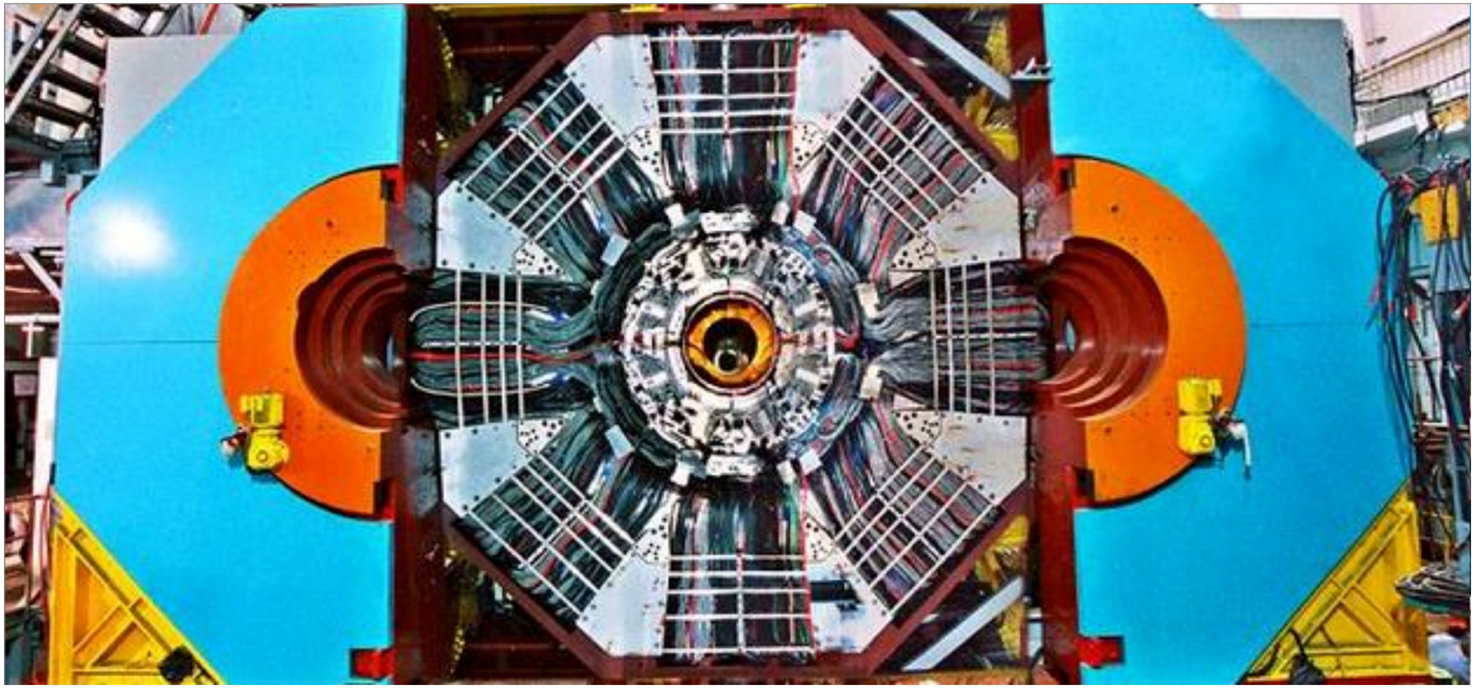


Recent results on hadron physics at BESIII

Xiao-Rui Lyu (吕晓睿)

University of Chinese Academy of Sciences (UCAS)

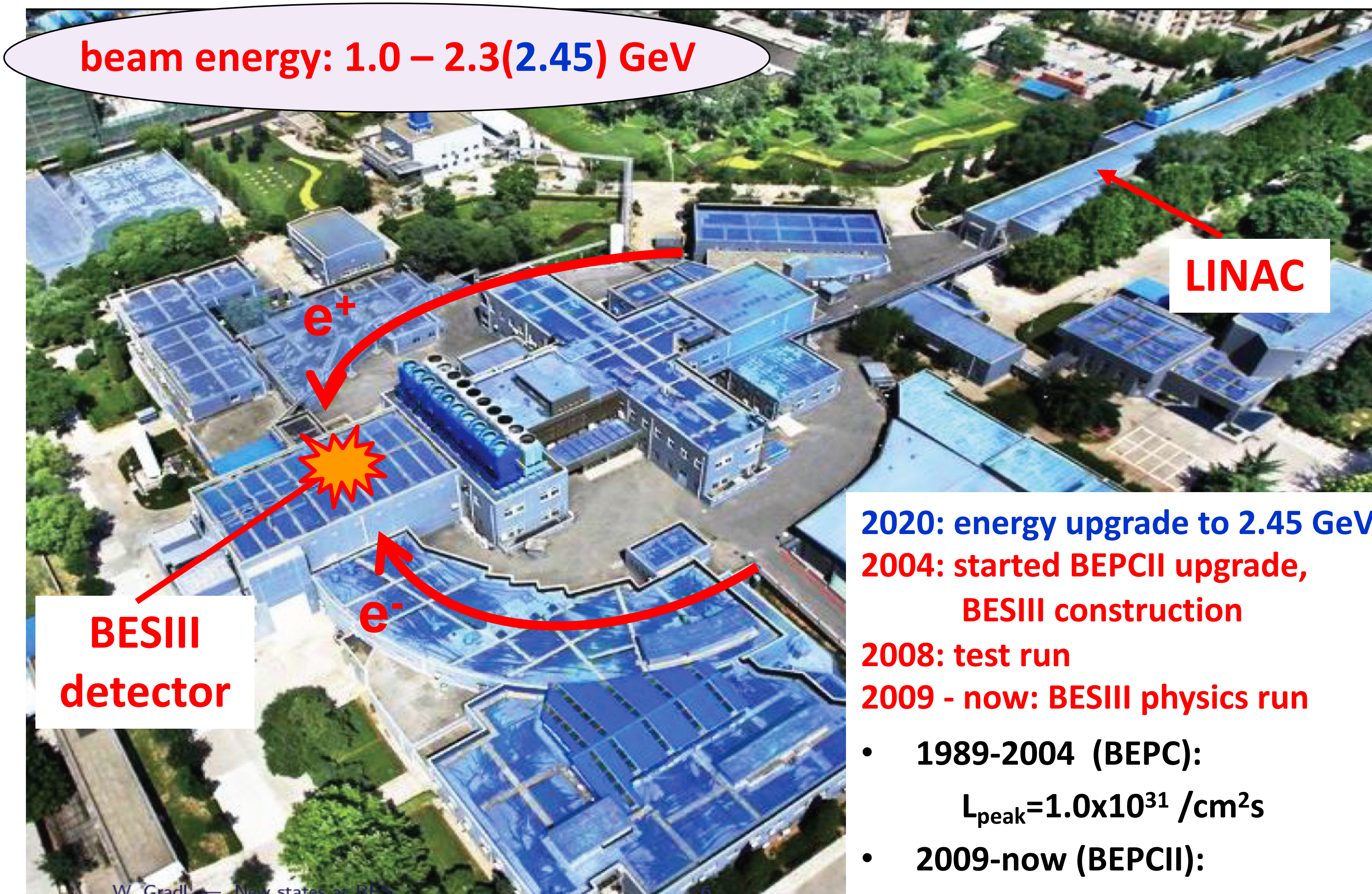
(On behalf of the BESIII collaboration)

Outline

- Introduction to BEPCII/BESIII
- Recent selected results on hadron physics
  - charmonium- and strangenium-like states
  - form factors of baryons
  - charmed hadron
- Prospects for the future
- Summary

Disclaimer: personal overview, not comprehensive

Beijing Electron Positron Collider (BEPCII)



2020: energy upgrade to 2.45 GeV

2004: started BEPCII upgrade, BESIII construction

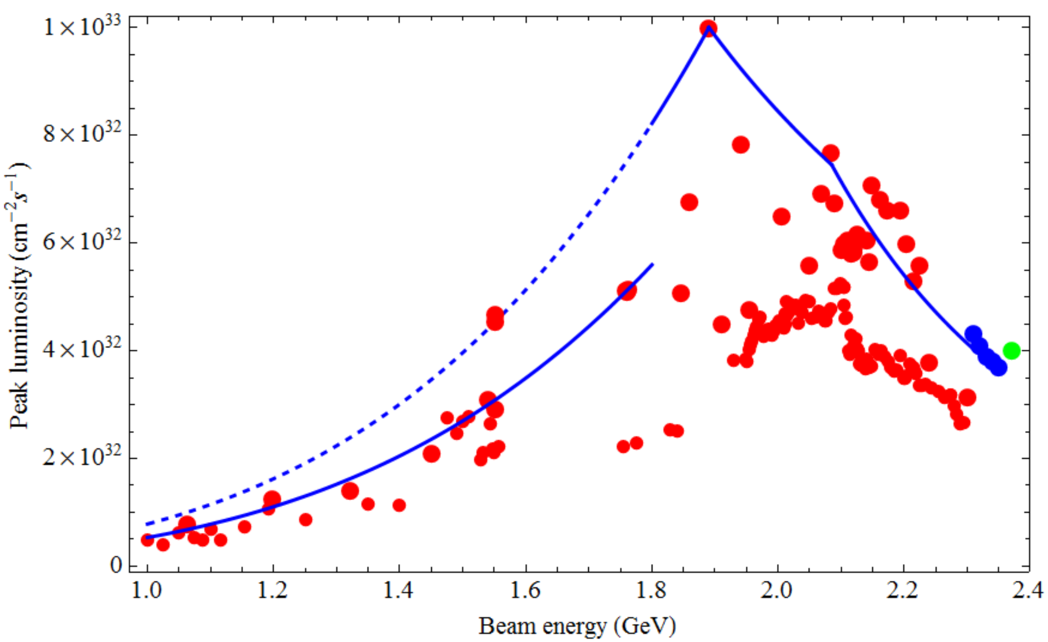
2008: test run

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)

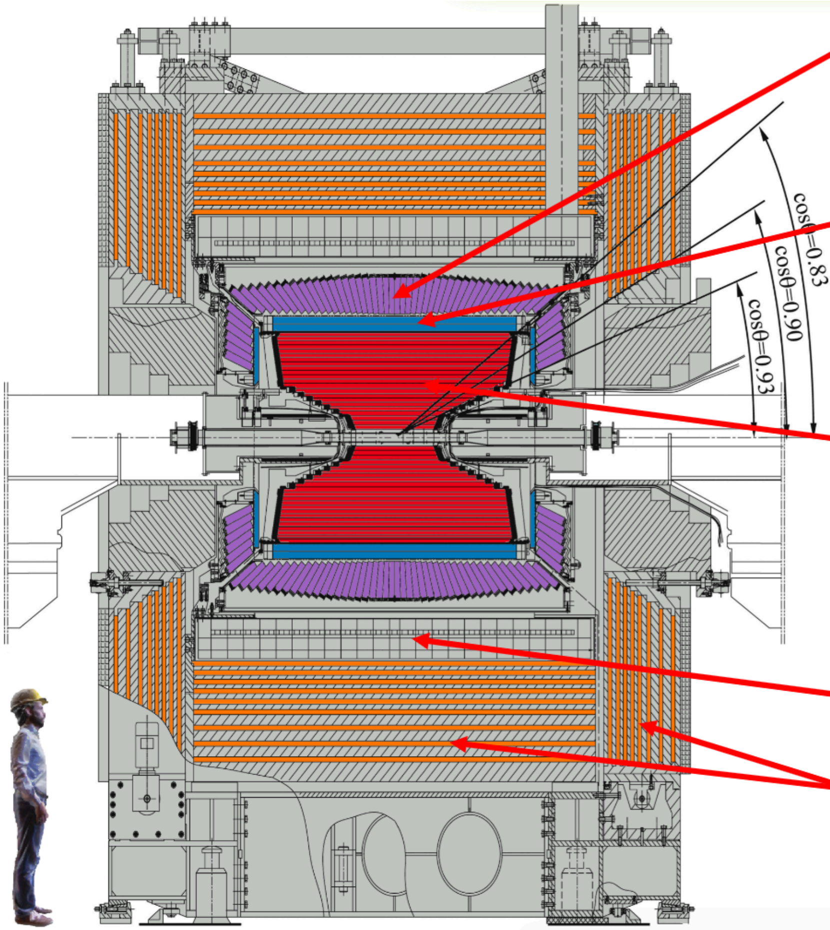
BEPCII upgrade

- Increase of beam energy 2.30→2.35(2018)→2.45 GeV(2020')
  - ➔ 2.35 GeV in 2018 summer (done)
  - ➔ 2.45 GeV in 2020 summer (done),
    change ISPB (Interaction region SePtum Bending) magnet
- Top-up injection (done)
  - Data taking efficiency increases by 20~30%



The BESIII detector

NIM A614, 345 (2010)



EMC: CsI crystals

$\Delta E/E$ = 2.5% @ 1 GeV - Barrel

$\Delta E/E$ = 5.0% @ 1 GeV - Endcaps

TOF:

σ_T = 80 ps Barrel

σ_T = 110 (60) ps Endcap

MDC: small cell & He gas

σ_{xy}= 130 μm

σ_p/p = 0.5% @1GeV

dE/dx = 6%

Magnet: 1T Super conducting

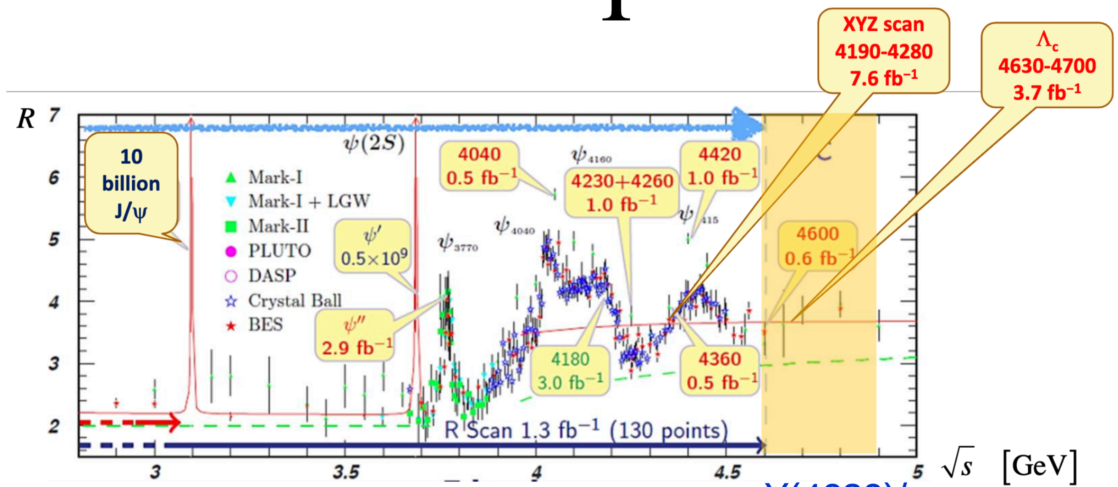
Muon ID: 9 layer RPC

Trigger: Tracks & Showers

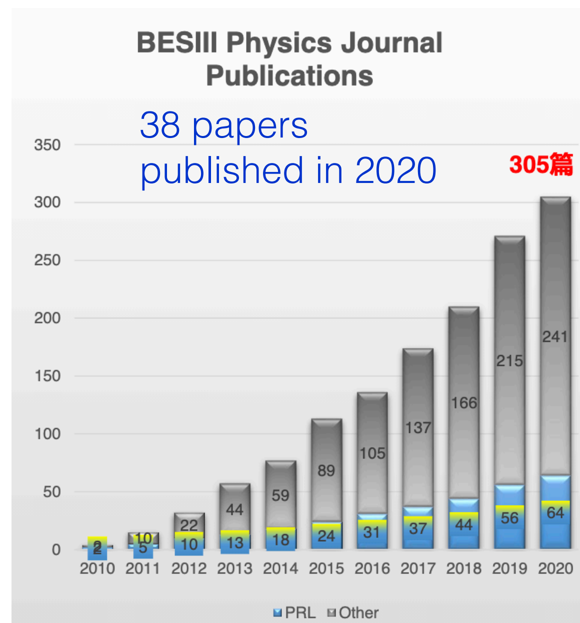
The new BESIII detector is hermetic for neutral and charged particle with excellent resolution, PID, and large coverage.

BESIII data sample

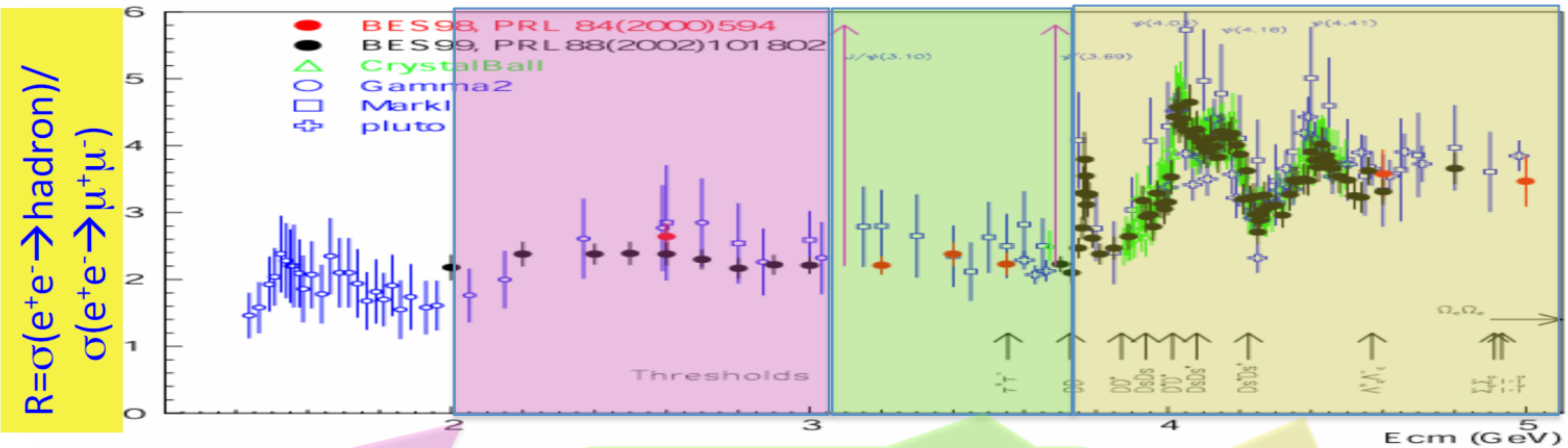
2009: 106M $\psi(2S)$
225M J/ψ
2010: 975 pb⁻¹ at $\psi(3770)$
2011: 2.9 fb⁻¹ *(total)* at $\psi(3770)$
482 pb⁻¹ at 4.01 GeV
2012: 0.45B *(total)* $\psi(2S)$
1.3B *(total)* J/ψ
2013: 1092 pb⁻¹ at 4.23 GeV
826 pb⁻¹ at 4.26 GeV
540 pb⁻¹ at 4.36 GeV
10 × 50 pb⁻¹ scan 3.81 — 4.42 GeV
2014: 1029 pb⁻¹ at 4.42 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: 5 × 500 pb⁻¹ scan 4.63 — 4.70 GeV *(+ extra)*



Y(4630)/
Y(4660)



Physics at tau-charm Energy Region

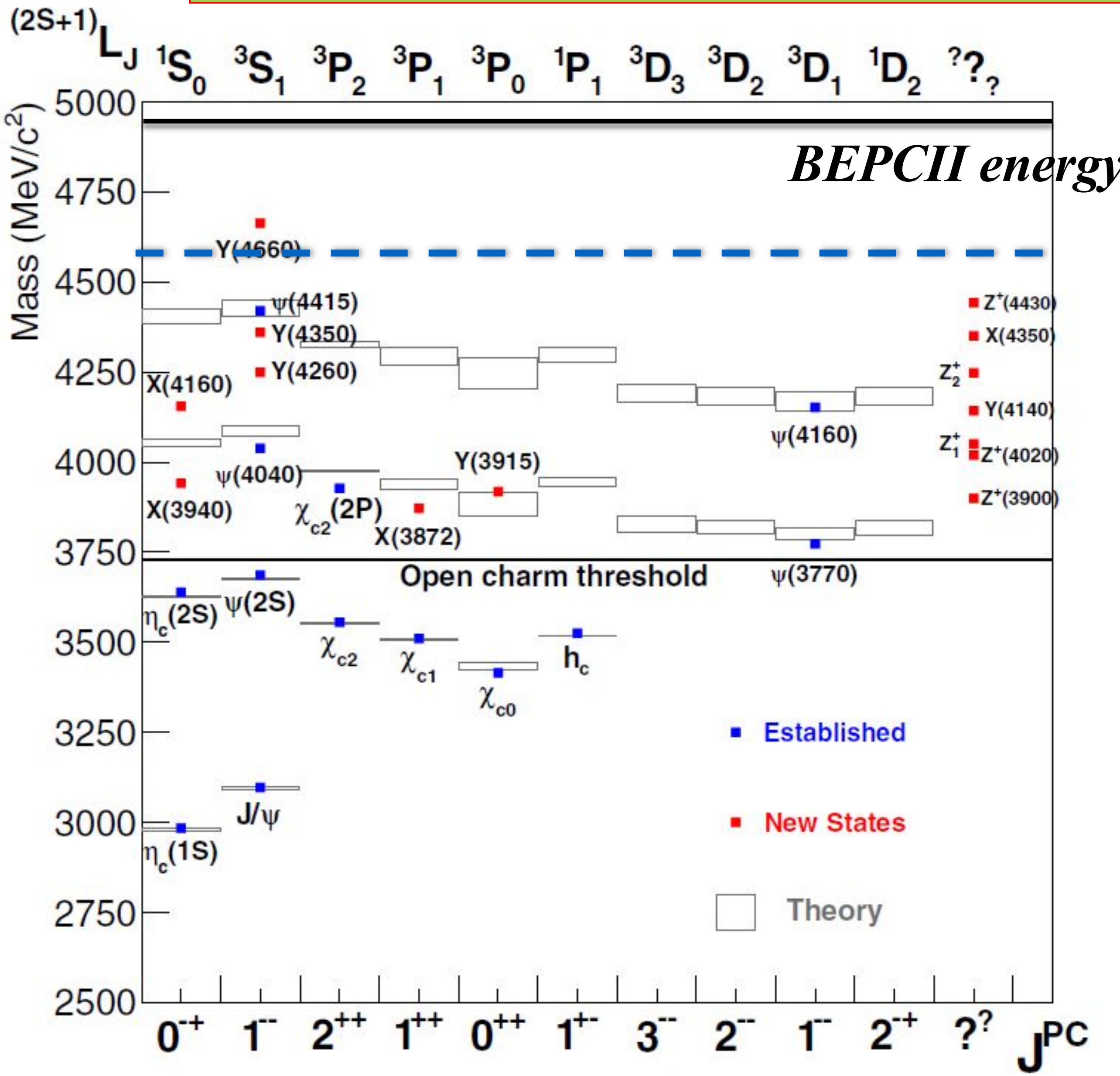


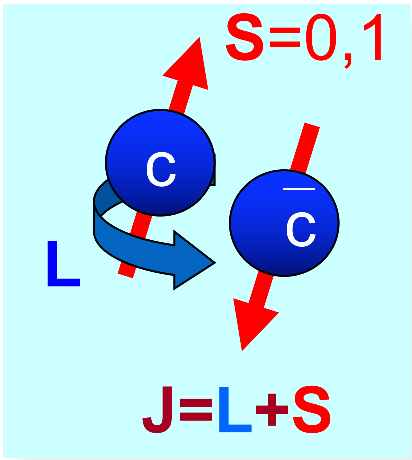
- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

- 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

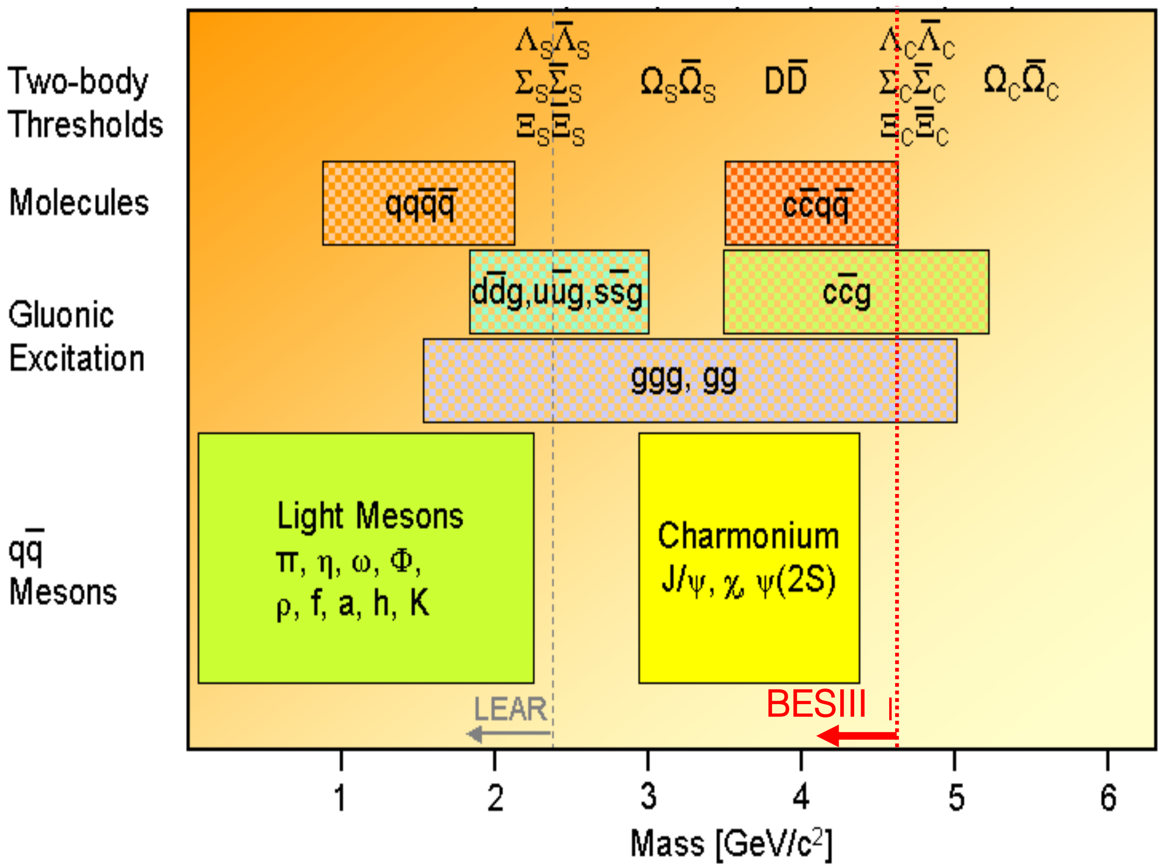
Charmonium Spectrum





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

Hadron Landscape



Hadron-physics challenges:

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

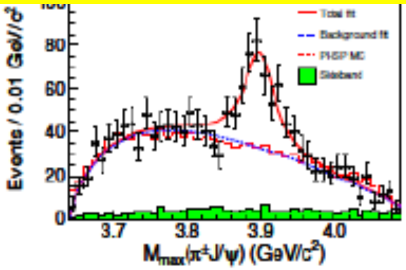
At BESIII, two golden measures to study hadron spectroscopy, *esp*., to search for exotics

- Light hadrons: charmonium radiative decays (act as spin filter)
- Heavy hadrons: direct production, radiative and hadronic transitions

The Zc Family at BESIII

Zc(3900)$^+$

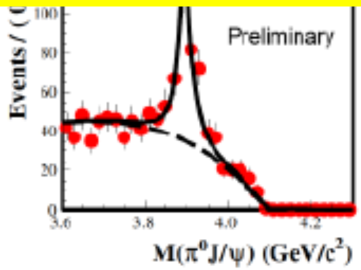
PRL 110, 252001 (2013)



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

Zc(3900)^0

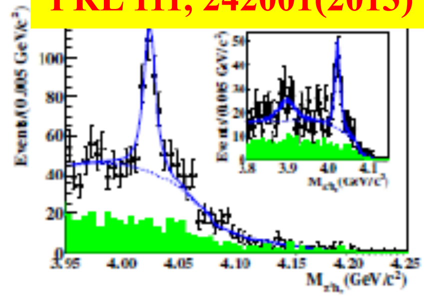
PRL 115, 112003 (2015)



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

Zc(4020)$^+$

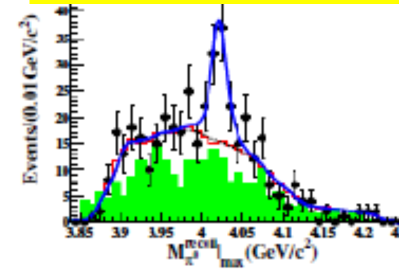
PRL 111, 242001(2013)



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

Zc(4020)^0

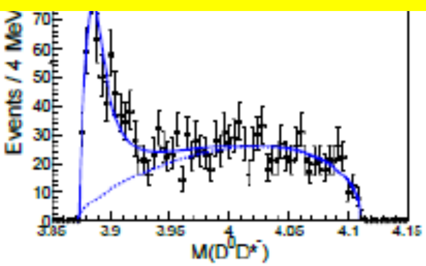
PRL113,212002 (2014)



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

Zc(3885)$^+$

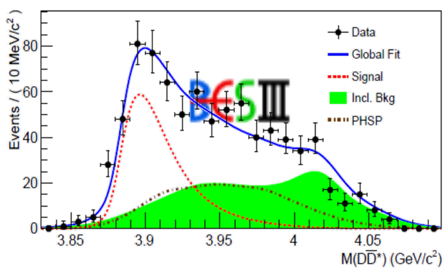
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



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

Zc(3885)^0

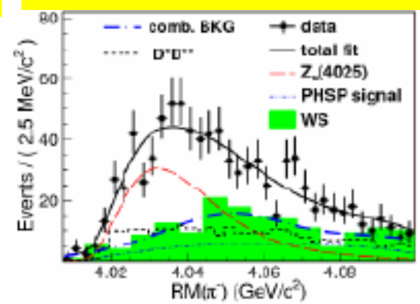
PRL 115, 222002 (2015)



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

Zc(4025)$^+$

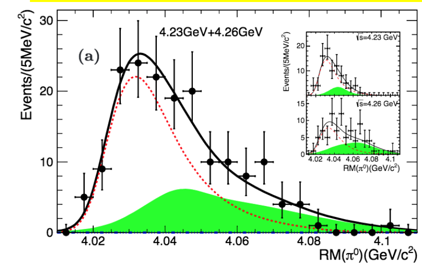
PRL 112, 132001 (2014)



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

Zc(4025)^0

PRL115, 182002 (2015)



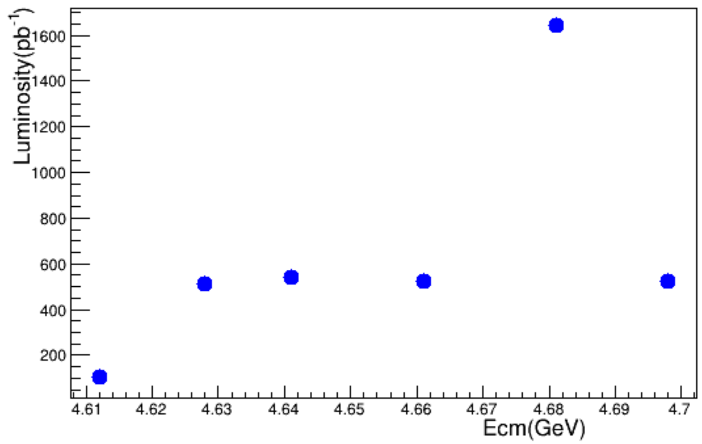
$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

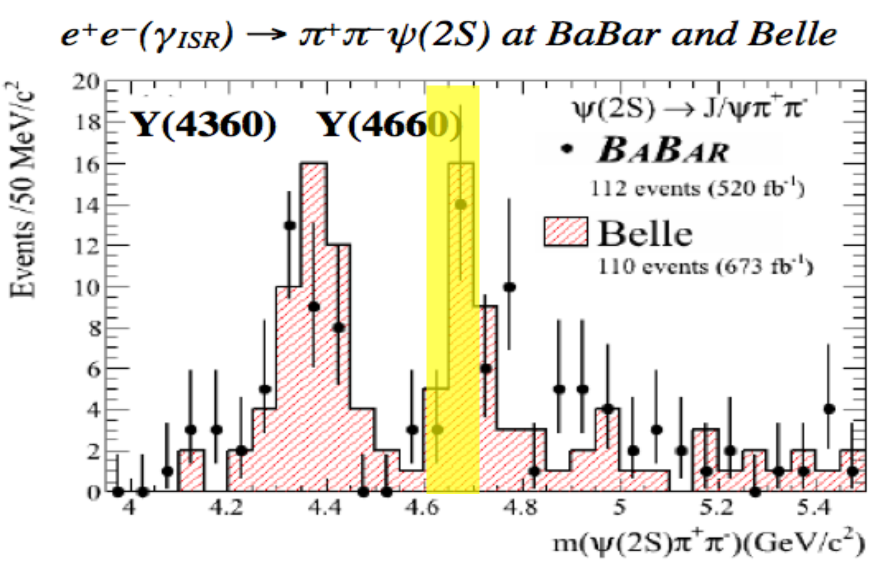
Which is the nature of these states?

If exists, there should be SU(3) counter-part Zcs state with strangeness

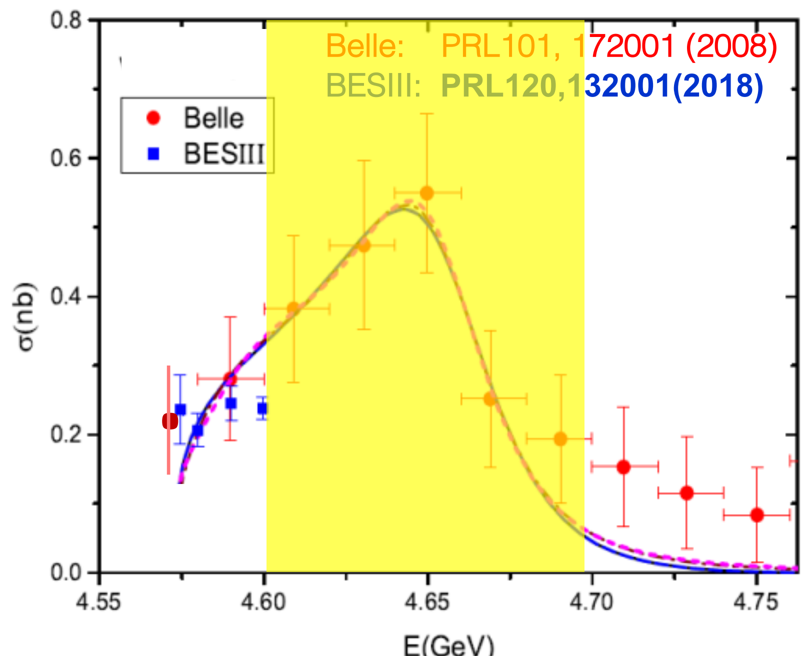
Data taking in 4.6-4.7 GeV in 2020

- 3.7fb^{-1} data was accumulated at 4.628, 4.641, 4.661, 4.681 and 4.698GeV in 2020.
- Y(4630) & Y(4660)





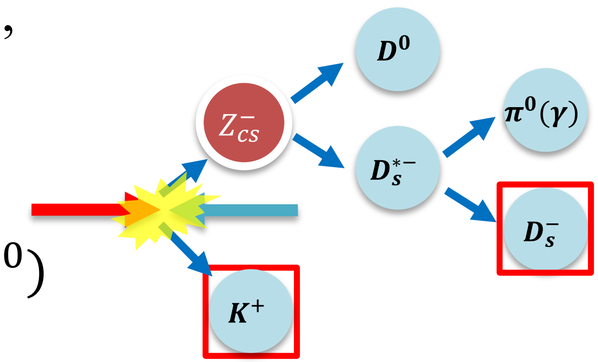
arXiv:1211.6271 and CHARM 2012



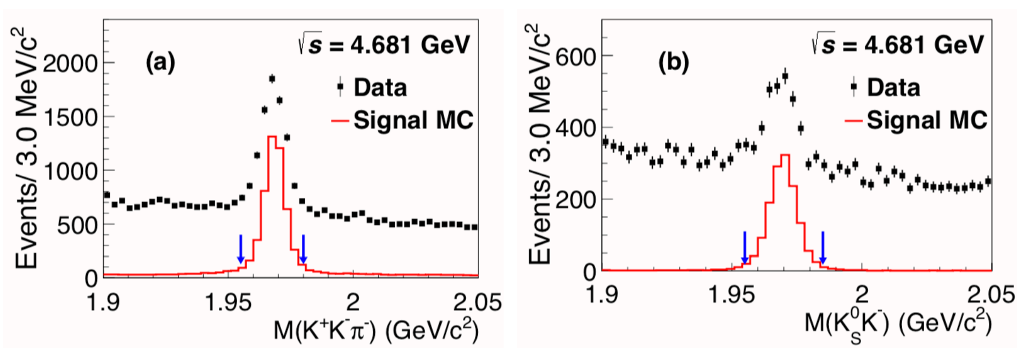
Observation of the $Z_{cs}(3985)^{\pm}$

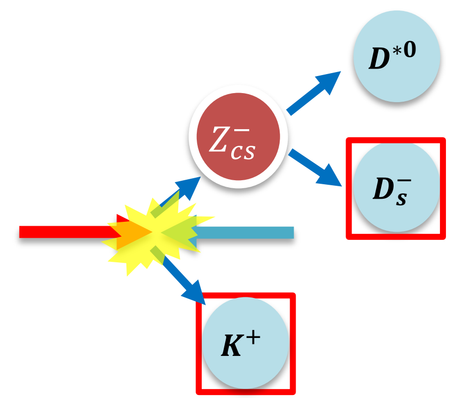
arXiv: 2011.07855

- We analyze 3.7fb^{-1} data accumulated at 4.628, 4.641, 4.661, 4.681 and 4.698GeV in 2020.
- **Partial reconstruction of K^+ and D_s^-**
- Signature in the **recoil mass spectrum of $K^+D_s^-$** to identify the process of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

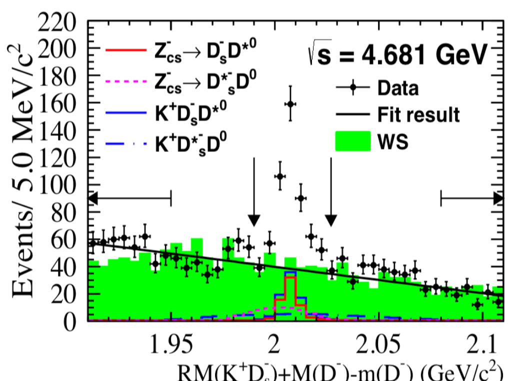


$e^+e^- \to K^+ D_s^{*-} D^0$





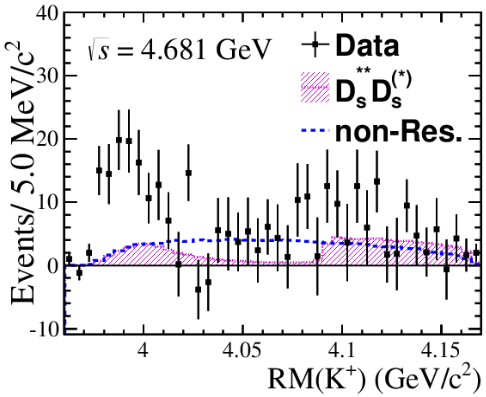
$e^+e^- \to K^+ D_s^- D^{*0}$

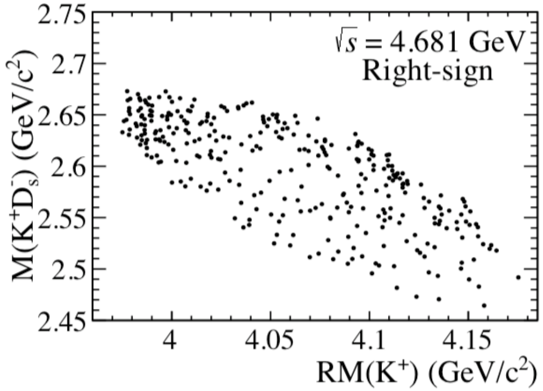


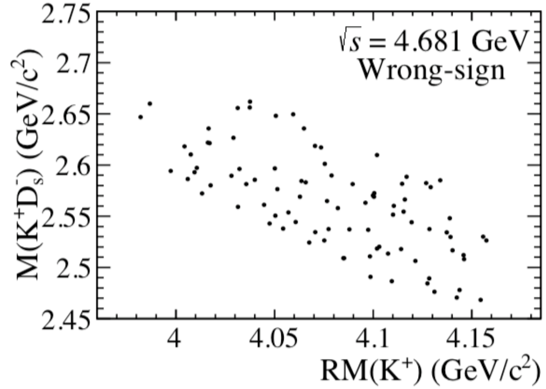
Observation of the $Z_{cs}(3985)^{\pm}$

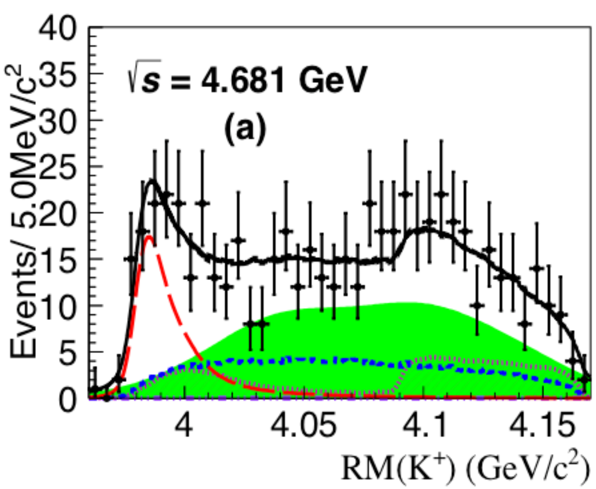
arXiv: 2011.07855

- Data driven background description: wrong Sign (WS) combination of D_s^- and K^-
- Conventional charmed mesons can not describe the enhancement below 4.0 GeV/c^2 at 4.681 GeV









- 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:

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

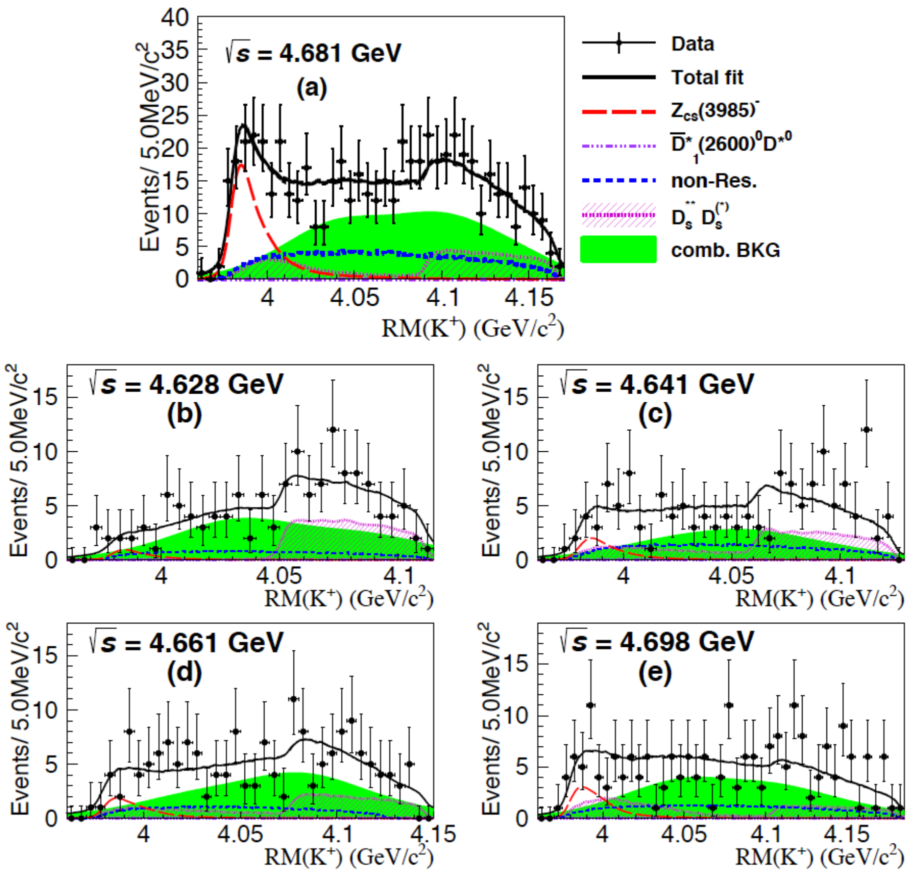
- Global significance: >5.3 $\boldsymbol{\sigma}$

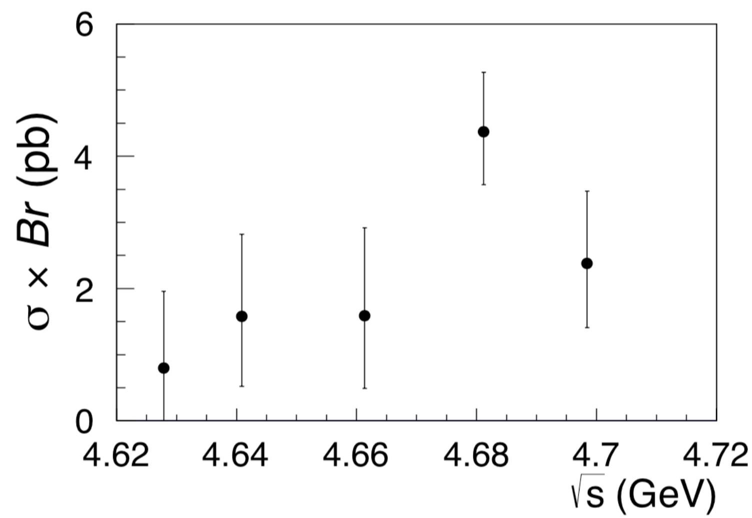
First candidate of the hidden-charm tetraquark with strangeness

Cross sections of the $Z_{cs}(3985)^{\pm}$ production

arXiv: 2011.07855

- Simultaneous fit to the five energy points





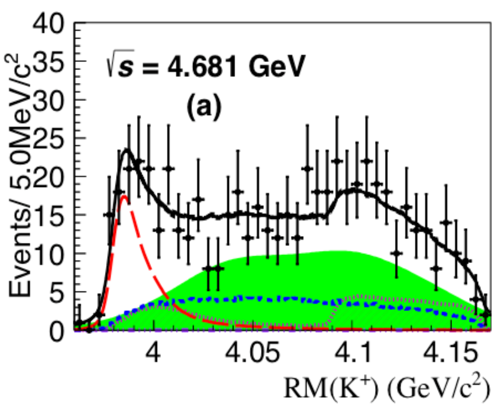
- Largest cross sections around 4.681 GeV

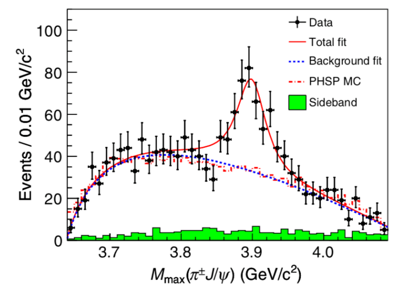
The Zcs (3985)$^{\pm}$ and Zc(3885)$^{\pm}$

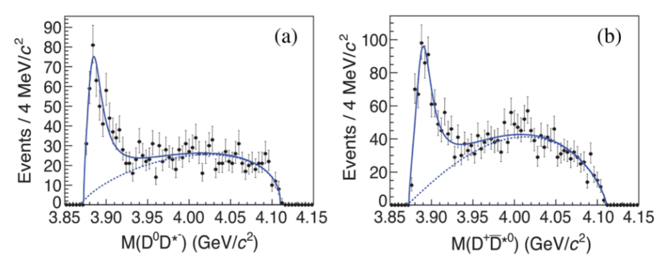
1643/pb data @4.681 GeV | 525/pb data @4.26 GeV

	$Z_{cs}(3985)^{\pm}$	$Z_c(3900)^{\pm}$	$Z_c(3885)^{\pm}$
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
$\sigma^{Born} \cdot \mathfrak{B}$ (pb)	$4.4^{+0.9}_{-0.8} \pm 1.4$	13.5±2.1±4.8	83.5±6.6±22.0

SU(3) partner of Zc(3900)?







$Z_{cs}(3985)$

$Z_c(3900)$

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

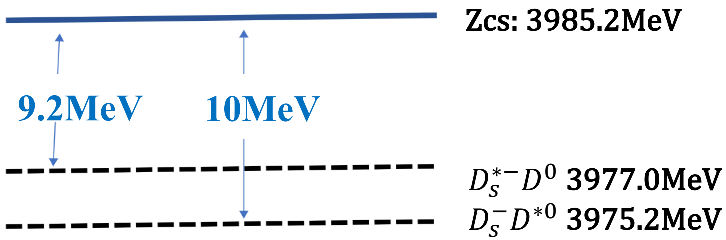
neutral/charged = 1

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

neutral/charged = 1/2

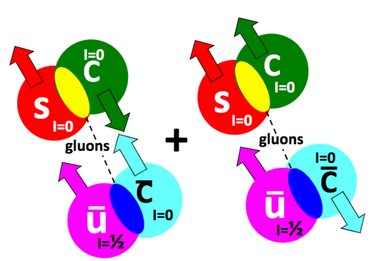
Interpretation on the nature of $Z_{cs}(3985)^{\pm}$

- 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

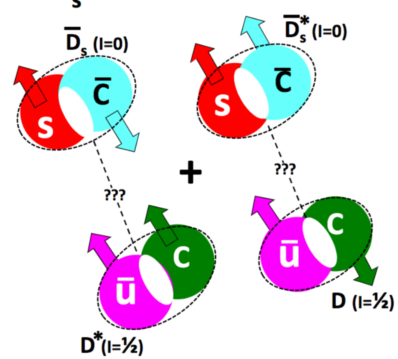


~10 MeV above D_sD^*/D_sD thresholds
similar to $Z_c(3900)$ & $Z_b(10,610)$
(DD*) (BB*)

diquark-antidiquark?



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



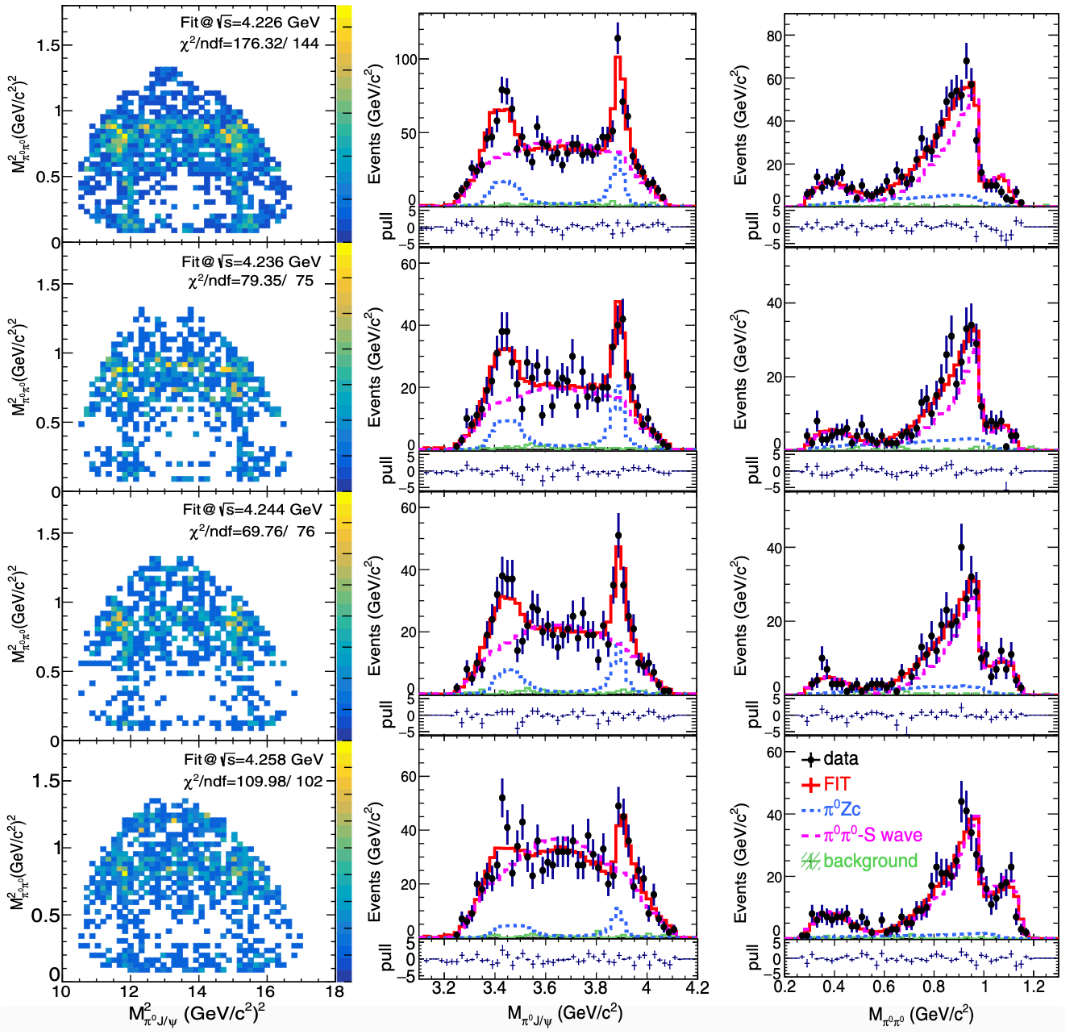
two general comments about
charm-tau factory program

from Marek Karliner

- $J/\psi\, K^{\pm}$ 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

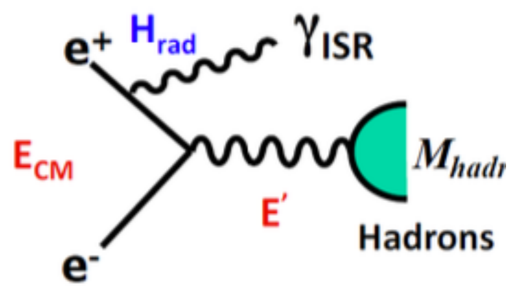
PWA of the $Z_c(3900)^0$

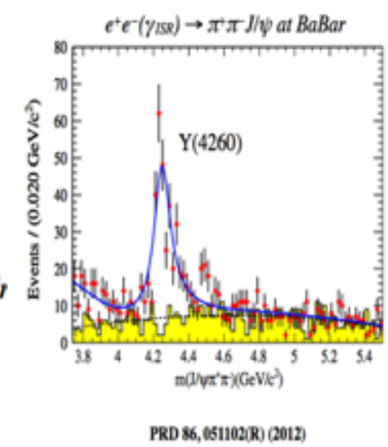
PRD 102, 012009 (2020)

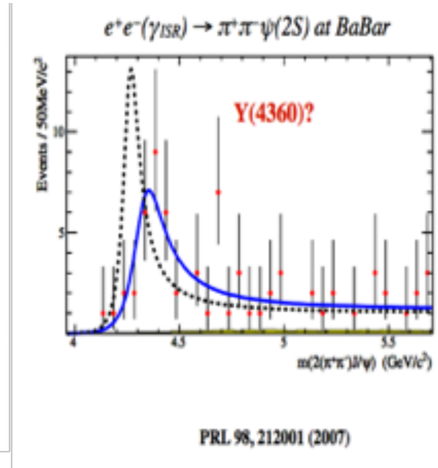


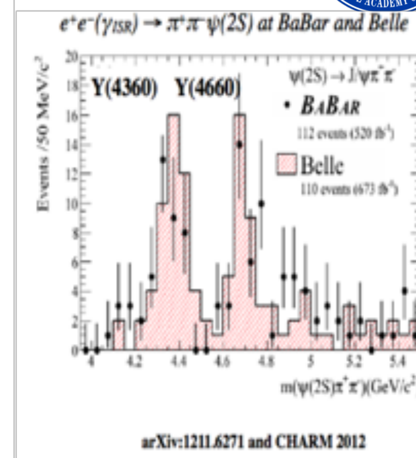
- Simultaneous PWA fit of $e^+e^-\to\pi^0\pi^0J/\psi$ to the four energy points
- The spin-parity of $Z_c(3900)^0$ is determined to be 1^+
- The nominal fit includes the intermediate process $\sigma J/\psi$, $f(980)J/\psi$, $f(1370)J/\psi$ and π^0 $Z_c(3900)^0$.
- Mass and width of $Z_c(3900)^0$ is measured:
  - $M(Z_c(3900)^0) = (3893.0\pm2.3\pm3.2)$ MeV/c^2,
  - $\Gamma(Z_c(3900)^0) = (44.2\pm5.4\pm8.3)$ MeV.

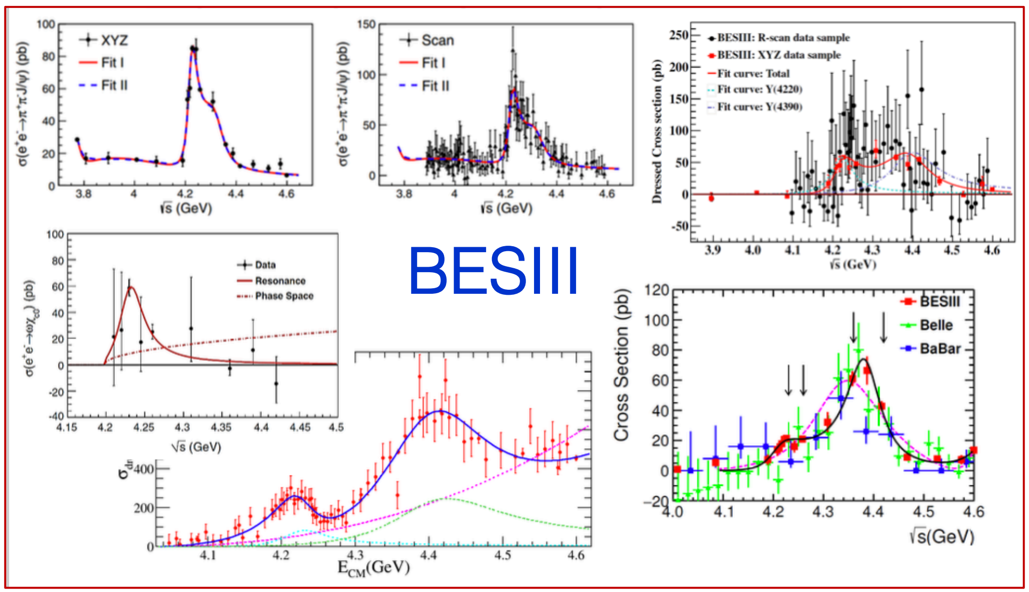
Y(4260) ➔ Y(4220) and new Y’s

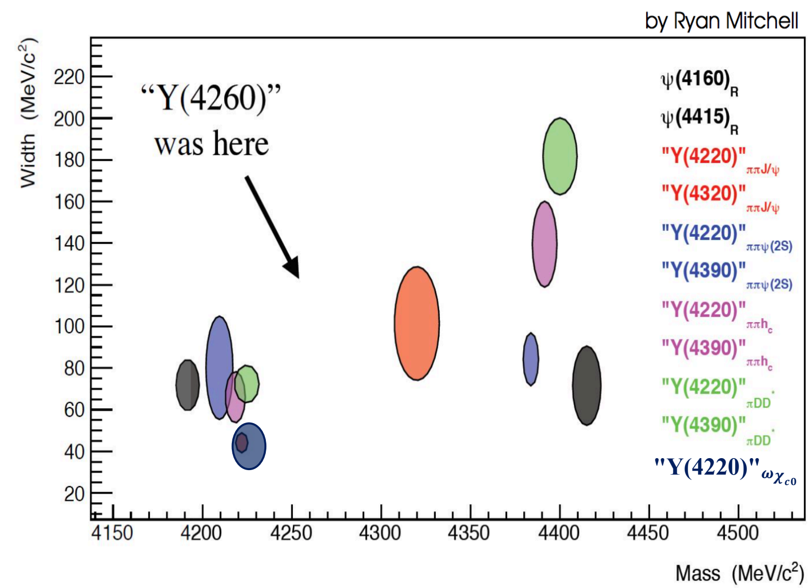








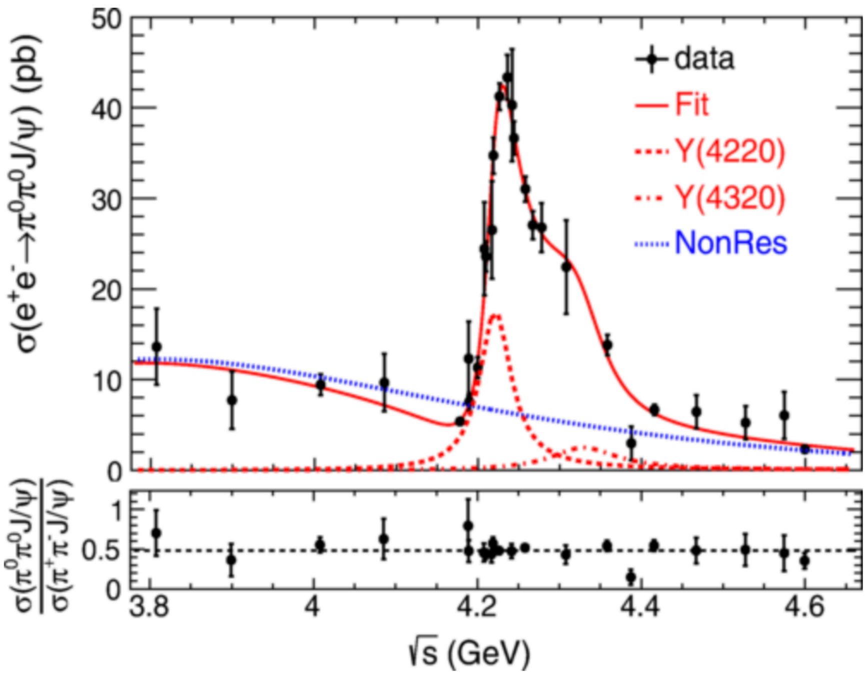




Cross section of $e^+e^- \to \pi^0\pi^0 J/\psi$

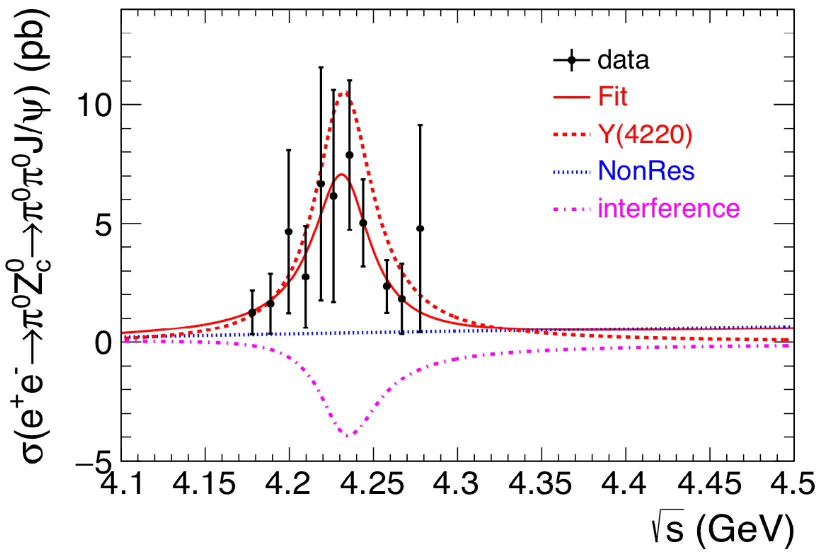
PRD 102, 012009 (2020)

- Cross sections relative to those of the charged channel $e^+e^- \to \pi^+\pi^- J/\psi$ follows isospin symmetry
- Fit to the $e^+e^- \to \pi^0\pi^0 J/\psi$ returns
  M(Y4220))=(4220.4±2.4±2.3) MeV/c^2 ; $\Gamma\big(\mathrm{Y(4220)}\big)$ =(46.2±4.7±2.1) MeV
- Stat. significance of the Y(4320) (fixed to the charged channel) is 4.2σ
- The mass and width are consistent with those measured in the charged process



Cross section of $e^+e^-\to\pi^0 Z_c(3900)^0$

PRD 102, 012009 (2020)



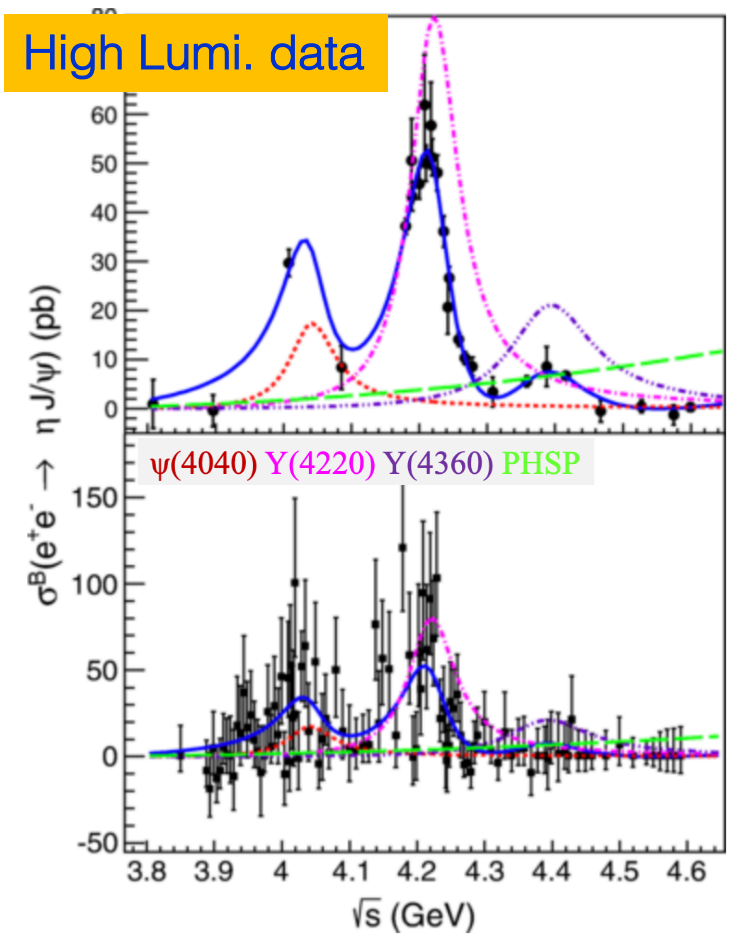
Parameters	Solution I	Solution II
$p_0(c^2/\mathrm{MeV})$	0.0 ± 11.3	
p_1	$(1.8 \pm 1.9) \times 10^{-2}$	
$M(R)$ (MeV/c^2)	4231.9 ± 5.3	
$\Gamma_{\mathrm{tot}}(R)$ (MeV)	41.2 ± 16.0	
$\Gamma_{ee}\mathcal{B}_{R\to\pi^0 Z_c(3900)^0}$ (eV)	0.53 ± 0.15	0.22 ± 0.25
$\phi(R)$	$(-103.9 \pm 33.9)^\circ$	$(112.7 \pm 43.0)^\circ$

- Zc(3900)^0 resonance parameters are fixed to the results of the previous four-energy-point fit
- The Born cross section of $e^+e^-\to\pi^0$Z$_c$(3900)^0 $\to\pi^0\ \pi^0 J/\psi$ is extracted.
- Clear structure around 4.2 GeV is observed
  - M = (4231.9±5.3±4.9) MeV/c^2,
  - Γ = (41.2±16.0±16.4) MeV.
- Compatible with the Y(4220) line shape
- Indication of correlation between the production of the Y(4220) and Z$_c$(3900).

Y(4220) and Y(4360) in $e^+e^- \to \eta J/\psi$

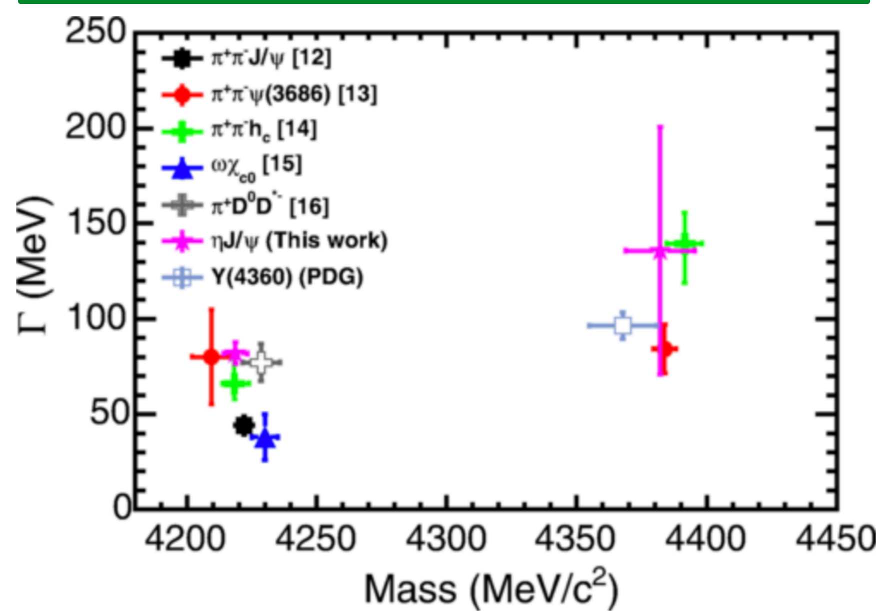
PRD 102, 031101(R) (2020)

- Assuming the lowest lying structure is the $\psi(4040)$
- Consistent with those of the Y(4220) and Y(4360) from previous measurements of different final states



two Y resonances:

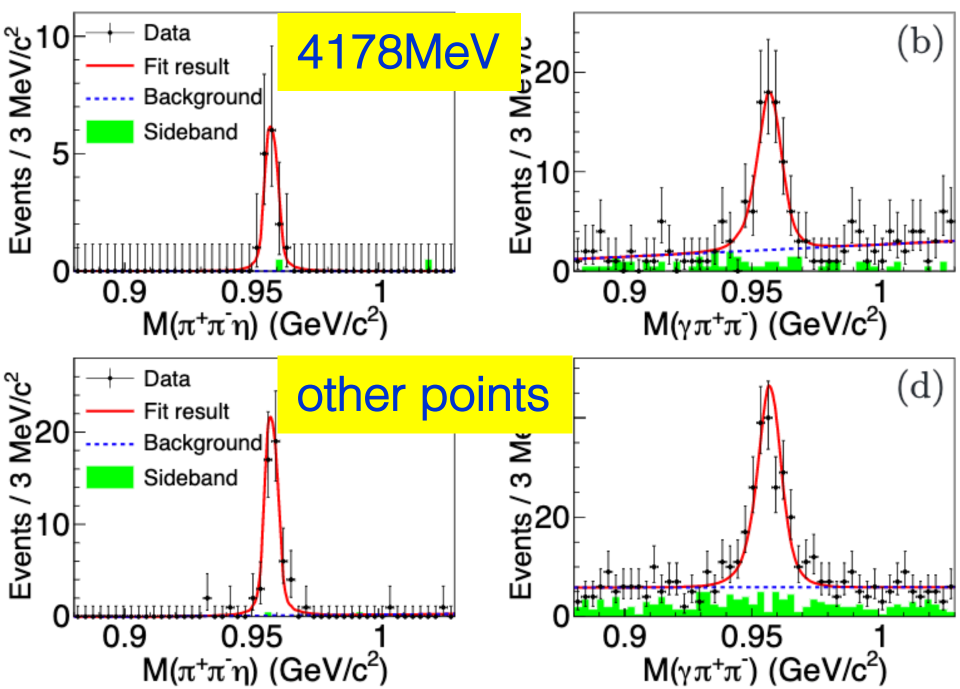
- mass (4218.6±3.8±2.5)MeV/c², width (82.0±5.7±0.4) MeV
- mass (4382.0±13.3±1.7)MeV/c², width (135.8±60.8±22.5)MeV

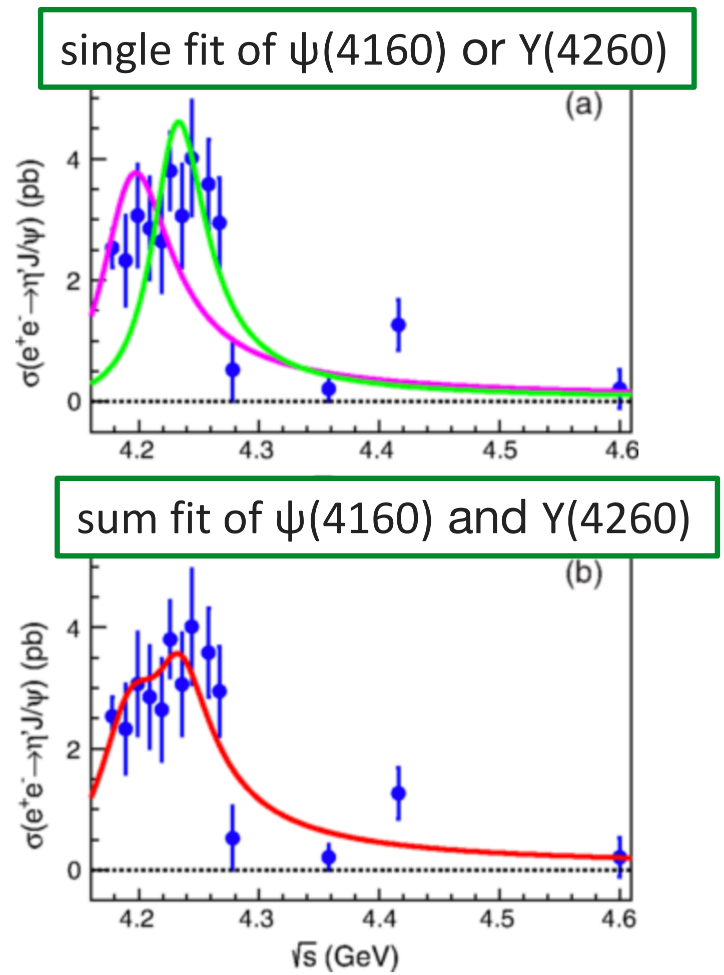


Cross section of $e^+e^- \to \eta' J/\psi$

PRD 101, 012008 (2020)

- Enhanced cross section around 4.2 GeV
- A coherent sum of the states of ψ(4160) and Y(4260) provide a reasonable description of the data
- Seems no enhancement around 4.36 GeV as that of $e^+e^- \to \eta J/\psi$

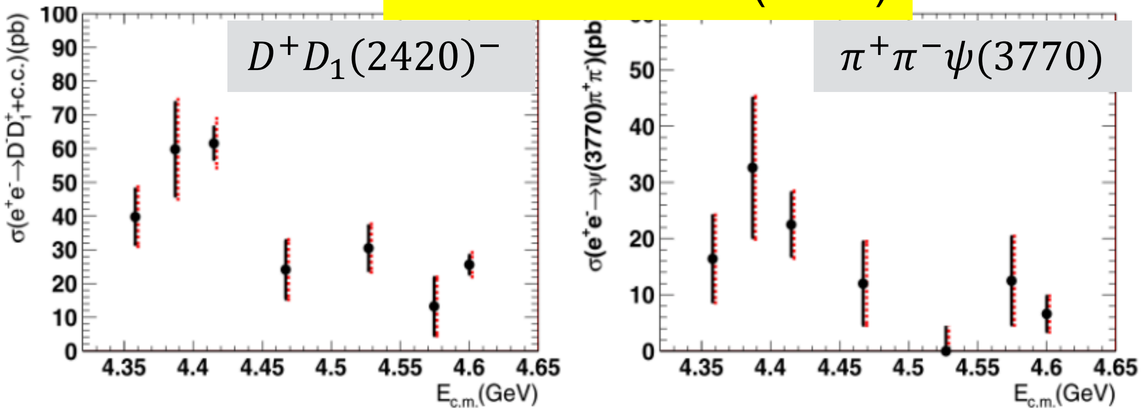




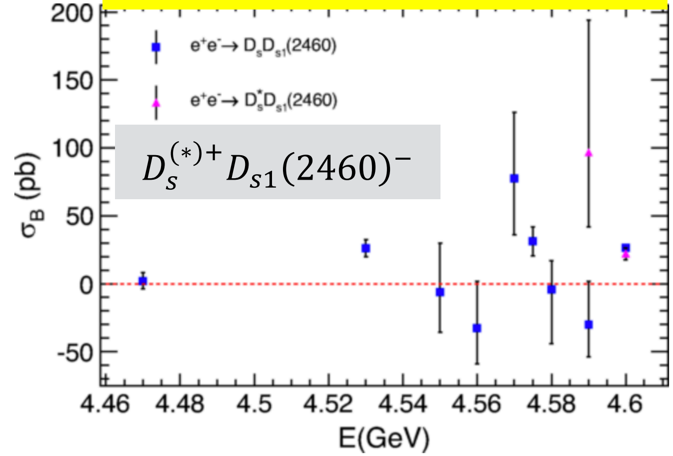
Cross sections of open charm final states

Partial reconstruction

PLB804.135395(2020)



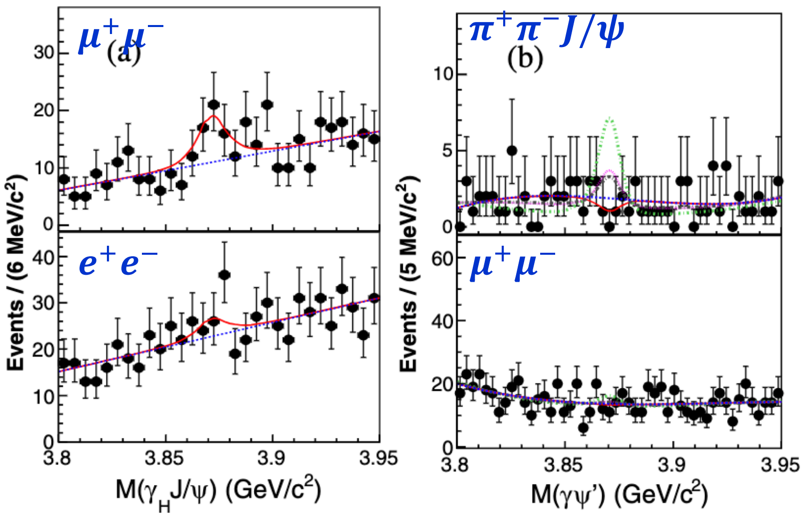
PRD101, 112008 (2020)

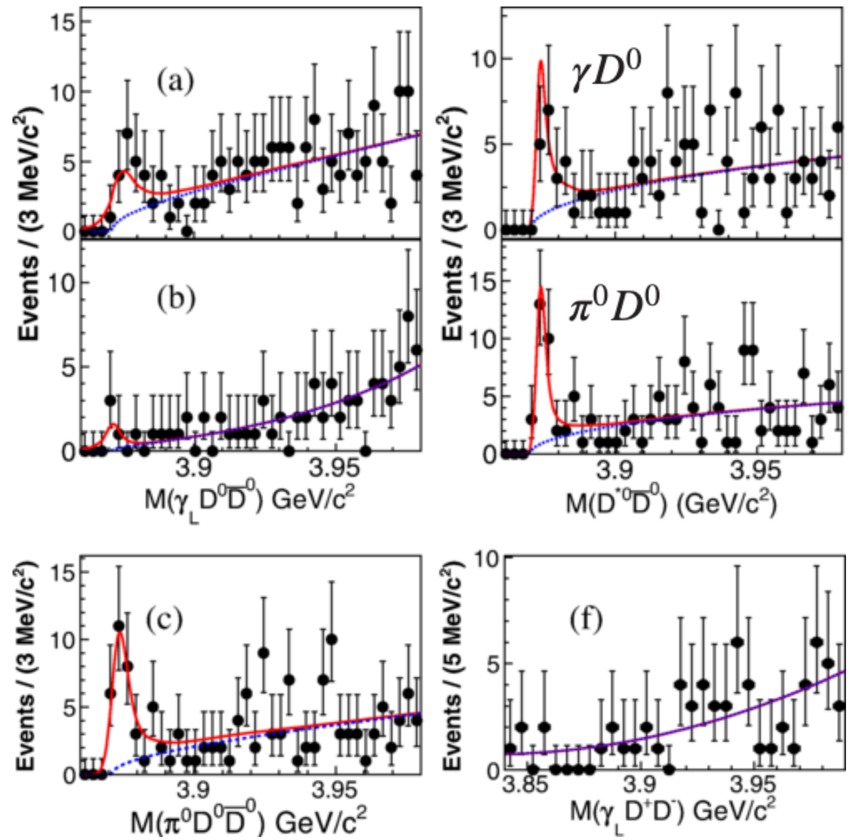


- Some indications of enhanced cross sections of $e^+e^- \to D^+D_1(2420)^-$ and $\pi^+\pi^-\psi(3770)$ between 4.36 and 4.42 GeV:
  ➔ potential contributions form the Y(4360) and $\psi(4415)$?
- No obvious structure in the cross sections of $e^+e^- \to D_s^{(*)+}D_{s1}(2460)^-$

More decays of the X(3872)/χ_{c1}(3872)

PRL124.242001(2020)





- No evidence of X(3872)→ $\gamma\psi'$

➔ $R_{\gamma\psi} = \frac{B(X(3872)\to\gamma\psi')}{B(X(3872)\to\gamma J/\psi)}$<0.59 (90% C.L.)

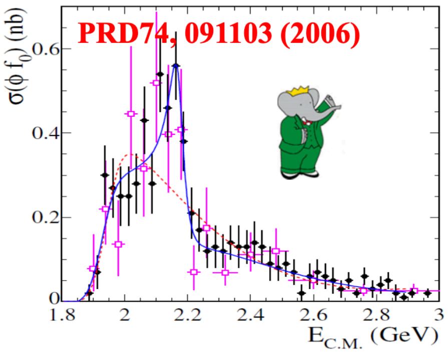
- Consistent with Belle, while disagree with LHCb and BaBar's results:
  LHCb: 2.46±0.64±0.29
  BaBar: 3.4±1.4

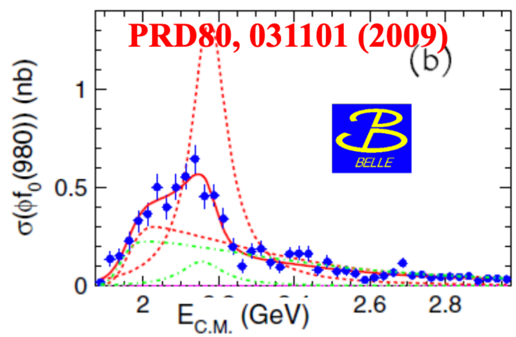
TABLE II. Relative branching ratios and UL on branching ratios compared with $X(3872)\to\pi^+\pi^- J/\psi$.

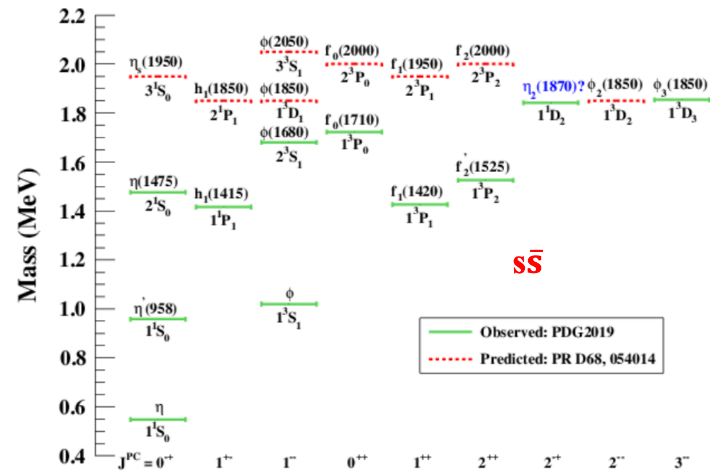
mode	$\gamma J/\psi$	$\gamma\psi'$	$\gamma D^0\bar{D}^0$	$\pi^0 D^0\bar{D}^0$	$D^{*0}\bar{D}^0 + c.c.$	γD^+D^-	$\omega J/\psi$	$\pi^0\chi_{c1}$
ratio	0.79 ± 0.28	-0.03 ± 0.22	0.54 ± 0.48	-0.13 ± 0.47	11.77 ± 3.09	$0.00^{+0.48}_{-0.00}$	$1.6^{+0.4}_{-0.3}\pm0.2$ [18]	$0.88^{+0.33}_{-0.27}\pm0.10$ [35]
UL	-	<0.42	<1.58	<1.16	-	<0.99	-	-

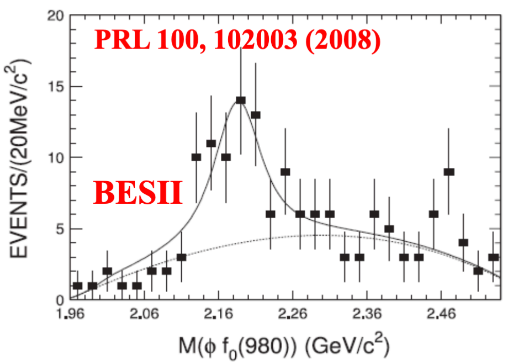
Studies on the $\phi(2170)$/Y(2175)

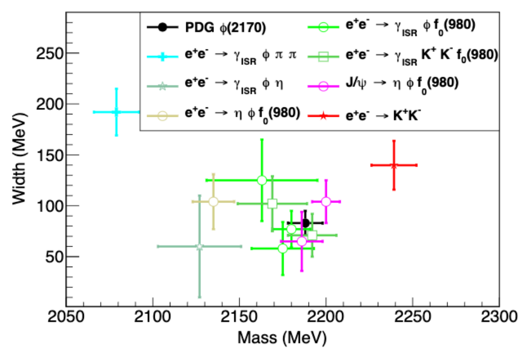
- A strangenium-like state: Y-particle with strange quark







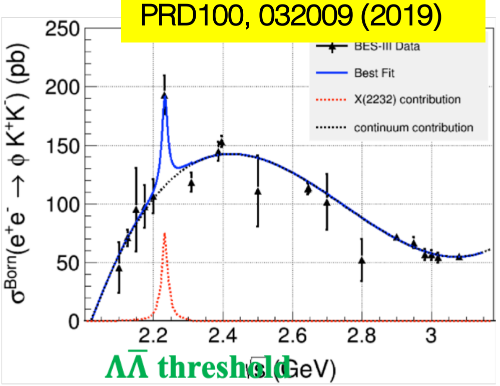




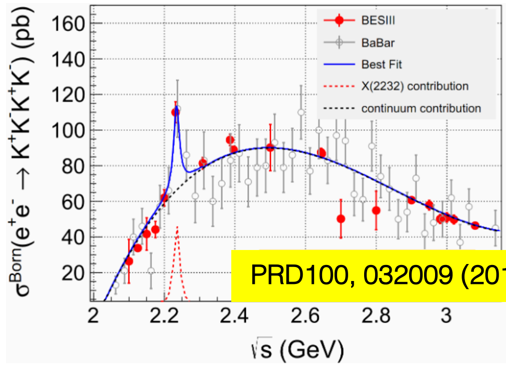
➢ **Theorists explain $\phi(2170)$ as**
- ✓ **$s\bar{s}g$ hybrid**
- ✓ **2^3D_1 or 3^3S_1 $s\bar{s}$**
- ✓ **tetraquark**
- ✓ **Molecular state $\Lambda\bar{\Lambda}$**
- ✓ **$\phi f_0(980)$ resonance with FSI**
- ✓ **Three body system ϕKK**

Further studies on the $\phi(2170)/Y(2175)$

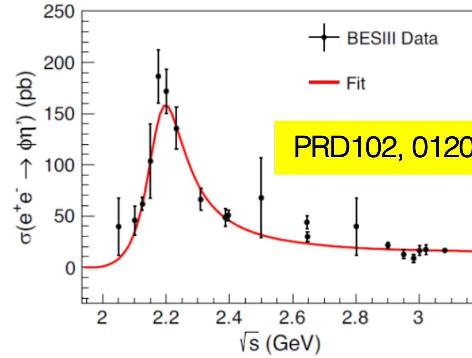
PRD100, 032009 (2019)



$\Lambda\bar{\Lambda}$ threshold



PRD100, 032009 (2019)

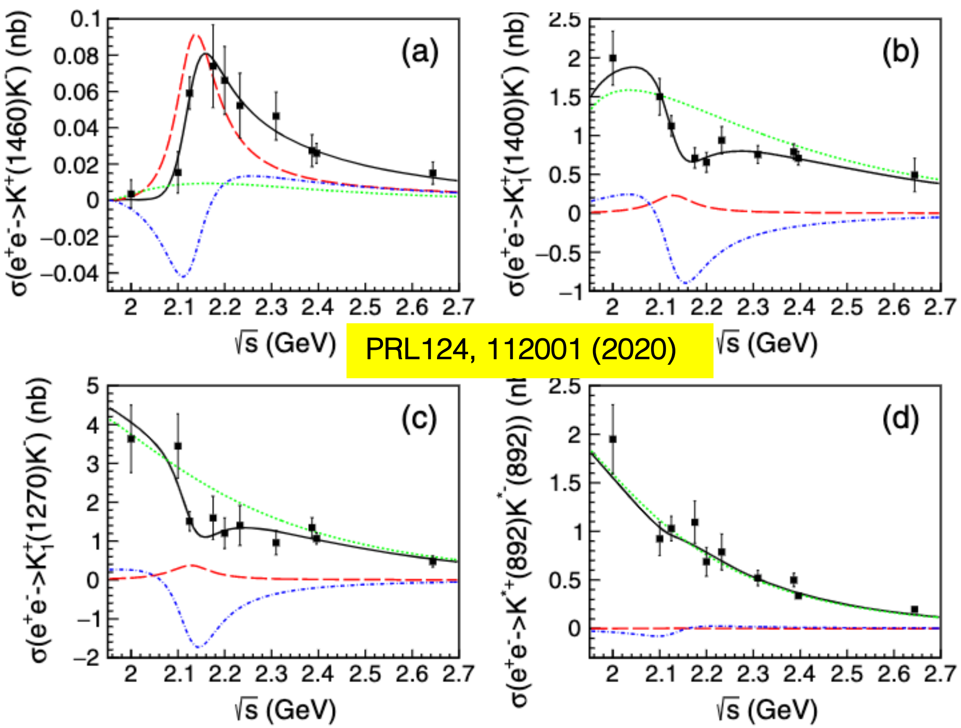


PRD102, 012008 (2020)

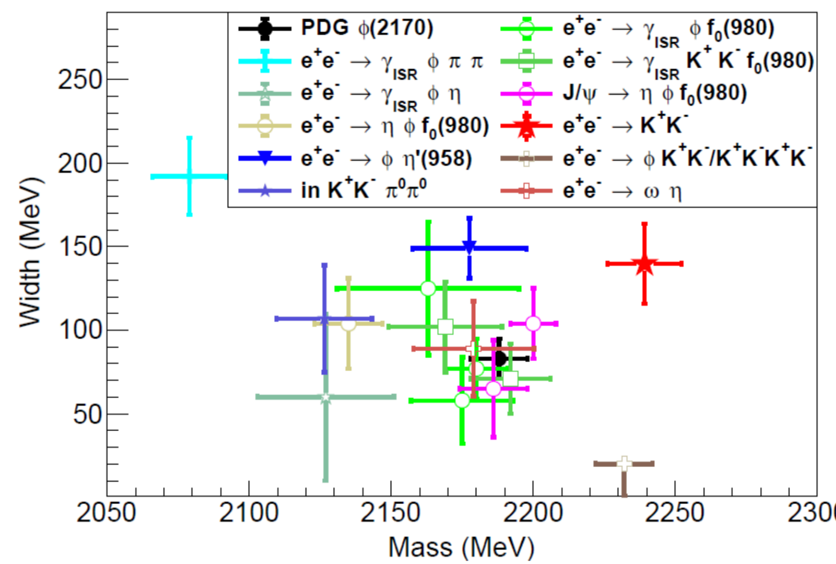
$$\frac{Br[\phi(2170)\to\phi\eta]\Gamma_{ee}}{Br[\phi(2170)\to\phi\eta']\Gamma_{ee}} = 0.23\pm0.10\pm0.18$$

disfavor hybrid scenario?

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



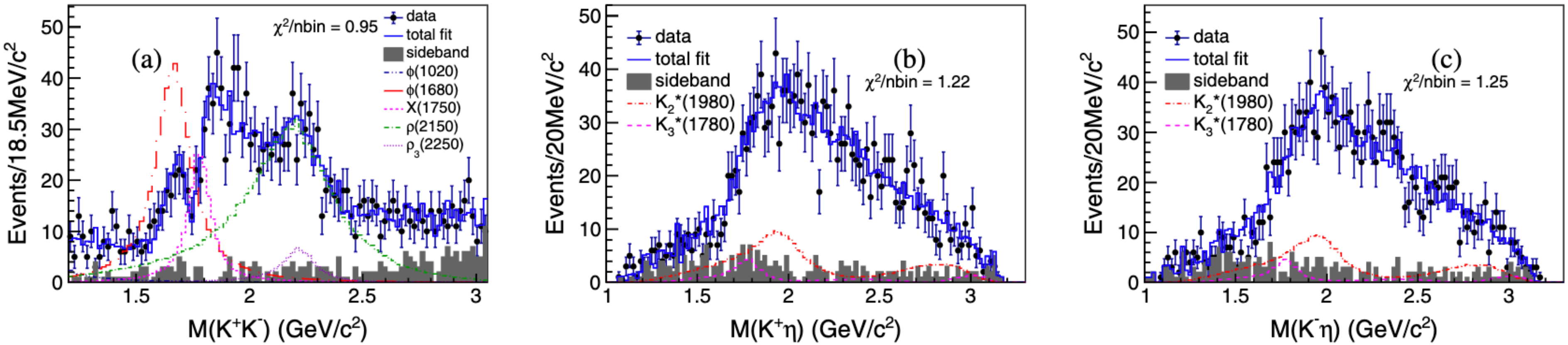
PRL124, 112001 (2020)



Partial wave analysis of $\psi(3686) \to K^+K^-\eta$

PRD101, 032008 (2020)

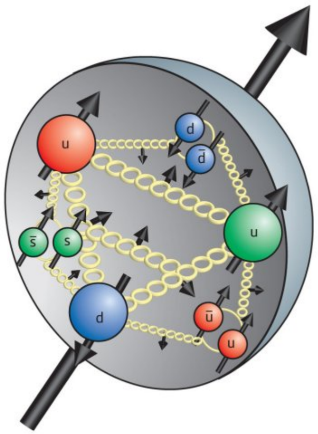
448M $\psi(3686)$ decays

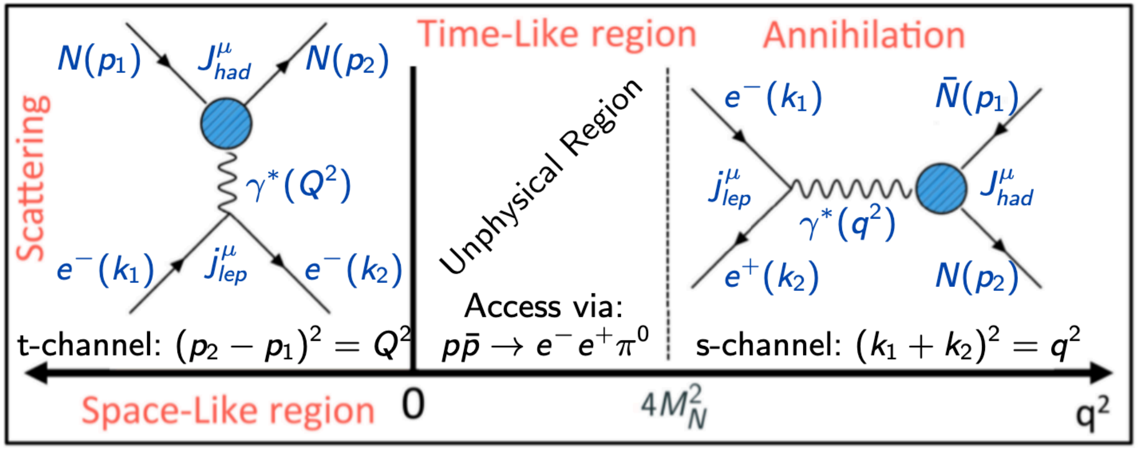


	This work		PDG [23]	
Resonance	M (MeV/c^2)	Γ (MeV)	M (MeV/c^2)	Γ (MeV)
$\phi(1680)$	1680^{+12+21}_{-13-21}	185^{+30+25}_{-26-47}	1680 ± 20	150 ± 50
$X(1750)$	1784^{+12+0}_{-12-27}	106^{+22+8}_{-19-36}	$(1720 \pm 20)_{\rho(1700)}$ $(1753.5 \pm 1.5 \pm 2.3)_{X(1750)}$ [15]	$(250 \pm 100)_{\rho(1700)}$ $(122.2 \pm 6.2 \pm 8.0)_{X(1750)}$ [15]
$\rho(2150)$	2255^{+17+50}_{-18-41}	$460^{+54+160}_{-48-90}$	$(2153 \pm 27)_{\rho(2150)}$ [31] $(2175 \pm 15)_{\phi(2170)}$	$(389 \pm 79)_{\rho(2150)}$ [31] $(61 \pm 18)_{\phi(2170)}$
$\rho_3(2250)$	2248^{+17+59}_{-17-5}	$185^{+31+17}_{-26-103}$	2232 [32]	220 [32]
$K_2^*(1980)$	2046^{+17+67}_{-16-15}	408^{+38+72}_{-34-44}	$1973 \pm 8 \pm 25$	$373 \pm 33 \pm 60$
$K_3^*(1780)$	1813^{+15+65}_{-15-16}	191^{+43+3}_{-37-81}	1776 ± 6	159 ± 21

- Dip around 1.75 GeV requires another 1^{--} resonance X(1750) to introduce interference with $\phi(1680)$: could be $\rho(1700)$ or X(1750) (photoproduction at FOCUS)
- Broad structure around 2.2 GeV: contributions from 1^{--} and/or 3^{--} resonances
- More statistics and couple channel analysis will be useful

Form factors of baryons



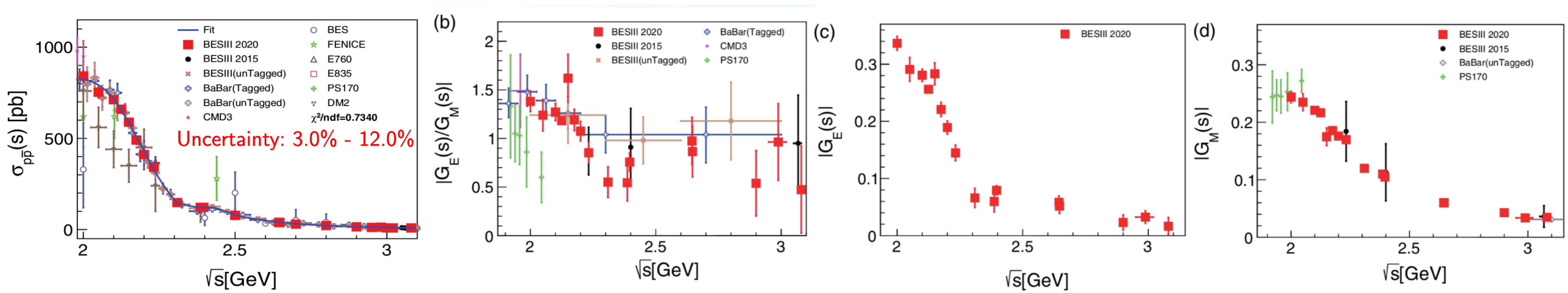


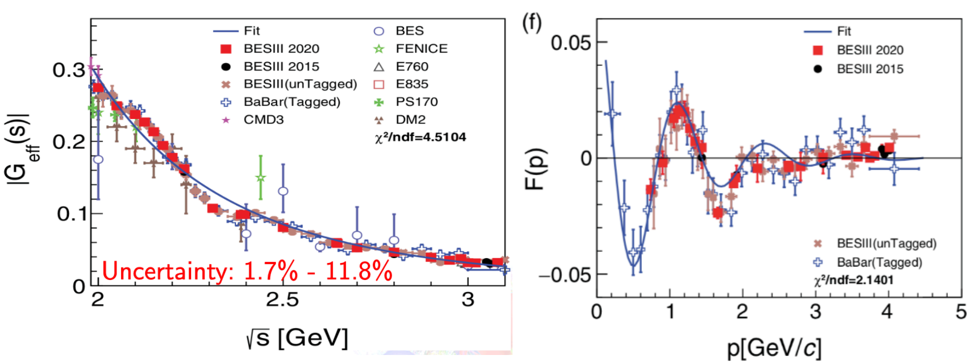
In the time-like region, access to the Electromagnetic Form Factors (EFF) of the baryons, which characterize the internal structure of the baryon

Threshold production of the nucleon

$$\frac{d\sigma_{p\bar{p}}(s)}{d\Omega} = \frac{\alpha^2\beta C}{4s}\left[|G_M(s)|^2(1+\cos^2\theta) + \frac{4m_p^2}{s}|G_E(s)|^2\sin^2\theta\right]$$

BESIII 2020 energy scan: PRL124, 042001 (2020)
BESIII untagged ISR: PRD99, 092002 (2019)
BESIII 2015 energy scan: PRD91, 112004(2015)



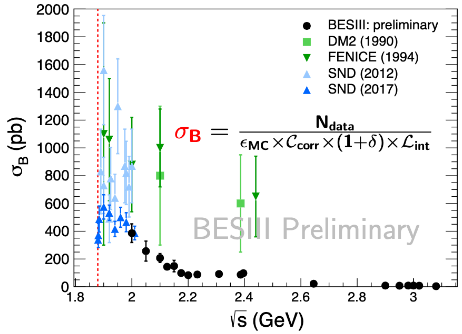


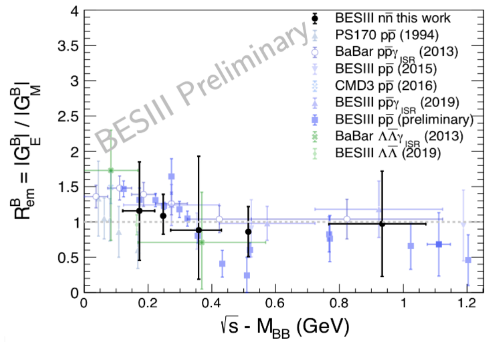
$$|G_{\rm eff}| = \sqrt{\frac{2\tau|G_{\rm M}|^2 + |G_{\rm E}|^2}{2\tau+1}}$$

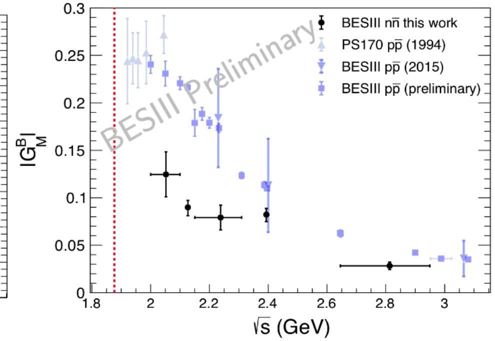
- BESIII provides best precisions: cross section threshold enhancement established
- Oscillating structures observed in the EFF after subtracted the modified dipole parameterization [PRL**114**, 232301 (2015)]
  - confirming the observation at BaBar

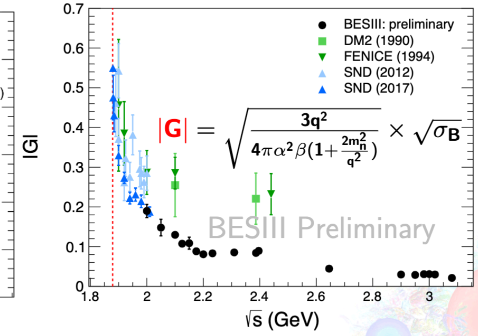
Threshold production of $e^+e^- \to n\bar{n}$

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

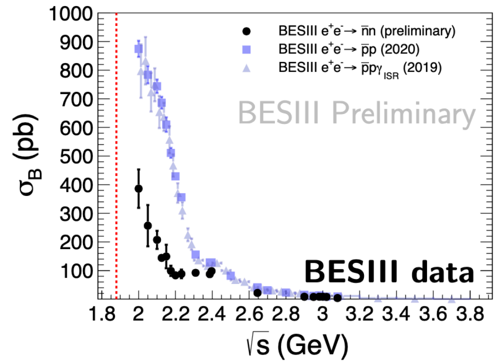


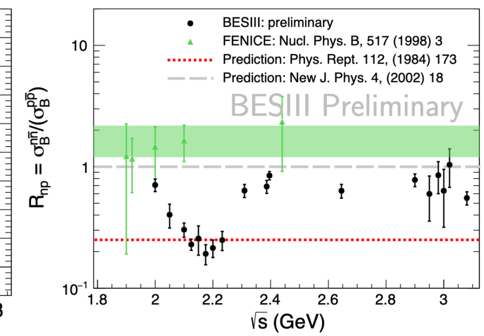


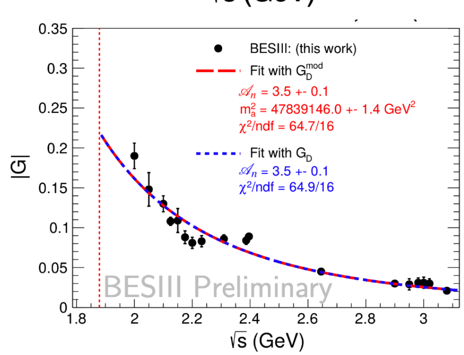


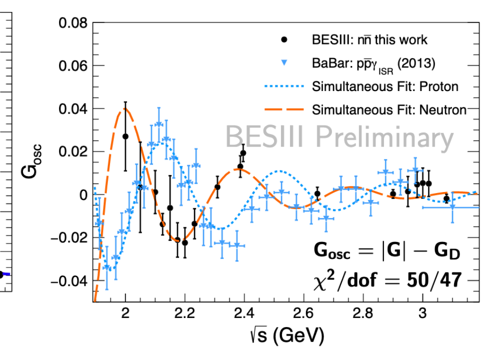


- XS measured in a wide range with unprecedented precision (~10%): confirming threshold enhancement
- EFF ratio R_{em} and G_M determined for the first time
- XS ratio between proton and neutron: do not support the FENICE conjecture, but are within the theoretical predictions
- Oscillation of EFF observed 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}





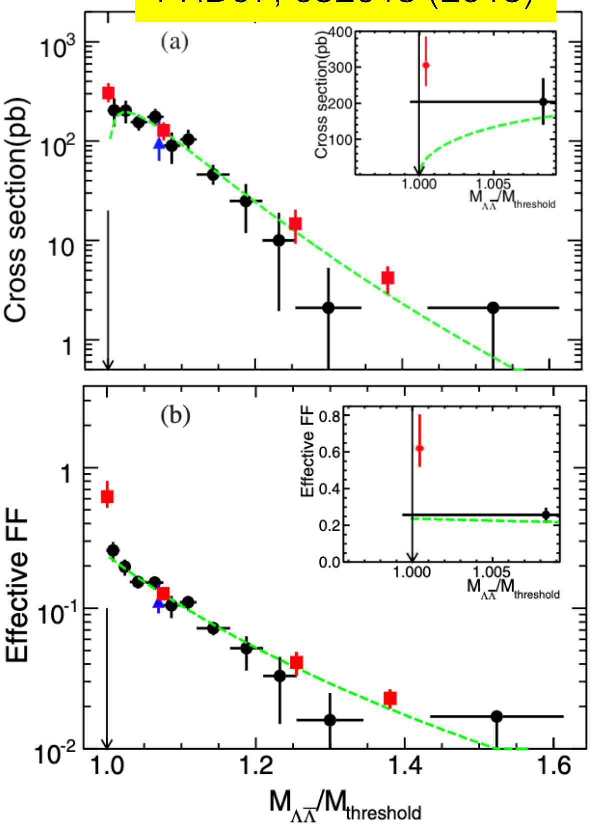




Form factors of hyperons

- 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

PRD97, 032013 (2018)



Threshold enhancement observed

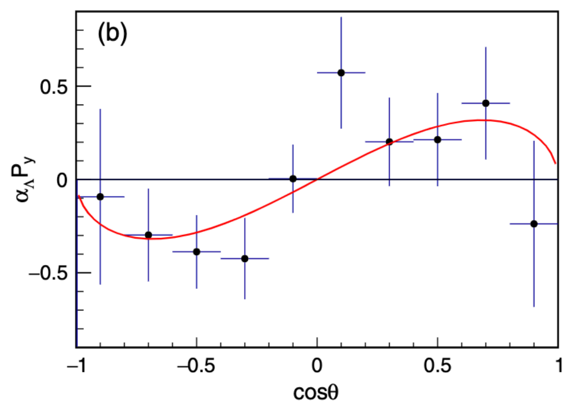
Unpolarized part — Polarized part — Spin correlated part

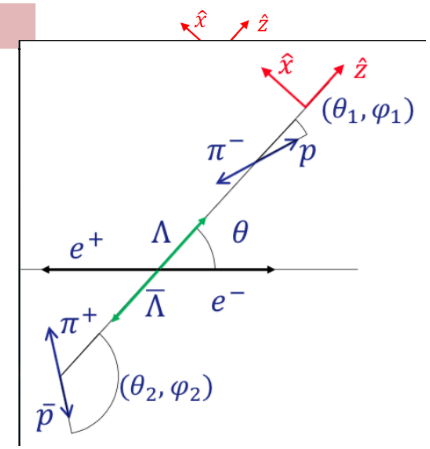
$$W(\boldsymbol{\xi}) = F_0(\boldsymbol{\xi}) + \eta F_5(\boldsymbol{\xi}) + \alpha\bar{\alpha}\,\left(F_1(\boldsymbol{\xi}) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\,F_2(\boldsymbol{\xi}) + \eta F_6(\boldsymbol{\xi})\right) + \sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\alpha F_3(\boldsymbol{\xi}) + \bar{\alpha}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

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

- First complete EFF measurement of the Λ at 2.396 GeV

PRL123,122003 (2019)



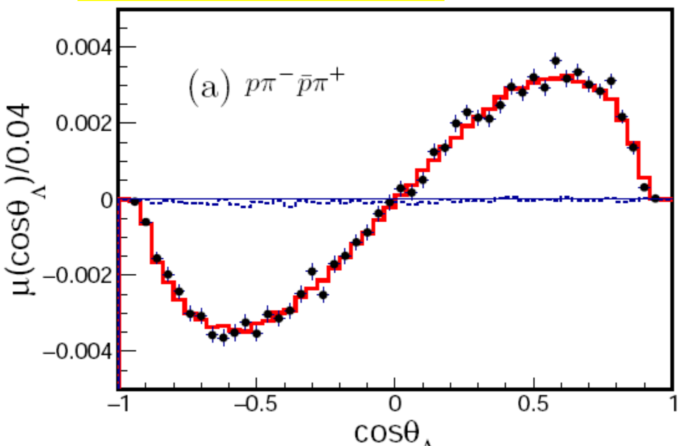


R	$0.96 \pm 0.14 \pm 0.02$
$\Delta\phi$	$37^\circ \pm 12^\circ \pm 6^\circ$

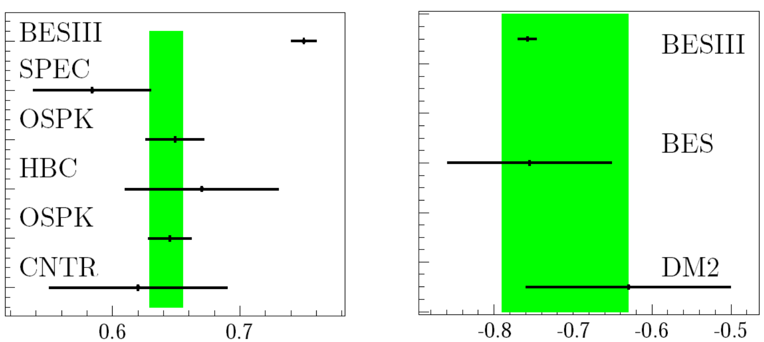
Hyperons produced at ψ peaks

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

Nature Physics (2019)



$\Delta\Phi = 42.4^\circ \pm 0.6^\circ(sta) \pm 0.5^\circ(sys.)$

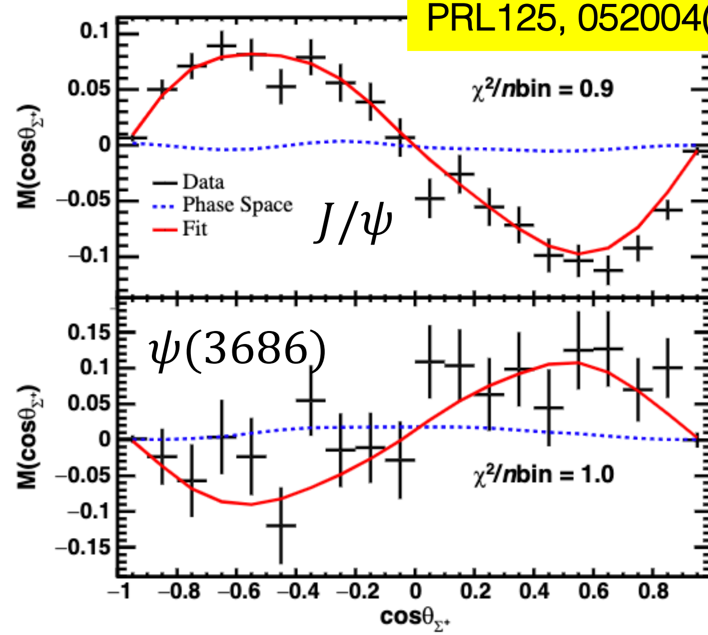


(a) α_- for $\Lambda \to p\pi^-$ (b) α_+ for $\bar{\Lambda} \to \bar{p}\pi^+$

Allow very precise determination of hyperon decay asymmetry

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

PRL125, 052004(2020)



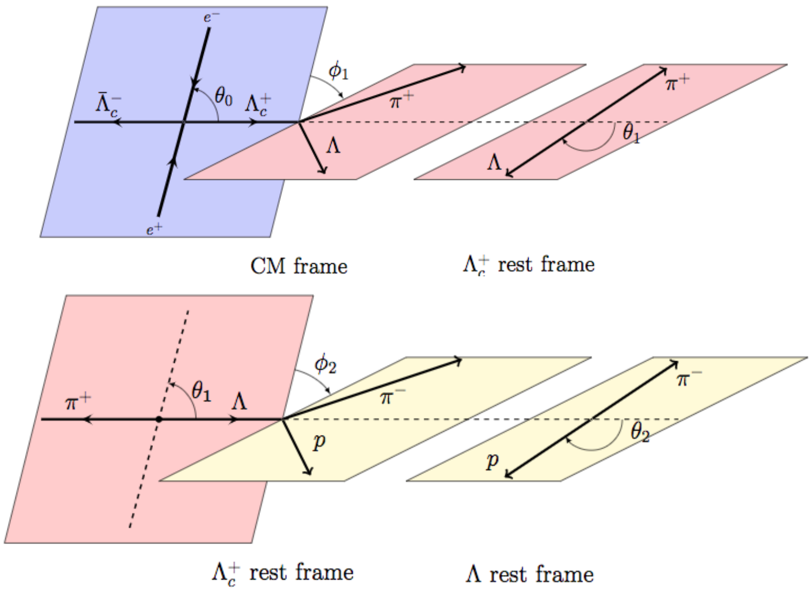
Parameter	Measured value
$\alpha_{J/\psi}$	$-0.508 \pm 0.006 \pm 0.004$
$\Delta\Phi_{J/\psi}$	$-0.270 \pm 0.012 \pm 0.009$
$\alpha_{\psi'}$	$0.682 \pm 0.03 \pm 0.011$
$\Delta\Phi_{\psi'}$	$0.379 \pm 0.07 \pm 0.014$
α_0	$-0.998 \pm 0.037 \pm 0.009$
$\bar{\alpha}_0$	$0.990 \pm 0.037 \pm 0.011$

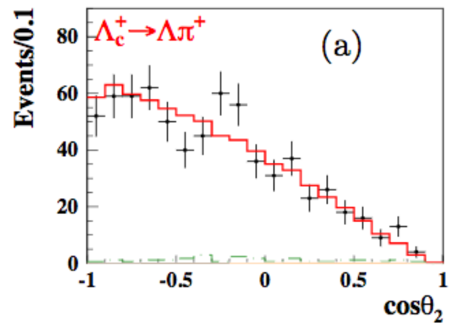
single tag method

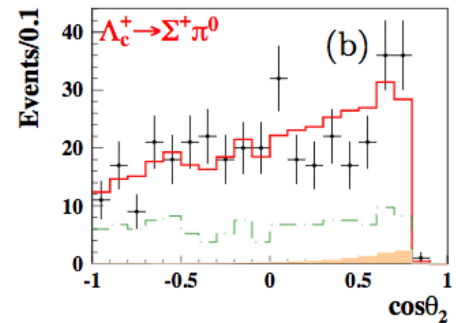
Λ_c decay asymmetries

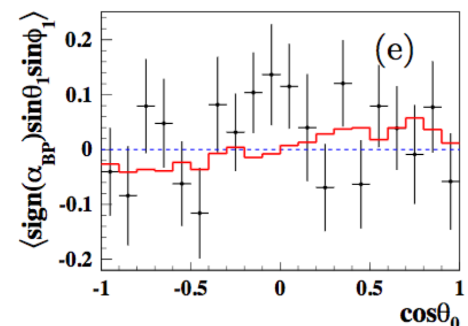
PRD100, 072004 (2019)

- 4(6)-fold angular analysis of the cascade decays of $\Lambda_c \to pK_s, \Lambda\pi^+, \Sigma^+\pi^0$ and $\Sigma^0\pi^+$ based on 567/pb data









$\Lambda_c^+ \to$		pK_S^0	$\Lambda\pi^+$	$\Sigma^+\pi^0$	$\Sigma^0\pi^+$
$\alpha_{BP}^{\Lambda_c^+}$	Predicted	-1.0 [16], 0.51 [11] -0.49 [10], -0.90 [10] -0.49 [17], -0.97 [18] -0.66 [19], -0.90 [30] -0.99 [20], -0.91 [31]	-0.70 [16], -0.67 [11] -0.95 [10], -0.99 [10] -0.96 [17], -0.95 [18] -0.99 [19], -0.86 [30] -0.99 [20], -0.94 [31]	0.71 [16], 0.92 [11] 0.79 [10] -0.49 [10] 0.83 [17], 0.43 [18] 0.39 [19], -0.76 [30] -0.31 [20], -0.47 [31]	0.70 [16], 0.92 [11] 0.78 [10], -0.49 [10] 0.83 [17], 0.43 [18] 0.39 [19], -0.76 [30] -0.31 [20], -0.47 [31]
	PDG [2]		-0.91 ± 0.15	-0.45 ± 0.32	
	This work	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.57 \pm 0.10 \pm 0.07$	$-0.73 \pm 0.17 \pm 0.07$

$\sin\Delta\phi = -0.28 \pm 0.13 \pm 0.03$

- Best precisions on the hadronic weak decay asymmetries
- The transverse polarization is firstly studied and found to be non-zero with 2.1σ

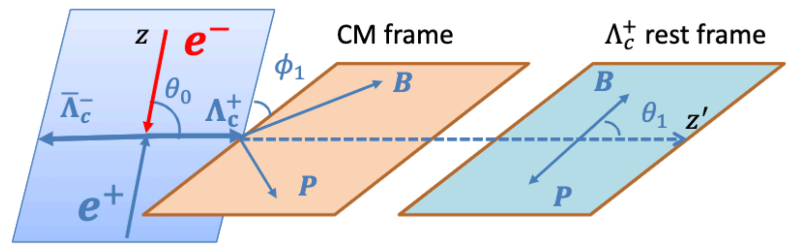
Spin determination of the Λ_c

single tag method

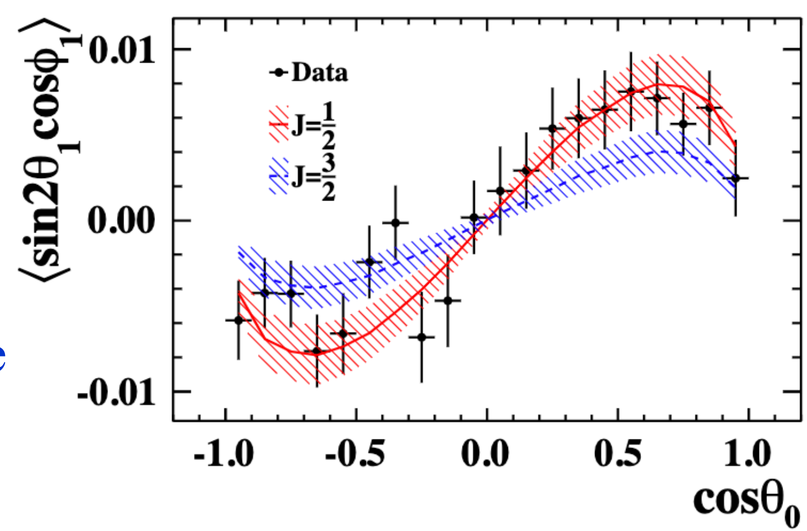
arXiv:2011.00396

- No experimental measurement of the spin of any charmed baryons
- Analysis of the decays of $\Lambda_c^+ \to pK_S, \Lambda\pi^+, \Sigma^+\pi^0$ and $\Sigma^0\pi^+$ based on 567/pb data

$$\mathcal{W}^{J=\frac{1}{2}}(\theta_0,\theta_1,\phi_1) \propto 1+\alpha\cos^2\theta_0+\mathcal{P}_{\mathcal{T}}\sin\theta_1\sin\phi_1,$$
$$\text{with } \mathcal{P}_{\mathcal{T}}=\alpha_{[pK_S^0]}\sqrt{1-\alpha^2}\cos\theta_0\sin\theta_0\sin\xi$$



$$\mathcal{W}^{J=\frac{3}{2}}(\theta_0,\theta_1,\phi_1) \propto 40r_0^0-10\sqrt{3}r_0^2(3\cos2\theta_1+1)$$
$$-60\left[r_1^2\sin2\theta_1\cos\phi_1+r_2^2\sin^2\theta_1\cos2\phi_1\right]$$
$$+\sin\theta_1\alpha_{[pK_S^0]}\left[8\sqrt{15}r^1_{-1}\sin\phi_1\right.$$
$$+90r^3_{-2}\sin2\theta_1\sin2\phi_1$$
$$\left.-9\sqrt{10}r^3_{-1}(5\cos2\theta_1+3)\sin\phi_1\right],$$



- Multidimensional likelihood fit to data under hypothesis of J=1/2 or J=3/2
- Data favors 1/2 over 3/2 with significance larger than 7.8 σ, consistent with the expectation of the naive quark model.

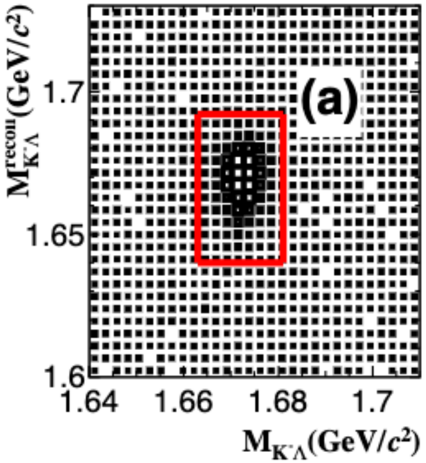
Spin properties of the Ω^-

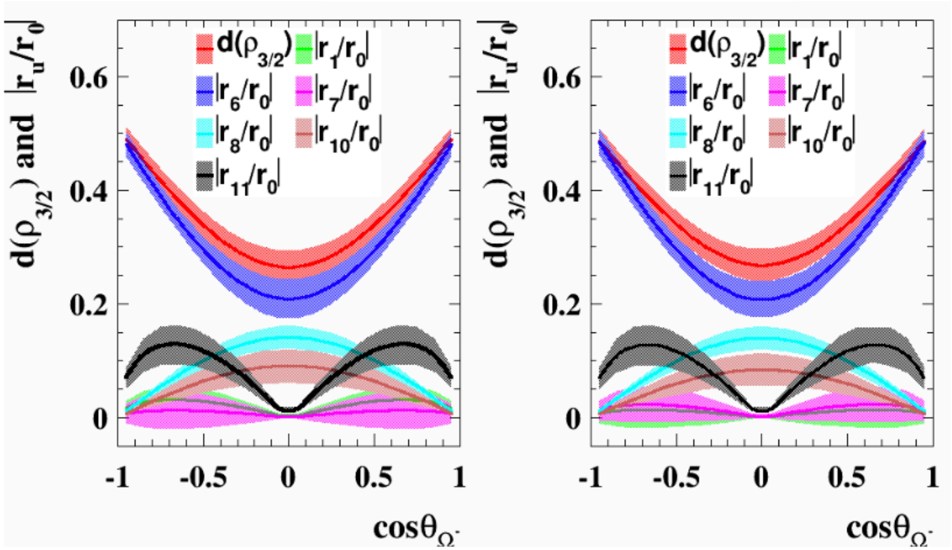
arXiv: 2007.03679

single tag method

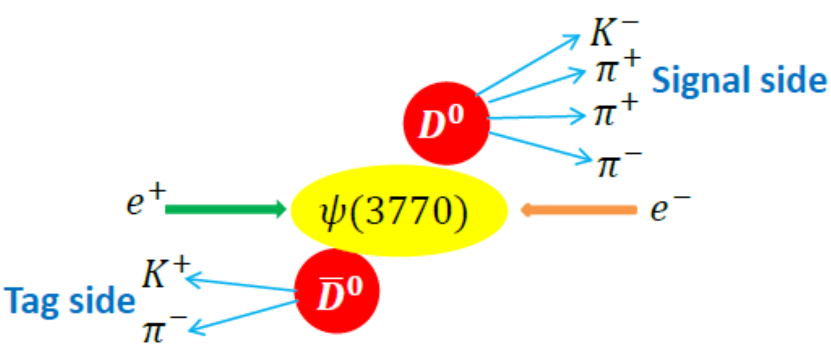
- The process $e^+e^- \to \psi(3686) \to \Omega^-\bar{\Omega}^+$, $\Omega^- \to \Lambda K^-$ for the spin 3/2 Ω^- is described by four form factors/helicity amplitudes
- The measurement confirms the spin 3/2 for the first time
- Helicity amplitudes are determined
- Decay asymmetry $\alpha_\Omega = -0.04 \pm 0.03$
- Degree of polarization

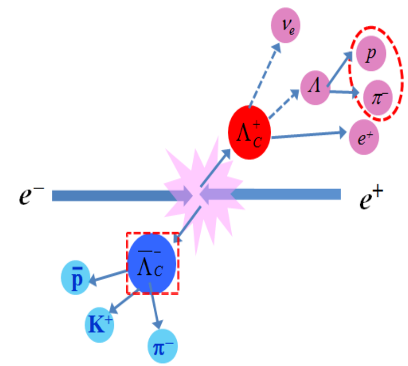
$$d(\rho_{3/2}) = \sqrt{\sum_{\mu=1}^{15}\left(\frac{r_\mu}{r_0}\right)^2} = 0.71 \pm 0.04$$





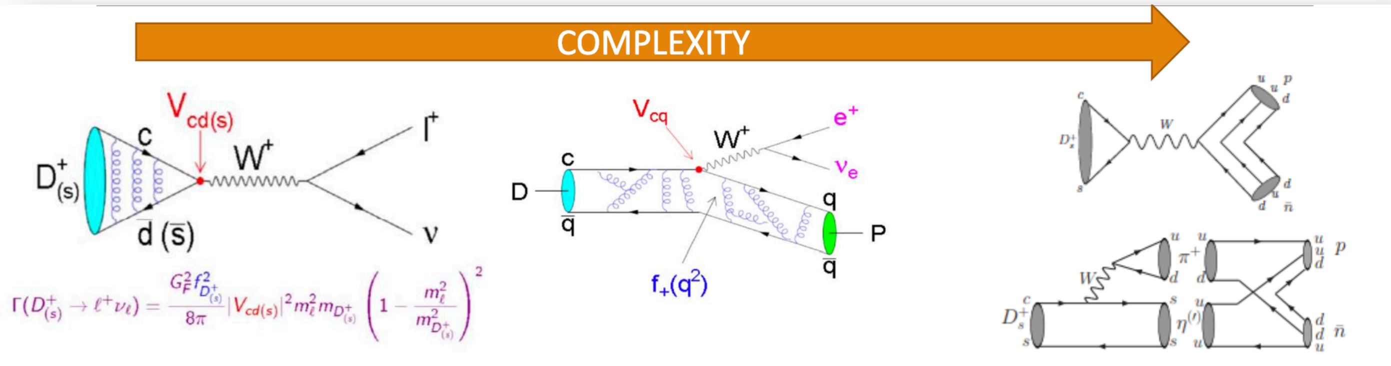
Charm hadron decays





2.93/fb at $\psi(3770)$

0.567/fb at 4.6 GeV



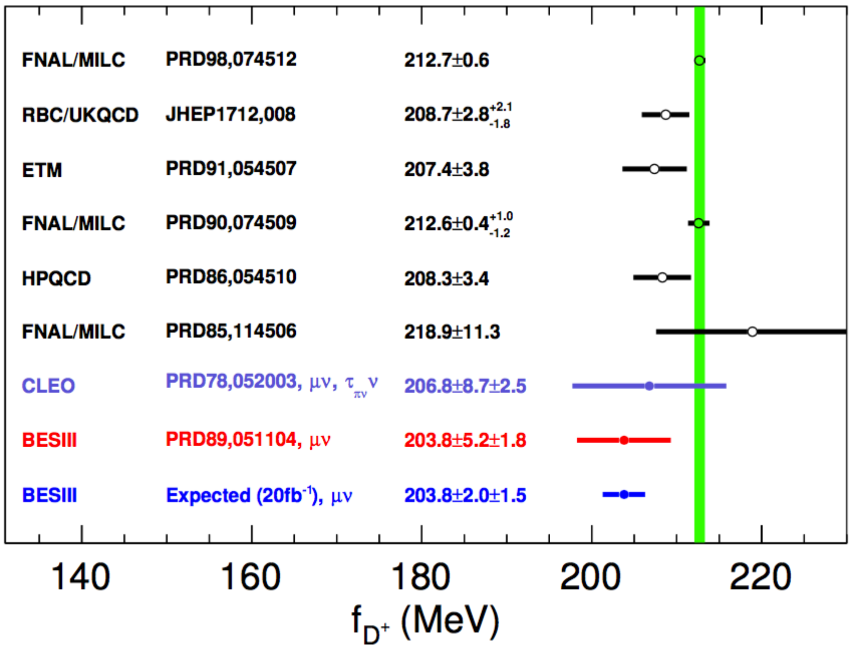
Take V_{cx} from fits to CKM assuming unitarity and measure f Precise test of lattice QCD in charm and extrapolate to beauty	Similar to leptonic decay but now q (= four-momentum of W) dependent Test QCD models of the form factor	Models of hadronic decay • Isospin • SU(3) flavour • Different amplitudes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

Decay constant $f_{D(s)}$

Inputs:

PDG2018 from CKM unitarity:

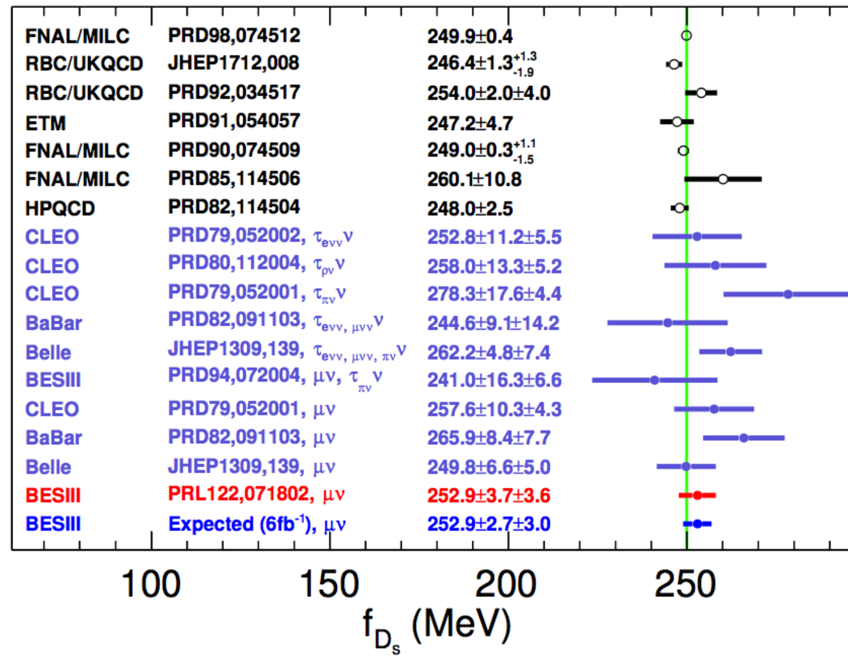
$$|V_{cd}| = 0.22438 \pm 0.00044$$



Inputs:

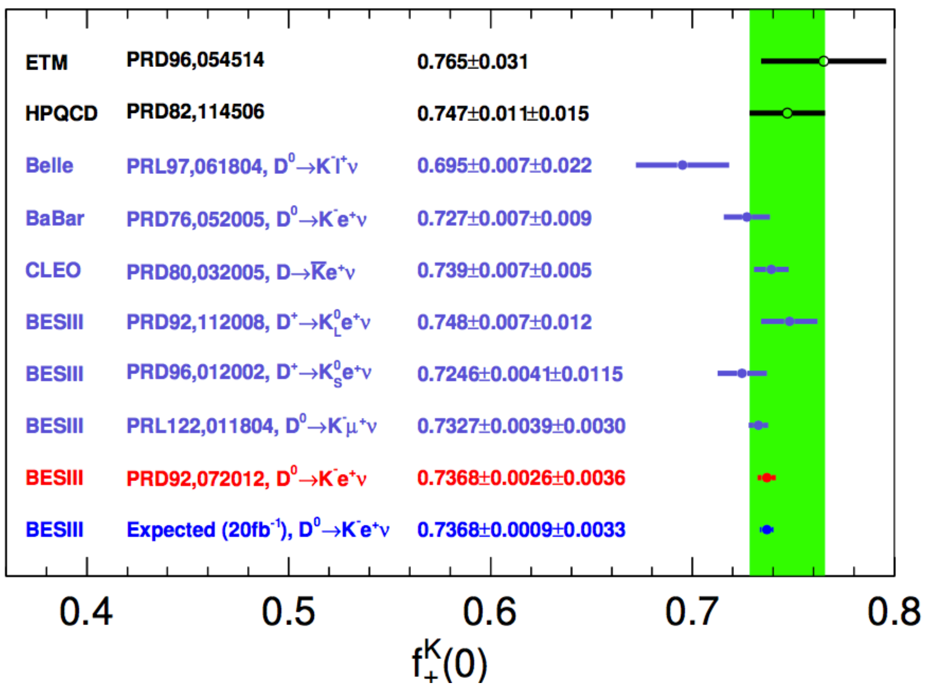
PDG2018 from CKM unitarity:

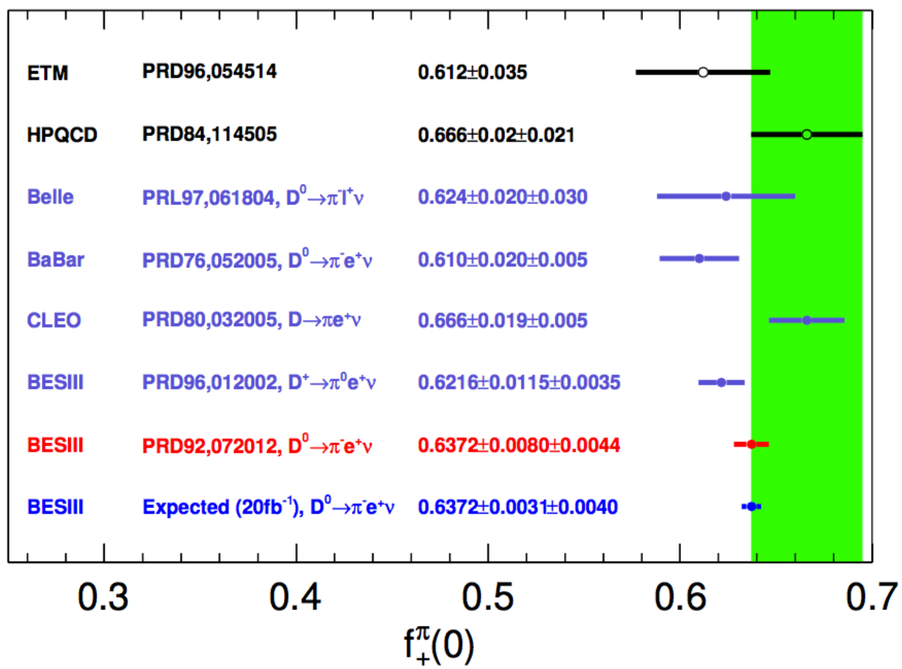
$$|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$$



- Precisions of LQCD results are superior to experimental ones
- Hint of slight tension between exp. & LQCD results

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





Precisions better than those of LQCD results

Strong phase of $D \to K_S h^+ h^-$

- Self-conjugate 3-body process
- BPGGSZ method: input to CKM UT γ angle measurement at LHCb and Belle (II)
- Useful for charm mixing study

$B^\pm$ events in bin i of Dalitz plot

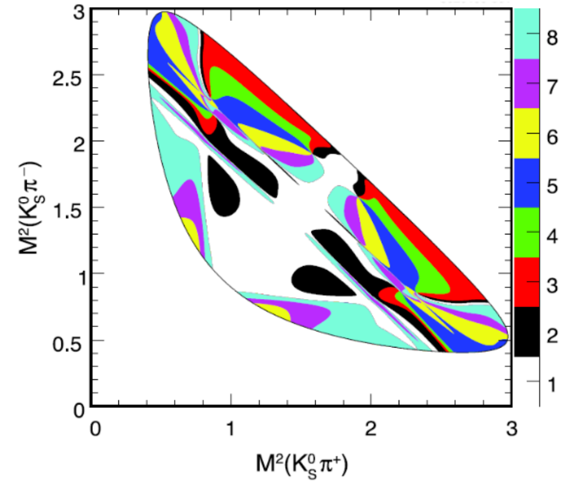
Number of events for flavour-tagged D sample

$x_\pm = r_B\cos(\delta_B \pm \gamma)$

$y_\pm = r_B\sin(\delta_B \pm \gamma)$

$$N_i^\pm = h(K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_\pm c_i \pm y_\pm s_i))$$

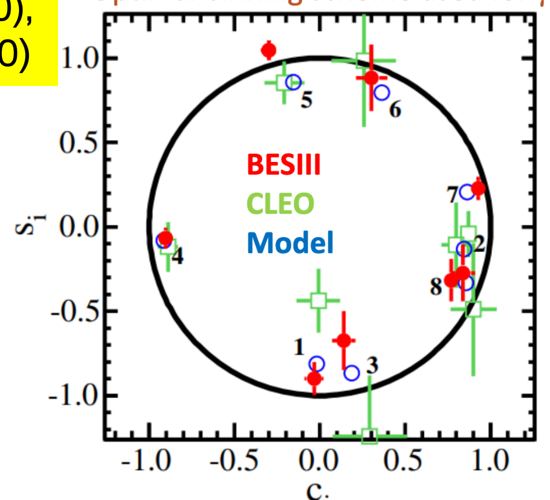
c_i, s_i : average in bin of cosine, sine of strong phase difference



PRL124, 241802 (2020), PRD101, 112002 (2020)

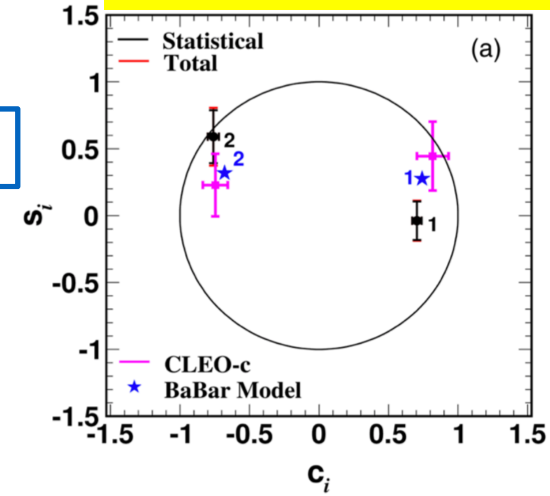
$K_S\pi^+\pi^-$

Optimal binning scheme used for γ



PRD102, 052008 (2020)

$K_SK^+K^-$

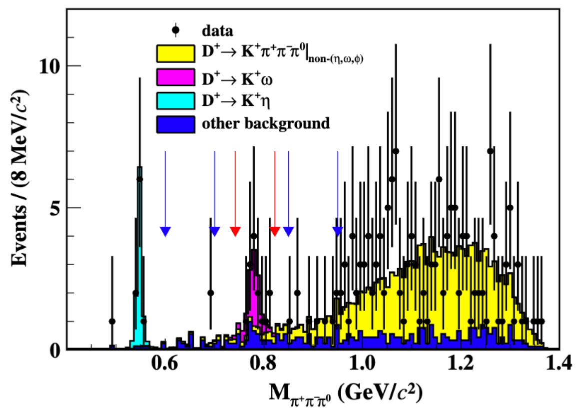


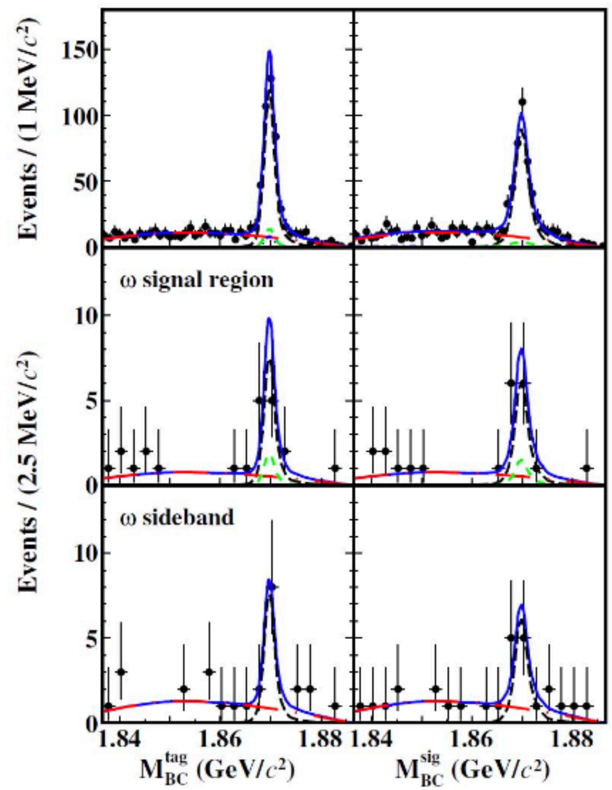
With inclusions of these strong phases to the recent LHCb γ angle measurement [***arxiv:2010.08483***], the relevant systematics are reduced to ~1 degree.

Observation of the DCS decay $D^+ \to K^+\pi^+\pi^-\pi^0$

PRL125, 141802 (2020)

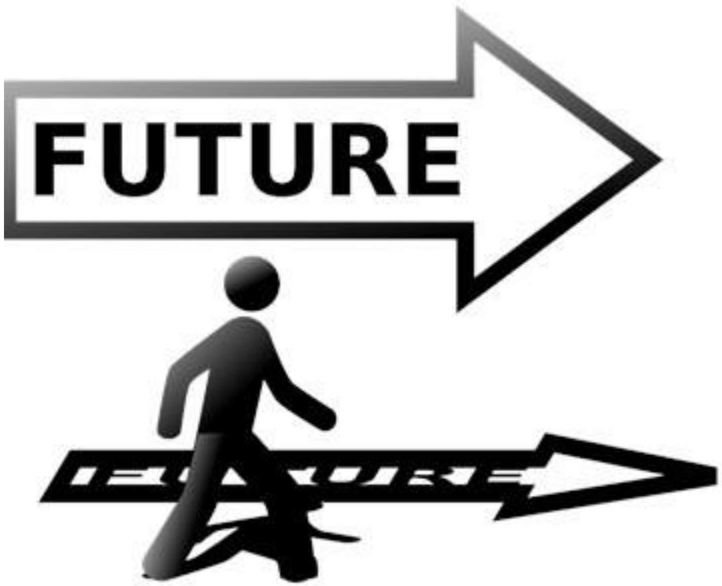
Double tag method



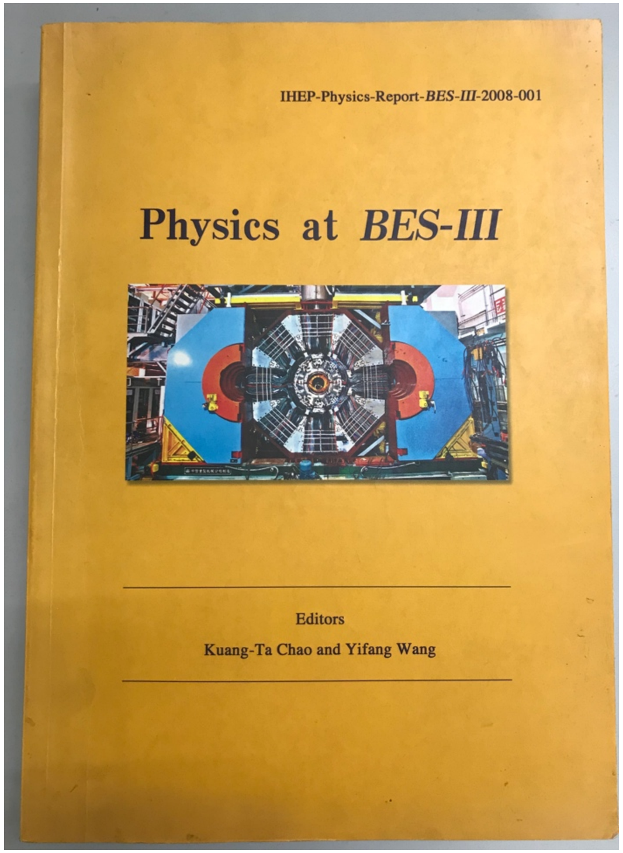


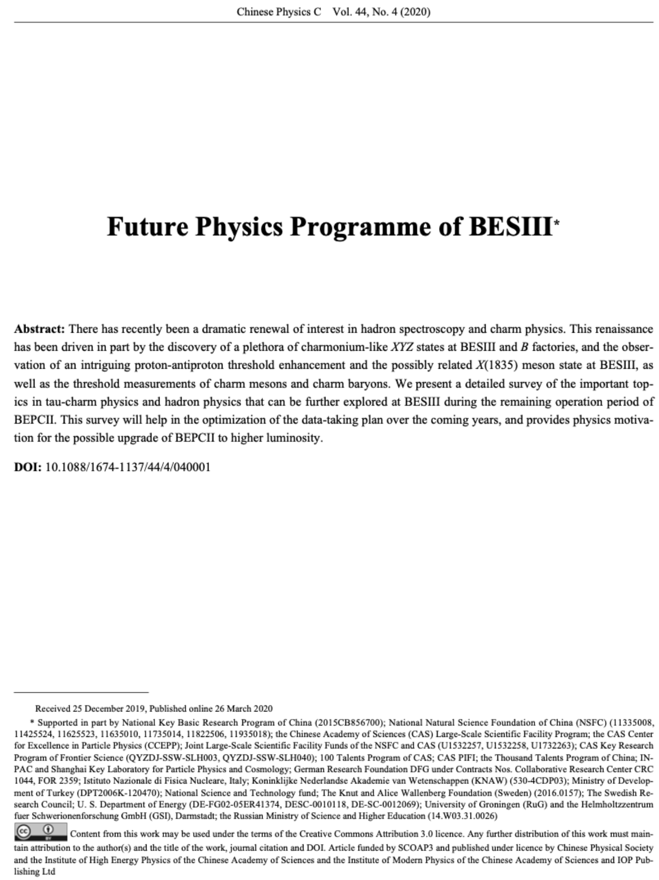
Decay mode	N_{DT}	$\mathcal{B}_{sig}$ ($\times 10^{-3}$)
$D^\pm \to K^\pm\pi\pi\pi^0$	350 ± 22	1.21 ± 0.08
$D^\pm \to K^\pm\omega$ (3.3σ)	$9.2^{+4.0}_{-3.4}$	$(5.7^{+2.5}_{-2.1}) \times 10^{-2}$
$D^+ \to K^+\pi\pi\pi^0$	181 ± 15	1.25 ± 0.11
$D^- \to K^-\pi\pi\pi^0$	165 ± 15	1.16 ± 0.11

- $\mathcal{B}^*_{D^+\to K^+\pi\pi\pi^0} = (1.13\pm0.08\pm0.03)\times10^{-3}$ subtracting the η, ω and ϕ
- $A_{CP} = (-0.04 \pm 0.06 \pm 0.01)$
- $\mathcal{B}^*_{D^+\to K^+\pi\pi\pi^0}/\mathcal{B}_{D^+\to K^-\pi\pi\pi^0} = (6.28 \pm 0.52)\tan^4\theta_C(\sim 0.29\%)$, significantly larger than (0.21-0.58)% from other DCS decays
- Possible sizeable isospin symmetry violation effects


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

Data taking plan of 2021-2022

- Study XYZ & charmed baryons [89 days]
  - 500 pb^{-1} per point at Ecm=4.74，4.78，4.84 GeV. [21+24+29 days]
  - 200 pb^{-1} at Ecm=4.90 GeV [15 days].
- Take 2.55B ψ' events & 10% lum. continuum data [62 days] ➔ 3B in total
- Take ψ(3770) data in reminder 2020-21 running year + full 2021-22 running year

  [(200-89-62)+200 = 249 days; ~16/fb]

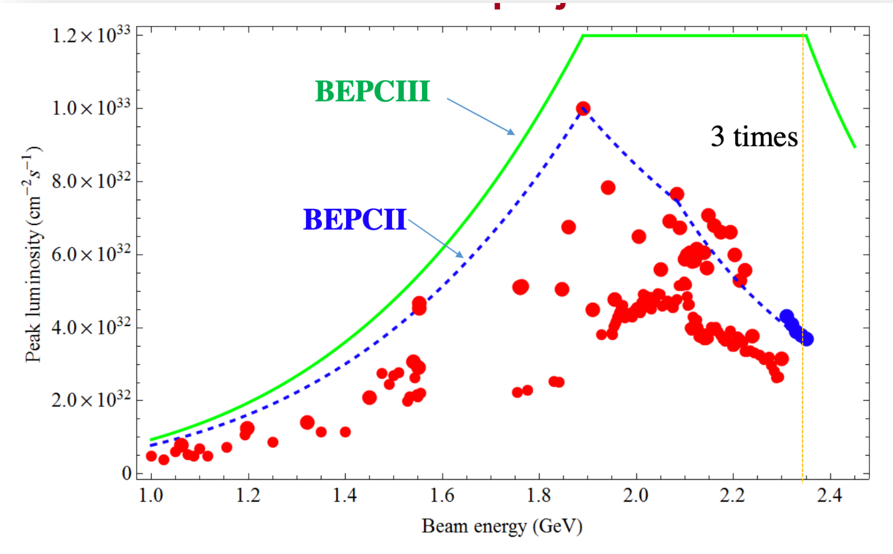
  May try to get 15 more days for another 1/fb ψ(3770) data. ➔ 20/fb in total

✓ So until 2022, we shall have 10B J/ψ, 3B $\psi(2S)$ and 20 /fb $\psi(3770)$ data

Proposal of the BEPCIII

- Following up with the beam energy and top-up upgrade, we are planning the next generation of BEPCIII (200 million CNY), to be implemented around 2022: the optimized energy is 2.35 GeV with luminosity 3 times higher than BEPCII.

	BEPCII	BEPCIII
Lum. $[10^{33}\mathrm{cm^{-2}s^{-1}}]$ **@2.35GeV**	**0.35**	**1.2**
β_y^* [cm]	**1.5**	**1.35**
Bunch current	7.1 mA	7.5 mA
Bunch number	56	120
SR Power [kW]	**110**	**250**
$\xi_{y,\mathrm{lum}}$	**0.029**	**0.039**
Emittance [nmrad]	**138**	**120**
Coupling [%]	**0.53**	**0.40**
Bucket Height	0.0069	0.091
$\sigma_{z,0}$ [cm]	1.54	1.24
σ_z [cm]	**1.69**	**1.39**
RF voltage	**1.6MV**	**3.5MV**



Major modification
- RF region
- Vacuum chamber
- Beam parameters

Summary

- **BESIII is successfully operating since 2008, and will continue to run for 5–10 years**
  – collected large data samples in the τ-charm mass region
- **Many exciting results have been published covering many aspects:**
  - ✓ XYZ states and light hadron spectroscopy
  - ✓ Form factors of the nucleon and hyperons
  - ✓ Charmed mesons and baryons
  - ✓ Rare decays and new physics search
  - ✓ …
- **Future goals:**
  50M D^0, 50M D^+, 15M Ds, 2M Λ_c, high-lumi. fine scan up to 4.94 GeV

Thank you!

谢谢！