Recent Progress on the Charmonium and XYZ states at BESIII

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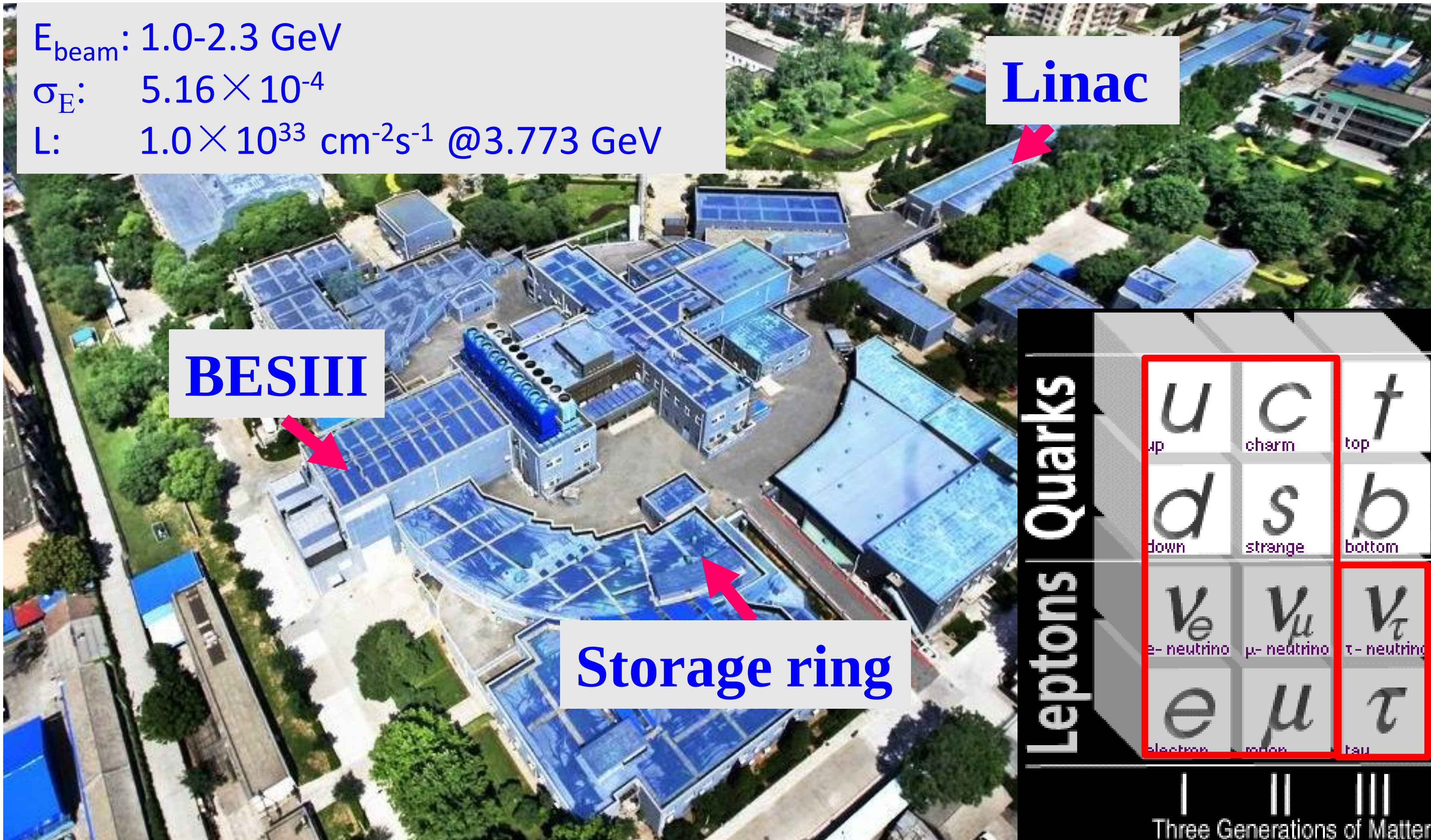
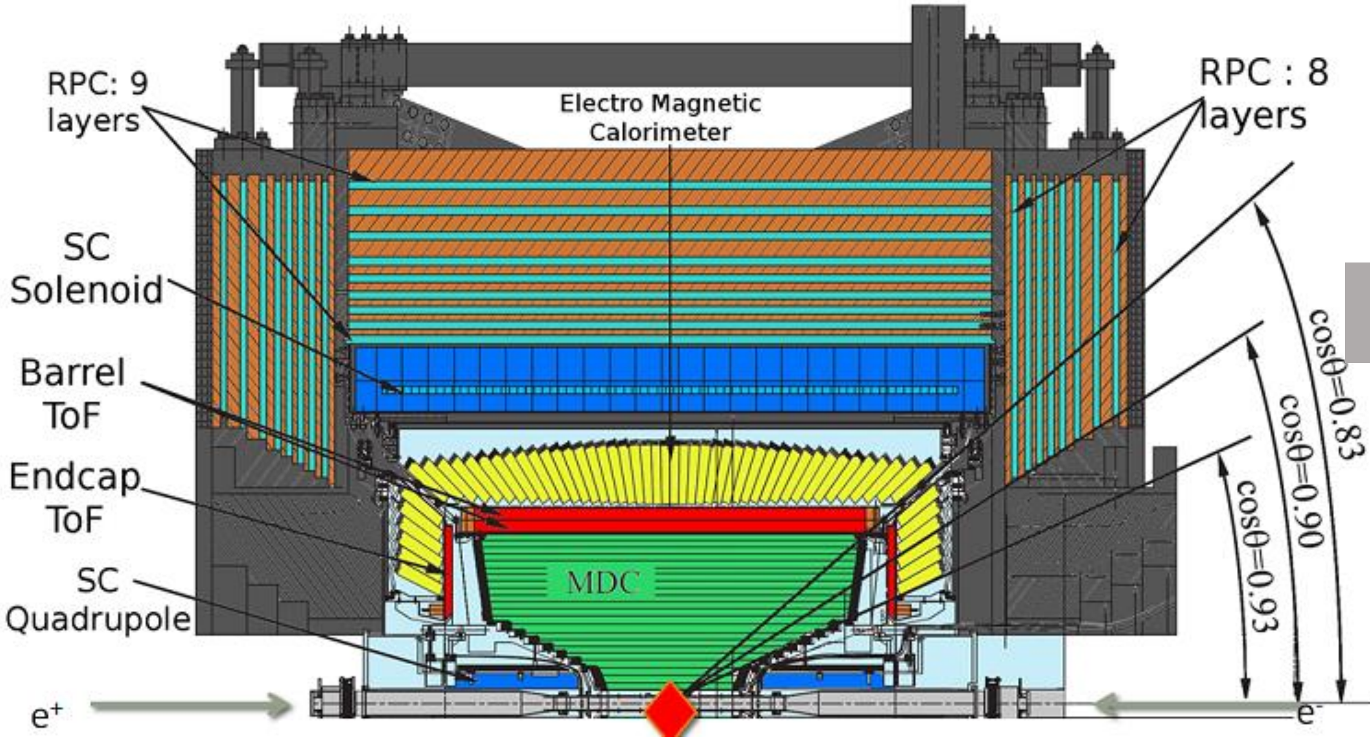
Beijing Electron Positron Collider (BEPCII)

E_{beam}: 1.0-2.3 GeV
σ_E: 5.16×10^{-4}
L: 1.0×10^{33} $cm^{-2}s^{-1}$ @3.773 GeV



BESIII detector



SC Magnet 1.0T

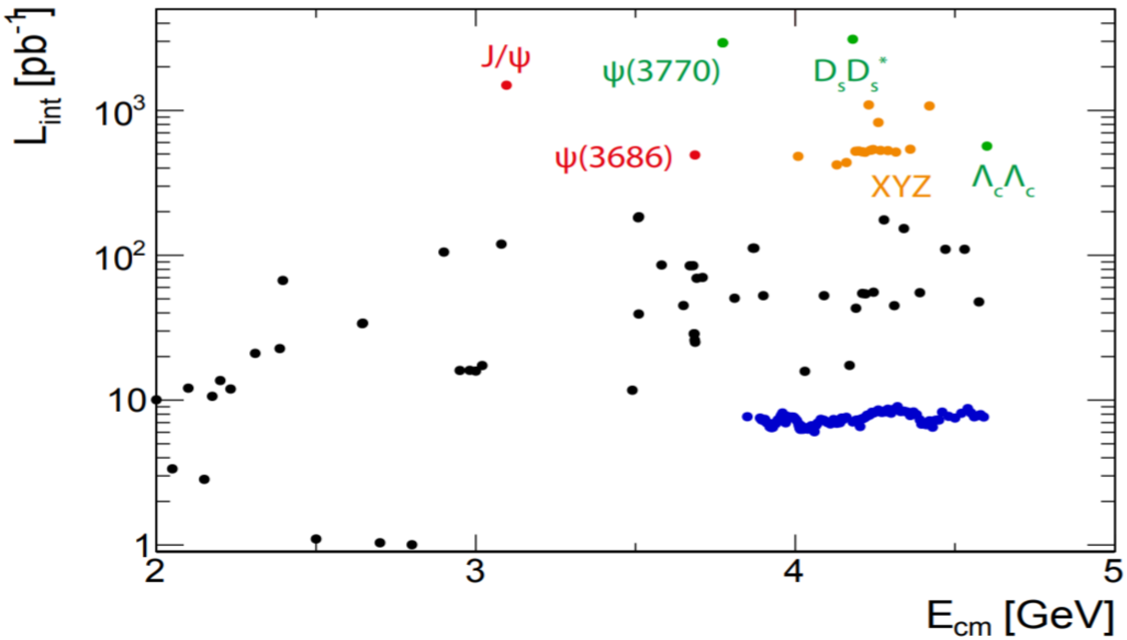
Main Drift Chamber
Small cell, 43 layer
σ_{xy}=130 μm, dE/dx~6%
σ_p/p = 0.5% at 1 GeV

Time Of Flight
Plastic scintillator
σ_T(barrel): 80 ps
σ_T(endcap): 110 ps
(endcap update with MRPC σ_T:65 ps)

Electromagnetic Calorimeter
CsI(Tl): L=28 cm (15X_0)
Energy range: 0.02-2GeV
Barrel σ_E 2.5%, σ_l 6mm
Endcap σ_E 5.0%, σ_l 9mm

Muon Counter
Resistive plate chamber
Barrel: 9 layers
Endcaps: 8 layers
$\sigma_{spatial}$: 1.48 cm

Data sets for Charmonium and XYZ study



- World largest data samples on J/ψ (~10 billion), $\psi(3686)$ (~0.45 billion)
- **XYZ data:**
  - 5 fb^{-1} e^+e^- collision data event in open charm region from 3.8 to 4.6 GeV in 2013
  - totally ~13 fb^{-1} data taken in 4.0~4.60 GeV, more data samples are being taken this year (~3.8 fb^{-1})
- **R-scan data:** 104 energy points from 3.85 to 4.59 GeV, integrated luminosity~ 0.79 fb^{-1}

The Charmonium System

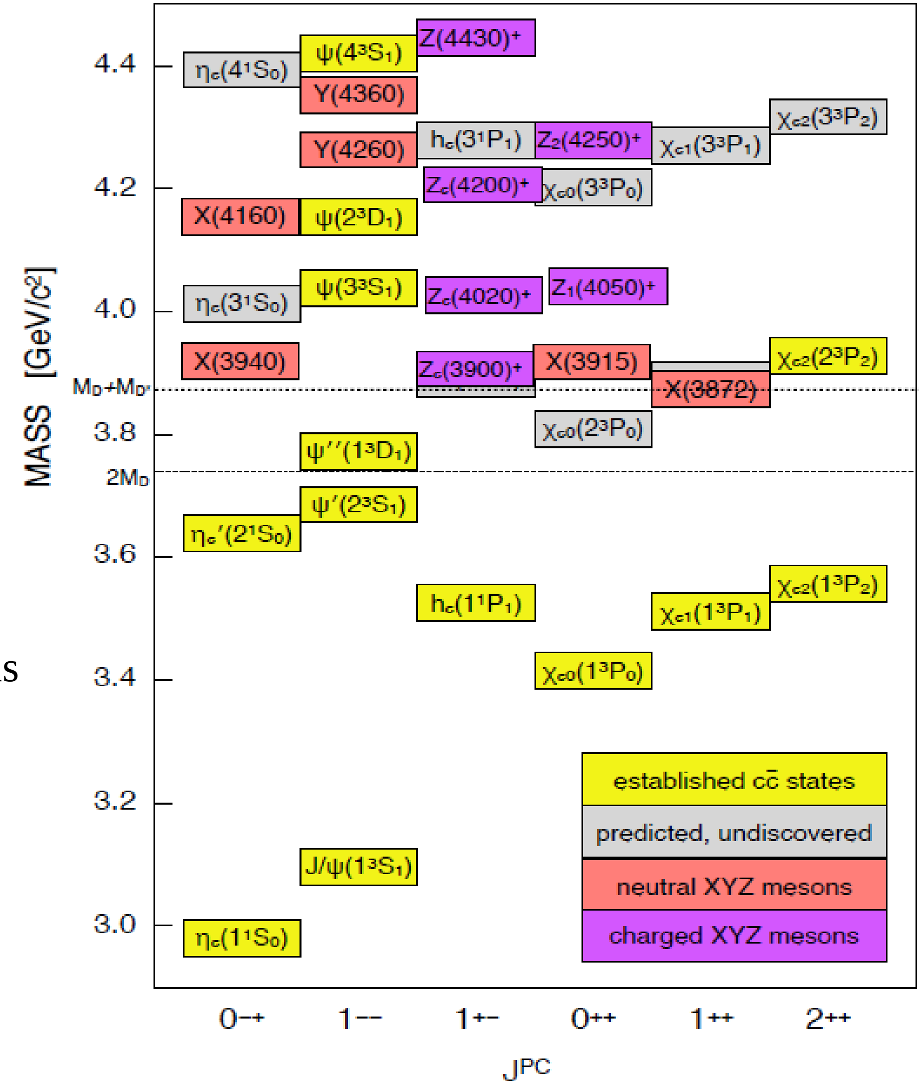
- $c\bar{c}$ bound states can be described using potential models
- All predicted states below the $D\bar{D}$ threshold have been found!
- Properties are in agreement with predictions
- Many unpredicted states were reported above the $D\bar{D}$ threshold, called "*XYZ*" states

- "XYZ" states
  - "X": Neutral, $J^{pc} \neq 1^{--}$

    Observed in radiative or hadronic transitions from Y.
  - "Y": Neutral, $J^{pc} = 1^{--}$

    Direct access in e^+e^-annihilation.
  - "Z": isospin triplets

    Observed in hadronic transitions from Y.



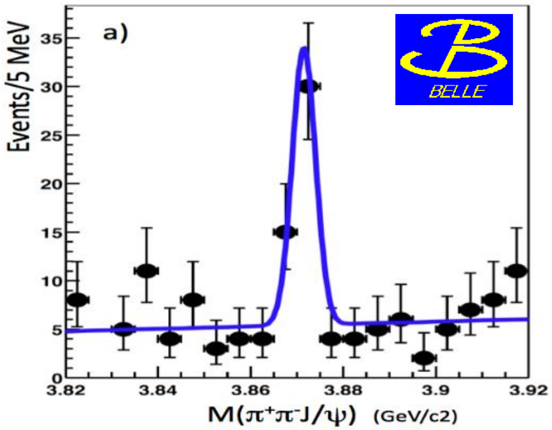
Recently highlight results in Charmonium and XYZ

- ✓ Observation of $X(3872) \to \pi^0 \chi_{c1}(1P)$ arXiv:1901.03992(accepted by PRL)
- ✓ Observation of $X(3872) \to \omega J/\psi$ arXiv:1903.04695(accepted by PRL)
- ✓ Open charm and radiative decay transitions of X(3872) (BESIII preliminary)
- ✓ Resonant structure in $e^+e^- \to \pi^+ D^0 D^{*-}$ Phys. Rev. Lett. 122, 102002 (2019)
- ✓ Resonant structure in $e^+e^- \to \omega \chi_{c0}$ Phys. Rev. D 99, 091103 (2019)
- ✓ Observation of $e^+e^- \to \pi^+\pi^-\psi$(3770) and $D_1(2420)\bar{D}$ arXiv: 1903.08126v1(submit to PRD)
- ✓ Evidence for $Z_c(3900) \to \rho^+\eta_c$ (BESIII preliminary) [in BACKUP]

The $X(3872)$ state

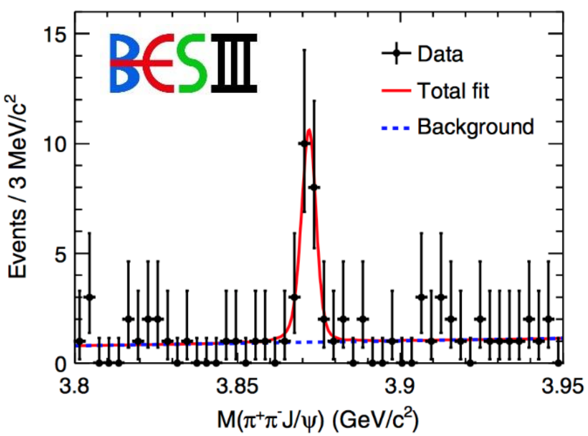
- **Discovery of $X(3872)$** ($J^{PC} = 1^{++}$)
  - First observed by Belle in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decay
  - Observed in $X(3872) \to \gamma J/\psi$ process by Babar and Belle
  - Evidence of $X(3872) \to \omega J/\psi$ reported by Belle and Babar
  - M(X(3872))=3871.69$\pm$0.17 MeV/c^2
  - $\Gamma < 1.2$ MeV (90% C.L.)
  - **At BESIII**, $X(3872)$ is observed via $e^{+}e^{-} \to \gamma X(3872) \to \gamma\pi^{+}\pi^{-}J/\psi$

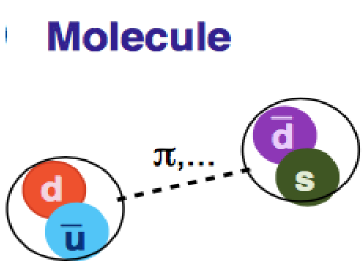
PRL. 92, 262001 (2003)



- **Possible configuration** for $X(3872)$
  - Conventional Charmonium state? χ_{c1}'?
  - Molecule-like $X(3872) = (D^{*0}\overline{D}^{0} + D^{0}\overline{D}^{*0})/\sqrt{2}$
  - Tetraquark
  - …

PRL. 112, 092001 (2014)

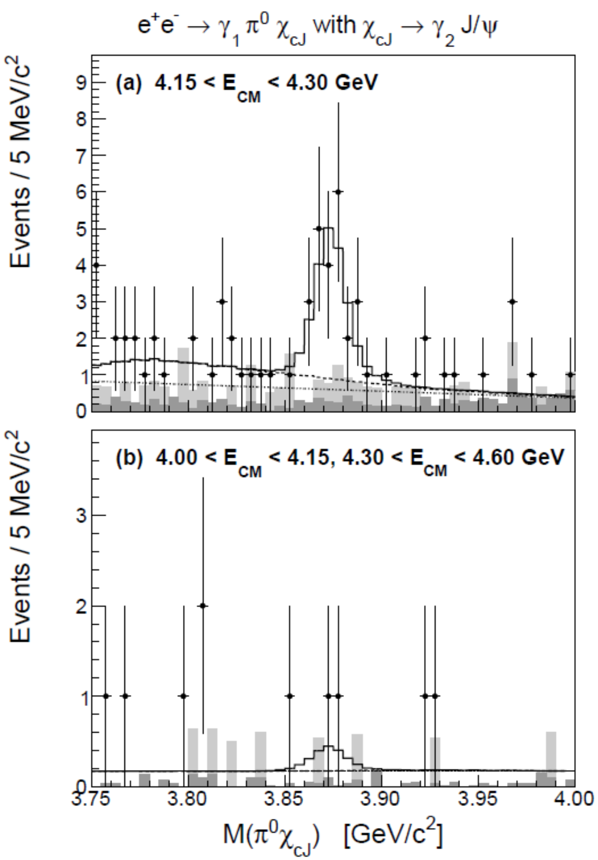


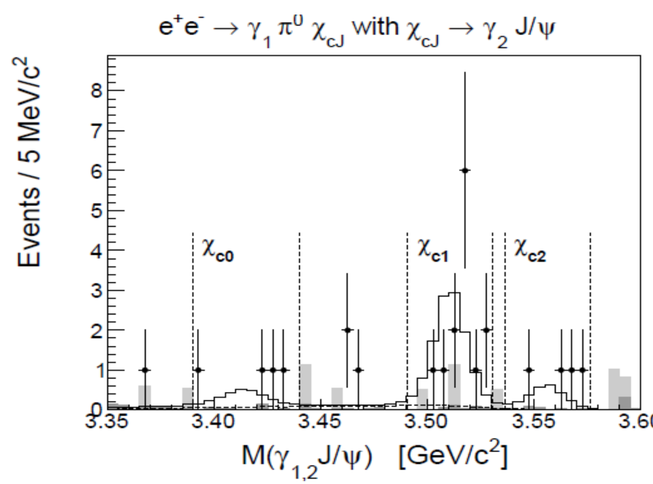


$X(3872) \to \pi^0 \chi_{c1}(1P)$

arXiv:1901.03992 (accepted by PRL)

- Data sample: 9.0 fb^{-1} data from 4.15 to 4.30 GeV
- Reconstructed processes:
  - Signal channel: $e^+e^- \to \gamma X(3872)$, $X(3872) \to \pi^0 \chi_{cJ}$ (with $\chi_{cJ} \to \gamma J/\psi$, $J/\psi \to l^+l^-$)





Clear signal of $X(3872)$ in Y(4260) zone, $N_{X(3872)} = 16.9^{+5.2}_{-4.9}$

No $X(3872)$ events outside of $Y(4260)$ zone

Clear cluster of $\chi_{c1}(1P)$ events in X(3872) mass window

First observation of $X(3872) \to \pi^0 \chi_{c1}(1P)$ with significance $>5\sigma$.

$X(3872) \to \pi^0 \chi_{c1}(1P)$

arXiv:1901.03992 (accepted by PRL)

- In conventional $c\bar{c}$ hypothesis, $\Gamma(X(3872) \to \pi^0 \chi_{c1})$~0.06 keV PRD 77, 014013(2008)
- In tetraquark/molecular state hypothesis, the decay width could be sizeable. PRD 92, 034019 (2015)

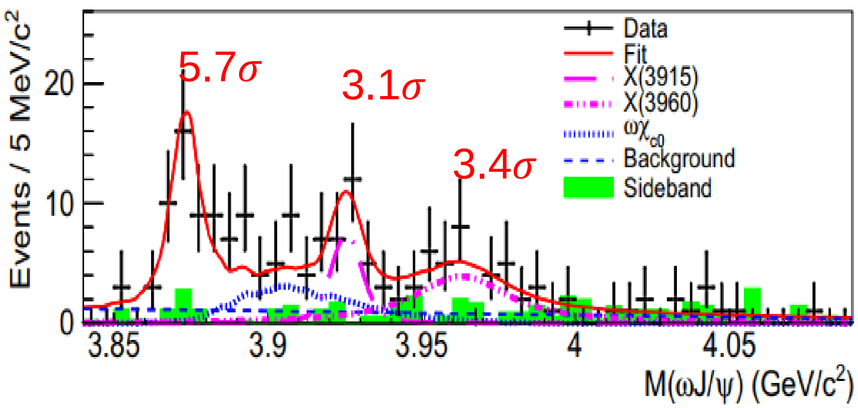
	$\pi^+\pi^- J/\psi$	$\pi^0\chi_{c0}$	$\pi^0\chi_{c1}$	$\pi^0\chi_{c2}$
Event yield	$84.1^{+10.1}_{-9.4}$	$1.9^{+1.9}_{-1.3}$	$10.8^{+3.8}_{-3.1}$	$2.5^{+2.3}_{-1.7}$
Signal significance (σ)	16.1	1.6	5.2	1.6
Efficiency (no ISR) (%)	32.3	8.8	14.1	12.8
Efficiency ratio (with ISR)	...	0.272	0.435	0.392
$\mathcal{B}(\chi_{cJ} \to \gamma J/\psi) \times \mathcal{B}(\pi^0 \to \gamma\gamma)$ (%)	...	1.3	33.5	19.0
Total systematic error (%)	...	17.0	11.9	9.4
$\mathcal{B}(X \to \pi^0\chi_{cJ})/\mathcal{B}(X \to \pi^+\pi^- J/\psi)$	...	$6.6^{+6.5}_{-4.5} \pm 1.1$ (19)	$\boxed{0.88^{+0.33}_{-0.27} \pm 0.10}$	$0.40^{+0.37}_{-0.27} \pm 0.04$ (1.1)

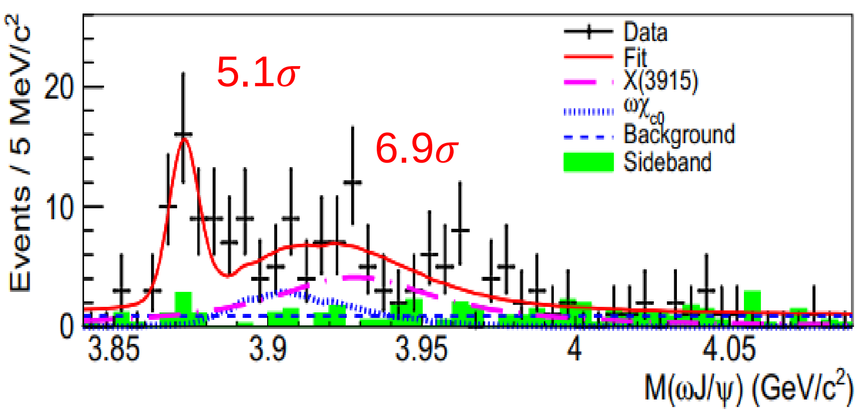
- Using $3.3\% < \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$<6.4%: $\mathcal{B}(X(3872) \to \pi^0\chi_{c1})$ ~3-6%.
- If $X(3872)$ interpret as $\chi_{c1}(2P)$: $\Gamma\left(X(3872)\right)$~1.0-2.0 keV, which is orders of magnitude smaller than all other observed charmonium states.
- This measurement disfavors the $c\bar{c}$ interpretation of $X(3872)$

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

arXiv:1903.04695 (accepted by PRL)

- Data sample: 11.6 fb^{-1} data from 4.008 to 4.600 GeV
- Signal process: $e^+e^- \to \gamma X \to \gamma\omega J/\psi$, with $\omega \to \pi^+\pi^-\pi^0$, $J/\psi \to l^+l^-$





- An unbinned maximum-likelihood fit performed to $\omega J/\psi$.
- Signal PDF:
- ✓ Three resonances hypothesis: (X(3872), X(3915) and X(3960))

  $N_{sig}(X(3872)) = 45 \pm 9 \pm 3$

- ✓ Two resonance hypothesis: (X(3872), X(3915))

  $N_{sig}(X(3872)) = 40 \pm 8 \pm 2$

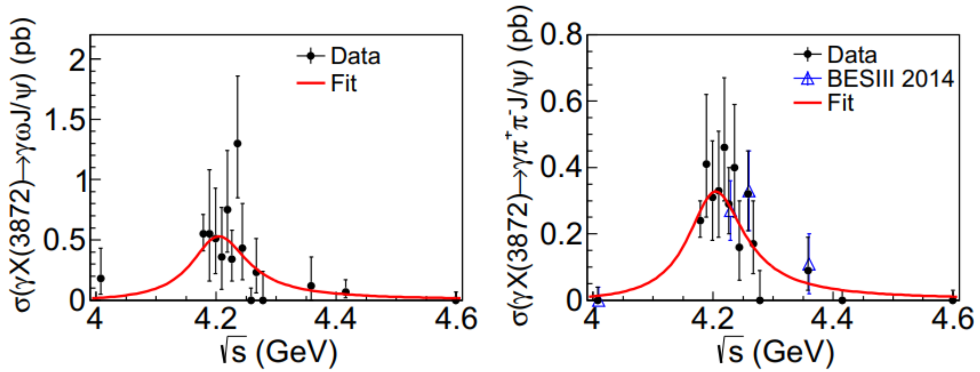
	Mass	Width
$X(3872)$	3873.3 ± 1.1 (3872.8 ± 1.2)	1.2 (1.2)
$X(3915)$	3926.4 ± 2.2 (3932.6 ± 8.7)	3.8 ± 7.5 (59.7 ± 15.5)
$X(3960)$	3963.7 ± 5.5	33.3 ± 34.2

Hard to distinguish the two hypotheses since only 2.5σ difference.

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

arXiv:1903.04695 (accepted by PRL)

- The production cross section of $e^+e^- \to \gamma X(3872)$ ($\sigma \cdot \mathcal{B}(X(3872) \to \omega J/\psi)$) is calculated at each energy point.



- The line-shape can be described by a single BW resonance Y(4200).
- A simultaneous fit to the $X(3872) \to \omega J/\psi$ and $\pi^+\pi^- J/\psi$ cross section gives

$$\mathrm{M}\big(Y(4200)\big) = 4200.6^{+7.9}_{-13.3} \pm 3.0\ \mathrm{MeV}/c^2$$

$$\Gamma\big(Y(4200)\big) = 115^{+38}_{-26} \pm 12\ \mathrm{MeV}$$

$\mathcal{R} \equiv \frac{\mathcal{B}(X(3872)\to\omega J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)} = 1.6^{+0.4}_{-0.3} \pm 0.2$, agree with the previous measurement.

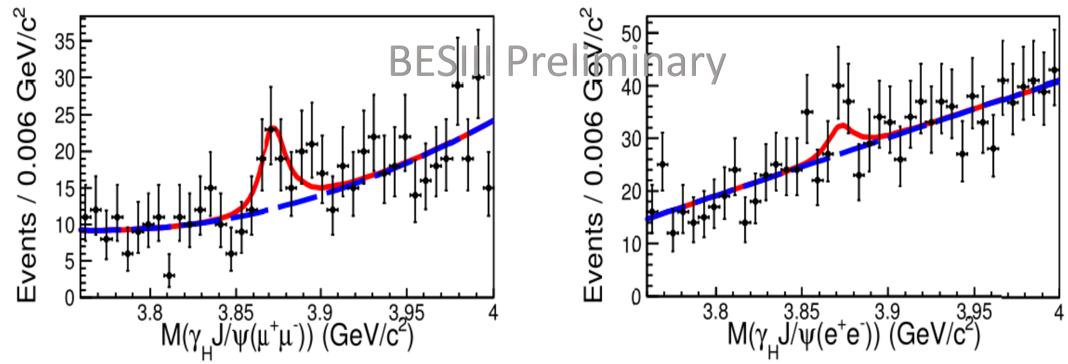
(0.8±0.3 from Babar)

$X(3872) \to \gamma J/\psi, \gamma\psi(3686), D^0\bar{D}^{*0}, \ \gamma D^+D^-$

- Data sample: 8.5 fb^{-1} from $\sqrt{s} = 4.178$ to 4.278 GeV

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

$J/\psi \to \mu\mu/ee$



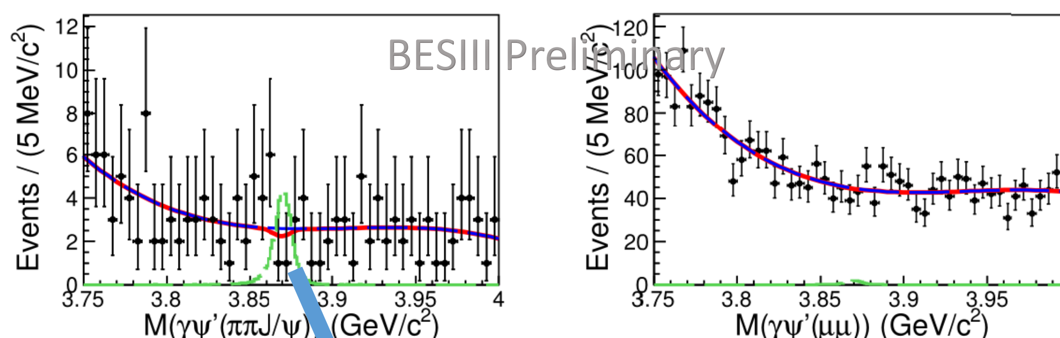
➢ Simultaneous fit; significance $> 3.5\sigma$

$X(3872) \to \gamma\psi(3686)$

$\psi(3686) \to \pi^+\pi^- J/\psi$

$\psi(3686) \to \mu\mu$

$\frac{B[X(3872)\to\gamma\psi(3686)]}{B[X(3872)\to\gamma J/\psi]} < 0.59$ at 90% C.L.



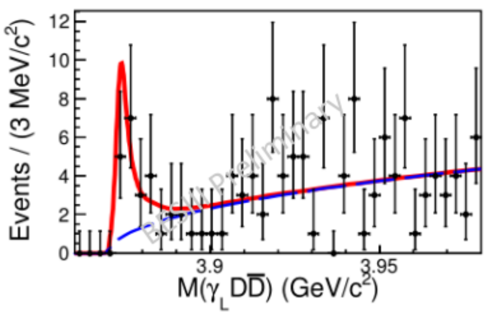
➢ Simultaneous fit; no evident signal

Expectation strength

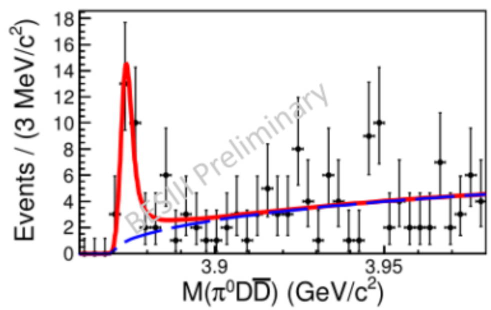
$X(3872) \to \gamma J/\psi, \gamma\psi(3686), D^0\bar{D}^{*0}, \gamma D^+D^-$

$X(3872) \to D^0\bar{D}^{*0} + c.c.$ $D^{*0} \to \gamma D^0, \pi^0 D^0$

$D^0 \to K\pi, K\pi\pi, K\pi\pi\pi$



$N_{DD^*} = (25.5 \pm 4.4)$

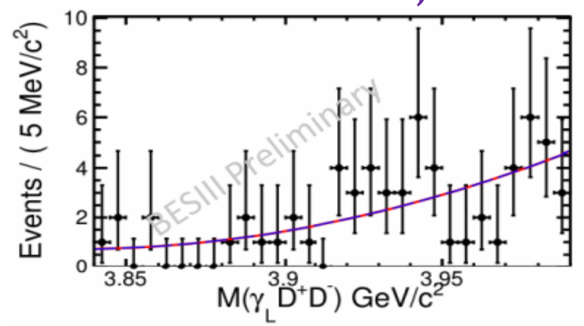


$N_{DD^*} = (32.5 \pm 5.5)$

- Simultaneous fit on $D^{*0} \to \gamma D^0$ and $\pi^0 D^0$
- Significance $> 7.4\sigma$

$X(3872) \to \gamma D^+D^-$

$D^\pm \to K\pi\pi, K\pi\pi\pi$



$N_{\gamma D^+D^-} = 0.0^{+0.5}_{-0.0}$

No evident signal for γD^+D^-

- Relative branching ratio compared with $X(3872) \to \pi^+\pi^- J/\psi$

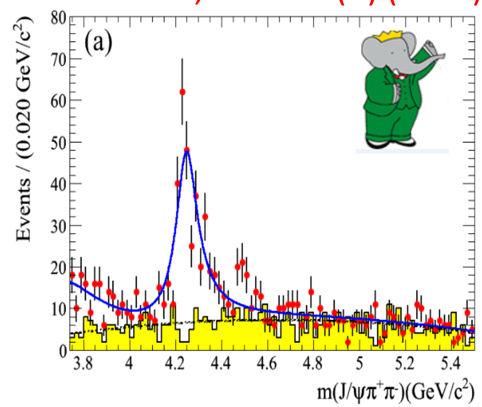
mode	$D^{*0}\bar{D}^0 + c.c.$	$\gamma J/\psi$	$\gamma\psi'$	γD^+D^-	$\omega J/\psi$	$\pi^0\chi_{c1}$
ratio	14.81 ± 3.80	0.79 ± 0.28	< 0.42	< 0.99	$1.7^{+0.4}_{-0.3} \pm 0.2$ [27]	$0.88^{+0.33}_{-0.27} \pm 0.10$ [37]

The Y states

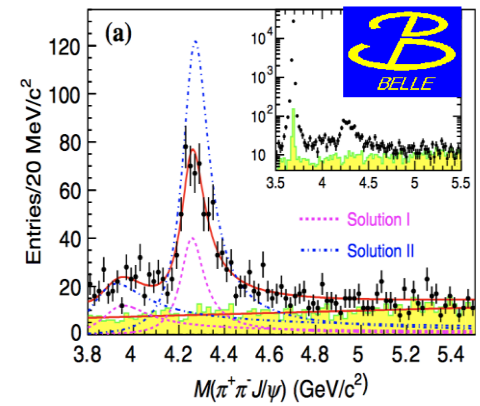
- Y(4260) in $e^+e^- \to \pi^+\pi^-J/\psi$
  - ➢ Discovery in ISR process by BaBar
  - ➢ Confirmed by Belle.

	PDG2018
M[Y(4260)]	4230±8 (MeV/c²)
Γ_{tot} [Y(4260)]	55±19(MeV)

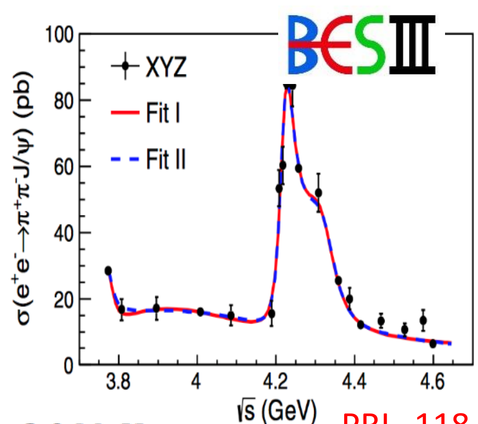
PRD 86, 051102 (R) (2012)

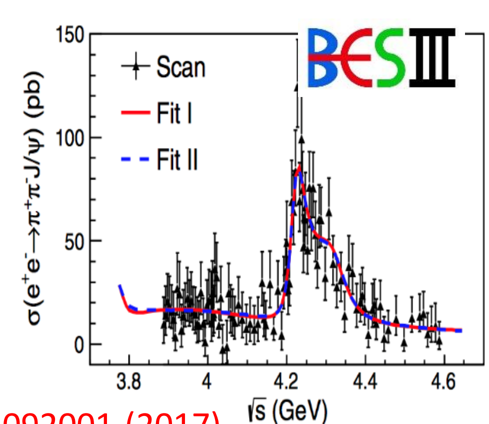


PRL 110, 252002 (2013)



- At BESIII, two resonant structures are observed in the energy region of Y(4260).
  - ➢ Y(4320) observed for the first time with 7.6σ significance.
  - ➢ No hint of Y(4008) which is seen in Belle.





PRL. 118, 092001 (2017)

$$M_1 = 4222.5 \pm 3.1 \pm 1.4\ \mathrm{MeV/c^2},\ \Gamma_1 = 44.1 \pm 4.3 \pm 2.0\ \mathrm{MeV}$$

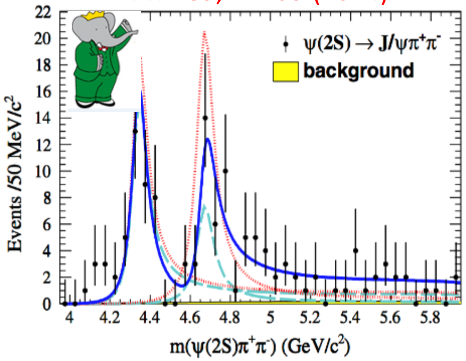
$$M_2 = 4320.0 \pm 10.4 \pm 7.0\ \mathrm{MeV/c^2},\ \Gamma_2 = 101.4^{+25.3}_{-19.7} \pm 10.2\ \mathrm{MeV}$$

The Y states

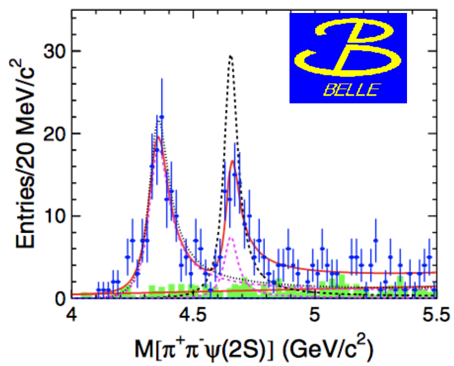
- Y(4360)， Y(4660) in $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$
  - Discovery in ISR process by Belle
  - Confirmed by Babar.
  - No evidence for the Y(4260)

	PDG2018
Γ_{tot} [Y(4260)]	55±19(MeV)
M[Y(4360)]	4368±13 (MeV/c^2)
Γ_{tot} [Y(4360)]	96±7(MeV)
M[Y(4660)]	4643±9 (MeV/c^2)
Γ_{tot} [Y(4660)]	72±11(MeV)

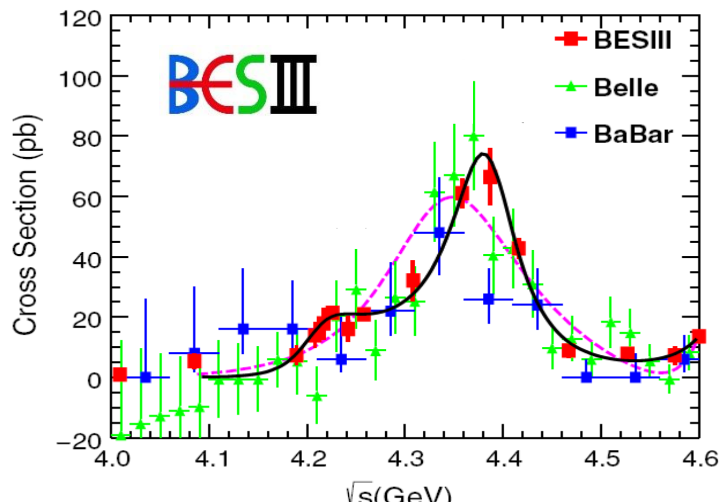
PRD 89, 11103 (2014)



PRD 91, 112007 (2015)



- At BESIII, two resonant structures observed in energy region 4.2-4.4 GeV
  - Y(4220) observed for the first time in this process with significance of 5.8σ



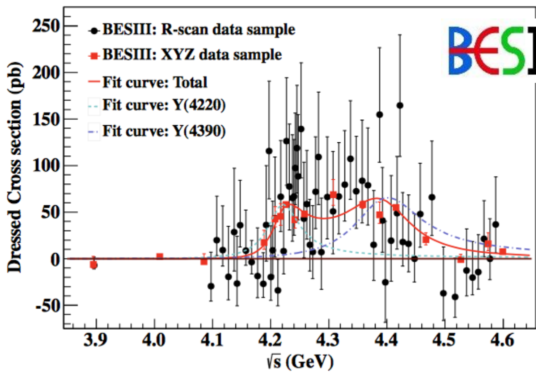
PRD96, 132004 (2017)

$$M_1 = 4209.5 \pm 7.4 \pm 1.4\ \mathrm{MeV/c^2},\ \Gamma_1 = 80.1 \pm 24.6 \pm 2.9\ \mathrm{MeV}$$

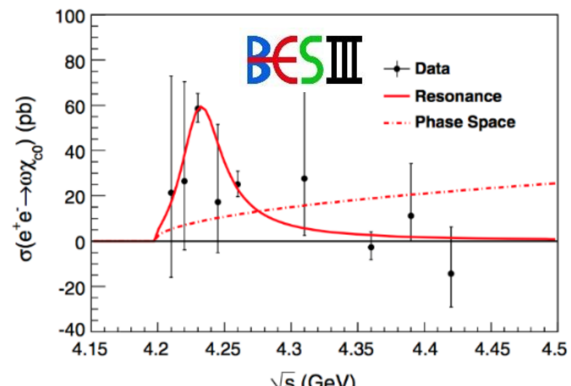
$$M_2 = 4383.8 \pm 4.2 \pm 0.8\ \mathrm{MeV/c^2},\ \Gamma_2 = 84.2 \pm 12.5 \pm 2.1\ \mathrm{MeV}$$

The Y states

- Some more Y states observed at BESIII
  - Y(4220), Y(4390) observed in $\pi^+\pi^- h_c$
  - Y(4220) observed in $\omega\chi_{c0}$



PRL 118, 092002 (2017)



PRL. 114, 092003 (2015)

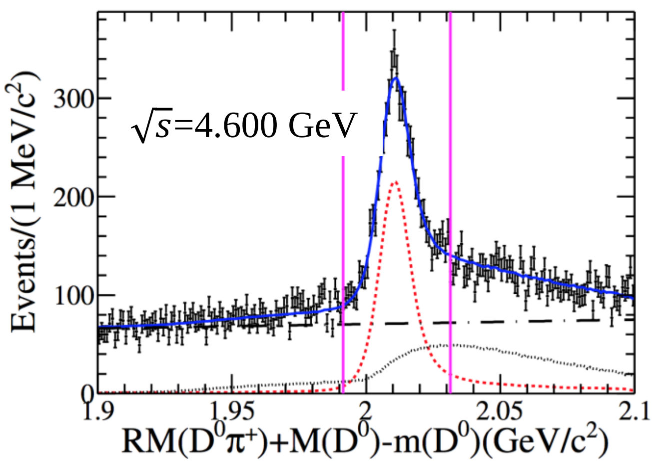
- Why "exotic"
  - No natural place within quark model.
  - Strongly coupling to $\pi^+\pi^- J/\psi$ rather charm decay modes.
  - Dip on R-value

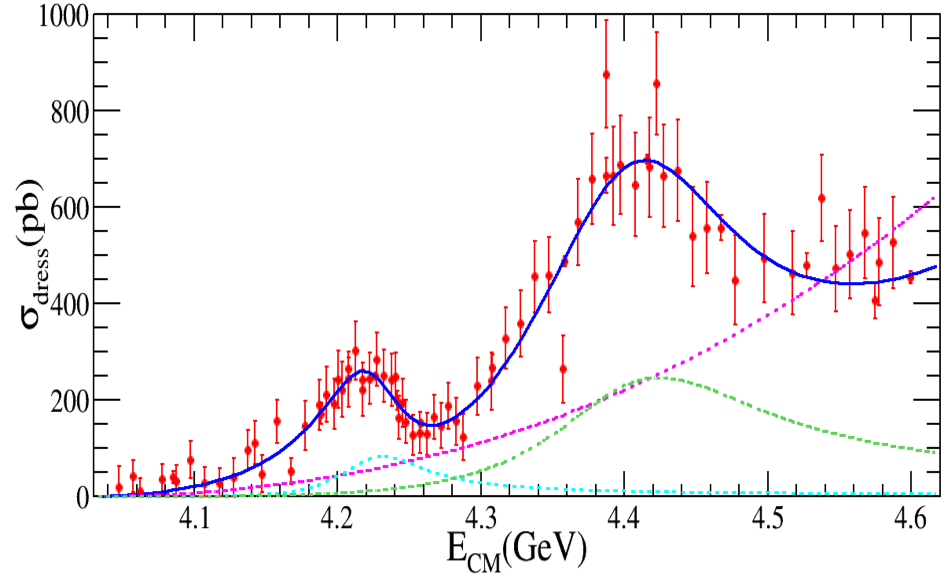
- Theoretical interpretation
  - Hybrid charmonium
  - Tetraquark
  - Hadronic molecule
  - …

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

Phys. Rev. Lett. 122, 102002 (2019)

- Using data sample from 4.05 to 4.60 GeV
- Reconstructed channel: $D^0 \longrightarrow K^-\pi^+$
- Using $RM(D^0\pi^+) + M(D^0) - m(D^0)$ to select D^{*-} signal
- Peaking background comes from isospin partner $e^+e^- \to \pi^+ D^- D^{*0}$





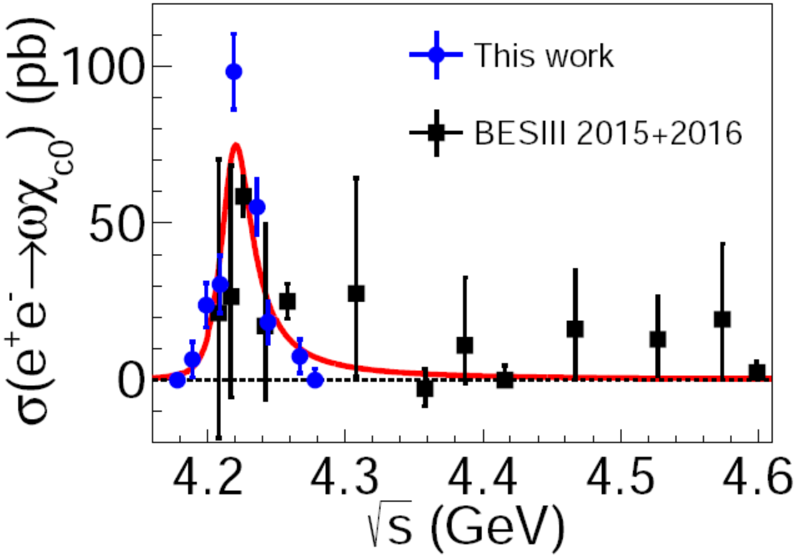
- Fit with a coherent sum of three-body PHSP and two BW functions
- Significance of two structures greater than 10σ over one structure assumption

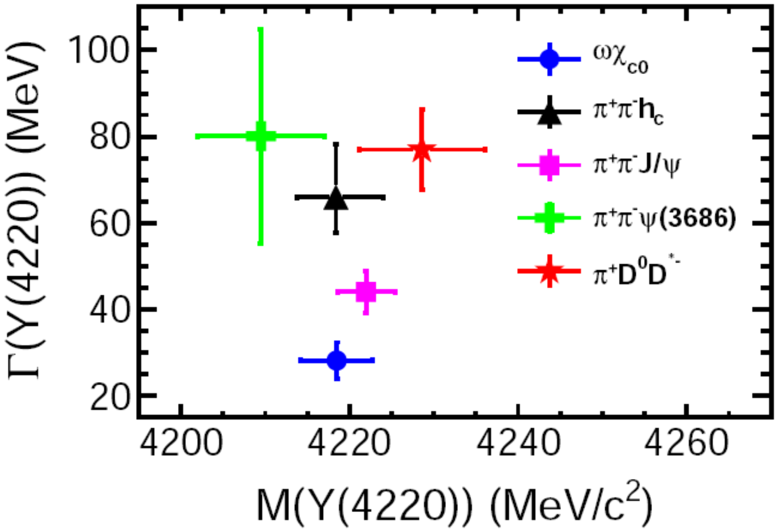
$M_1 = 4228.6 \pm 4.1 \pm 6.3\ \mathrm{MeV/c^2}$, $\Gamma_1 = 77.1 \pm 6.8 \pm 6.8\ \mathrm{MeV}$

The resonance parameters around 4.40 GeV strongly depend on the model and need further studies

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

Phys. Rev. D 99, 091103 (2019)





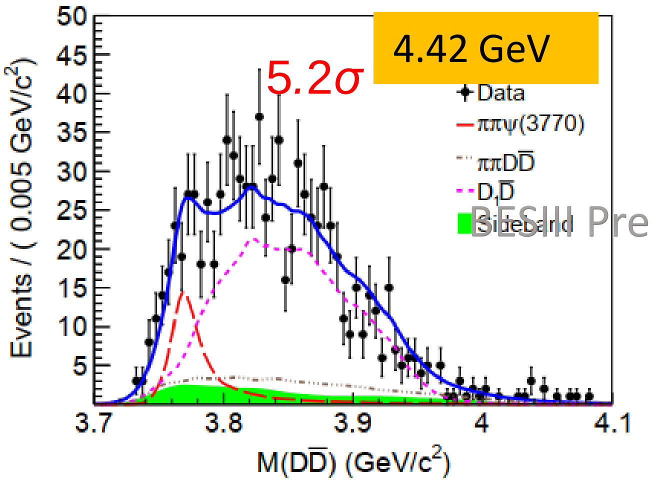
- Data sample: 7 fb^{-1} from 4.178 to 4.278 GeV
- The χ_{c0} is reconstructed from $\pi^+\pi^-$ and K^+K^-
- This observation confirms and improves the previous result

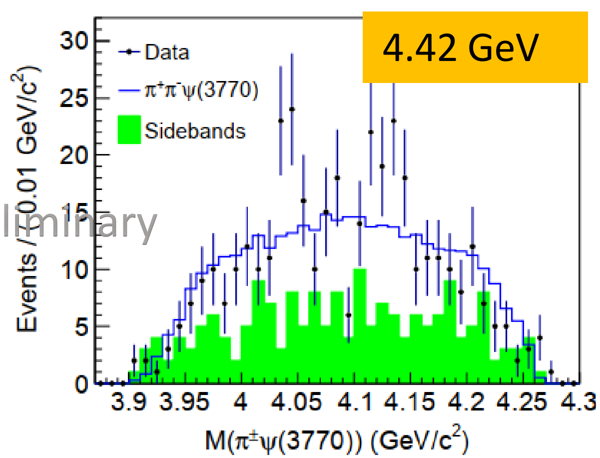
M = (4218.5 ± 1.6 ± 4.0) MeV/c^2

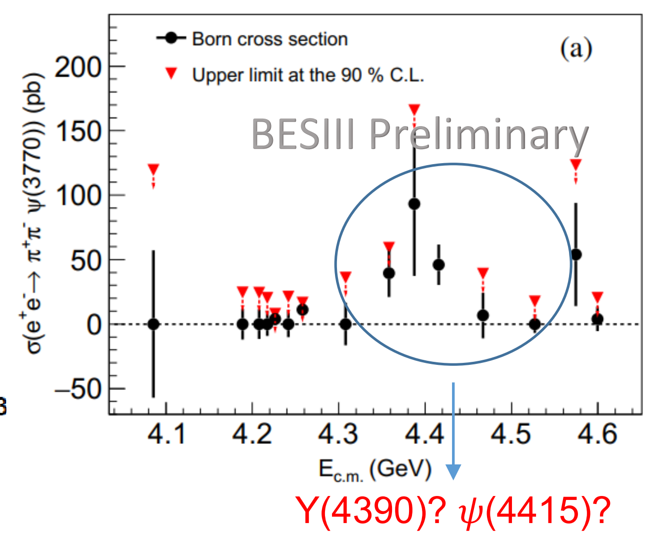
Γ = (28.2.0 ± 3.9 ± 1.6) MeV

$e^+e^- \to \pi^+\pi^-\psi(3770), D_1(2420)\bar{D}$

- Study the intermediate states of $e^+e^- \to \pi^+\pi^- D^0\bar{D}^0$, $e^+e^- \to \pi^+\pi^- D^+D^-$
  - $D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^+\pi^-\pi^0$
  - $D^+ \to K^-\pi^+\pi^+, K^-\pi^+\pi^+\pi^0, K_S^0\pi^+, K_S^0\pi^+\pi^0,$ and $K_S^0\pi^+\pi^+\pi^-$



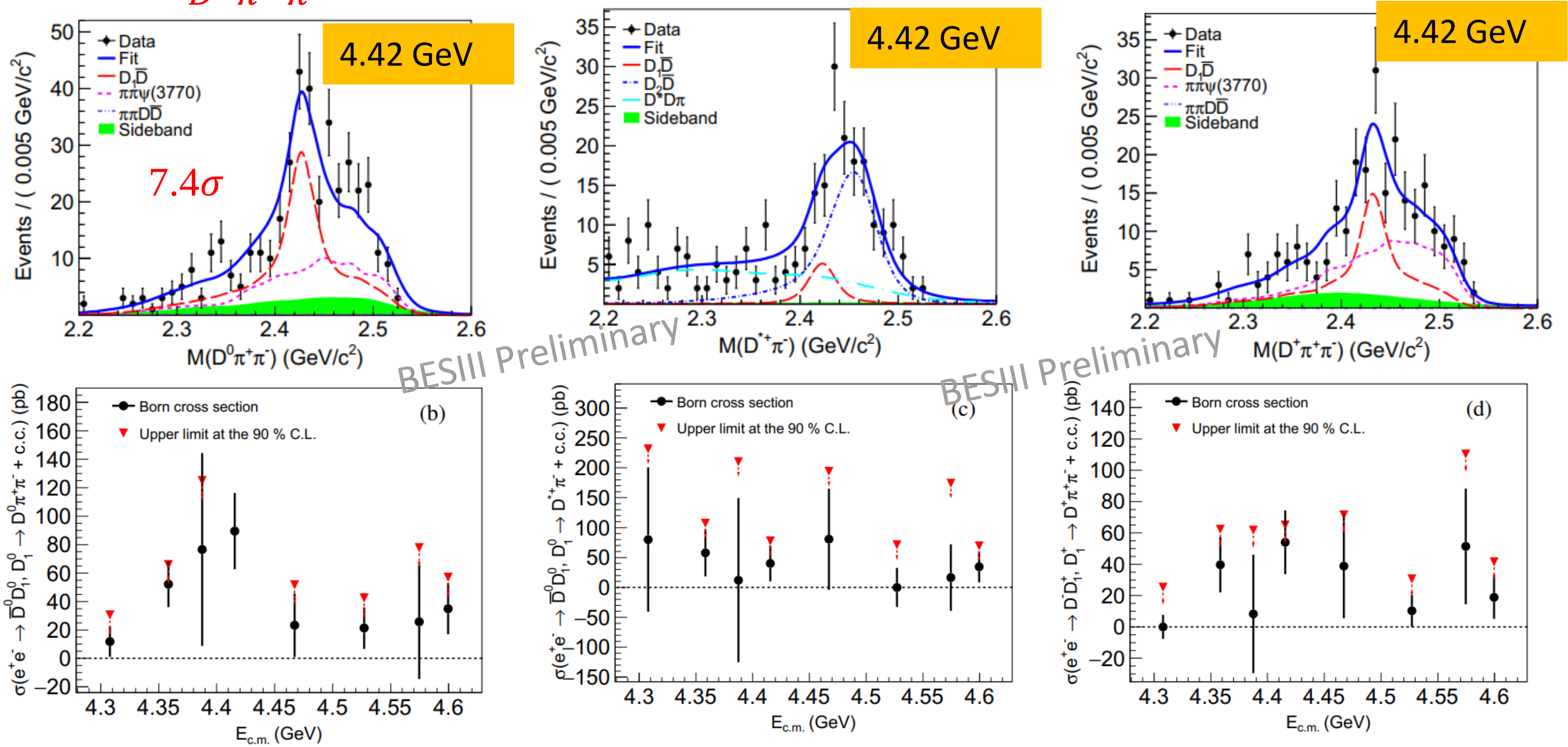




- $e^+e^- \to \pi^+\pi^-\psi(3770)$ is observed for the first time at 4.42 GeV.
- Hints in $\pi^\pm\psi(3770)$ mass spectrum at 4.04 and 4.13 GeV/c^2 in $\sqrt{s}$ = 4.42 GeV data
- Clear structure in line-shape of $\pi^+\pi^-\psi(3770)$

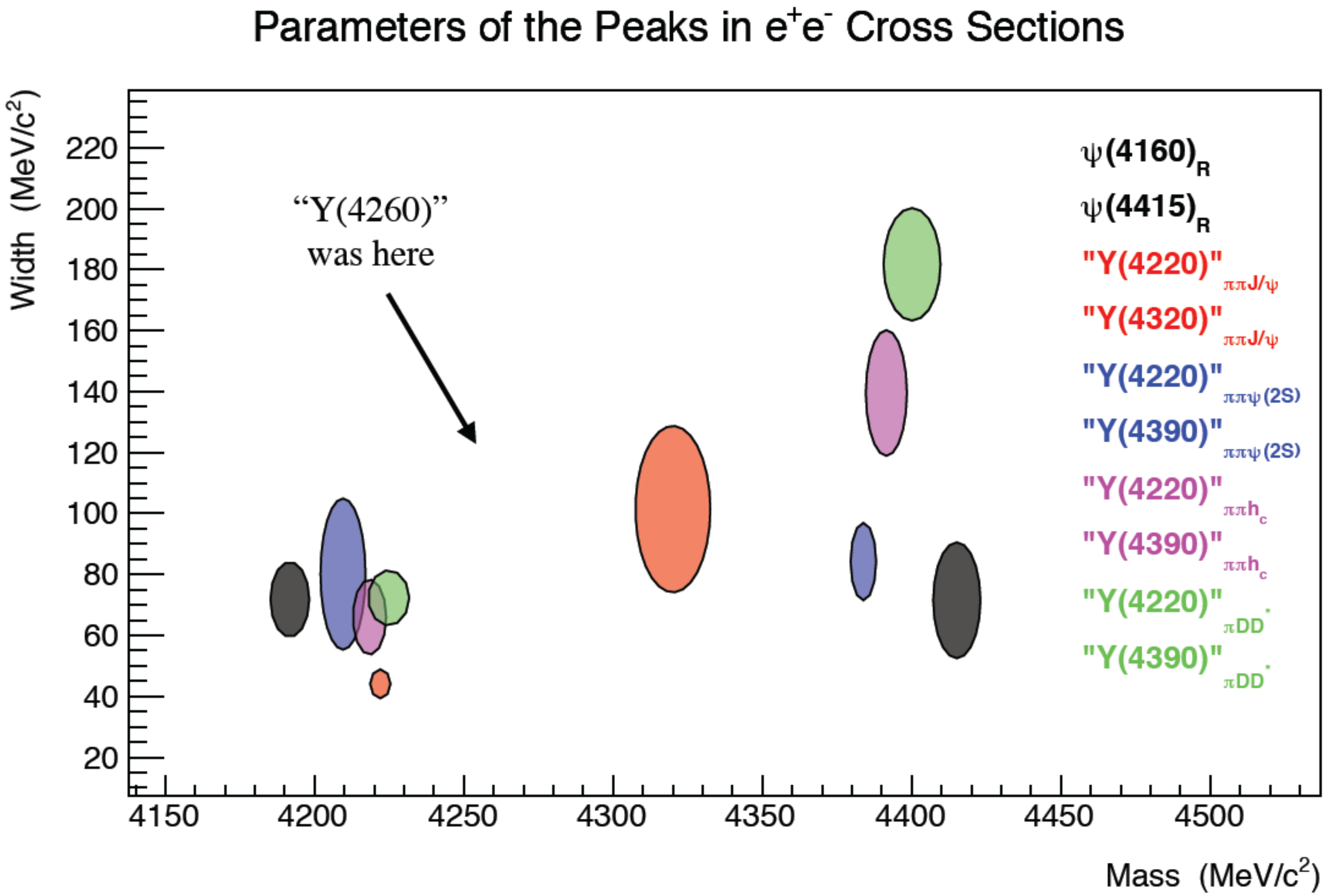
$e^+e^- \to \pi^+\pi^-\psi(3770), D_1(2420)\bar{D}$

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



- Three different decay channels ($D^0\pi^+\pi^-$, $D^{*+}\pi^-$, and $D^+\pi^+\pi^-$) are used to search for $D_1(2420)$
- Clear structure in the line-shape of $e^+e^- \to D_1(2420)\bar{D}$

The Y states


Parameters of the Peaks in e+e- Cross Sections
Width (MeV/c2)
220
200
180
160
140
120
100
80
60
40
20
4150
4200
4250
4300
4350
4400
4450
4500
Mass (MeV/c2)
"Y(4260)"
was here
ψ(4160)R
ψ(4415)R
"Y(4220)"ππJ/ψ
"Y(4320)"ππJ/ψ
"Y(4220)"ππψ(2S)
"Y(4390)"ππψ(2S)
"Y(4220)"ππhc
"Y(4390)"ππhc
"Y(4220)"πDD*
"Y(4390)"πDD*

Summary

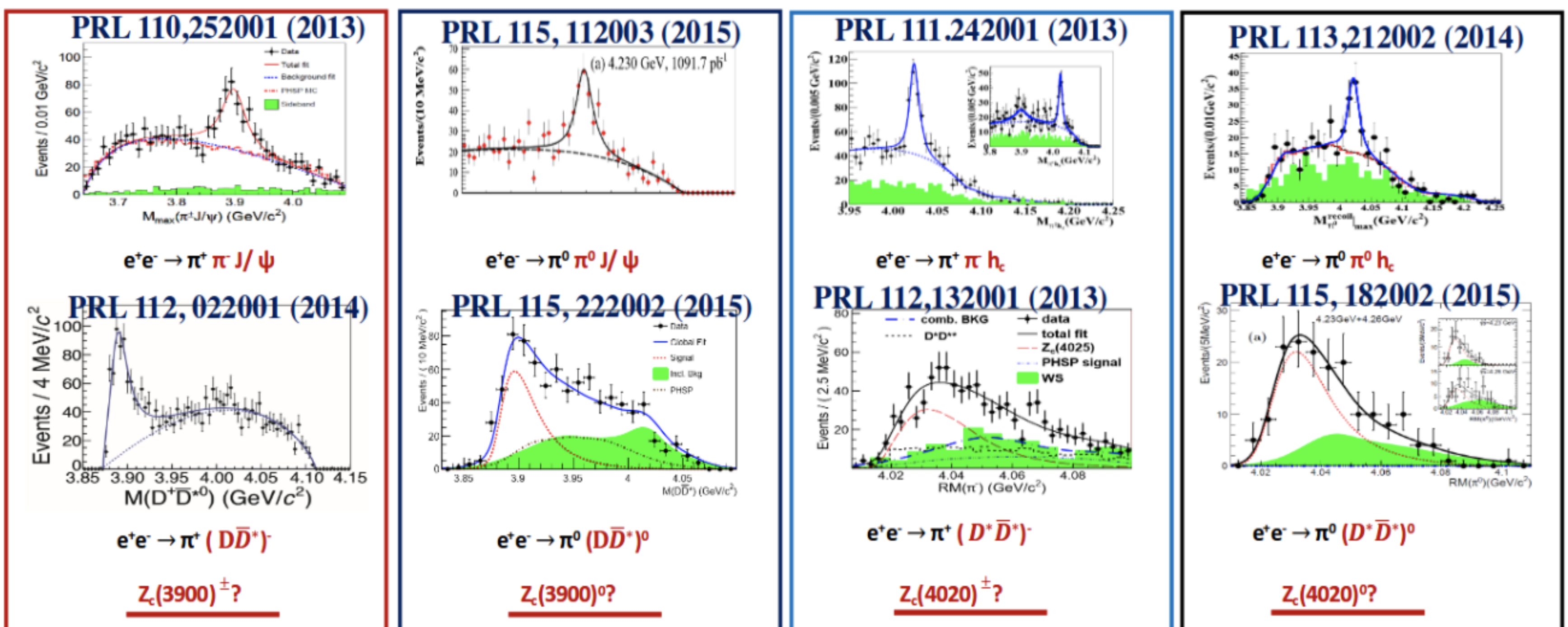
- BESIII has achieved great progress recently in Charmonium system, especially in XYZ studies, which help discriminate different theoretical interpretation.
  - New decay mode $X(3872) \to \pi^0 \chi_{c1}$ is observed
  - First firm observation of $X(3872) \to \omega J/\psi$
  - Exclusive decays of X(3872) is searched
  - Two enhancement observed in the lineshape of $e^+e^- \to \pi^+ D^0 D^{*-}$
  - Improved measurement of process $e^+e^- \to \omega \chi_{c0}$
  - Line-shape measured for process $e^+e^- \to \pi^+\pi^-\psi(3770), D_1(2420)\bar{D}$
- There are still many remain unanswered questions.
- BESIII continues taking data and increasing the beam energy, more results in Charmonium system are foreseen.

Thanks

Backup

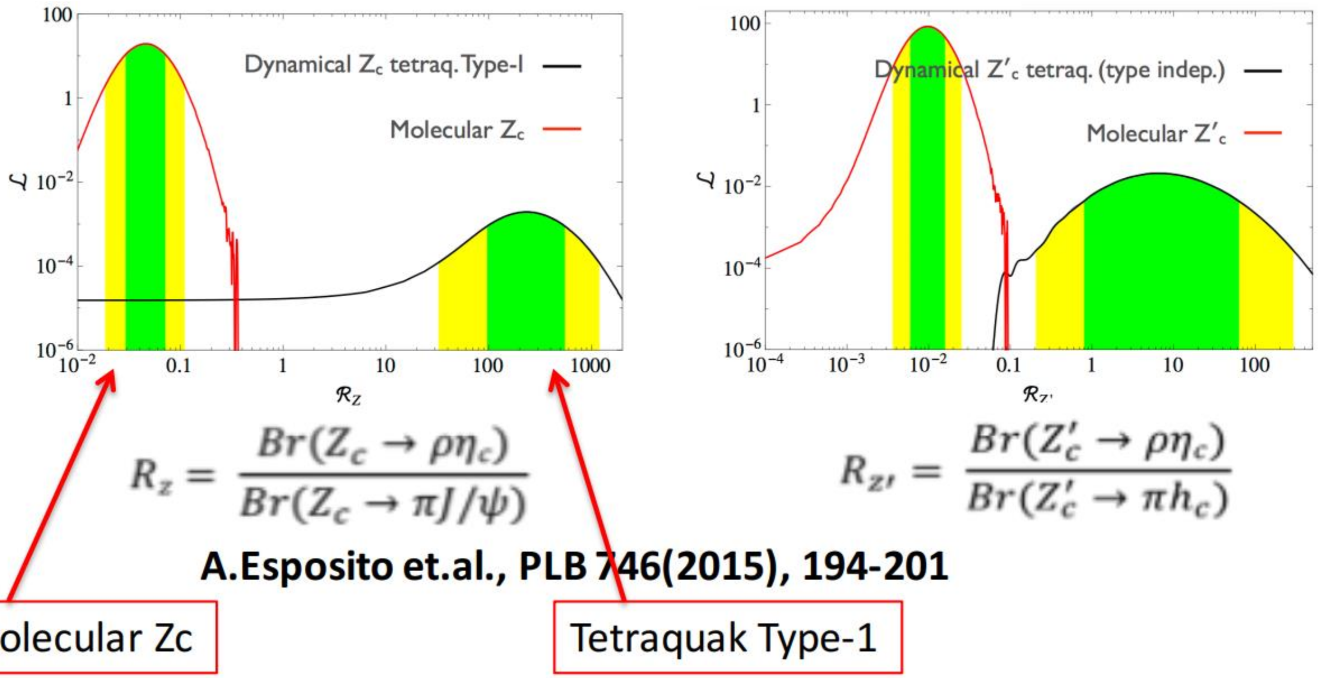
The Z states

- Discovery of a resonant structure decaying to $J/\psi\pi^{\pm}$ in $e^+e^- \to \pi^+\pi^- J/\psi$ by BESIII , and observed via ISR in Belle.
- Absolutely exotic !
  - Decays to J/ψ => contain $c\bar{c}$
  - Electrically charged => contains $u\bar{d}$
  - Very close to the DD^* threshold
- Z states at BESIII



$Z_c(3900)^{\pm} \to \rho^{\pm}\eta_c$

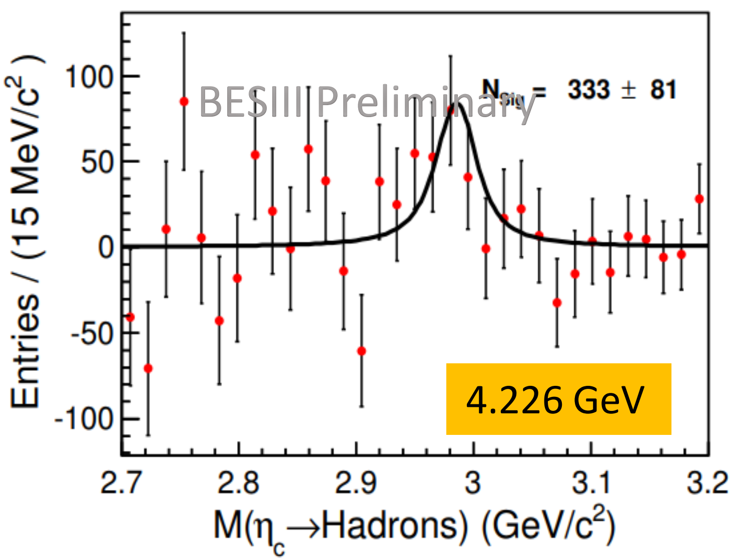
- The ratio of $\mathcal{B}(Z_c \to \rho\eta_c)/\mathcal{B}(Z_c \to \pi J/\psi)$ can be used to discriminate between the molecule and tetraquark scenarios.

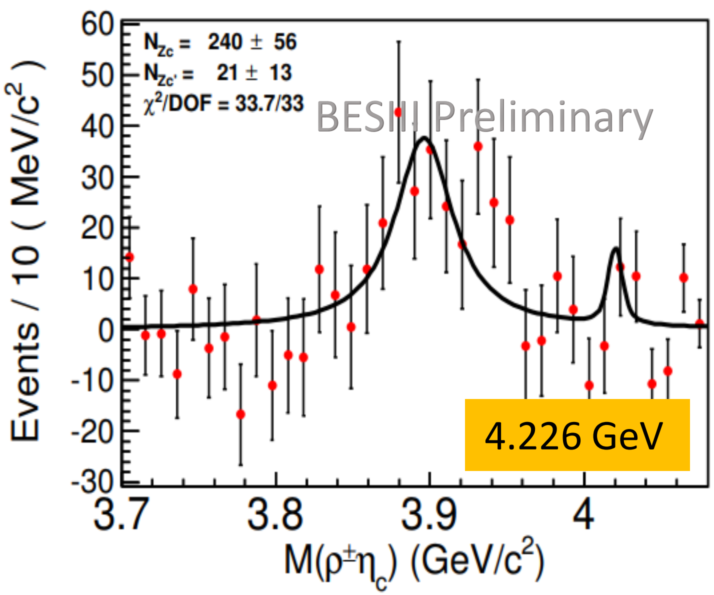


- The green band and yellow band show the 1σ and 2σ confidence range of the corresponding theoretical model

$Z_c(3900)^{\pm} \to \rho^{\pm}\eta_c$

- $\pi^+\pi^-\pi^0\eta_c$ final state is studied with η_c reconstructed from 9 hadronic decay modes: ($p\bar{p}$, $2(K^+K^-)$, $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0$, $p\bar{p}\pi^0$, $K_sK\pi$, $\pi^+\pi^-\eta$, $K^+K^-\eta$ and $\pi^+\pi^-\pi^0\pi^0$)
- First evidence for the $Z_c(3900)^{\pm} \to \rho^{\pm}\eta_c$ is observed with 3.9σ significance at 4.226 GeV.
- No significant signal is observed in $Z_c(4020)^{\pm} \to \rho^{\pm}\eta_c$



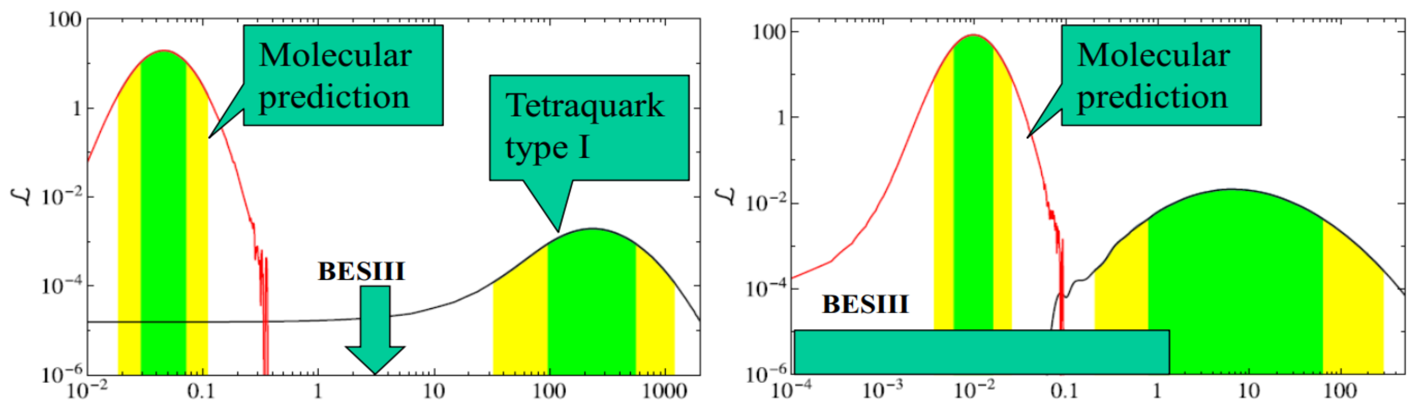


$Z_c(3900)^{\pm} \to \rho^{\pm}\eta_c$

- The production Born cross section is calculated at 4.226 GeV:

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

	$\sqrt{s} = 4.226$ GeV	$\sqrt{s} = 4.258$ GeV	$\sqrt{s} = 4.358$ GeV	Type-I	Type-II	Molecule
$R_{Z_c(3900)}$	2.2 ± 0.9	< 5.6	...	230^{+330}_{-140}	$0.27^{+0.40}_{-0.17}$	$0.046^{+0.025}_{-0.017}$
$R_{Z_c(4020)}$	< 1.6	< 0.9	< 1.4		$6.6^{+56.8}_{-5.8}$	$0.010^{+0.006}_{-0.004}$



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$$\mathcal{R}_Z = \frac{Br(Z_c \to \rho\eta_c)}{Br(Z_c \to \pi J/\psi)} \qquad \mathcal{R}_{Z'} = \frac{Br(Z'_c \to \rho\eta_c)}{Br(Z'_c \to \pi J/\psi)}$$

This measurement doesn't agree with both molecular Zc and tetraquark Zc Type-1 assumptions.