Charmonium Spectroscopy at BESIII and the new hadrons

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On behalf of the BESIII collaboration

Indiana University

PWA11/ATHOS6

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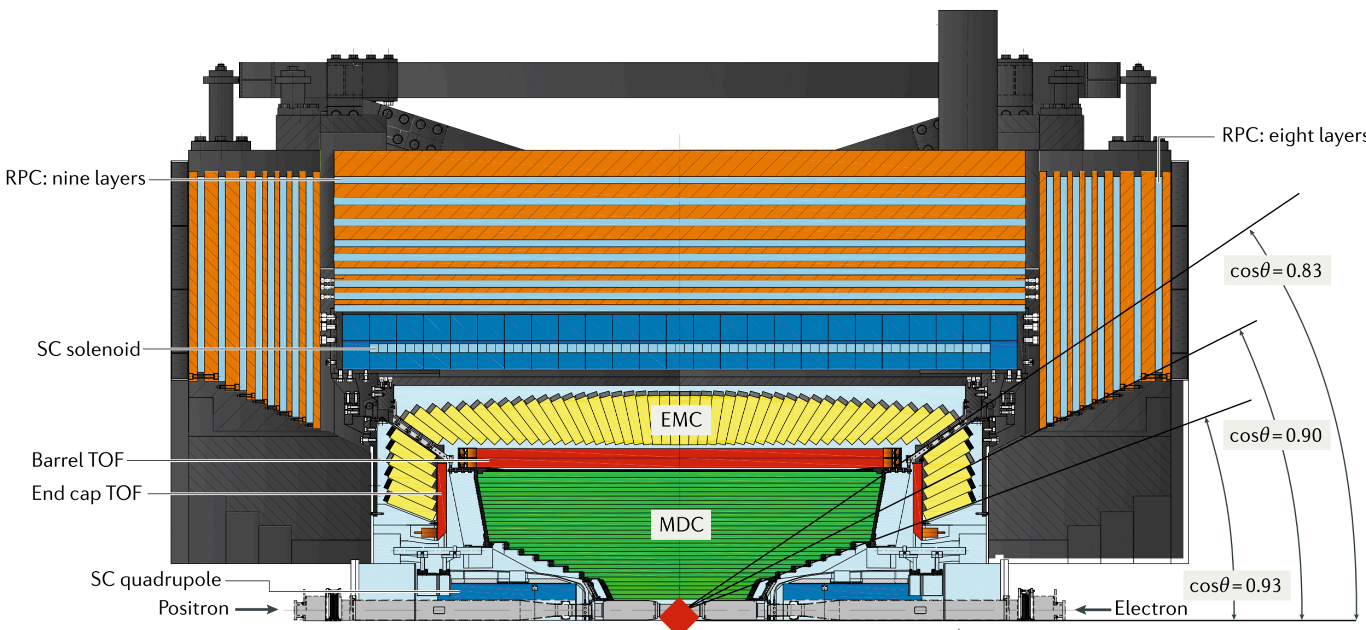
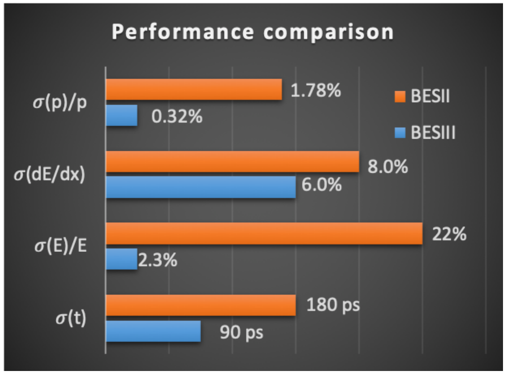
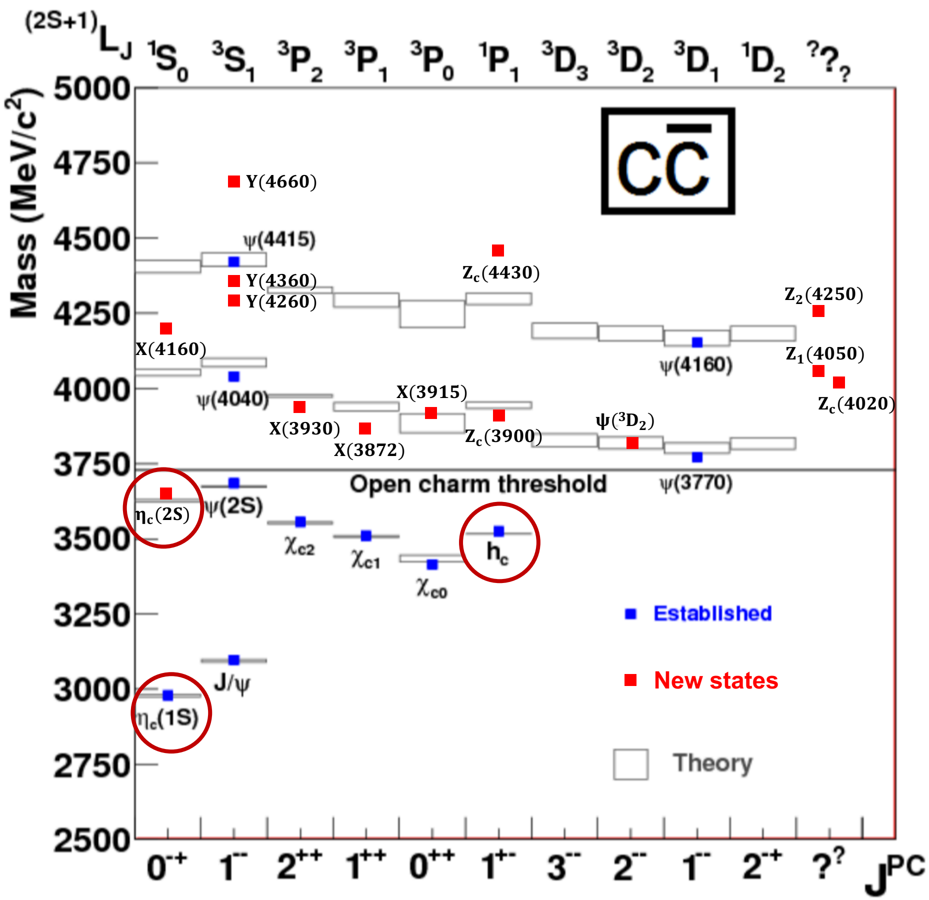
BEPCII and BESIII

- A unique e^+e^- machine in the τ-charm energy region.
  - High luminosity: 10^{33} $cm^{-2}s^{-1}$ @ 3.77 GeV
  - Excellent and stable detector performance: 2009-now
  - Studies at the near-threshold energy: $\sqrt{s}$ = 2~4.6 GeV
  - Clean environment and well controlled initial states
  - Rich physics coverage: Light hadron spectroscopy, Charmonium spectroscopy, Exotic hadrons, Charmed meson/baryons physics, et. al.



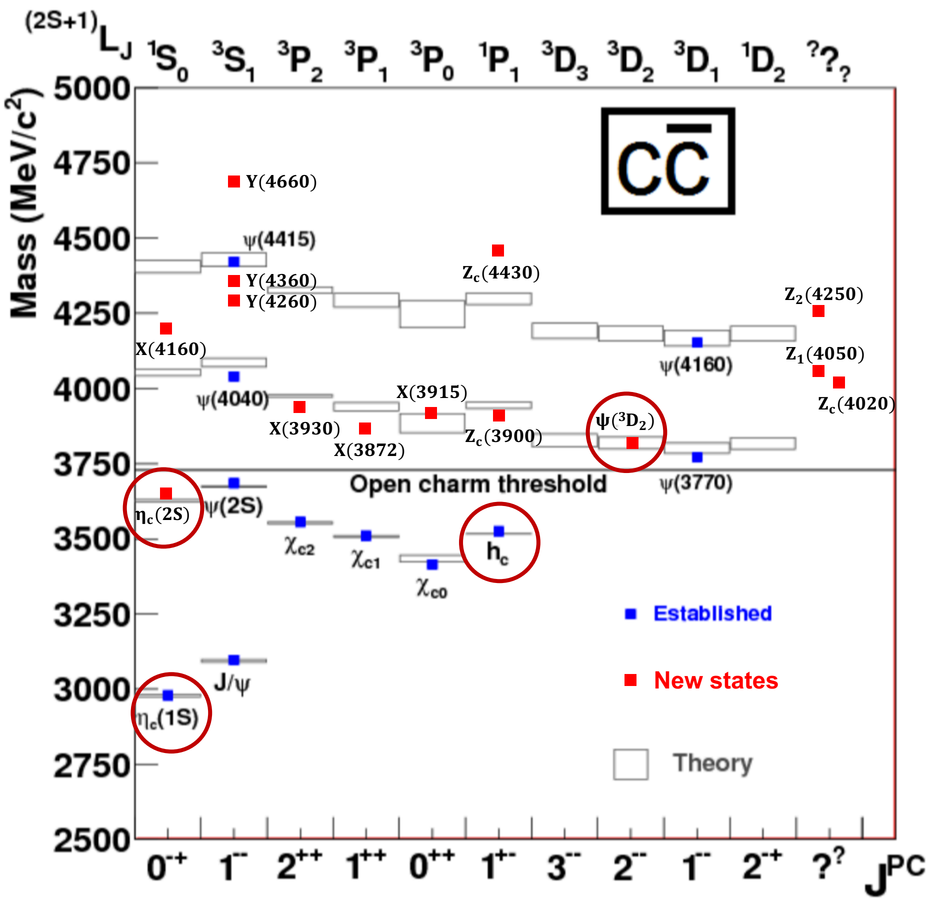


Charmonium spectroscopy @ BESIII



- **Precise measurement of η_c and h_c**
  - PRL 108, 222002(2012)
  - PRL 104,132002(2010)
  - PRD 86, 092009 (2012)
- **Observation of $\psi' \to \gamma\eta_c(2S)$**
  - PRL 109, 042003 (2012)

Charmonium spectroscopy @ BESIII



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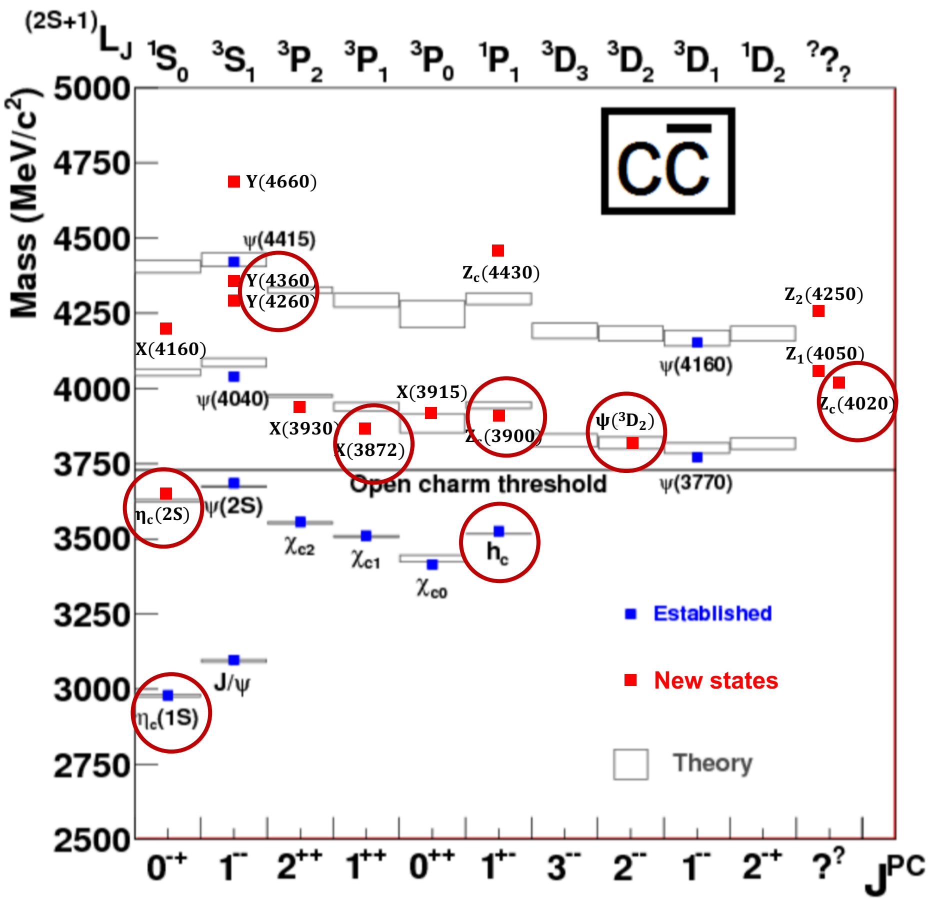
Charmonium spectroscopy @ BESIII



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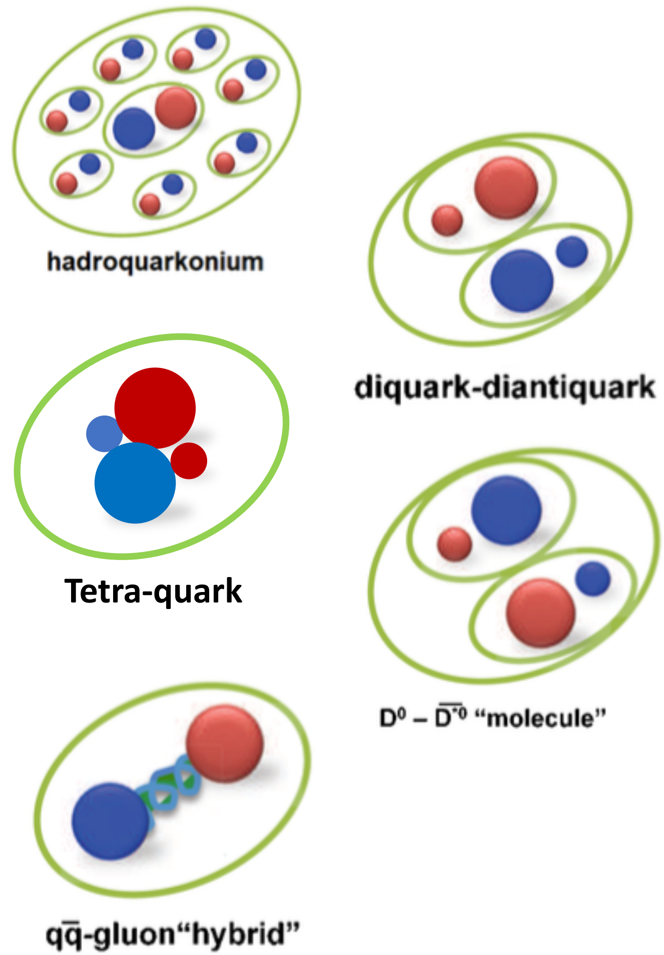
  - PRL 115, 011803 (2015)
- **Observation of Zc(3900), Zc(3885), Zc(4020), Zc(4025)**
  - PRL 110, 252001(2013)
  - PRL 112, 022001(2014)
  - PRL 111, 242001(2013)
  - PRL 112, 132001(2014) …
- **Observation of Y(4260)→ γX(3872)**
  - PRL 112 (2014) 092001
- **Observation of Y(4220) and Y(4390)**
  - PRL 118, 092001 (2017)
  - PRL 118, 092002 (2017)

Open questions

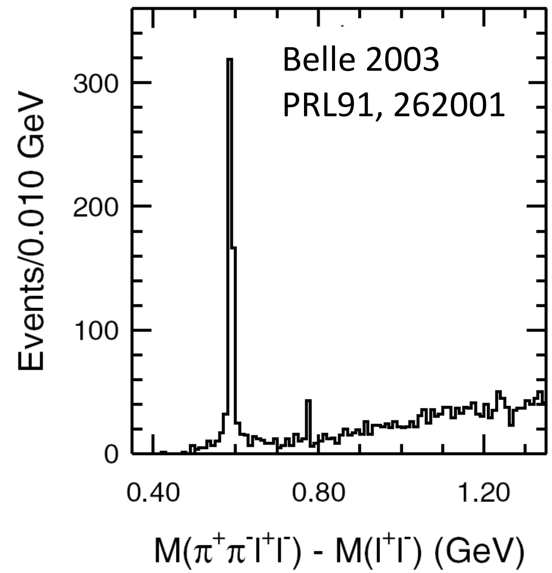
What's inside these XYZ states? And how these quarks interact with each other?

- Is X(3872) a molecule states? What's the relation between X(3872) and Y(4260) and Zc(3900)
- Is Y(4260) a hybrid state? Or is it one state? How to understand the new observed vector exotic states? E.g. Y(4360), Y(4390) and Y(4660)
- We know Zc should be a four-quark state, but how the quarks interact with each other inside the Zc?

Need more effort from both experimental and theoretical sides to answer these questions!



Is $\mathbf{X(3872)}$ molecule?



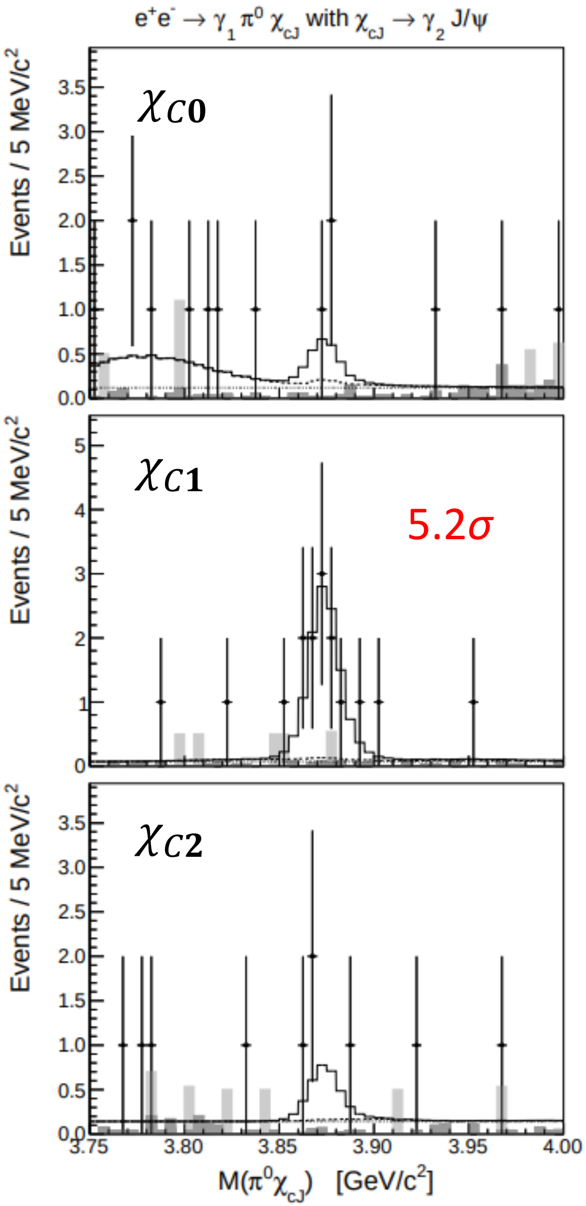
X(3872) -- still puzzling

- χ'_{c1} ? Too narrow. Theoretical prediction >16 MeV
- Hybrid? mass too low
- Tetra-quark? no charged partner be found
- Good candidate for molecule.
  - Narrow state
  - Close to $D^{*0}\overline{D}^0$ threshold.
  - No iso-spin partner

  But
  - It is difficult to explain the large radiative decay rates and substantial $\pi^+\pi^- J/\psi$ under molecule model
- Or a molecule mixing with a charmonium state having the same quantum numbers?

Demands more experimental constraints and theoretical insight

Observation of $X(3872) \to \pi^0 \chi_{C1}$



- If X(3872) is charmonium state, this transition is predicted to be: $\Gamma(X(3872) \to \pi^0 \chi_{C1})$~0.06keV. [PRD 77, 014013(2008)]
- Under molecule or tetra-quark models, the decay width is sizeable. [PRD 92, 034019(2015)]
- $e^+e^- \to \gamma X(3872) \to \gamma \pi^0 \chi_{CJ}$ is studied at BESIII
- $X(3872) \to \pi^0 \chi_{C1}$ is observed with significance 5.2 σ, meanwhile, $X(3872) \to \pi^0 \chi_{C0,2}$ signals are not significant.
- $\mathrm{R} = \frac{\mathrm{B}(X(3872) \to \pi^0 \chi_{C1})}{\mathrm{B}(X(3872) \to \pi^+\pi^- J/\psi)} = 0.88^{+0.33}_{-0.27} \pm 0.10$
- With input B($X(3872) \to \pi^+\pi^- J/\psi$)=3.2~6.4%, the $\Gamma(X(3872) \to \pi^0 \chi_{C1})$ is measured to be: 0.5~1 keV
- Measured decay width favors the molecule or tetra-quark models.

PRL. 122, 202001 (2019)

Study of $X(3872)$ radiative decay

- The $\boldsymbol{R_\psi} = \frac{B(X(3872)\to\gamma\psi')}{B(X(3872)\to\gamma J/\psi)}$ is predicted to be :

$\sim 4\times10^{-3}$ molecule *PLB 598, 197 (2004), PRD 90, 0540104 (2014)*
1.2~15 pure charmonium *PRD 72 054026 (2005), PLB 697, 3 (2011)*
0.5~5 molecule&charmonium mixture *RRD 73, 014014(2006)*

- Previous measurements

$\boldsymbol{R_\psi}$	Experiment	significance	
		$(X(3872)\to\gamma J/\psi)$	$X(3872)\to\gamma\psi'$
3.4 ± 1.4	$BABAR$	3.6σ	3.5σ
2.46 ± 0.64 ± 0.29	LHCb	> 8σ	4.4σ
<2.1 90% $C.L.$	Belle	5.5σ	0.4σ

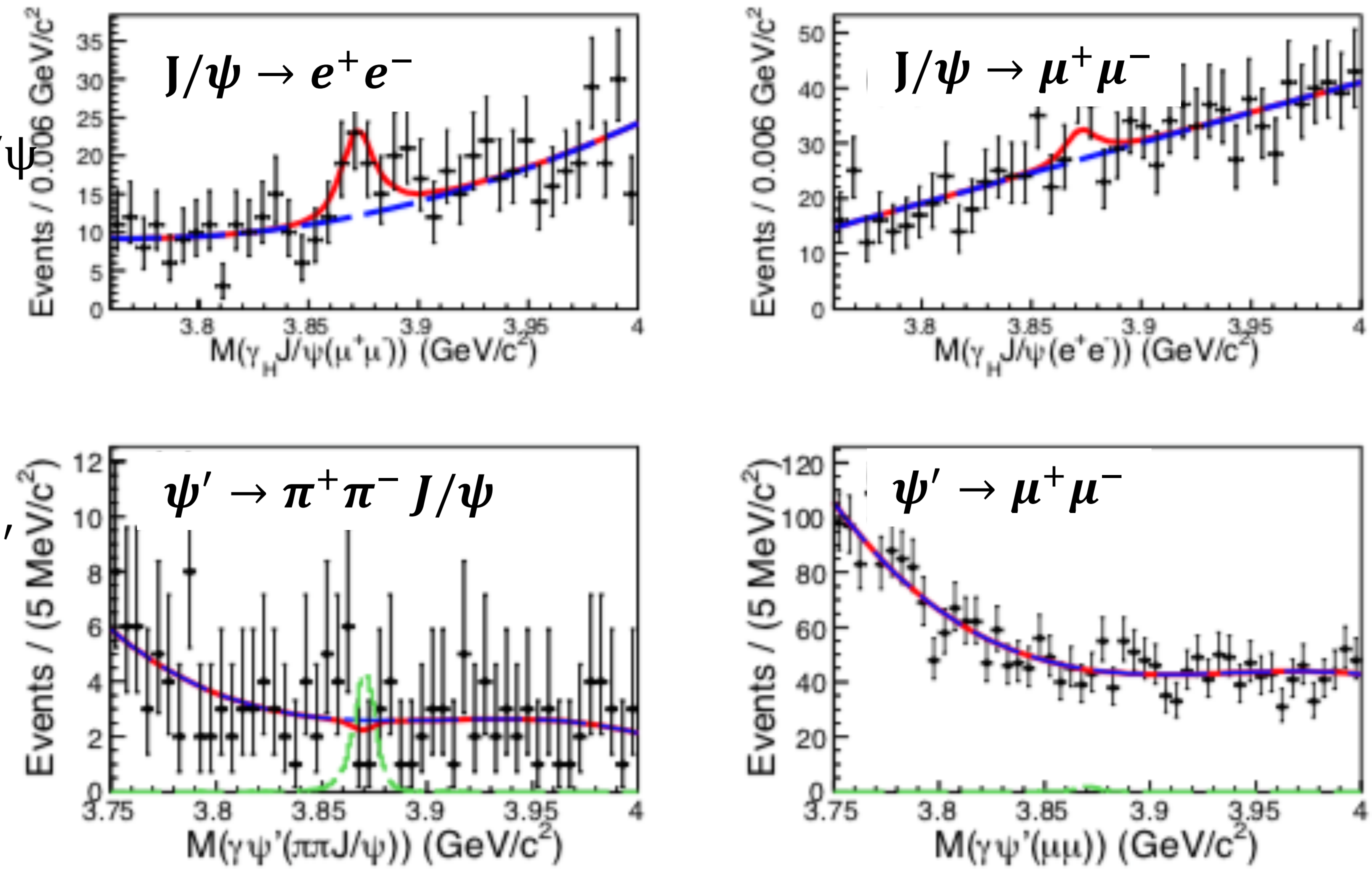
- Measure $\boldsymbol{R_\psi}$ at BESIII is necessary!

Study of $X(3872)$ radiative decay

BESIII preliminary

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

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



Evidence of $X(3872) \to \gamma J/\psi$ is found with significance 3.5 σ

No significant $X(3872) \to \gamma\psi'$ is observed

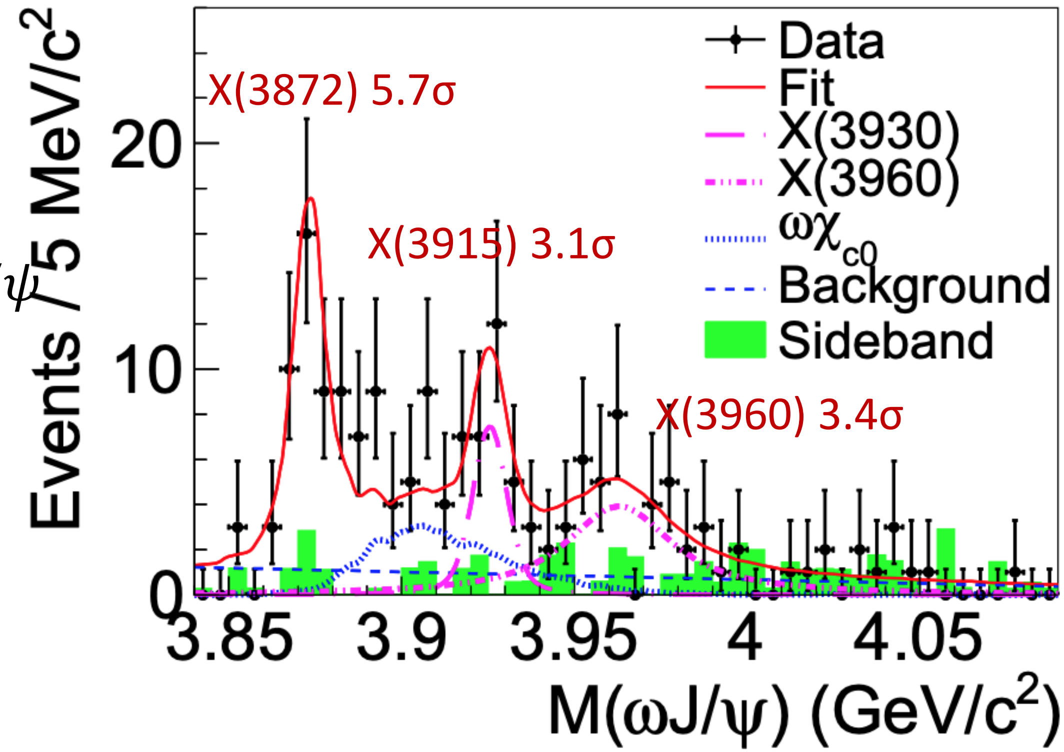
$$\mathbf{R}_{\psi} = \frac{B(X(3872)\to\gamma\psi')}{B(X(3872)\to\gamma J/\psi)} < 0.59 \text{ @ } 90\%\text{C. L.}$$

Disfavor charmonium and charmonium-molecule mixture scenario

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

- Belle and BABAR reported 4σ evidence
  $$R = \frac{B(X(3872) \to \pi^+\pi^-\pi^0 J/\psi)}{B(X(3872) \to \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4 \pm 0.3$$
- BESIII observed $X(3872) \to \omega J/\psi$ with significance 5.7σ
- Evidence of $X(3915) \to \omega J/\psi$
- Measured $\mathbf{R = 1.6^{+0.4}_{-0.3} \pm 0.2}$

BESIII, PRL122, 232002 (2019)

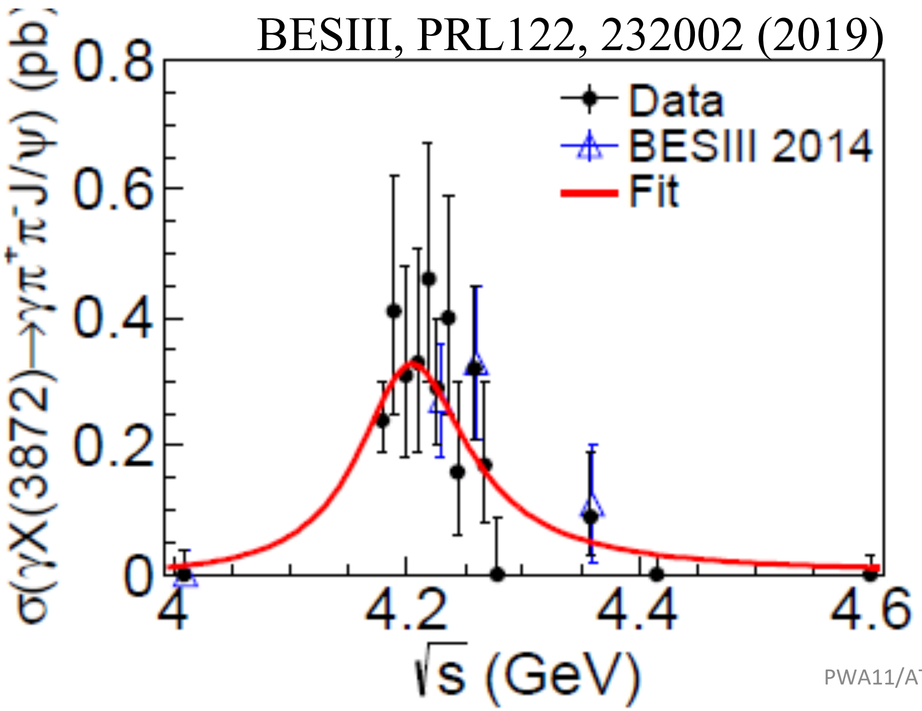


Observation of $X(3872) \to \omega J/\psi$

- What's the relation between Y(4260) and X(3872)?
- BESIII observed hint of $Y(4260) \to \gamma X(3872)$ with $X(3872) \to \pi^+\pi^- J/\psi$
- An enhanced rate is expected for the decay $Y(4260) \to \gamma X(3872)$ based on the assumption that the $Y(4260)$ is a $D\overline{D}_1$ molecule and $X(3872)$ is $D\overline{D}^*$ molecule [Phys. Lett. B 725, 127 (2013)].
- Energy dependent cross section of $e^+e^- \to \gamma X(3872)$ consistent with previous result.

Cross section of $e^+e^- \to \gamma X(3872)$ with $X(3872) \to \omega J/\psi$

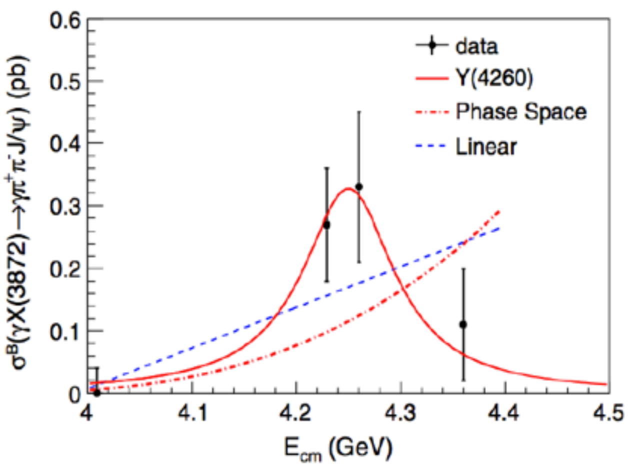
BESIII, PRL122, 232002 (2019)



Cross section

Old

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



→ Suggests production in *Y*(4260) decays

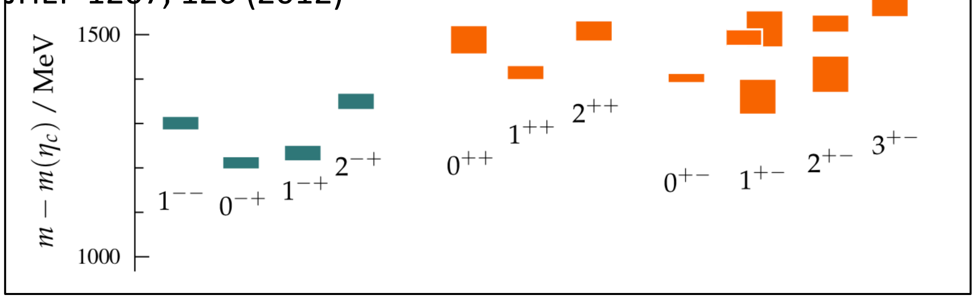
BESIII, PRL112, 092001 (2013)

Vector exotic states in e^+e^- annihilation: Y

Is Y(4260) hybrid?

- Strongly couple to the low-lying charmonium.
- According to lattice QCD simulation, both the 1^{--} and 1^{-+} hybrid charmonium lie around 4.26 GeV

JHEP 1207, 126 (2012)



Phys. Rev. D 79, 094504 (2009)

J^{PC}	mass (MeV)
2^{-+}	$\sim$ 4320
1^{--}	4260
1^{-+}	$\sim$ 4200
0^{-+}	$\sim$ 4190

The lightest charmonium hybrid multiplets based on lattice QCD

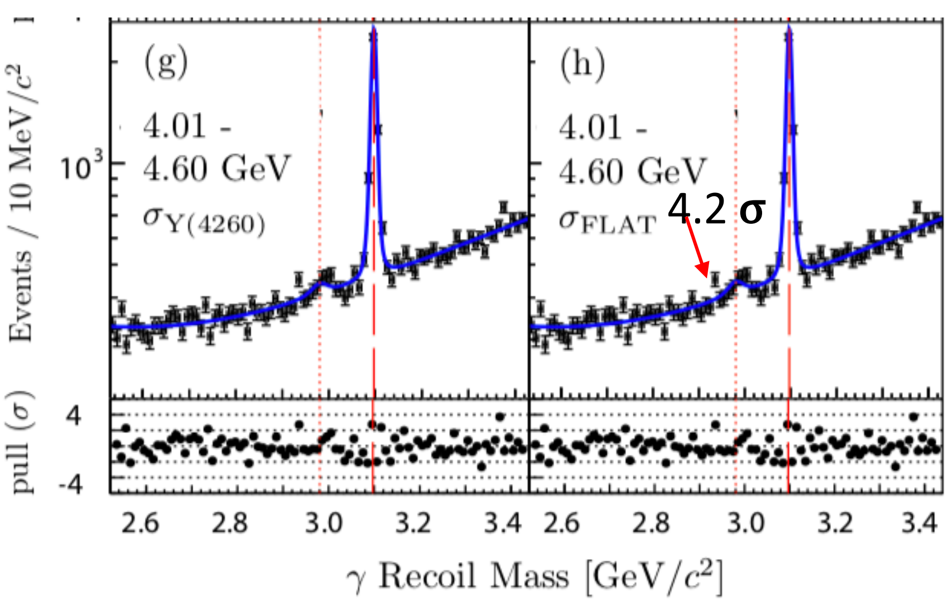
Opportunities:

- Search for quantum number partners of Y(4260)
- Search for spin-singlet hidden-charm decay mode, because the $c\bar{c}$ pair is a spin-singlet at initial state .

Search for $Y(4260) \to \gamma\chi_{C0}$ and $\gamma\eta_c$

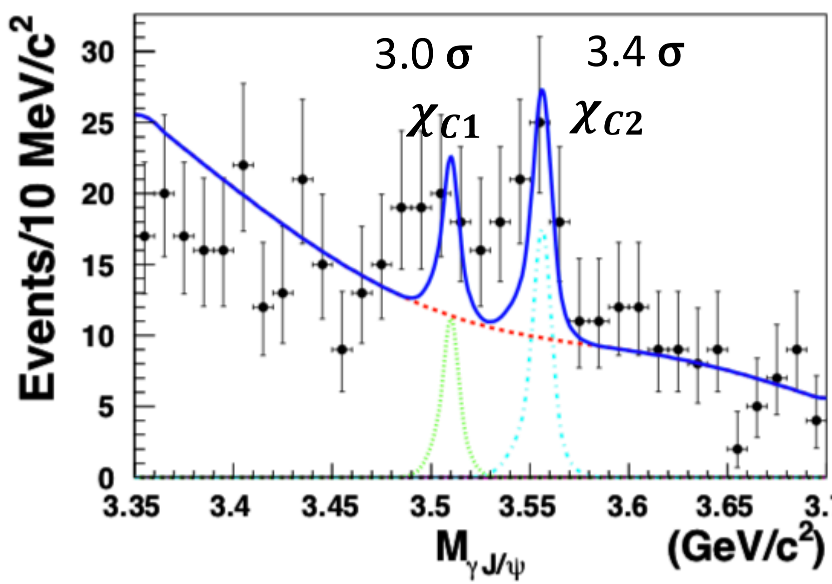
- If Y(4260) is a hybrid state, lattice QCD calculations predict that its rate of decay to $\boldsymbol{\gamma\eta_c}$ will be enhanced relative to $\boldsymbol{\gamma\chi_{C0}}$ $[\boldsymbol{PRD}\ \mathbf{79, 094504\ (2009)}]$
- Contrast to the pattern for conventional $\boldsymbol{\psi}$ states
- BESIII studied these two processes, but didn't found clear signals

$\mathbf{e^+e^- \to \gamma\eta_c}$



Chin.Phys. C39 (2015), 041001

$\mathbf{e^+e^- \to \gamma\chi_{CJ}}$



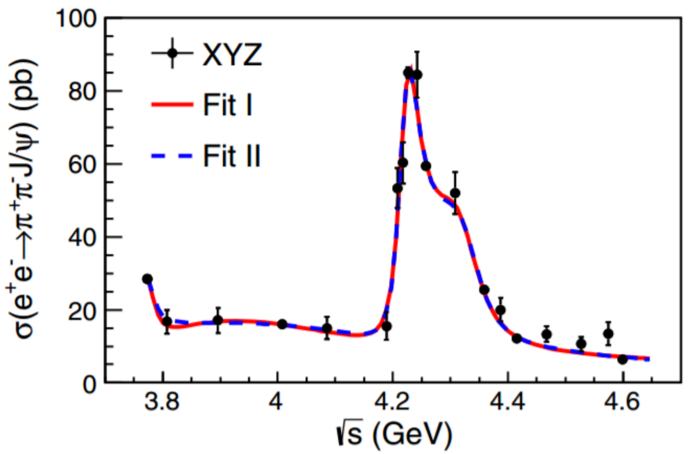
PhysRevD.96.051101 (2017)

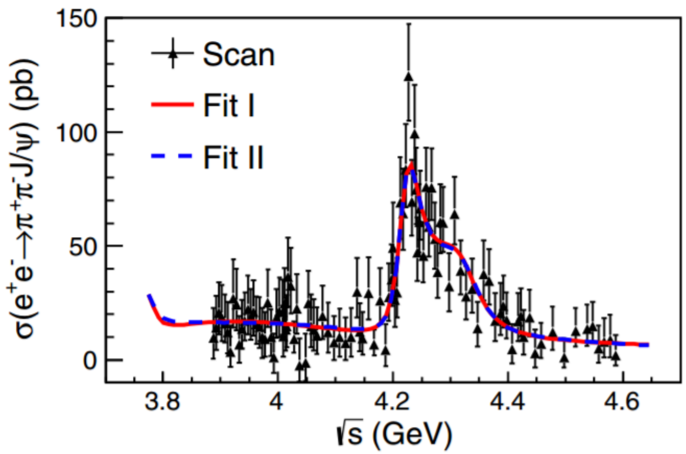
Study of $e^+e^- \to \pi^+\pi^- J/\psi$ cross section

Is Y(4260) one state?

➢Recent study of exclusive process $e^+e^- \to \pi^+\pi^- J/\psi$ shows a fine structure near 4.2 GeV: Y(4220) and Y(4390)

PRL 118, 092001 (2017)





Fit with 3 (fit1) or 2 (fit2) coherent BW

M = 4222.0±3.1±1.4 MeV (lower)

Γ= 44.1±4.3±2.0 MeV (narrower)

A 2nd resonance Y2 with

M=4320.0±10.4±7.0MeV/c2

Γ =$101.4^{+25.3}_{-19.7}$±10.2MeV

Y(4260)

M = 4263.0±9 MeV

Γ= 95±14 MeV

Observed for the first time, significance >7.6 **σ**

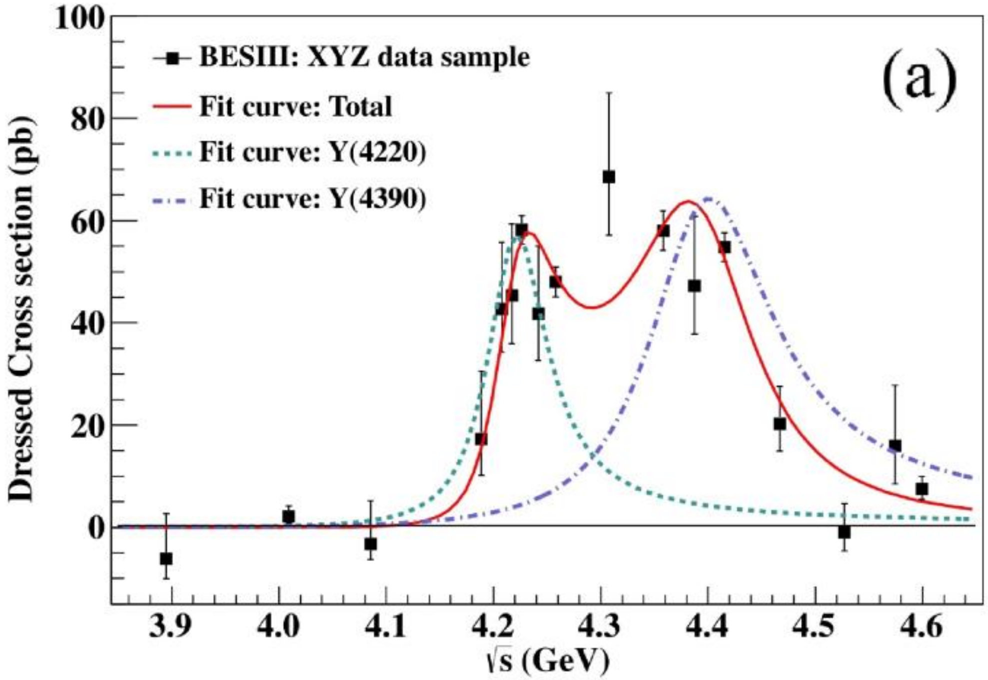
Cross section of $e^+e^- \to \pi^+\pi^- h_c$

PRL118, 092002 (2017)

$$\sigma(m) = \left| B_1(m)\sqrt{\frac{P(m)}{P(M_1)}} + e^{i\phi} B_2(m)\sqrt{\frac{P(m)}{P(M_2)}} \right|^2$$

$B_i(m)$: constant width Breit-Wigner function
$P(m)$: 3-body phase space factor
ϕ: relative phase between two resonances

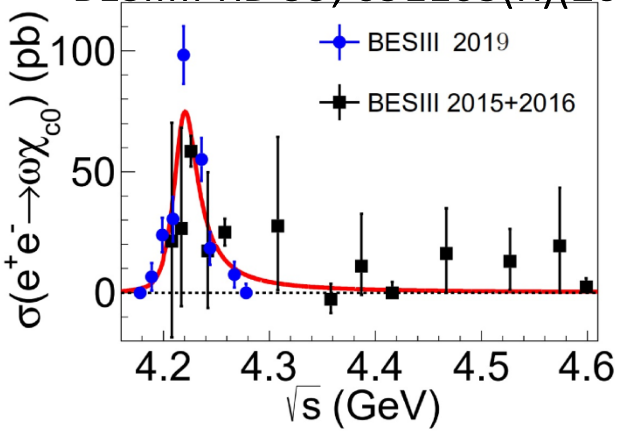
significance of two structures assumption over one structure > 10 σ

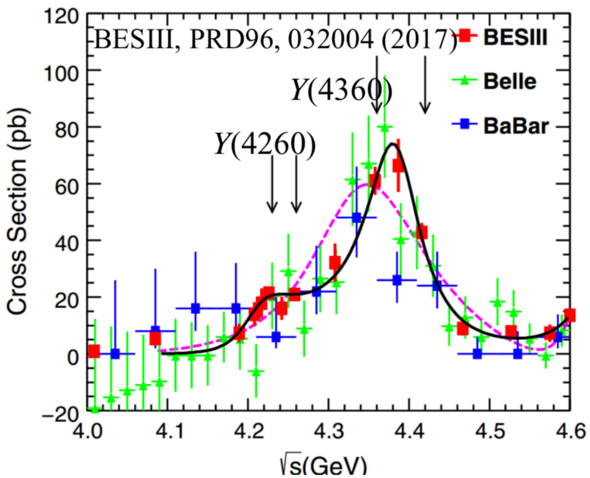


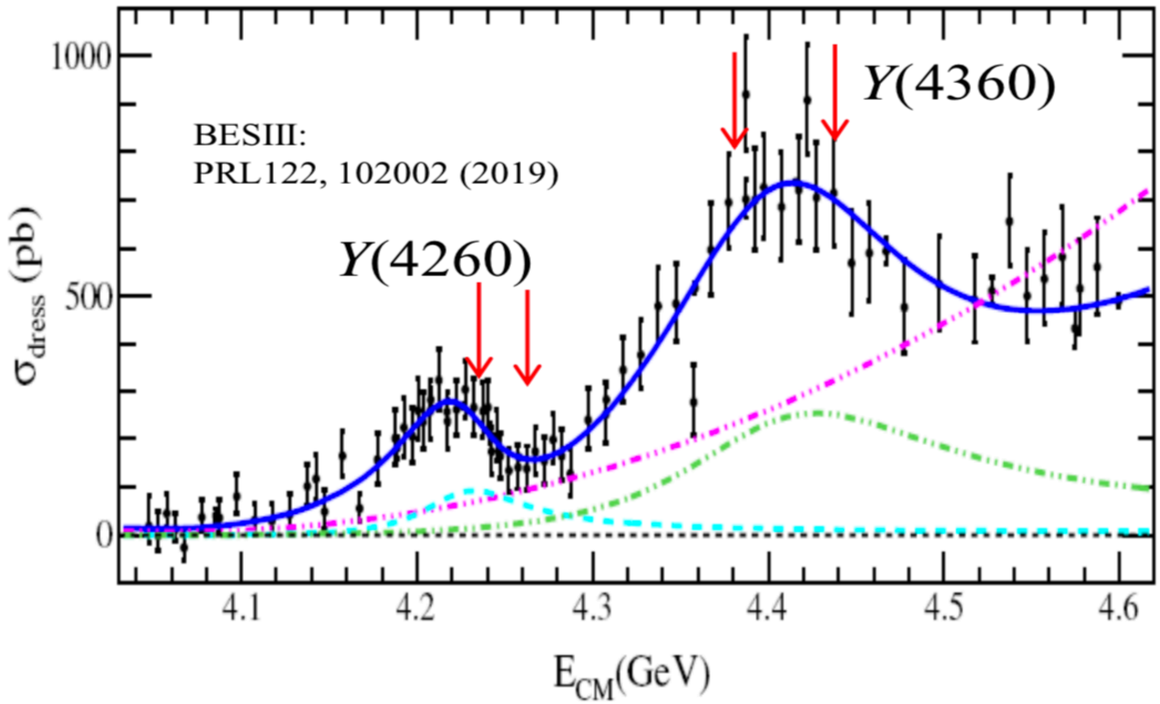
	M (MeV)	Γ_{tot} (MeV)	Γ_{ee}•Br (eV)	ϕ (rad)
Y(4220)	4218.4±4.0±0.9	66.0±9.0±0.4	4.6±4.1±0.8	--
Y(4390)	4391.6±6.3±1.0	139.5±16.1±0.6	11.8±9.7±1.9	3.1±1.5±0.2

Study of $e^+e^- \to \omega\chi_{C0}, \pi^+\pi^-\psi'$ and $\pi^+D^0D^{*-}$

BESIII:PRD 99, 091103(R)(2019)







Process	M_1 (MeV/c^2)	Γ_1 (MeV)	M_2 (MeV/c^2)	Γ_2 (MeV)
$e^+e^- \to \omega\chi_{c0}$	$4230 \pm 8 \pm 6$	$38 \pm 12 \pm 2$ [37]		
$e^+e^- \to \pi^+\pi^- J/\psi$	$4220.0 \pm 3.1 \pm 1.4$	$44.1 \pm 4.3 \pm 2.0$	$4320.0 \pm 10.4 \pm 7.0$	$101.4^{+25.3}_{-19.7} \pm 10.2$[9]
$e^+e^- \to \pi^+\pi^- h_c$	$4218.4^{+5.5}_{-4.5} \pm 0.9$	$66.0^{+12.3}_{-8.3} \pm 0.4$	$4391.5^{+6.3}_{-6.8} \pm 1.0$	$139.5^{+16.2}_{-20.6} \pm 0.6$ [10]
$e^+e^- \to \pi^+D^0D^{*-} + c.c$	$4224.8 \pm 5.6 \pm 4.0$	$72.3 \pm 9.1 \pm 0.9$	$4400.1 \pm 9.3 \pm 2.1$	$181.7 \pm 16.9 \pm 7.4$ [38]
$e^+e^- \to \pi^+\pi^-\psi(3686)$	$4209.5 \pm 7.4 \pm 1.4$	$80.1 \pm 24.6 \pm 2.9$	$4383.8 \pm 4.2 \pm 0.8$	$84.2 \pm 12.5 \pm 2.1$

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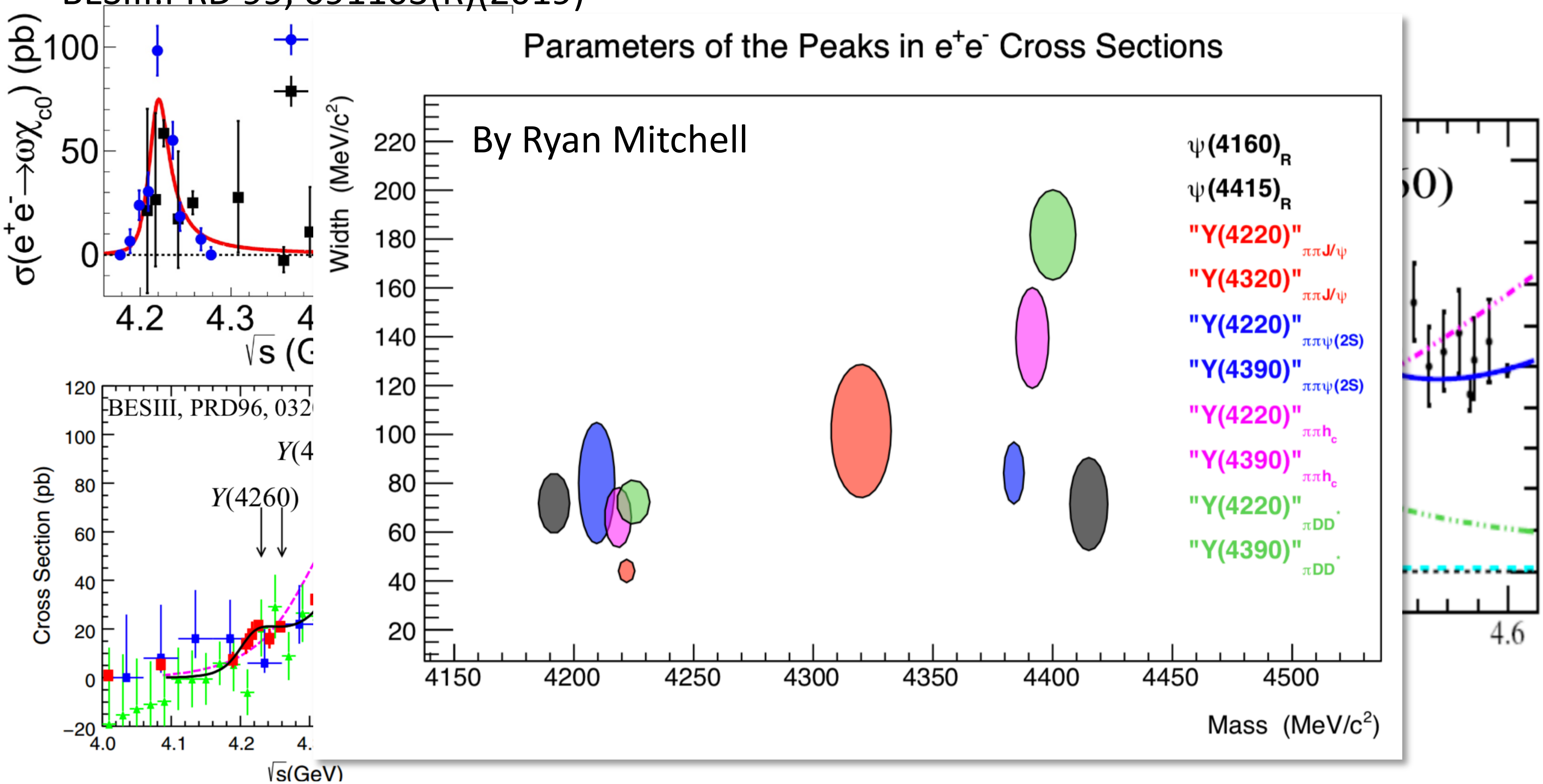
BESIII:PRD 99, 091103(R)(2019)



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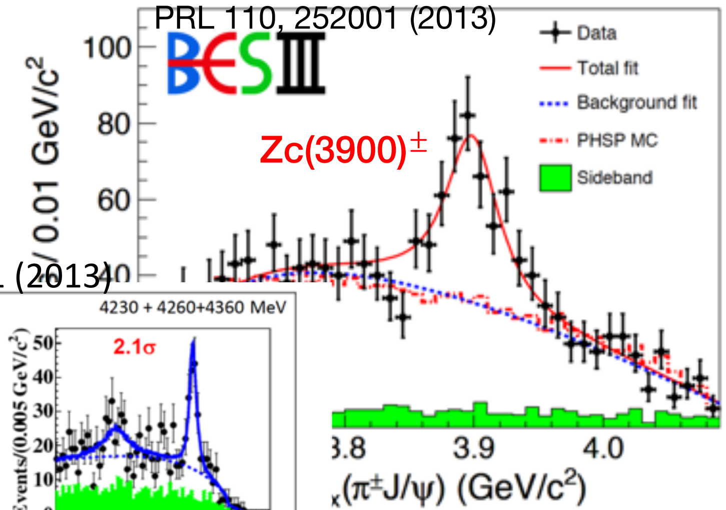
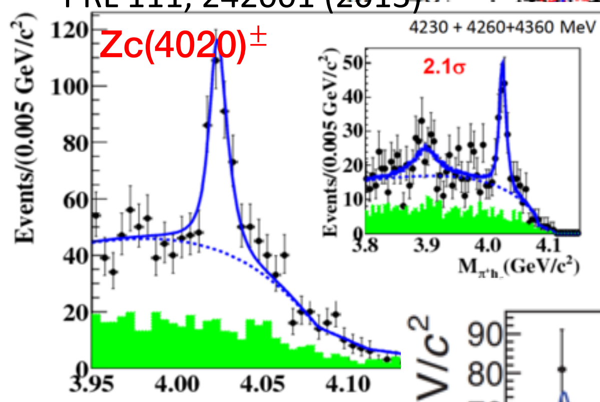
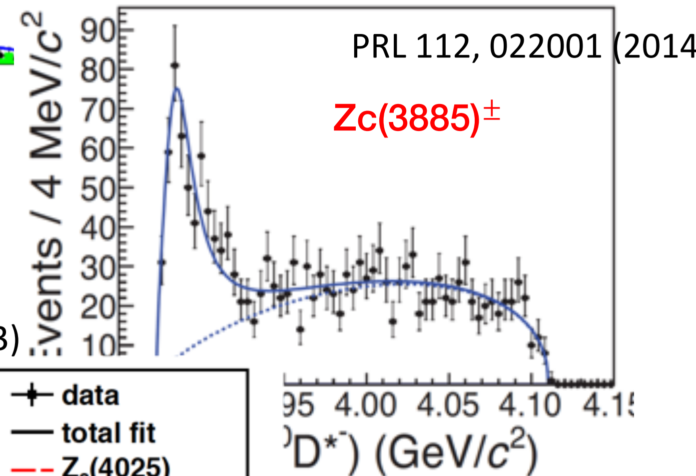
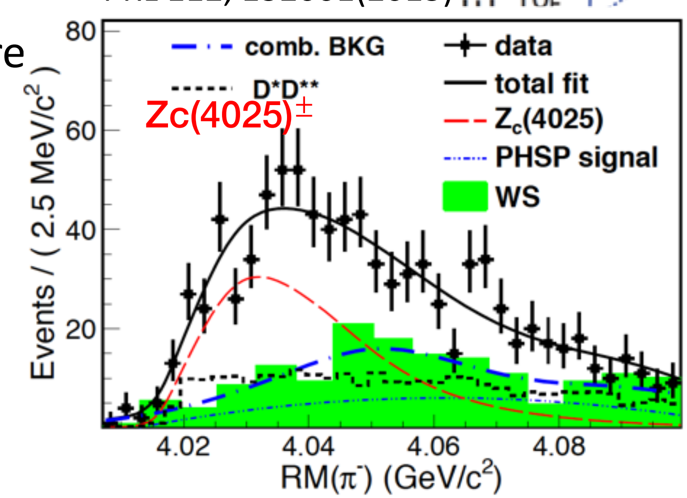
Breakthrough in 2013

- Although dozens of neutral exotic states were found, despite their unexpected properties, one could not exclude them as conventional quarkonium.
- Their J^{PC} and flavor quantum numbers are compatible with quarkonium.
- BESIII discovered $Z_c^{\pm}(3900)/Z_c^{\pm}(4020)$, whose decay into $J/\psi\ /h_c\pi^{\pm}$ reveals their constituents to be $c\bar{c}u\bar{d}$.
- Charged quarkonium like states are manifestly exotic states





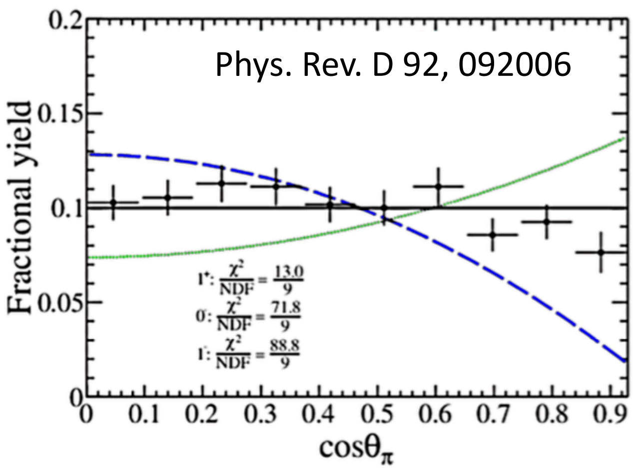




Summary of Z – J^P

Angular analysis of Zc(3885)

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

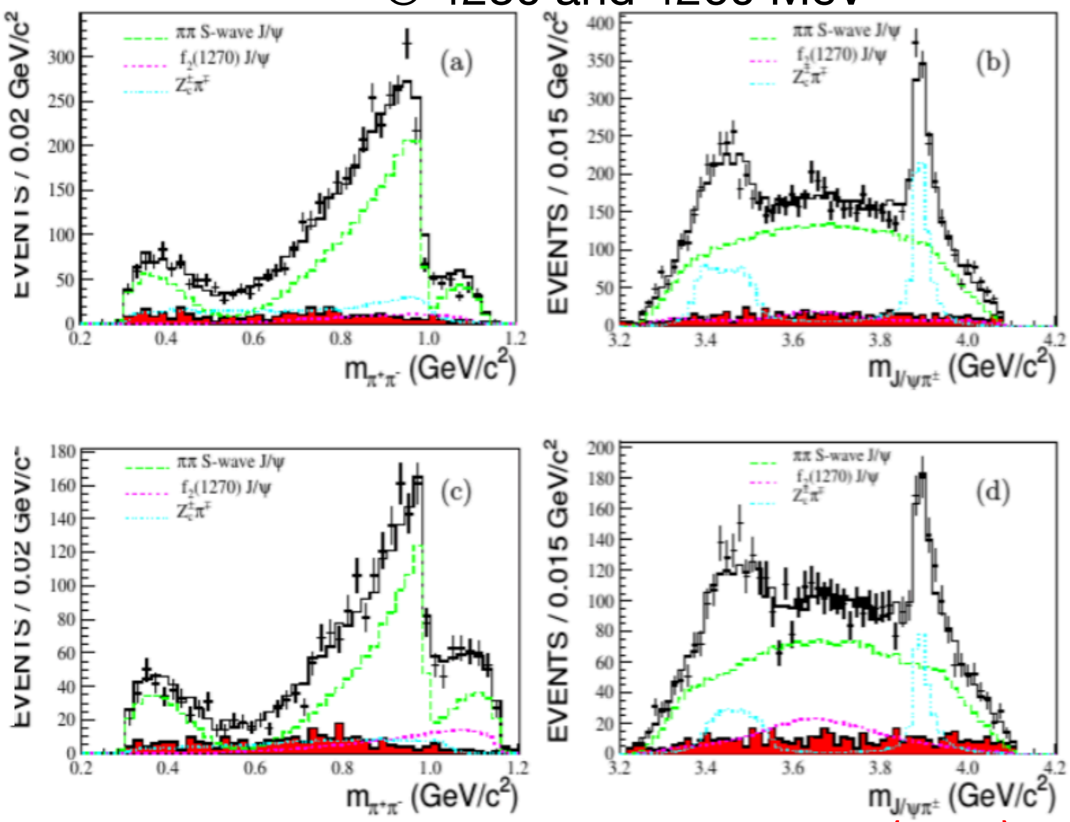


Efficiency corrected event yield in 10 bins in $|\cos\theta_\pi|$

data clearly favour $J^P = 1^+$ for $D\bar{D}^*$ structure

confirms J^P for $Z_c(3885)$ from single-tags

PWA of $e^+e^- \to \pi^+\pi^- J/\psi$ @ 4230 and 4260 MeV



PRL 119,072001 (2017)

J^P	$\Delta(-2\ln L)$	significance
1^+ over 0^-	89.0	7.3σ
1^+ over 1^-	214.0	$> 8\sigma$
1^+ over 2^-	103.6	$> 8\sigma$
1^+ over 2^+	387.0	$> 8\sigma$

Both Zc(3900) and Zc(3885) favor J^P=1^+

Data clearly favours $J^P = 1^+$

$\mathbf{Z_c}$ – tetra-quark or molecule?

Are they Tetra-quarks?

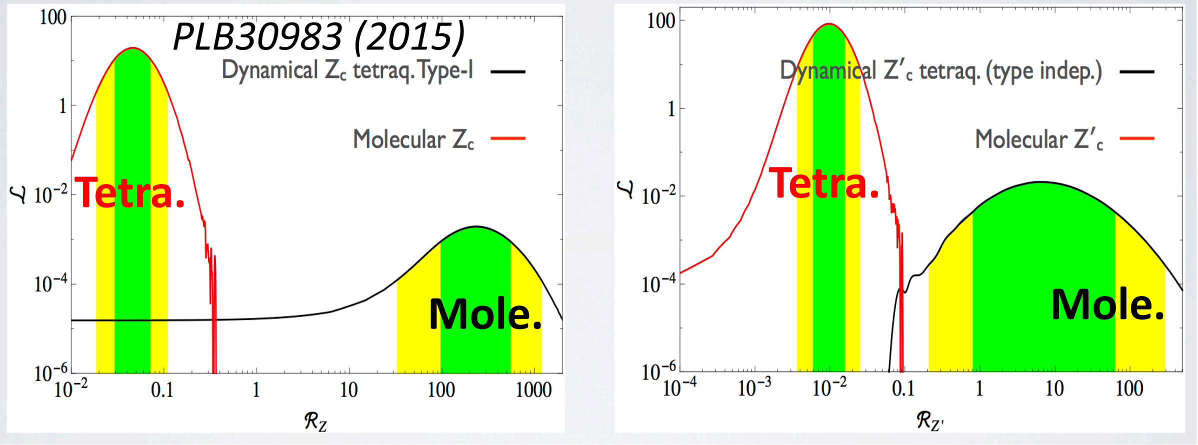
- Tetra-quarks will fall apart into a pair of open-flavor mesons or one quarkonium plus light mesons very easily
- Their widths are expected to be large while $\boldsymbol{Z_c}$ states are quite narrow
- The higher $Z_c^{\pm}(4020)$ has not been observed in the s-wave $\bar{D}D^*$ mode

Or Molecule?

- $\boldsymbol{Z_c}$ mass are close to $\bar{D}^{(*)}D^*$
- Narrow widths of the resonances in decay into quarkonium and pion, despite the large phase space, this implies a very small overlap of the wave functions
- X(3872) can be regarded as a I=0 $\bar{D}D^*$ molecule

Search for $e^+e^- \to \pi Z_c, Z_c \to \rho\eta_c$

- The decay of $Z^{(\prime)}{}_c \to \rho\eta_c$ will provide an essential hint to experimentally distinguish the tetraquarks (Type-1) and molecular model.

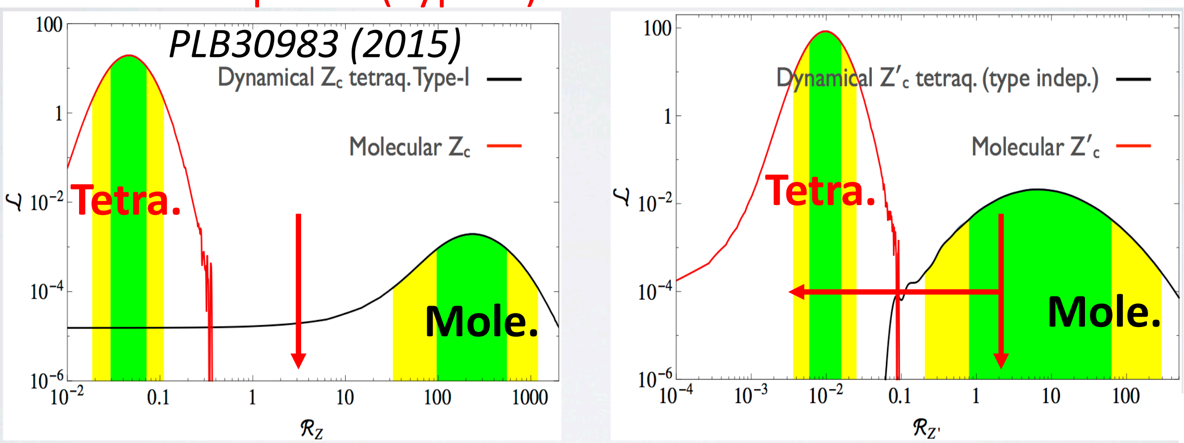


$$R_z = \frac{Br(Zc \to \rho\eta_c)}{Br(Zc \to \pi J/\psi)}$$

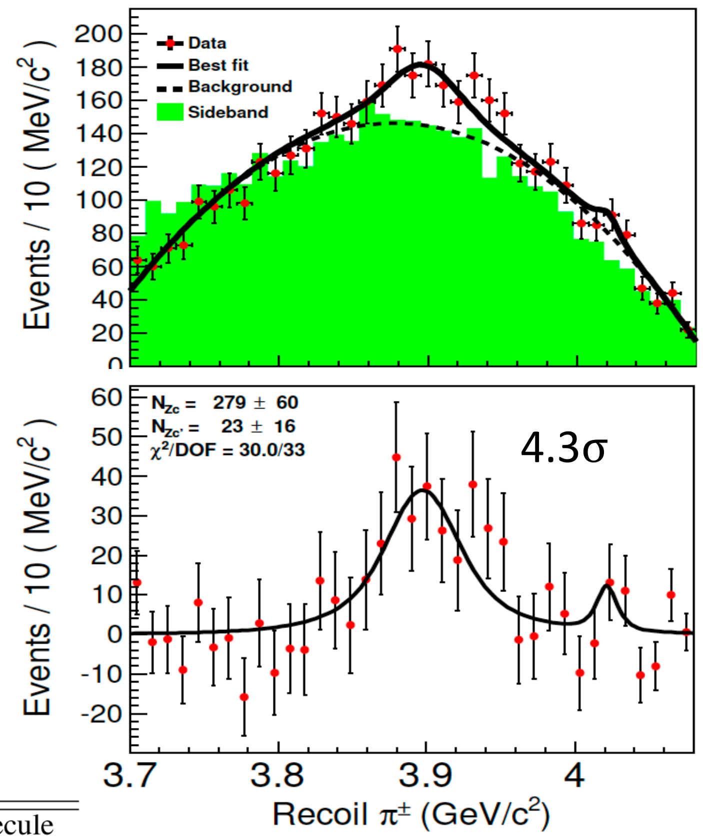
$$R'_z = \frac{Br(Z'c \to \rho\eta_c)}{Br(Z'c \to \pi hc)}$$

Search for $e^+e^- \to \pi Z_c, Z_c \to \rho\,\eta_c$

- The decay of $Z^{(\prime)}{}_c \to \rho\eta_c$ will provide an essential hint to experimentally distinguish the tetraquarks (Type-1) and molecular model.



arXiv:1906.00831



$e^+e^- \to \pi Z_c, Zc \to \rho\,\eta_c$

$$R_z = \frac{Br(Zc \to \rho\eta_c)}{Br(Zc \to \pi J/\psi)} \qquad R'_z = \frac{Br(Z'c \to \rho\eta_c)}{Br(Z'c \to \pi hc)}$$

- Strong evidence of $Z_c \to \rho\,\eta_c$ is observed
- Measured R_z is close to Tetraquark model prediction

	$\sqrt{s} = 4.226$ 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	$6.6^{+56.8}_{-5.8}$		$0.010^{+0.006}_{-0.004}$

Future plan and perspective of BESIII

- **Accelerator and detector upgrade**
  - Accelerator energy: Emax = 2.45 GeV
  - Top-up injection: level off instantaneous luminosity gain ≈ 30% in Lint
  - Endcap TOF: upgrade finished 2015
    - TOF resolution: 110 ps ¬ 60 ps
    - 95% π/K separation up to 1.4 GeV
  - New inner MDC: CGEM upgrade in progress (installation 2020)
- **Data plan (may be changed slightly in future)**
  - 3×10^{9} ψ(3686)
  - 10 fb^{-1} on ψ(3770)
  - Large Zc samples: 5 fb^{-1} each at 4.23, 4.42 GeV
  - 6 fb^{-1} at 4.18 GeV, 5 fb^{-1} at 4.64 GeV
  - Continue XYZ scan (500 fb^{-1} per point between 4.0 and 4.6 GeV)

Summary

- **BESIII experiment play an important role in the study of charmonium spectroscopy, especially for the charmonium-like state**
- ***Is X(3872) a molecule states?***
  - $X(3872) \to \pi^0 \chi_{C1}$ 👍
  - $X(3872)$ radiative decay 👍
  - $X(3872) \to \omega J/\psi$ 👍
- ***Is Y(4260) a hybrid state?***
  - $\mathbf{e^+e^-} \to \boldsymbol{\gamma\eta_c}$ and $\boldsymbol{\gamma\chi_{C0}}$ 🤔
- ***Or is it one state?***
  - $\mathbf{e^+e^-} \to \ \boldsymbol{\pi^+\pi^-}\ \mathbf{J/\psi}$, 👎
  - $\mathbf{e^+e^-} \to \boldsymbol{\pi^+\pi^- h_c}$ 👎
  - $\mathbf{e^+e^-} \to \ \boldsymbol{\pi^+\pi^-\psi'}$ 👎
  - $\mathbf{e^+e^-} \to \ \boldsymbol{\pi^+} D^0 D^{*-}$. 👎
- ***What's inside the Zc?***
  - PWA of $\mathbf{e^+e^-} \to \boldsymbol{\pi^+\pi^- J/\psi}$ $J^P = 1^+$
  - $\boldsymbol{Z_c \to \rho\,\eta_c}$ favor tetra-quark

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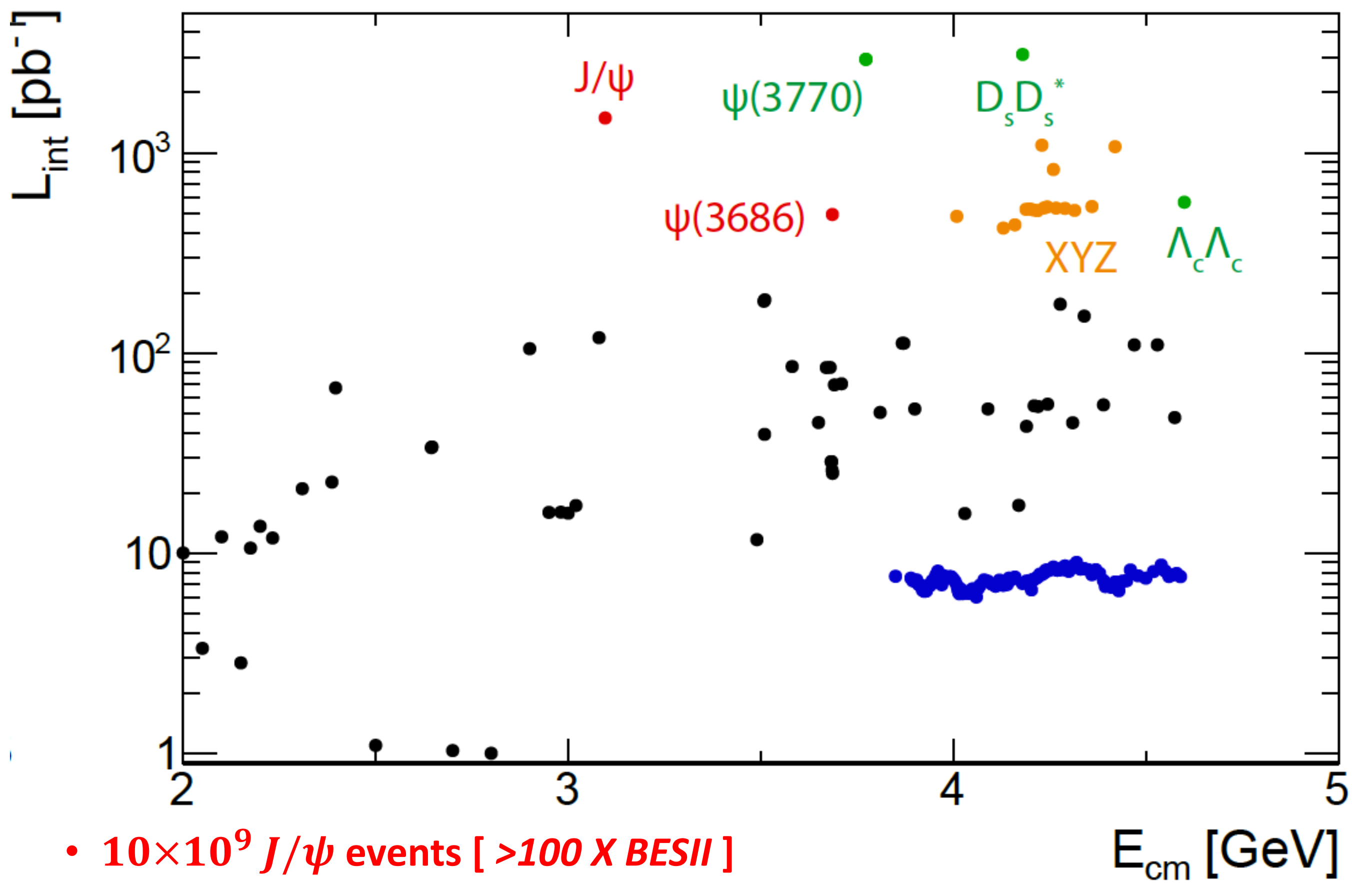
Thanks!

Backup

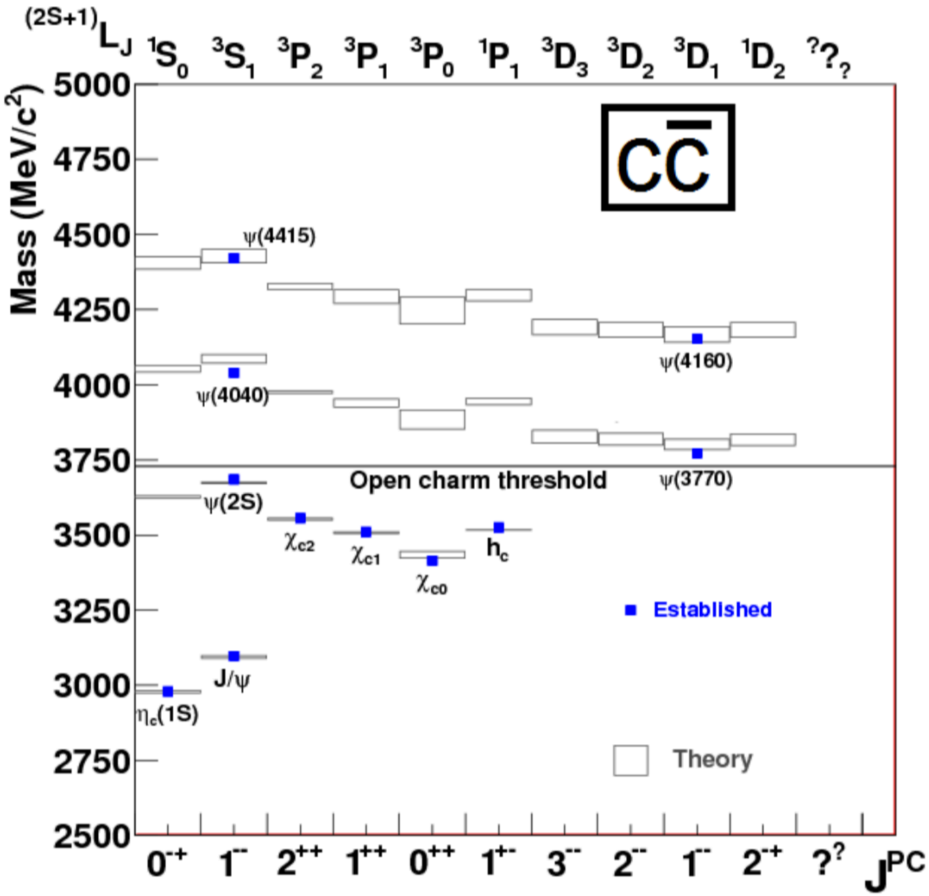
Data sets @ BESIII

10 years data taking at BESIII !



- 10×10^9 J/ψ events [*>100 X BESII*]
- 448×10^6 $\psi(3686)$ events [*20 X CLEO-c*]
- 2.93 fb^{-1} $\psi(3770)$ [*3.5 X CLEO-c*], ~3 fb^{-1} at 4.18 GeV and 0.5 fb^{-1} at 4.6 GeV
- ~1.5 fb^{-1} (130 points) for R scan & QCD (2~4.6 GeV)
- ~12 fb^{-1} data set for XYZ states > 3.8 GeV

Review of charmonium spectroscopy



Before 2000

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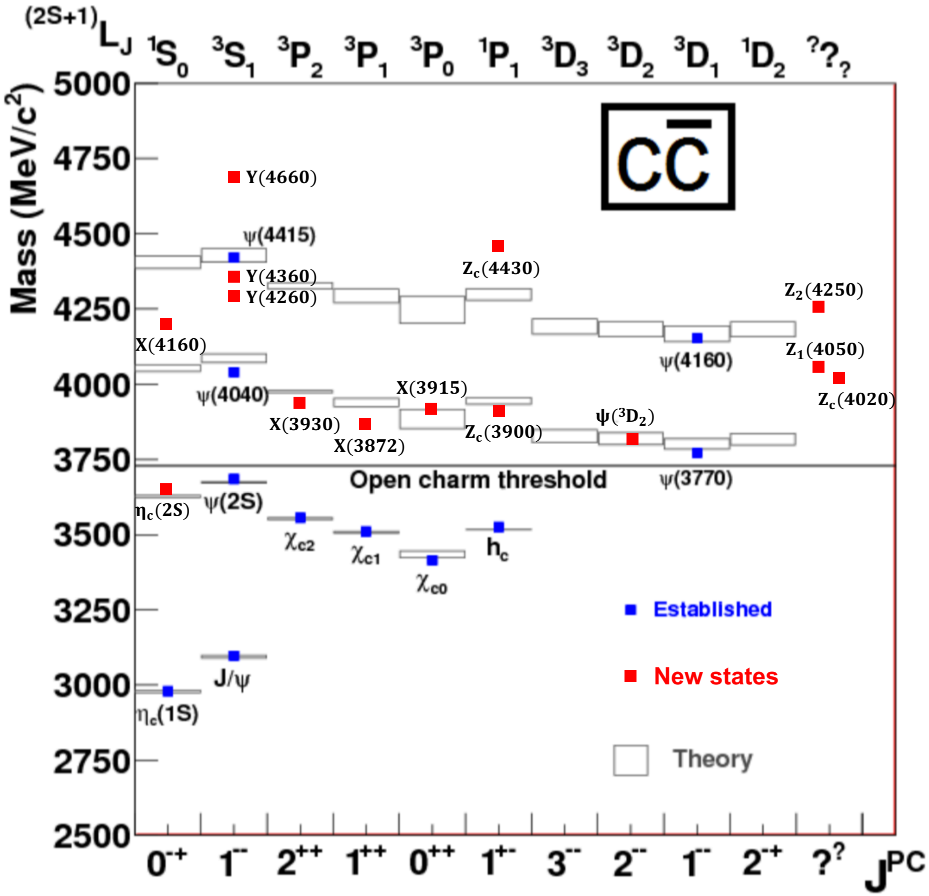

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Post B-factories era

- ➢ With high-lum. B and charm factories, more detailed studies of known states and searching for missing states became possible.
- ➢ A bunch of new states were observed in experiment, but:
  - They don’t fill the expected slots
  - They have unexpected properties