XYZ at BESIII

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On behalf of BESIII collaboration

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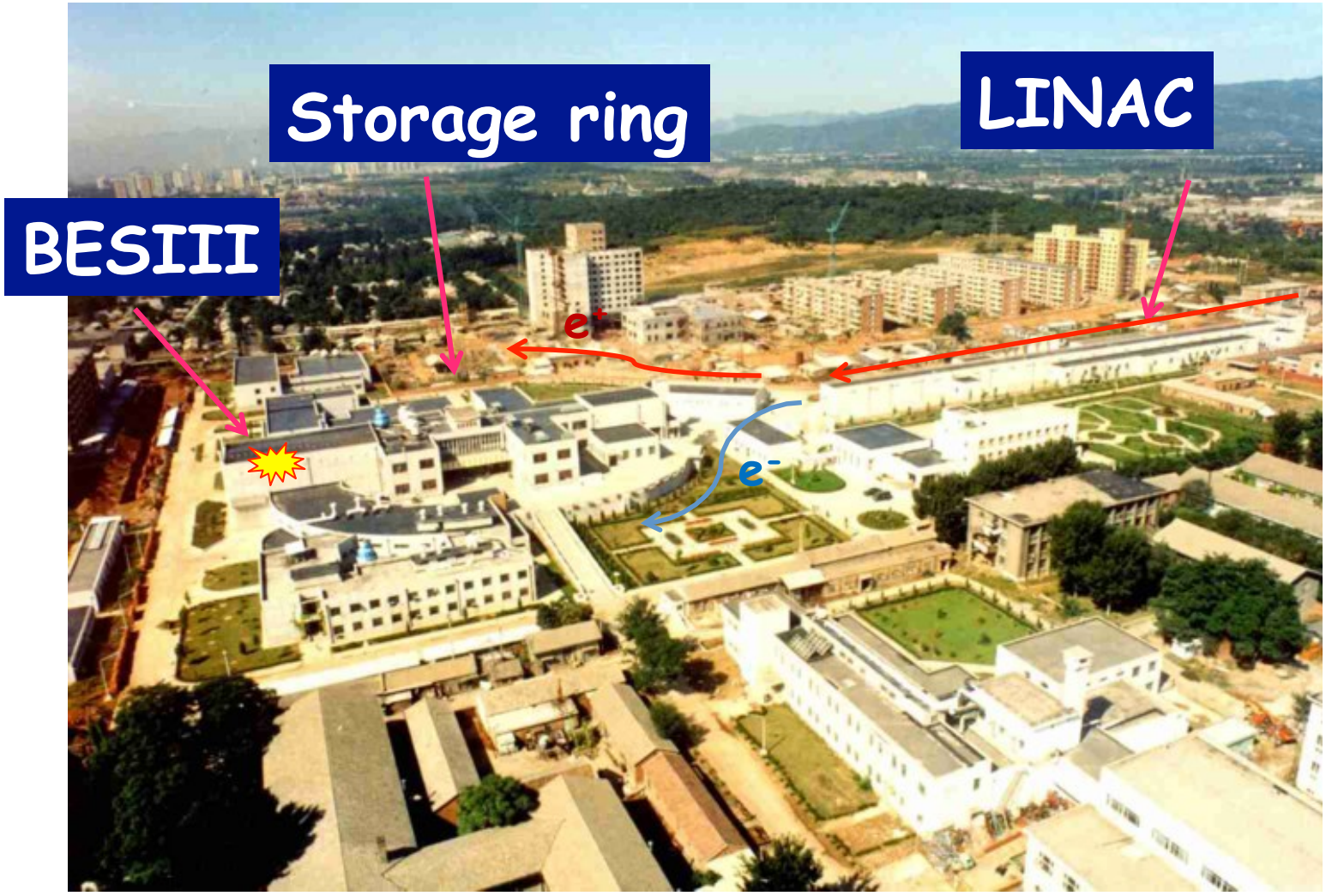
Outline

- Introduction
  - BEPCII and BESIII
  - BESIII data samples
- $Y(1^{--})$ states
  - $Y\rightarrow\pi^+\pi^- J/\psi$ (ψ'), $Y\rightarrow\pi^+\pi^- h_c$, $Y\rightarrow\omega\chi_{cJ}$, $Y\rightarrow\pi^+ D^0 D^{*-}$
  - Simultaneous fit of all the above channels
- A quick view of the Zc states in BESIII
  - Evidence of $Zc(3900)\rightarrow\rho\eta_c$
  - Determination of J^p of Zc(3900)
  - Structures in $e^+e^-\rightarrow\pi^+\pi^-\psi'$
- Observation of $e^+e^-\rightarrow\gamma X(3872)$, $X(3872)\rightarrow\pi^+\pi^- J/\psi$
- Summary

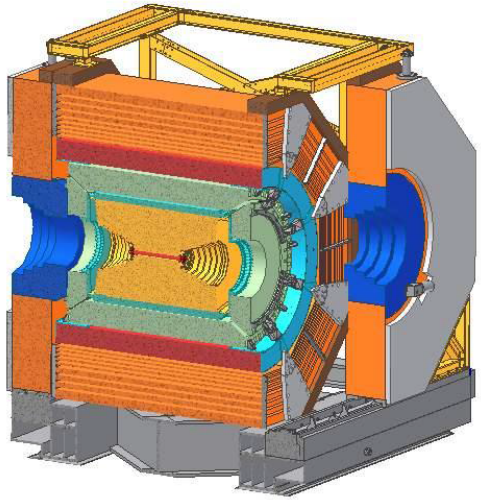
Beijing Electron and Positron Collider(BEPCII)

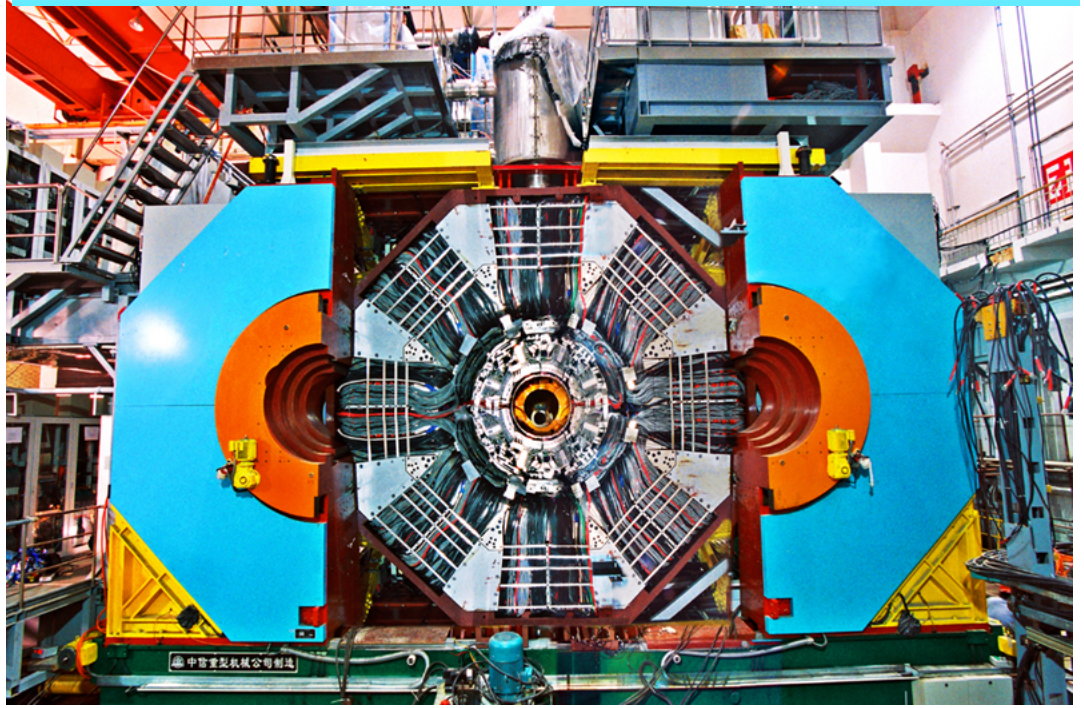


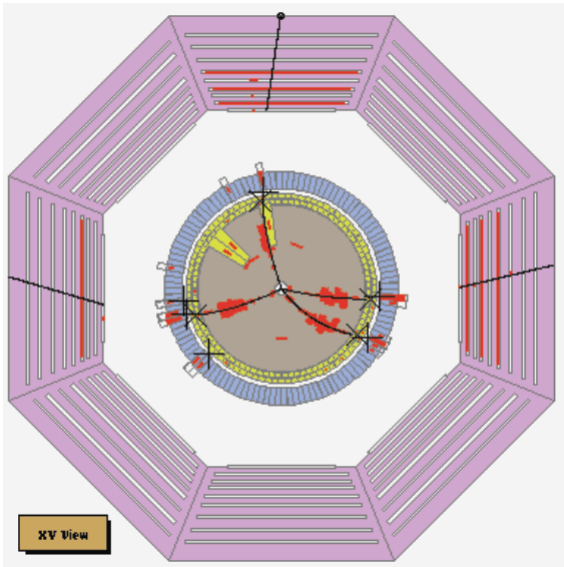
Beam energy: 1~2.3GeV

Beijing Spectrometer (BESIII)

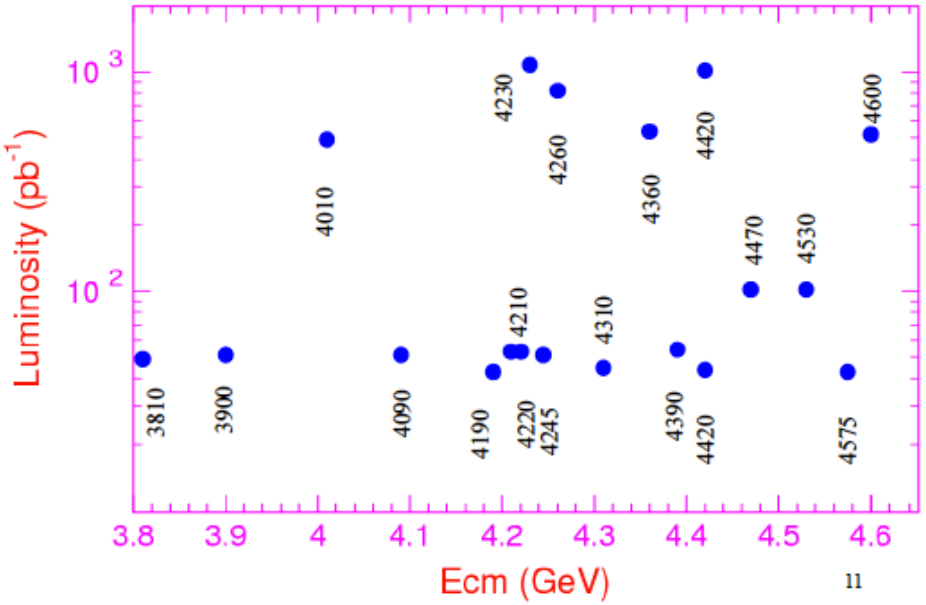
- Inner to Outside：
- ✓ Main Drift chamber(MDC),
- ✓ Time of flight System(TOF),
- ✓ Electromagnetic Calorimeter(EMC),
- ✓ Solenoid super-conducting magnet(SSM),
- ✓ Muon chamber(MUC)
- Acceptance: 93% of 4π

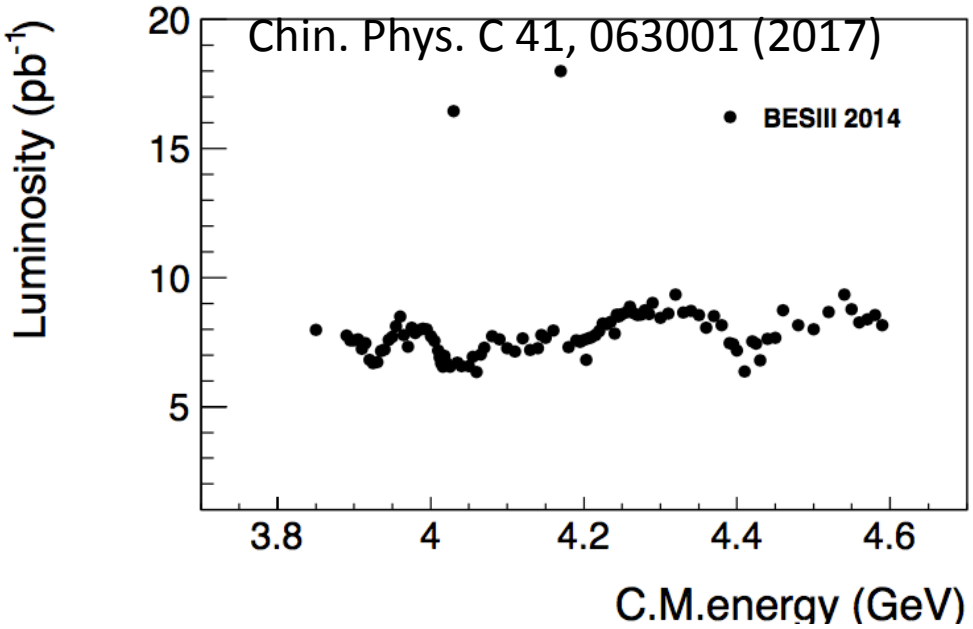






BESIII data sets for XYZ study





XYZ data

- 5 fb^{-1} e^+e^- collision data event in open charm region from 3.8-4.6GeV.
- Massive events on several special energy points: Such as
  - 4.26GeV, 828pb^{-1}
  - 4.36GeV, 544pb^{-1}
  - 4.23GeV, 1100pb^{-1}

R-scan data

- Dozens of energy points with luminosity < 20 pb^{-1}
- Initially taken for R study, can also help the XYZ study

Part I:

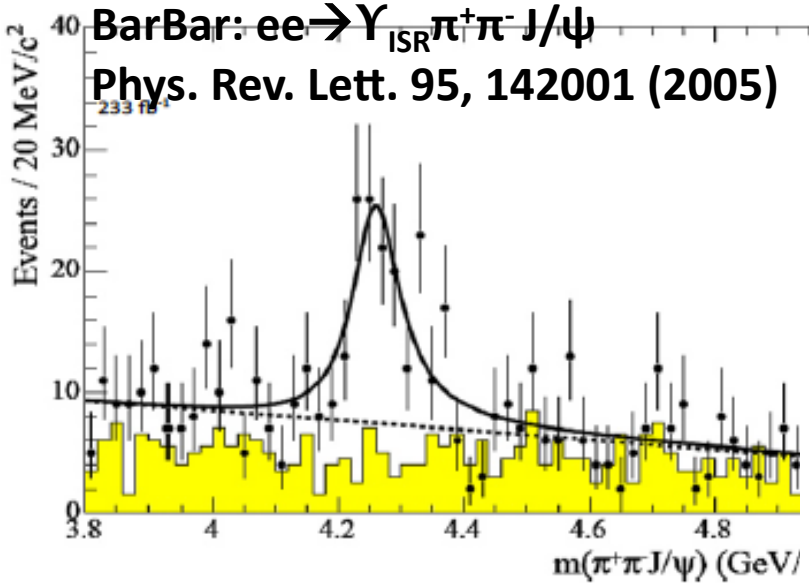
$e^+e^- \rightarrow \psi(1^{--})$ (well estabilished)→…

or

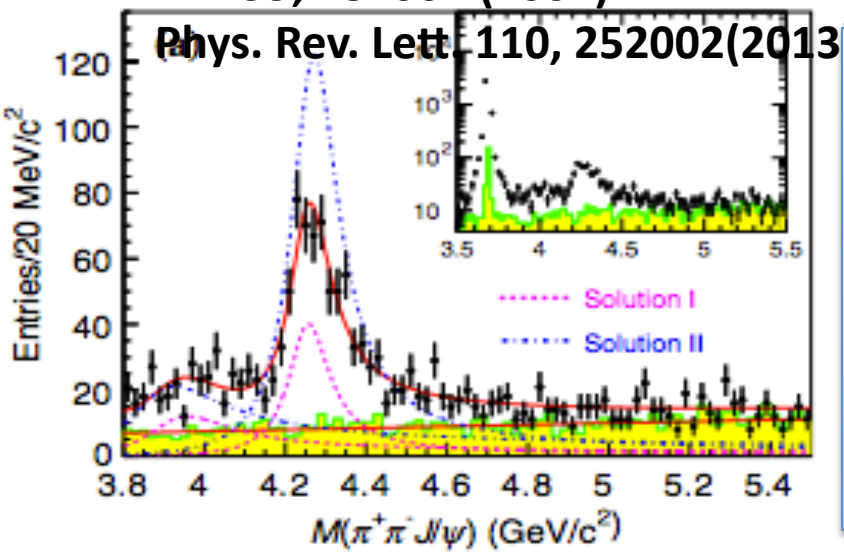
$e^+e^- \rightarrow Y(1^{--})$ (not so well estabilished)→…

Y(4260) & Y(4360): some history

BarBar: ee→$\Upsilon_{ISR}\pi^+\pi^- J/\psi$
Phys. Rev. Lett. 95, 142001 (2005)

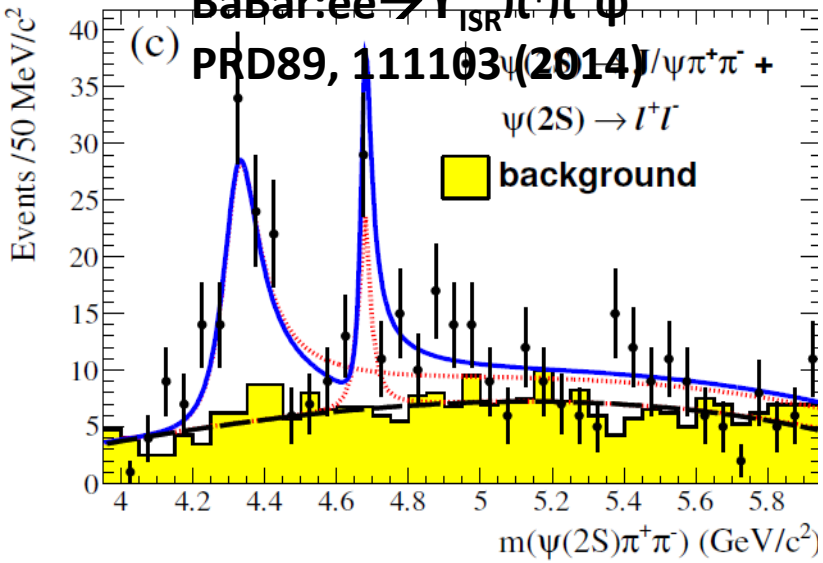


Belle: ee→$\Upsilon_{ISR}\pi^+\pi^- J/\psi$
PRL 99, 182004 (2007)
Phys. Rev. Lett. 110, 252002(2013)

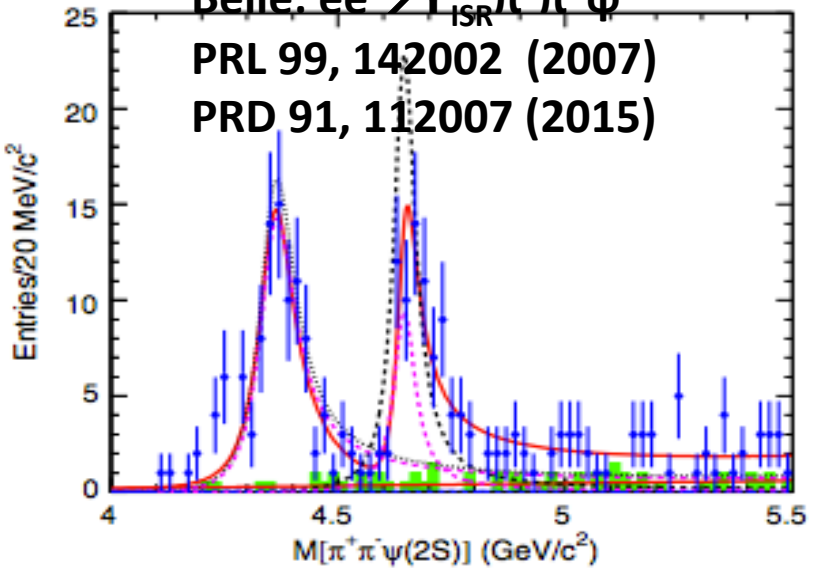


Y(4260)
PDG value
Without BES
Result:
Mass=
4251±9 MeV
width=
120±12 MeV

BaBar:ee→$\Upsilon_{ISR}\pi^+\pi^-\psi'$
PRD89, 111103 (2014)

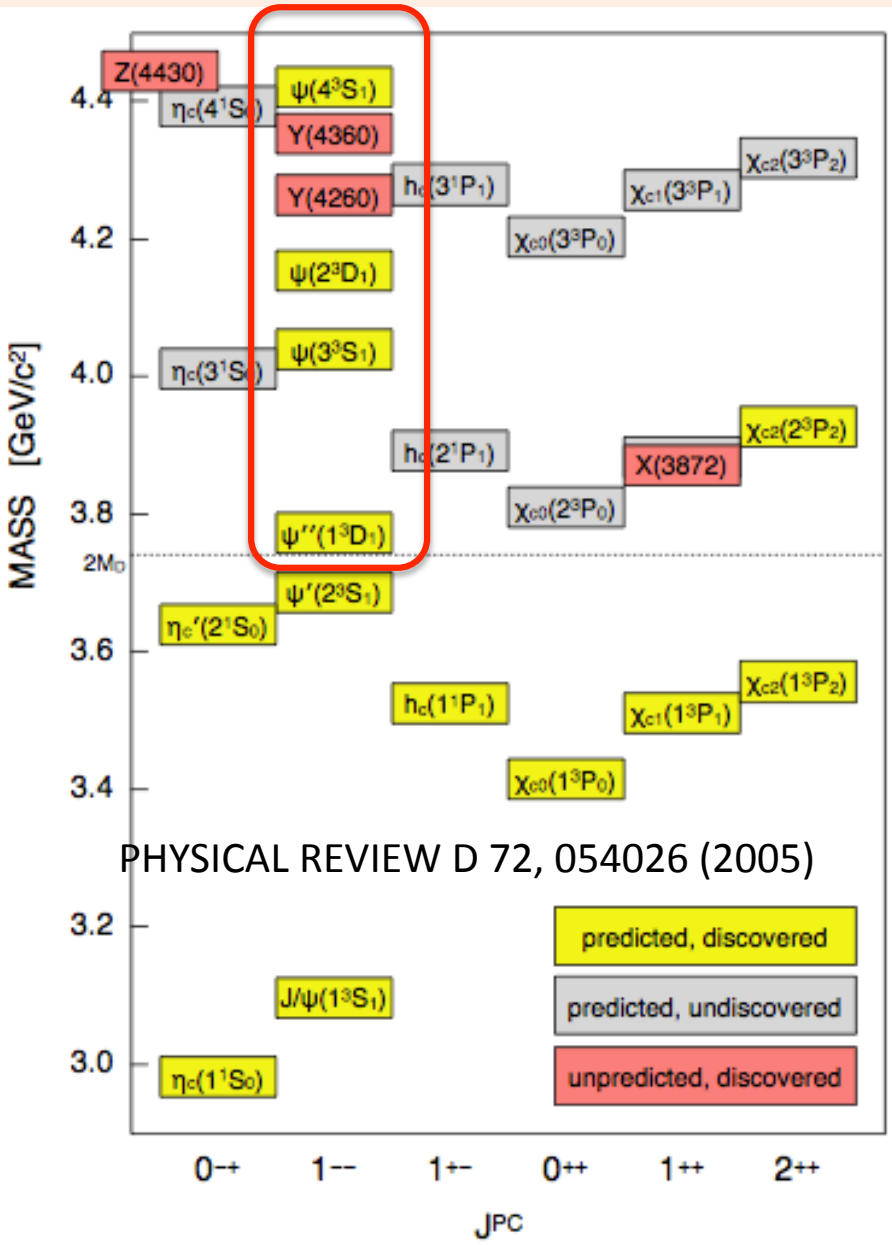


Belle: ee→$\Upsilon_{ISR}\pi^+\pi^-\psi'$
PRL 99, 142002 (2007)
PRD 91, 112007 (2015)



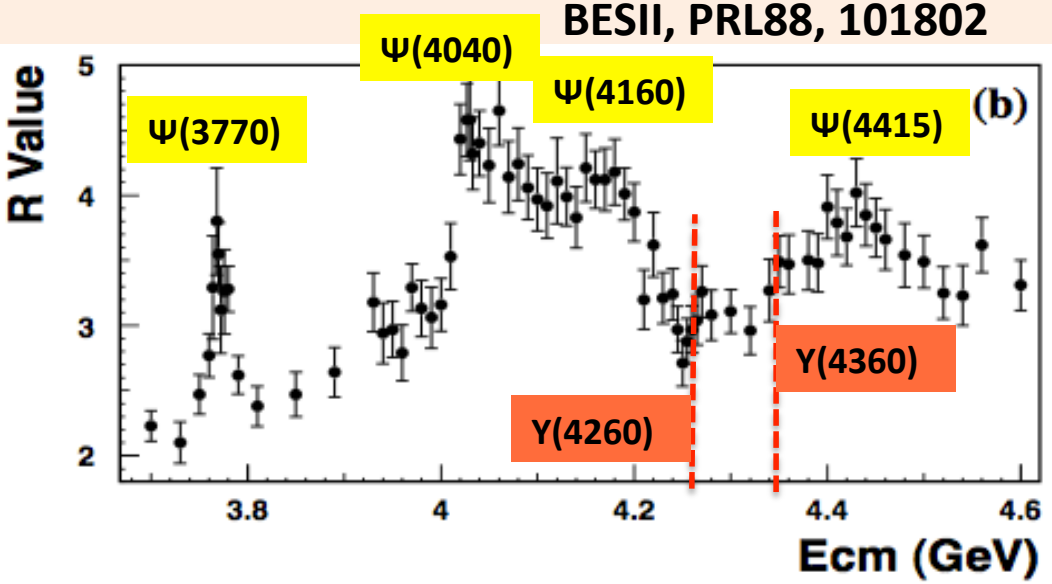
Y(4360)
PDG mass
4346±6 MeV
PDG width
102±10 MeV

The exotics with Y(1^{--}) states



PHYSICAL REVIEW D 72, 054026 (2005)

BESII, PRL88, 101802



❑Y(4260), Y(4360) are not predicted by the Potential model:

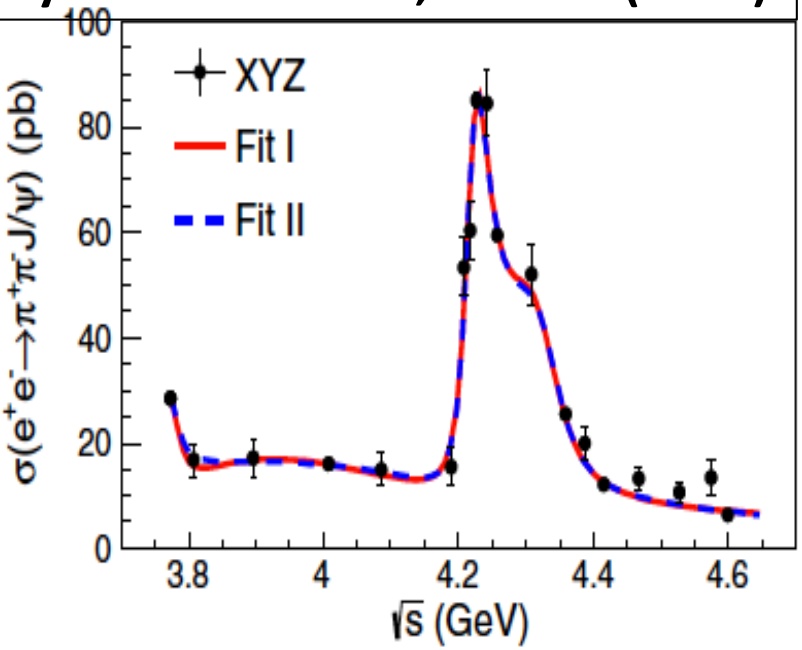
"Y" are observed in the ISR process, they should be 1^{--} states.

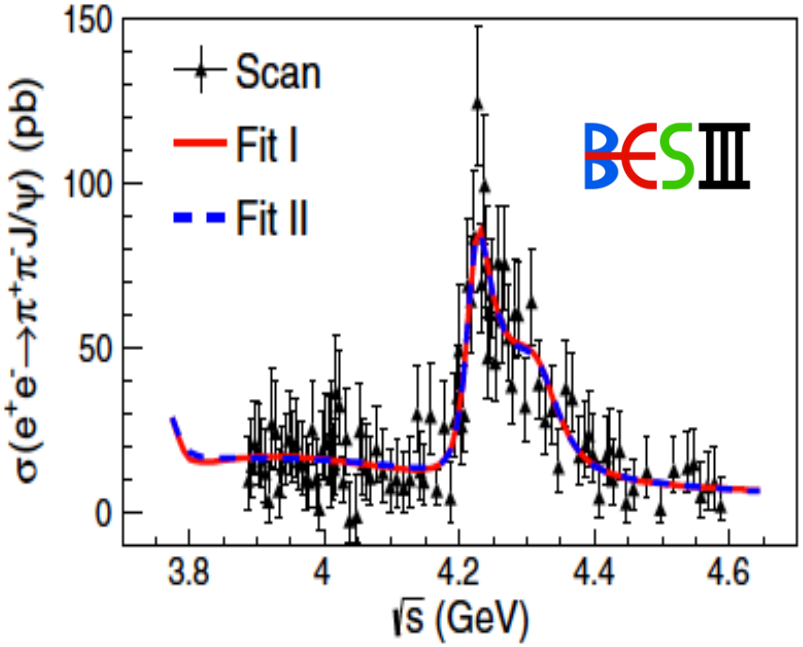
All the predicted 1^{--} charmonium are already discovered (ψ(4040), ψ(4160), ψ(4415) and showing as peaks in R value.

→No place for Y(4260), Y(4360). Some of them might not be charmonium.

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

Phys. Rev. Lett. 118, 092001 (2017)

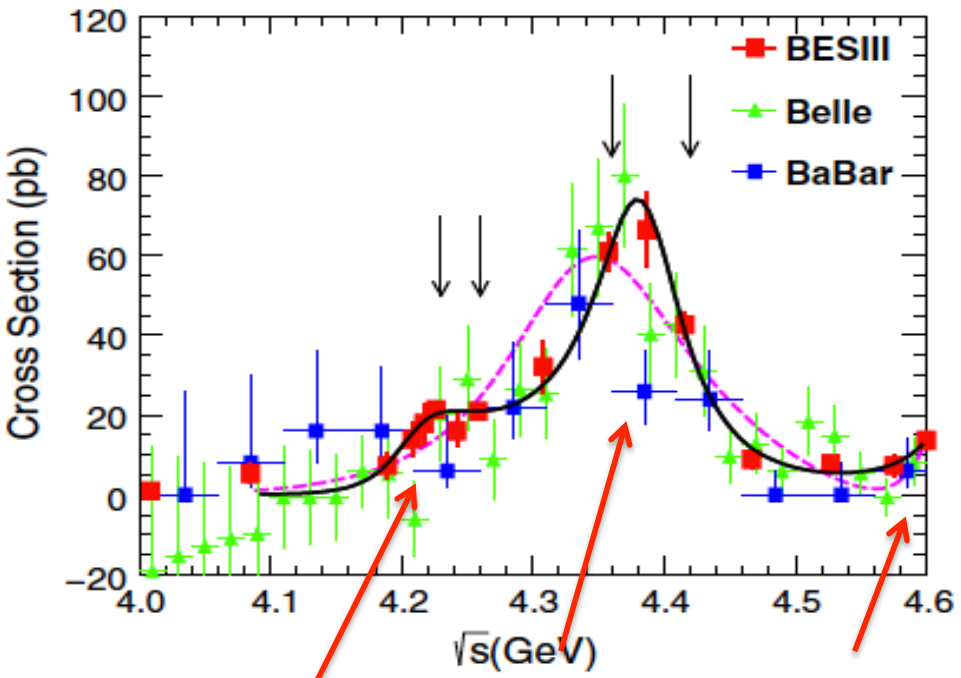




- Simultaneous fit to XYZ data (left) and R-scan data (right)
- Coherent sum of two Breit-Wigner like structure plus one incoherent ψ(3770)
  - M = (4222.0±3.1±1.4) MeV, Γ = (44.1±4.3±2.0) MeV ,
    Lower and narrower than previous Y(4260) PDG value
  - M = (4320.0±10.4±7) MeV, Γ = (101.4±25±10) MeV ,
    a little bit lower than Y(4360) PDG
- Compare with one Breit-Wigner fit, the significance of the second Breit-wigner is 7.6σ
- Is this Y(4260) + Y(4360) ? The first observation of Y(4360)→$\pi^+\pi^- J/\psi$?
- Y(4008) is not confirmed

$e^+e^- \rightarrow \pi^+\pi^-\psi'$

PRD 96, 032004 (2017)



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

Y(4220) with 5.8σ

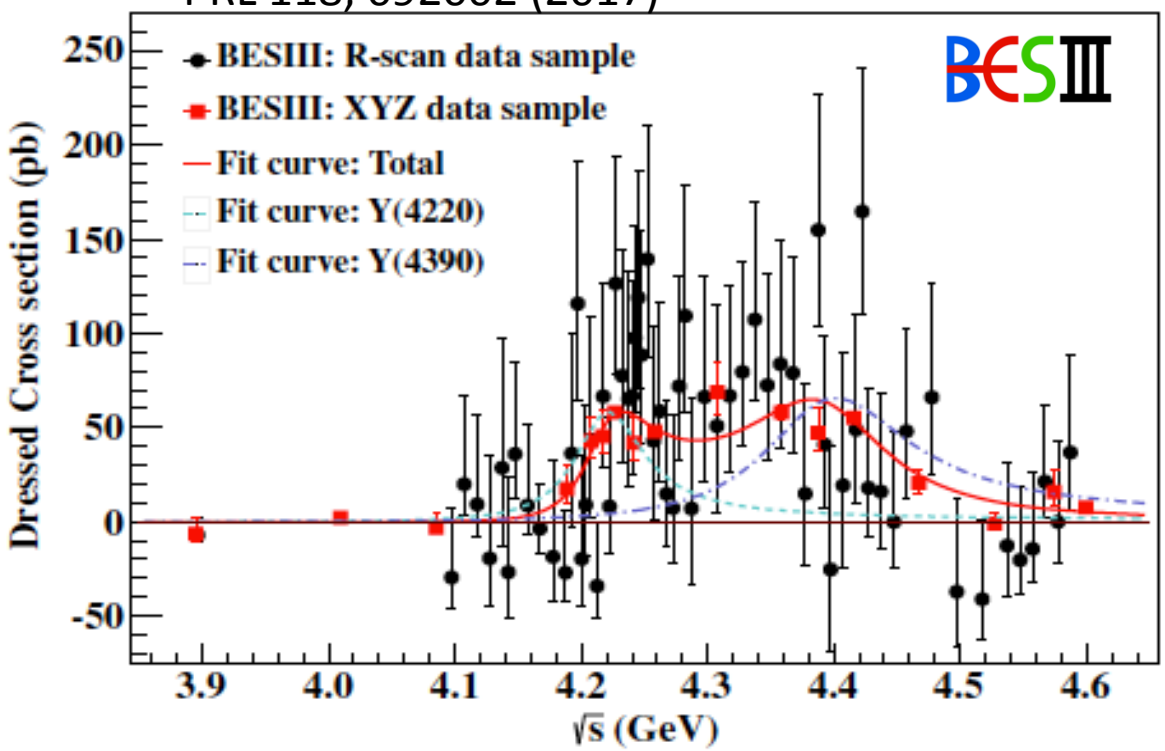
Y(4360)

Tail of Y(4660)

- **Cross section of $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ has been measured at 16 energy points from 4.008 to 4.600 GeV.**
- **Y(4220) is needed(5.8σ)**

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

PRL 118, 092002 (2017)

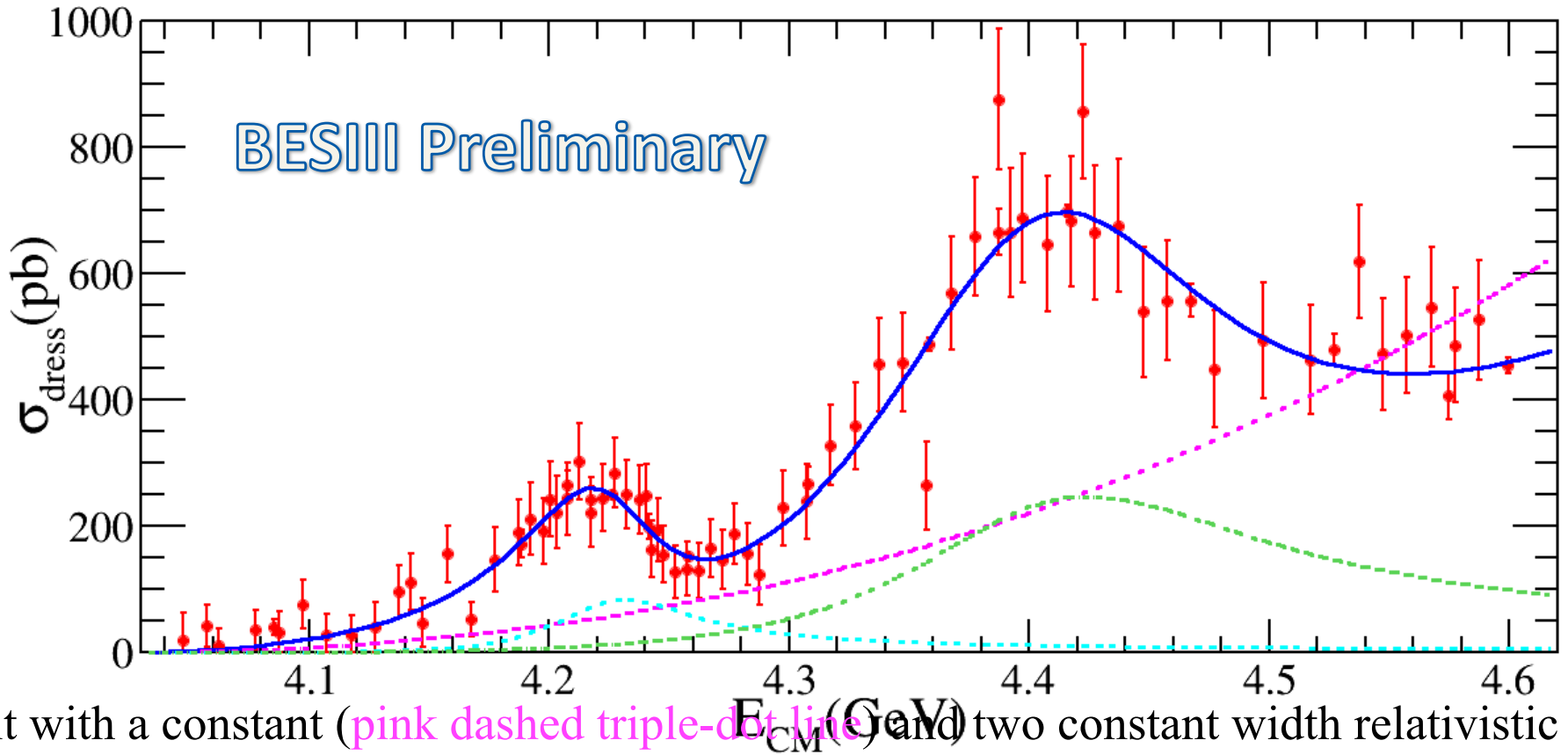


- Fitted with coherent sum of two Breit-Wigner like structue
  - $M_1=4218.4^{+5.5}_{-4.5}\pm0.9$ MeV/c^2, $\Gamma_1=66.0^{+12.3}_{-8.3}\pm0.4$ MeV → Y(4220)
  - $M_2=4391.5^{+6.3}_{-6.8}\pm1.0$ MeV/c^2, $\Gamma_2=139.5^{+16.2}_{-20.6}\pm0.6$ MeV → Y(4390)
- The Y(4220) here is consistent with the states observed in $\pi^+\pi J/\psi$ around 4222MeV

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

$$\sigma_{dress} = \frac{N^{obs}}{\mathcal{L}(1+\delta^r)B(D^0 \to K^-\pi^+)\varepsilon}$$

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



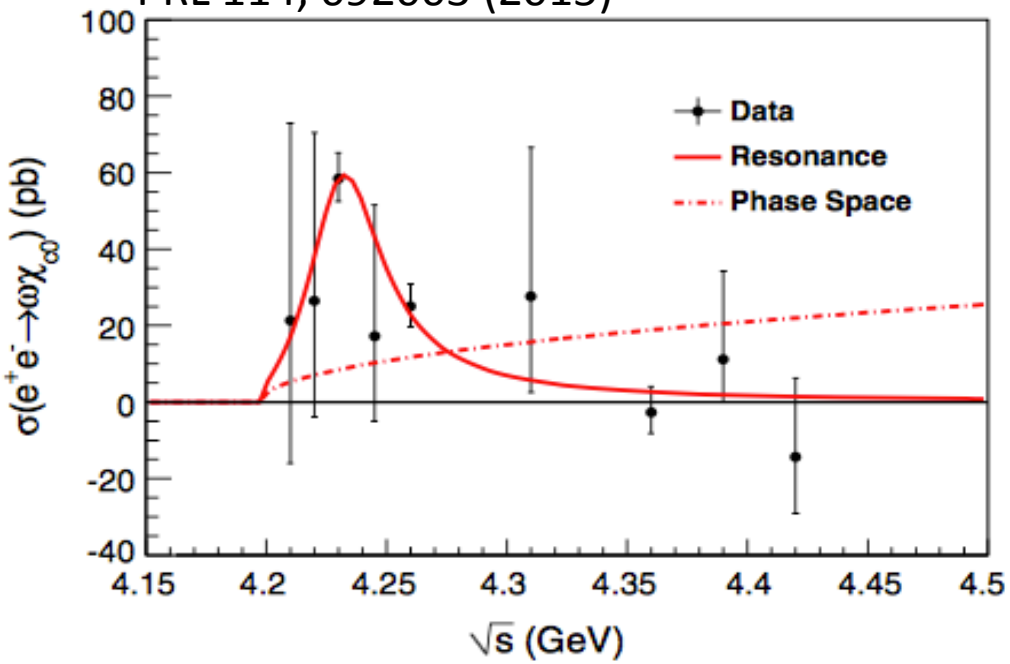
Fit with a constant (pink dashed triple-dot line) and two constant width relativistic BW functions (green dashed double-dot line and aqua dashed line).

$M(Y(4220)) = (4224.8 \pm 5.6 \pm 4.0)\,\text{MeV}/c^2$, $\Gamma(Y(4220)) = (72.3 \pm 9.1 \pm 0.9)\,\text{MeV}$.

$M(Y(4390)) = (4400.1 \pm 9.3 \pm 2.1)\,\text{MeV}/c^2$, $\Gamma(Y(4220)) = (181.7 \pm 16.9 \pm 7.4)\,\text{MeV}$.

$e^+e^- \rightarrow \omega\chi_{cJ}$

PRL 114, 092003 (2015)



- **Only $\omega\chi_{c0}$ has significant signal**
- **The cross section is fitted with coherent sum of a Breit-Wigner and a phase space term**

$$M = 4230 \pm 8 \pm 6 \text{ MeV}, \Gamma = 38 \pm 12 \pm 2 \text{ MeV}$$

- **The mass and width here is compatible with the Y observed in $\pi^+\pi^- J/\psi$ and $e^+e^- \rightarrow \pi^+\pi^- h_c$**

Coupled channels fit

- The Y states in these channels

	$Y(4220)$		$Y(4320)/Y(4360)/Y(4390)$	
	M (MeV/c^2)	Γ (MeV)	M (MeV/c^2)	Γ (MeV)
$\omega\chi_{c0}$ [13]	$4226 \pm 8 \pm 6$	$39 \pm 12 \pm 2$		
$\pi^+\pi^- h_c$ [14]	$4218.4^{+5.5}_{-4.5} \pm 0.9$	$66.0^{+12.3}_{-8.3} \pm 0.4$	$4391.5^{+6.3}_{-6.8} \pm 1.0$	$139.5^{+16.2}_{-20.6} \pm 0.6$
$\pi^+\pi^- J/\psi$ [7]	$4222.0 \pm 3.1 \pm 1.4$	$44.1 \pm 4.3 \pm 2.0$	$4320.0 \pm 10.4 \pm 7.0$	$101.4^{+25.3}_{-19.7} \pm 10.2$
$\pi^+\pi^-\psi(3686)$ [11]	$4209.1 \pm 6.8 \pm 7.0$	$76.6 \pm 14.2 \pm 2.4$	$4383.7 \pm 2.9 \pm 6.2$	$94.2 \pm 7.3 \pm 2.0$
$\pi^+ D^0 D^{*-} + c.c.$ [15]	$4224.8 \pm 5.6 \pm 4.0$	$72.3 \pm 9.1 \pm 0.9$	$4400.1 \pm 9.3 \pm 2.1$	$181.7 \pm 16.9 \pm 7.4$

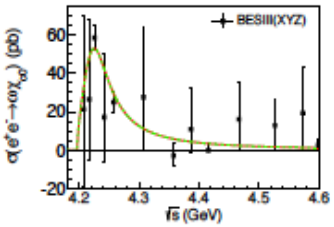
- Assume these two peaks structure are from same two states.
- Fit theses cross sections simultaneously with the interference between the Y states considered
- The result from CLEO, BaBar, Belle are also used
- The fit result gives:

Parameter	$Y(4220)$	$Y(4390)$	$Y(4660)$
M (MeV/c^2)	$4216.5 \pm 1.4 \pm 3.2$	$4383.5 \pm 1.9 \pm 6.0$	$4623.4 \pm 10.5 \pm 16.1$
Γ (MeV)	$61.1 \pm 2.3 \pm 3.1$	$114.5 \pm 5.4 \pm 9.9$	$106.1 \pm 16.2 \pm 17.5$

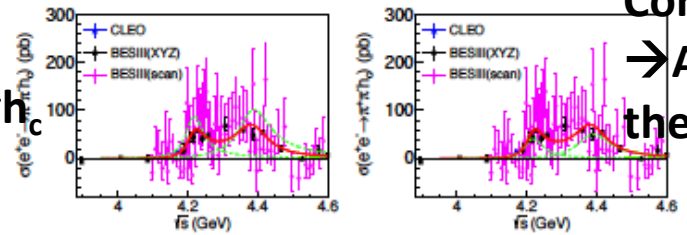
Coupled channels fit

arXiv:1805.03565

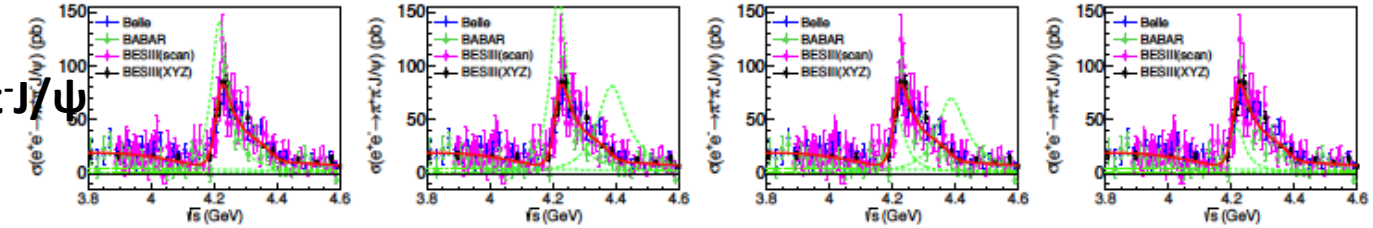
$e^+e^- \to \omega\chi_{cJ}$



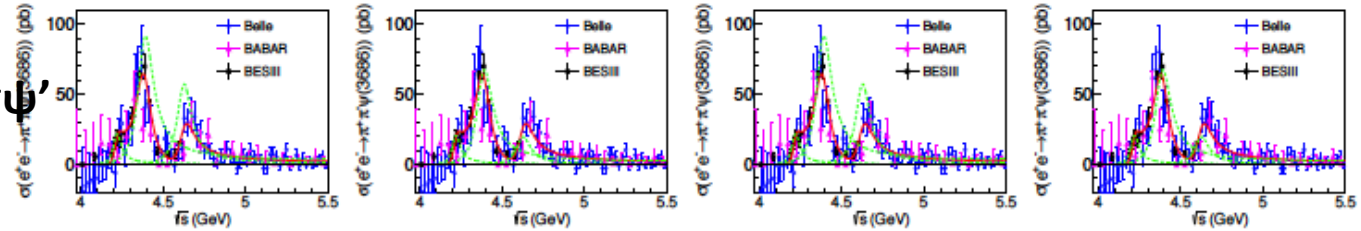
$e^+e^- \to \pi^+\pi^- h_c$



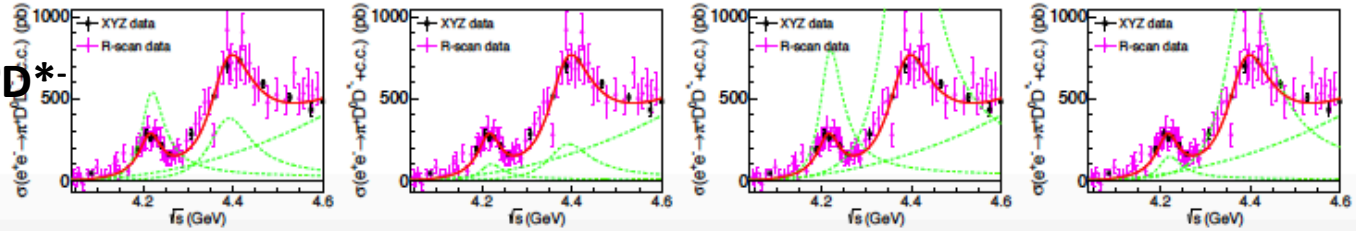
$e^+e^- \to \pi^+\pi^- J/\psi$



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



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



- The fit give χ^2/ndf=0.97, which indicate that the two same states assumption is reasonable.

- There are multi-solution problem. Each column Corresponding to one solution.
  → Ambiguity in couple fraction between Y states and these channels.

Part II: Zc states

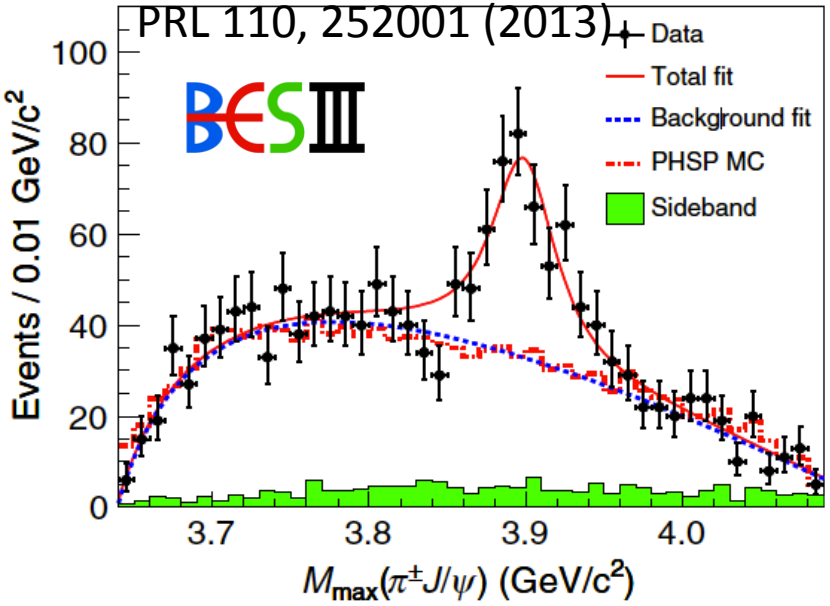
e+e- →πZc

Zc →π(J/ψ,ψ', hc) or D*D(*)

$(q\bar{q}c\bar{c})$?

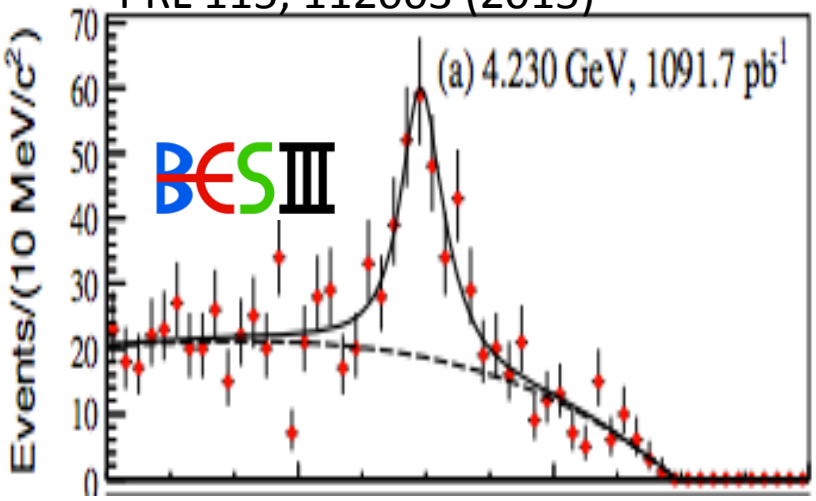
$Zc(3900)^{\pm,0}$ in $\pi^+\pi^-$ J/ψ, $\pi^0\pi^0$ J/ψ

PRL 110, 252001 (2013)



- $e^+e^- \rightarrow \pi^+\pi^-$ J/ψ
- Measured with 525pb^{-1} data at E_{cms}=4.26GeV
- The peak is not a kinematic reflection of $\pi^+\pi^-$ system
- Zc(3900) parameters, S-wave BW
  M=(3899.0±3.6±4.9) MeV, Γ=(46±10±20)MeV
- Significance > 8σ

PRL 115, 112003 (2015)

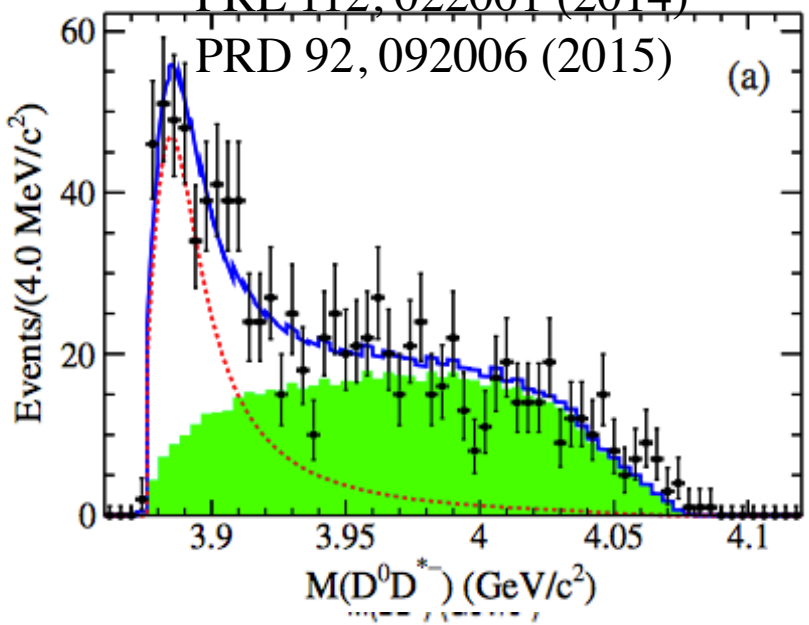


- $e^+e^- \rightarrow \pi^0\pi^0$ J/ψ
- M=3894.8±2.3±2.7 MeV,
  Γ=29.6±8.2±8.2 MeV
- IsoSpin triplet.
- $Zc(3900)^0 \rightarrow \pi^0$ J/ψ , C parity of Zc^0=-1

$Zc(3885)^{\pm,0}$ in

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

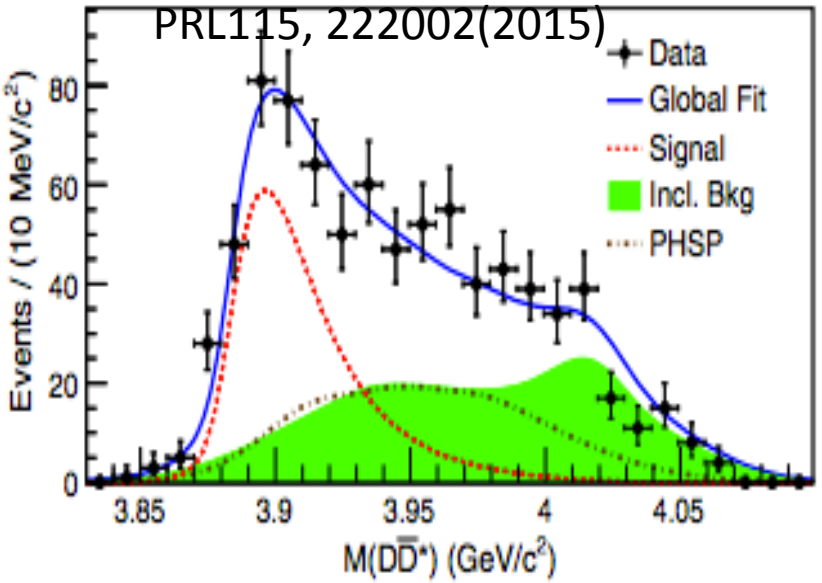
PRL 112, 022001 (2014)
PRD 92, 092006 (2015)



$$e^+e^- \to \pi^\pm Z_c(3885)^\pm \to \pi^\pm(D\overline{D^*})^\mp$$

- M=3881.7±1.6±1.6 MeV,
  Γ=26.6±2.0±2.1 MeV
- The mass is close to the threshold of DD*

PRL115, 222002(2015)



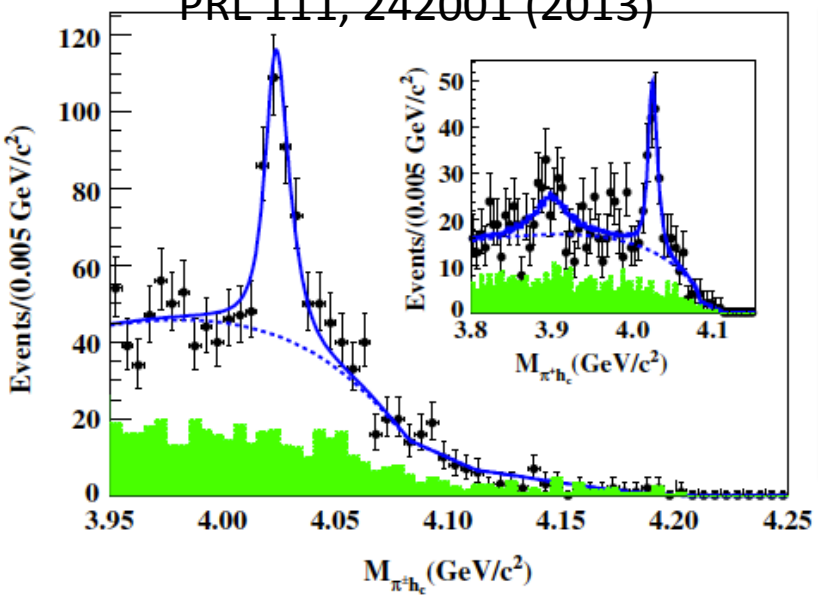
$$e^+e^- \to \pi^0 Z_c(3885)^0 \to \pi^0(D\overline{D^*})^0$$

$$M = 3885.7^{+4.3}_{-5.7} \pm 8.4 \quad MeV$$

$$\Gamma = 35^{+11}_{-12} \pm 15 \quad MeV$$

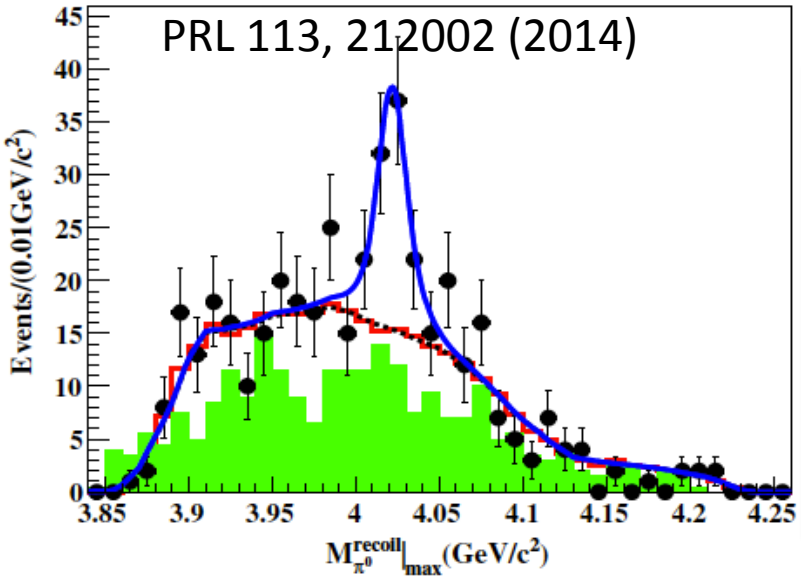
$Z_c(4020)^{\pm,0}$ in $e^+e^- \to \pi^+\pi^- h_c$, $\pi^0\pi^0 h_c$

PRL 111, 242001 (2013)



- $e^+e^- \to \pi^+\pi^- h_c$
- M=4022.9±0.8±2.7 MeV,
- Γ =7.9±2.7±2.6 MeV
- significance of Zc(4020) >8.9σ,
- significance of Zc(3900) =2.1σ

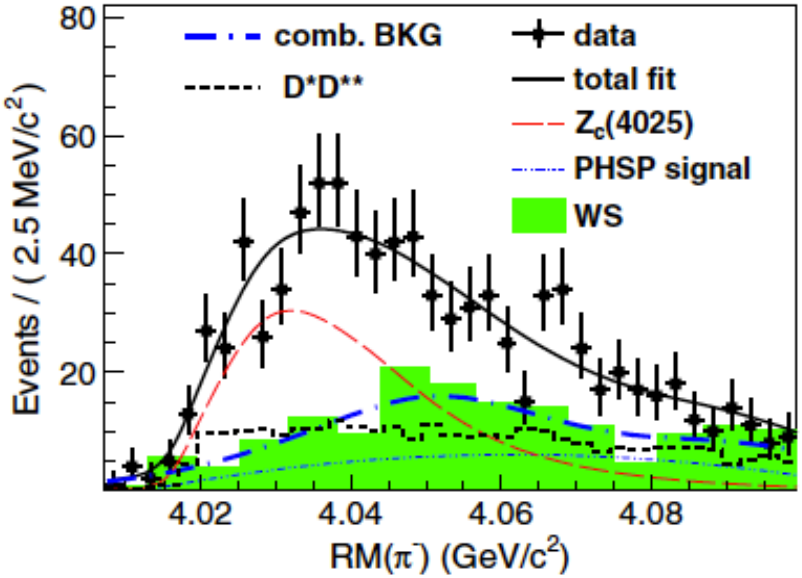
PRL 113, 212002 (2014)



- $e^+e^- \to \pi^0\pi^0 h_c$
- Mass=4023.9±2.2±3.8 MeV,
- Width is fixed to Charged mode
- significance of Zc(4020) >5σ
- Another Isospin-triplet.
- Zc(4020) is near the mass threshold of (D*D*)

$Zc(4025)^{\pm,0} \rightarrow (D^* \overline{D}^*)^{\mp,0}$

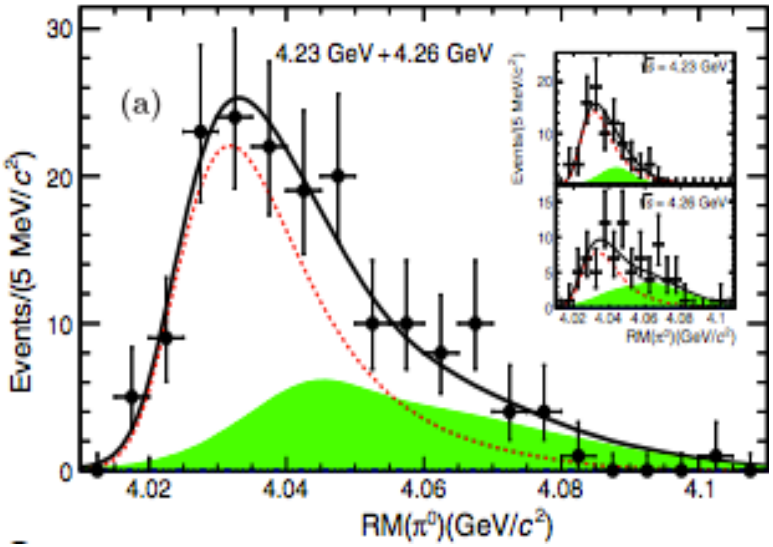
PRL 112, 132001 (2014)



$e^+e^- \rightarrow \pi^\pm Z_c(4025)^\mp \rightarrow \pi^\pm (D^* \overline{D^*})^\mp$

- **$Zc(4025)^\pm$ parameters, S-wave BW**
  M=(4026.3±2.6±3.7) MeV,
  Γ=(24.8±5.6±7.7)MeV
- **Significance > 10σ**

PRL 115, 182002 (2015)



$e^+e^- \rightarrow \pi^0 Z_c(4025)^0 \rightarrow \pi^0 (D^* \overline{D^*})^0$

$M = 4025.5^{+2.0}_{-4.7} \pm 3.1 \quad MeV$

$\Gamma = 23.0 \pm 6.0 \pm 1.0 \quad MeV$

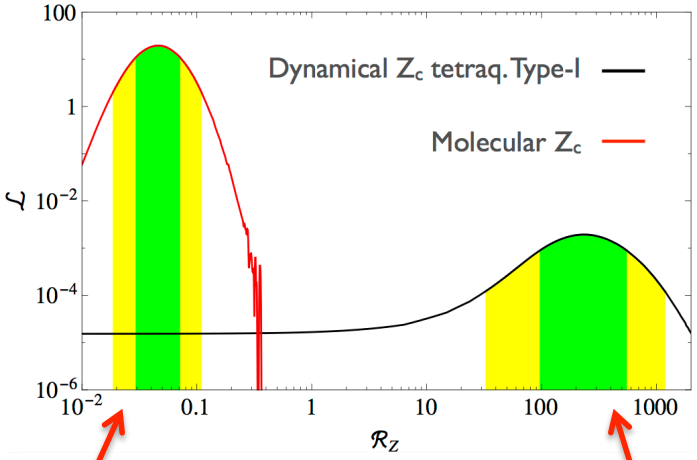
The BESIII result for Zc family

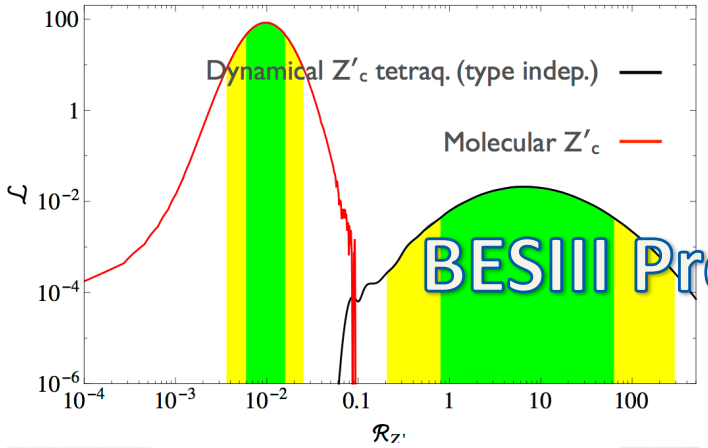
For reference: the mass threshold of m(DD*)~3875MeV, M(D*D*)~4014MeV

- **Is Zc(3900) and Zc(3885) same sates? Zc(4020) and Zc(4025)?**

	C/N	channel	Mass (MeV)	Width (MeV)	σ(ee→πZc, Zc→...) @4.26GeV pb
Zc(3900)	charged	$\pi^{\pm} J/\psi$	3899.0±3.6±4.9	46±10±20	13.5±5.2
	Neutral	$\pi^{0} J/\psi$	3894.8±2.3±2.7	29.6±8.2±8.2	4.0±0.9
Zc(3885)	charged	$(DD^*)^{\pm}$	3881.7±1.6±1.6	26.6±2.0±2.1	108.4±6.9±8.8
	Neutral	$(DD^*)^{0}$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$	47±9±10
Zc(4020)	Charged	$\pi^{\pm} h_c$	4022.9±0.8±2.7	7.9±2.7±2.6	7.4±1.7±2.1±1.2
	Neutral	$\pi^{0} h_c$	4023.9±2.2±3.8	Fixed	8.5±2.9±1.1±1.3
Zc(4025)	charged	$(D^*D^*)^{\pm}$	4026.3±2.6±3.7	24.8±5.6±7.7	89.0±18.7
	Neutral	$(D^*D^*)^{0}$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	23.0±6.0±1.0	43.4±8.0±5.4

Search for $e^+e^- \to \pi Z_c^{(\prime)}, Z_c^{(\prime)} \to \rho\,\eta_c$





BESIII Preliminary

$$R_z = \frac{Br(Z_c \to \rho\eta_c)}{Br(Z_c \to \pi J/\psi)}$$

$$R_{z\prime} = \frac{Br(Z_c' \to \rho\eta_c)}{Br(Z_c' \to \pi h_c)}$$

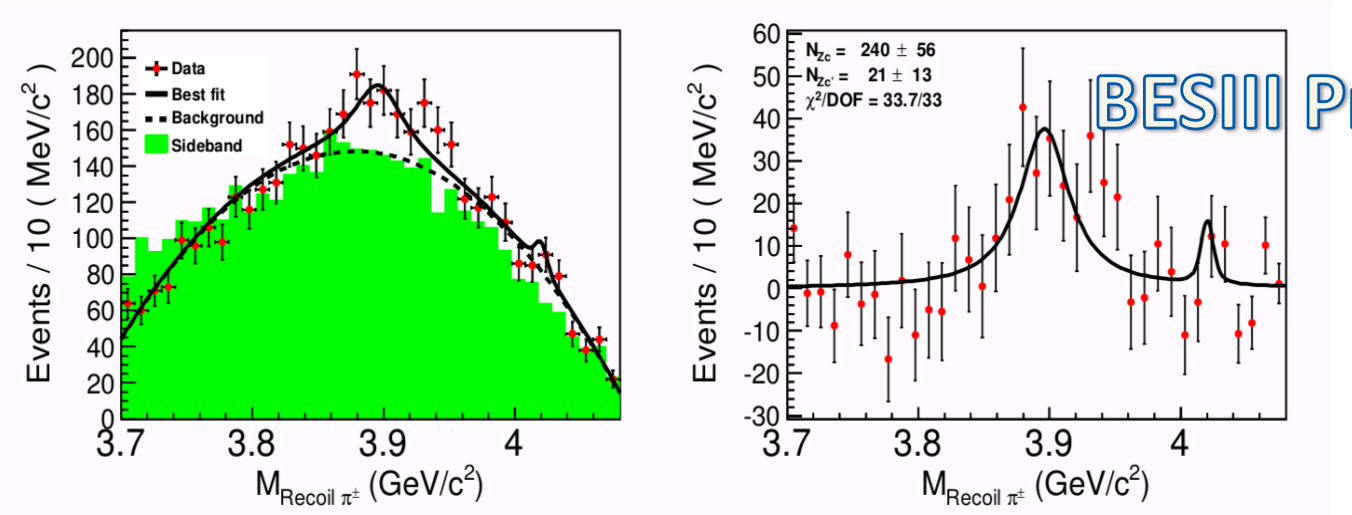
A.Esposito et.al., PLB 746(2015), 194-201

Molecular Zc

Tetraquak Type-1

- **This channel is important for the discrimination between different multi-quark schemes.**
- **The green band and yellow band show the 1σ and 2σ confidence range of the corresponding theoretical model.**

Search for $e^+e^- \to \pi Z_c^{(\prime)}, Z_c^{(\prime)} \to \rho\,\eta_c$

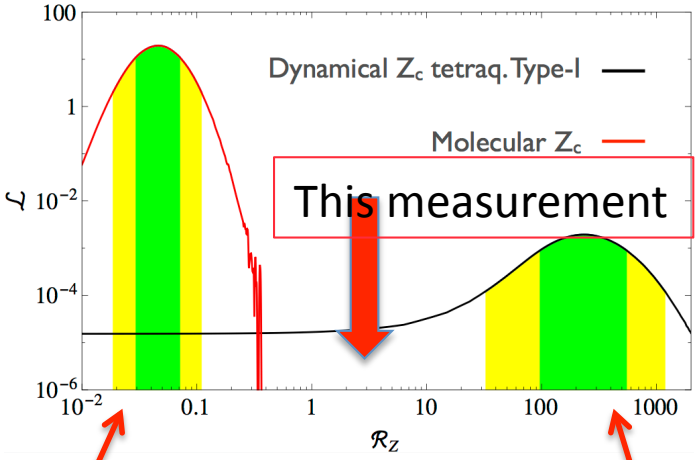


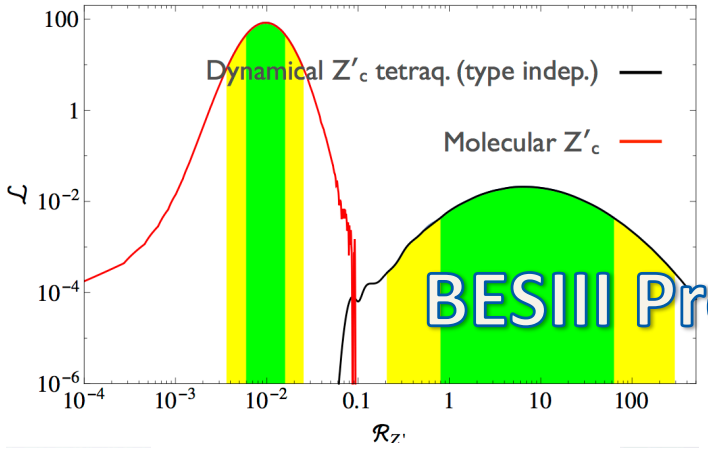
$e^+e^- \to \pi Z_c, Z_c \to \rho\,\eta_c$ @ 4.23 GeV

- Nine η_c channels are used to reconstruct η_c.
- After the η_c and ρ mass window, a hint of $Z_c(3900)$ peak can be seen on the recoiled mass of the bachelor π.
- The green histogram is η_c sideband. Z_c parameter are fixed to latest measurement.

- Strong evidence of Zc(3900) →$\rho\eta_c$ is observed at √s=4.23GeV, with statistical significance 4.3σ(3.9σ including systematic uncertainty)
- No significant Zc'(4020)→$\rho\eta_c$ observed.

Comparison between measurement and prediction





BESIII Preliminary

$$R_z = \frac{Br(Z_c \to \rho\eta_c)}{Br(Z_c \to \pi J/\psi)}$$

$$R_{z'} = \frac{Br(Z'_c \to \rho\eta_c)}{Br(Z'_c \to \pi h_c)}$$

A.Esposito et.al., PLB 746(2015), 194-201

Molecular Zc

Tetraquak Type-1

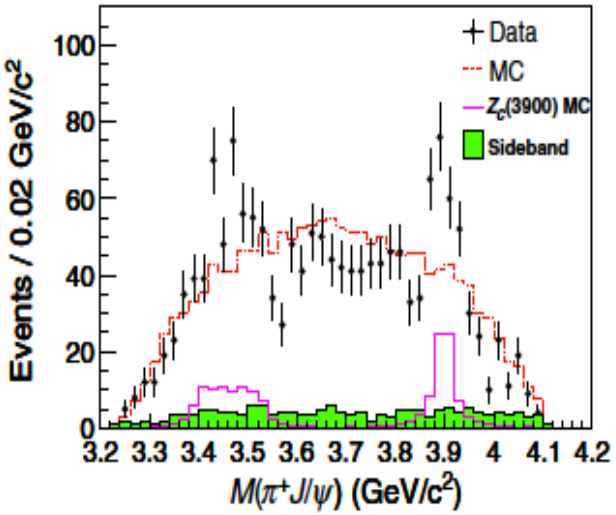
- **The cross section measured at √s= 4.23GeV**

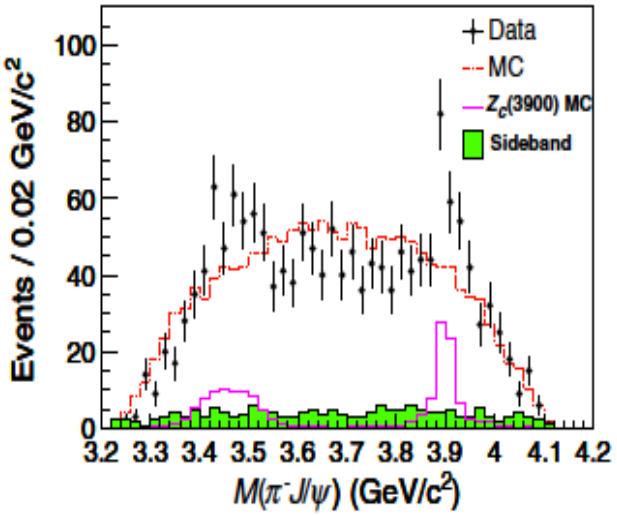
$$\sigma^B(e^+e^- \to \pi^+\pi^-\pi^0\eta_c) = (46 \pm 12 \pm 10)\text{pb}$$
$$\sigma^B(e^+e^- \to \pi Z_c, Z_c \to \rho\eta_c) = (47 \pm 11 \pm 11)\text{pb}$$

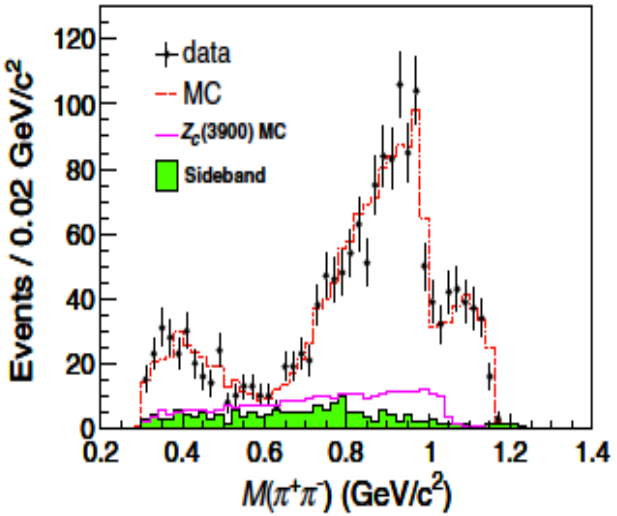
$$\Rightarrow R_z = 2.1 \pm 0.8$$

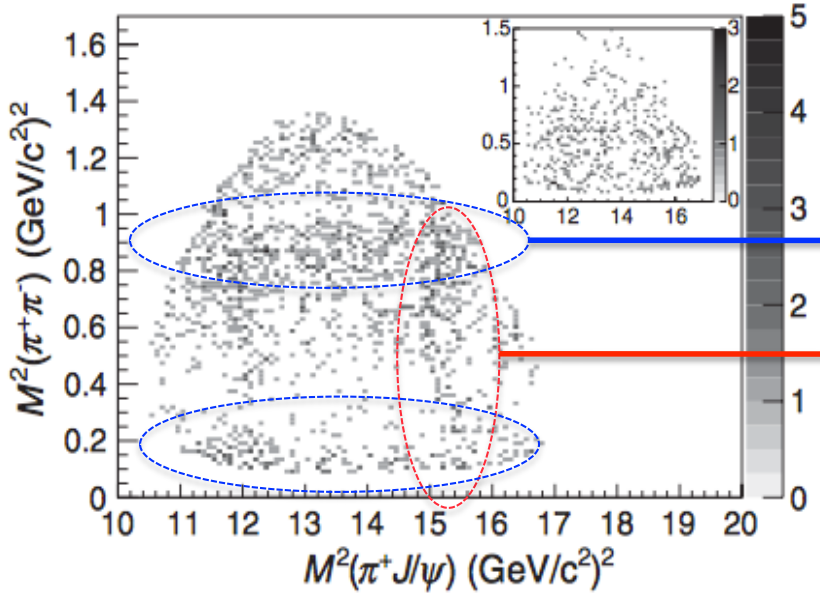
- **Our measurement doesn't agree with both molecular Zc and tetraquark Zc Type-1 assumptions**

Amplitude analysis for $e^+e^- \rightarrow \pi^+\pi^- J/\psi$









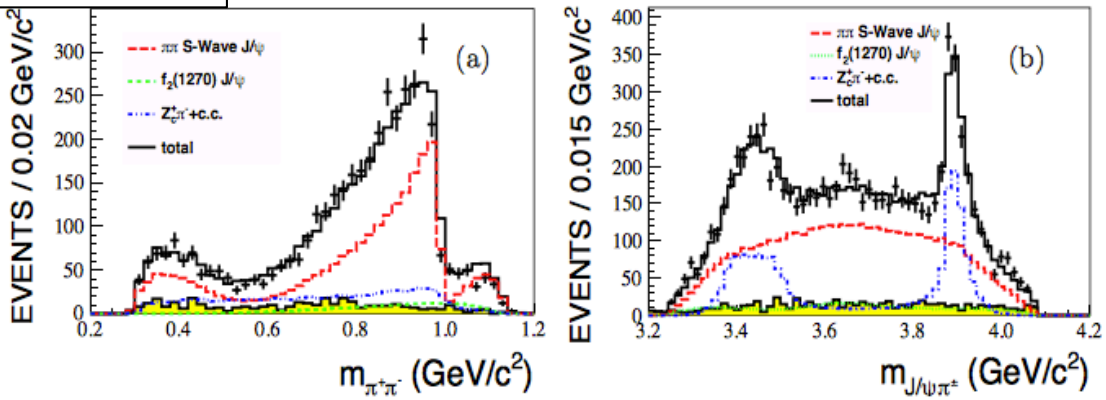
$\pi^+\pi^-$ component

Zc(3900) band

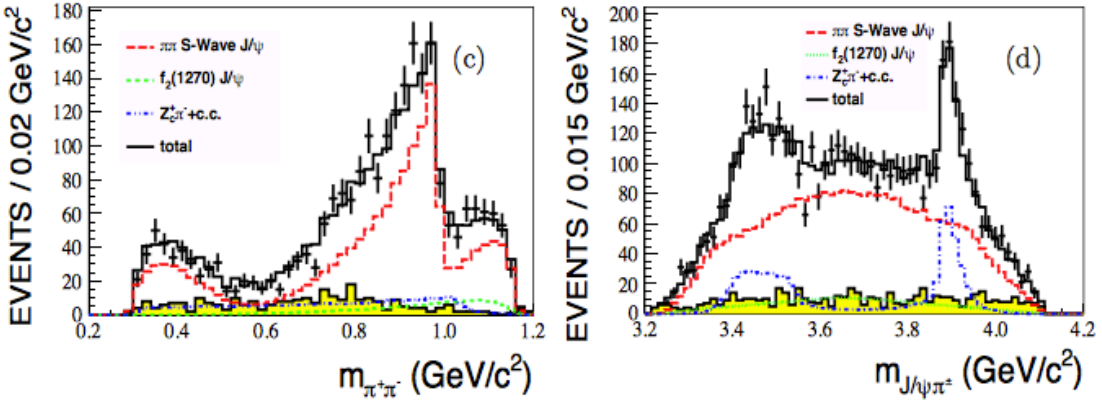
Amplitude analysis

Determination of J^p of Zc(3900)

PRL 119, 072001 (2017)



√s=4.23GeV



√s=4.26GeV

- **Amplitude analysis with helicity formalism formalism taking $\pi^+\pi^- J/\psi$ as final states**
- **Simultaneous fit to data samples at 4.23GeV and 4.26GeV**
- **$\pi^+\pi^-$ spectrum is parameterized with σ, $f_0(980)$, $f_2(1270)$ and $f_0(1370)$**

Determination of J^p of Zc(3900)

- **Zc is parameterized with Flatte formula**

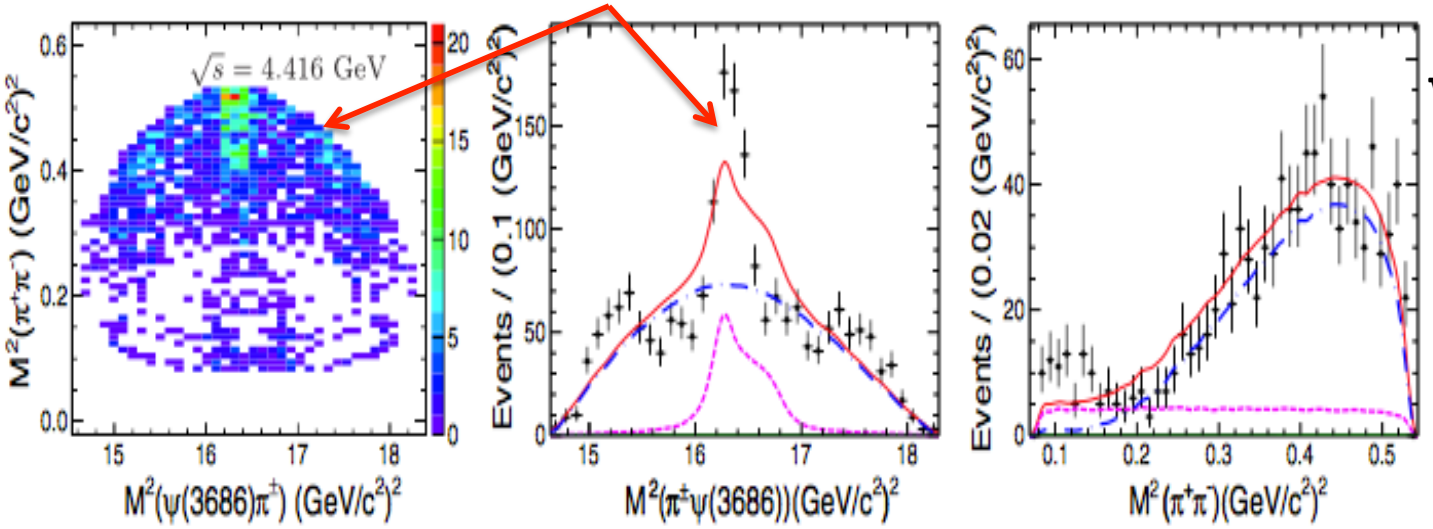
$$BW(s, M, g_1', g_2') = \frac{1}{s - M^2 + i[g_1'\rho_1(s) + g_2'\rho_2(s)]}$$

- **M=(3901.5±2.7±38.0) MeV, g_1'=(0.075±0.006±0.025)GeV^2, g_2'/g_1'=27.1±2.0±1.9**

  Which corresponding to pole Mass= (3881.2±4.2±52.7) MeV, pole width=(51.8±4.6±36.0)MeV
- **J^p of Zc favor to be 1^+ with statistical significance larger than7σ over other quantum numbers**
- **The significance of Zc(4020) process is found to be 3σ**

Structure in $\pi^+\pi^-\psi'$

PRD 96, 032004 (2017) **Zc(4020)?**



√s=4.416GeV

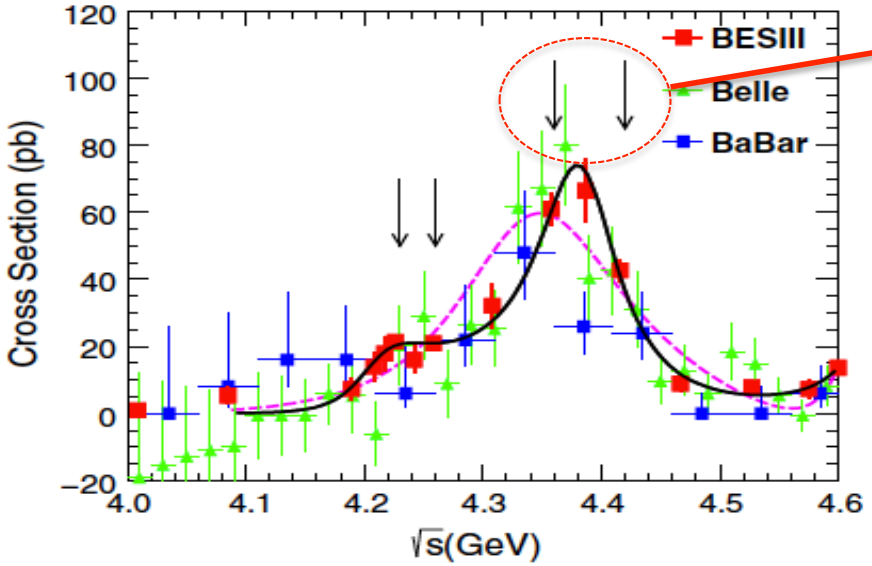
- **A narrow peak around 4.03GeV is observed on $M(\pi^\pm\psi')$,**
- **a 2D fit is performed on dalitz plot. Where x, y represent $M^2(\pi^+\psi')$, $M^2(\pi^-\psi')$**

$$\frac{p\cdot q/c^2}{(M_R^2-x)^2+M_R^2\cdot\Gamma^2/c^4}+\frac{p\cdot q/c^2}{(M_R^2-y)^2+M_R^2\cdot\Gamma^2/c^4},$$

- **M=4032.1±2.4 MeV, Γ =26.1±5.3 MeV**

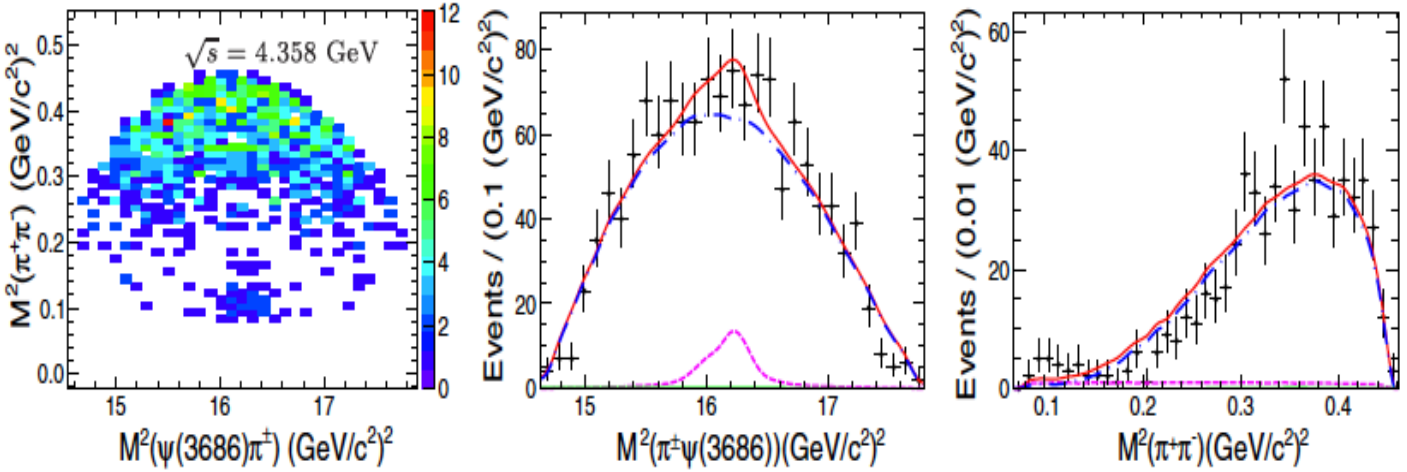
The fit quality is bad.

Structure in $\pi^+\pi^-\psi'$



√s=4.416GeV and √s=4.358GeV are both at the Y(4360) peak?

√s=4.358GeV

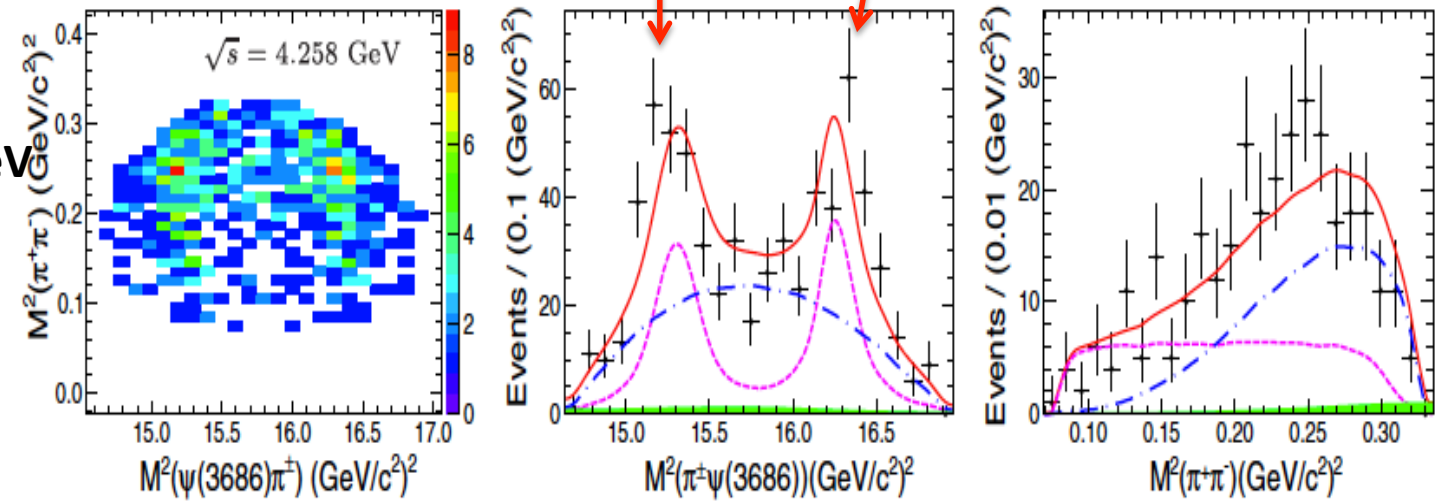


Where is the Zc(4020) peak if 4.416GeV and 4.358GeV are both dominant from Y(4360)?

Structure in $\pi^+\pi^-\psi'$

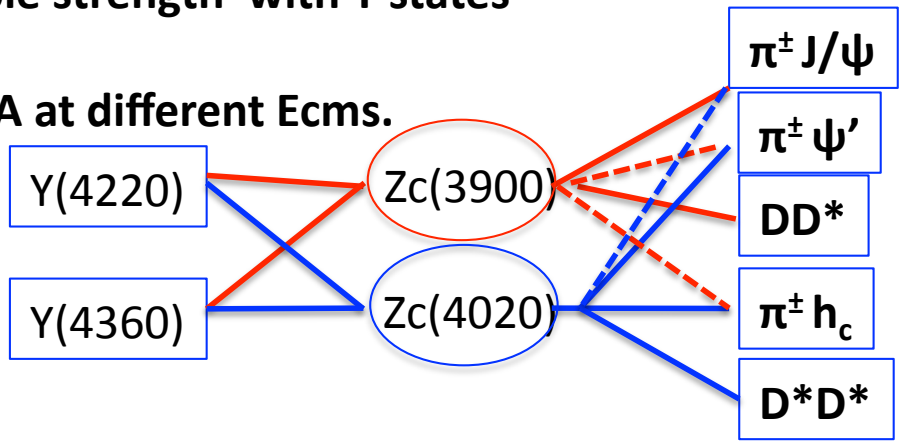
Zc(3900)? Zc(4020)?

√s=4.258GeV



- ❑At a certain Ecms, it might has overlap between different Y states.
- ❑Different Zc states have different couple strength with Y states
- ❑One Zc decay to different channels
- ❑ To clarify their relation, we need PWA at different Ecms.

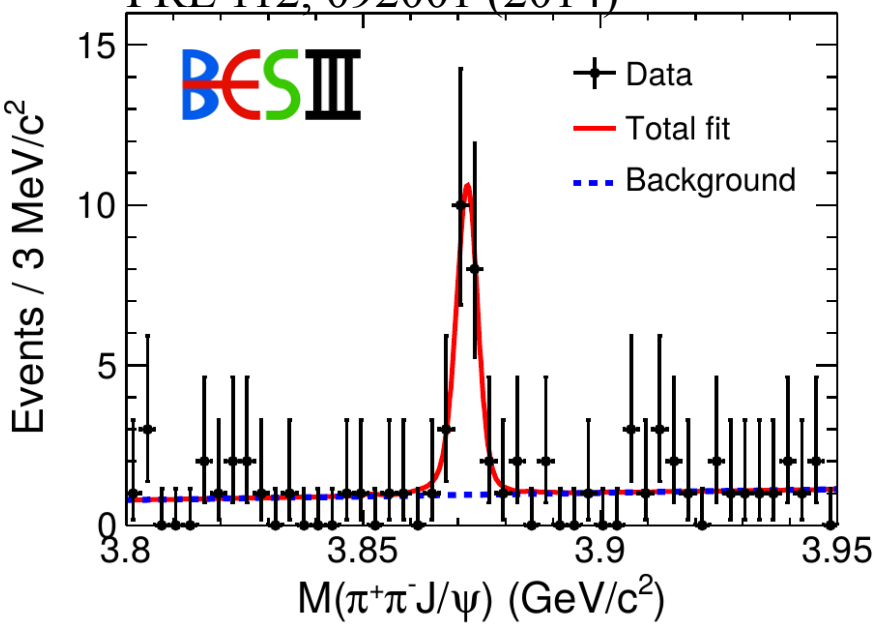
Coupled channels analysis?

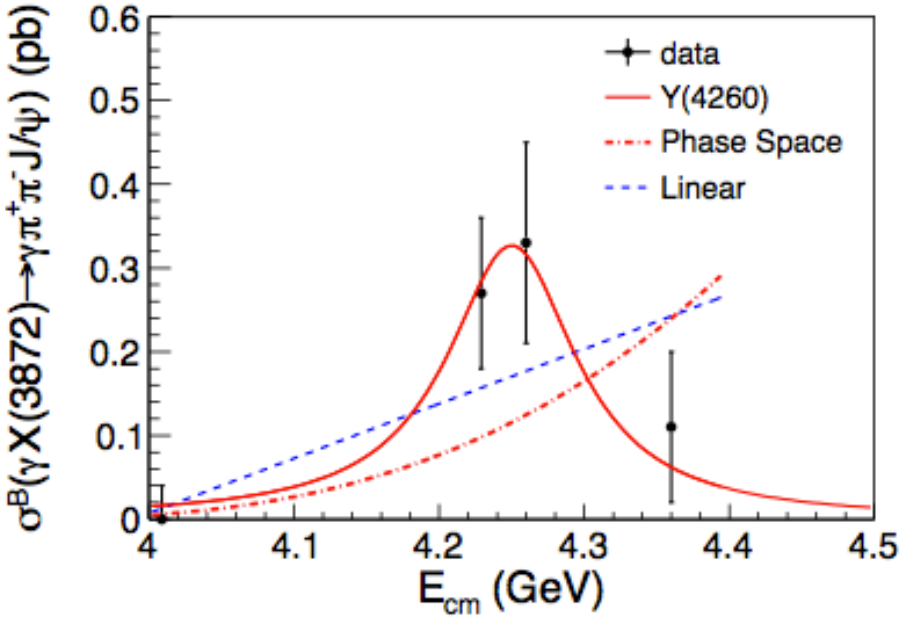


Part III: X states

$e^+e^- \to \gamma X(3872)$, $X(3872) \to \pi^+\pi^- J/\psi$.

PRL 112, 092001 (2014)





- X(3872) is sitting at the threshold of DD*.
- $J^{PC}=1^{++}$ *(CDF, LHCb)*
- X（3872） is candidate of exotic states for long time: molecular states, tetraquark states, Mixture of excited χ_{c1} and D^0D^{*0} bound state.

- BESIII observed $e^+e^- \to \gamma X(3872)$, $X(3872) \to \pi^+\pi J/\psi$.
- $e^+e^- \to \gamma X(3872)$ → Charge parity of X(3872)=+1.
- It seems that $X(3872)$ is from the radiative transition of $Y(4260)$

Summary

- With more BESIII data, we have observed some hyperfine structures of Y states
  - ✓ mass of Y(4230)→Y(4220)
  - ✓ Y(4360) peak on Y(4220) shoulder in e^+e^- →$\pi^+\pi^- J/\psi$
  - ✓ Y(4220) peak on Y(4360) shoulder in e^+e^- →$\pi^+\pi^- \psi'$
- Two triplets of Zc(3900) and Zc(4020) has been established
- We have tried many new ideas to understand these states' relation and properties
  - ✓ A couple channel fit of cross sections of Y's decay
  - ✓ PWA to get the J^p of Zc(3900)
  - ✓ Searching new decay channels under the theorist's guidance
- The entanglement between XYZ states require PWA which is challenging.

What's inside the XYZ states?

The ball for world cup since 1930

2018

A four quark states?