XYZ at BESIII

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(on behalf of the BESIII Collaboration)

Conference on Flavor Physics and CP violation(FPCP)
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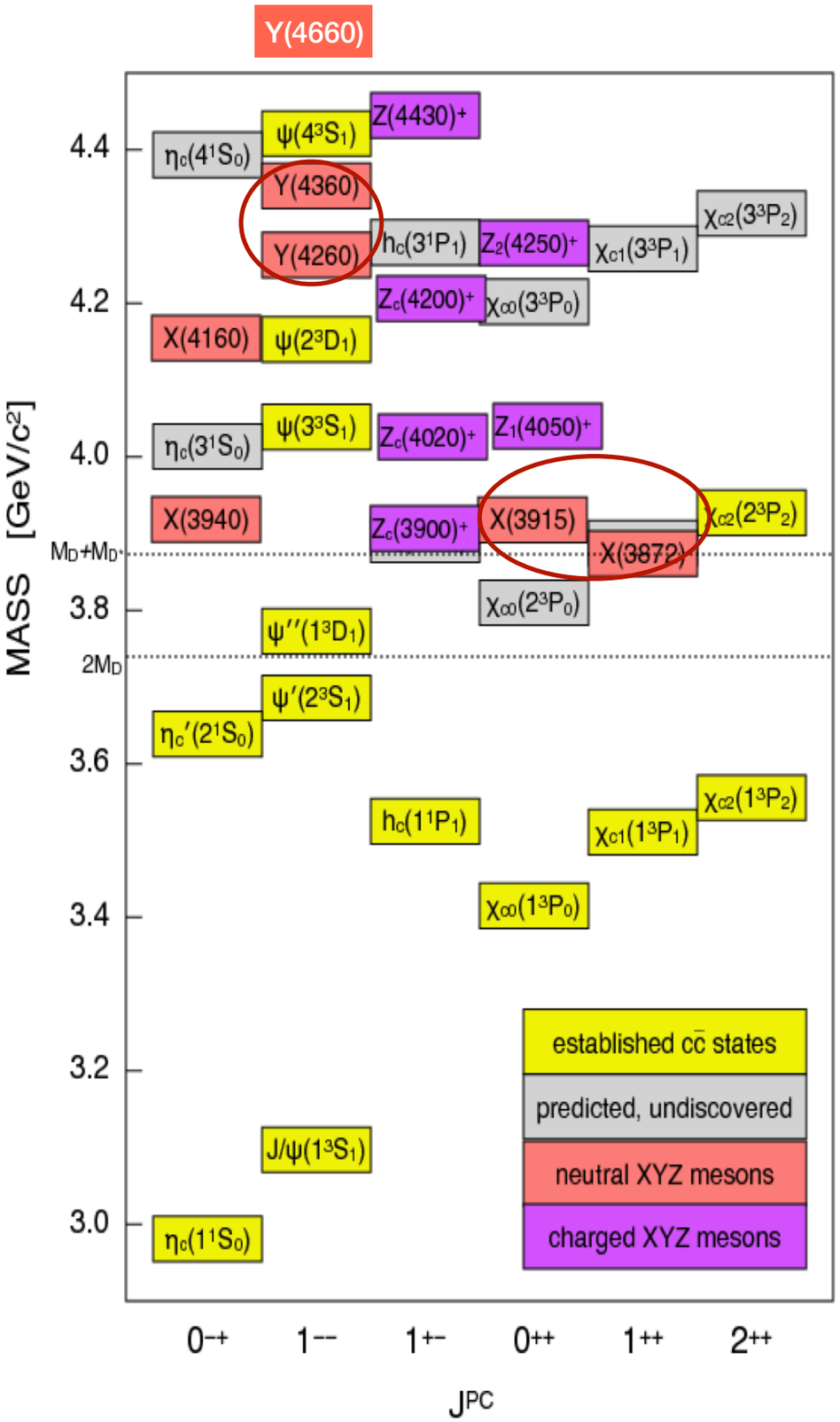
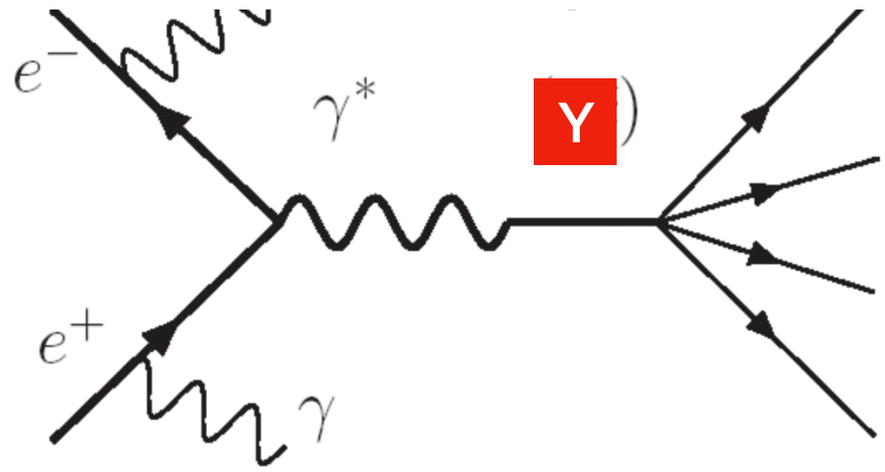
XYZ Physics at BESIII





BESIII can directly generate $Y(1^{--})$ states by e^+e^- annihilation.

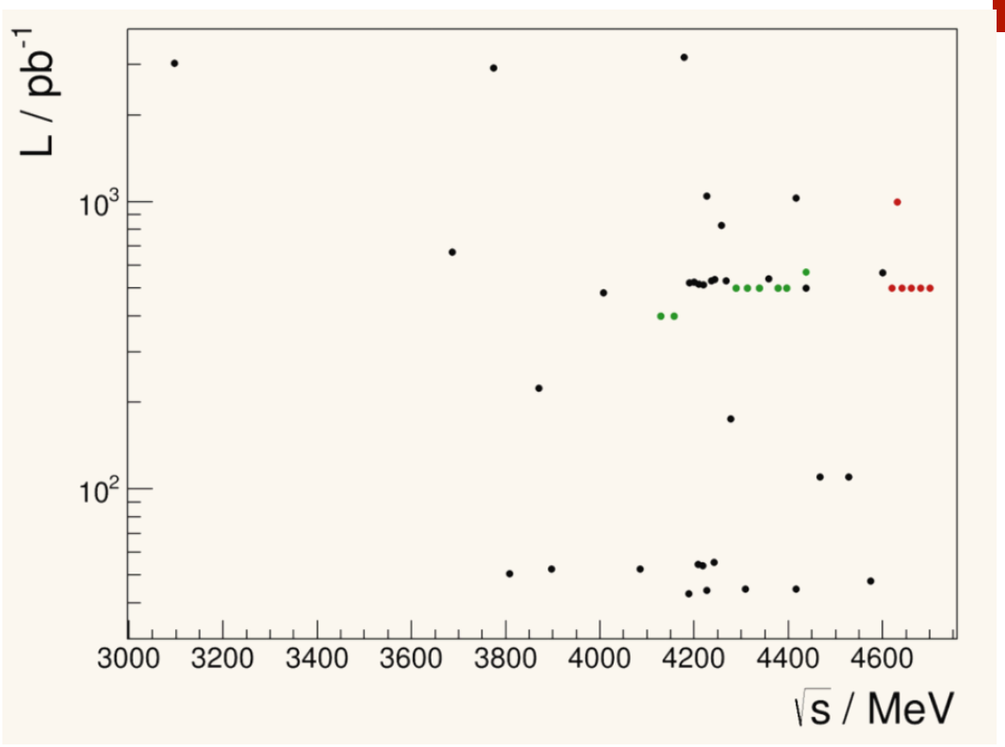
Can get other states (like X or Z) by radiative decay or hadronic transition from Y or ψ.

Experimental Purpose

- **search for more XYZ states, study their properties and new decays modes**
- **look for transitions between different states**

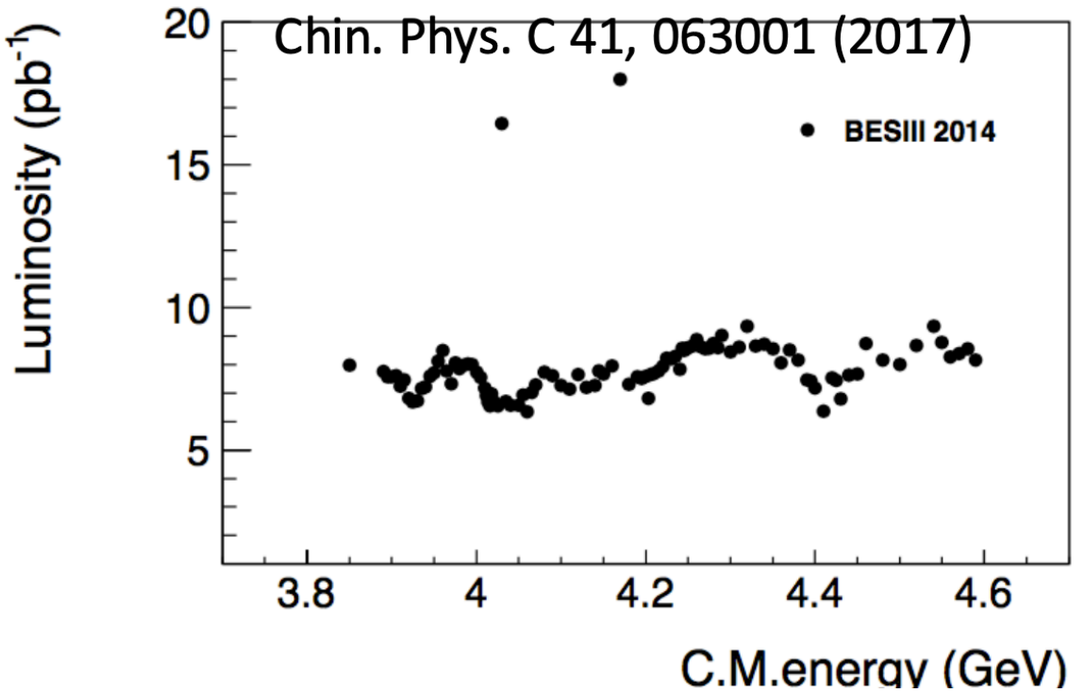
Data set for XYZ study at BESIII

XYZ data



- **~12 fb^{-1} e$^+$e$^-$ collision data event in open charm region (from 3.8-4.6GeV) has been collected by BESIII**
- **8 energies around $\Lambda_c\bar{\Lambda}_c$ (from 4.1-4.4GeV) has been taken in 2019**
- **energies above 4.6GeV has been taken in 2020**

R-scan data



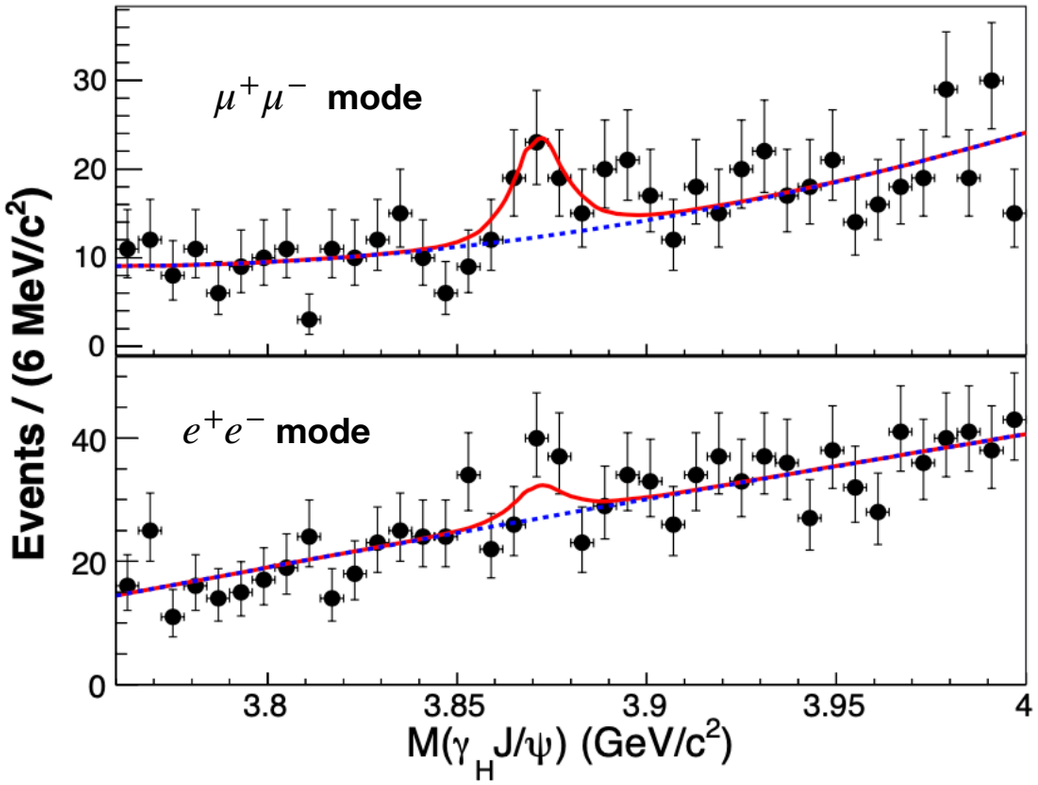
- **104 energy points between 3.85 and 4.59 GeV**
- **For Open Charm Cross Section Study**

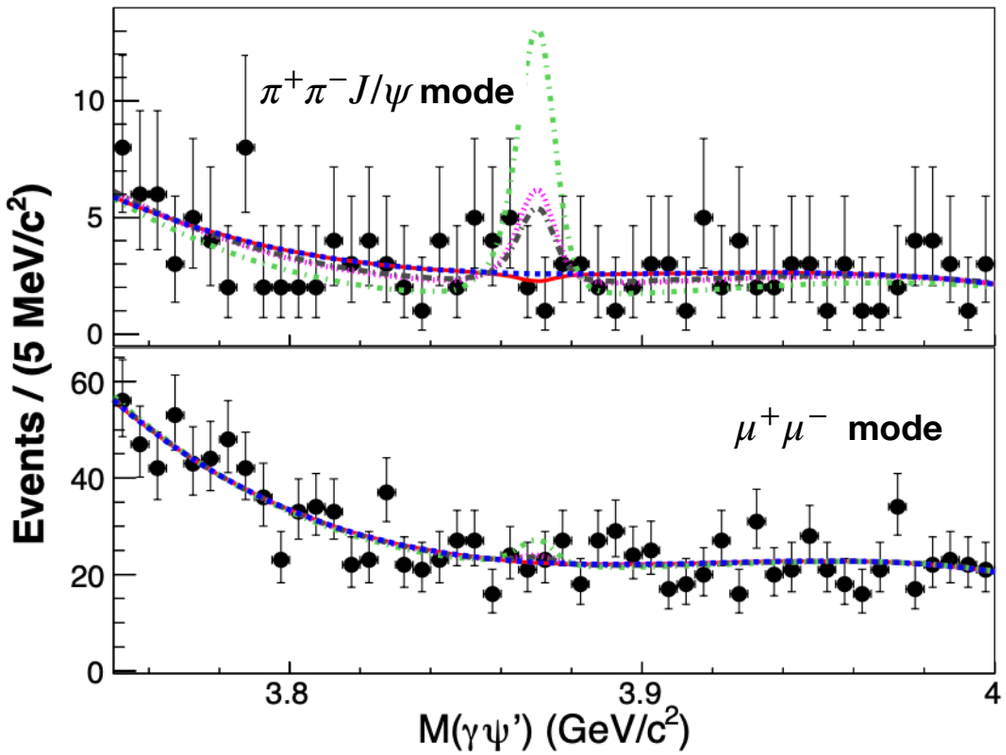
The X states

I. Radiative transitions of X(3872)
II. Hadronic decay of X(3872):
$X(3872) \to D^{*0}\bar{D}^{0}$

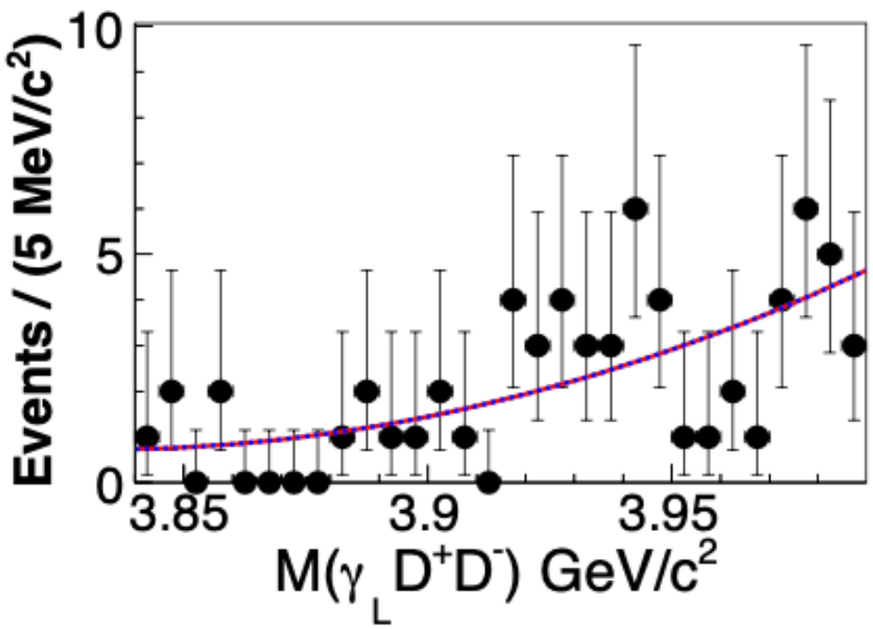
Radiative transitions of X(3872)

arXiv:2001.01156, accepted by PRL



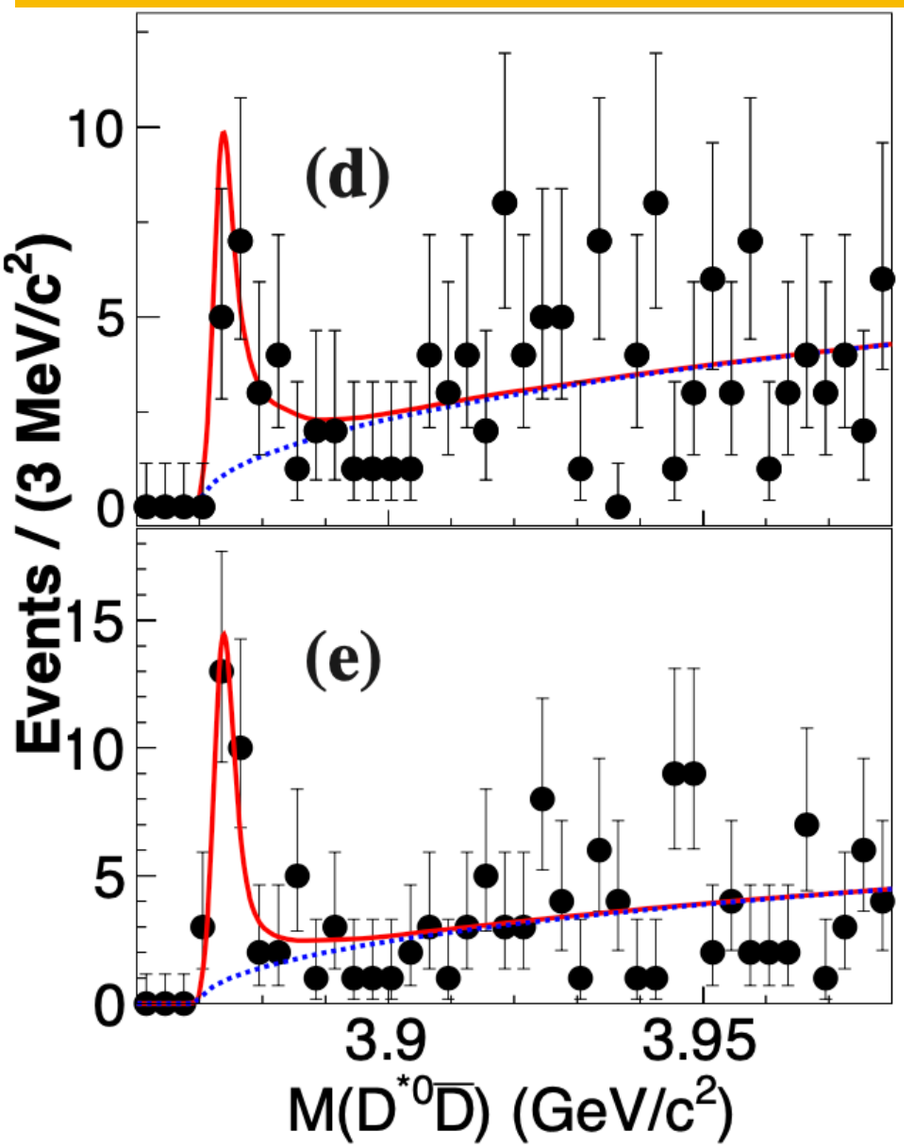


- **Study the process of $X(3872) \to \gamma J/\psi, \gamma\psi(2S), \gamma D^+D^-$ with data sample between 4.178 and 4.278GeV**
- **Find the evidence of $X(3872) \to \gamma J/\psi$ with 3.5σ**
- **No evidence signal for $X(3872) \to \gamma\psi(2S), \gamma D^+D^-$**



$X(3872) \to D^{*0}\bar{D}^{0}$

arXiv:2001.01156, accepted by PRL



- **Observed $X(3872) \to D^{*0}\bar{D}^{0}$ with statistic significances of 7.4σ**
- **Measured the relative branching ratios compared with $X(3872) \to \pi^{+}\pi^{-}J/\psi$**
- **The UL on the ratio**

$$R_{\gamma\psi} = \frac{Br(X(3872) \to \gamma\psi(2S))}{Br(X(3872) \to \gamma J/\psi)} < 0.59 \text{ at 90\% C.L.}$$

Consistent with Belle measurement and Global fit

LHCb: $R_{\gamma\psi} = 2.46 \pm 0.64 \pm 0.29$

Belle: $R_{\gamma\psi} < 2.1(90\,\%\,CL)$

not likely a conventional charmonium state but rather a molecule or a mixture of molecule and charmonium

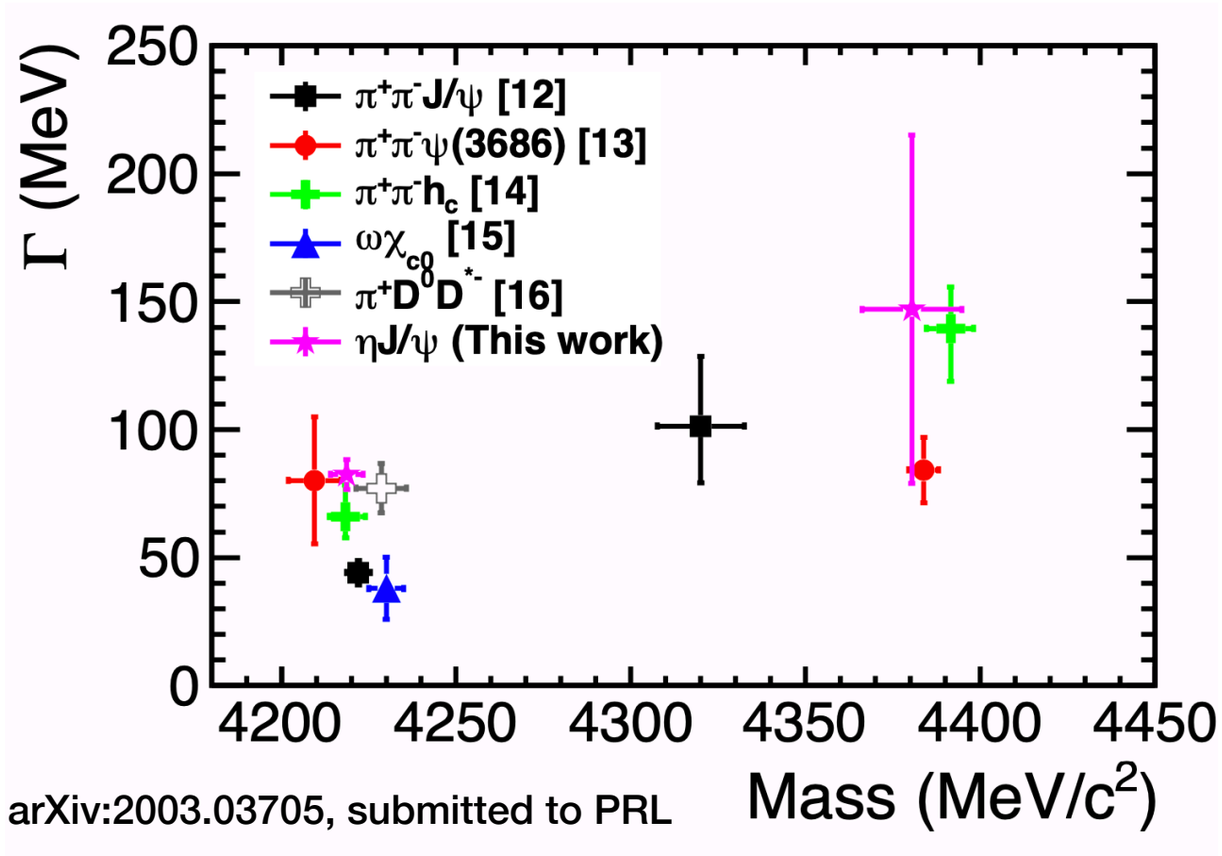
TABLE II. Relative branching ratios and UL on branching ratios compared with $X(3872) \to \pi^{+}\pi^{-}J/\psi$.

mode	$\gamma J/\psi$	$\gamma\psi'$	$\gamma D^{0}D^{0}$	$\pi^{0}D^{0}D^{0}$	$D^{*0}D^{0} + c.c.$	$\gamma D^{+}D^{-}$	$\omega J/\psi$	$\pi^{0}\chi_{c1}$
ratio	0.79 ± 0.28	-0.03 ± 0.22	0.54 ± 0.48	-0.13 ± 0.47	11.77 ± 3.09	$0.00^{+0.48}_{-0.00}$	$1.6^{+0.4}_{-0.3} \pm 0.2$ [18]	$0.88^{+0.33}_{-0.27} \pm 0.10$ [35]
UL	-	< 0.42	< 1.58	< 1.16	-	< 0.99	-	-

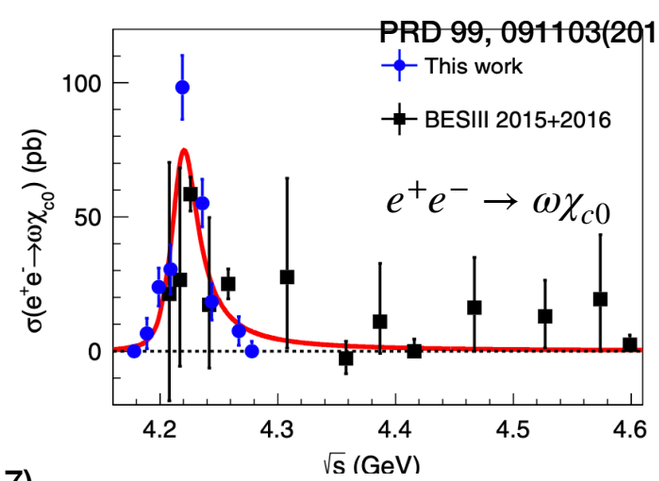
The Y states

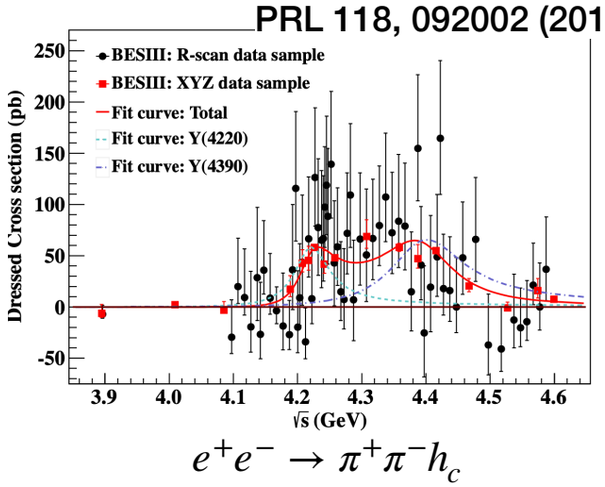
I. **Measured the mass and width of Y(4220) and Y(4360) from the different processes**
II. **The enhancement in $e^+e^- \to \eta' J/\psi$ and $e^+e^- \to D^+D^-\pi^+\pi^-$**

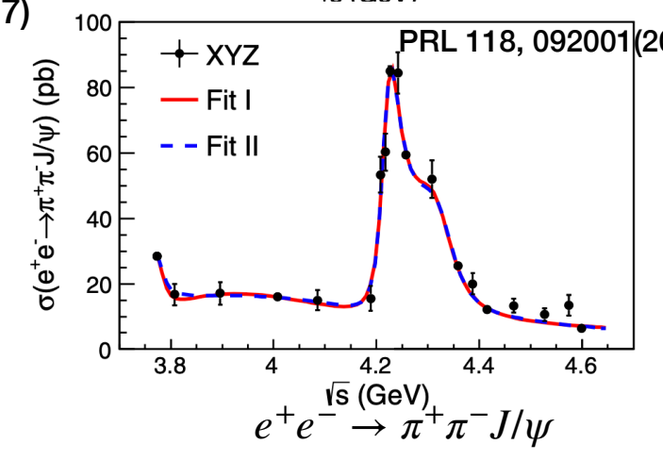
Y(4220) & Y(4360)

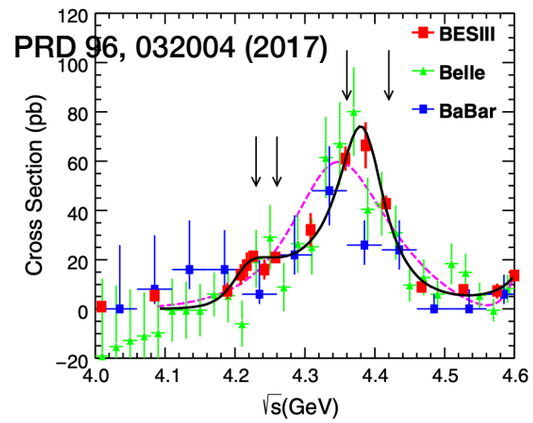


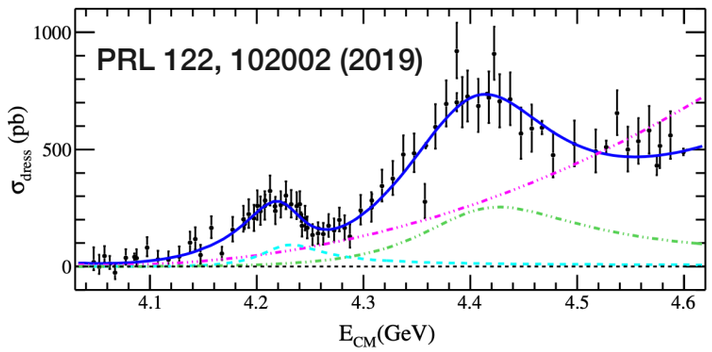
arXiv:2003.03705, submitted to PRL

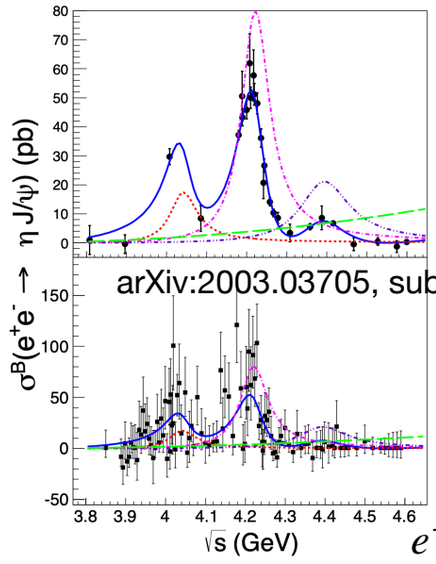










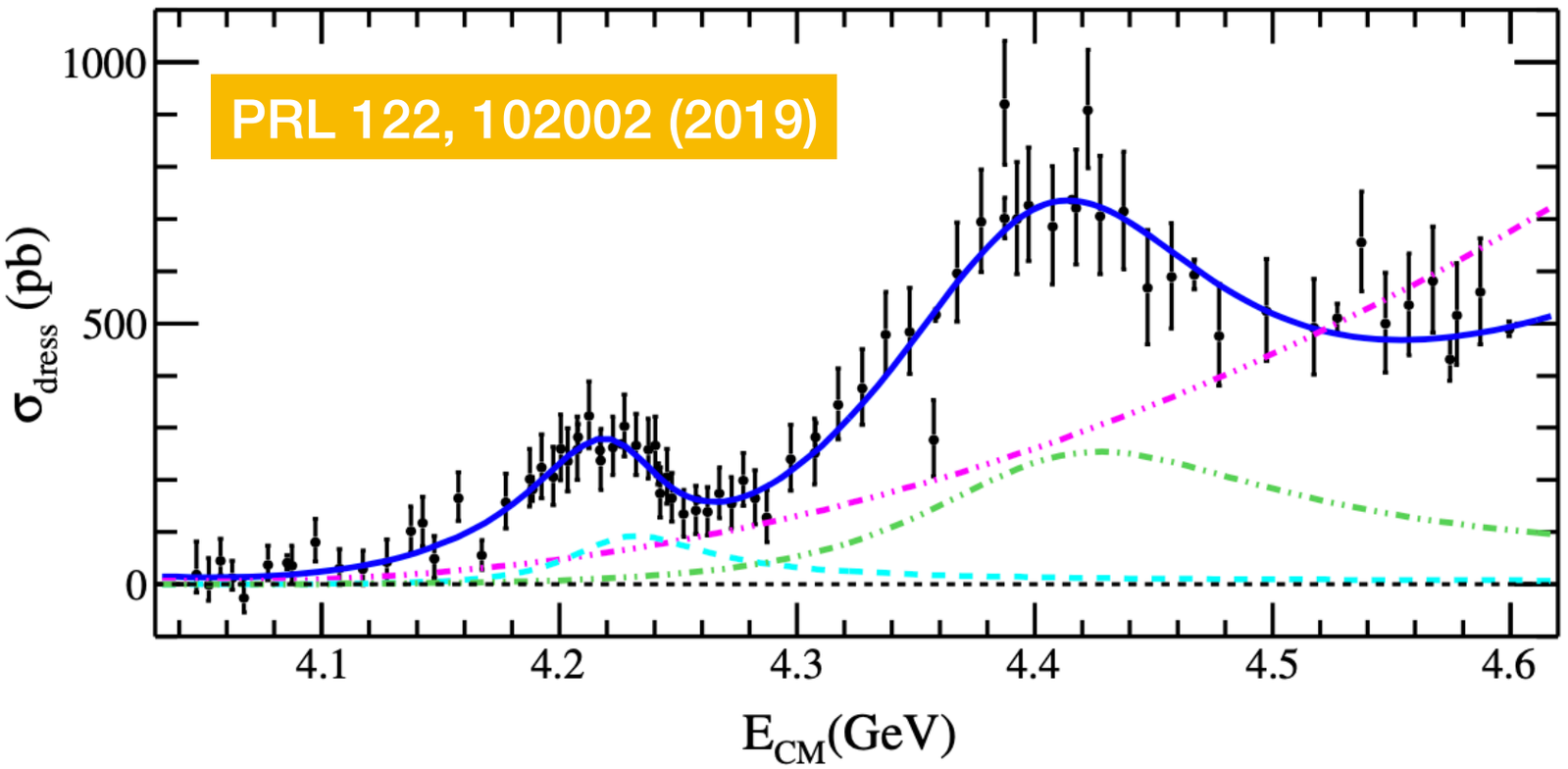


arXiv:2003.03705, submitted to PRL

- **Measured the mass and width of Y(4220) and Y(4360) from the different processes**
- **The measured resonant parameters of the two observed structures are consistent or close.**
- **The intrinsic scenario for the difference on width is still unknown.**

Further experimental studies with higher statistics are needed

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



The pink line describes the phase-space contribution;
The green line describes the R_2 contribution;
The light blue dashed line describes the R_1 contribution.

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

$$B_j(m) = [(\sqrt{12\pi\Gamma_j^{\rm el}\Gamma_j})/(m^2 - M_j^2 + iM_j\Gamma_j)]$$

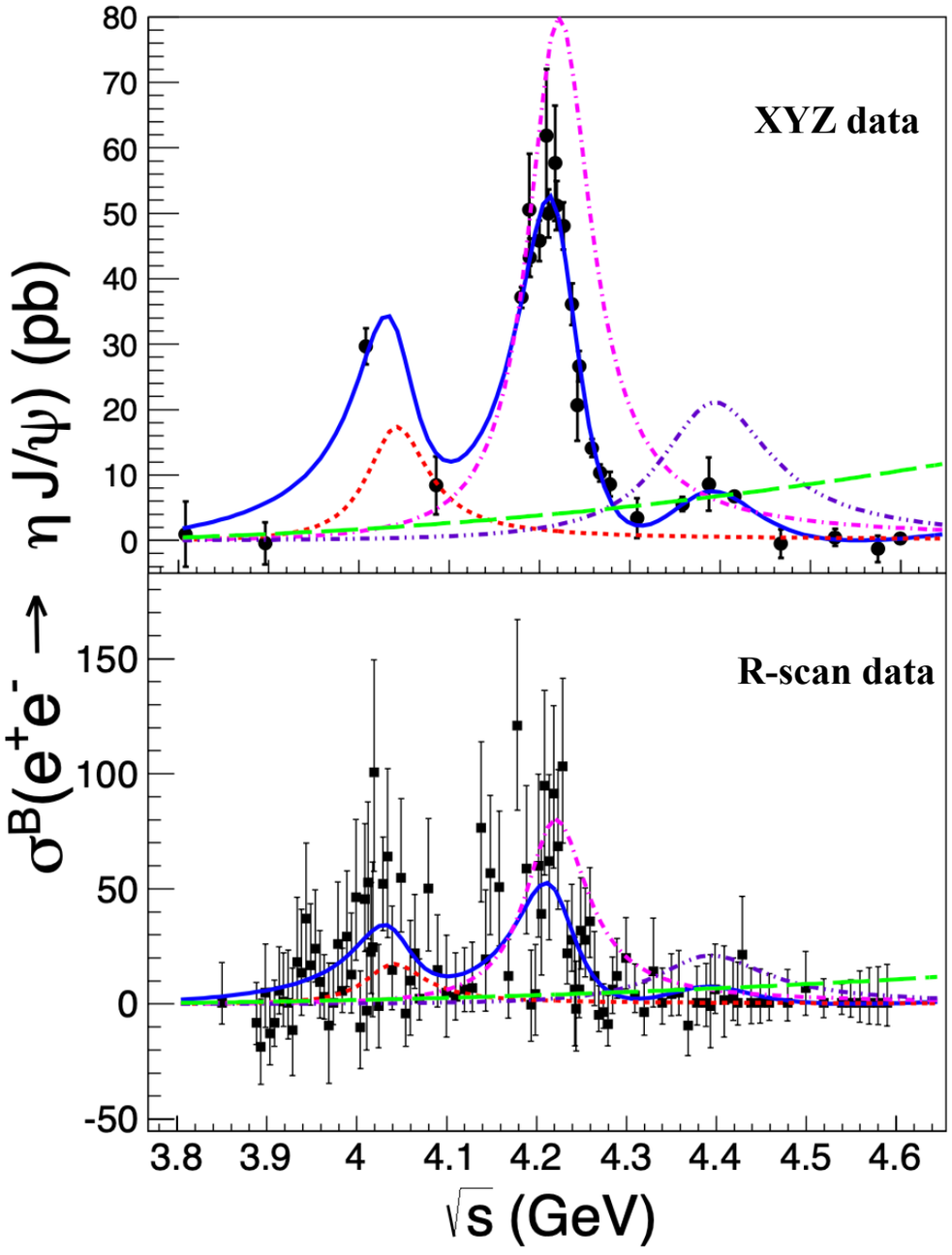
- **Measured the cross section of $e^+e^- \to \pi^+ D^0 D^{*-}$ from 4.05 to 4.60 GeV**
- **Fit the cross section with three body phase space and two relativistic Breit-Wigner functions**
- $M_1 = 4228.6 \pm 4.1 \pm 6.3\text{MeV}, \quad \Gamma_1 = 77.0 \pm 6.8 \pm 6.3\text{MeV}$

  consistent with previous observations of the Y(4220) state and the theoretical prediction of a $D\bar{D}_1(2420)$ molecule.
- **The second enhancement is not from a single known resonance.**

  detailed amplitude analysis is required for better understanding

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

arXiv:2003.03705, submitted to PRL



The blue curves are the fit results;
the red curves for ψ(4040);
the pink curves for Y (4220);
the purple curves for Y (4360);
the green curves for the P-PHSP component.

- **Using data from center-of-mass 3.81 to 4.60GeV**

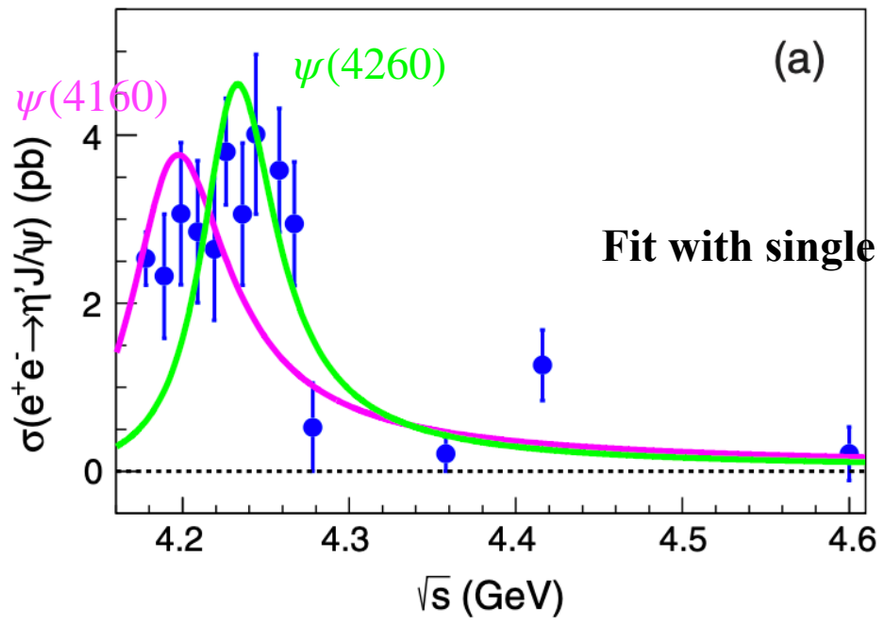
- **Maximum-likelihood fit including three resonances is performed by assuming the lowest lying structure is the ψ(4040).**

- $M_1 = (4218.7 \pm 4.0 \pm 2.5) MeV/c^2, \quad \Gamma_1 = (82.5 \pm 5.9 \pm 0.5) MeV$
  $M_2 = (4380.4 \pm 14.2 \pm 1.8) MeV/c^2, \quad \Gamma_1 = (147.0 \pm 63.0 \pm 25.8) MeV$
  Consistent with those of the Y (4220) and Y (4360) from previous measurements of different final states

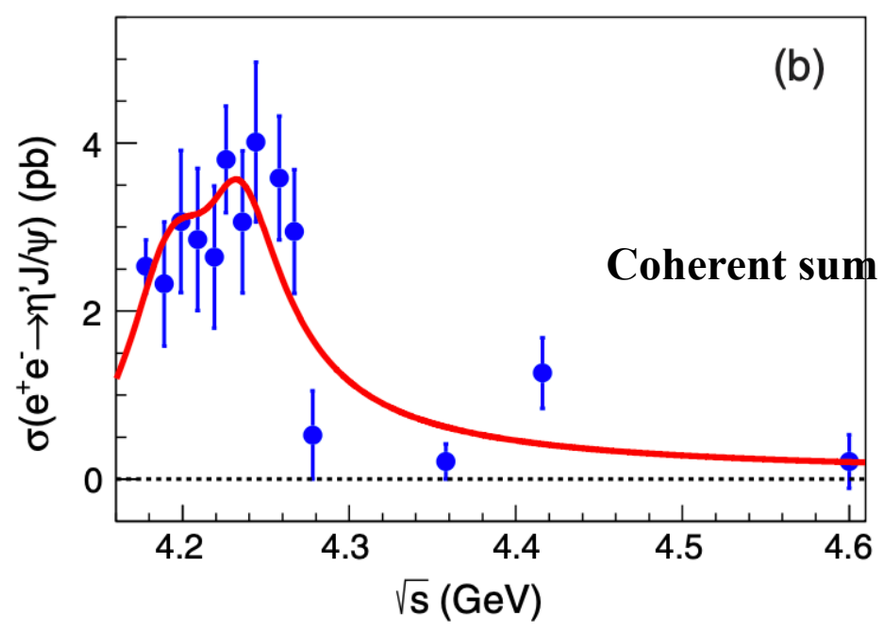
- **First time, we observe the decays of the Y (4220) and Y (4360) into ηJ/ψ final states.**

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

PRD 101, 012008 (2020)



Fit with single resonance

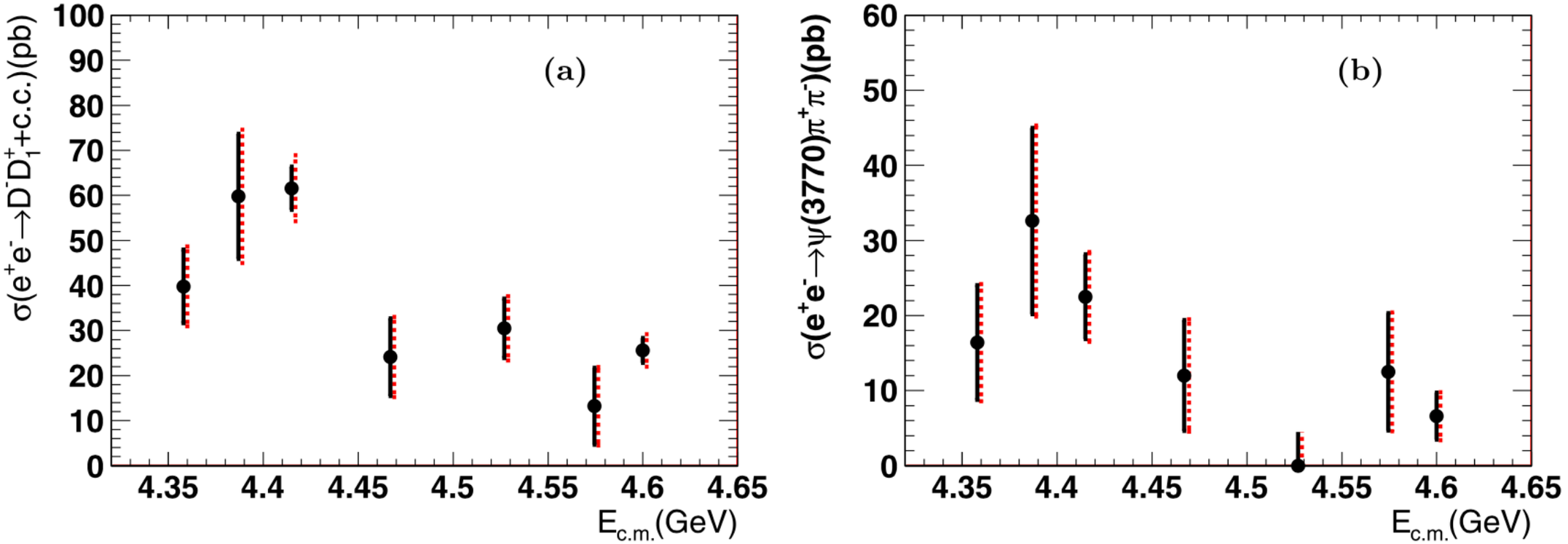


Coherent sum of $\psi(4160)$ and $\psi(4260)$ resonance

- **Using data from center-of-mass 4.178 to 4.600 GeV**
- **The dependence of the cross section on shows an enhancement around 4.2GeV**
- **The shape of the cross section cannot be fully explained with single $\psi(4160)$ or $\psi(4260)$**

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

PLB 804 (2020) 135395



- Using data from center-of-mass 4.3 to 4.6GeV
- There are some indications of enhanced cross sections for both processes between 4.36 and 4.42GeV

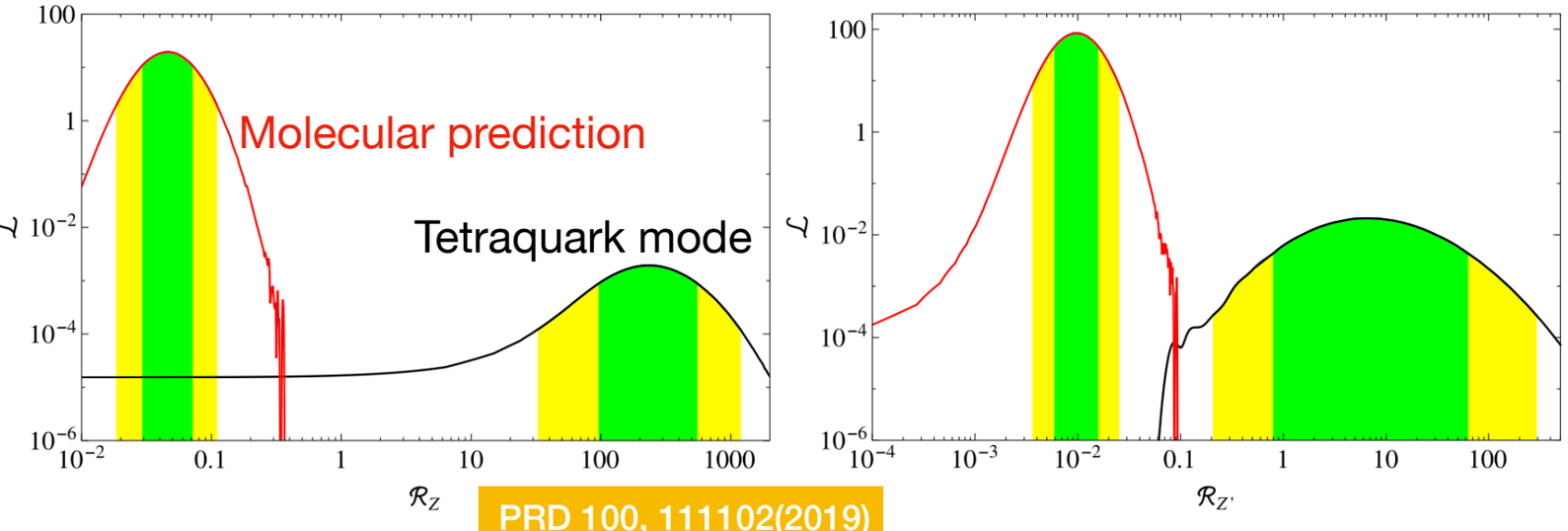
The Zc states

i. $Z_c^{(\prime)} \to \rho\eta_c$

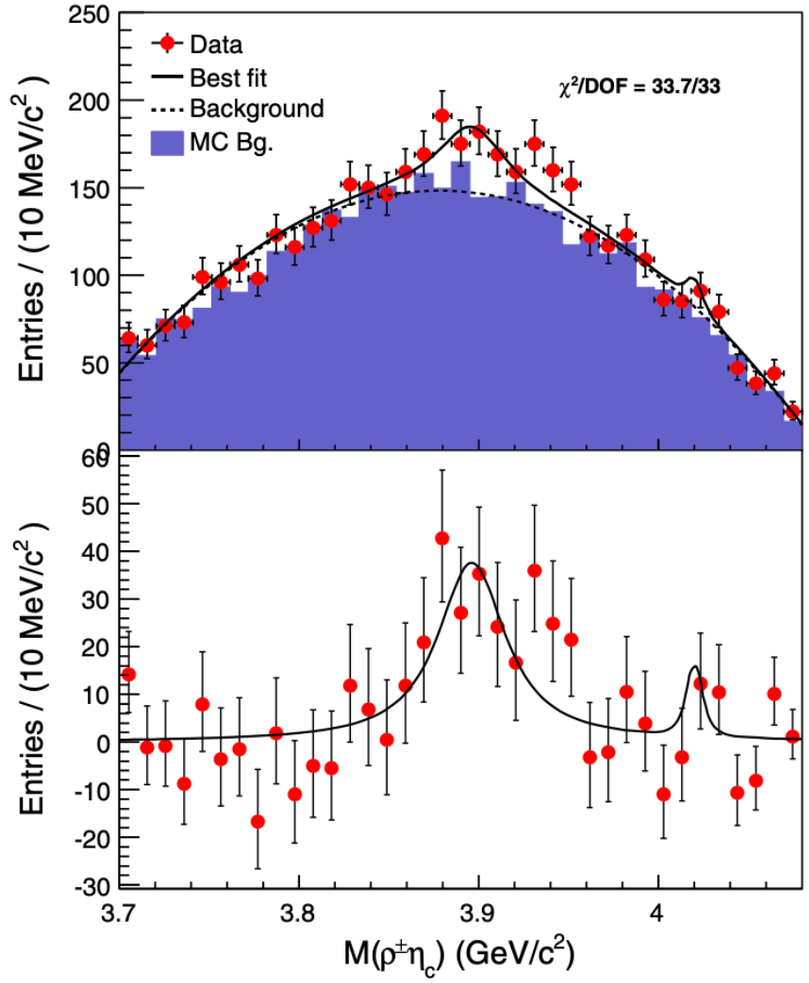
ii. $Z_c(3900)^0 \to \pi^0 J/\psi$ **in** $e^+e^- \to \pi^0\pi^0 J/\psi$

$Z_c^{(\prime)} \to \rho\eta_c$

PLB 746, (2015)194-201



PRD 100, 111102(2019)



- **Theoretical expectation the ratio of branch fraction:**

$$R_z = \frac{Br(Z_c \to \rho\eta_c)}{Br(Z_c \to \pi J/\psi)}, \quad R_{z'} = \frac{Br(Z_c' \to \rho\eta_c)}{Br(Z_c' \to \pi J/\psi)},$$

Can help us understand the nature of Zc, especially in molecular prediction and tetraquark model.

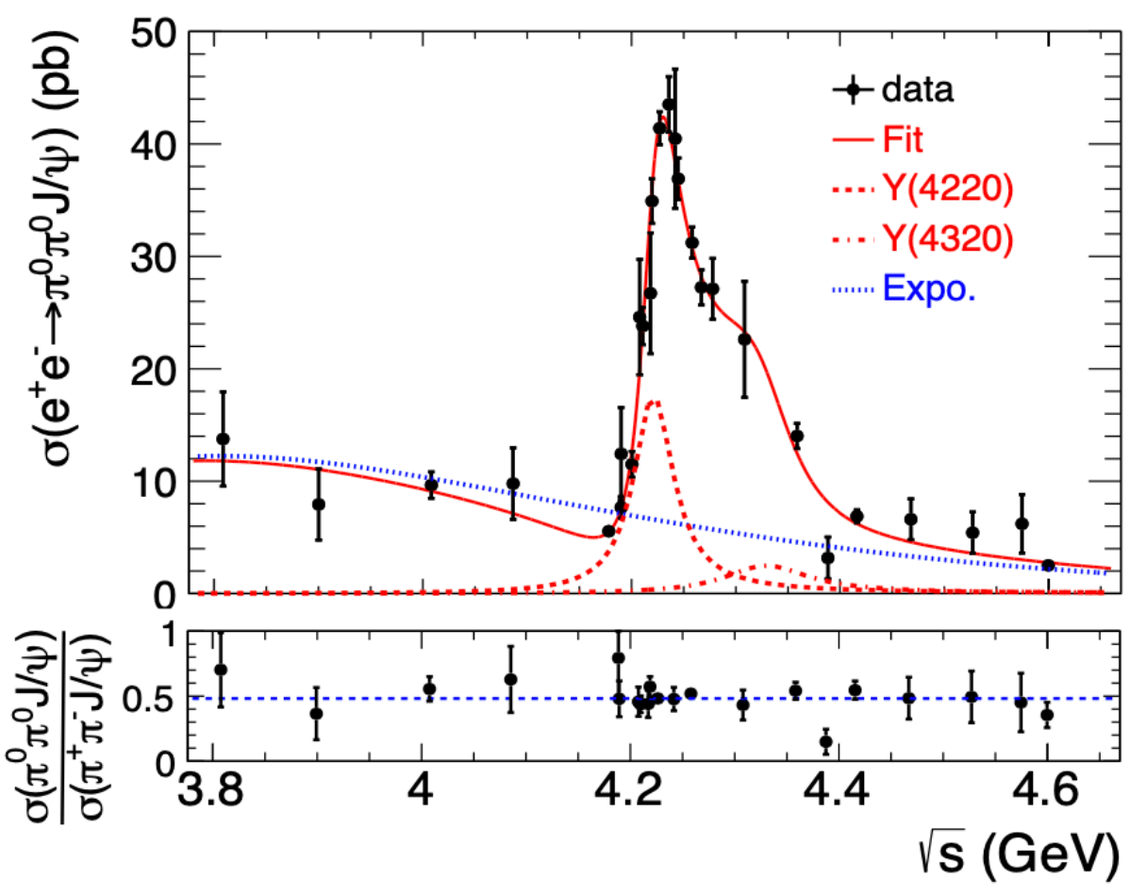
- **Study the process of with 5 energies between 4.20 to 4.6 GeV**
- **Nine decay channel to reconstruct η_c**
- **Strong evidence of $Z_c(3900)^\pm \to \rho^\pm\eta_c$ at $\sqrt{s} = 4.23$GeV(4.3σ)**
- **No significant $Z_c'(4020) \to \rho\eta_c$ observed**
- **R_z=2.3, This measurement does not agree with molecular and tetraquark assumption.**

TABLE III. Comparison of the measured $R_{Z_c(3900)}$ and $R_{Z_c(4020)}$ with the theoretical predictions.

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]

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

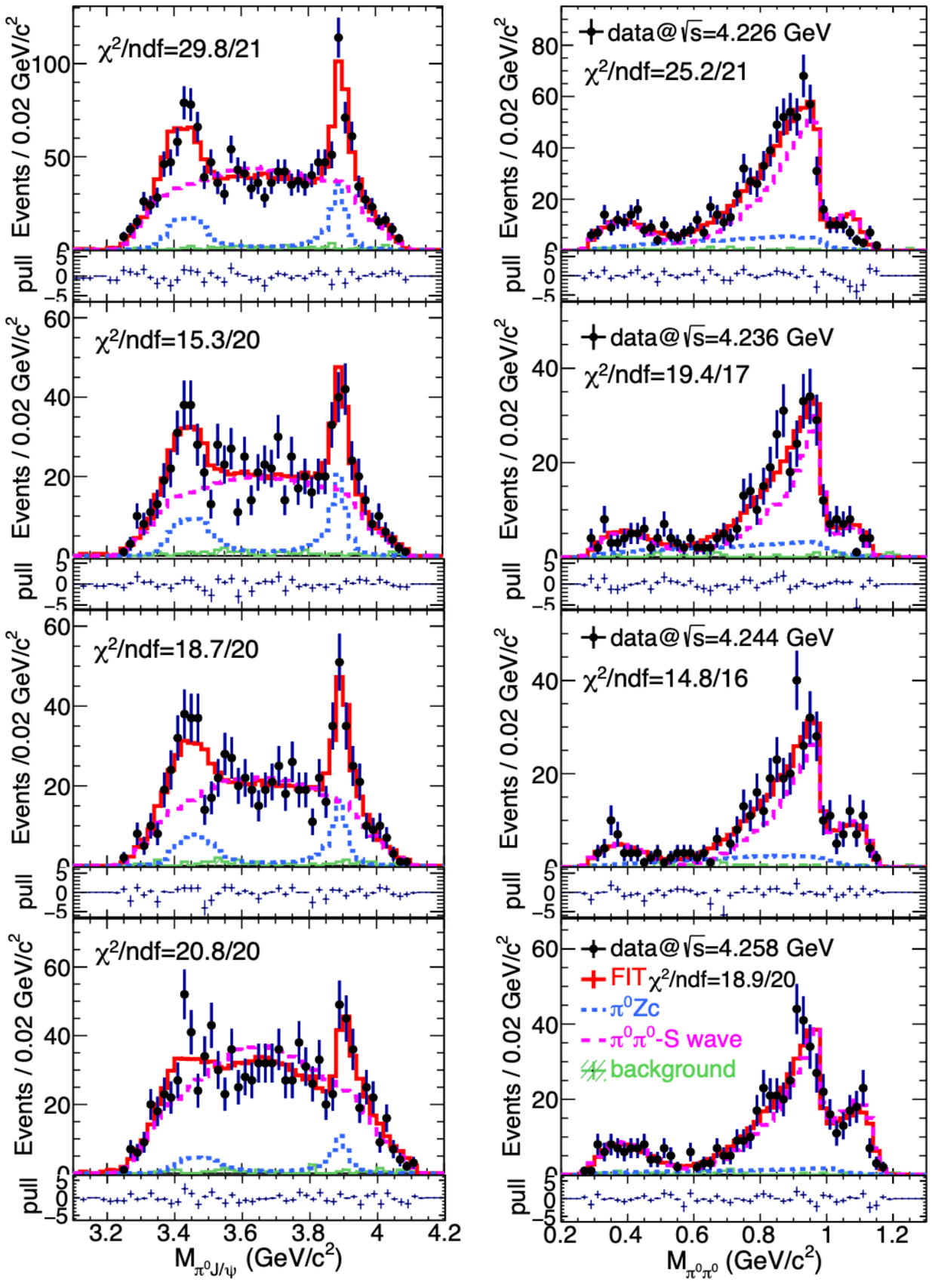
arXiv:2004.13788, submitted to PRD



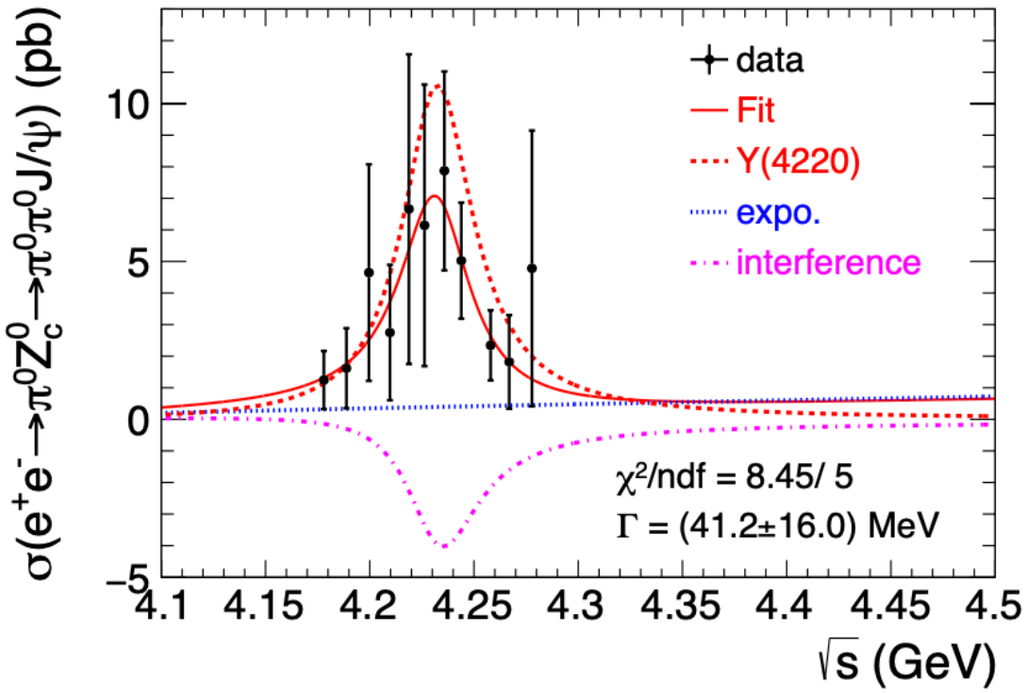
- **Using the center-of-mass energy between 3.81 and 4.60 GeV**
- **confirms the existence of the charmonium-like state Y (4220)**
- **Measured the mass and width:**

  $M = (4220.4 \pm 2.4 \pm 2.3) MeV/c^2, \quad \Gamma = (46.2 \pm 4.7 \pm 2.1) MeV$
- **Consistent with those measured in the process** $e^+e^- \to \pi^+\pi^- J/\psi$ PRL 118, 092001 (2017).

The average ratio of the cross section $e^+e^- \to \pi^0\pi^0 J/\psi$ to that of $e^+e^- \to \pi^+\pi^- J/\psi$ is 0.48 ± 0.02, which is consistent with isospin symmetry.



$\pi^0\pi^0$ S-wave contribution dominates.



- **Observed $Z_c(3900)^0$ in the $\pi^0 J/\psi$ invariant mass spectrum.**
- **the nominal fit includes the intermediate processes $e^+e^- \to \sigma J/\psi, f_0(980)J/\psi, f_0(1370)J/\psi$, and $\pi^0 Zc(3900)^0$.**
- **The spin-party of the $Z_c(3900)^0$is determined to be $J^P = 1^+$(with >9σ over other hypotheses)**
- **The mass and width:**
  $M = (3893.0 \pm 2.3)MeV/c^2, \quad \Gamma = (44.2 \pm 5.4)MeV$
- **Fit the Born cross section of $e^+e^- \to \pi^0 Z_c(3900)^0 \to \pi^0\pi^0 J/\psi$, get a structure with mass $(4231.9 \pm 5.3 \pm 4.9)MeV/c^2$and width $(41.2 \pm 16.0 \pm 16.4)MeV$,which compatible with Y(4220)**

The results indicate a strong correlation between the production of the Y (4220) and the Zc(3900)

Summary & Outlook

- **X states:**

  - **New decay modes observed in** $X(3872)$

- **Y states:**

  - **Measured the mass and width of Y(4220) and Y(4360) from the different processes**

- **Zc states:**

  - **Determined the** $Z_c(3900)^0$ $J^P = 1^+$

- $\sqrt{s} \geq 4.6GeV$ **data samples have been taken this year may help us understand Y(4660)**

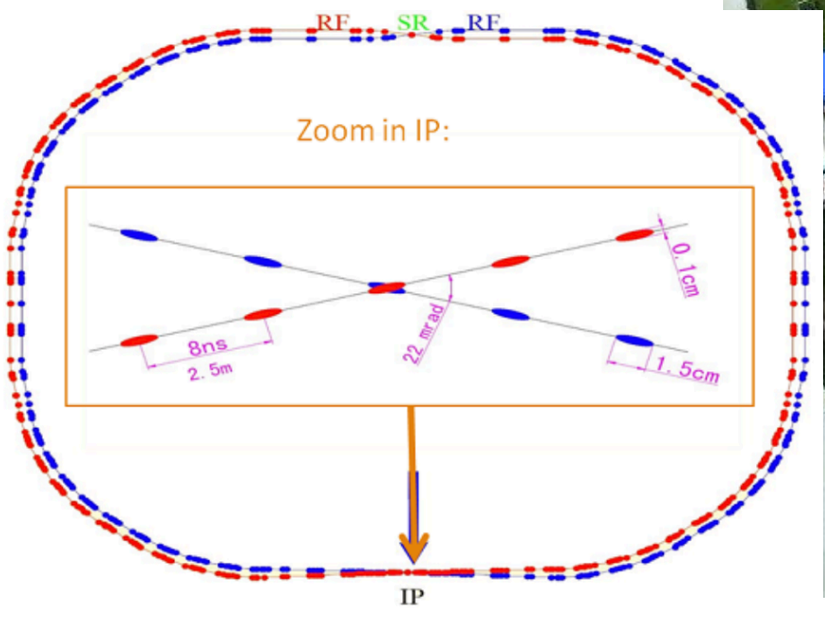
Back up

Beijing Electron and Positron Collider(BEPCII)

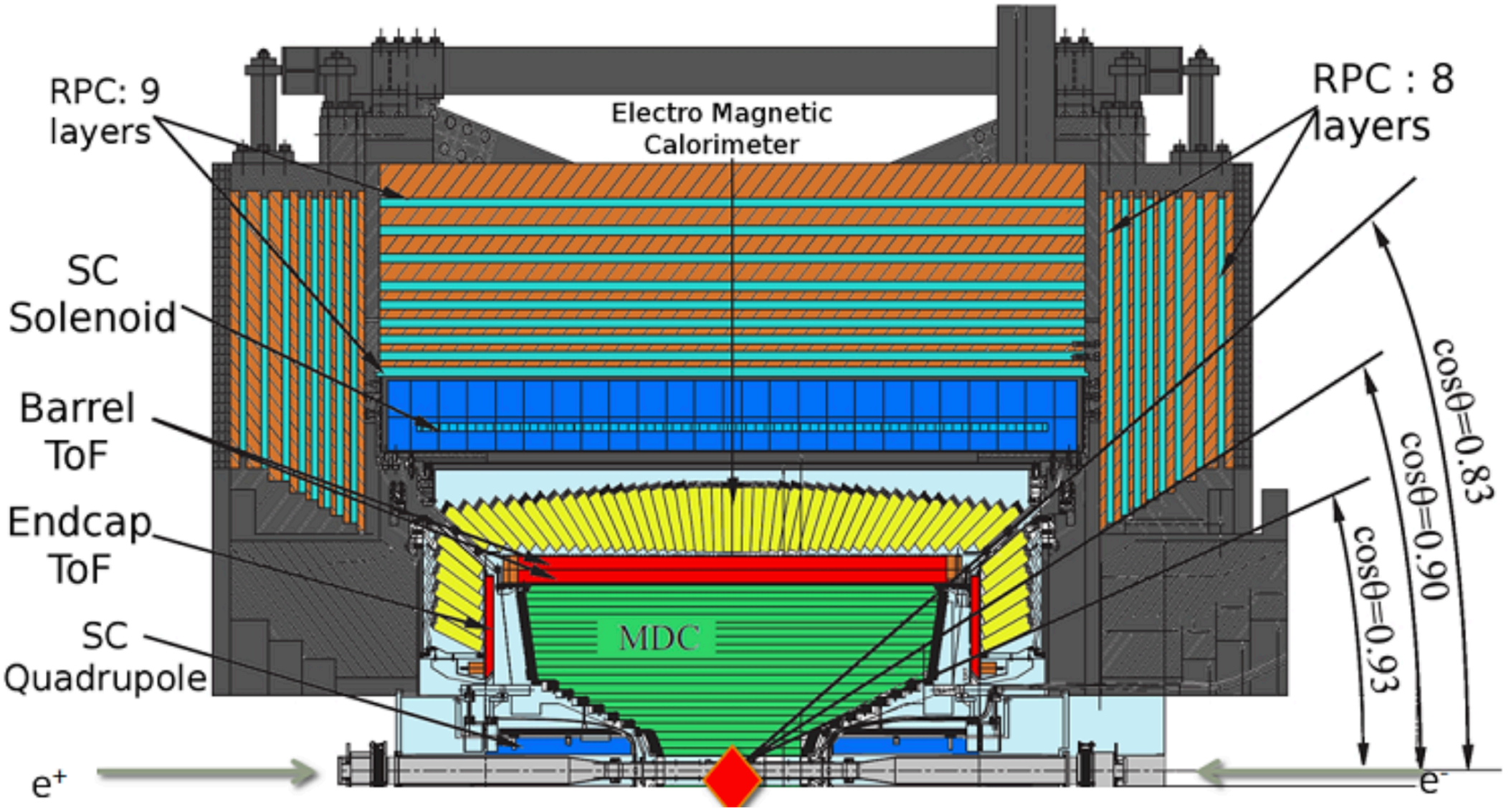
Beam Energy: 1~2.3 GeV(upgrade 2.45 GeV)

Crossing angle: ±11 mrad

Design luminosity: $10^{33}cm^{-2}s^{-1}$ at $\sqrt{s} = 3.78$ GeV(achieved in 2016)



Beijing Spectrometer (BESIII)



Inner to Outside:

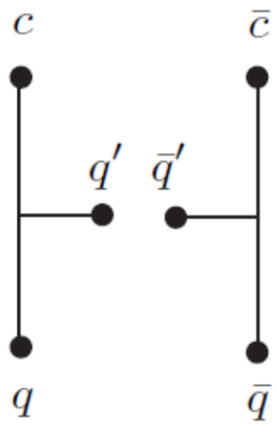
Main Drift chamber(MDC)
Time of flight System(TOF)
Electromagnetic Calorimeter(EMC)
Solenoid super-conducting magnet(SSM)
Muon chamber(MUC)

Y(4660) in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$

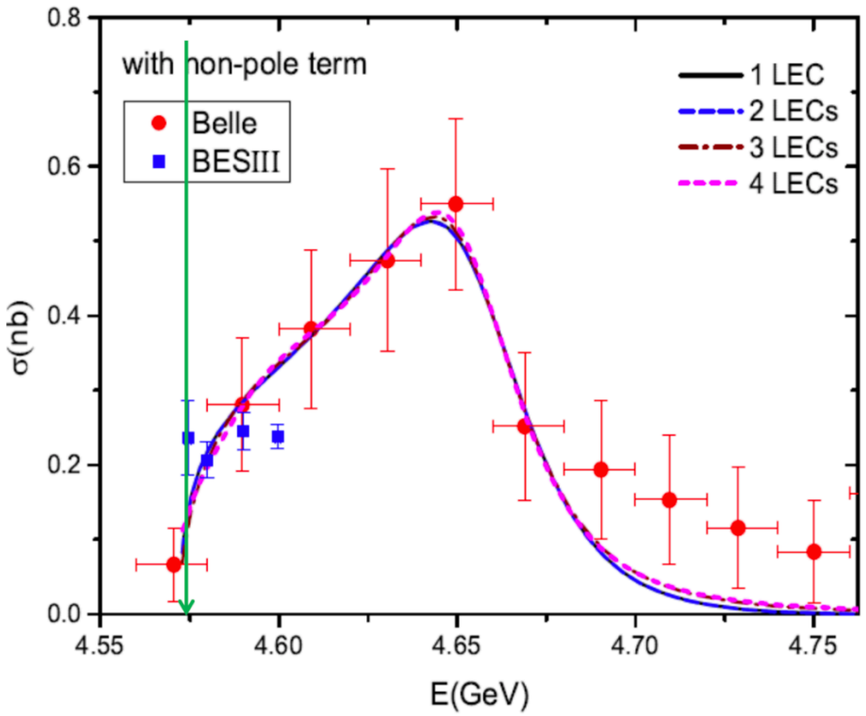
- $Y(4660) \to \pi^+\pi^-\psi(3686), \sigma_{peak}(e^+e^- \to \pi^+\pi^-\psi(3686)) \sim 0.04nb$
- $Y(4660) \to \Lambda_c^+\bar{\Lambda}_c^-, \sigma_{peak}(e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-) \sim 0.5nb$
- **Y(4660) baryonic coupling > 10 mesonic coupling** unexpected

Is Y(4660) a charm baryonium?

PRD 72, 031502(2005), PRL104, 132005(2010)



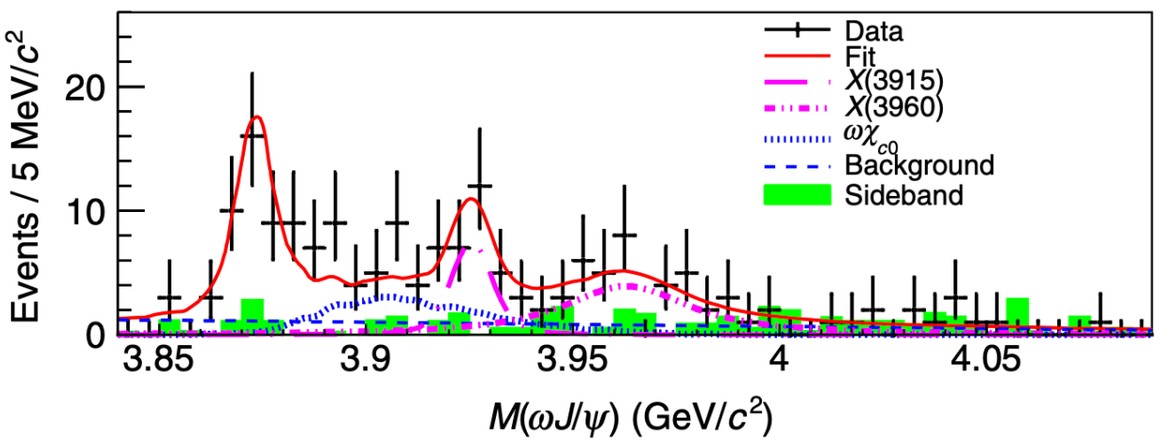
- **Using 10 decay processes to reconstruct Λc, $\sigma(e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-)$ is measured at 4 energy point**
- **Currently, BESIII and Belle does not agree so well**
- **The data above 4.6GeV is taking by BESIII, It will be helpful to confirm baryonium hypothesis.**

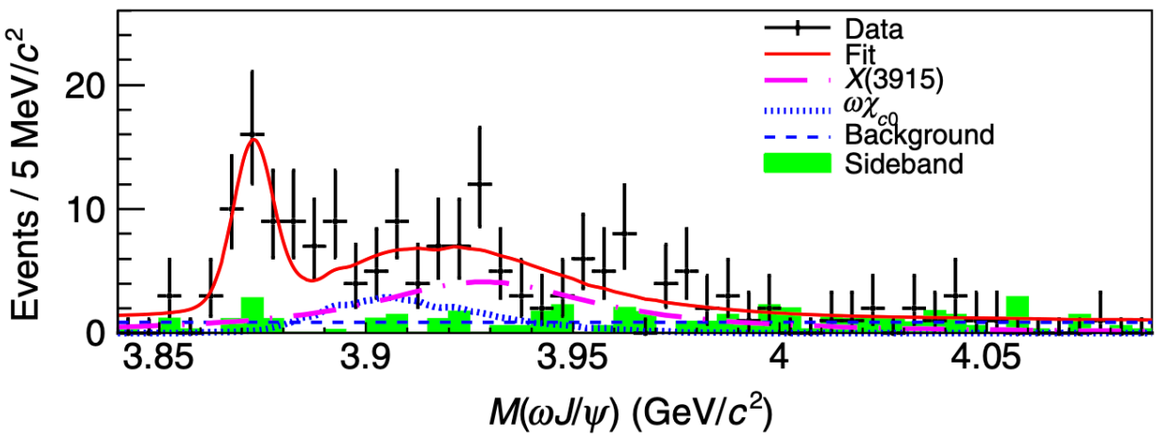


PRL101, 172001 (2008), PRL120, 132001 (2018), PRD 96, 116001 (2017)

$X(3872) \to \omega J/\psi$

PRL 122, 232002 (2019)





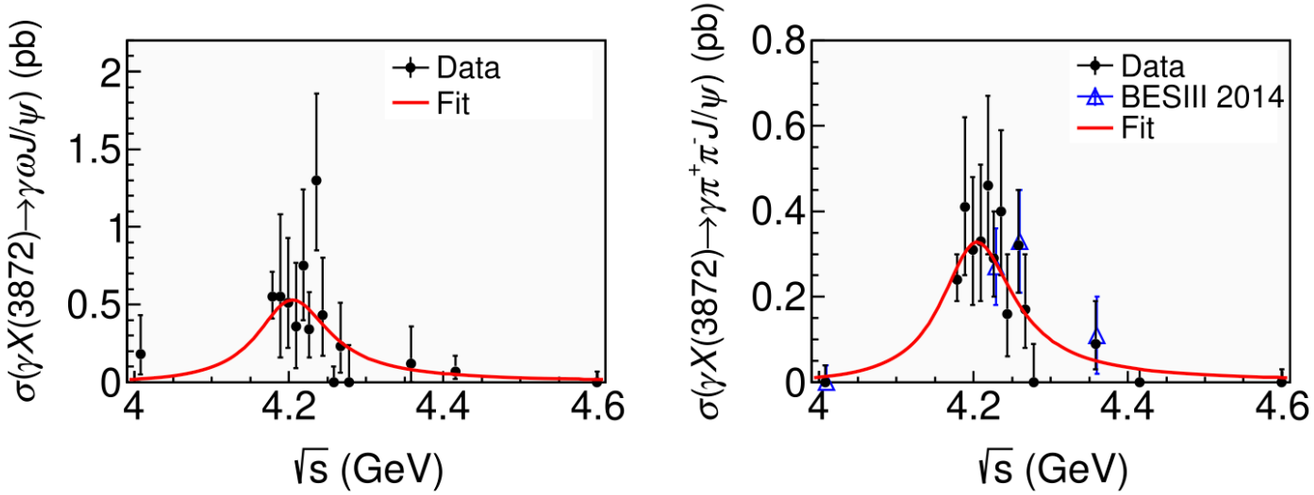
Up: Fit with X(3872)+ X(3915) + X(3960)

Bottom: fit with X(3872)+ X(3915)

- **Using data from center-of-mass from 4.008 to 4.6GeV**
- **BESIII observed** $X(3872) \to \omega J/\psi$ **in** $e^+e^- \to \gamma X(3872)$ **with > 5σ, including systematic error**
- **M[(X(3872)]=**$(3873.3 \pm 1.1 \pm 1.0)\ \mathrm{MeV/c^2}$
- **At least one additional resonance X(3915)**

Relative decay ratio: $R = \dfrac{B[X(3872) \to \omega J/\psi]}{B[X(3872) \to \pi^+\pi^- J/\psi]} = 1.6^{+0.4}_{-0.3} \pm 0.2$

Provide important input for the hadronic molecule interpretation for the X(3872) resonance



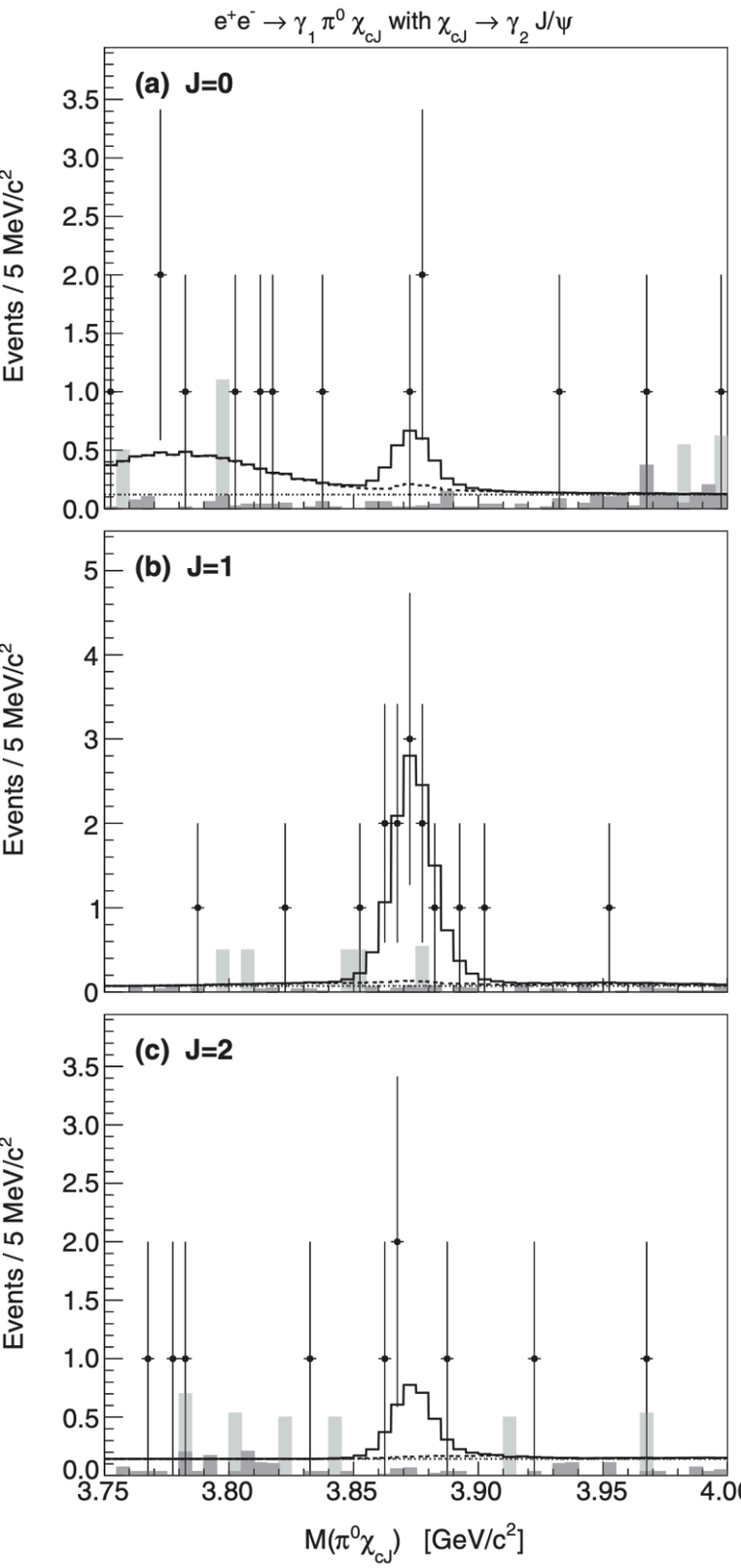
Simultaneous fit to the cross section of $\gamma X(3872) \to \gamma\omega J/\psi$ **and** $\gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$ **with single Breit-Wigner resonance**

$M[Y(4200)] = 4200.6^{+7.9}_{-13.2} \pm 3.0\ \mathrm{MeV/c^2}$, $\Gamma[Y(4200)] = 115^{+38}_{-26} \pm 12\ \mathrm{MeV}$

agree with $\psi(4160)$ or Y(4220)

$X(3872) \to \pi^0 \chi_{c1}$

PRL 122, 202001 (2019)



- A clear X(3872) signal is seen within the range of 4.15< Ecm < 4.30 GeV(data from 4.0 to 4.6 GeV)
- First observation of $X(3872) \to \pi^0 \chi_{c1}(1P)$ with statistical significance 5.2σ
- No signal for χ_{c0} and χ_{c1}

$$R_j = \frac{B(X(3872) \to \pi^0 \chi_{cj})}{B(X(3872) \to \pi^+\pi^- J/\psi)}$$

R_0<19 (90% U.L.)

$R_1 = 0.88^{+0.33}_{-0.27} \pm 0.10$

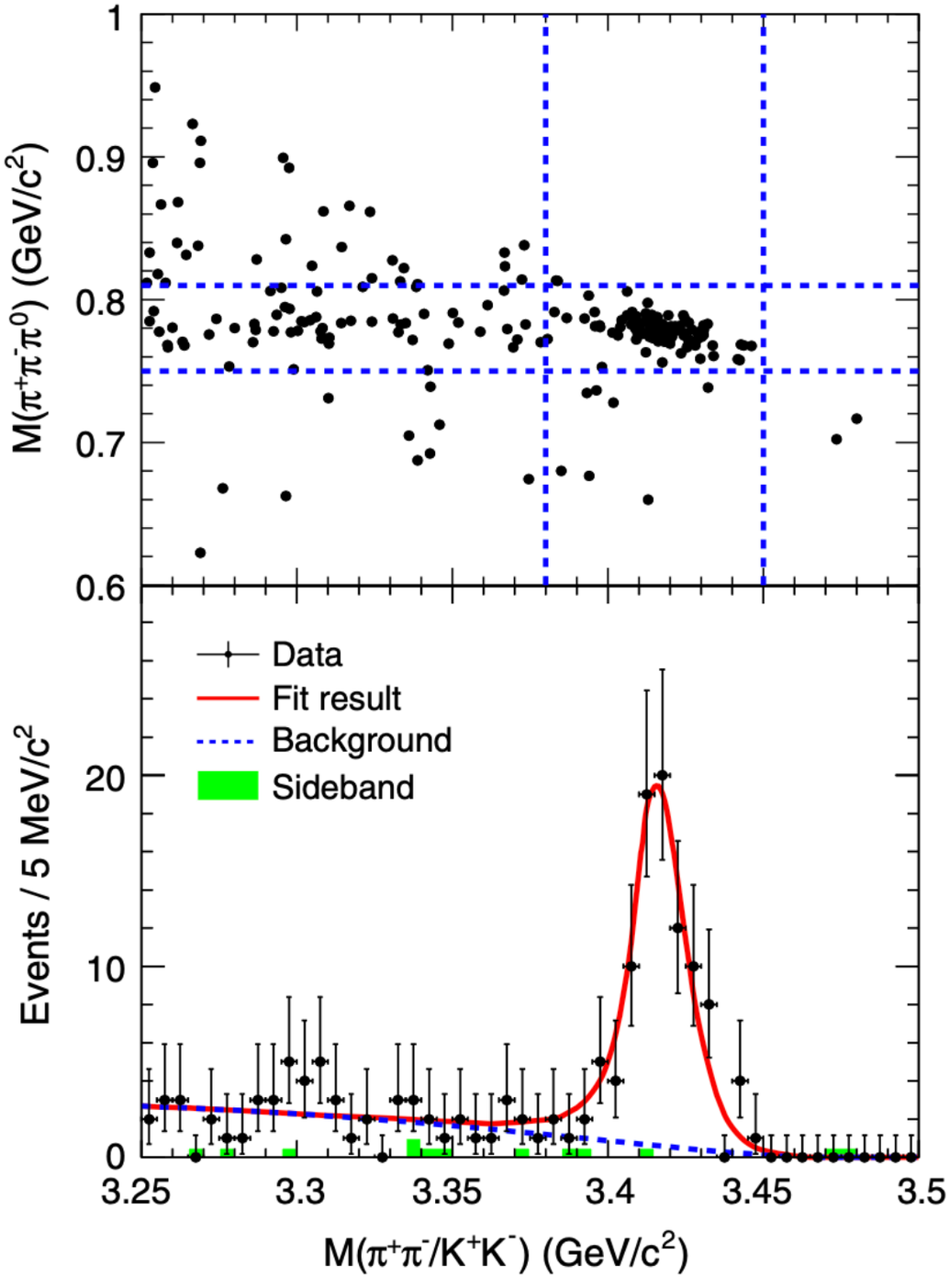
R_2<1.0 (90% U.L.)

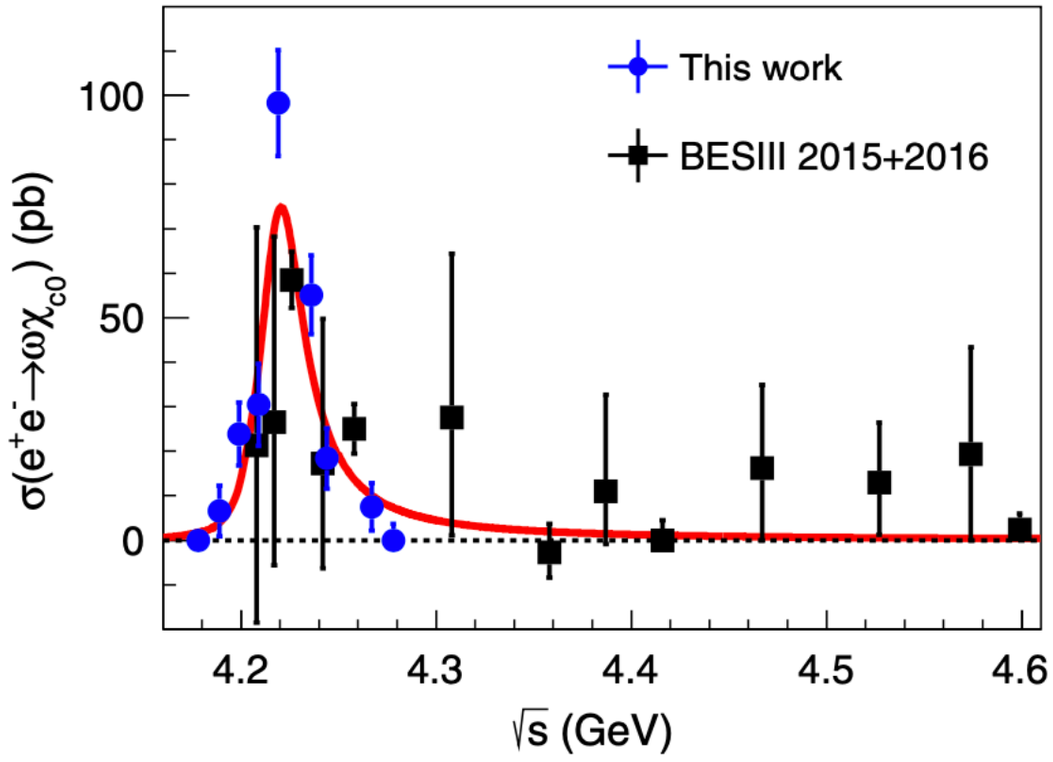
- If X(3872) is the $\chi_{c1}(2p)$ state of charmonium, then $\Gamma(X(3872) \to \pi^0 \chi_{c1}) \sim 0.06$ from PRD77,014013(2008)
- Using $Br(X(3872) \to \pi^+\pi^- J/\psi)$>3.2%, $Br(X(3872) \to \pi^+\pi^- J/\psi)$<6.4%, and R_1=0.88, we get $Br(X(3872) \to \pi^0 \chi_{c1})$ 3~6%, Which imply an unrealistically small $\Gamma_{ToT}(X(3872)) \sim 0.5 - 1$keV —>

Large R disfavor $\chi_{c1}(2P)$ interpretation of X(3872)

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

PRD 99, 091103(2019)



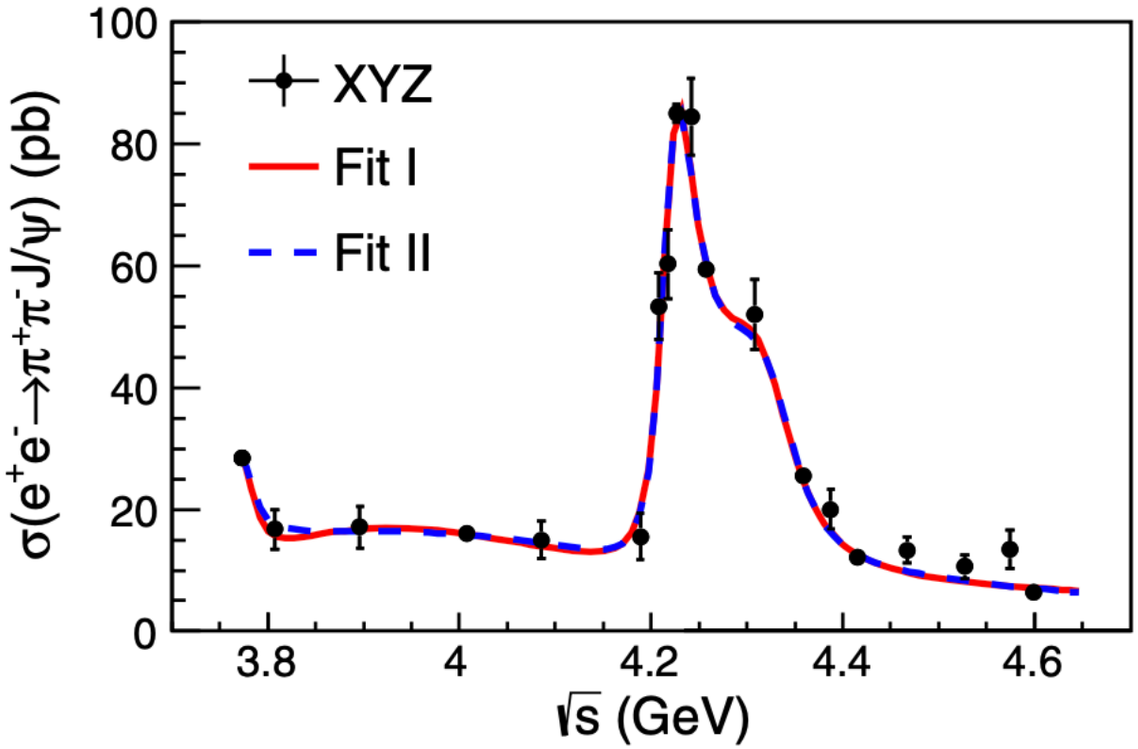


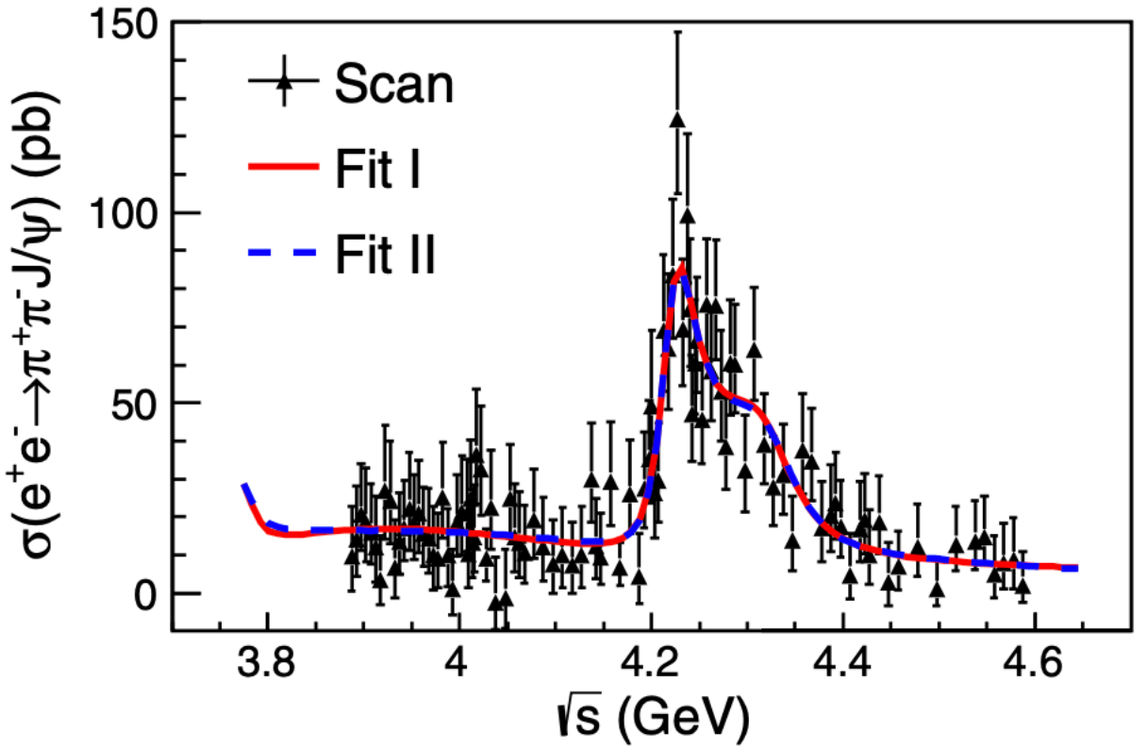
- **Using data from center-of-mass 4.178 to 4.278GeV**
- **Measured the cross section of $e^+e^- \to \omega\chi_{c0}$, $\omega \to \pi^+\pi^-\pi^0, \chi_{c0} \to \pi^+\pi^-/K^+K^-$ from 4.178 to 4.278GeV**
- $M_1 = 4218.5 \pm 1.6 \pm 4.0\text{MeV}, \quad \Gamma_1 = 28.2 \pm 3.9 \pm 1.6\text{MeV}$

confirms the result of previous study

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

PRL 118, 092001(2017)

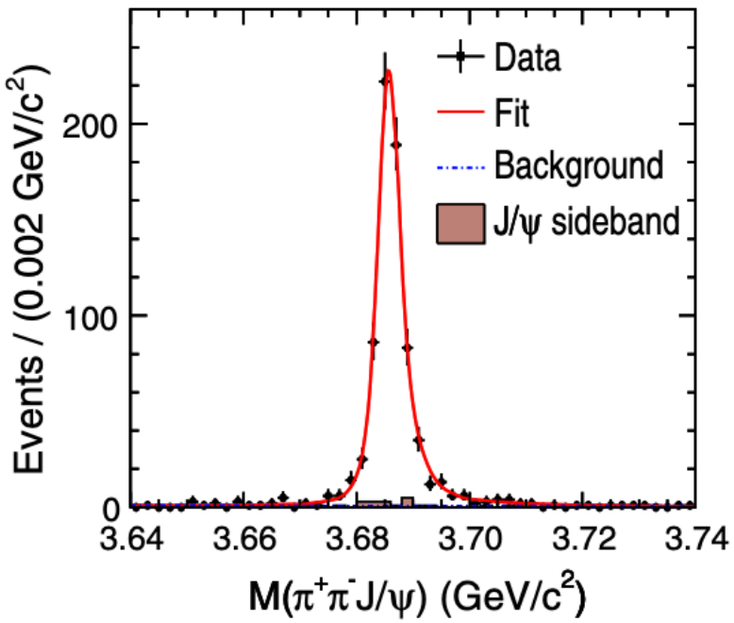


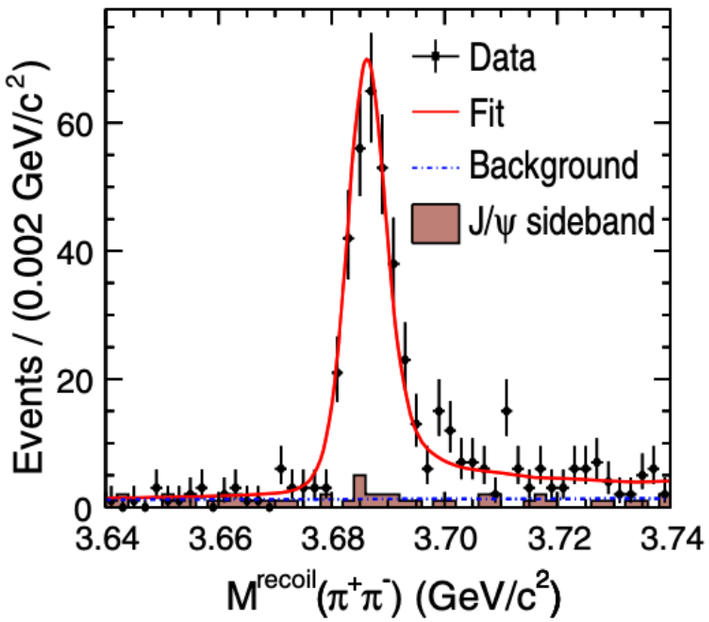


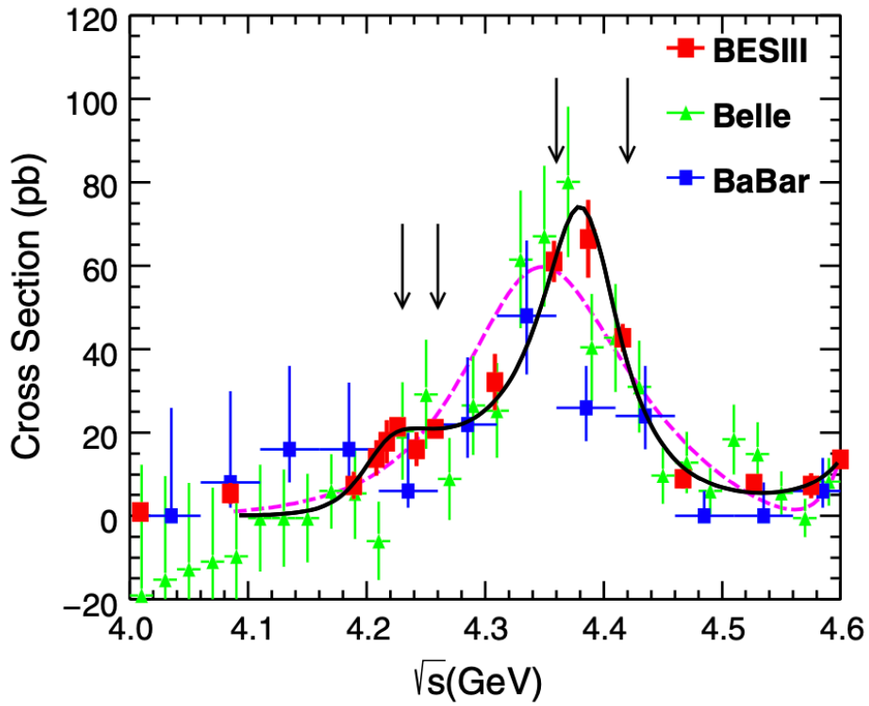
- **Simultaneous fit to XYZ data and R-scan data with the coherent sum of two BW like structure plus one incoherent** $\psi(3770)$
- $M_1 = 4222.0 \pm 3.1 \pm 1.4\text{MeV}, \quad \Gamma_1 = 44.1 \pm 4.3 \pm 2.0\text{MeV}$
- $M_2 = 4320.0 \pm 10.4 \pm 7.0\text{MeV}, \quad \Gamma_2 = 101.4^{+25.3}_{-19.7} \pm 2.0\text{MeV}$
- **7.6σ significance for two Breit-Wigner hypothesis than one Breit-Wigner**

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

PRD 96, 032004 (2017)



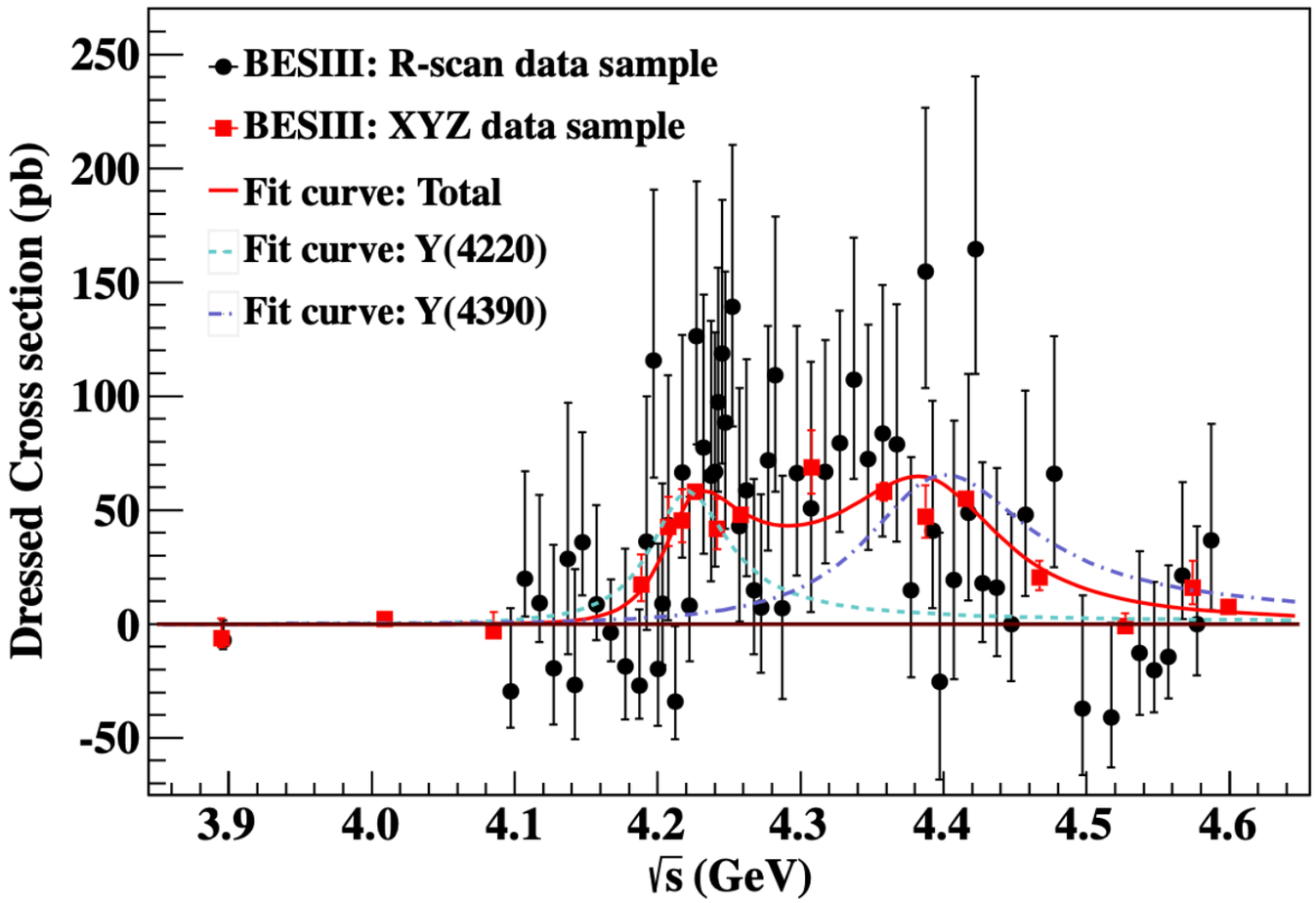




- **Using 5.1 fb^{-1} of data at 16 energy points from 4.008 to 4.600GeV measured the cross section of** $e^+e^- \to \pi^+\pi^-\psi(3686)$
- $M_1 = 4209.5 \pm 7.4 \pm 1.4\text{MeV}, \quad \Gamma_1 = 80.1 \pm 24.6 \pm 2.9\text{MeV}$ **(with 5.8σ)**
- $M_1 = 4383.8 \pm 4.2 \pm 0.8\text{MeV}, \quad \Gamma_1 = 84.2 \pm 4.2 \pm 0.8\text{MeV}$

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

PRL 118, 092002 (2017)



- **Measured dressed cross section of $e^+e^- \to \pi^+\pi^- h_c$ from 3.896 to 4.6GeV**
- **Fit the cross section with the coherent sum of two Breit-Wigner functions**
- $M_1 = 4218.4^{+5.5}_{-4.5} \pm 0.9\text{MeV}, \quad \Gamma_1 = 66.0^{+12.3}_{-0.83} \pm 0.4\text{MeV}$
- $M_2 = 4391.5^{+6.3}_{-6.8} \pm 1.0\text{MeV}, \quad \Gamma_2 = 139.5^{+16.2}_{-20.6} \pm 0.6\text{MeV}$