



BESIII results on X and Z states

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In memory of Prof. Misha Voloshin...

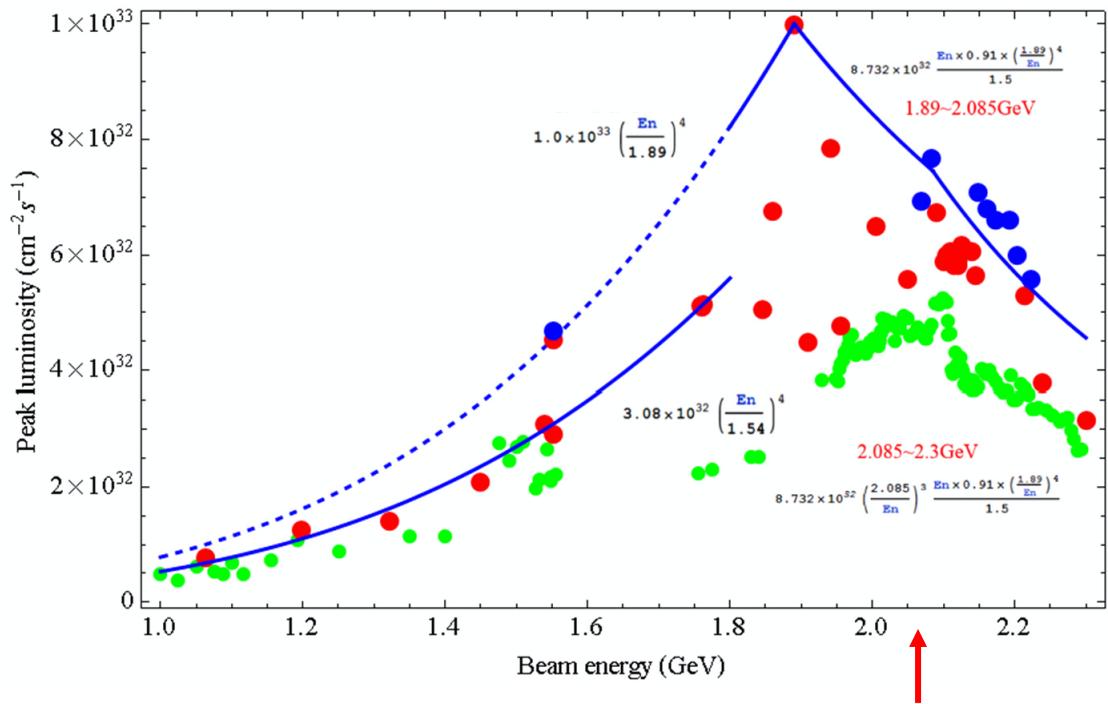


Outline

- Introduction to BESIII
- X-states at BESIII
- Z-states at BESIII
 - Z-states in hidden-charm final states
 - Z-states in open-charm final states
- Summary

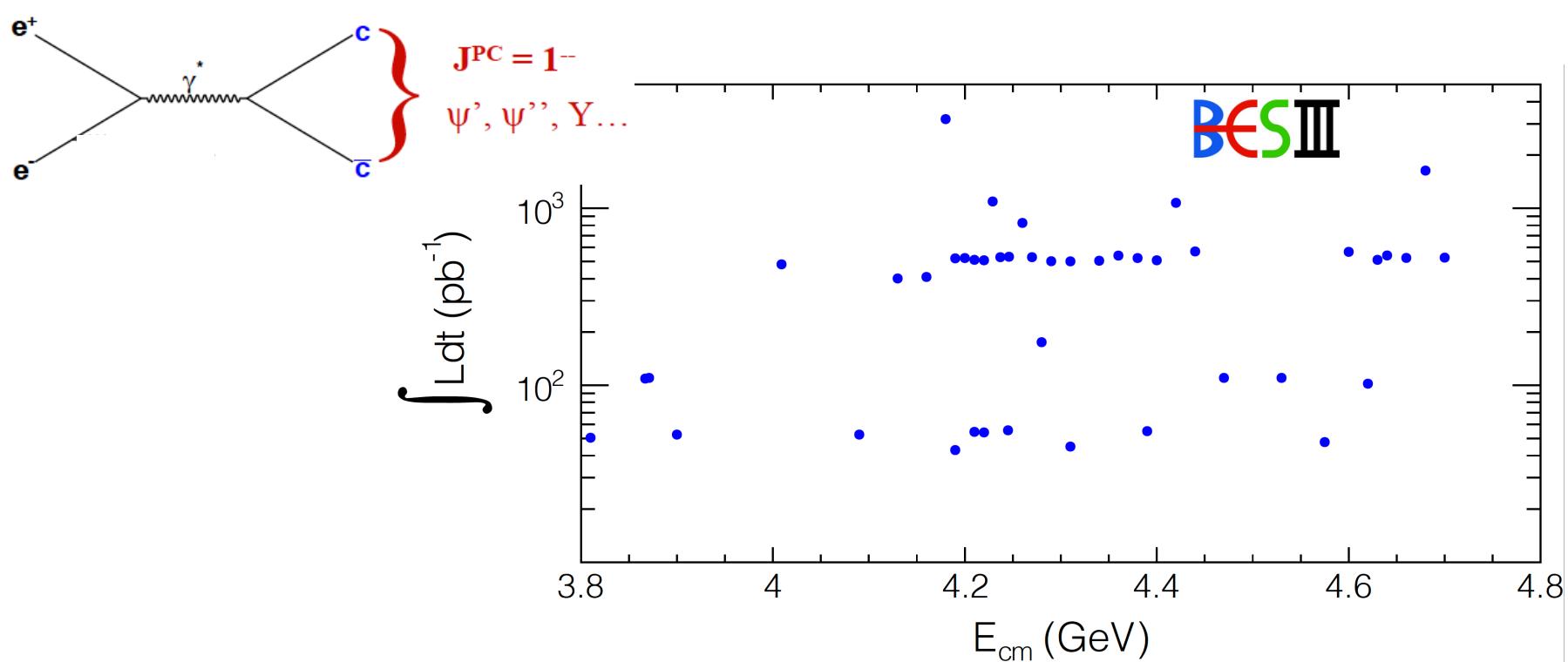


BEPCII Luminosity



- Center-of-Mass energy: $2.0 - 4.936\text{ GeV}$
- Design Luminosity @ $\psi(3770)$: $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (achieved in 2016)
- Energy spread: 1.1 MeV @ 3.686 GeV

Data sets at BESIII

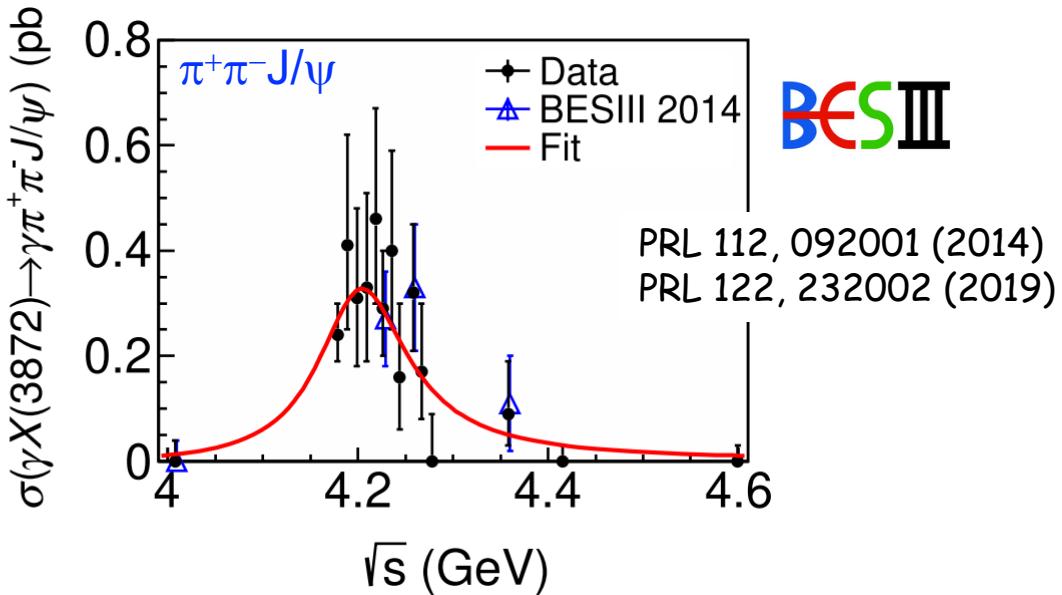
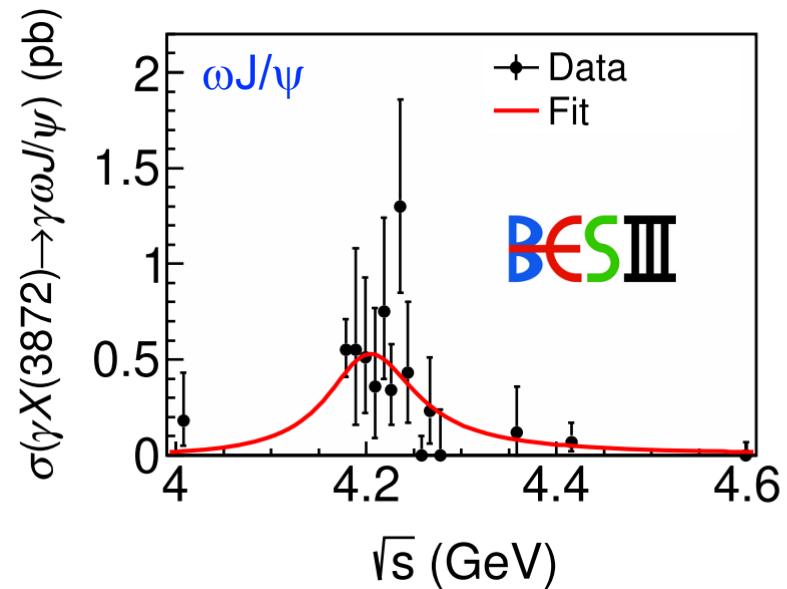


- A scan experiment for vector charmonium-(like) states
- Over 20 fb $^{-1}$ data between 3.8 – 4.7 GeV during last 7 years
- Scan step 500 pb $^{-1}$ /10 MeV; will continue...

X-states at BESIII

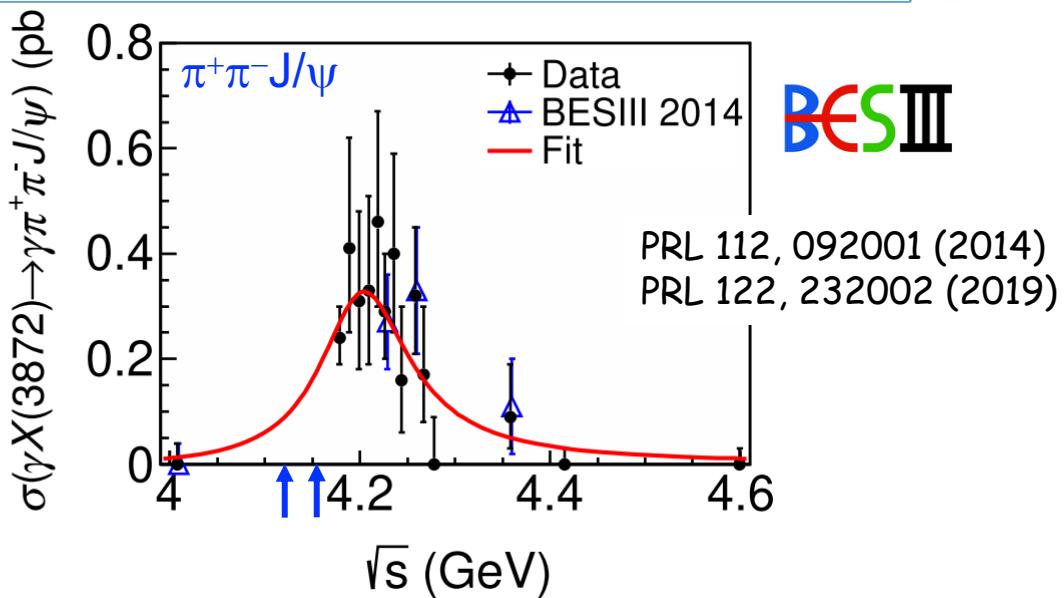
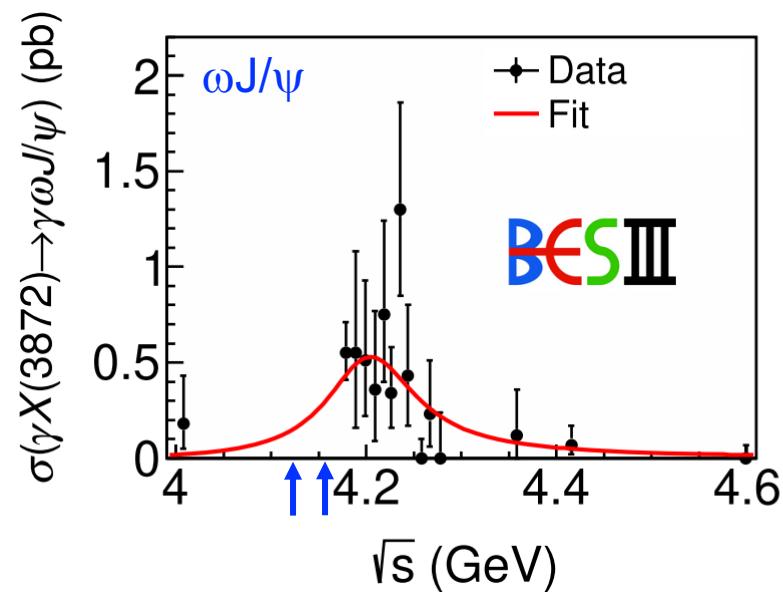


Production of $e^+e^- \rightarrow \gamma X(3872)$



- Production cross section ~ 0.3 pb @ 4.2 GeV with $\pi^+\pi^-J/\psi$ channel
[Phys. Rev. Lett. 124, 152001](#)
- According to BaBar's measurement $\text{Br}[X(3872) \rightarrow \pi^+\pi^-J/\psi] = (4.1 \pm 1.3)\%$
- $\sigma[e^+e^- \rightarrow \gamma X(3872)] \sim 7.3$ pb level; Daily luminosity $L=30$ pb $^{-1}$ at BESIII \rightarrow BESIII will produce ~ 200 events per day ("super mini-factory")

$Y(4260) \rightarrow \gamma X(3872)$

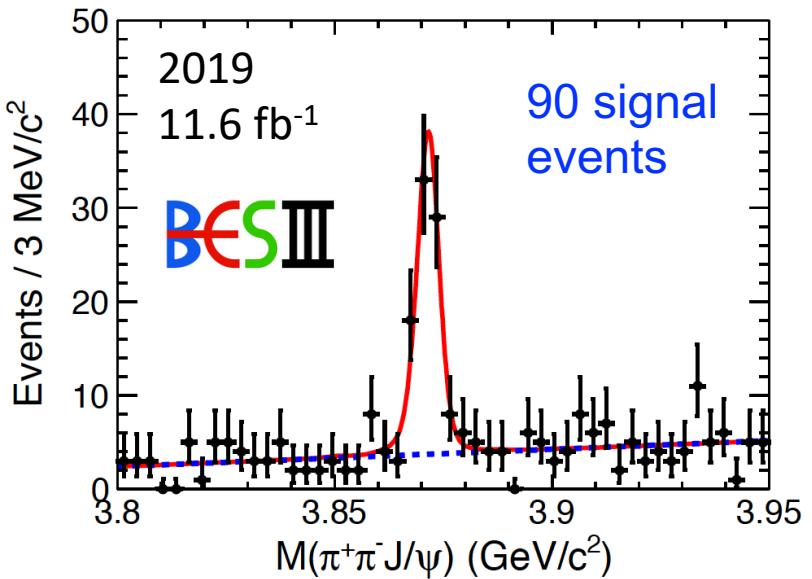
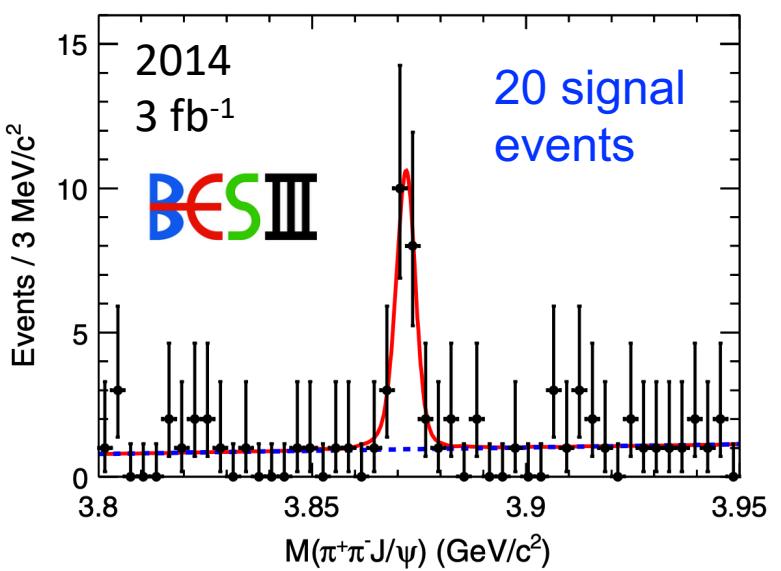


- $e^+e^- \rightarrow \gamma X(3872)$ cross section line shape by BESIII
- $M = 4200.6^{+7.9}_{-13.3} \pm 3.0$ MeV, $\Gamma = 115^{+38}_{-26} \pm 12$ MeV
- Unique at BESIII, $Br[Y(4260) \rightarrow \gamma X(3872)]/Br[Y \rightarrow \pi^+ \pi^- J/\psi] \sim 9\%$

Strongly suggest the $Y(4260) \rightarrow \gamma X(3872)$ transition → *Commonality between Y(4260) & X(3872)...*

PLB 725, 127 (2013) / RMP 90, 015003 (2018)

$X(3872) \rightarrow \pi^+ \pi^- J/\psi$

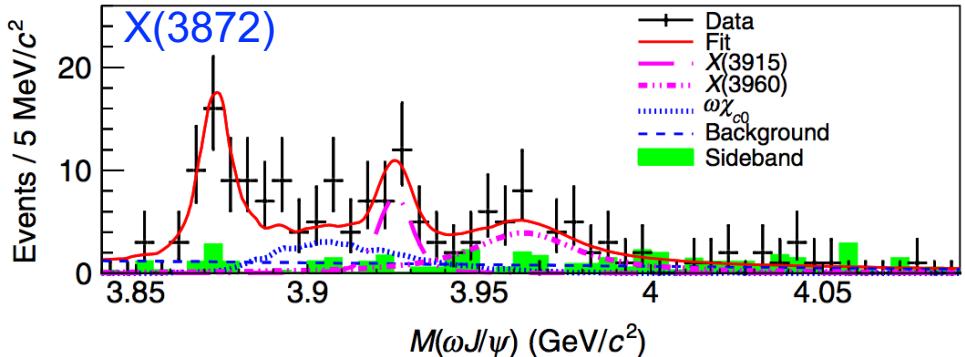


- $X(3872) \rightarrow \pi^+ \pi^- J/\psi$ is still the golden channel (productive & clean);
(20 signal events in 2014 → ~90 signal events in 2019)
- ISR $\psi(2S)$ events as reference, remaining background $\pi^+ \pi^- \pi^+ \pi^-$ etc.
- Radiative photon angular distribution is on progress...

X(3872) → ωJ/ψ

BESIII

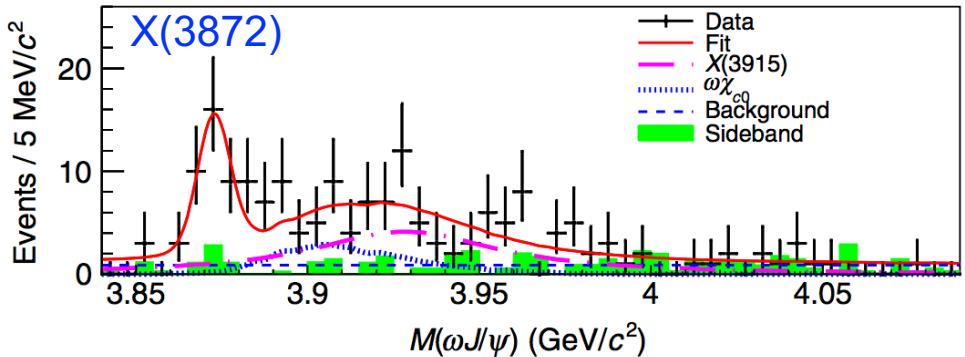
PRL 122, 232002 (2019)



➤ $e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma\omega J/\psi$ at BESIII

➤ Observed $X(3872) \rightarrow \omega J/\psi$ signal with $>5\sigma$ significance (first time)

$$\text{Br}[X \rightarrow \omega J/\psi] / \text{Br}[X \rightarrow \rho J/\psi] = 1.6^{+0.4}_{-0.3} \pm 0.2$$



➤ Big iso-spin violation effect (x10 amplitude)

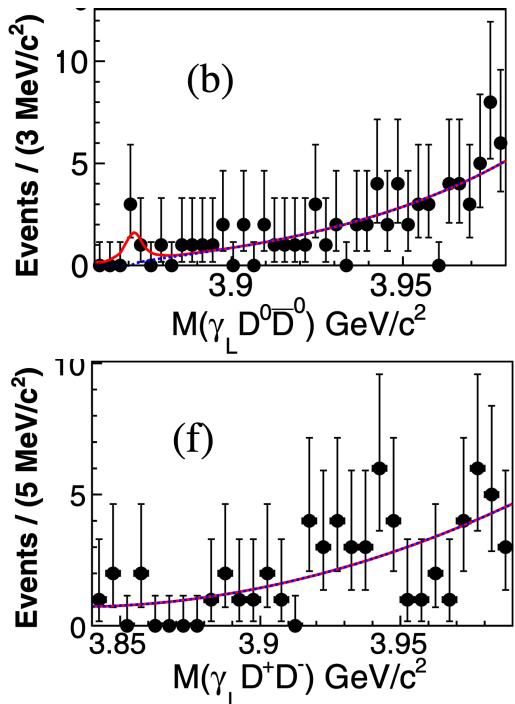
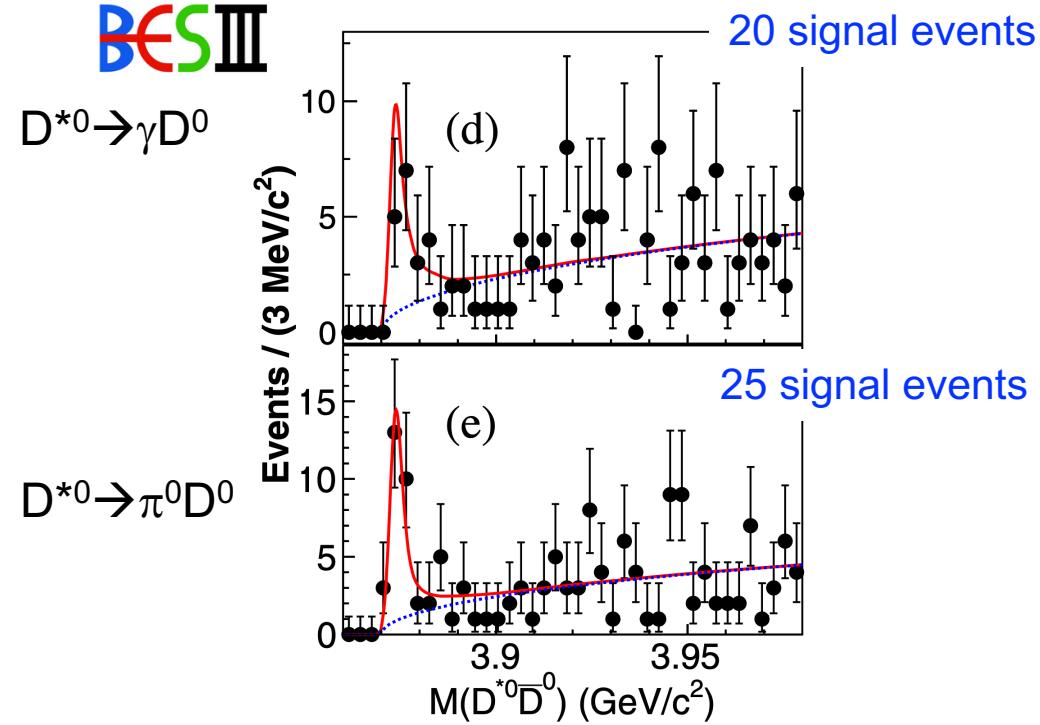
➤ X(3872) is very exotic !

$$R_{X(3872)} = \left| \frac{A(\rho J/\psi)}{A(\omega J/\psi)} \right| \sim 0.2 - 0.3$$

$$R_{\psi(2S)} = \frac{g_{\pi^0 J/\psi}}{g_{\eta J/\psi}} \approx 0.03$$

PRD 85, 011501(R) (2012)

$X(3872) \rightarrow \overline{D^0} D^{*0}$

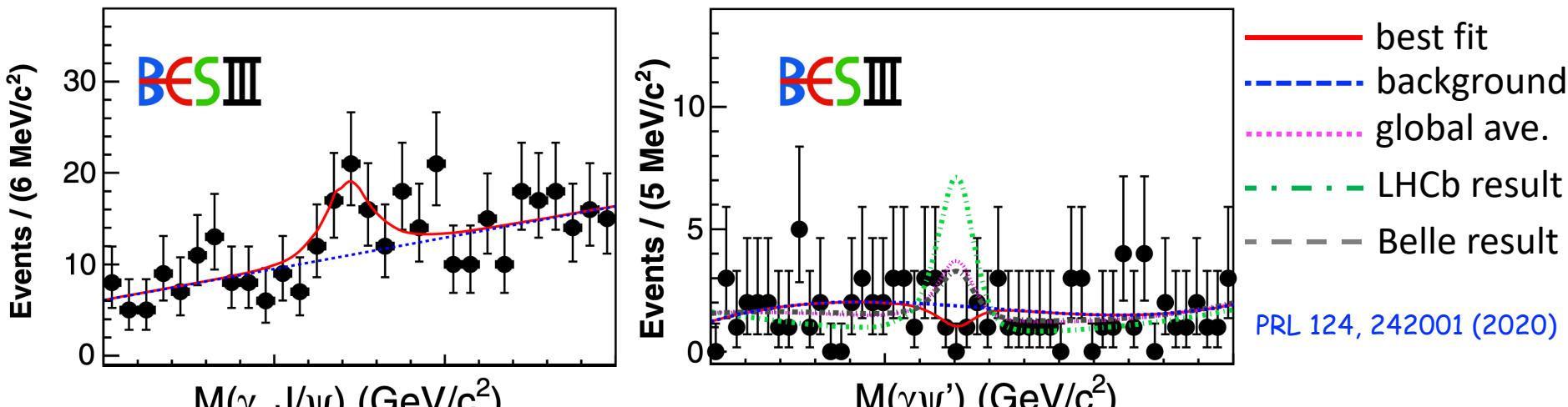
BESIII


PRL 124, 242001 (2020)

$X(3872) \rightarrow \overline{D^0} D^{*0}$ is dominant

- BESIII observed the decay $X(3872) \rightarrow \overline{D^0} D^{*0}$ with $>7.4\sigma$ significance.
- No obvious signal observed from $\gamma D^+D^-/\gamma D^0\bar{D}^0$

$X(3872) \rightarrow \gamma J/\psi \& \gamma \psi(2S)$



- 3.5σ evidence for $X(3872) \rightarrow \gamma J/\psi$
- No signal for the $X(3872) \rightarrow \gamma \psi(2S)$ decay at BESIII
- In tension with the LHCb measurement (C.L. < 0.0048)

Molecule?

$$\frac{B[X(3872) \rightarrow \gamma \psi(2S)]}{B[X(3872) \rightarrow \gamma J/\psi]} < 0.59 \text{ (BESIII) @ 90% C.L.}$$

$$\frac{B[X(3872) \rightarrow \gamma J/\psi]}{} < 2.1 \text{ (Belle) @ 90% C.L.}$$

Tetraquark?

$$= 3.4 \pm 1.4 \text{ (BaBar)}$$

$$= 2.46 \pm 0.64 \pm 0.29 \text{ (LHCb)}$$

PRL 107, 091803 (Belle)

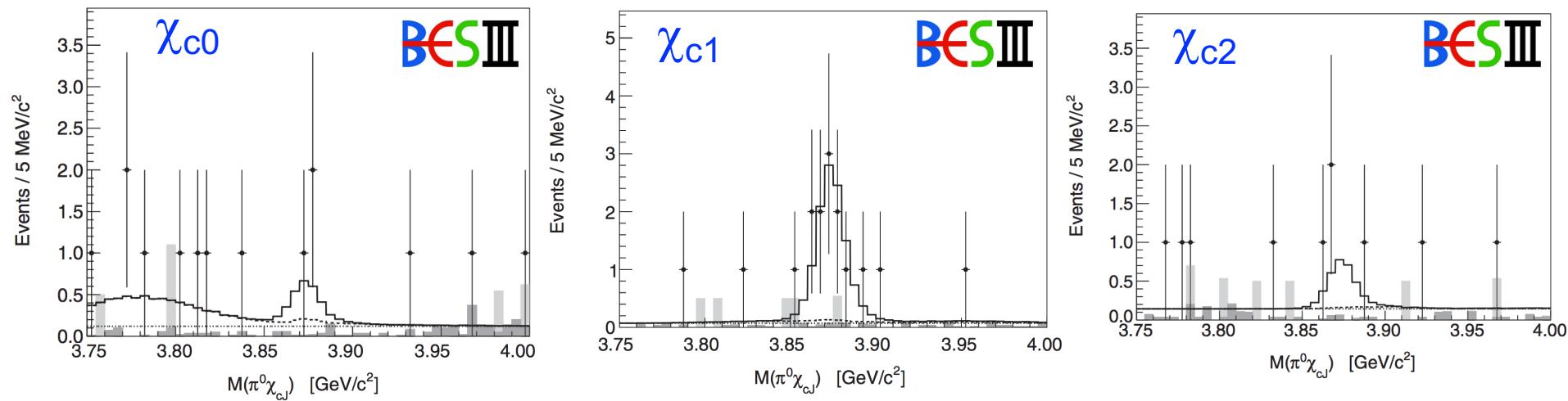
PRL 102, 132001 (BaBar)

NPB 886(665) (LHCb)



New decay modes of $X(3872) \rightarrow \pi^0 \chi_{c1}$

PRL 122, 202001 (2019)

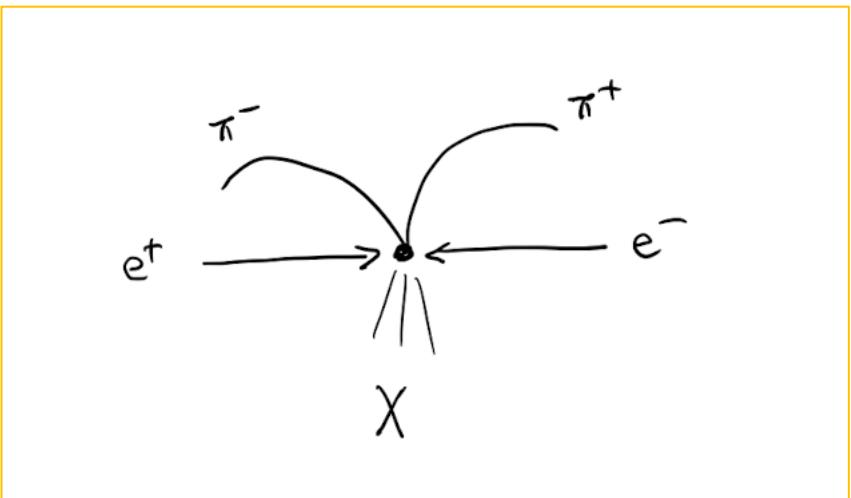
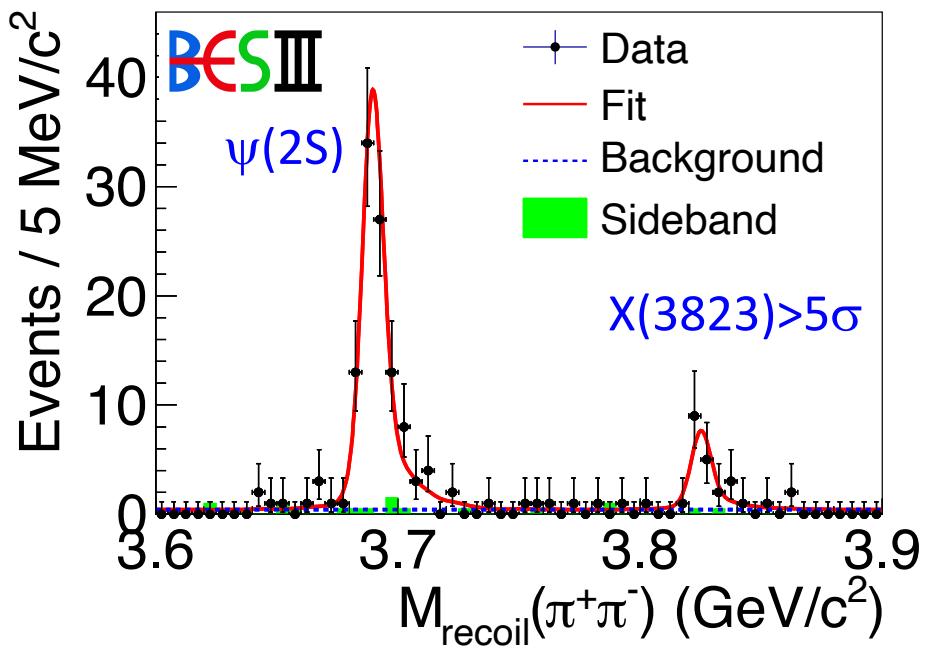


- Search for new decay modes, very clean environment
- Observed the $X(3872) \rightarrow \pi^0 \chi_{c1}$ decay for the first time with $>5\sigma$ significance
- Iso-spin violation, comparable decay rate with $\rho^0 J/\psi \rightarrow$ disfavor $\chi_{c1}(2P)$

$B[X(3872) \rightarrow \pi^0 \chi_{c0}] / B[X(3872) \rightarrow \rho J/\psi] < 19$ @ 90% C.L.
 $B[X(3872) \rightarrow \pi^0 \chi_{c1}] / B[X(3872) \rightarrow \rho J/\psi] = 0.88^{+0.33}_{-0.27} \pm 0.10$
 $B[X(3872) \rightarrow \pi^0 \chi_{c2}] / B[X(3872) \rightarrow \rho J/\psi] < 1.1$ @ 90% C.L.

$$X(3823) = \psi(1^3D_2)$$

PRL115, 011803 (2015)



- E706 & Belle report evidence
- BESIII study $e^+e^- \rightarrow \pi^+\pi^-\chi(3823) \rightarrow \pi^+\pi^-\gamma\chi_{c1}$
- $M = (3821.7 \pm 1.3 \pm 0.7) \text{ MeV}$, Γ is small

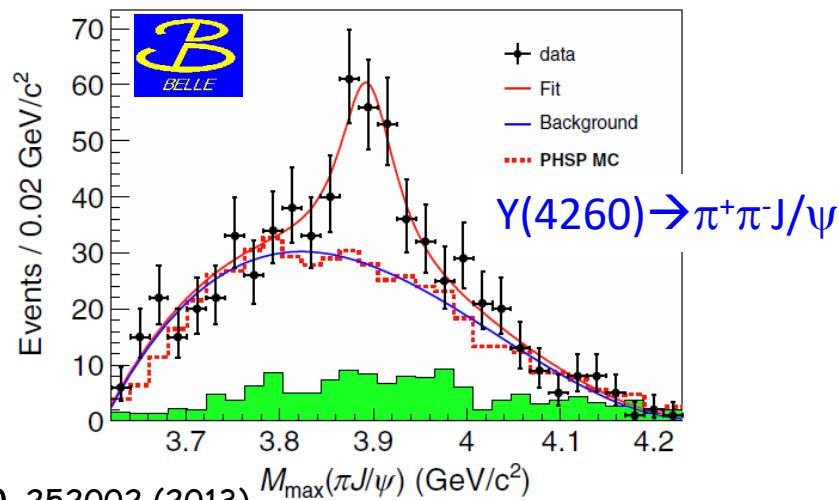
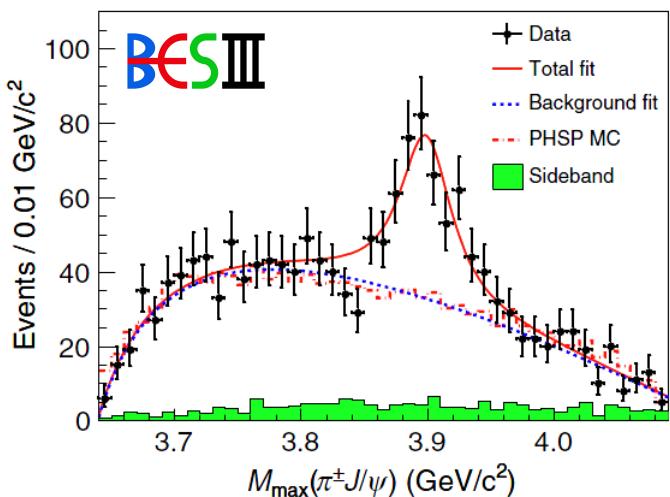
Z-states at BESIII

- Z_c states in hidden-charm final state
- Z_c states in open-charm final state

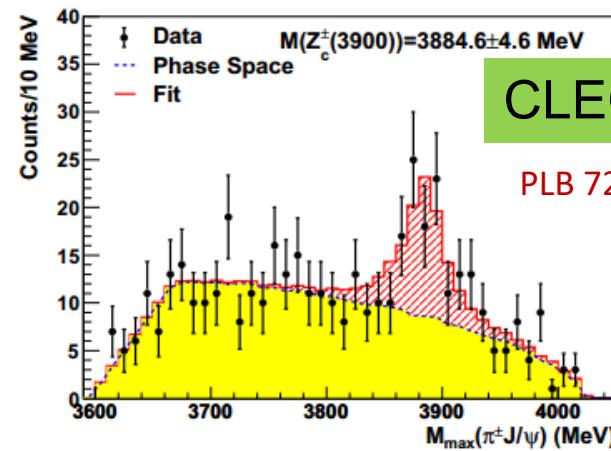


$Z_c(3900)$ – Solid signal

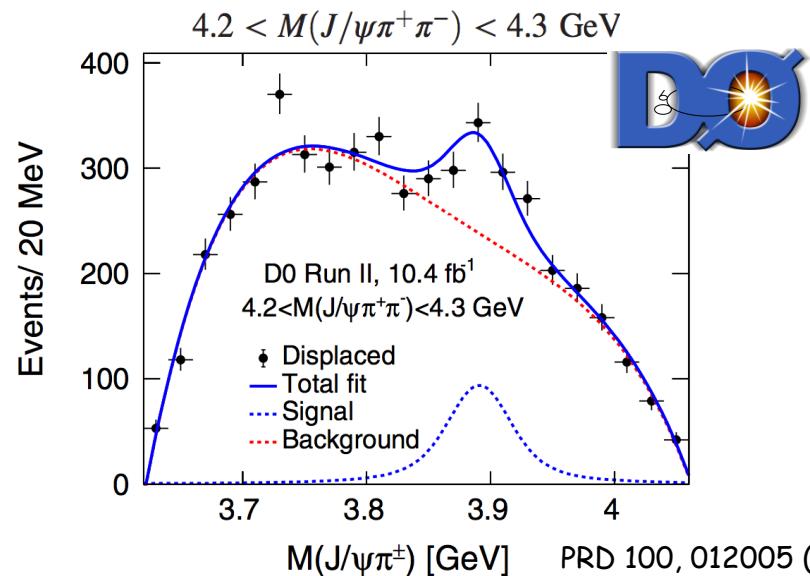
PRL 110, 252001 (2013)



PRL 110, 252002 (2013)



PLB 727(2013) 366

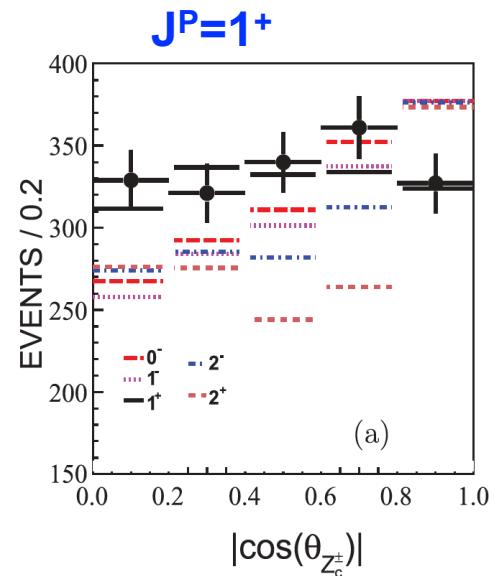
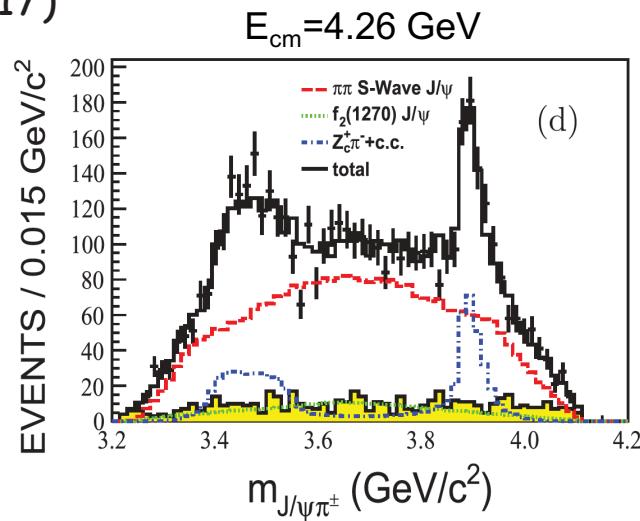
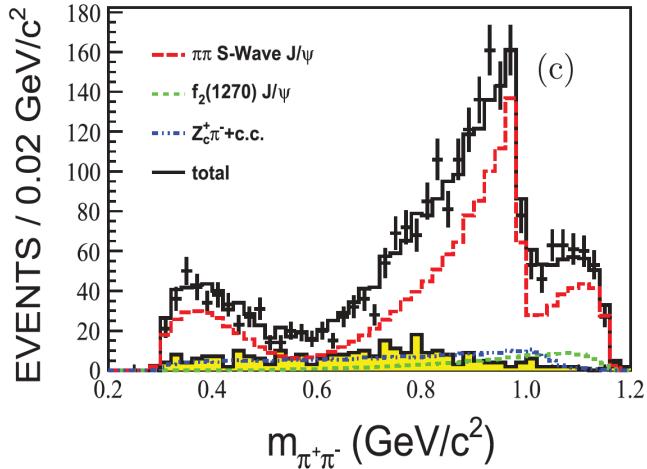


PRD 100, 012005 (2019)

$Z_c(3900)$ spin-parity

BESIII

PRL 119, 072001 (2017)

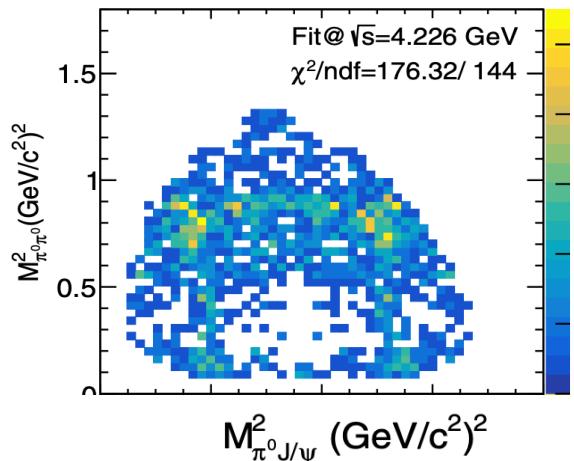
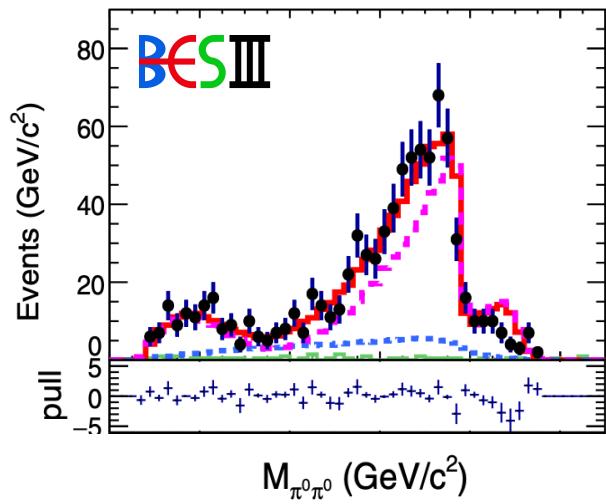
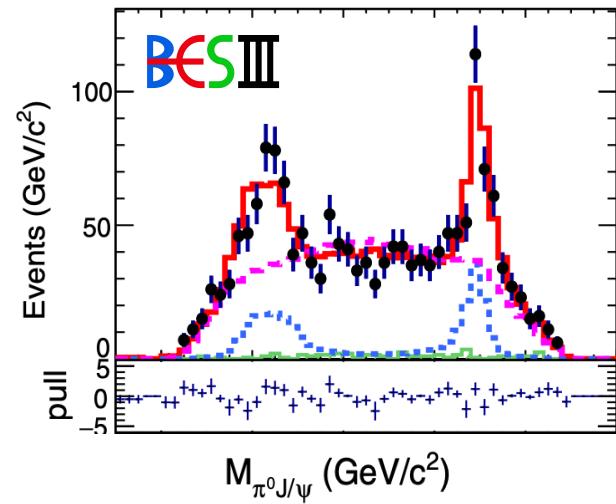


- With 1.92 fb^{-1} data @ 4.23 & 4.26 GeV, partial-wave-analysis is performed at BESIII
- $Z_c(3900)$ signal is significant, $\pi\pi$ amplitude is dominant by S-wave

Hypothesis	$\Delta(-2 \ln L)$	$\Delta(\text{ndf})$	Significance
1^+ over 0^-	94.0	13	7.6σ
1^+ over 1^-	158.3	13	10.8σ
1^+ over 2^-	151.9	13	10.5σ
1^+ over 2^+	96.0	13	7.7σ

$Z_c(3900)^0$ – Isospin partner

12.4 fb^{-1} $e^+e^- \rightarrow \pi^0\pi^0 J/\psi$



PRL 115, 112003 (2015)
PRD 102, 012009 (2020)

- Observation of isospin partner $Z_c(3900)^0$ with $> 10\sigma$ significance (1D & PWA)
- Mass= $(3893.0 \pm 2.3 \pm 3.2)$ MeV/c 2 , $\Gamma=(44.2 \pm 5.4 \pm 8.3)$ MeV
- Spin-parity $J^P=1^+$; agree with the charged candidate
- Cross section measurement suggest the decay $Y(4260) \rightarrow \pi Z_c(3900)$

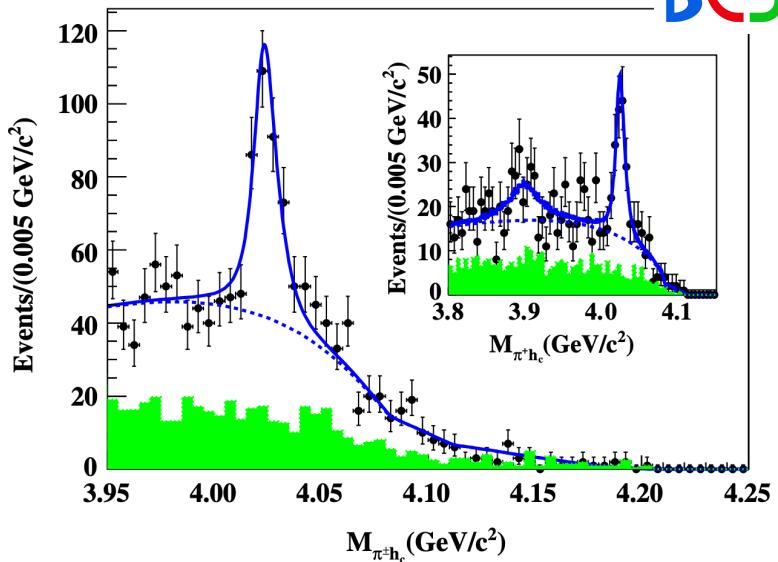
An isospin triplet established !



$Z_c(4020)$ & $Z_c(4020)^0$

PRL 111, 242001 (2013)

BESIII

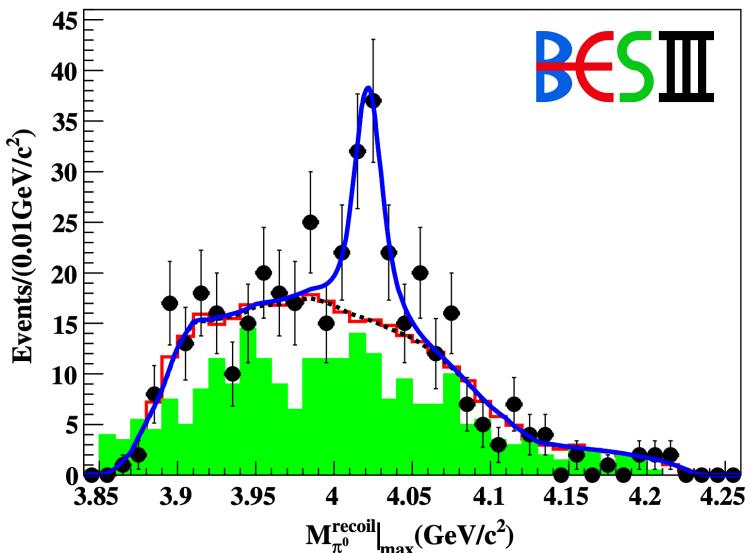


Charged $Z_c(4020)^\pm$ in $e^+e^- \rightarrow \pi^+\pi^- h_c$

- Mass = $(4022.9 \pm 0.8 \pm 2.7)$ MeV
- $\Gamma = (7.9 \pm 2.7 \pm 2.6)$ MeV
- Significance: $> 8.9\sigma$

PRL 113, 212002 (2014)

BESIII



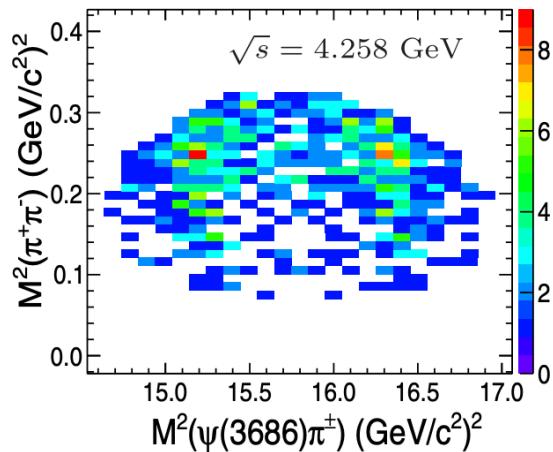
Neutral $Z_c(4020)^0$ in $e^+e^- \rightarrow \pi^0\pi^0 h_c$

- Mass = $(4023.9 \pm 2.2 \pm 3.8)$ MeV
- Γ : fixed to charged partner
- Significance: 5σ

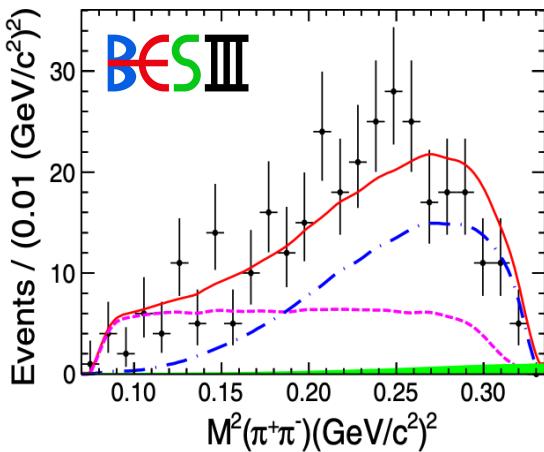
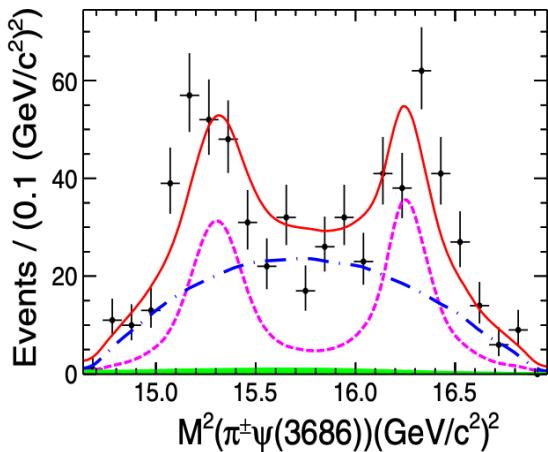
Excited state of $Z_c(3900)$?



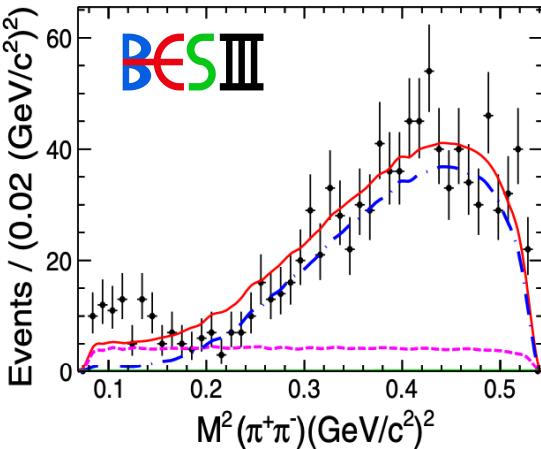
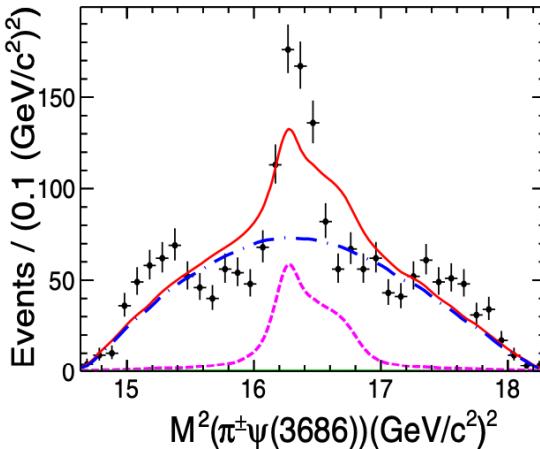
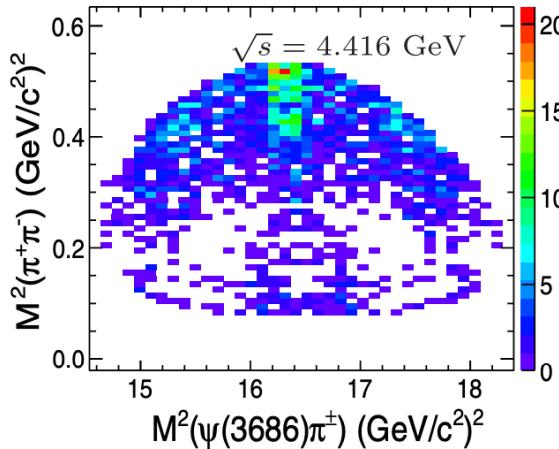
Z_c(4030)



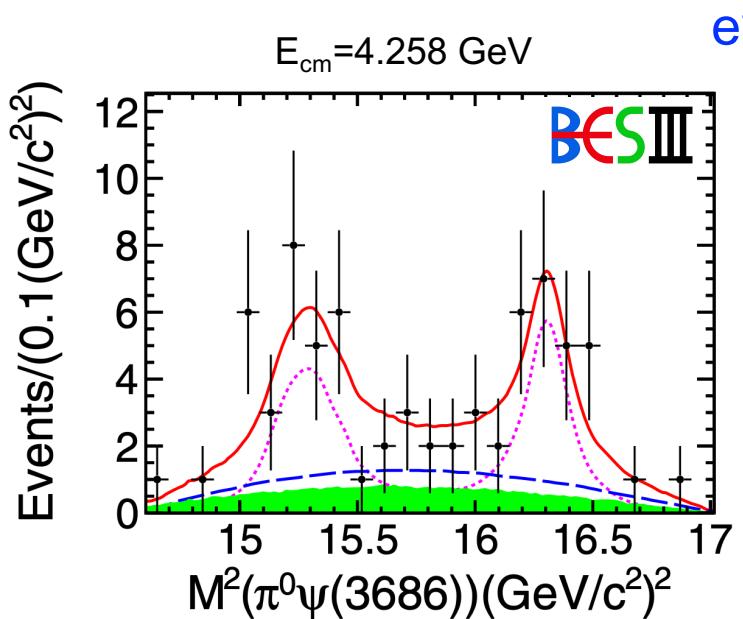
$e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$



Seems a structure around 4.03 GeV (fit not good); situation is complicated !

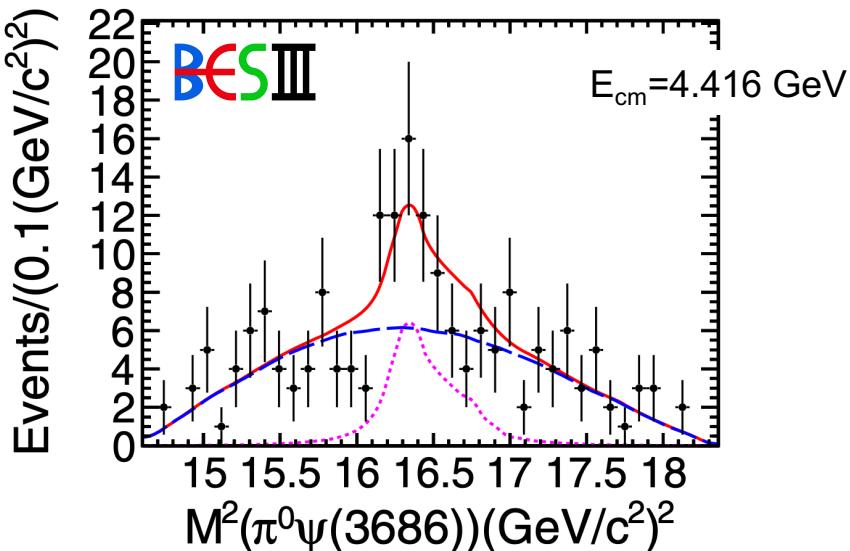


$Z_c(4030)^0$



$e^+e^- \rightarrow \pi^0\pi^0\psi(2S)$

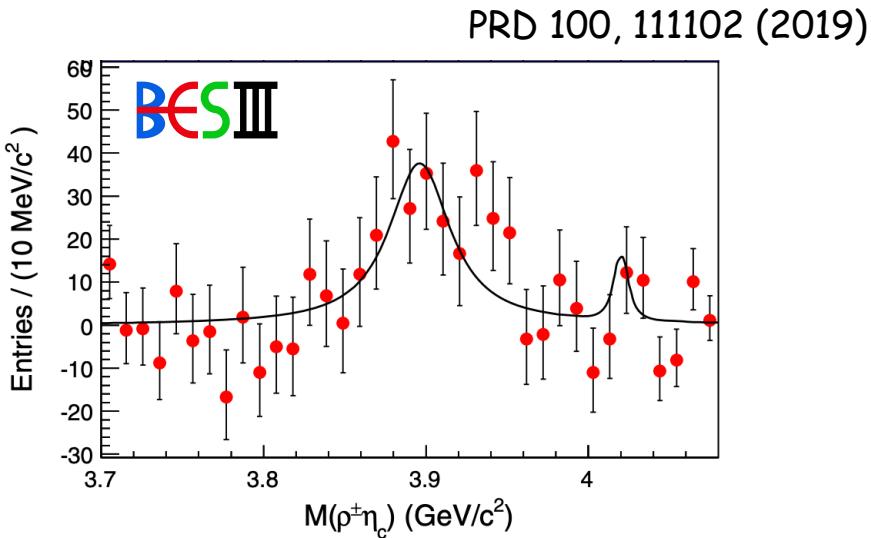
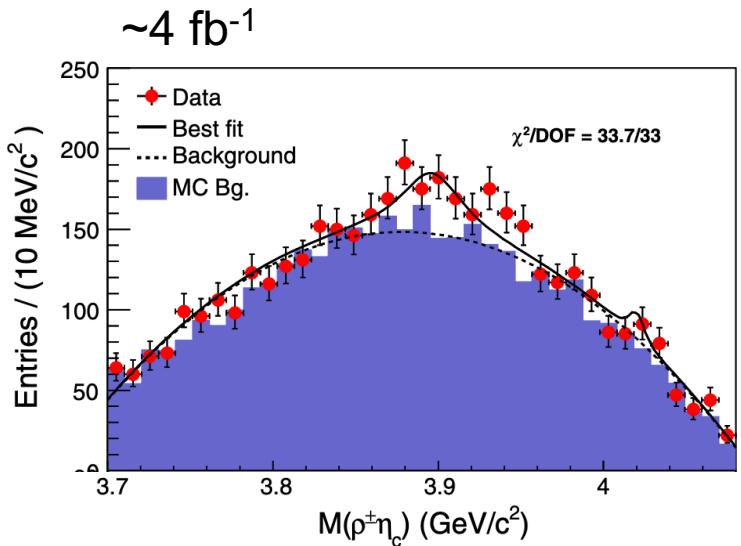
PRD 97, 052001 (2018)



- Very similar mass distributions observed in the neutral mode
- Seems a structure around 4.03 GeV (fit not good) !
- More complete PWA analysis is ongoing with much more data at BESIII

An isospin triplet ?

$Z_c(3900) \rightarrow \rho \eta_c$



- Search for Z-states in $e^+e^- \rightarrow \pi^+ Z_c^- \rightarrow \pi^+ \rho^- \eta_c$
- 4.2 σ evidence for $\pi^+ \pi^- \pi^0 \eta_c$
- 3.9 σ evidence for $Z_c(3900) \rightarrow \rho \eta_c$
- Yield comparable to $\pi J/\psi$

Relative ratio to $\pi J/\psi$

Ratio	Measurement	Tetraquark	Molecule
$R_{Z_c(3900)}$	2.3 ± 0.8 [29]	230^{+330}_{-140} [12]	$0.046^{+0.025}_{-0.017}$ [12]
		$0.27^{+0.40}_{-0.17}$ [12]	1.78 ± 0.41 [17]
		0.66 [13]	6.84×10^{-3} [18]
		0.56 ± 0.24 [14]	0.12 [19]
		0.95 ± 0.40 [15]	
		1.08 ± 0.88 [16]	
		1.28 ± 0.37 [17]	
		1.86 ± 0.41 [17]	
$R_{Z_c(4020)}$	< 1.2 [4]	$6.6^{+56.8}_{-5.8}$ [12]	$0.010^{+0.006}_{-0.004}$ [12]

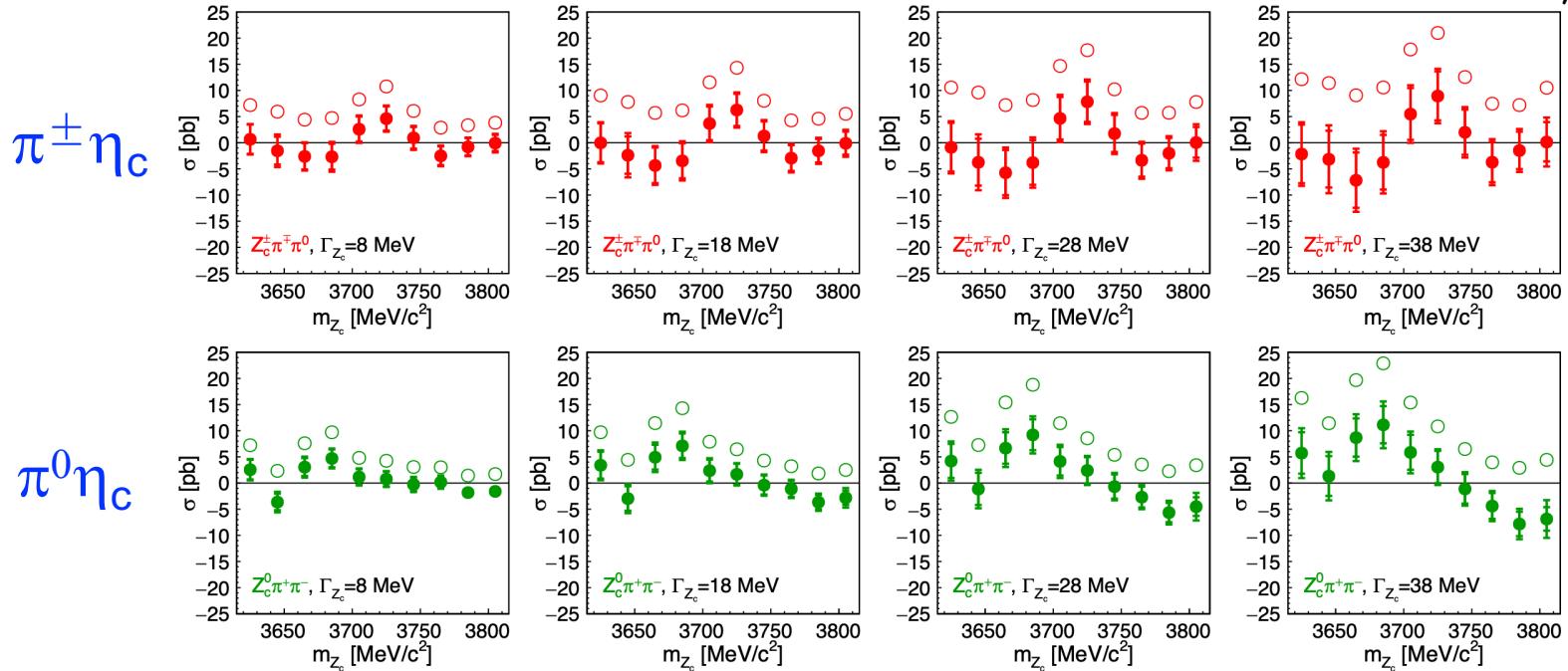
Multi-Channels

BESIII

$\sim 7 \text{ fb}^{-1}$

$e+e-\rightarrow\pi^+\pi^-\pi^0\eta_c / \pi^+\pi^-\eta_c / \gamma\pi^0\eta_c$

PRD 103, 032006 (2021)



- Only $e+e-\rightarrow\pi^+\pi^-\pi^0\eta_c$ events are observed with $>5.2\sigma$ significance
- Search for $Z\rightarrow\pi^\pm/\pi^0\eta_c$ and no signal was found ($<3\sigma$)
- Search in $e+e-\rightarrow\eta_c\eta\pi^+\pi^- / \pi^+\pi^-\chi_{cJ}$, no signal observed

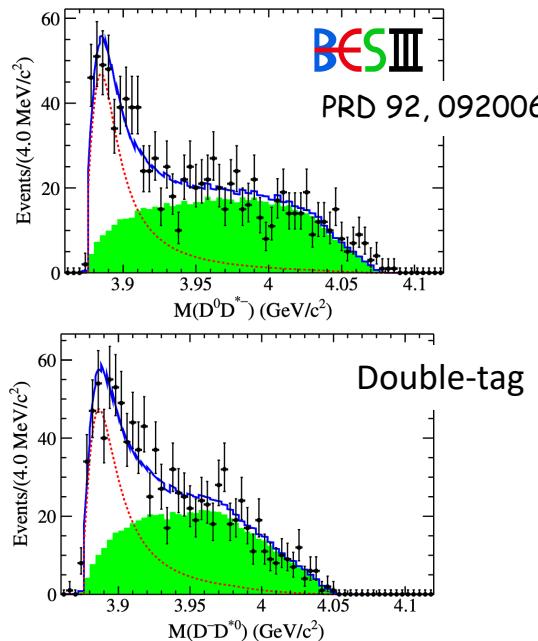
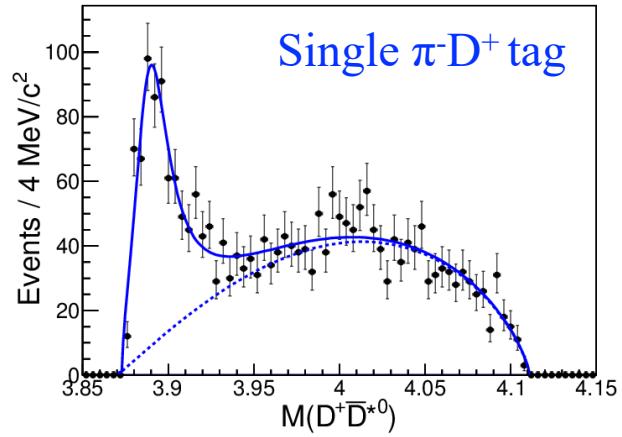
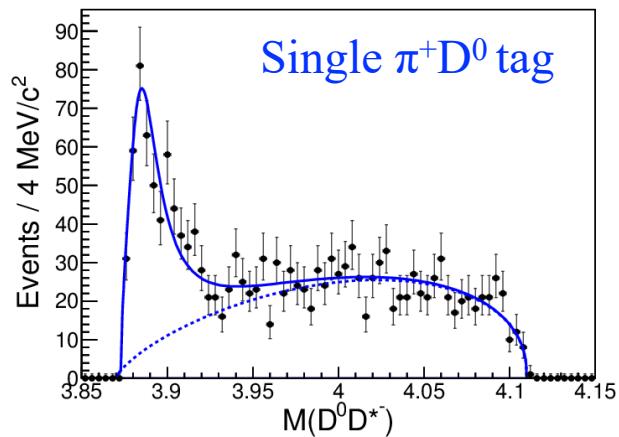
PRD 103, 032004 (2021)
arXiv: 2012.02682



$Z_c(3885)$

PRL 112, 022001 (2014)

BESIII



- Search for a near threshold enhancement $Z \rightarrow D^0 D^{*-} \& D^- D^{*0}$
- Mass and width similar to $Z_c(3900)$, could be same resonance!

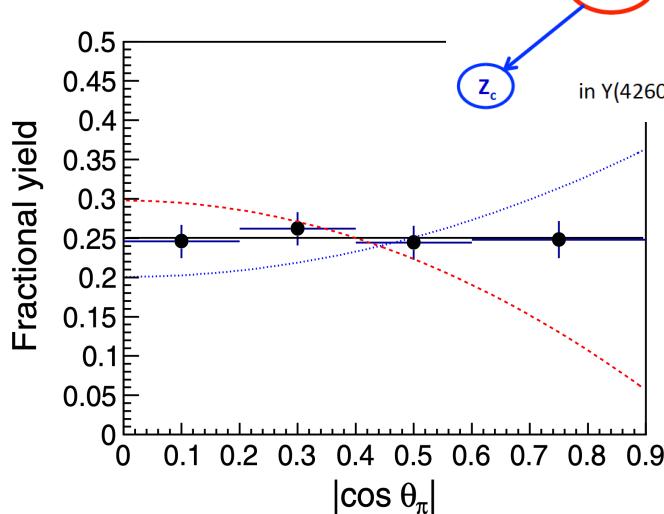
Pole position	$Z_c(3885) \rightarrow D\bar{D}^*$
Mass (MeV/c^2)	$3883.9 \pm 1.5 \pm 4.2$
Γ (MeV)	$24.8 \pm 3.3 \pm 11.0$
$\sigma \times \mathcal{B}$ (pb)	$83.5 \pm 6.6 \pm 22.0$

$$\frac{\Gamma[Z_c(3900) \rightarrow D\bar{D}^*]}{\Gamma[Z_c(3900) \rightarrow \pi J/\psi]} = 6.2 \pm 1.1_{\text{stat}} \pm 2.7_{\text{sys}}$$

$Z_c(3885)$

PRL 112, 022001 (2014)

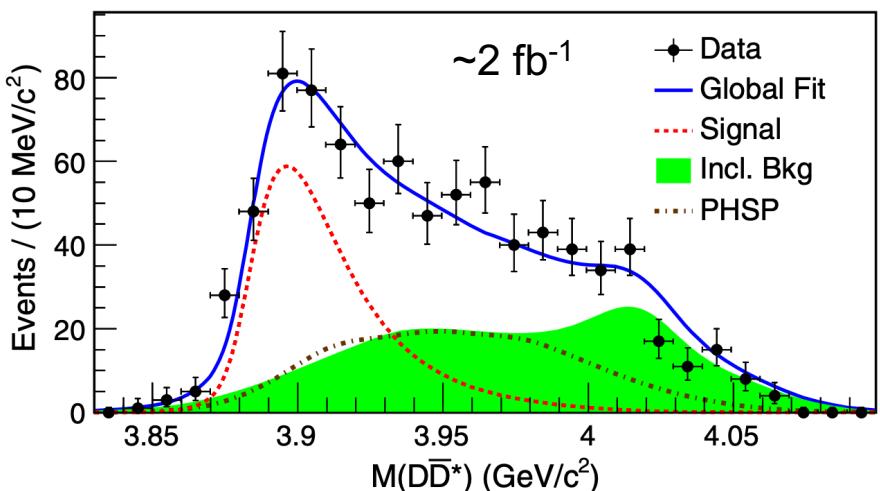
BESIII



PRL 115, 222002 (2015)

BESIII

$Z_c(3885)^0 \rightarrow D^+D^{*-} \& D^0D^{*0}$



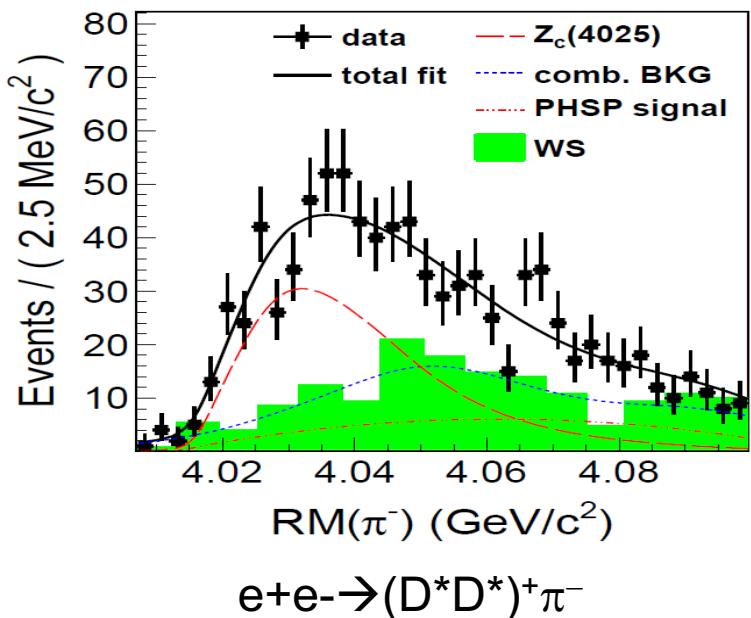
➤ Neutral partner observed with $>10\sigma$

State	$m_{\text{pole}}(\text{MeV}/c^2)$	$\Gamma_{\text{pole}}(\text{MeV})$
$Z_c(3885)^+$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
$Z_c(3885)^+$	$3881.7 \pm 1.6 \pm 2.1$	$26.6 \pm 2.0 \pm 2.3$
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$

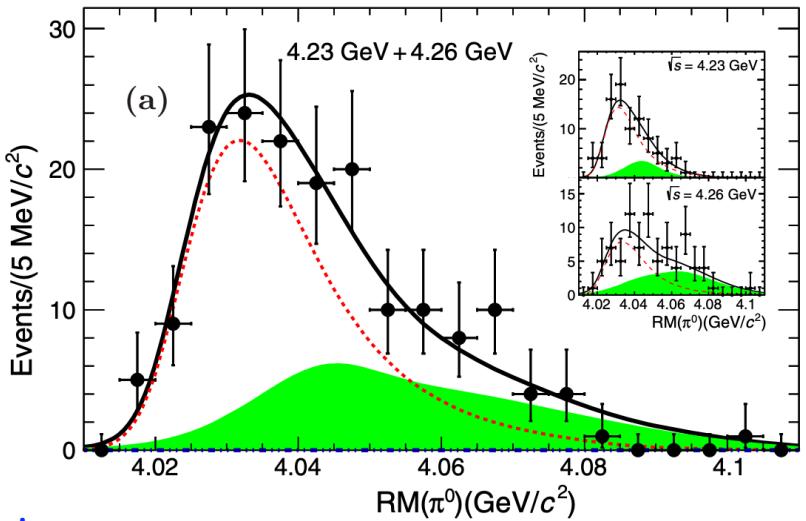
Isospin triplet established!

$Z_c(4025)$

BESIII PRL 112, 132001 (2014)



BESIII PRL 115, 182002 (2015)



Isospin triplet

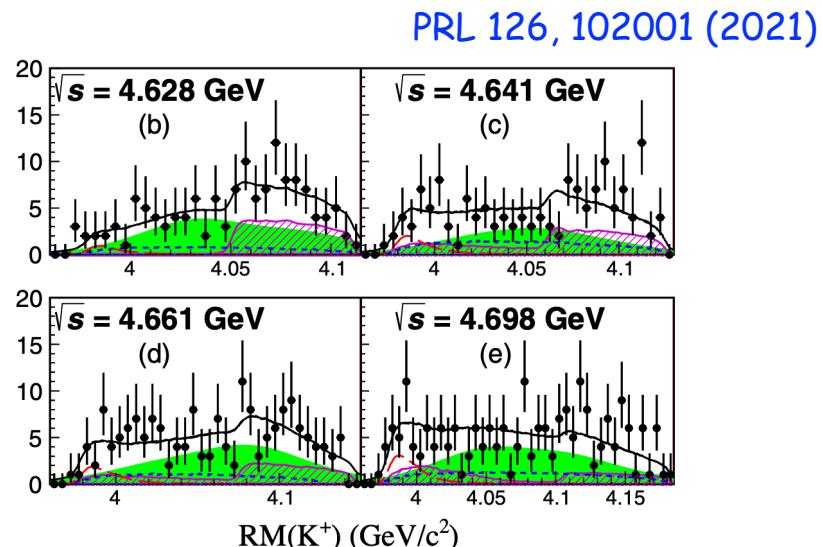
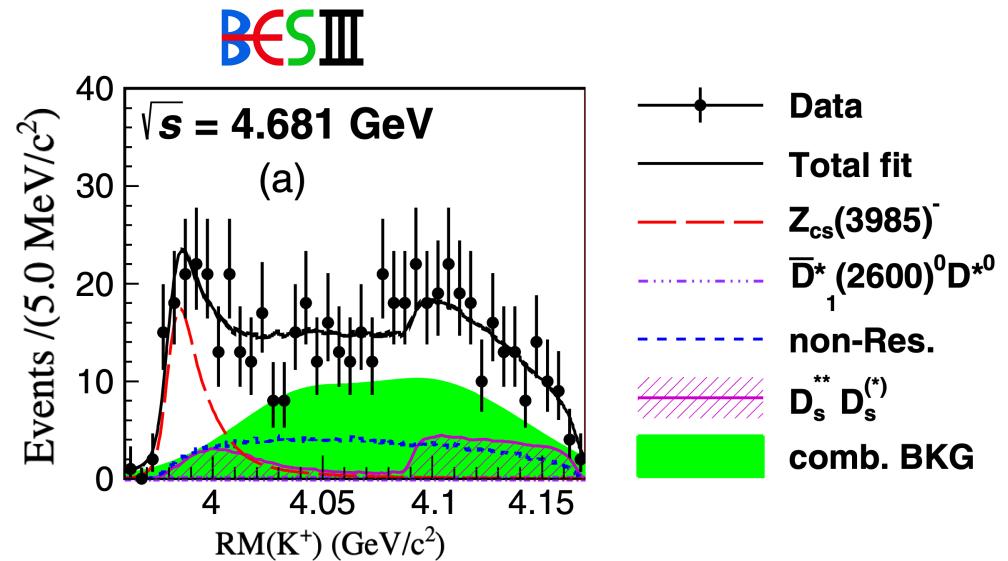
Charged $Z_c(4025) \rightarrow (D^*D^*)^\pm$

- $M = (4026.3 \pm 2.6 \pm 3.7) \text{ MeV}$
- $\Gamma = (24.8 \pm 5.6 \pm 7.7) \text{ MeV}$
- Significance: $> 10\sigma$

Neutral $Z_c(4025)^0 \rightarrow (D^*D^*)^0$

- $M = (4025.5^{+2.0}_{-4.7} \pm 3.1) \text{ MeV}$
- $\Gamma = (23.0 \pm 6.0 \pm 1.0) \text{ MeV}$
- Significance: 7.4σ

$Z_{\text{cs}}(3985)$

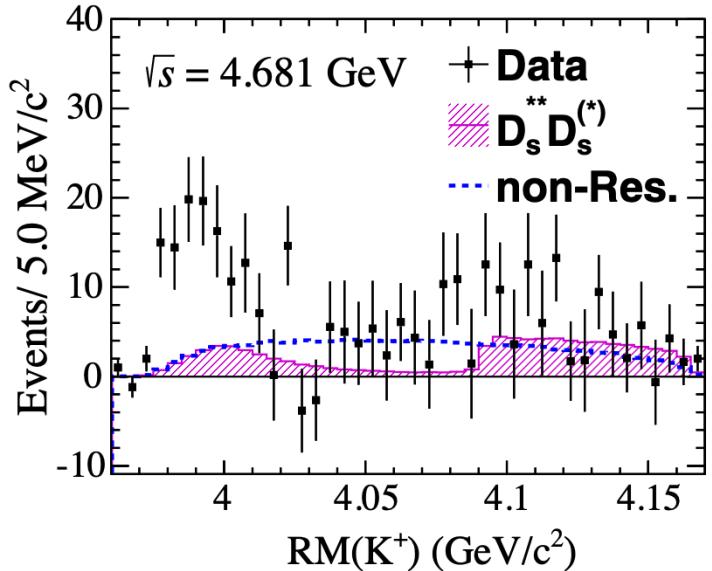


- Search for the Z-state with strange quark in $e^+e^- \rightarrow K^+(D_s D^*/D_s^* D^-)$
- A near threshold structure was observed at BESIII [See Y. Xu's talk]
- $M = 3982.5^{+1.8}_{-2.6} \pm 2.1 \text{ MeV}/c^2; \Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0 \text{ MeV}$

Partner of $Z_c(3900)$ with s quark?

$Z_{\text{cs}}(3985)$

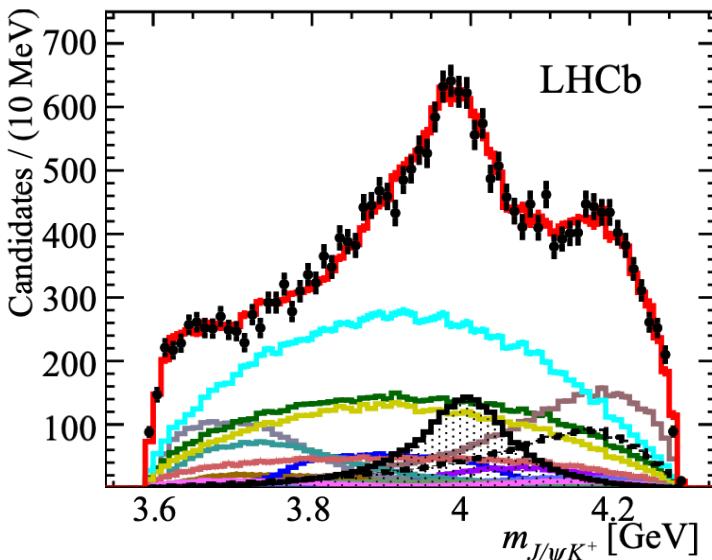
BESIII PRL 126, 102001 (2021)



BESIII $e^+e^- \rightarrow K^+(D_s D^*/D_s^* D)^-$

- Mass: $(3982.5^{+1.8}_{-2.6} \pm 2.1) \text{ MeV}/c^2$
- Width: $(12.8^{+5.3}_{-4.4} \pm 3.0) \text{ MeV}$
- Open charm final state

arXiv:2103.01803



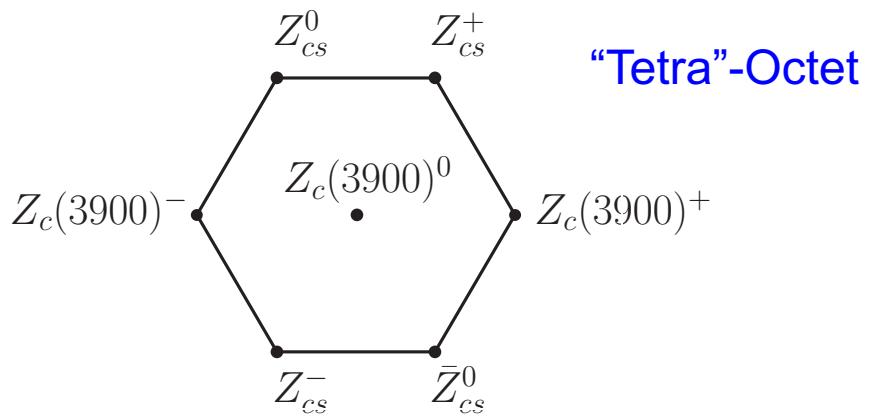
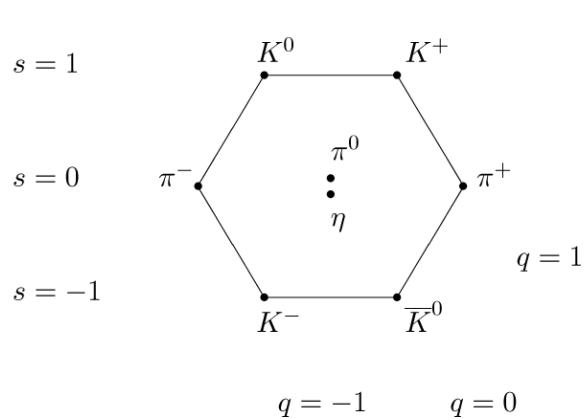
LHCb $Z_{\text{cs}}(4000)$ in $B^+ \rightarrow \phi(J/\psi K^+)$

- Mass: $(4003^{+6^{+4}}_{-14}) \text{ MeV}/c^2$
- Width: $(131 \pm 15 \pm 26) \text{ MeV}$
- $J^P=1^+$
- Hidden charm final state

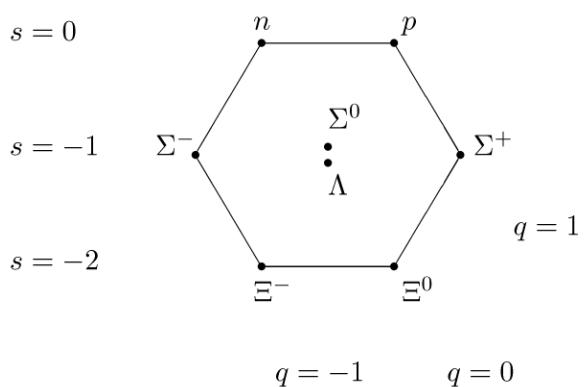
Same state or not ?



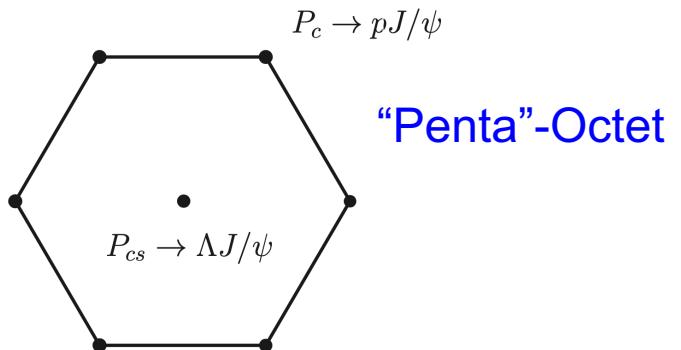
“Eightfold Way”



1960s



2020s





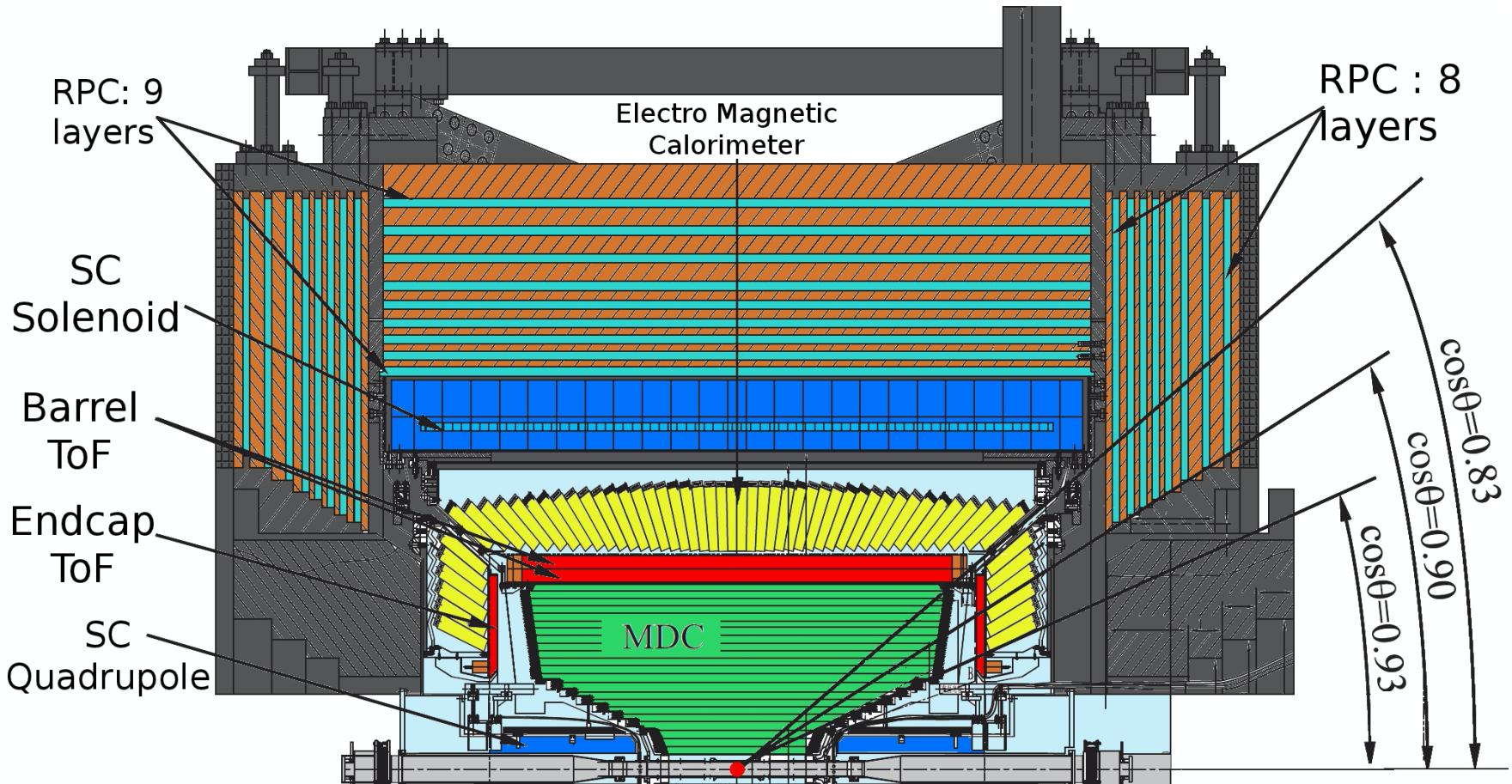
Summary

- BESIII is quite active and productive in the study of XYZ particles.
- For X(3872), unique production & clean environment allow us to explore more...
- For charged Z-states, new observation of $Z_{cs}(3985)$ and a series of search & measurements
- 6 decades of development → A new era of spectroscopy !

Thanks for your attention !

BESIII experiment

A 4π detector





Backup