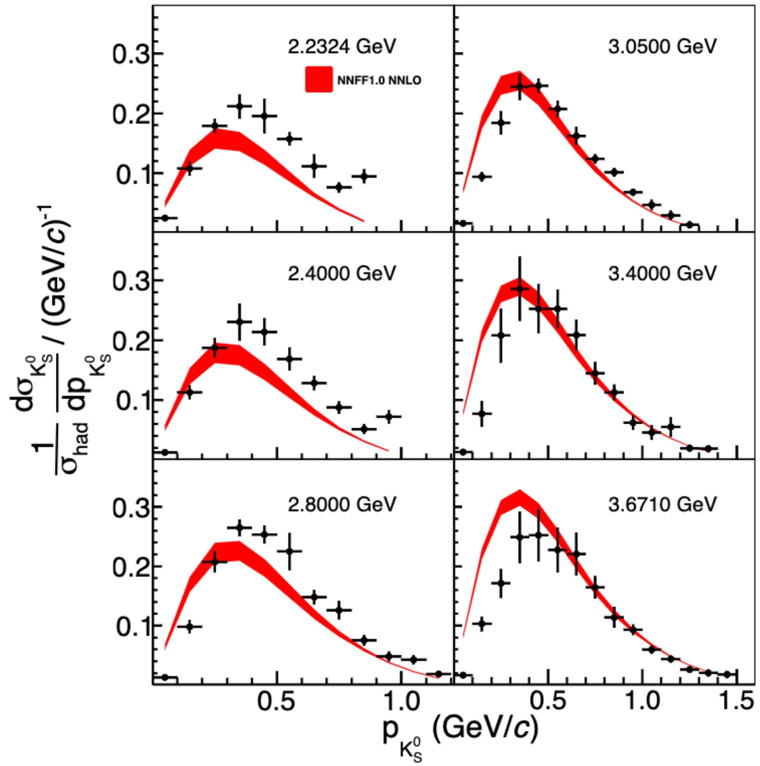
- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

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

Inclusive π^0 and K_S production in e^+e^- annihilations

PRL130, 231901 (2023)

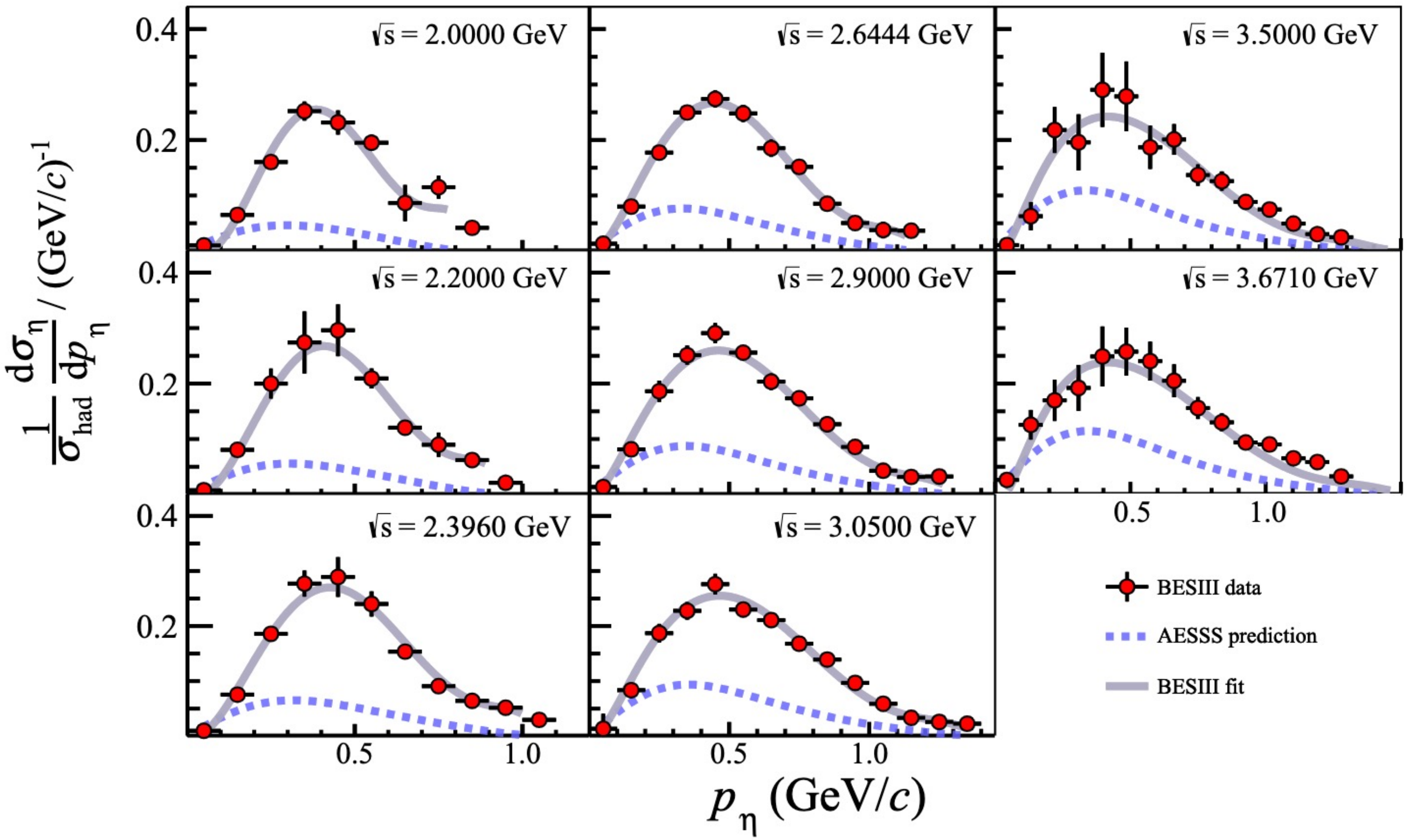




- broad z_h coverage from 0.1 to 0.9
- the agreement between data and theoretical calculations degenerates as the c.m. energies decrease
- provide brand new inputs in low-energy region to global fits of fragmentation function

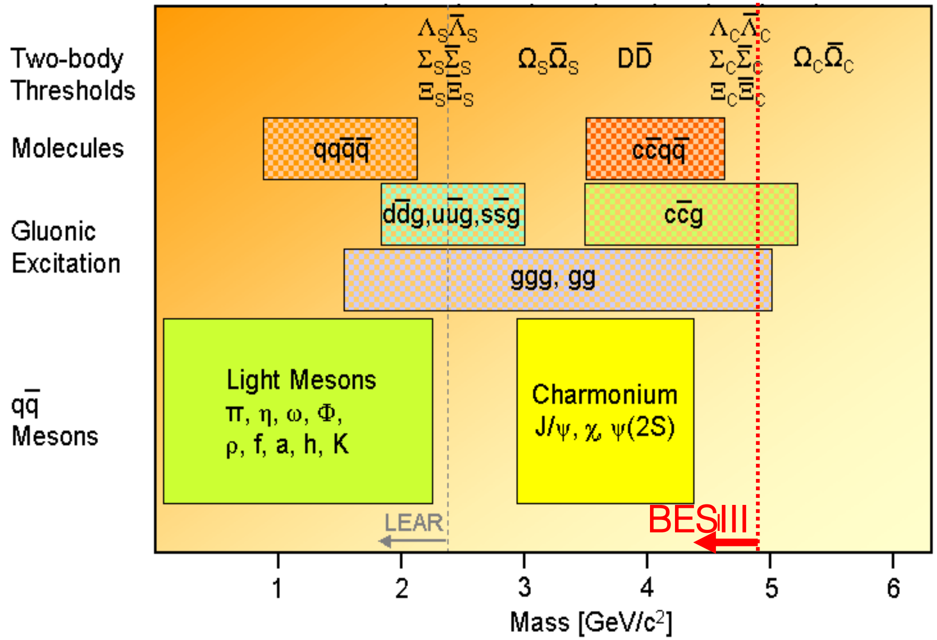
Inclusive η production in e^+e^- annihilations

PRL133, 021901 (2024)



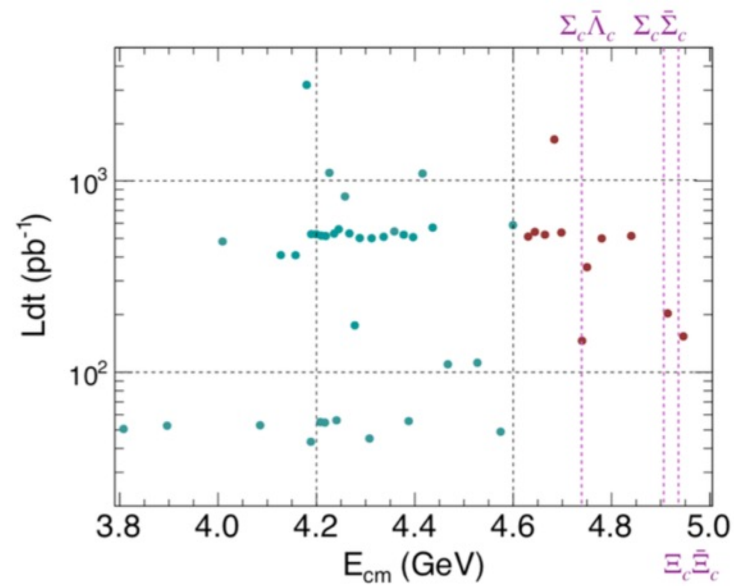
Hadron Spectroscopy

Hadron Landscape



Hadron-physics challenges:

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

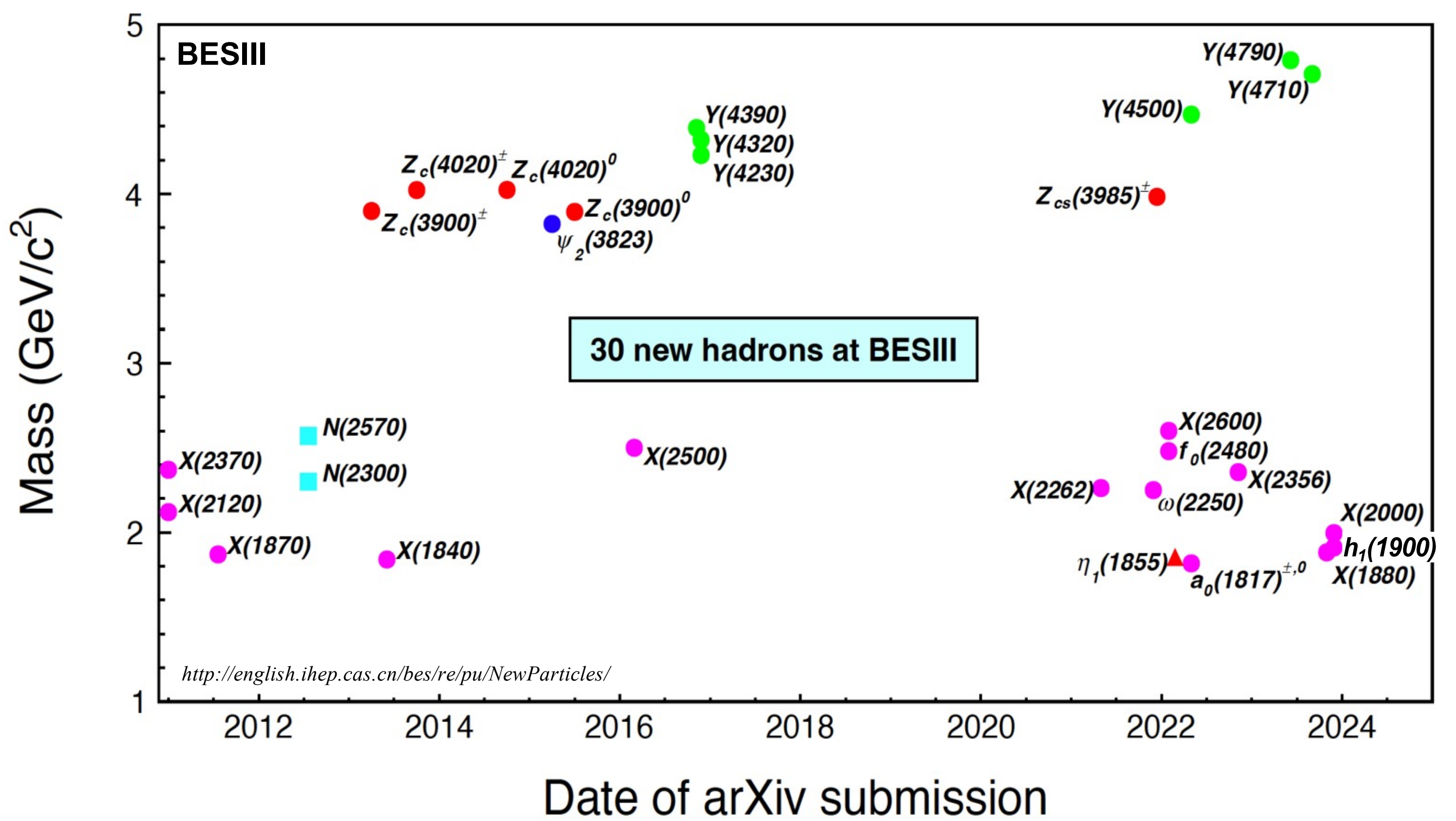


XYZ studies: about 23 /fb data above 3.8 GeV

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 3 B $\psi(2S)$**)
- Heavy hadrons: direct production, radiative and hadronic transitions (**data above 3.8 GeV**)

Discovered hadrons



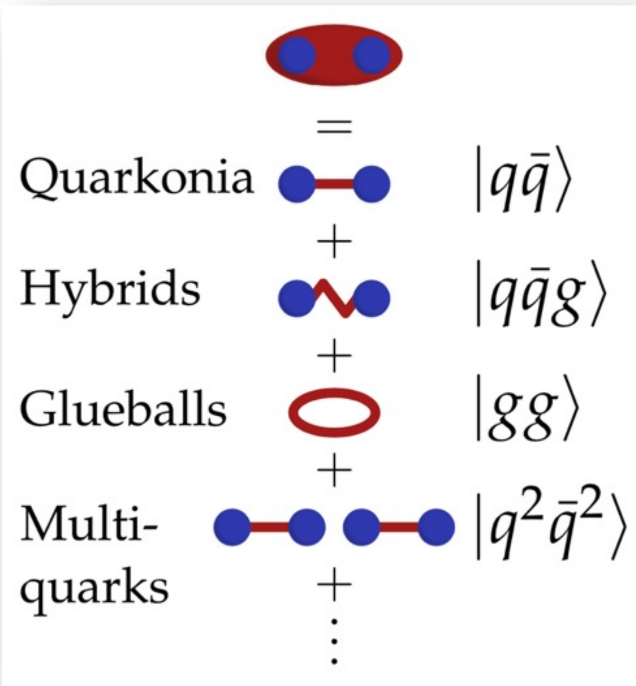
Main PWA tools

- 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]

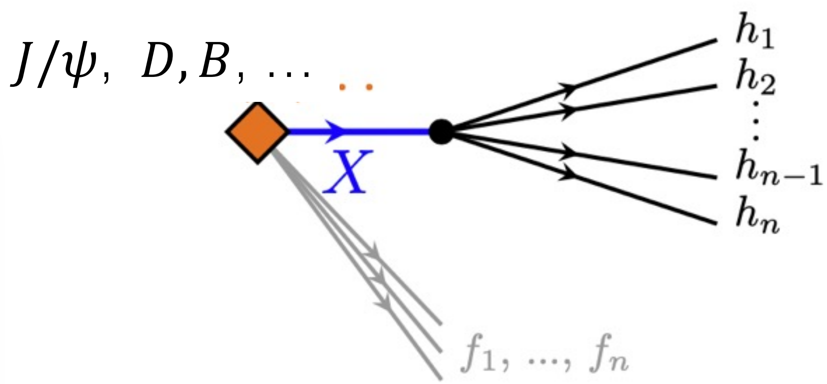
TF-PWA: Partial Wave Analysis with TensorFlow

- 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

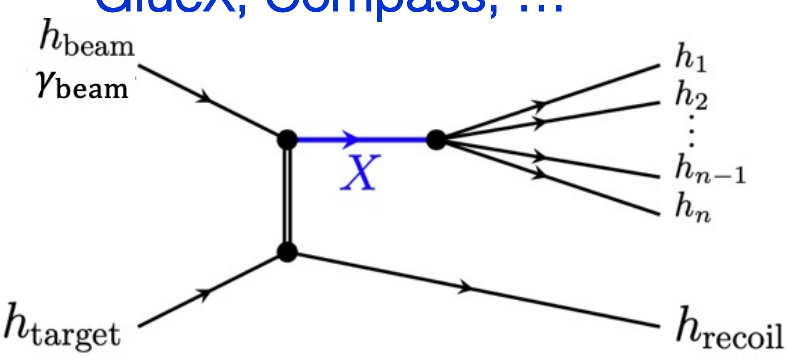
Light hadron spectroscopy



BESIII, LHCb, Belle (II) …



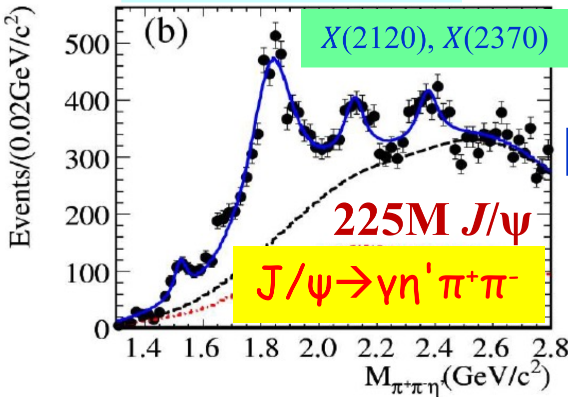
GlueX, Compass, …



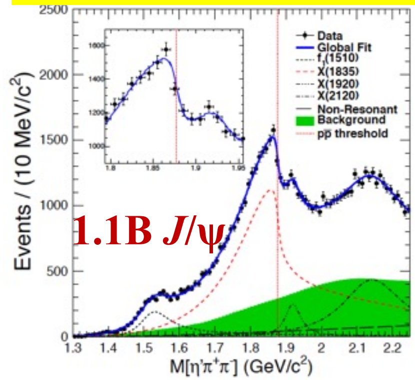
BESIII

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

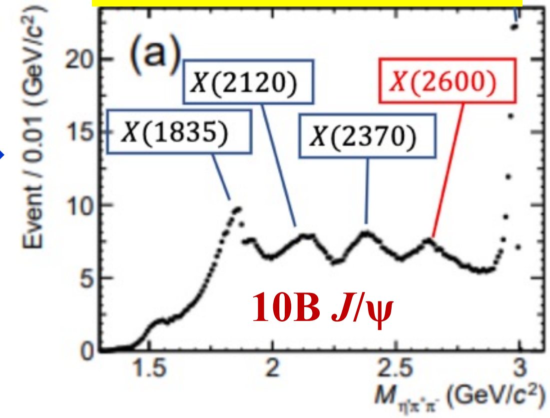
$J/\psi \to \gamma\eta'\pi^+\pi^-$

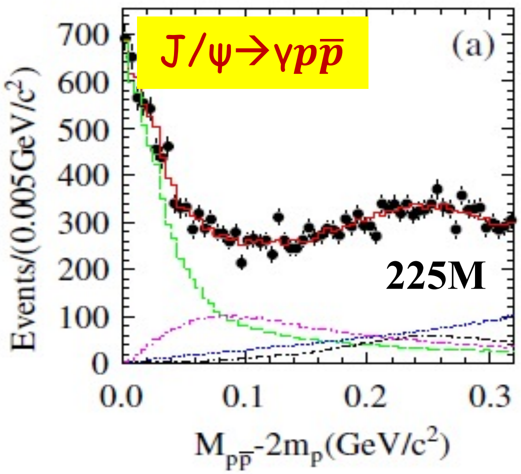


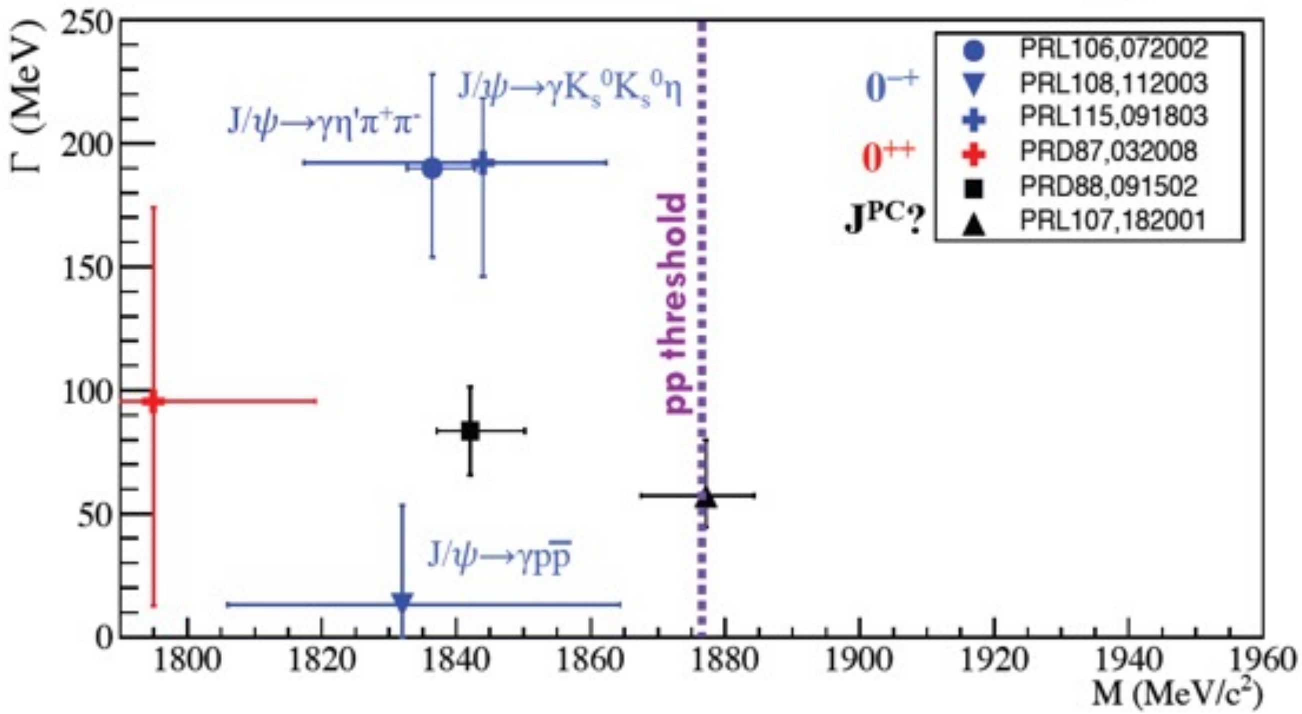
PRL117, 042002 (2016)



PRL129, 042001 (2022)



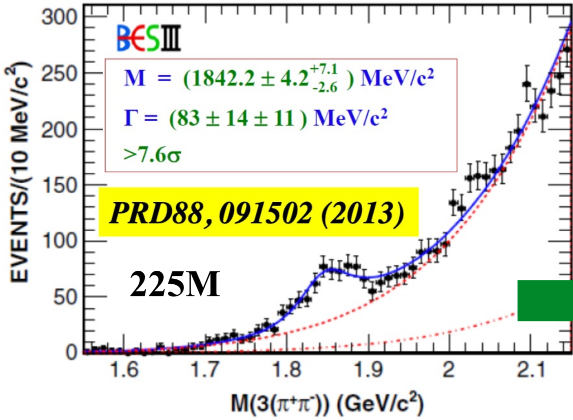




Are they the same state? It is crucial to understand their connections.

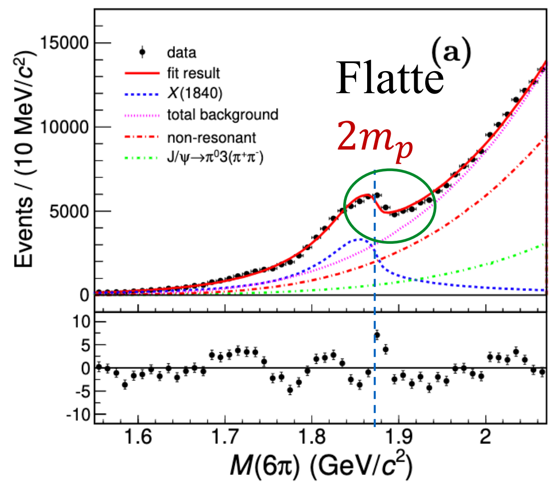
Anomolous lineshape of X(1840) in $J/\psi \to \gamma 3(\pi^+\pi^-)$

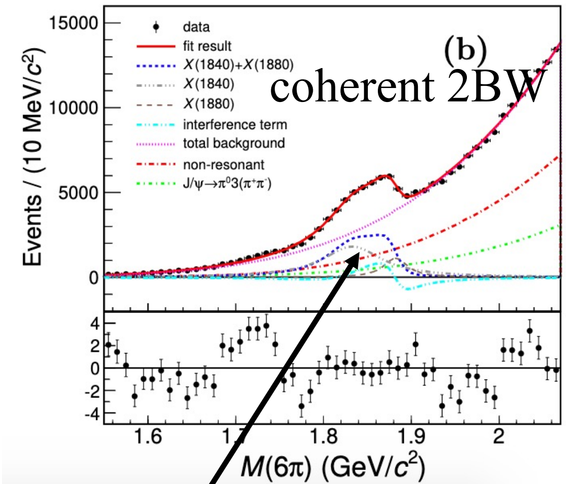
PRL132, 151901 (2024)



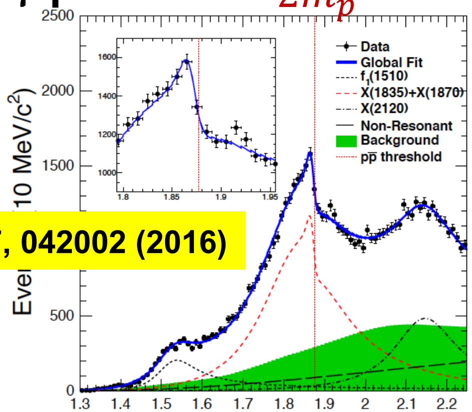
10B J/ψ events are analyzed:

50x more than the previous BESIII work





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



PRL 117, 042002 (2016)

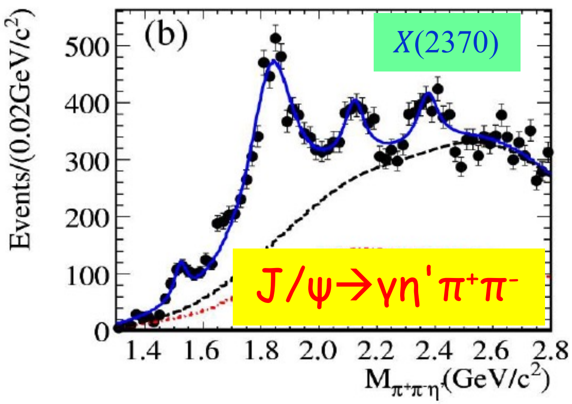
$X(1835)$	
Mass (MeV/c^2)	$1825.3 \pm 2.4^{+17.3}_{-2.4}$
Width (MeV/c^2)	$245.2 \pm 13.1^{+4.6}_{-9.6}$
$X(1870)$	
Mass (MeV/c^2)	$1870.2 \pm 2.2^{+2.3}_{-0.7}$
Width (MeV/c^2)	$13.0 \pm 6.1^{+2.1}_{-3.8}$

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)	$30.7 \pm 5.5 \pm 2.4$	
$\mathcal{B}_{X(1880)}(\times 10^{-5})$	$0.29 \pm 0.20 \pm 0.09$	$1.19 \pm 0.31 \pm 0.18$

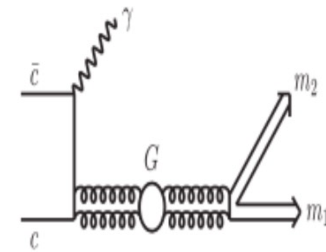
X(2370) in $J/\psi \to \gamma K_S K_S \eta'$

PRL 132.181901 (2024)

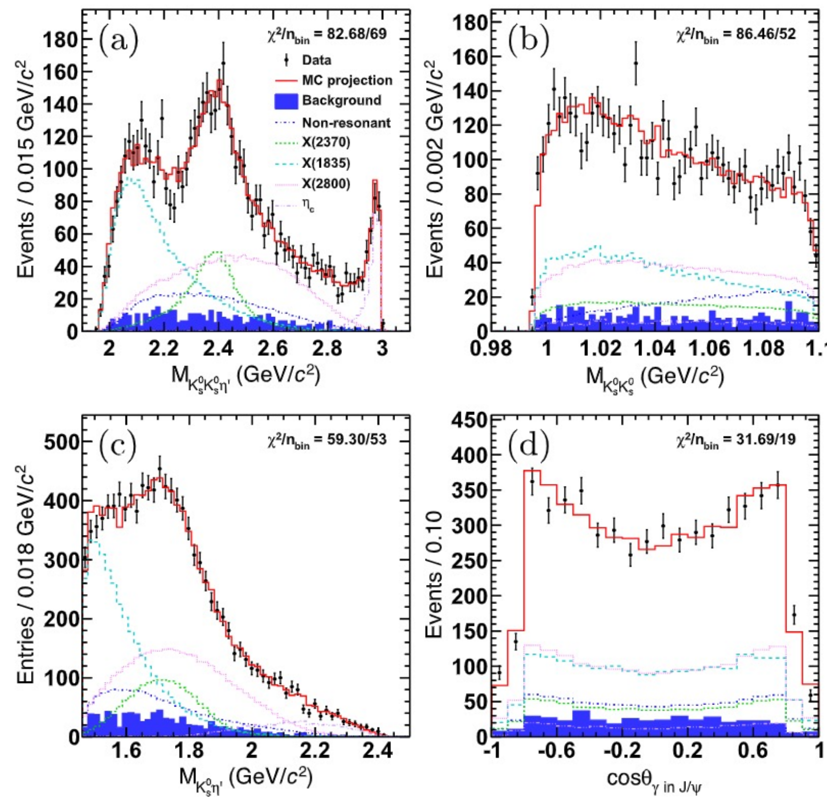
$X(2370)$ firstly seen in $J/\psi \to \gamma\pi^+\pi^-\eta'$

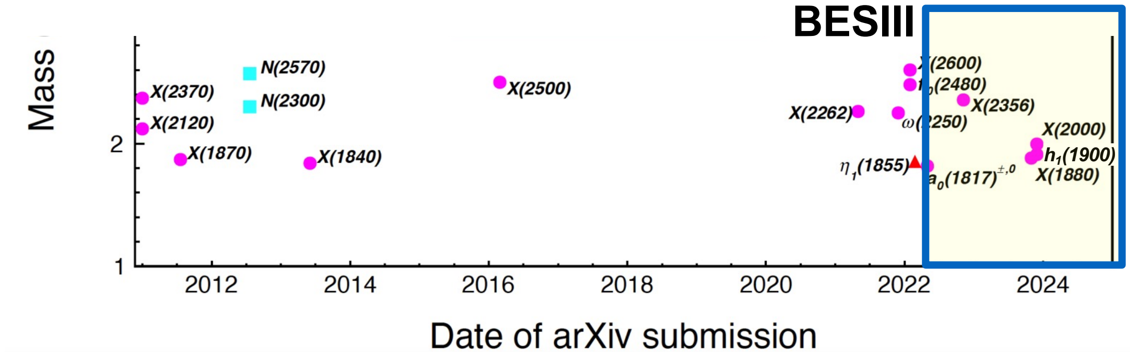


J/ψ radiative decays are gluon-rich processes



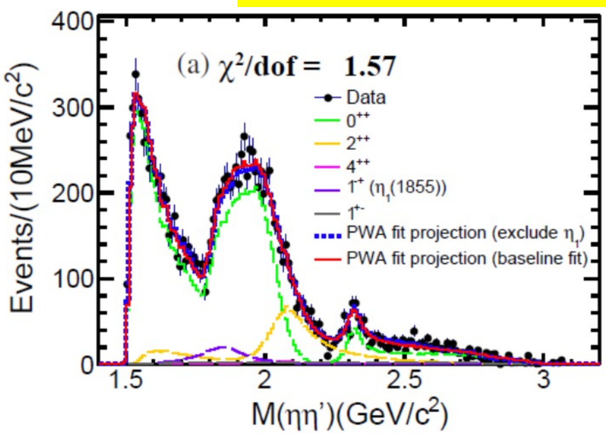
- Partial wave analysis $J/\psi \to \gamma K_S K_S \eta'$ in 10B J/ψ decays
- X(2370) $\to K_S K_S \eta'$ significance larger than 14 σ
- mass $2395 \pm 11^{+26}_{-94}$ MeV/c^2
- width $188^{+18}_{-17}{}^{+124}_{-33}$ MeV
- spin-parity is determined to be 0^{-+}
- candidate for lightest pseudoscalar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





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

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

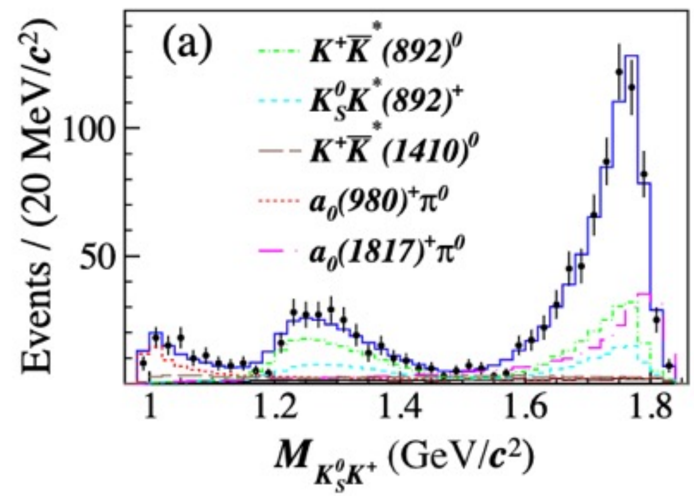


PWA of $J/\psi \to \gamma\eta\eta'$ in 10B J/ψ events

Must be exotic state!
Hybrid? Molecule? Tetraquark?

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

PRL129, 182001 (2022)

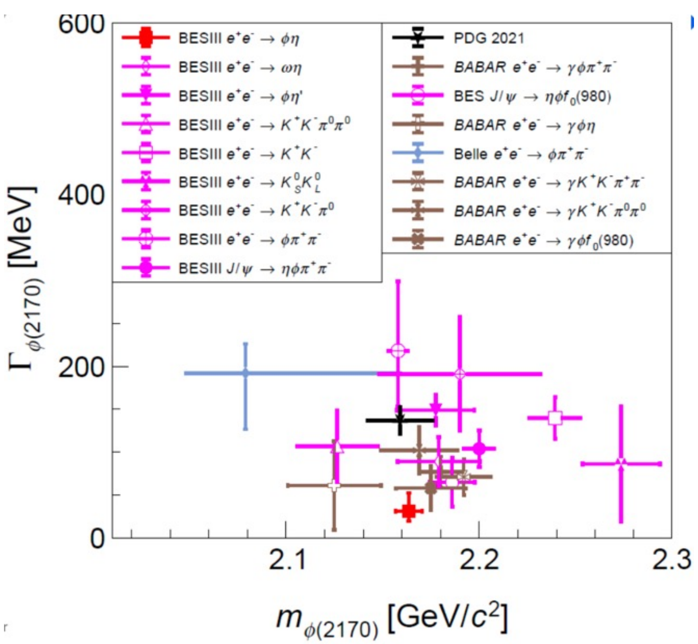


A new a_0 isospin triplet!

Rediscovery of Y(2175)/$\phi(2170)$

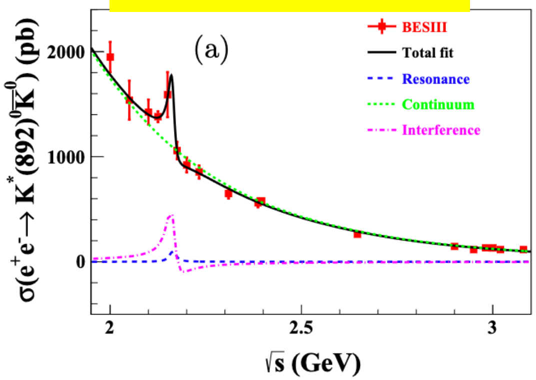
- A strangeonium(-like) state: Y-particle with strange quark

➢ **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**

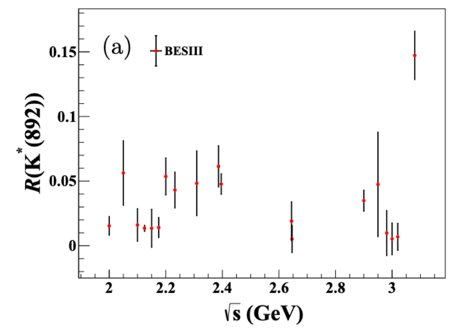


$e^+e^- \to K^*(892)^0\bar{K}^0$

JHEP 01, 180(2024)



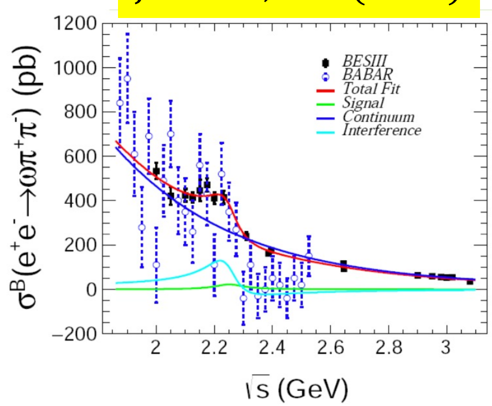
$$R(K^*(892)) = \frac{\sigma(e^+e^- \to K^*(892)^+K^-)}{\sigma(e^+e^- \to K^*(892)^0\bar{K}^0)}$$



R<0.2: much less than 1?

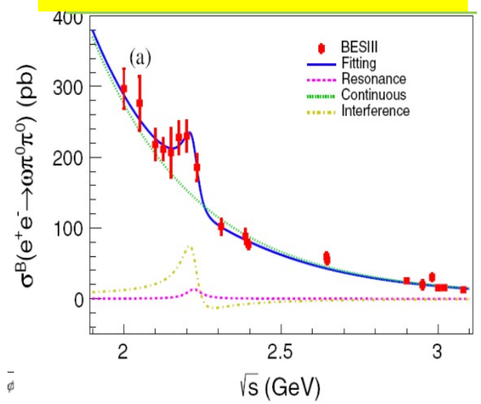
$e^+e^- \to \omega\pi^+\pi^-$

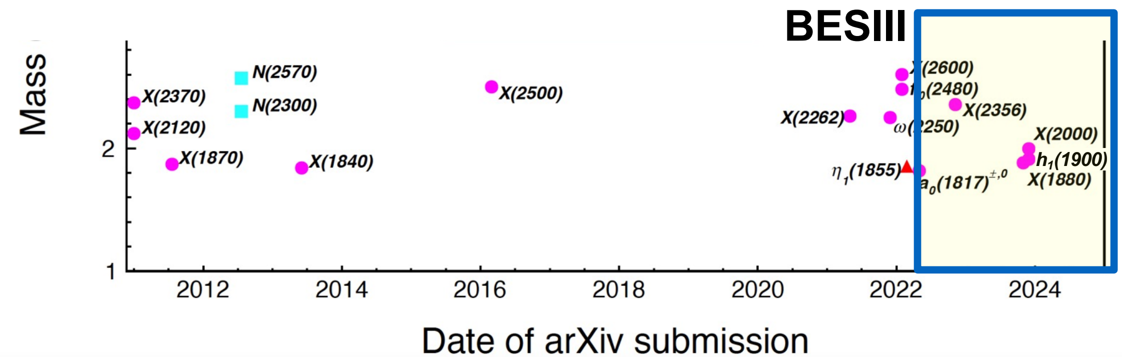
JHEP 01, 111 (2023)



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

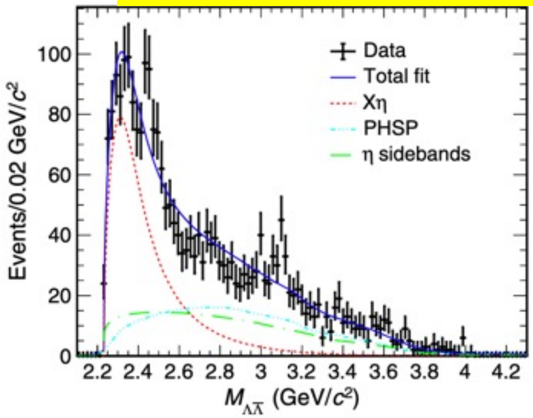
PRD105, 032005 (2022)





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

PRD 107, 112001 (2023)

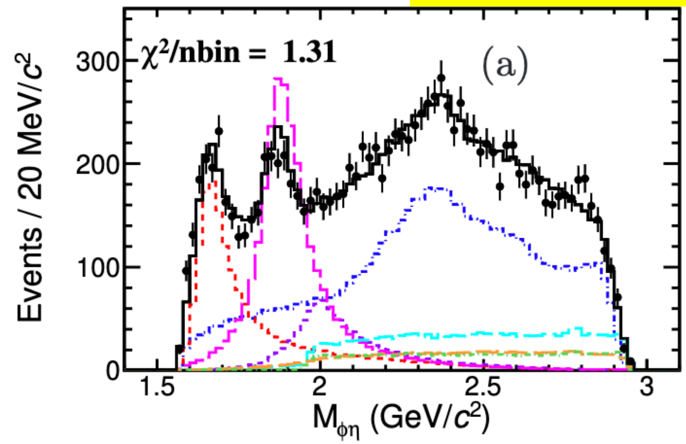


- Clear enhancement is seen near the $\Lambda\bar{\Lambda}$ mass threshold combining 31 datasets
- Simultaneous 1D fit to the $\Lambda\bar{\Lambda}$ mass spectra assuming a 1^{--} state:
  mass: $2536 \pm 7 \pm 15$ MeV/c^2
  width: $304 \pm 28 \pm 54$ MeV

hexaquark? baryonium?

New strangeonium in $J/\psi \to \phi\eta\pi^0$

arXiv:2311.0704

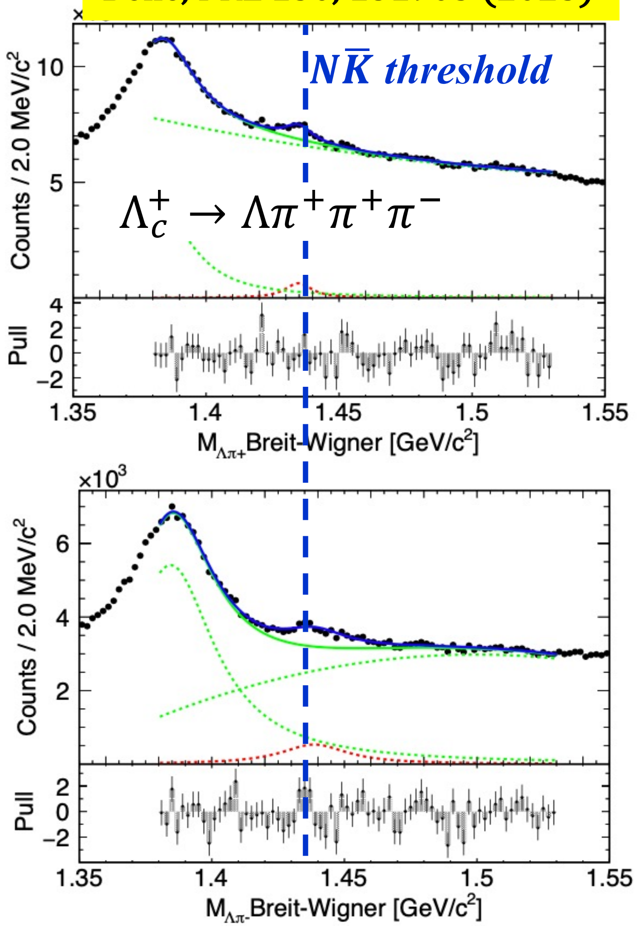


PWA fit to the isospin violating process $J/\psi \to \phi\eta\pi^0$ in 10B J/ψ events

Observations:
- $h_1(1900)(\mathbf{1}^{+-})$:
  $h_1(2P)$ strangeonium state?
- X(2000) $(\mathbf{1}^{--})$:
  $\phi(3S)$ or $\phi(3D)$ strangeonium state?

Hyperons from charmed baryon decays

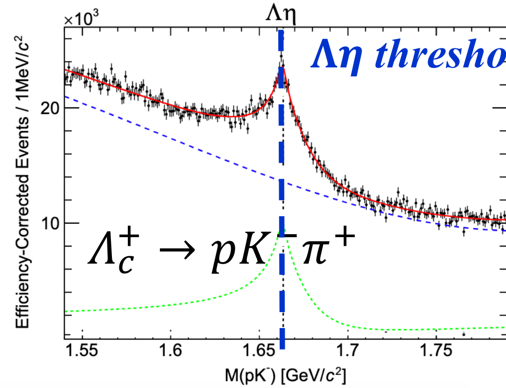
Belle, PRL 130, 151903 (2023)



Enhancement around 1.43 GeV

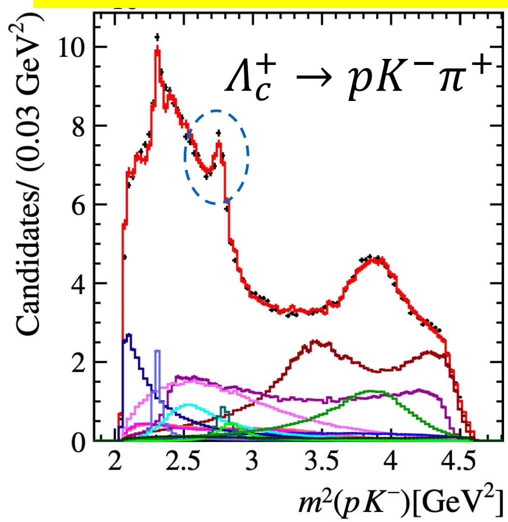
$\Sigma(1430)$ or $N\bar{K}$ threshold cusp?

BELLE, PRD108, L031104 (2023)

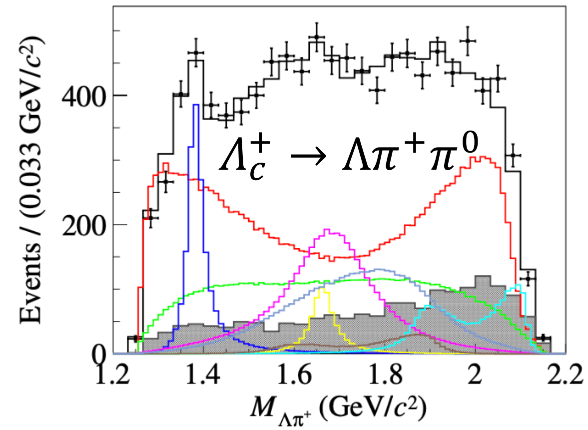


Λη threshold cusp enhanced due to Λ(1670)

LHCb, PRD108, 012023 (2023)

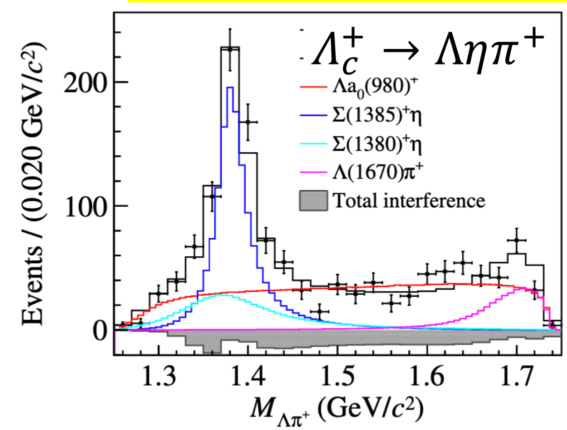


BESIII, JHEP12(2022)033



Many Σ^* contributions

BESIII, arXiv:2407.12270

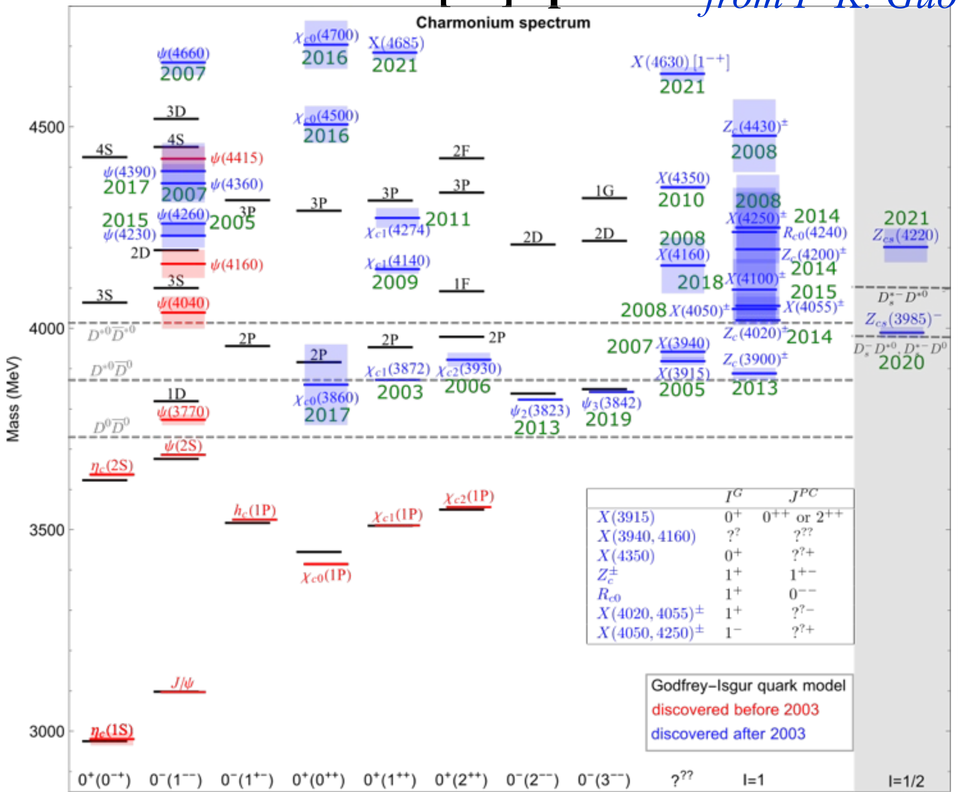


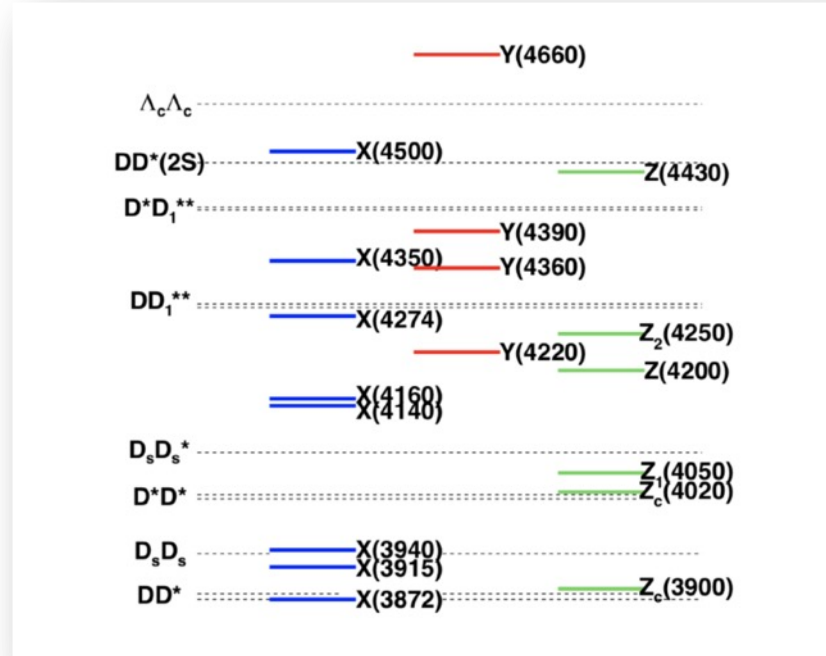
Evidence for $\Sigma(1380)^+$

Overpopulated charmonium spectrum

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

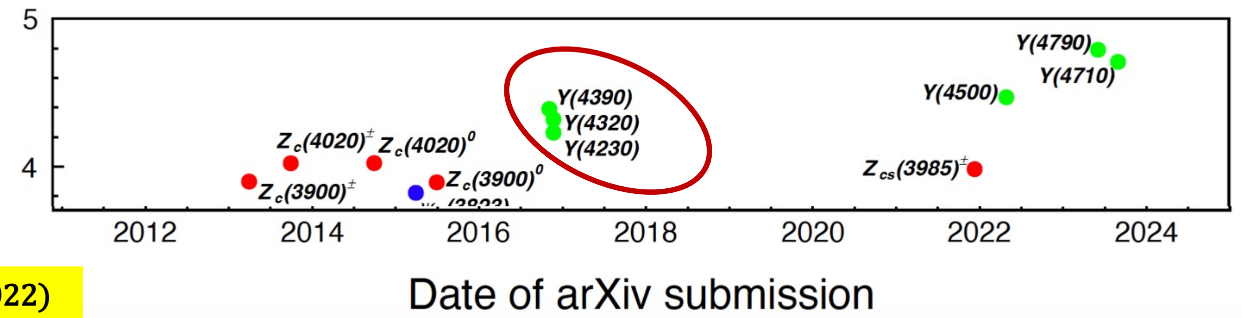
arXiv:1511.01589, arXiv:1812.10947



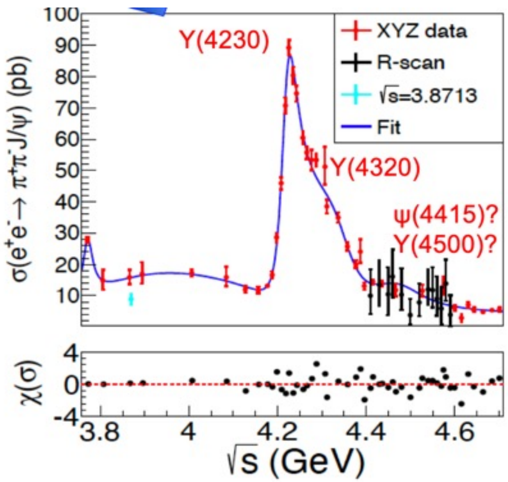


Overpopulated observed new charmonium-like states, i.e. "XYZ":

- 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



PRD106, 072001 (2022)

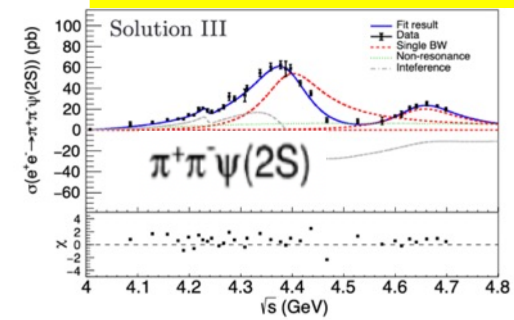


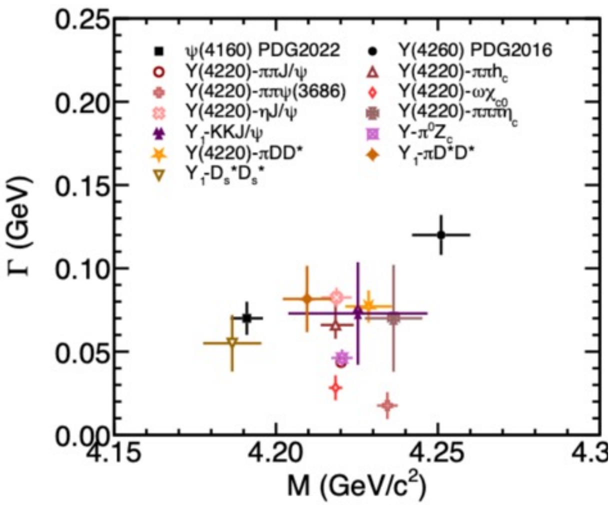
Y(4260) ➔ Y(4230) & Y(4320)

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

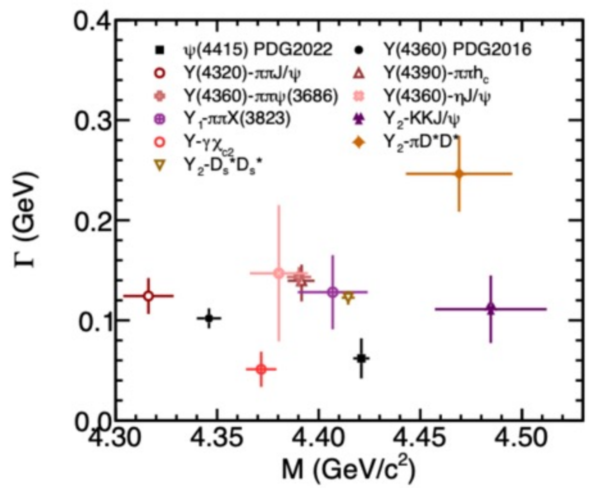
$M_{Y(4320)}$ = 4298 ± 12± 26 MeV/c²
$\Gamma_{Y(4320)}$ = 127 ± 17± 10 MeV

PRD 104, 052012 (2021)

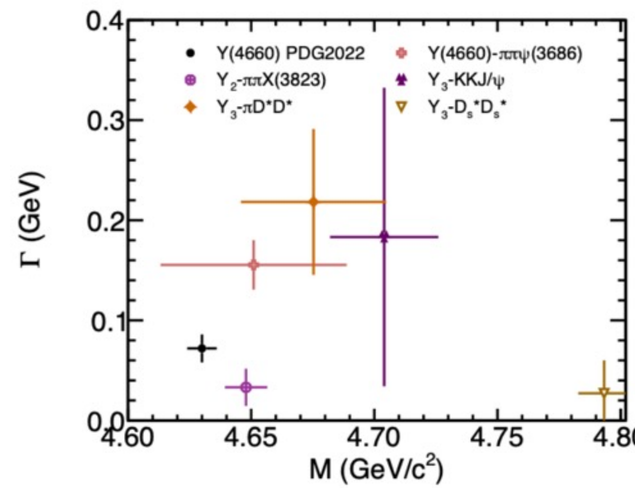




Y(42XX)



Y(43XX), $\psi(4415)$, Y(4500)

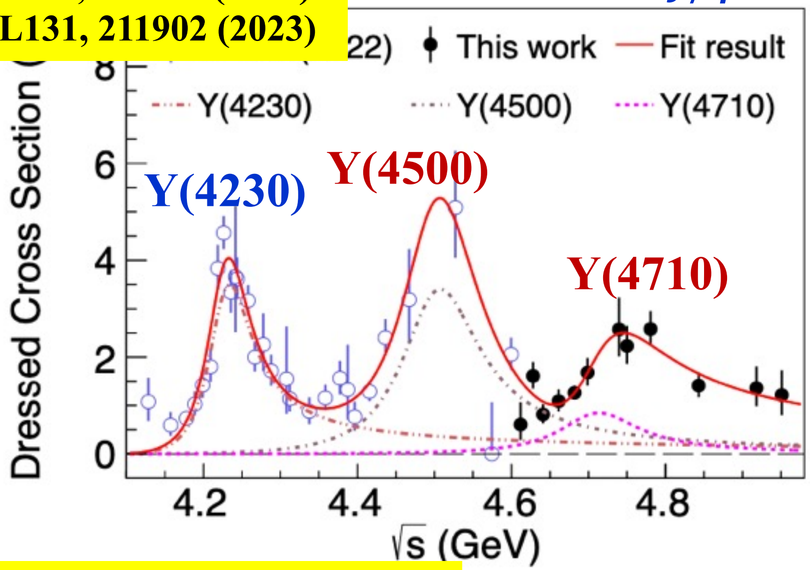


Y(46XX), Y(47XX)

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

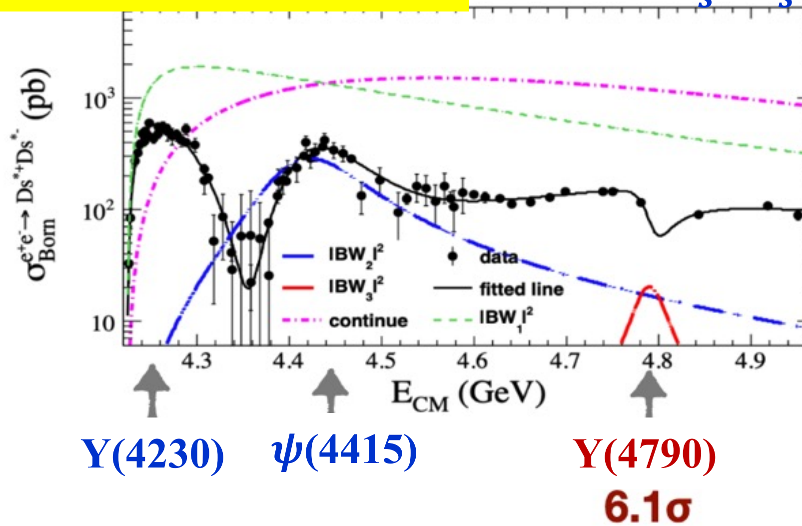
CPC 46, 111002 (2022)
PRL131, 211902 (2023)

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



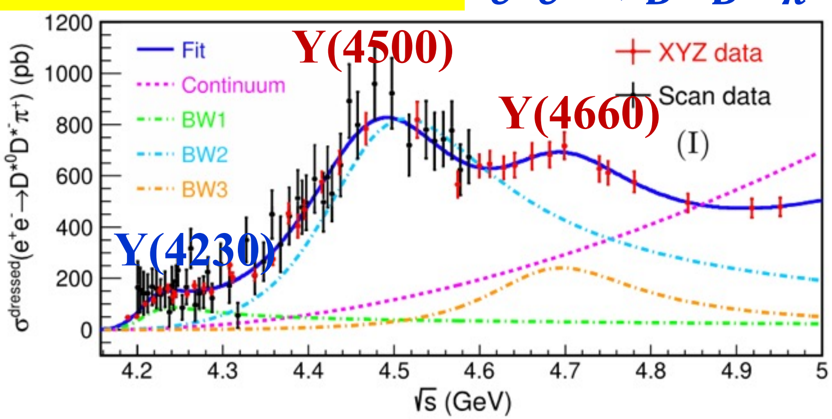
PRL131, 151903 (2023)

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



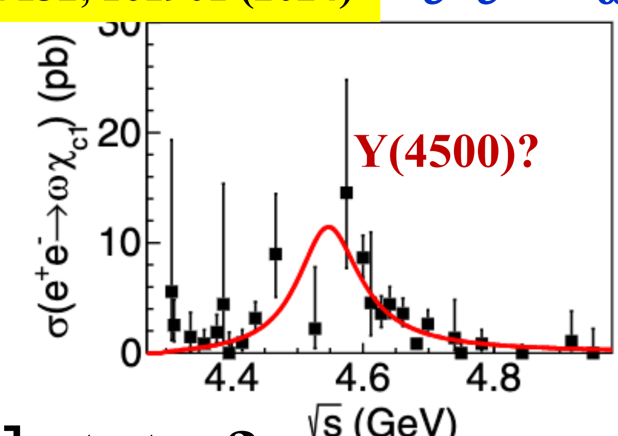
PRL130, 121901 (2023)

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



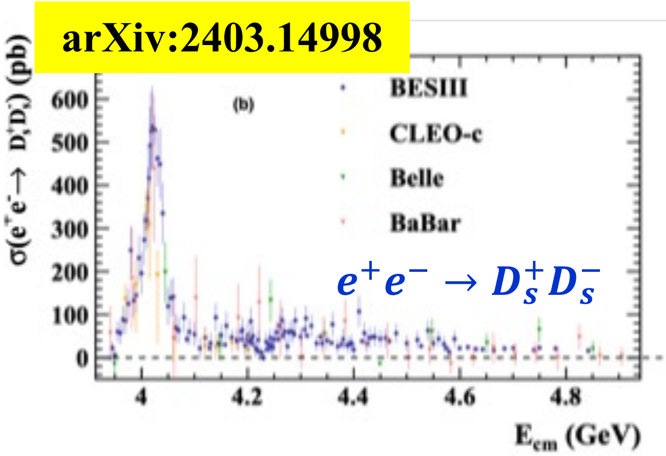
PRL 132, 161901 (2024)

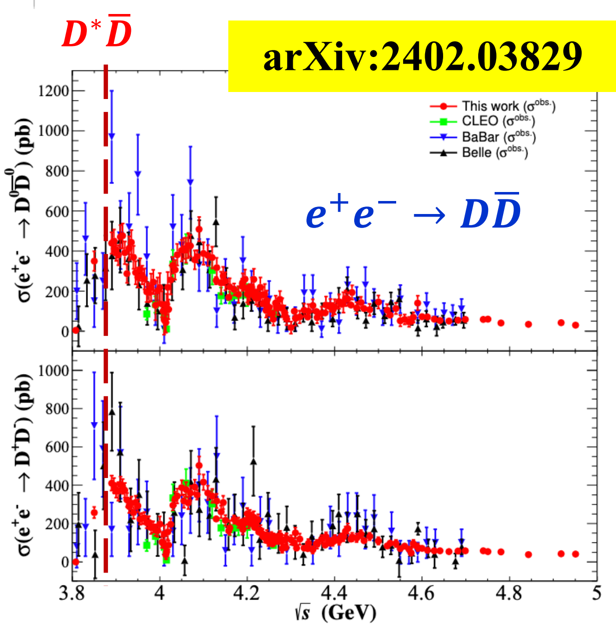
$e^+e^- \to \omega\chi_{c1}$



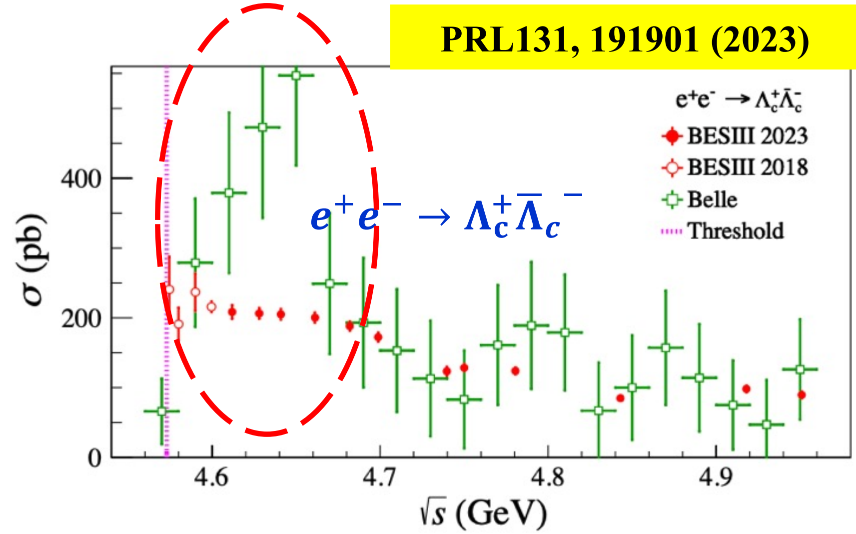
Are they $[c\bar{c}s\bar{s}]$ states?

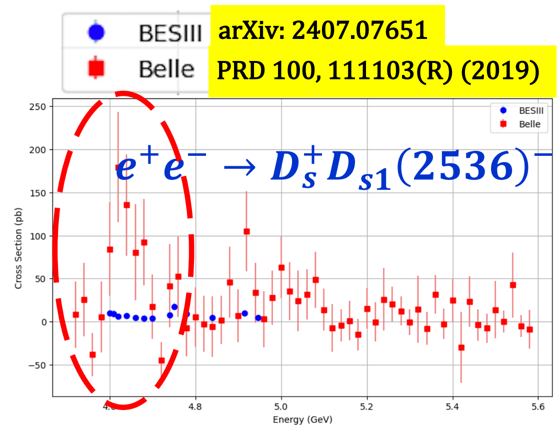
BESIII Cross sections of charmed hadron pairs

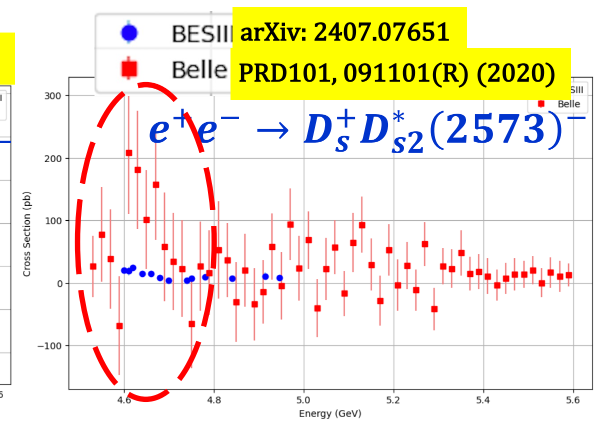




Rich ψ/Y resonances in the final states of the charmed hadron pairs.





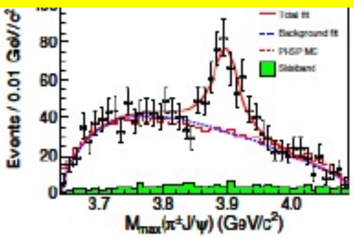


- **Mind**: Tension of cross sections near threshold between direct (BESIII) and ISR(Belle) methods
- BESIII negates the $Y(4630)$ reported by Belle

The Zc Family at BESIII

Zc(3900)$^+$

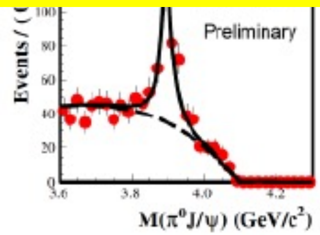
PRL 110, 252001 (2013)



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

Zc(3900)^0

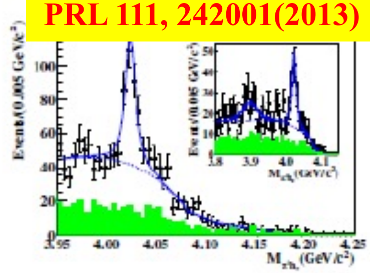
PRL 115, 112003 (2015)



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

Zc(4020)$^+$

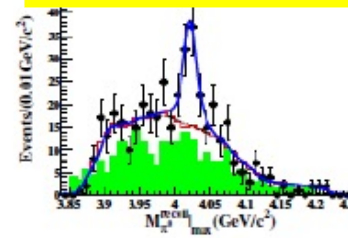
PRL 111, 242001(2013)



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

Zc(4020)^0

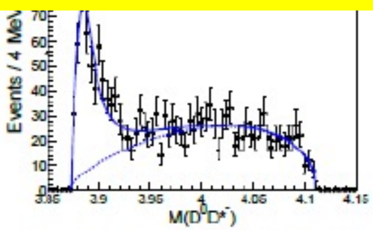
PRL113,212002 (2014)



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

Zc(3885)$^+$

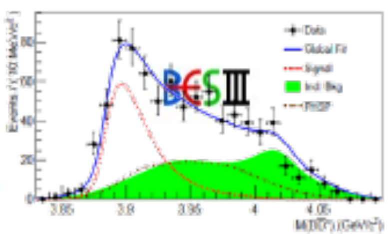
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



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

Zc(3885)^0

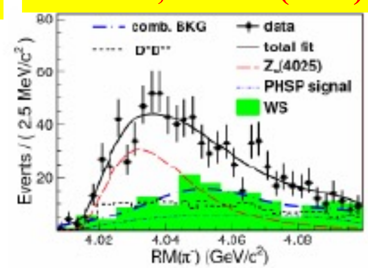
PRL 115, 222002 (2015)



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

Zc(4025)$^+$

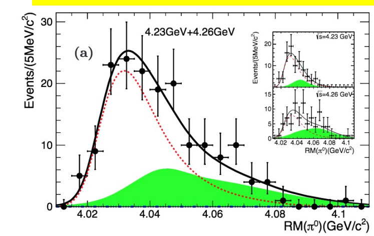
PRL 112, 132001 (2014)



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

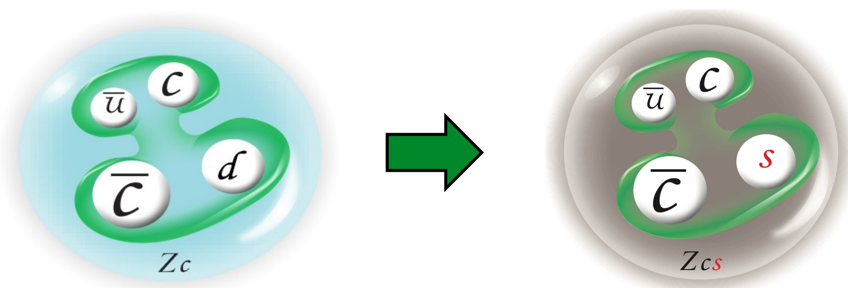
Zc(4025)^0

PRL115, 182002 (2015)



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

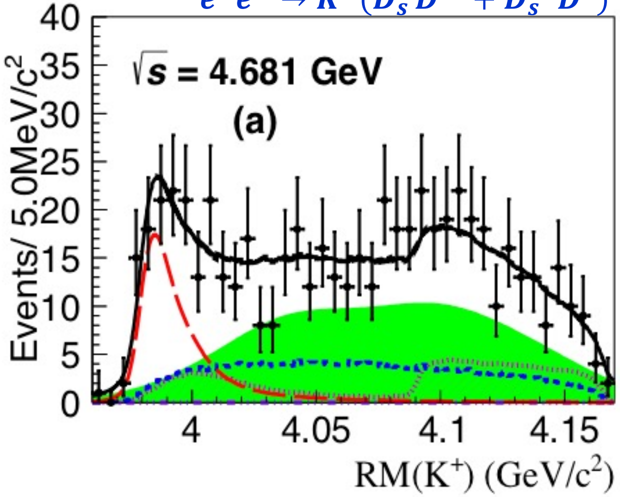
Which is the nature of these states?
If exists, there should be SU(3) counter-part Zcs state with strangeness



Studies on the Z_{cs} states

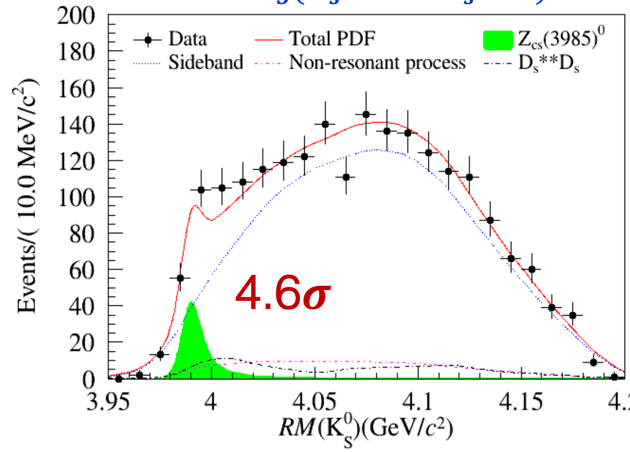
$Z_{cs}(3985)^+$ **PRL126, 102001 (2021)**

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



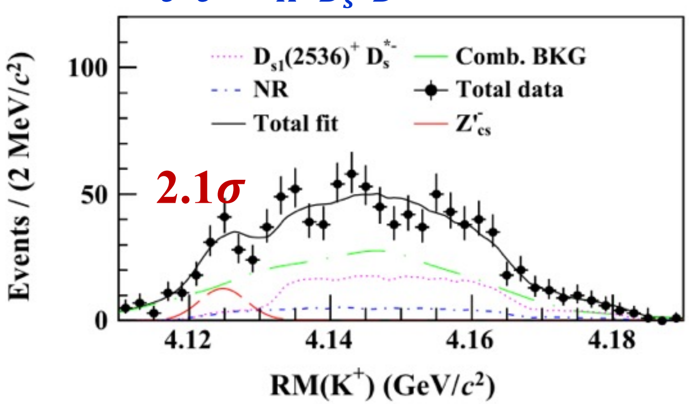
$Z_{cs}(3985)^0$ **PRL129, 112003 (2022)**

$e^+e^- \to K_S(D_s^- D^{*+} + D_s^{*-} D^+)$



Search for Z'_{cs} **CPC47, 033001 (2023)**

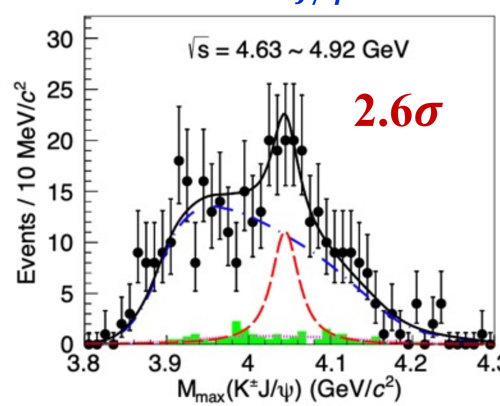
$e^+e^- \to K^+ D_s^{*-} D^{*0}$



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

Search for $Z_{cs}^+ \to K^+ J/\psi$ **arXiv:2308.15362**

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



mass: $4044 \pm 6\ \mathrm{MeV}/c^2$

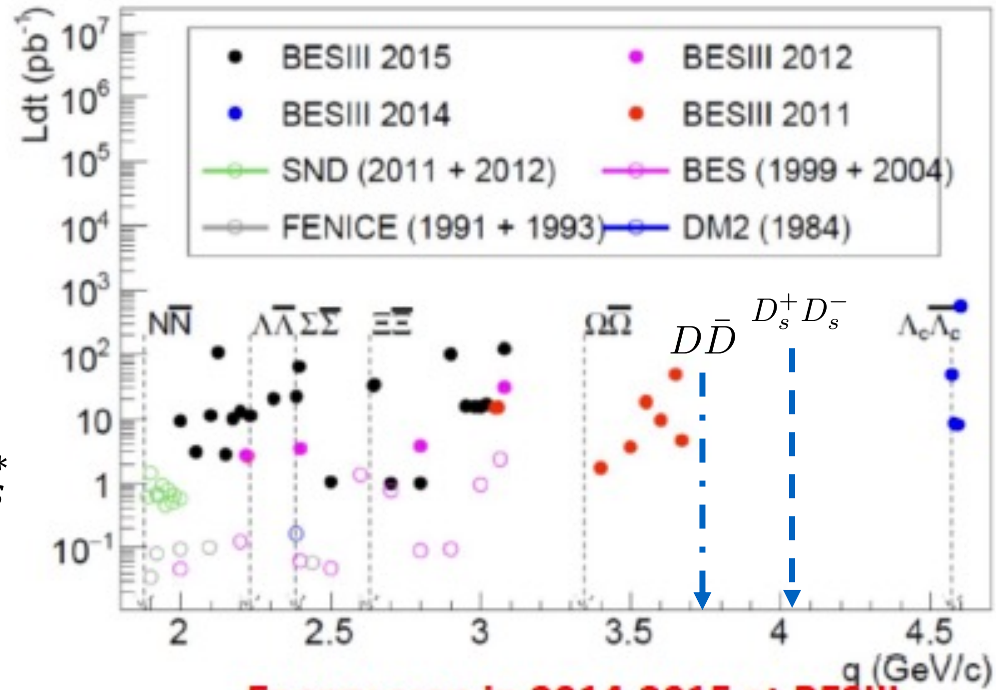
width: 36 ± 16 MeV

Precision measurement

Unique data sets near thresholds

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

3.773 GeV, 20 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}, $D_s\bar{D}_s^*$
4.6-4.95 GeV, 6.4 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;**

BESIII advantage: unique data near to the thresholds

Known initial 4-momentum

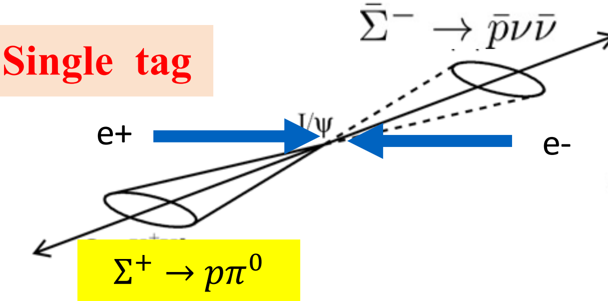
Known beam energy: pair productions

Decay with neutron & π^0

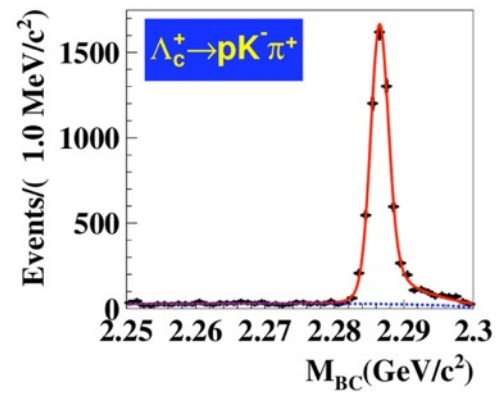
Decay with invisibles: neutrinos

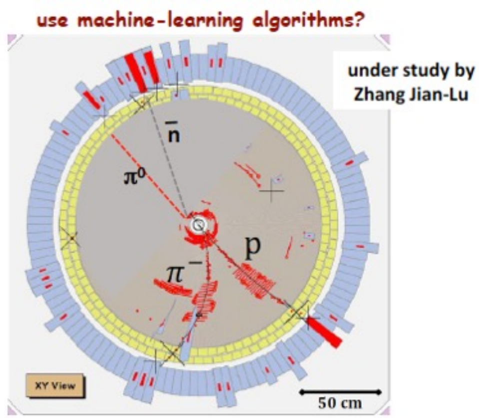
Missing mass or missing energy

Single tag

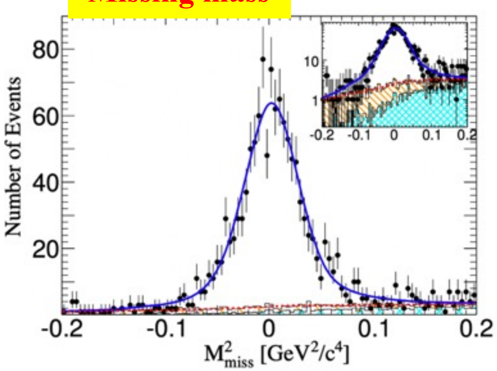


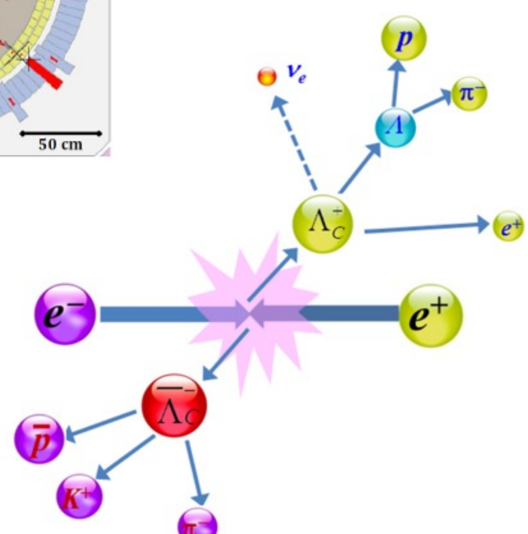
Excellent resolution
Beam-constraint Λ_c mass



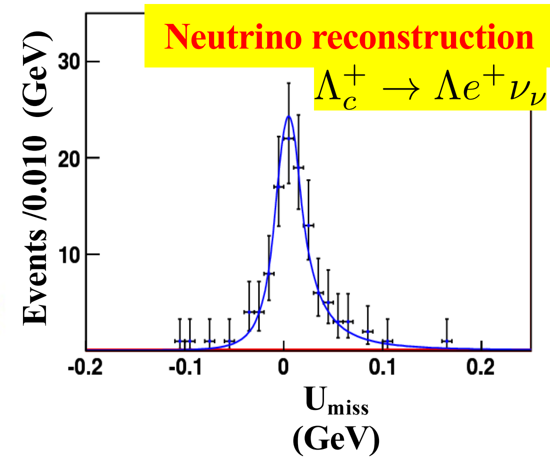


Missing mass

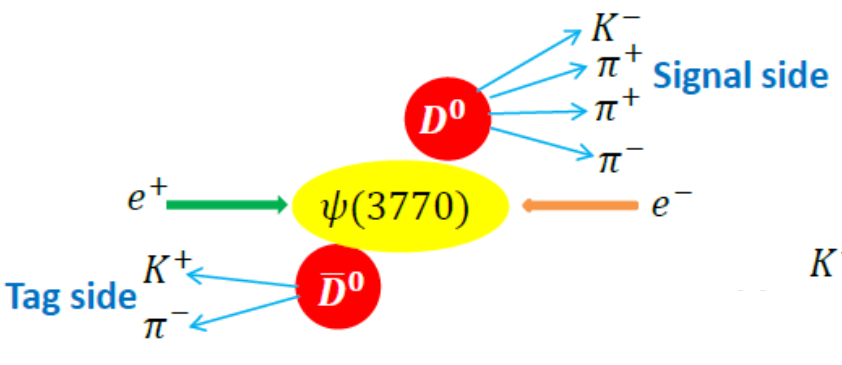




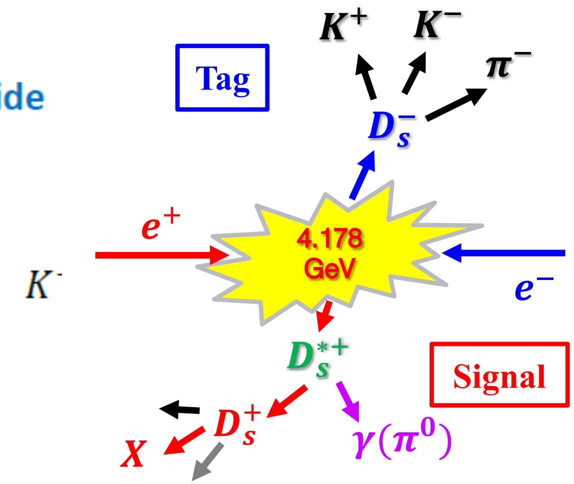
Neutrino reconstruction
$\Lambda_c^+ \to \Lambda e^+ \nu_\nu$

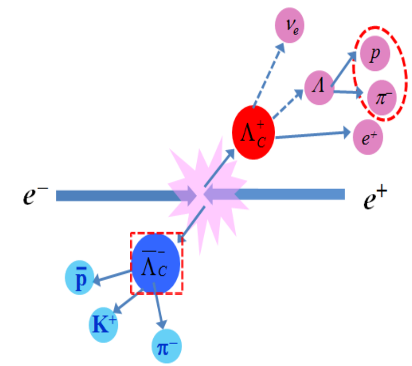


Charm hadron decays



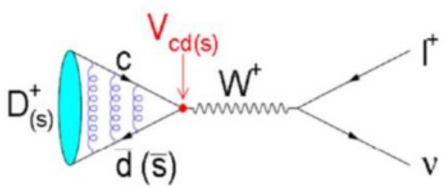
2.93/fb at $\psi(3770)$



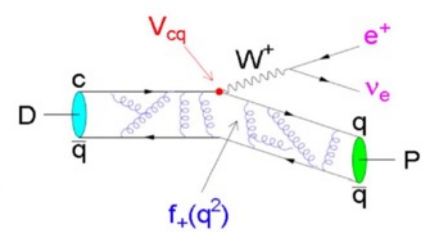


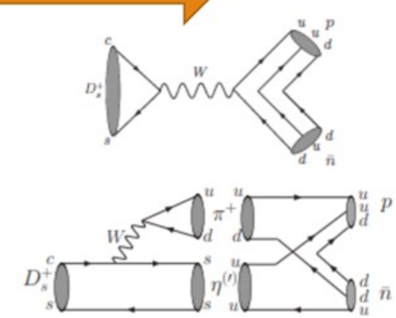
0.567/fb at 4.6 GeV

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

Precision measurement of CKM elements -- Test EW theory

CKM matrix elements are fundamental SM parameters that describe the mixing of quark fields due to weak interaction.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM matrix

BESIII + B factories + LQCD

Three generations of quark?

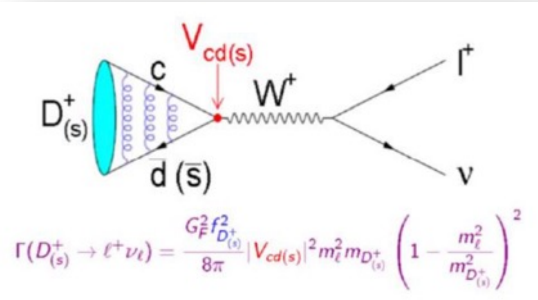
Unitary matrix?

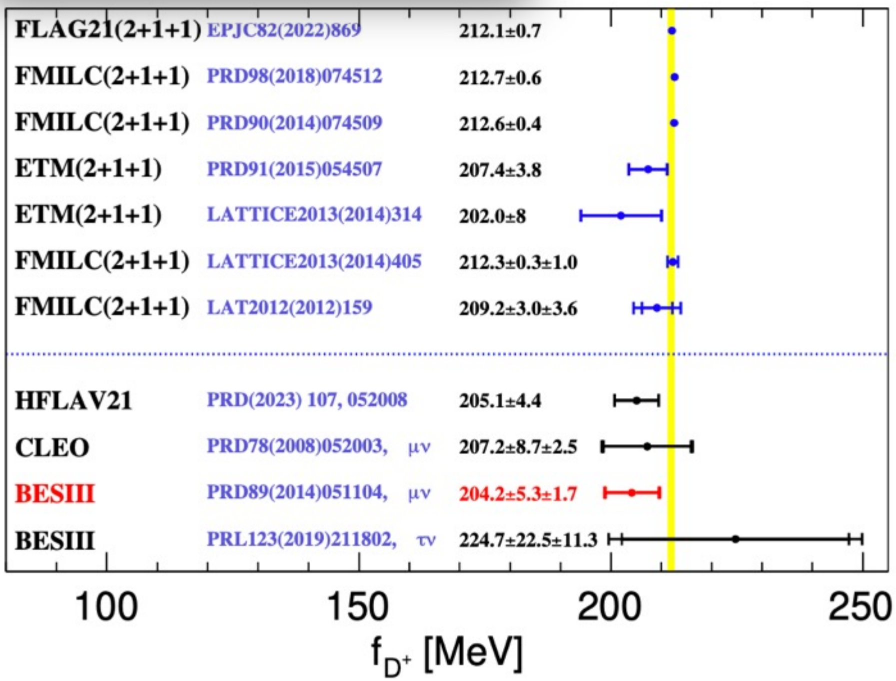
Expected precision < 2% at BESIII

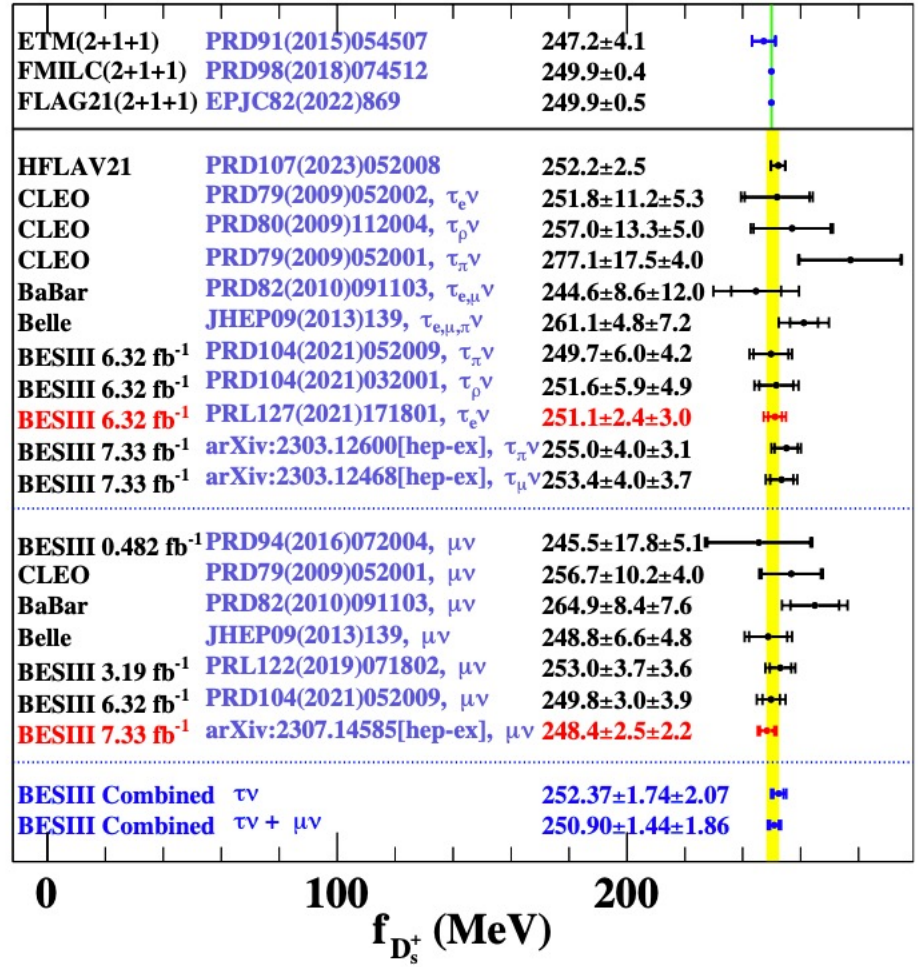
BESIII + B factories + LHCb + LQCD

- **Precision measurement of CKM matrix elements**
- **A precise test of SM model**
- **New physics beyond SM?**

$D^+_{(s)}$ decay constant

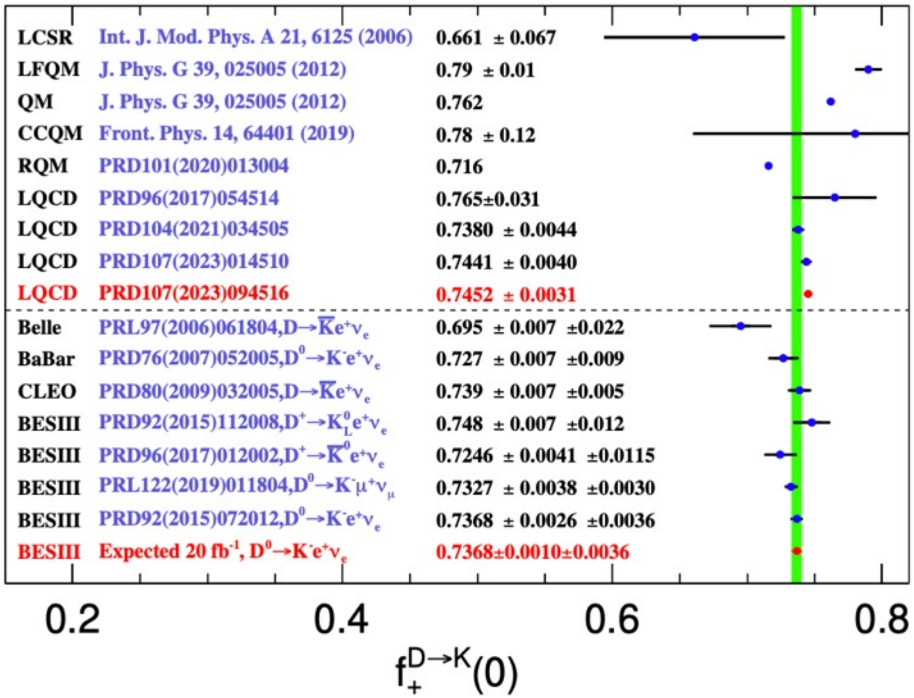


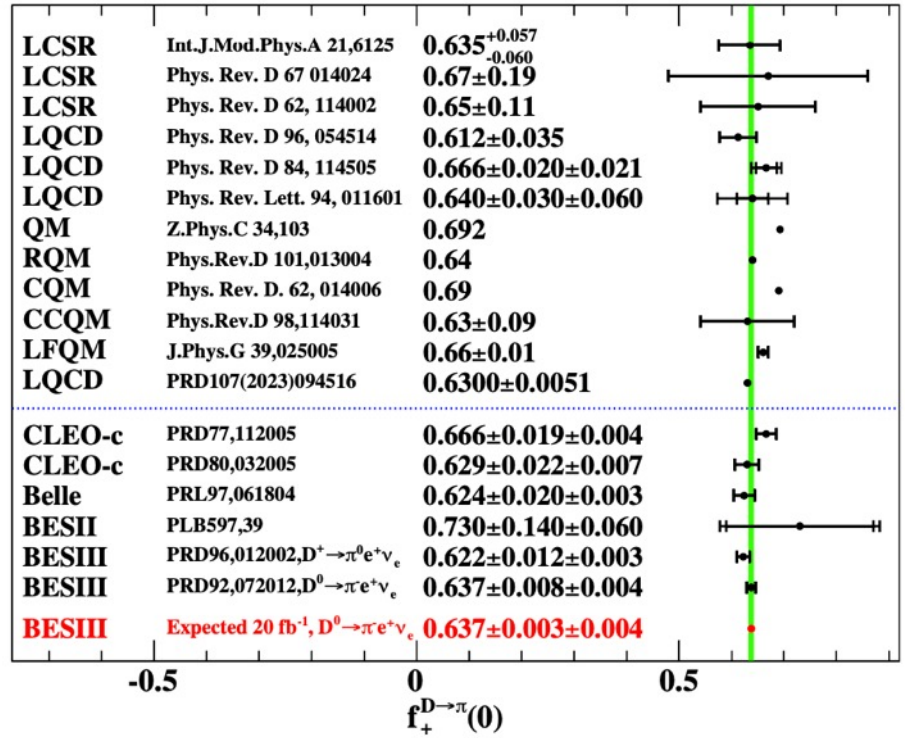


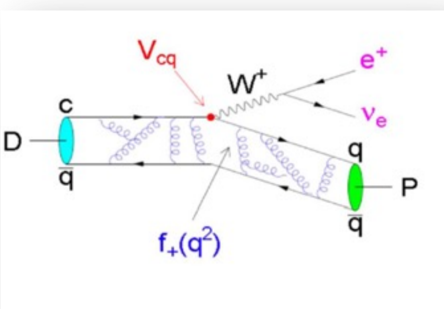


- Highest precision for f_{D^+} in single decay mode:
  $D^+ \to \mu^+\nu_\mu$: 2.7% (2.93 fb^{-1})→1.8% (7.9 fb^{-1})→1.3% (20 fb^{-1})
- Highest precision for $f_{D_s^+}$: 1.3% (7.33 fb^{-1} $D_s^+ \to \mu^+\nu_\mu$)→ 0.9% (Combine all $D_s^+ \to \ell^+\nu_\ell$)

Form factors $f_+^{D\to h}$

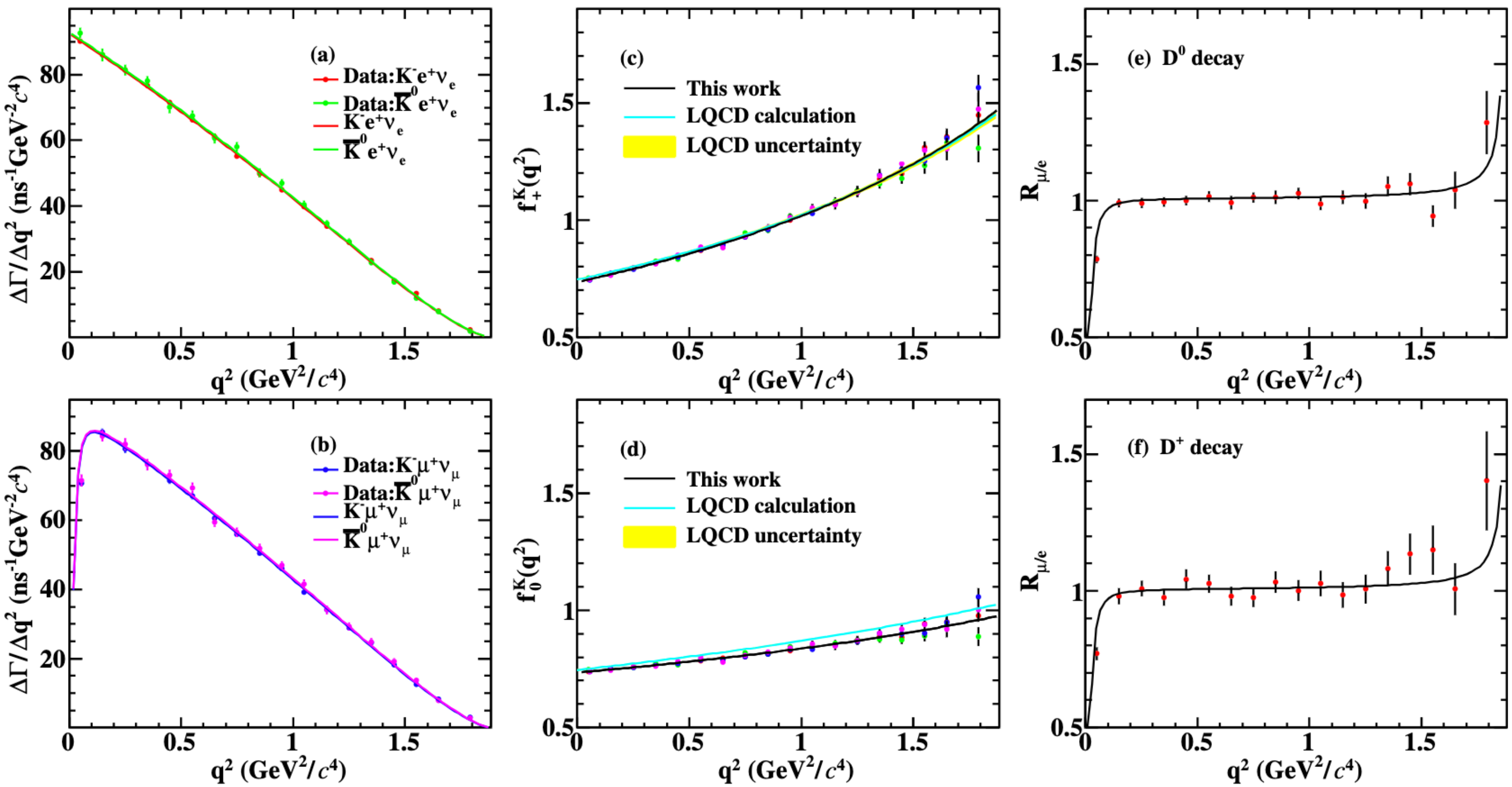






- LQCD has repaid improvement on precisions
- Systematics on from factors at BESIII will be dominant and crucial for further 20/fb charm data

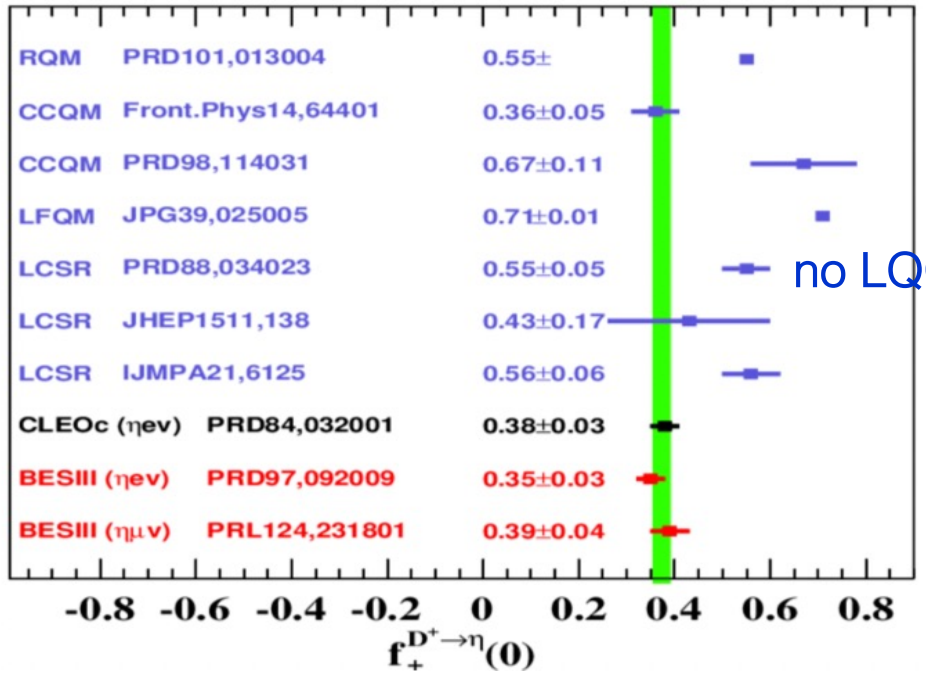
Energy-dependent form factors



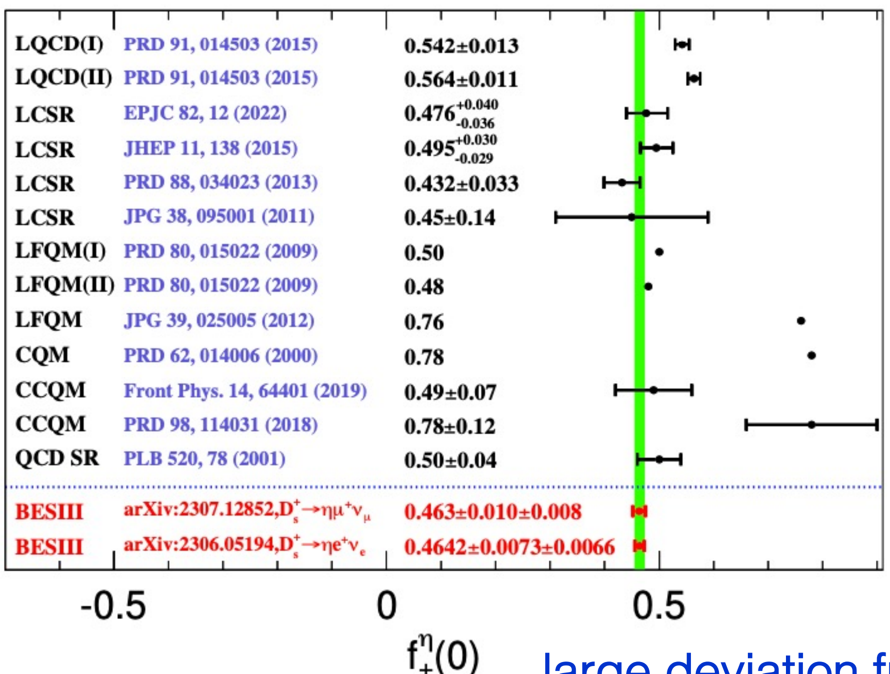
data: BESIII, arXiv:2408.09087
LQCD: PRD 107, 094516 (2023)

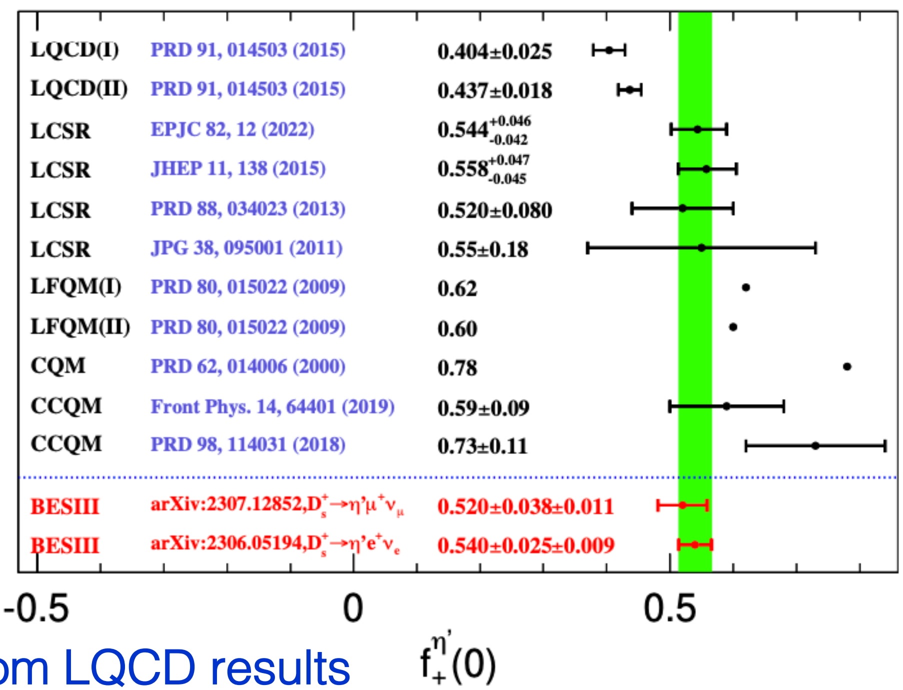
amazing agreement

$\eta^{(\prime)}$ semileptonic mode



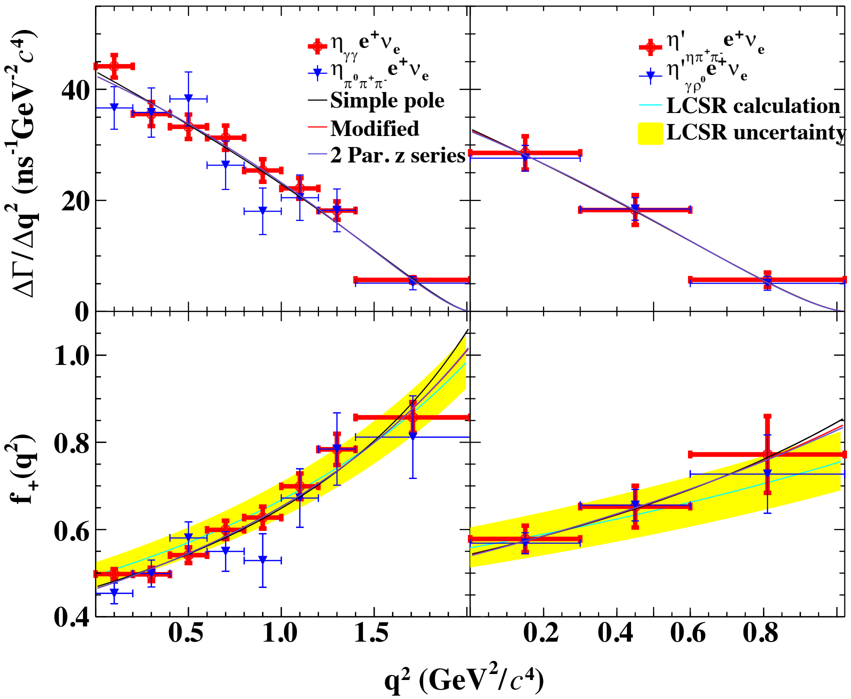
no LQCD result yet (?)

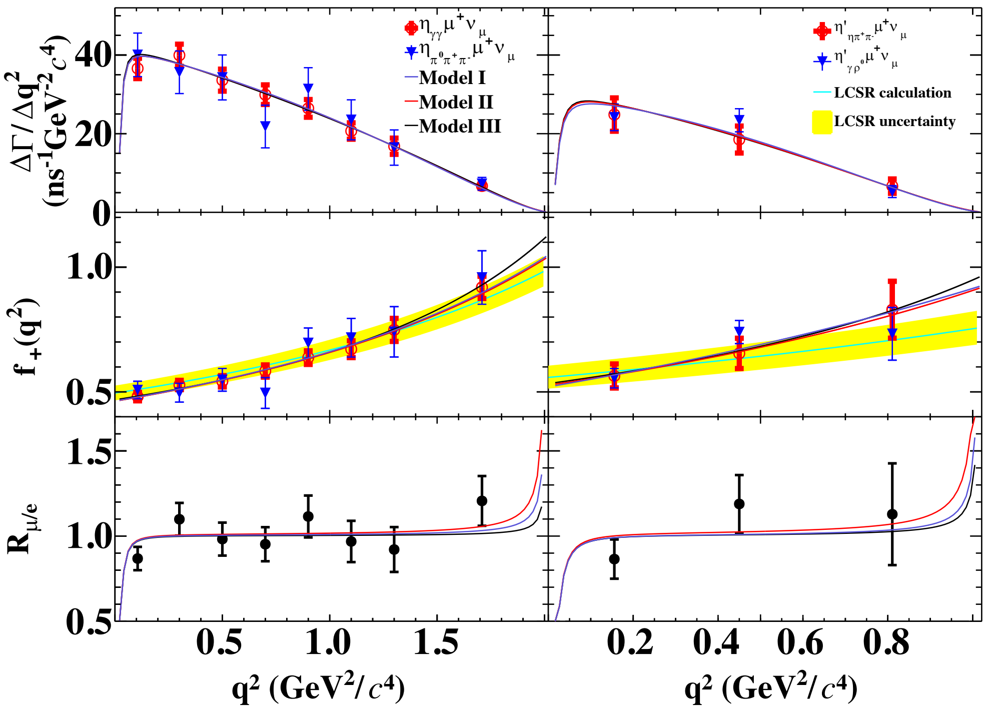




large deviation from LQCD results

Energy-dependent form factors





$$\mathcal{R}^{\eta^{(\prime)}}_{\mu/e} = \mathcal{B}_{D_s^+\to\eta^{(\prime)}\mu^+\nu_\mu}/\mathcal{B}_{D_s^+\to\eta^{(\prime)}e^+\nu_e}$$

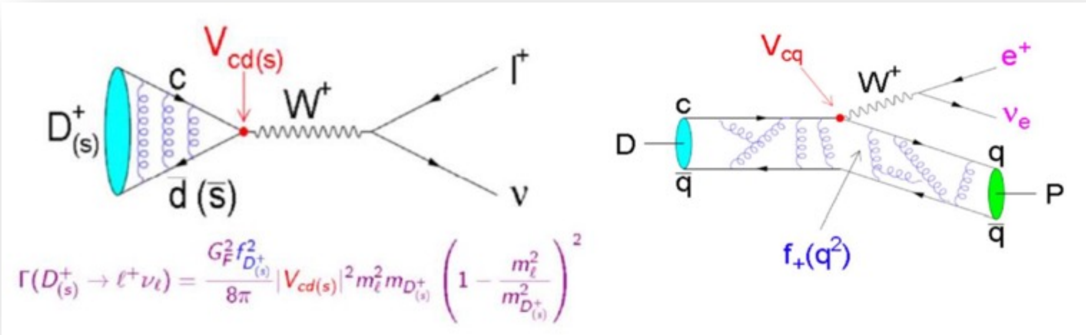
data: BESIII, PRD108, 092003 (2023), PRL132, 091802 (2024)
LCSR: JHEP11, 138 (2015)

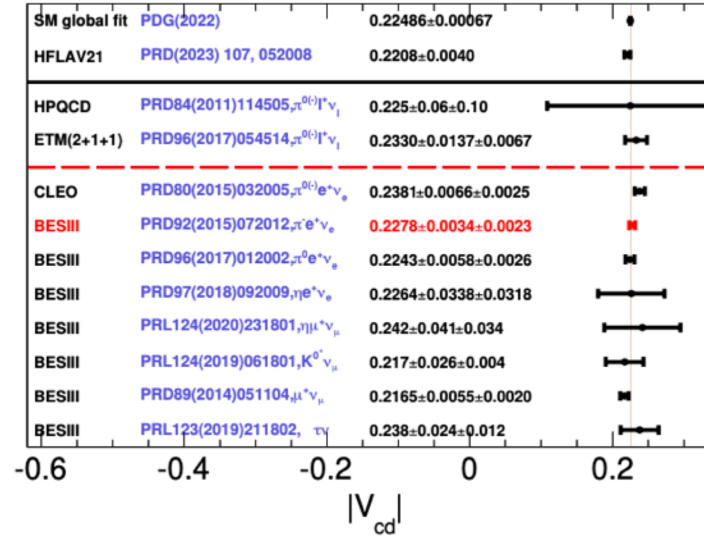
More form factors

Chain	Ref.	$L/E_{\rm cm}$ ($\rm fb^{-1}$/GeV)	BF(%)	FF
$D^0 \to K^{*-} e^+ \nu_e$	PRD99,0111003	2.93/3.773	$1.434 \pm 0.029 \pm 0.032$	$r_V = 1.46 \pm 0.07 \pm 0.02$ $r_2 = 0.67 \pm 0.06 \pm 0.01$
$D^+ \to \bar{K}^{*0} e^+ \nu_e$	PRD94,032001	2.93/3.773	$3.77 \pm 0.03 \pm 0.08$	$r_V = 1.411 \pm 0.058 \pm 0.007$ $r_2 = 0.788 \pm 0.042 \pm 0.008$
$D \to \rho e^+ \nu_e$	PRL122,062001	2.93/3.773	D^0: $0.1445 \pm 0.0058 \pm 0.0039$ D^+: $0.1860 \pm 0.0070 \pm 0.0061$	$r_V = 1.695 \pm 0.083 \pm 0.051$ $r_2 = 0.845 \pm 0.056 \pm 0.039$
$D^0 \to \rho^- \mu^+ \nu_\mu$	PRD104,L091103	2.93/3.773	$0.135 \pm 0.009 \pm 0.009$	–
$D^+ \to \omega e^+ \nu_e$	PRD92,071101	2.93/3.773	$0.163 \pm 0.011 \pm 0.008$	$r_V = 1.24 \pm 0.09 \pm 0.06$ $r_2 = 1.06 \pm 0.15 \pm 0.05$
$D^+ \to \omega \mu^+ \nu_\mu$	PRD101,072005	2.93/3.773	$0.177 \pm 0.018 \pm 0.011$	–
$D_s^+ \to K^{*0} e^+ \nu_e$	PRL122,061801	3.19/4.178	$0.237 \pm 0.026 \pm 0.020$	$r_V = 1.67 \pm 0.34 \pm 0.16$ $r_2 = 0.77 \pm 0.28 \pm 0.07$
$D_s^+ \to \phi e^+ \nu_e$	PRD97,012006	0.482/4.009	$2.26 \pm 0.45 \pm 0.09$	–
$D_s^+ \to \phi \mu^+ \nu_\mu$	arXiv:2307.03024	7.33/4.128-4.226	$2.25 \pm 0.09 \pm 0.07$	$r_V = 1.58 \pm 0.17 \pm 0.02$ $r_2 = 0.71 \pm 0.14 \pm 0.02$

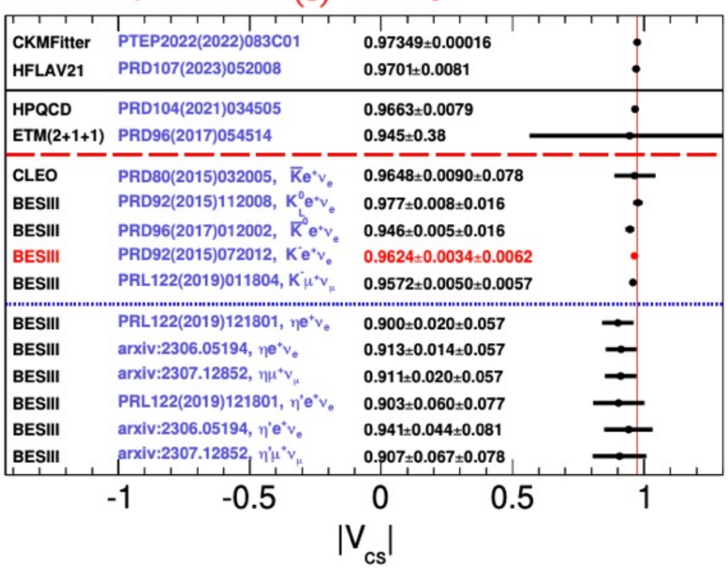
- **Precisions is being improved much with full 20/fb $\psi(3770)$ data**
- **LQCD calculations are desired.**

Measurement of |Vcs| and |Vcd|

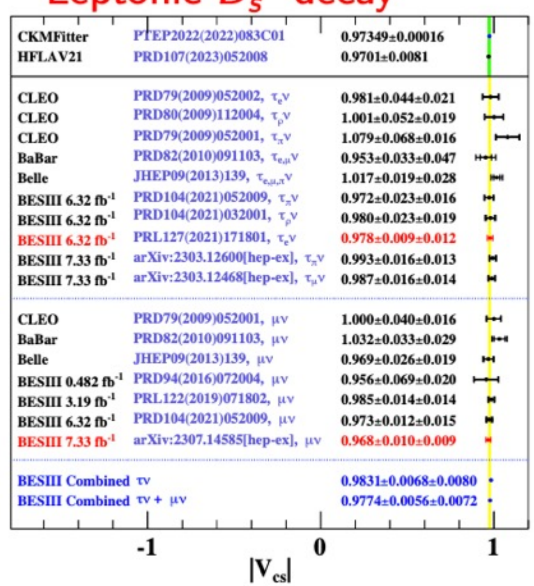




Semileptonic $D_{(s)}$ decay



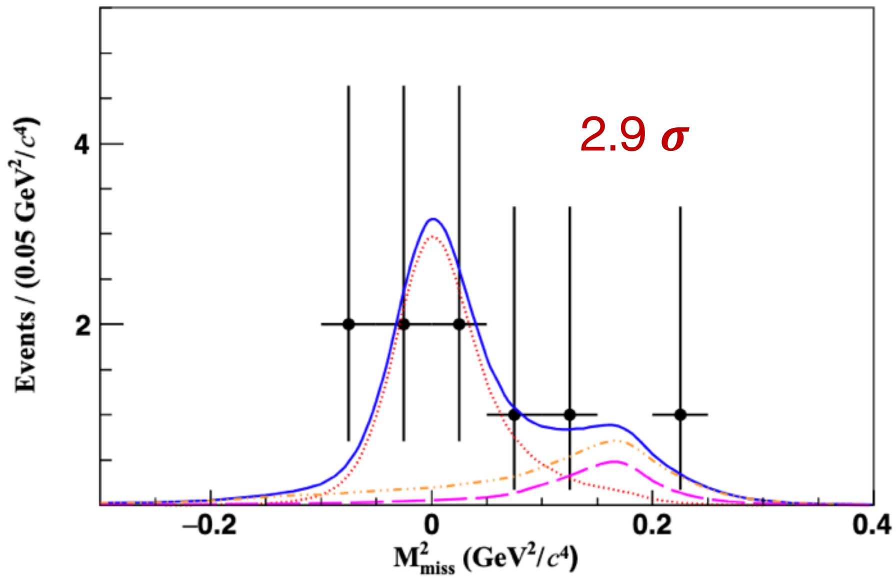
Leptonic D_s^+ decay

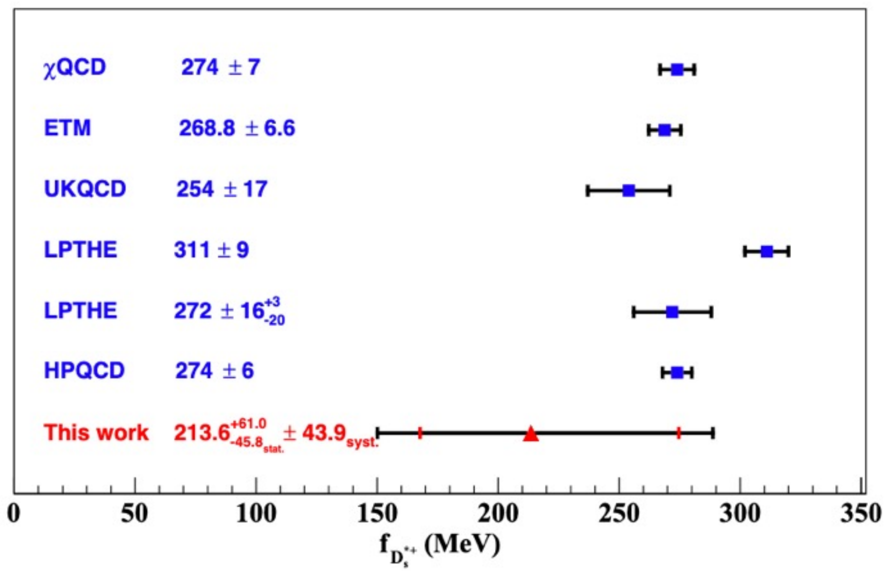


- Great precision improvement due to LQCD form factors
- No sign of conflicts between direct measurement and indirect fit

Study on $D_s^{*+} \to e^+\nu$

PRL 131, 141802 (2023)



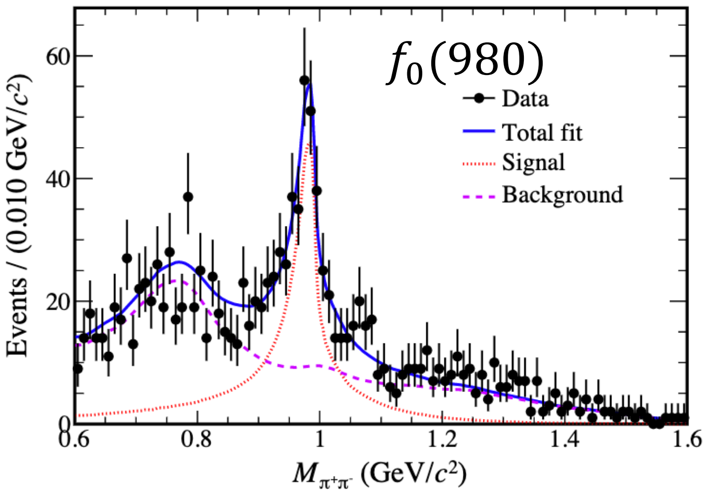


- Branching fraction is determined to be $(2.1^{+1.2}_{-0.9\,\mathrm{stat.}} \pm 0.2_{\mathrm{syst.}}) \times 10^{-5}$

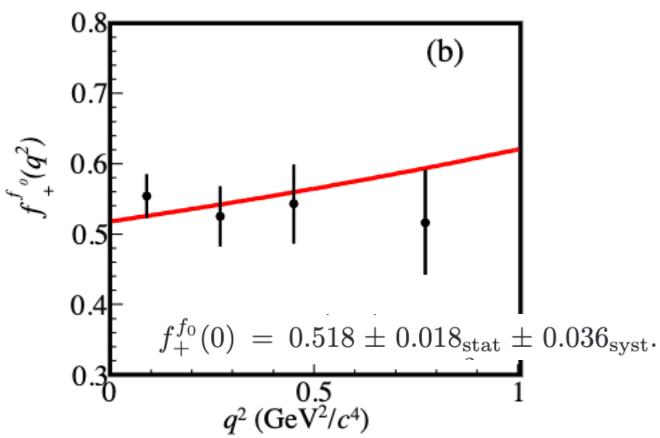
an avenue to study the weak decays of vector charmed mesons in experiment

Excited light hadrons via charm SL decays

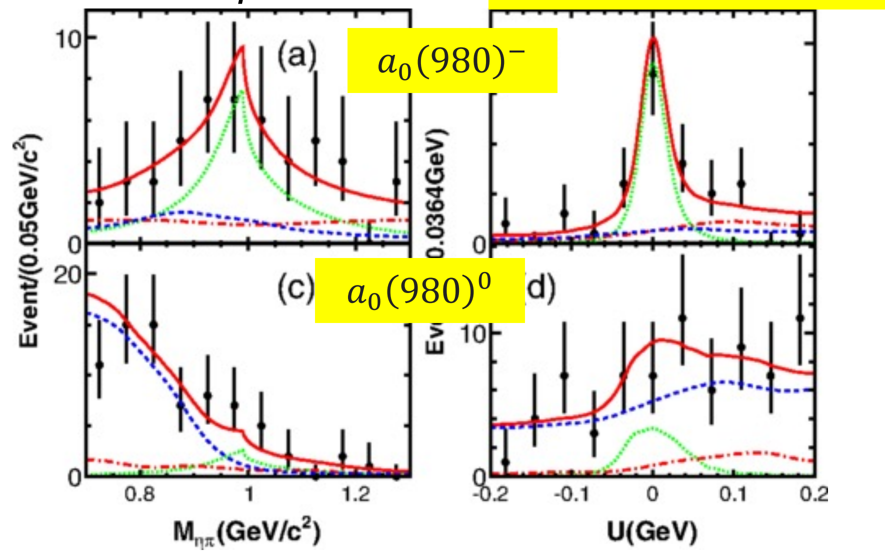
$D_s^+ \to \pi^+\pi^- e^+\nu$ **PRL132, 141901(2024)**



$$BF(D_s^+ \to f_0(980)e^+\nu, f_0(980) \to \pi^+\pi^-) = (1.72 \pm 0.13_{stat} \pm 0.10_{syst}) \times 10^{-3}$$



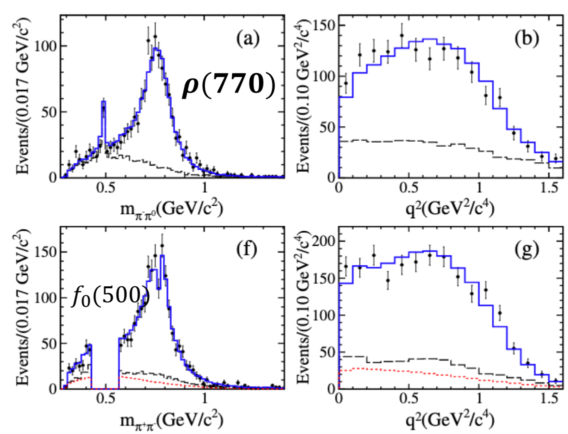
$D^{0(+)} \to \eta\pi^{0(-)} e^+\nu$ **PRL121, 081802 (2018)**



$$\mathcal{B}(D^0 \to a_0(980)^- e^+\nu_e) \times \mathcal{B}(a_0(980)^- \to \eta\pi^-) = [1.33^{+0.33}_{-0.29}(\mathrm{stat}) \pm 0.09(\mathrm{syst})] \times 10^{-4}$$

$$\mathcal{B}(D^+ \to a_0(980)^0 e^+\nu_e) \times \mathcal{B}(a_0(980)^0 \to \eta\pi^0) = [1.66^{+0.81}_{-0.66}(\mathrm{stat}) \pm 0.11(\mathrm{syst})] \times 10^{-4}.$$

$D^{0(+)} \to \pi^-\pi^{0(+)} e^+\nu$ **PRL122, 062001 (2019)**

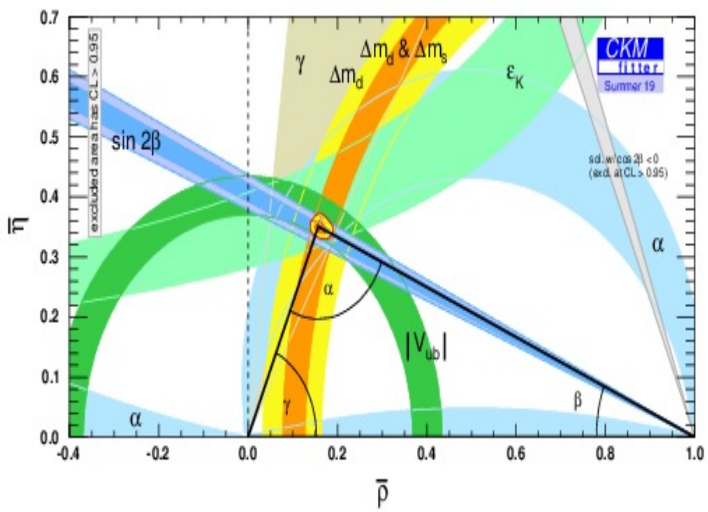


Hadronic decays of charm mesons

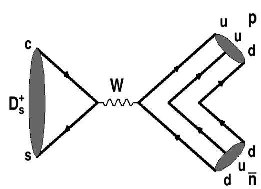
- **Strong phase measurement with quantum correlated $\psi(3770) \rightarrow D^0\bar{D}^0$ is crucial in the model-independent determinations of γ and charm mixing/direct CPV.**
  - γ is the least well known CKM constrain
  - γ status: Pre-LHCb: $\gamma = (73^{+22}_{-25})°$

    Direct measurement $\gamma = (73.5\ ^{+4.2}_{-5.1})^o$,

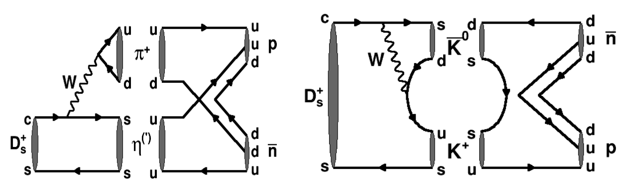
    indirect measurement $\gamma = (65.8\ ^{+1.0}_{-1.7})^o$



- **Probe non-perturbative QCD**
  - Help to understand hadron spectroscopy
  - Study SU(3) flavor symmetry
  - Study short and long distance effects



Short-distance



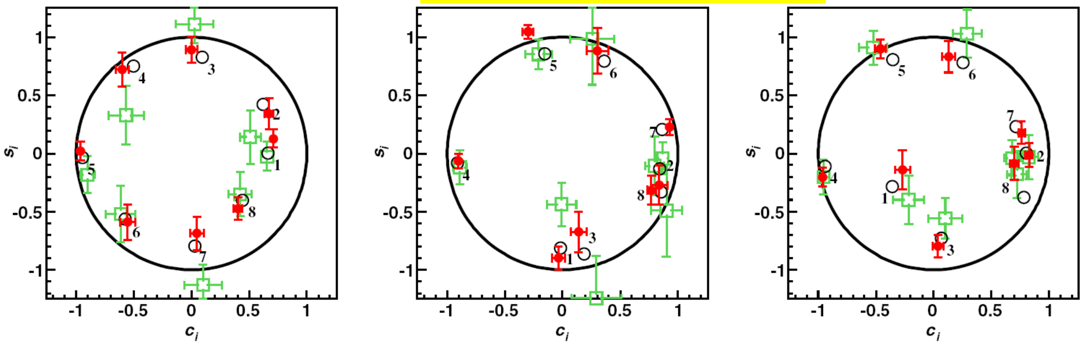
Long-distance effect

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

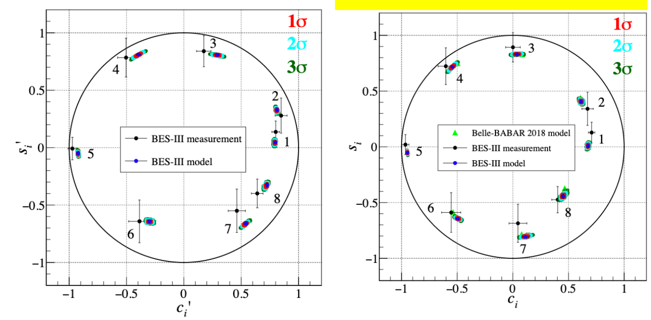
$2.93\ \mathrm{fb}^{-1}@E_{cm} = 3.773\ \mathrm{GeV}$
$e^+e^- \to \psi(3770) \to D\bar{D}$

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

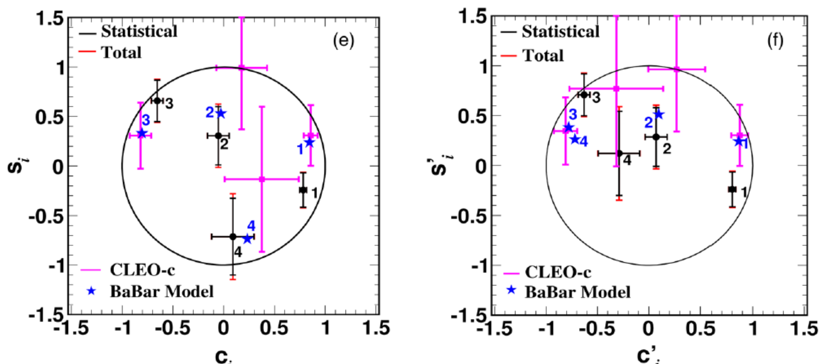
Constraint on γ measurement ~ 0.9^0



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

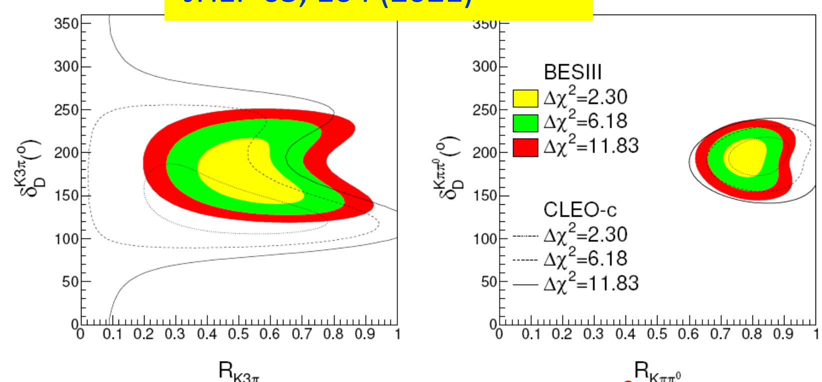


■ **MI $D \to K^0_{S/L}K^+K^-$** PRD102, 052008 (2020)



Constraint on γ measurement ~ 1.3^0

■ $D \to K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^0$ JHEP 05, 164 (2021)



Constraint on γ measurement ~ 6^0

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

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

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

BESIII data @3770 MeV (2.93 fb^{-1} ➔ 20 fb^{-1})

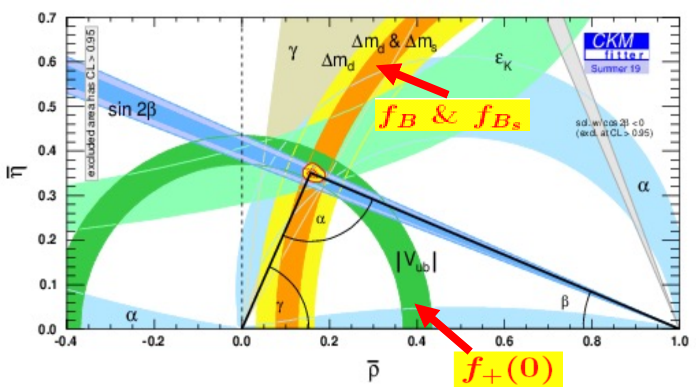
$\psi(3770) \rightarrow D^0\overline{D^0}$ quantum correlation➔strong phase parameters between D^0 and $\overline{D}^0$ decays

➔inputs to LHCb measurement of γ

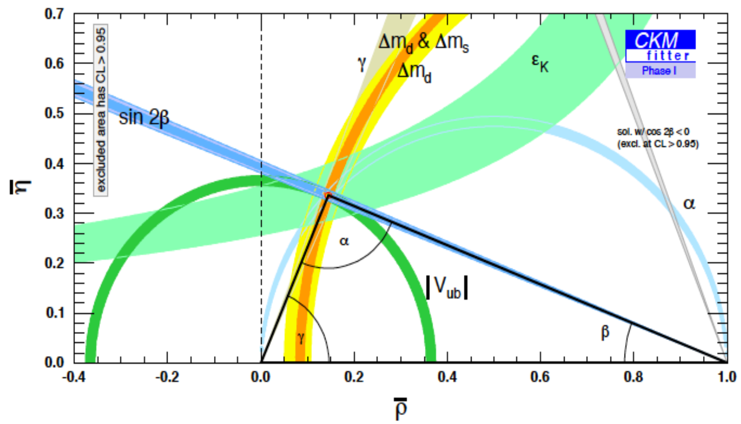
Belle II (arXiv:1808.10567): 1.5^0 with 50 ab^{-1}

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

Physics publications on the Λ_c^+

Published 17 papers

(7 PRLs)

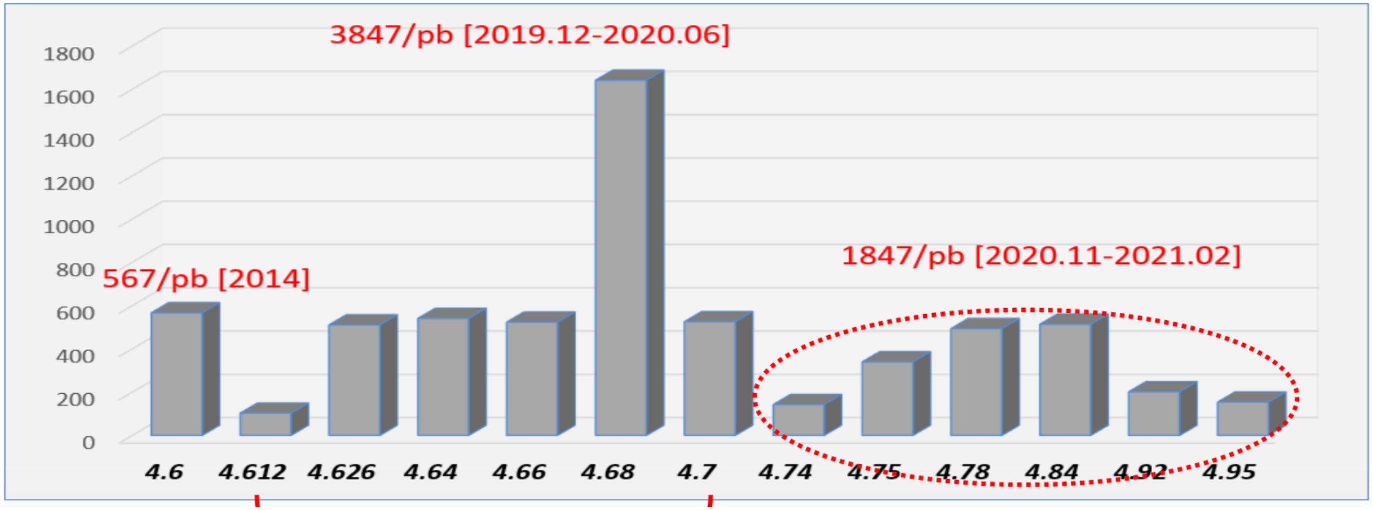
- A series of precise absolute BF measurements: hadronic, semi-leptonic and inclusive decays
- Observation of decays into neutron $\Lambda_c^+ \to nK_s\pi^+, \Sigma^-\pi^+\pi^+\pi^0$
- Observation of Cabbibo-suppressed decay $\Lambda_c^+ \to p\pi^+\pi^-$
- First evidence of Cabbibo-suppressed decay $\Lambda_c^+ \to p\eta$
- 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	
$\Lambda_c^+\Lambda_c^-$ cross section	**PRL 120,132001(2018)**

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 $\Lambda_c^+ \to p K^- e^+ \nu_e$
- 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 $\Lambda_c^+ \to \gamma \Sigma^+$

Semi-leptonic decay

- ✓ Form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ — *PRL129, 231803 (2022)*
- ✓ $\Lambda_c^+ \to pK^- e^+ \nu_e$ — *PRD106, 112010 (2022)*
- ✓ *LFU test of* $\Lambda_c^+ \to \Lambda l^+ \nu_l$, — *PRD108, L031105 (2023)*
- ✓ Observation of $\Lambda_c^+ \to n e^+ \nu_e$ — *Submitted to NC*
- ✓ Search for $\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e$ and $pK_s \pi^- e^+ \nu_e$ — *PLB843, 137993 (2023)*

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)*
- ✓ $\Lambda_c^+ \to nK_s K^+$ — *arXiv:2311.17131*
- ✓ $\Lambda_c^+ \to \Sigma^- K^+ \pi^+$ — *arXiv:2309.05484*
- ✓ $\Lambda_c^+ \to nK_s \pi^+ \pi^0$ — *arXiv:2401.06813*

Hadronic CS decays

- ✓ $\Lambda_c^+ \to p\pi^0, p\eta, p\eta', p\omega$ — *PRD106, 072002 (2022); JHEP11, 137 (2023); arXiv:2311.06883*
- ✓ $\Lambda_c^+ \to \Lambda K^+, \Lambda K^+ \pi^0$ — *PRD106, L111101 (2022); PRD109, 032003 (2024)*
- ✓ $\Lambda_c^+ \to \Sigma^+ K_s, \Sigma^0 K^+$ — *PRD106, 052003 (2022)*
- ✓ $\Lambda_c^+ \to \Sigma^+ K^+ \pi^-$ — *JHEP09, 125 (2023);*

Hadronic CF decays

- ✓ PWA of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ — *JHEP 12, 033(2022)*
- ✓ W-exchange-only process $\Xi^0 K^+$ — *PRL132, 031801 (2024)*
- ✓ $\Lambda_c^+ \to \Xi^0 K^+ \pi^0$ — *PRD109, 052001 (2024)*
- ✓ PWA of $\Lambda_c^+ \to \Lambda\pi^+\eta$ — *arXiv:2407.12270*
- ✓ $\Lambda_c^+ \to pK_L, pK_L\pi^0, pK_L\pi^+\pi^-$ — *arXiv:2406.18083*

28 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)*

Rare decay

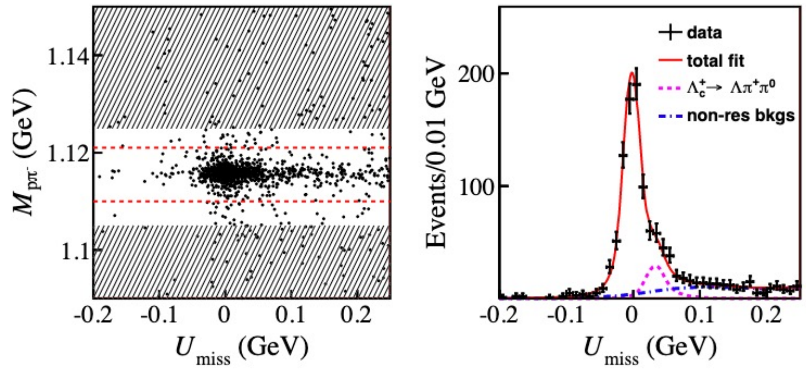
- ✓ $\Lambda_c^+ \to \gamma\Sigma^+$ — *PRD107, 052002 (2023)*

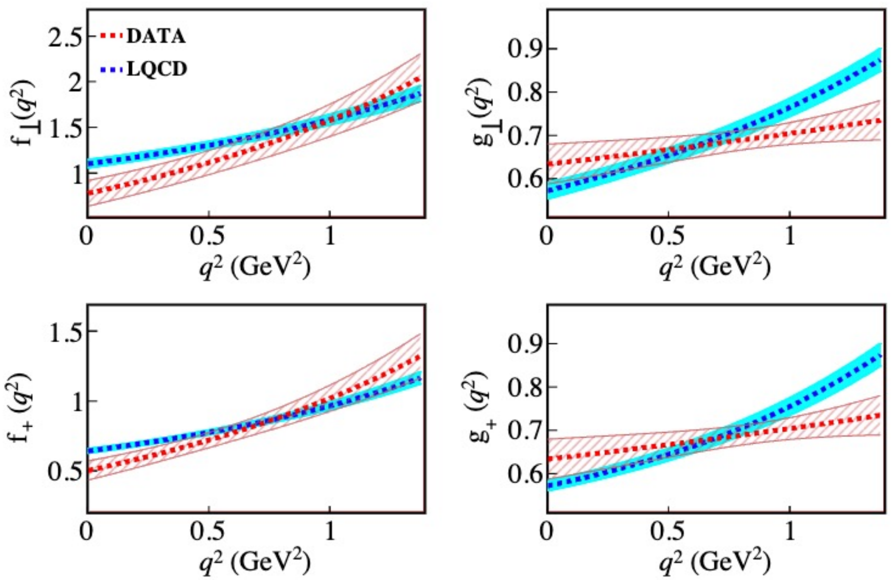
Production and excited Λ_c^+

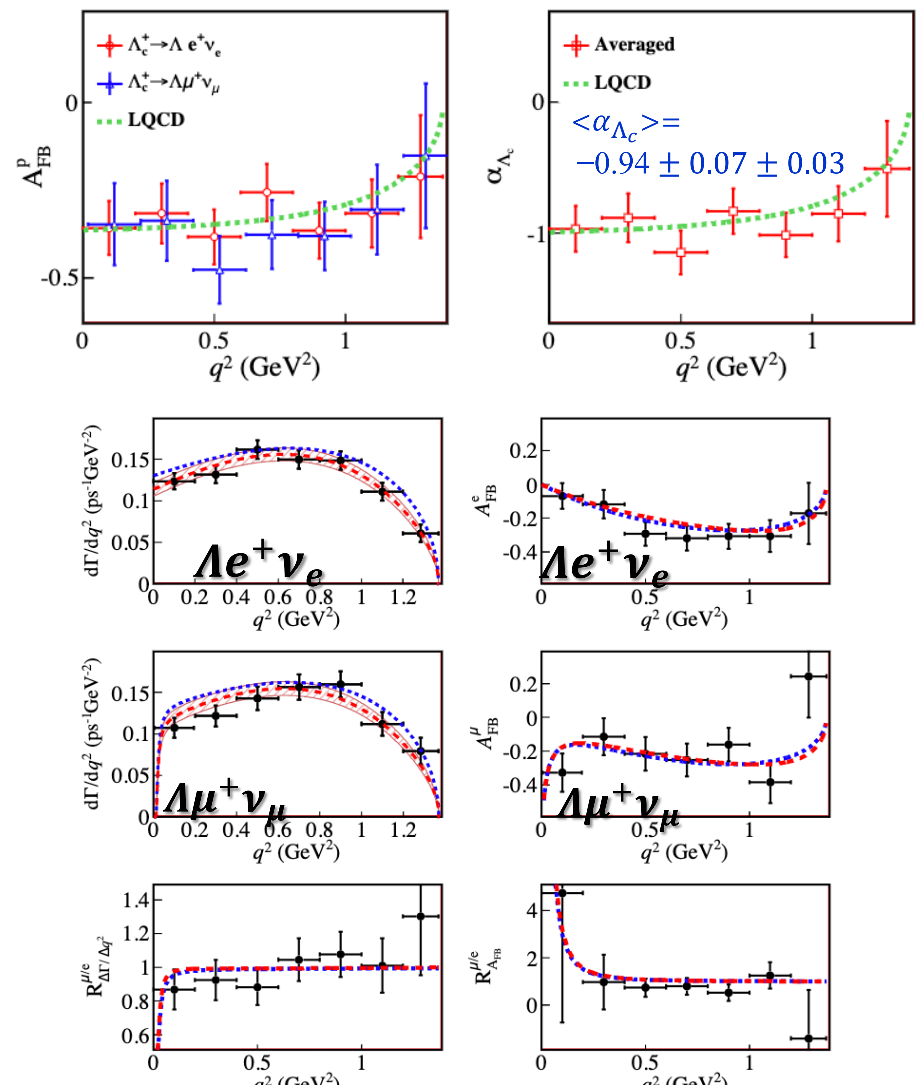
- ✓ $\Lambda_c^+ \bar{\Lambda}_c^-$ *lineshape and form factor* — *PRL107, 052002 (2023)*
- ✓ $\Lambda_c(2595)^+$ *and* $\Lambda_c(2625)^+$ *production and decay* — *arXiv:2312.08414; arXiv:2401.09225*

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

PRD 108, L031105 (2023)

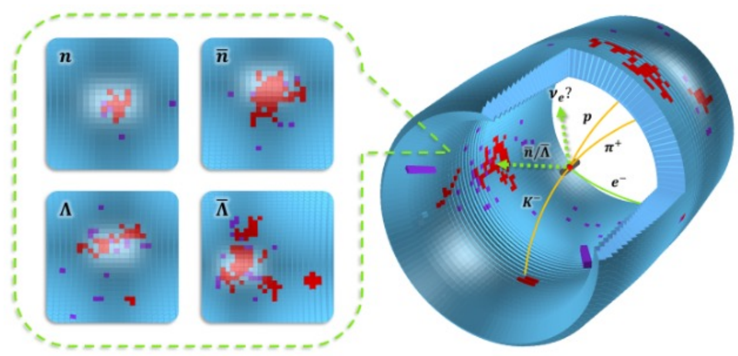


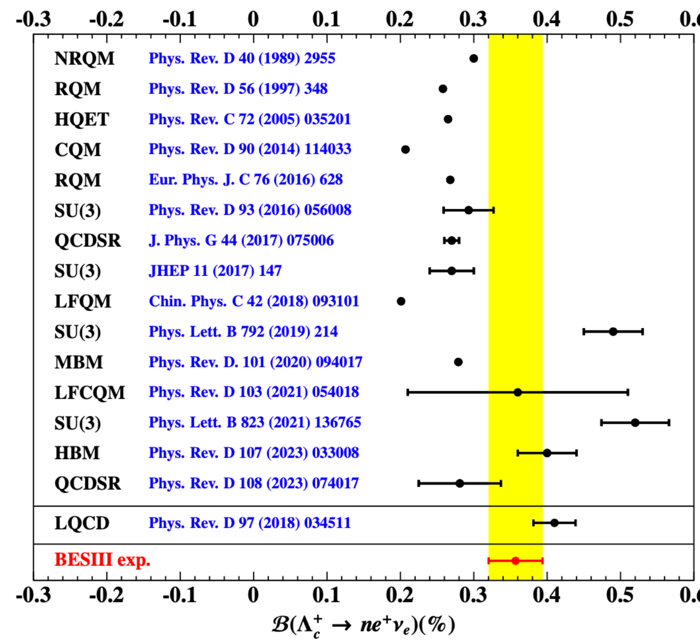




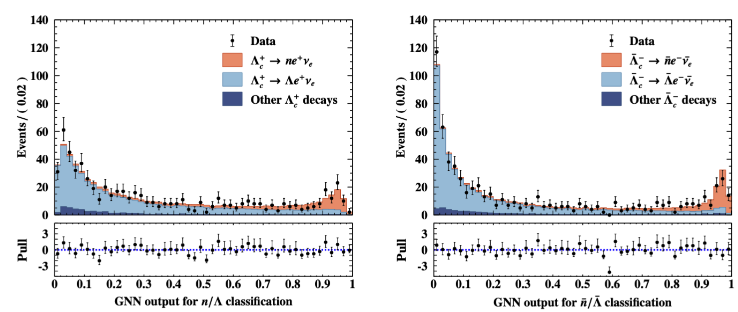
Observation of $\Lambda_c^+ \to n e^+ \nu_e$ with Machine Learning

Submitted to NC





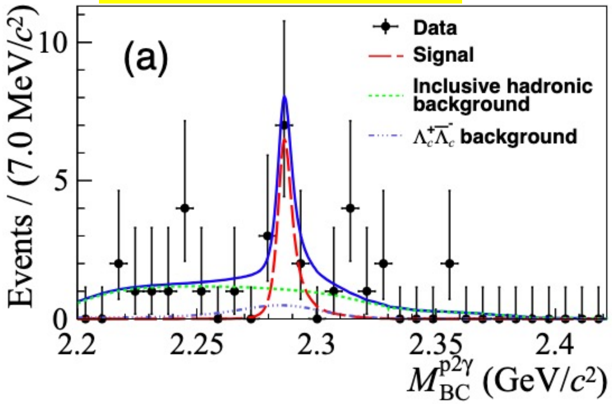
- A novel Deep Learning is utilized to separate signals from dominant background of dominant backgrounds from $\Lambda_c^+ \to \Lambda(\to n\pi^0)e^+\nu$
- Train GNN with **ParticleNet** using control data from $J/\psi \to \bar{p}n\pi^+, \bar{p}\Lambda K^+$ and c.c. modes based on 10B J/ψ decays
- First observation of $\Lambda_c^+ \to n e^+ \nu_e$
  - $\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e) = (0.357 \pm 0.034_{\text{stat}} \pm 0.014_{\text{syst}})\%$ $(> 10\sigma)$
  - $|V_{cd}| = 0.208 \pm 0.011_{\text{exp.}} \pm 0.005_{\text{LQCD}} \pm 0.001_{\tau_{\Lambda_c^+}}$
- This measurement demonstrates a level of precision comparable to the LQCD prediction.
- The result provides significant insights, shedding light on the di-quark structure within the Λ_c^+ core and the $\pi - N$ clouds in the low Q^2.

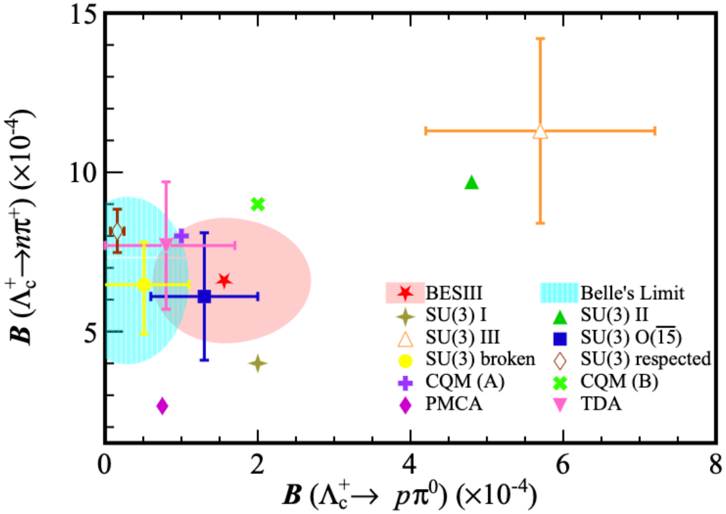


SCS decays of $\Lambda_c^+ \to p\pi^0$ and $p\eta$

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

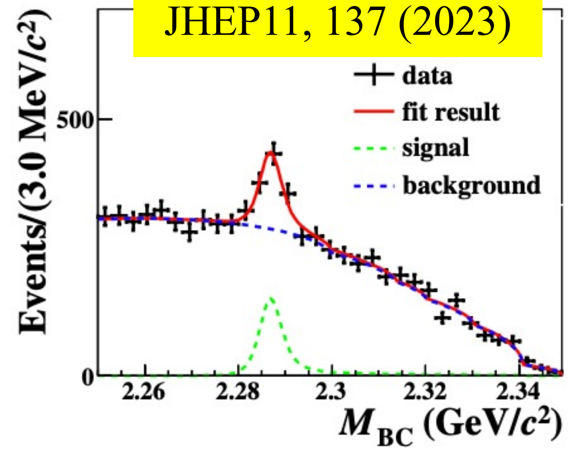
arXiv:2311.06883





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

JHEP11, 137 (2023)

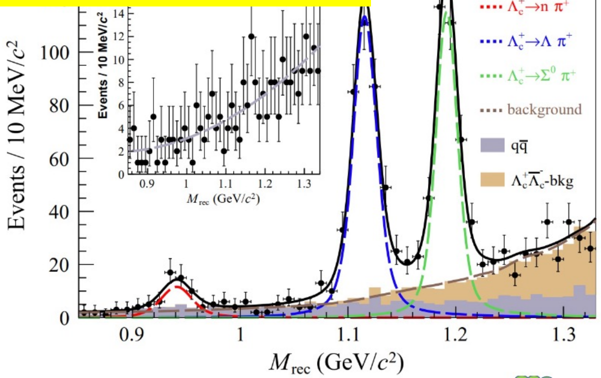


		$\mathcal{B}(\Lambda_c^+ \to p\eta)$	$\mathcal{B}(\Lambda_c^+ \to p\omega)$
BESIII		$1.24 \pm 0.28 \pm 0.10$ [22]	—
LHCb		—	$0.94 \pm 0.32 \pm 0.22$ [23]
Belle		$1.42 \pm 0.05 \pm 0.11$ [24]	$0.827 \pm 0.075 \pm 0.075$ [25]
This paper		$1.57 \pm 0.11 \pm 0.04$	$1.11 \pm 0.20 \pm 0.07$
Current algebra	Uppal [13]	0.3	—
	Cheng [26]	1.28	—
SU(3) flavor symmetry	Sharma [14]	$0.2^a(1.7^b)$	—
	Geng [27]	$1.25^{+0.38}_{-0.36}$	—
	Geng [28]	1.30 ± 0.10	—
	Hsiao [29]	1.24 ± 0.21	—
	Geng [30]	—	0.63 ± 0.34
	Hsiao [31]	—	1.14 ± 0.54
	Zhong [32]	$1.36^a(1.27^b)$	—
Topological diagram method	Hsiao [33]	1.42 ± 0.23^c (1.47 ± 0.28^d)	—
Heavy quark effective theory	Singer [34]	—	0.36 ± 0.02

Recent results on Λ_c hadronic decays

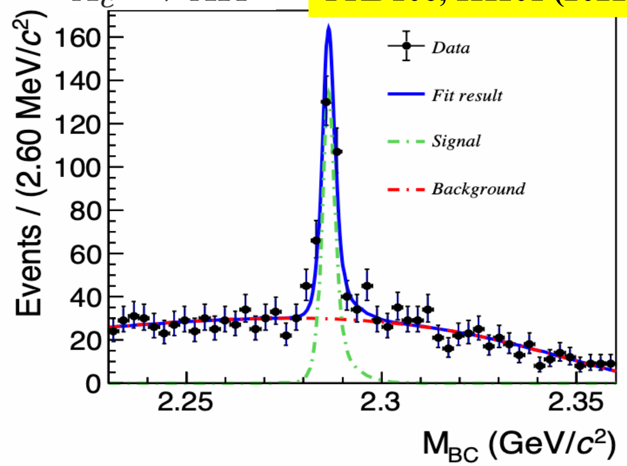
Observation of $\Lambda_c^+ \to n\pi^+$

PRL128, 142001 (2022)



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

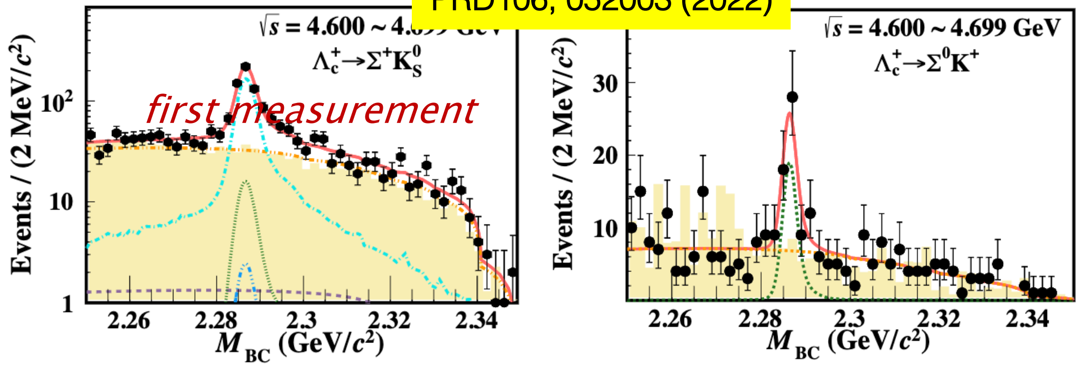
PRD106, 111101 (2022)



Many CS modes are explored.

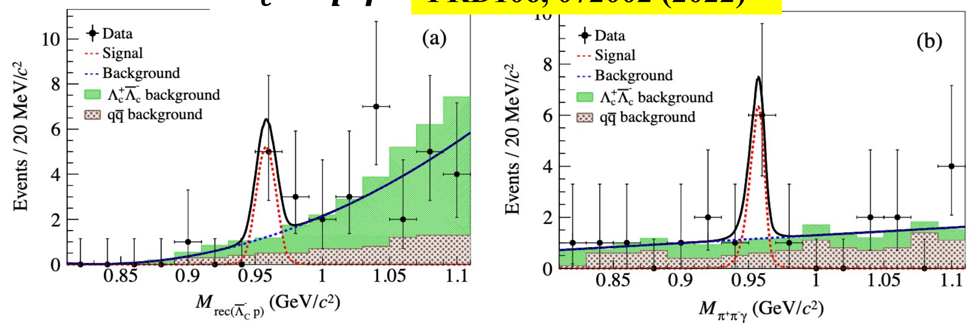
Determination of the BF for $\Lambda_c^+ \to \Sigma^+ K_S$ and $\Sigma^0 K^+$

PRD106, 052003 (2022)

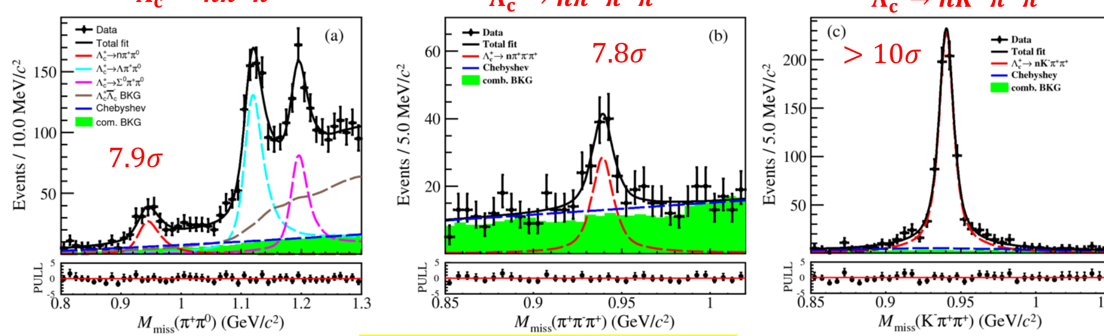


$\Lambda_c^+ \to p\eta'$

PRD106, 072002 (2022)



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



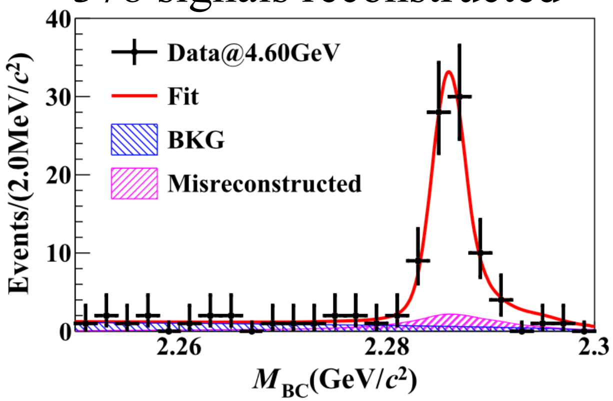
CPC47, 023001 (2023)

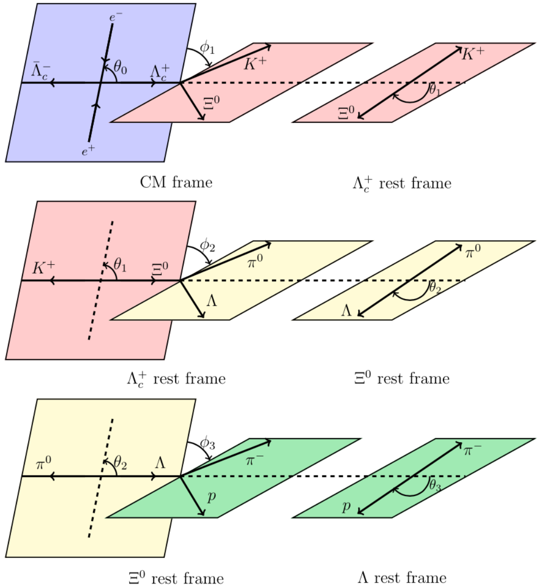
Decay asymmetry in W-exchange-only process $\Lambda_c^+ \to \Xi^0 K^+$

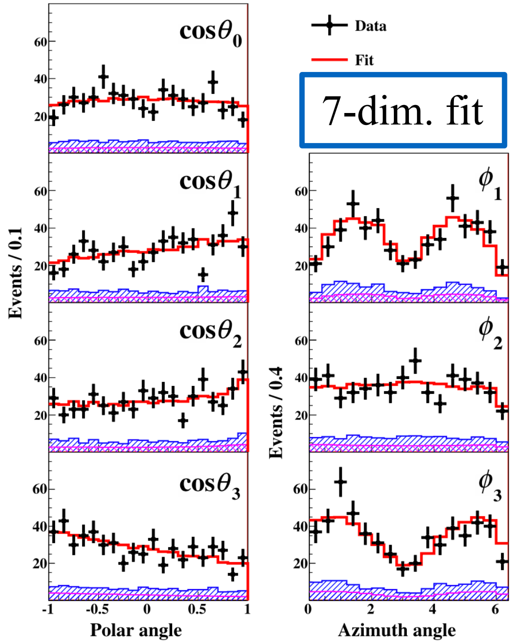
three-level cascade decay $\Lambda_c^+ \to \Xi^0 K^+, \Xi^0 \to \Lambda\pi^0, \Lambda \to p\pi^-$

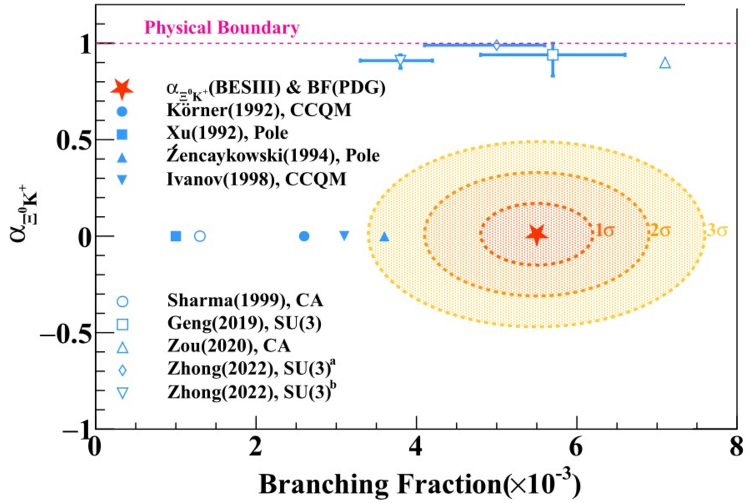
PRL132, 031801(2024)

~378 signals reconstructed



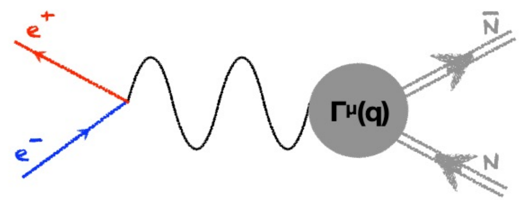


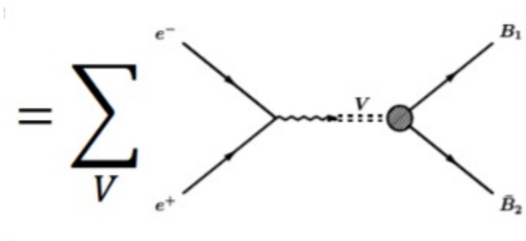


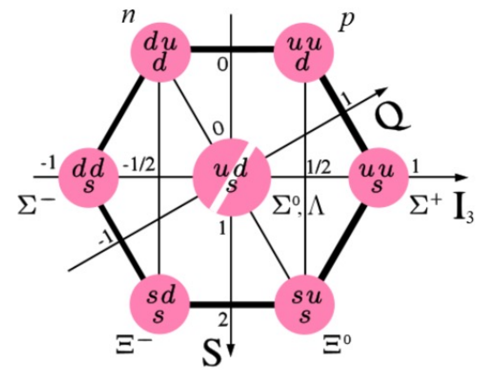


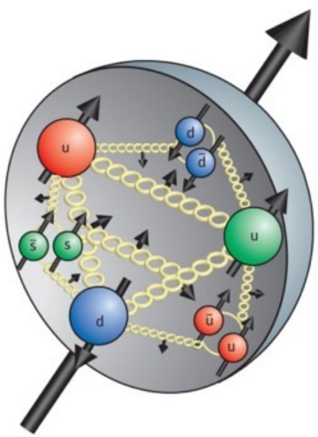
- First determination of decay asymmetry $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16 \pm 0.03$, consistent with zero
- No theoretical model explains the current results
- First determination on phase difference $\delta_p - \delta_s$, with two solutions of $\pi/2$ and $-\pi/2$

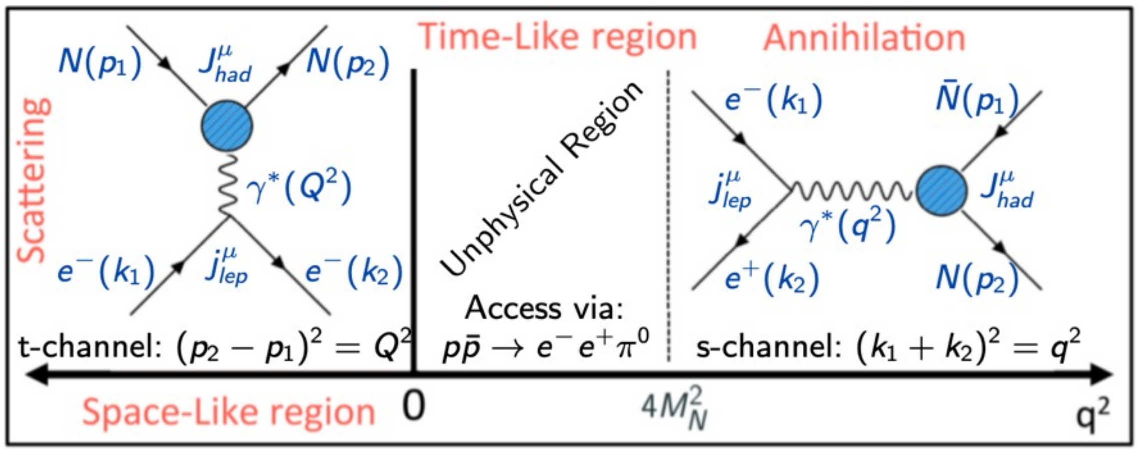
Form factors of baryons





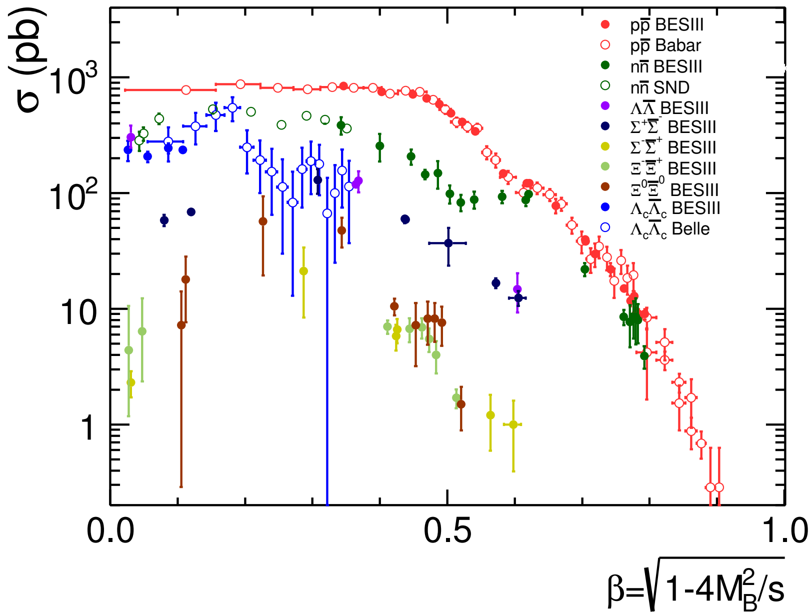


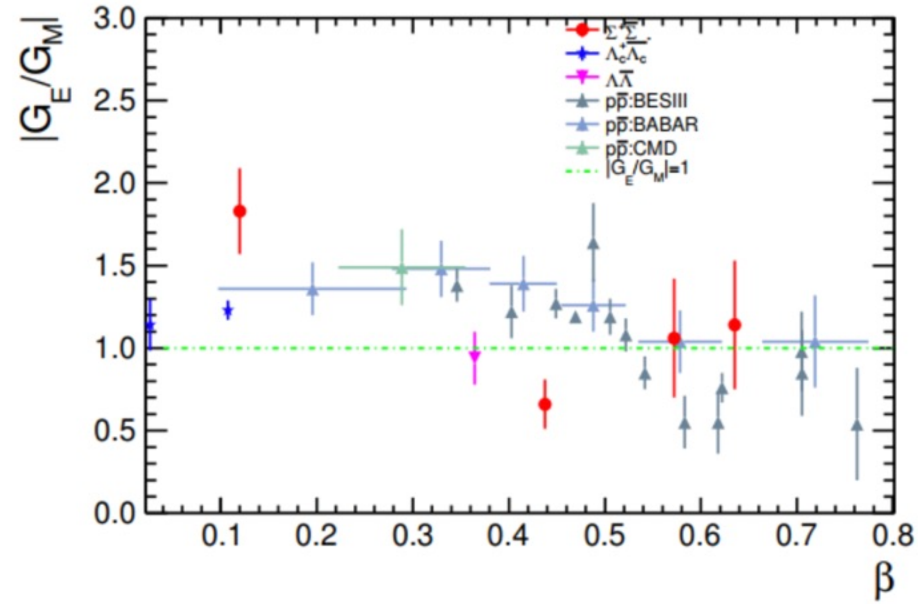




In the time-like region, access to the Electromagnetic Form Factors (EFF) of the baryons, which characterize the internal structure of the baryon

Baryon pair production



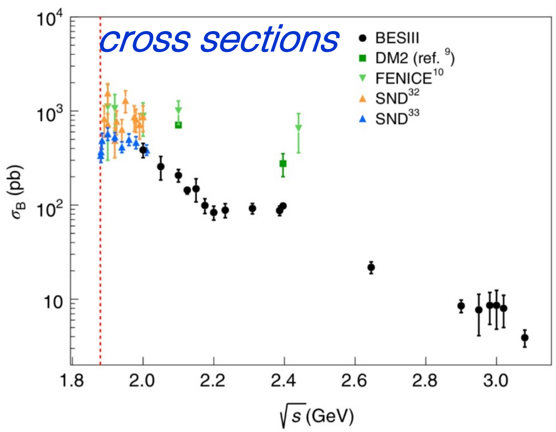


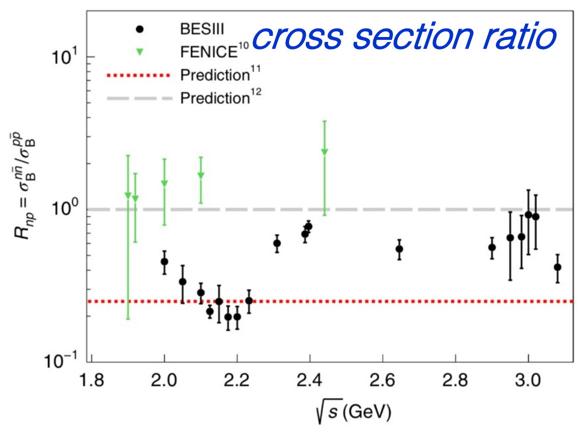
- Abnormal threshold effects observed in various baryon pair production: $p\bar{p}$, $\Lambda\bar{\Lambda}$, $\Lambda_c^+\bar{\Lambda}_c^-$ …
- $|G_E/G_M|$ ratio significantly larger than 1 at low beta for p, Λ_c^+, Σ^+, indicating large D-wave near threshold.

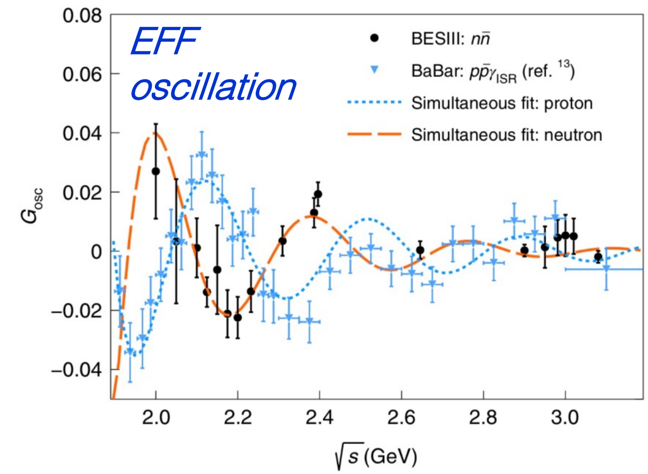
Threshold production of $e^+e^- \to n\bar{n}$

- Very challenging measurement due to pure neutron final states
- BESIII takes three approaches and provide validations among each other

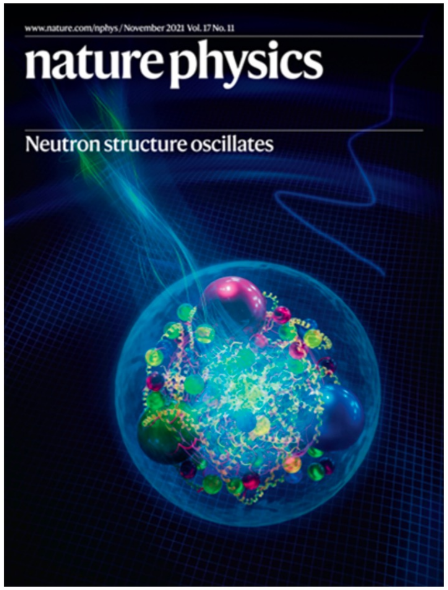
Nature Physics 17, 1200 (2021)







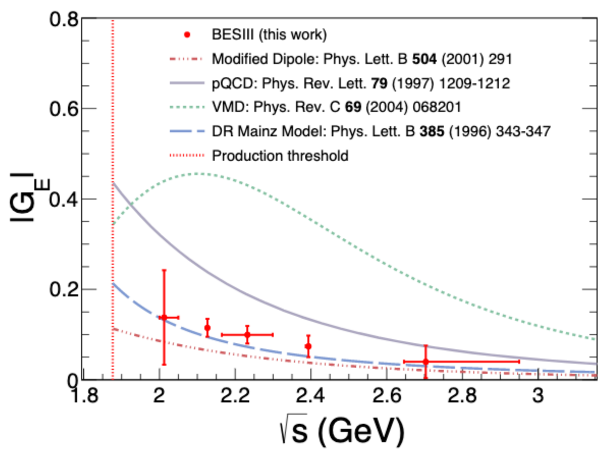
- XS measured in a wide range with unprecedented precision (~10%): confirming threshold enhancement
- XS ratio between proton and neutron: do not support the FENICE conjecture, but are within the theoretical predictions
- Oscillation of EFF observed in neutron data: simultaneous fit of proton and neutron data gives shared frequency (5.55±0.28) GeV^{-1} with almost orthogonal phase difference of (125±12)^{O}

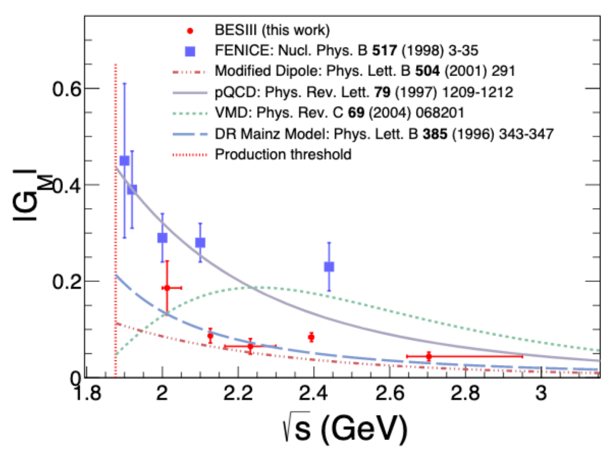


Separated electric and magnetic form factors of the neutron in time-like region

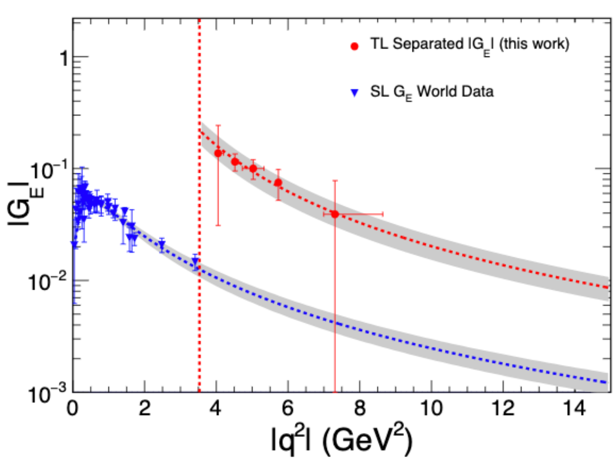
PRL130, 151905 (2023)

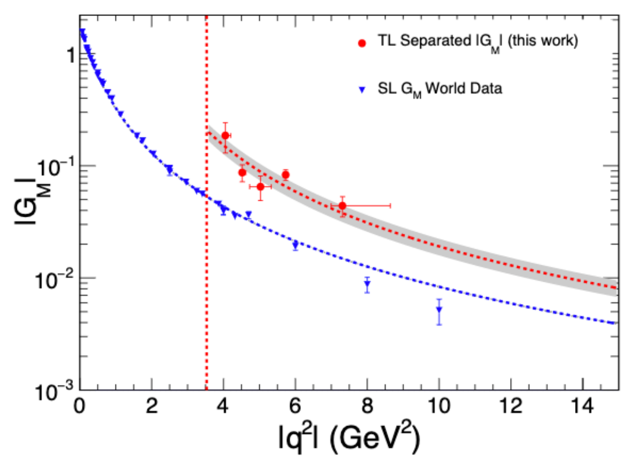
A spin-half particle, such as the nucleon, described by two EMFFs: $G_E(q^2)$ and $G_M(q^2)$, which are Fourier-transforms of the intrinsic electric and magnetic distributions of the nucleon in the Breit frame





- G_M: lower than FENICE results
- G_E and G_M: agree more with Dispersion Relations (DR)





Time-like (TL) vs Space-like (SL)

not sign of following the tendency of

$$\mathcal{R}^{E,M} \equiv \left|\frac{G^{TL}_{E,M}(q^2)}{G^{SL}_{E,M}(-q^2)}\right| \xrightarrow{|q^2|\to\infty} 1$$

Hyperon physics at BESIII

10 billion J/psi events collected

- Large rates in J/ψ decays
- Quantum entangled pair productions
- Background free, high efficiency

Hai-Bo Li, arXiv:1612.01775
A. Adlarson, A. Kupsc, arXiv:1908.03102

a hyperon factory!

Decay mode	$\mathcal{B}(\times10^{-3})$	$N_B\ (\times10^6)$
$J/\psi \to \Lambda\bar{\Lambda}$	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

CPV in SM is small：			# events	Experiments
B meson :	O(1)	discovered (2001）	10^3	***B factory***
K meson :	O(10^{-3})	discovered (1964）	10^6	***Fix targets***
D meson :	O(10^{-4})	discovered(2019）	10^8	***LHCb***
Hyperon :	O(10^{-4})	no evidence (10^{-2})	O(10^8)	***Fix targets***
				→ BESIII ?

1980

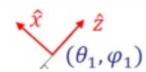
2008

Relative phase of Form Factors(FFs)

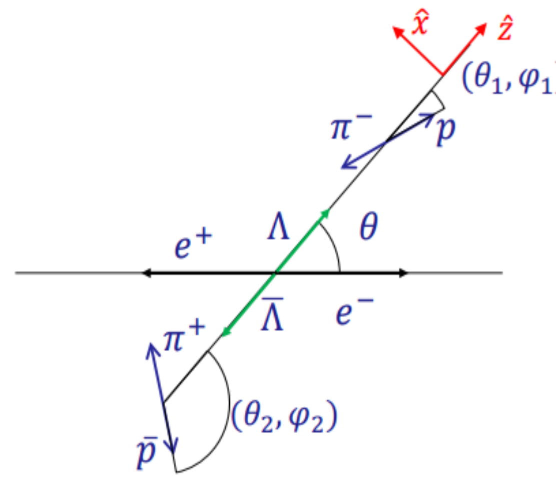
- Through the weak decay of hyperons, we could probe its polarization. Hence more information of the EFF can be studied
- $\Delta\phi$ is the phase angle difference of G_E and G_M: can be explored via angular analysis of the spin-coherent hyperon-pair weak decays

Unpolarized part | Polarized part | Spin correlated part

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



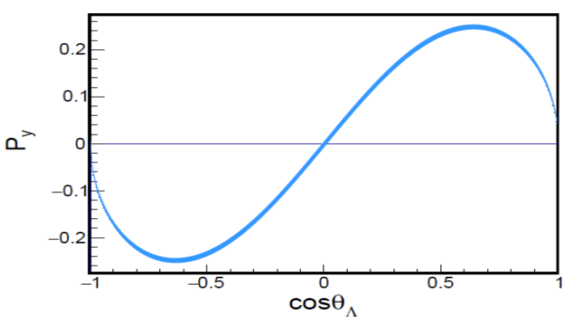
$$R = |G_E/G_M|,\ \Delta\Phi = \Phi_E - \Phi_M,\ \eta = \frac{\tau - R^2}{\tau + R^2}$$



polarization-term

independent α_- and α_+ dependence

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



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

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

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

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

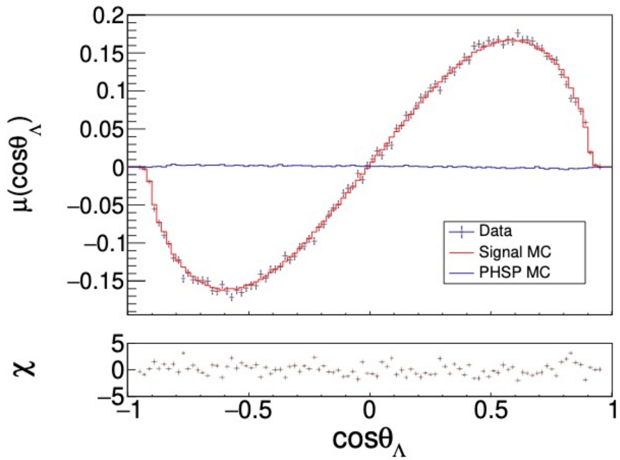
CP asymmetry:

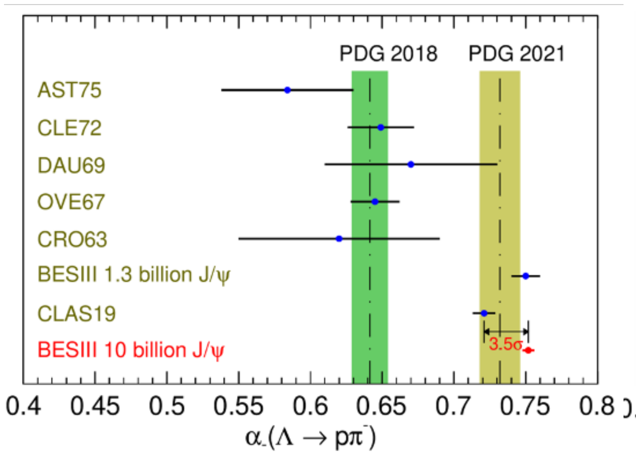
$$A = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}}, \quad B = \frac{\beta+\bar{\beta}}{\beta-\bar{\beta}}.$$

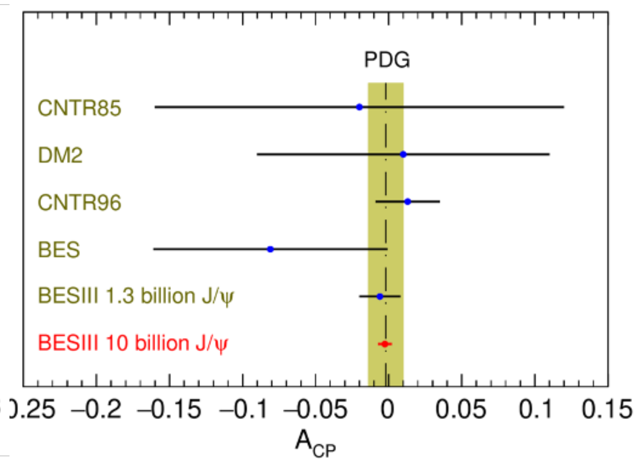
Updated Λ decay asymmetry in $J/\psi \to \Lambda\bar{\Lambda}$

PRL129, 131801(2022)

- Updated results based on 10B J/ψ events: ~0.42M signals
- Perfect fit to data
- Decay asymmetries with improved precisions are consistent with previous BESIII results
- Sensitivity of A_{CP} is improved to the level of below 0.5%







Par.	This Work*	Previous results **	PDG 2018 ***
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0024$	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027
$\Delta\Phi$	$0.7521 \pm 0.0042 \pm 0.0080$	$0.740 \pm 0.010 \pm 0.009$	-
α_-	$0.7519 \pm 0.0036 \pm 0.0019$	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013
α_+	$-0.7559 \pm 0.0036 \pm 0.0029$	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08
A_{CP}	$-0.0025 \pm 0.0046 \pm 0.0011$	$0.006 \pm 0.012 \pm 0.007$	-
$\alpha_{\pm,avg.}$	$0.7542 \pm 0.0010 \pm 0.0020$	$0.754 \pm 0.003 \pm 0.002$	-

CPV in $\Xi^- \to \Lambda\pi^-$ decay with $\Lambda \to p\pi^-$

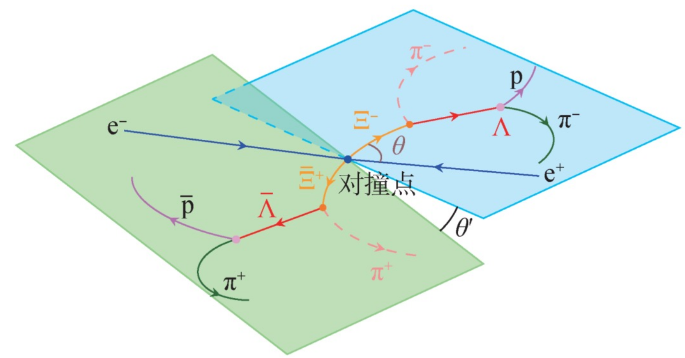
BESIII

Nature 606, 64 (2022)

$$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$$

Based on 1.3 B J/ψ events (13% of total J/ψ events)
9-dimentional fit: ~73K signals

Parameter	This work	Previous result	
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$	38
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad.	–	
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010	22
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad.	-0.037 ± 0.014 rad.	22
$\alpha_{\bar{\Xi}}$	$0.371 \pm 0.007 \pm 0.002$	–	
$\phi_{\bar{\Xi}}$	$-0.021 \pm 0.019 \pm 0.007$ rad.	–	
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$	3
$\alpha_{\bar{\Lambda}}$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	3
$\xi_p - \xi_s$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad.	–	
$\delta_p - \delta_s$	$(-4.4 \pm 3.6 \pm 1.8) \times 10^{-2}$ rad.	$(8.7 \pm 3.3) \times 10^{-2}$ rad.	2
A_{CP}^{Ξ}	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–	
$\Delta\phi_{CP}^{\Xi}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad.	–	
A_{CP}^{Λ}	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$	3
$< \phi_\Xi >$	$0.016 \pm 0.014 \pm 0.007$ rad.		



First measurement of baryon weak phase difference

We obtain the same precision for ϕ as HyperCP with ***three orders of magnitude*** smaller data sample!

HyperCP: $\phi_{\Xi,HyperCP} = -0.042 \pm 0.011 \pm 0.011$
BESIII: $<\phi_\Xi> = 0.016 \pm 0.014 \pm 0.007$

HyperCP: PRL 93(2004) 011802

$$J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda(p\pi^-)\pi^-\bar{\Lambda}(\bar{n}\pi^0)\pi^+$$

10B J/ψ decays

PRL132, 101801 (2024)

Parameters	This work	Previous result
$\alpha_{J/\psi}$	$0.611 \pm 0.007^{+0.013}_{-0.007}$	$0.586 \pm 0.012 \pm 0.010$ [17]
$\Delta\Phi_{J/\psi}$ (rad)	$1.30 \pm 0.03^{+0.02}_{-0.03}$	$1.213 \pm 0.046 \pm 0.016$ [17]
α_{Ξ}	$-0.367 \pm 0.004^{+0.003}_{-0.004}$	$-0.376 \pm 0.007 \pm 0.003$ [17]
ϕ_{Ξ} (rad)	$-0.016 \pm 0.012^{+0.004}_{-0.008}$	$0.011 \pm 0.019 \pm 0.009$ [17]
$\bar{\alpha}_{\Xi}$	$0.374 \pm 0.004^{+0.002}_{-0.004}$	$0.371 \pm 0.007 \pm 0.002$ [17]
$\bar{\phi}_{\Xi}$ (rad)	$0.010 \pm 0.012^{+0.002}_{-0.013}$	$-0.021 \pm 0.019 \pm 0.007$ [17]
$\alpha_{\Lambda-}$	$0.764 \pm 0.008^{+0.005}_{-0.006}$	$0.7519 \pm 0.0036 \pm 0.0024$ [35]
$\alpha_{\Lambda+}$	$-0.774 \pm 0.009^{+0.005}_{-0.005}$	$-0.7559 \pm 0.0036 \pm 0.0030$ [35]
$\alpha_{\Lambda 0}$	$0.670 \pm 0.009^{+0.009}_{-0.008}$	0.75 ± 0.05 [28]
$\bar{\alpha}_{\Lambda 0}$	$-0.668 \pm 0.008^{+0.006}_{-0.008}$	$-0.692 \pm 0.016 \pm 0.006$ [18]
$\delta_P - \delta_S$ (rad)	$0.033 \pm 0.020^{+0.008}_{-0.012}$	$-0.040 \pm 0.033 \pm 0.017$ [17]
$\xi_P - \xi_S$ (rad)	$0.007 \pm 0.020^{+0.018}_{-0.005}$	$0.012 \pm 0.034 \pm 0.008$ [17]
$A^{\Xi}_{\rm CP}$	$-0.009 \pm 0.008^{+0.007}_{-0.002}$	$0.006 \pm 0.013 \pm 0.006$ [17]
$\Delta\phi^{\Xi}_{\rm CP}$ (rad)	$-0.003 \pm 0.008^{+0.002}_{-0.007}$	$-0.005 \pm 0.014 \pm 0.003$ [17]
$A^{-}_{\rm CP}$	$-0.007 \pm 0.008^{+0.002}_{-0.003}$	$-0.0025 \pm 0.0046 \pm 0.0012$ [35]
$A^{0}_{\rm CP}$	$0.001 \pm 0.009^{+0.005}_{-0.007}$	-
$A^{\Lambda}_{\rm CP}$	$-0.004 \pm 0.007^{+0.003}_{-0.004}$	-
$\alpha_{\Lambda 0}/\alpha_{\Lambda-}$	$0.877 \pm 0.015^{+0.014}_{-0.010}$	1.01 ± 0.07 [28]
$\bar{\alpha}_{\Lambda 0}/\alpha_{\Lambda+}$	$0.863 \pm 0.014^{+0.012}_{-0.008}$	$0.913 \pm 0.028 \pm 0.012$ [18]

CPV in $\Xi^0 \to \Lambda\pi^0$ decay

PRD108, L031106 (2023)

$J/\psi \to \Xi^0\bar{\Xi}^0 \to \Lambda\pi^0\bar{\Lambda}\pi^0$ in 10B J/ψ decays

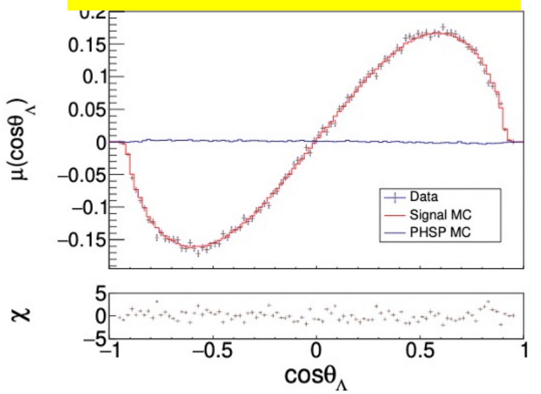
Parameter	This work	Previous result
$\alpha_{J/\psi}$	$0.514 \pm 0.006 \pm 0.015$	0.66 ± 0.06 [34]
$\Delta\Phi$(rad)	$1.168 \pm 0.019 \pm 0.018$	-
α_Ξ	$-0.3750 \pm 0.0034 \pm 0.0016$	-0.358 ± 0.044 [18]
$\bar{\alpha}_\Xi$	$0.3790 \pm 0.0034 \pm 0.0021$	0.363 ± 0.043 [18]
ϕ_Ξ(rad)	$0.0051 \pm 0.0096 \pm 0.0018$	0.03 ± 0.12 [18]
$\bar{\phi}_\Xi$(rad)	$-0.0053 \pm 0.0097 \pm 0.0019$	-0.19 ± 0.13 [18]
α_Λ	$0.7551 \pm 0.0052 \pm 0.0023$	0.7519 ± 0.0043 [13]
$\bar{\alpha}_\Lambda$	$-0.7448 \pm 0.0052 \pm 0.0017$	-0.7559 ± 0.0047 [13]
$\xi_P - \xi_S$(rad)	$(0.0 \pm 1.7 \pm 0.2) \times 10^{-2}$	-
$\delta_P - \delta_S$(rad)	$(-1.3 \pm 1.7 \pm 0.4) \times 10^{-2}$	-
A_{CP}^Ξ	$(-5.4 \pm 6.5 \pm 3.1) \times 10^{-3}$	$(-0.7 \pm 8.5) \times 10^{-2}$ [18]
$\Delta\phi_{CP}^\Xi$(rad)	$(-0.1 \pm 6.9 \pm 0.9) \times 10^{-3}$	$(-7.9 \pm 8.3) \times 10^{-2}$ [18]
A_{CP}^Λ	$(6.9 \pm 5.8 \pm 1.8) \times 10^{-3}$	$(-2.5 \pm 4.8) \times 10^{-3}$ [13]
$\langle\alpha_\Xi\rangle$	$-0.3770 \pm 0.0024 \pm 0.0014$	-
$\langle\phi_\Xi\rangle$(rad)	$0.0052 \pm 0.0069 \pm 0.0016$	-
$\langle\alpha_\Lambda\rangle$	$0.7499 \pm 0.0029 \pm 0.0013$	0.7542 ± 0.0026 [13]

	$J/\psi \to \Xi^0\bar{\Xi}^0$	$J/\psi \to \Xi^-\bar{\Xi}^+$
Parameter	Ξ^0 (this work)	Ξ^- (from Ref. [15])
$\alpha_{J/\psi}$	$0.514 \pm 0.006 \pm 0.015$	$0.586 \pm 0.012 \pm 0.010$
$\Delta\Phi$(rad)	$1.168 \pm 0.019 \pm 0.018$	$1.213 \pm 0.046 \pm 0.016$
α_Ξ	$-0.3750 \pm 0.0034 \pm 0.0016$	$-0.376 \pm 0.007 \pm 0.003$
$\bar{\alpha}_\Xi$	$0.3790 \pm 0.0034 \pm 0.0021$	$0.371 \pm 0.007 \pm 0.002$
ϕ_Ξ(rad)	$0.0051 \pm 0.0096 \pm 0.0018$	$0.011 \pm 0.019 \pm 0.009$
$\bar{\phi}_\Xi$(rad)	$-0.0053 \pm 0.0097 \pm 0.0019$	$-0.021 \pm 0.019 \pm 0.007$
$\xi_P - \xi_S$(rad)	$(0.0 \pm 1.7 \pm 0.2) \times 10^{-2}$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$
$\delta_P - \delta_S$(rad)	$(-1.3 \pm 1.7 \pm 0.4) \times 10^{-2}$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$
A_{CP}^Ξ	$(-5.4 \pm 6.5 \pm 3.1) \times 10^{-3}$	$(6 \pm 13 \pm 6) \times 10^{-3}$
$\Delta\phi_{CP}^\Xi$(rad)	$(-0.1 \pm 6.9 \pm 0.9) \times 10^{-3}$	$(-5 \pm 14 \pm 3) \times 10^{-3}$
$\langle\phi_\Xi\rangle$	$0.0052 \pm 0.0069 \pm 0.0016$	$0.016 \pm 0.014 \pm 0.007$

Polarization behavior in different hyperon pair productions

$J/\psi \to \Lambda\bar{\Lambda}$

PRL129, 131801(2022)

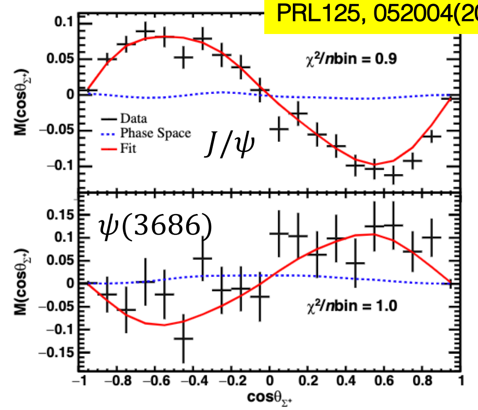


$\Delta\Phi = (0.7521 \pm 0.0042 \pm 0.0066)rad$

$A_{CP}=(-0.25 \pm 0.46 \pm 0.12)\%$

$e^+e^- \to \psi \to \Sigma^+\bar{\Sigma}^- \to p\bar{p}\pi^0\pi^0$

PRL125, 052004(2020)

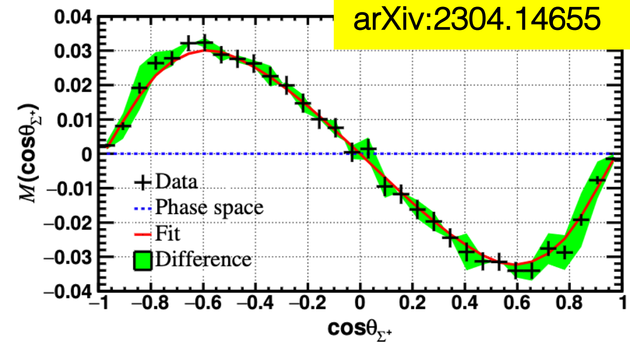


$\Delta\Phi[J/\psi] = 15.5° \pm 0.7° \pm 0.5°$ $\Delta\Phi[\psi'] = 21.7° \pm 4.0° \pm 0.8°$

$A_{CP}=(-0.4 \pm 3.7 \pm 1.0)\%$

$e^+e^- \to J/\psi \to \Sigma^+\bar{\Sigma}^- \to n\pi^+\bar{p}\pi^0$

arXiv:2304.14655

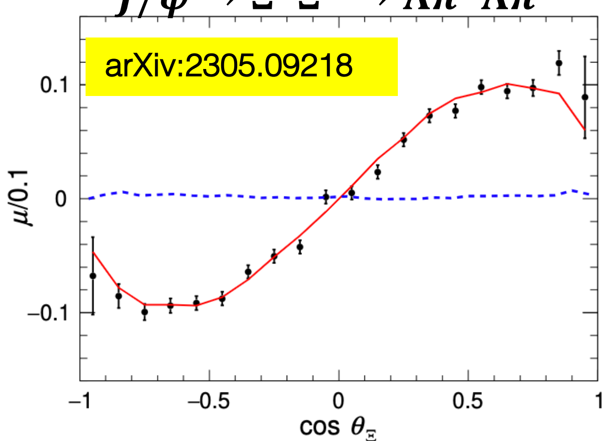


$\Delta\Phi = (-277.2 \pm 4.4 \pm 4.1)\times 10^{-3}$ rad

$A_{CP} = (-8.0 \pm 5.2 \pm 2.8)\%$

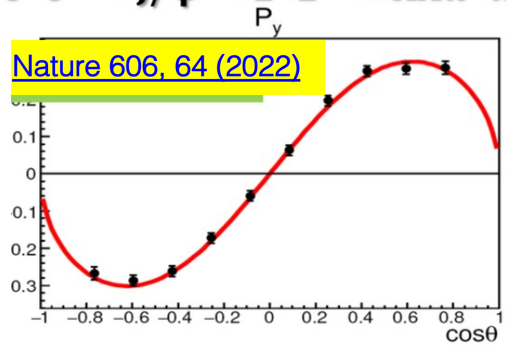
$J/\psi \to \Xi^0\bar{\Xi}^0 \to \Lambda\pi^0\bar{\Lambda}\pi^0$

arXiv:2305.09218



$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda\bar{\Lambda}\pi^+\pi^-$

Nature 606, 64 (2022)

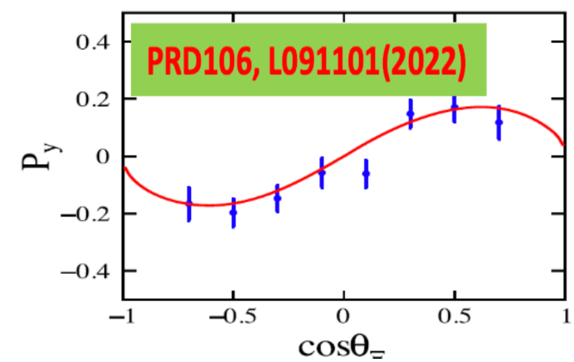


$\Delta\Phi = (1.213 \pm 0.046 \pm 0.016)rad$

$A_{CP}=(0.60 \pm 1.34 \pm 0.56)\%$

$e^+e^- \to \psi' \to \Xi^-\bar{\Xi}^+ \to \Lambda\bar{\Lambda}\pi^+\pi^-$

PRD106, L091101(2022)



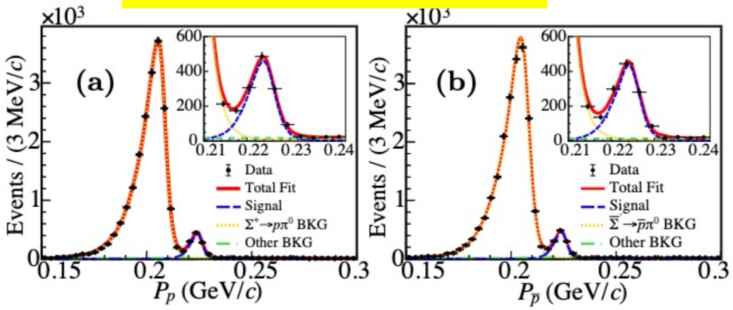
$\Delta\Phi = (0.667 \pm 0.111 \pm 0.058)$ rad.

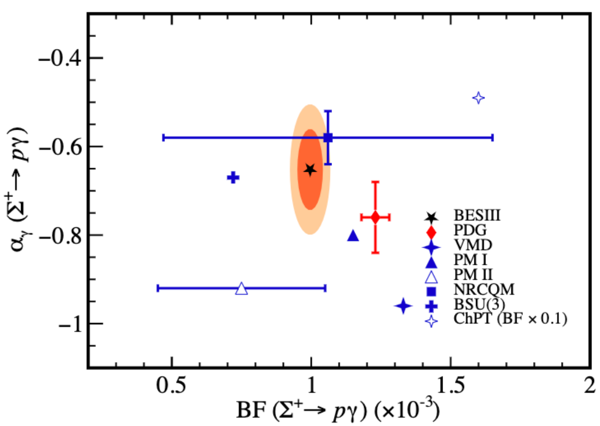
$A_{CP} = (-1.5 \pm 5.1 \pm 1.0)\%$

Study on hyperon rare decays

$\Sigma^+ \to \gamma p$ from $J/\psi \to \Sigma^+\bar{\Sigma}^-$

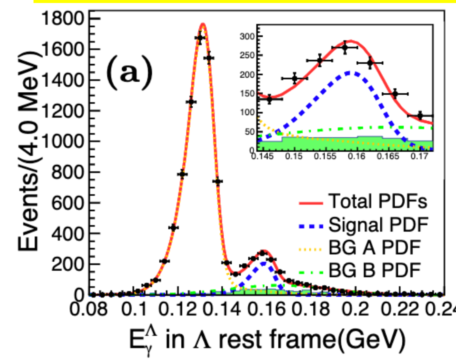
PRL 130, 211901 (2023)

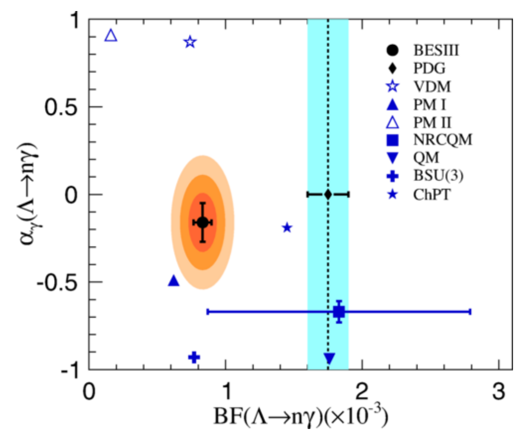




$\Lambda \to \gamma n$ in $J/\psi \to \Lambda\bar{\Lambda}$

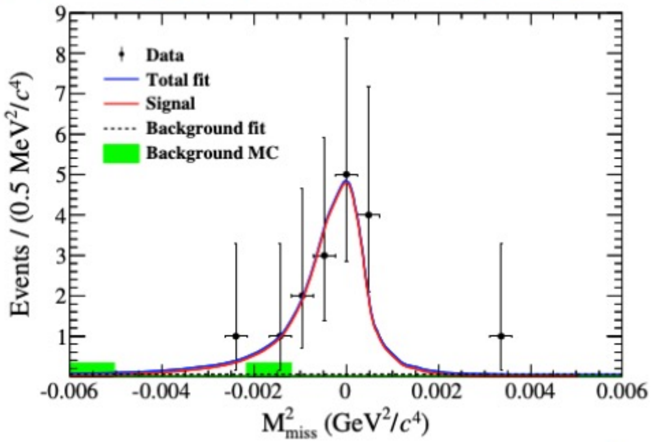
PRL129, 212002 (2022)



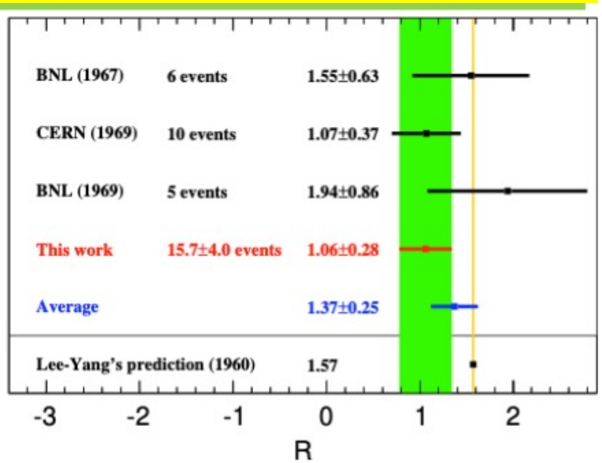


Study on hyperon rare decays

$\Sigma^+ \to \Lambda e^- \nu$ via $J/\psi \to \Sigma^+ \bar{\Sigma}^-$

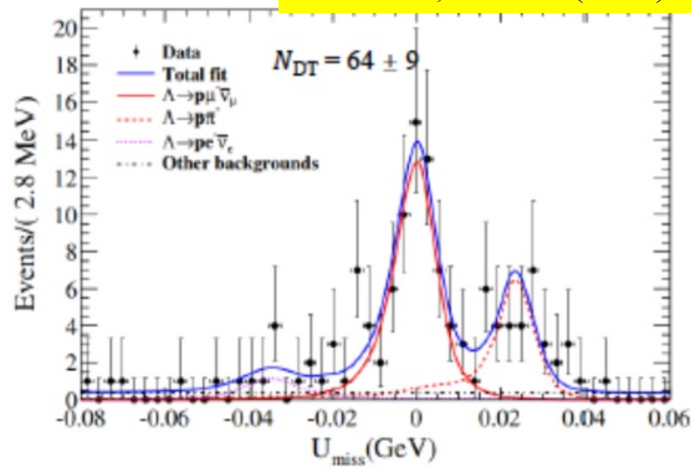


PRD 107, 072010 (2023)

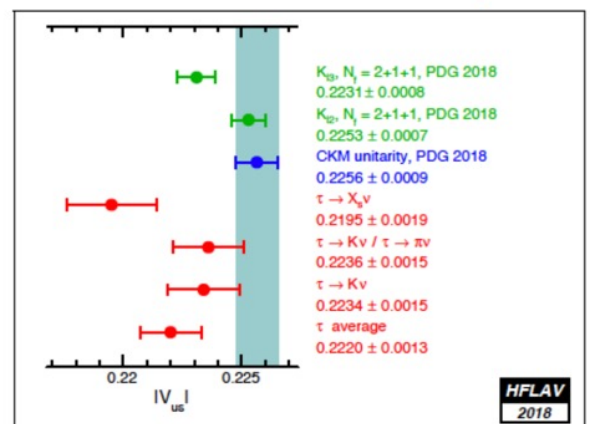


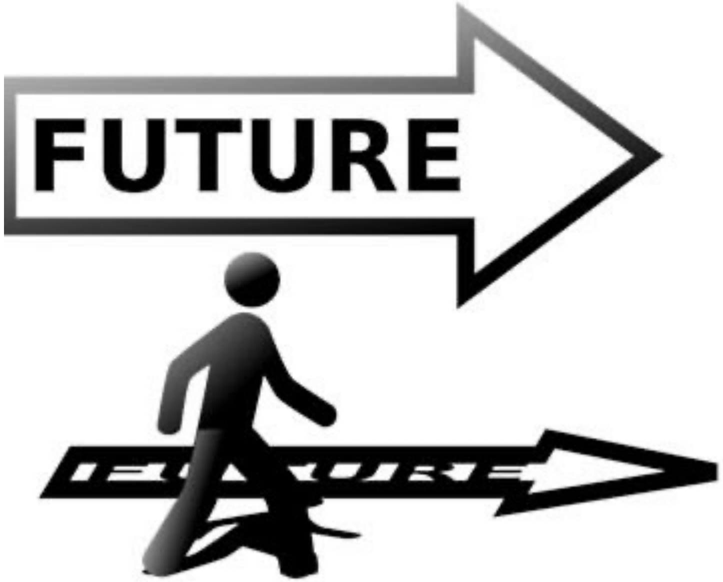
$\Lambda \to p\mu^- \nu$ in $J/\psi \to \Lambda\bar{\Lambda}$

PRL 127, 121802 (2023)

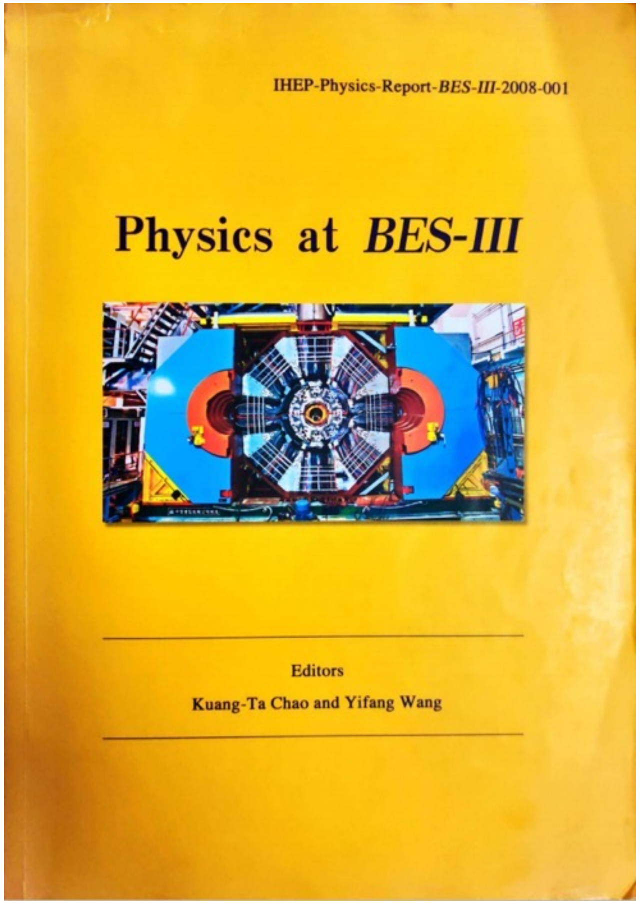


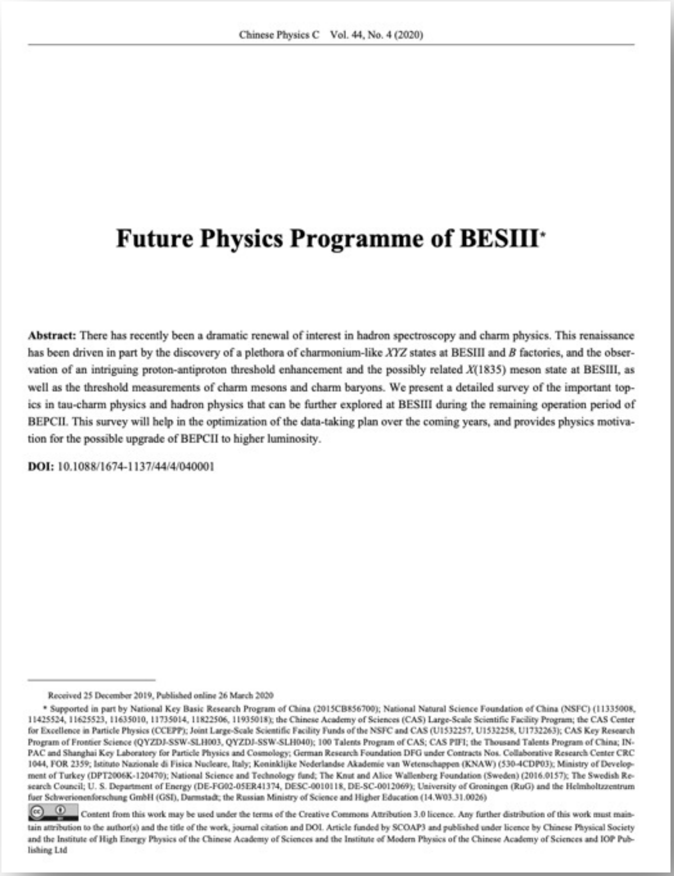
inconsistent |Vus| measurement




FUTURE

BESIII Physics




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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Int. J. Mod. Phys. A 24, S1-794 (2009) [arXiv:0809.1869 [hep-ex]].

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

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 until 2024

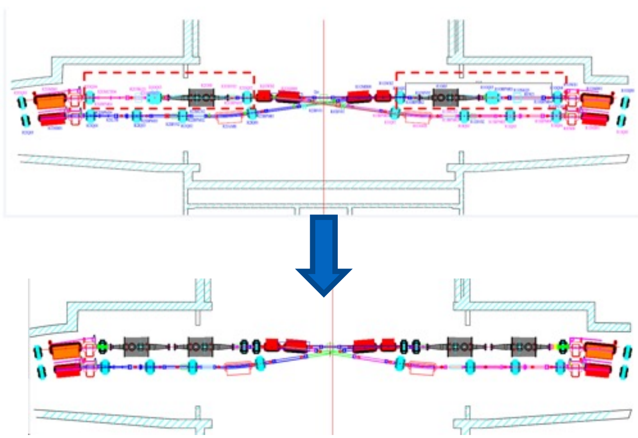
~55 fb^{-1}

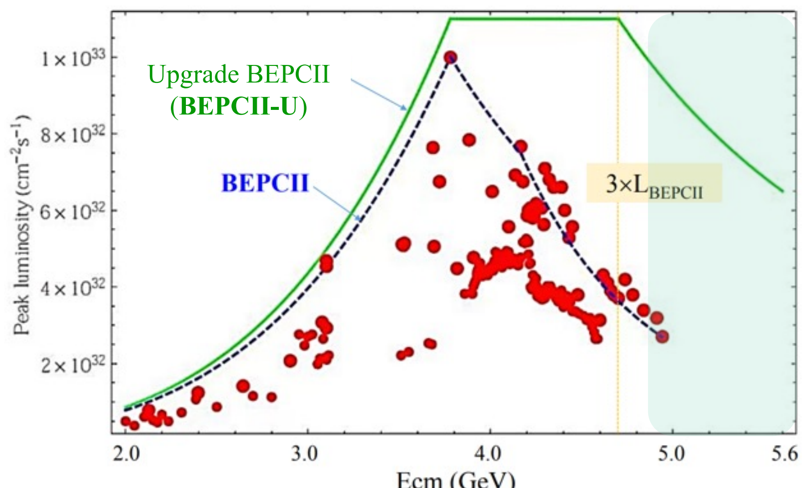
Proposal of the upgrade BEPCII

✓ 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

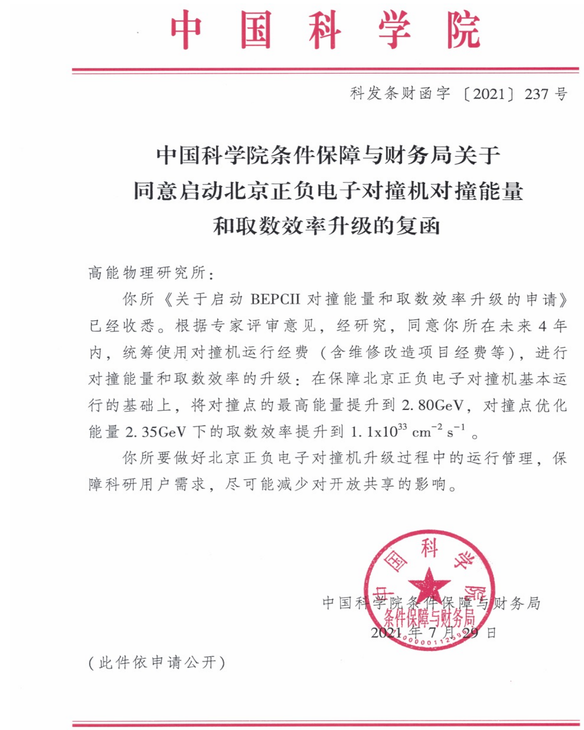
	BEPCII	BEPCII-U
Lum [$10^{32}cm^{-2}s^{-1}$]	3.5	11
β_y^* [cm]	1.5	1.35
Bunch Current [mA]	7.1	7.5
Bunch Num	56	120
SR Power [kW]	110	250
$\xi_{y,\mathrm{lum}}$	0.029	0.033
Emittance [nmrad]	147	152
Coupling [%]	0.53	0.35
Bucket Height	0.0069	0.011
$\sigma_{z,0}$ [cm]	1.54	1.07
σ_z [cm]	1.69	1.22
RF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





Project timeline of BEPCII-U

- **Idea begins in 2018：BEPCII operation meeting**
- April, 2019 ： The first formal report and discussion on Development Workshop of IHEP
- September, 2019: The first communication with CAS
- October, 2019: BEPCII-U plan as Science and Education Infrastructure Project
- May, 2020：The first review on accelerator
- July, 2020：The second formal report and discussion on Development Workshop of IHEP (including the cost)
- September, 2020：The accomplish of the project design report
- April, 2021：Review on design report
- June, 2021：The Design Report delivery to CAS
- **July , 2021： The Design Report Approved by CAS**



中 国 科 学 院

科发条财函字〔2021〕237 号

中国科学院条件保障与财务局关于同意启动北京正负电子对撞机对撞能量和取数效率升级的复函

高能物理研究所：

你所《关于启动 BEPCII 对撞能量和取数效率升级的申请》已经收悉。根据专家评审意见，经研究，同意你所在未来 4 年内，统筹使用对撞机运行经费（含维修改造项目经费等），进行对撞能量和取数效率的升级：在保障北京正负电子对撞机基本运行的基础上，将对撞点的最高能量提升到 2.80GeV，对撞点优化能量 2.35GeV 下的取数效率提升到 $1.1\times10^{33}\ cm^{-2}\ s^{-1}$。

你所要做好北京正负电子对撞机升级过程中的运行管理，保障科研用户需求，尽可能减少对开放共享的影响。

中国科学院条件保障与财务局

2021 年 7 月 29 日

（此件依申请公开）

Project Cost: ~150M CNY

- 2024 .7-12, Shut down for hardware dismantling and installation
- 2025-2028, Operation at 2.3~2.5GeV, prepare for energy upgrade
- 2028.6-9, Energy upgrade to 2.8GeV
- 2028.9~2030, Operation at 2.5~2.8GeV

✓ **Phase I: Luminosity tripled to $11\times10^{32}cm^{-2}s^{-1}$ @ 2.35GeV**

✓ **Phase II: energy increase 2.47GeV➔2.80GeV**

Future data taking with BEPCII-U

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.

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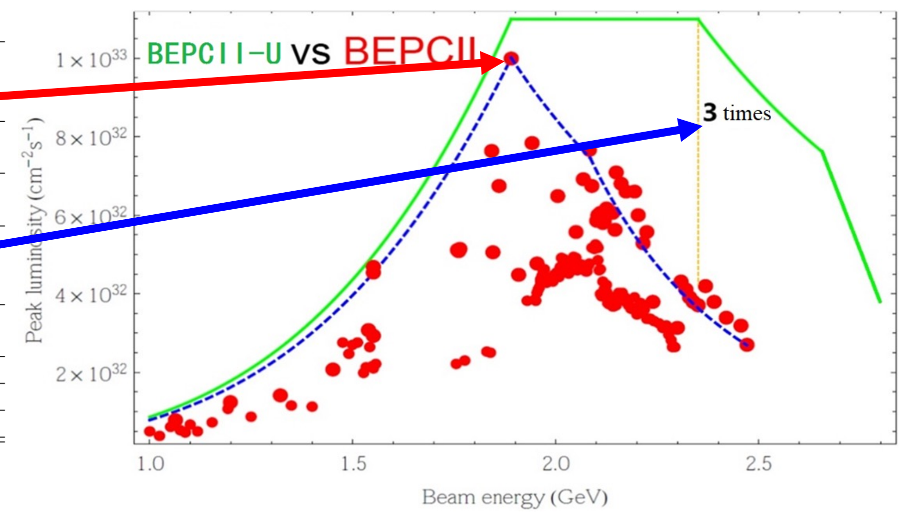
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

Goal: Integral luminosity > 6 fb^{-1}

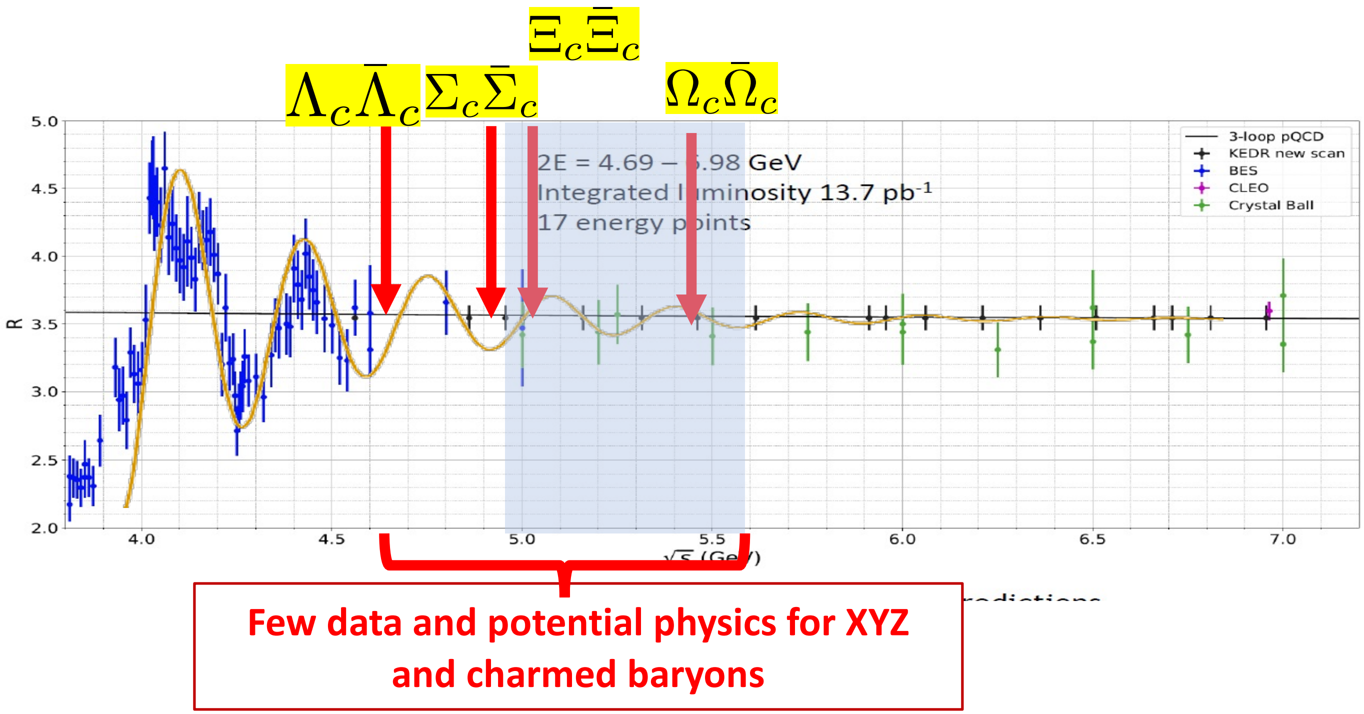
$\psi(3770)$, 8.2 fb^{-1} ← 219 days

Remaining 3.8 fb^{-1}, lower pressure for accelerator operation in 2023~2024

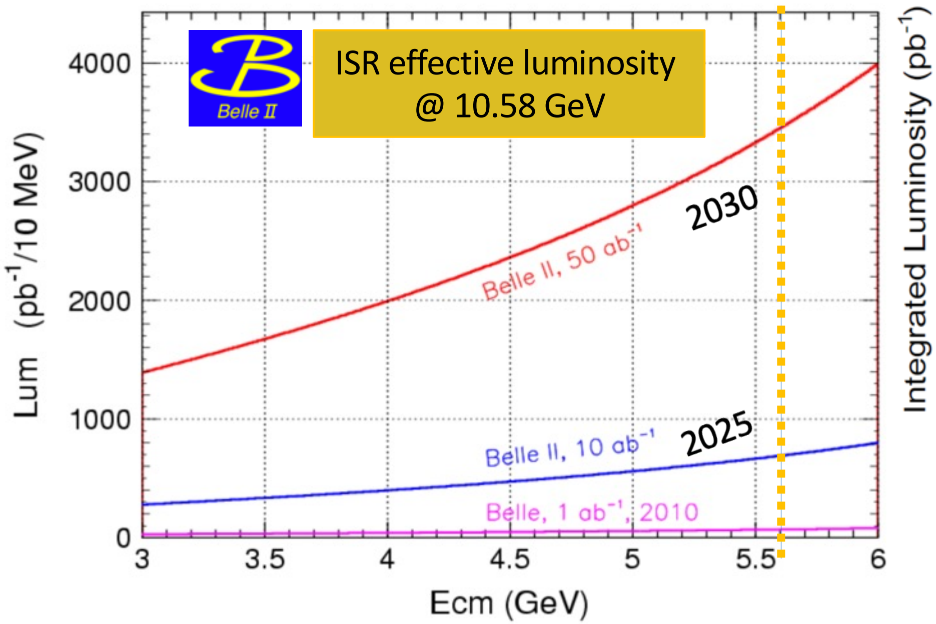


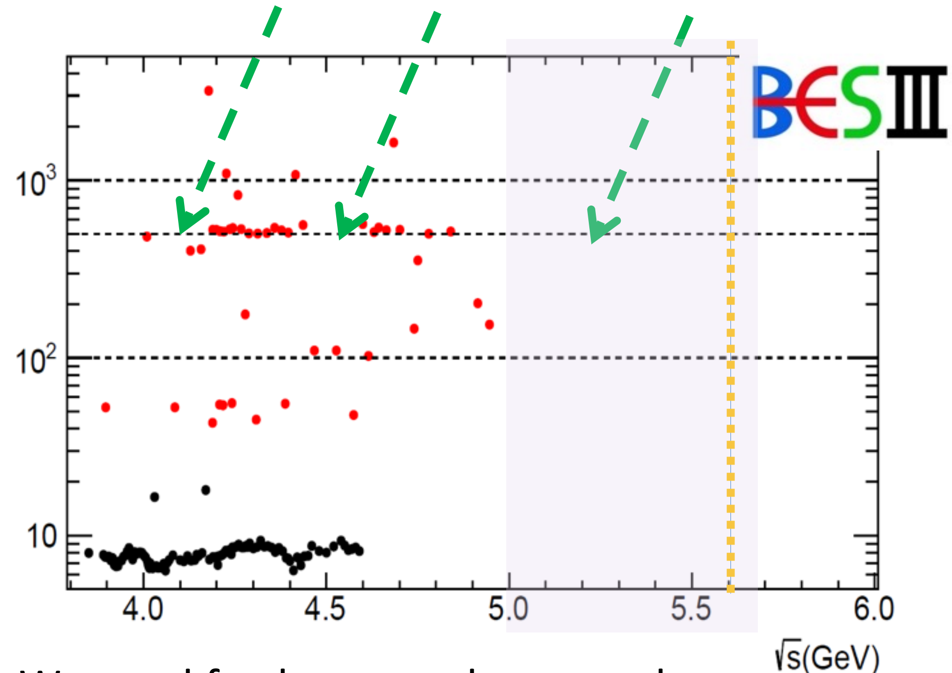
Potential physics with BEPCII-U

- ✓ 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



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: $\Lambda_c \bar{\Lambda}_c$
- ✓ 4.95 -4.97GeV: $\Xi_c \; \bar{\Xi}_c$
  5.4 -5.6 GeV: $\Omega_c^0 \bar{\Omega}_c^0$

Summary

- BESIII is successfully operating since 2008, and will continue to run for 5–10 years
  – collect large data samples in the energy range 2.0~5.6 GeV
- Cover a large scope of physics topics
  - ✓ Charmed mesons and baryons
  - ✓ XYZ states and light hadron spectroscopy
  - ✓ Form factors of the nucleon and hyperons
  - ✓ Low-Q^2 QCD studies: R value, multi-meson production, fragmentation function, …
  - ✓ Rare decays and new physics search
  - ✓ …
- **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 and energy upgrade
- Future STCF would be an important next generation facility

Thank you!

谢谢!

Λ_c^+ decay asymmetries

Predictions and measurements	$\alpha^{pK_S^0}_{\Lambda_c^+}$	$\alpha^{\Lambda\pi^+}_{\Lambda_c^+}$	$\alpha^{\Sigma^0\pi^+}_{\Lambda_c^+}$	$\alpha^{\Sigma^+\pi^0}_{\Lambda_c^+}$	$\alpha^{\Xi^0 K^+}_{\Lambda_c^+}$
CLEO(1990) [1]	-	$-1.0^{+0.4}_{-0.1}$	-	-	-
ARGUS(1992) [2]	-	-0.96 ± 0.42	-	-	-
Körner(1992), CCQM [3]	-0.10	-0.70	0.70	0.71	0
Xu(1992), Pole [4]	0.51	-0.67	0.92	0.92	0
Cheng, Tseng(1992), Pole [5]	-0.49	-0.96	0.83	0.83	-
Cheng, Tseng(1993), Pole [6]	-0.49	-0.95	0.78	0.78	-
Źencaykowski(1994), Pole [7]	-0.90	-0.86	-0.76	-0.76	0
Źencaykowski(1994), Pole [8]	-0.66	-0.99	0.39	0.39	0
CLEO(1995) [9]	-	$-0.94^{+0.21+0.12}_{-0.06-0.06}$	-	$-0.45 \pm 0.31 \pm 0.06$	-
Alakabha Datta(1995), CA [10]	-0.91	-0.94	-0.47	-0.47	-
Ivanov(1998), CCQM [11]	-0.97	-0.95	0.43	0.43	0
Sharma(1999), CA [12]	-0.99	-0.99	-0.31	-0.31	0
FOCUS(2006) [13]	-	$-0.78 \pm 0.16 \pm 0.19$	-	-	-
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	0.02
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	-