Recent results from the BESIII Experiment

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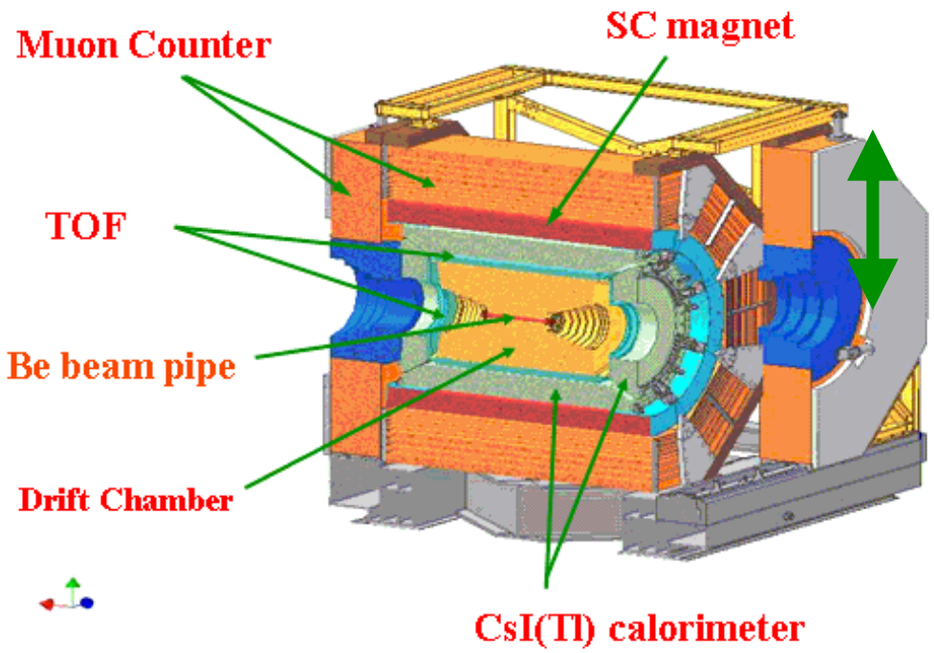
- Experiment:
  - most states are quark-antiquark mesons or three-quark baryons
  - little evidence for hybrids or glueballs
- Can we find evidence for these more interesting hadrons that are, in principle, allowed by QCD?

The Experiment: BESIII at BEPCII



BESIII

Multipurpose Detector

(Scale)

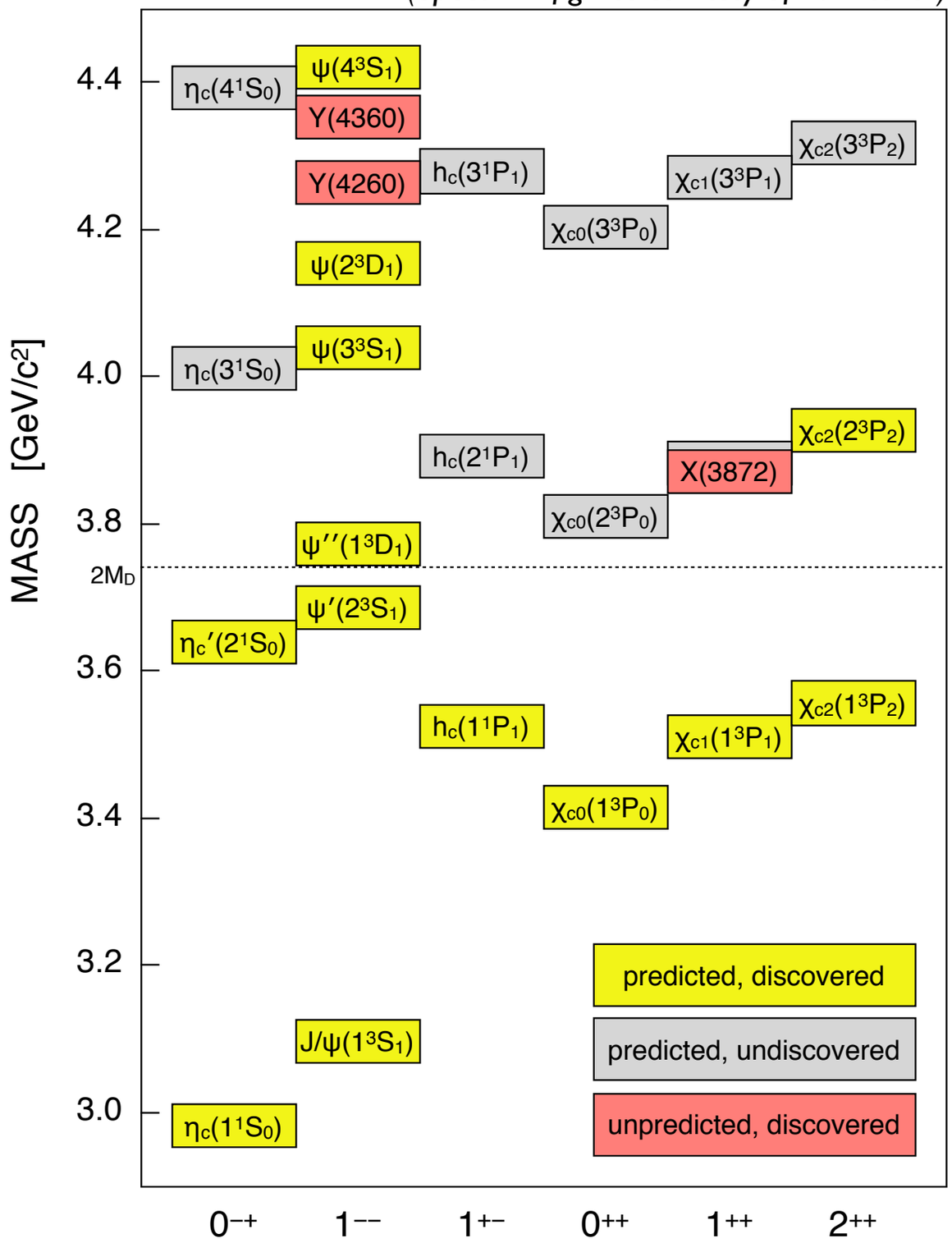
e^+e^-
Collisions with
E_{cm} from
≈2 GeV to 4.6 GeV

Running in 4 GeV
region since late 2012

The Landscape

- all states below $D\overline{D}$ threshold have been observed
- charm anti-charm potential model describes spectrum below $D\overline{D}$ threshold
- attempt to understand fundamental structure by studying
  - pattern of masses
  - transitions between states
- states with unconventional charmonium properties began appearing in the spectrum about a decade ago

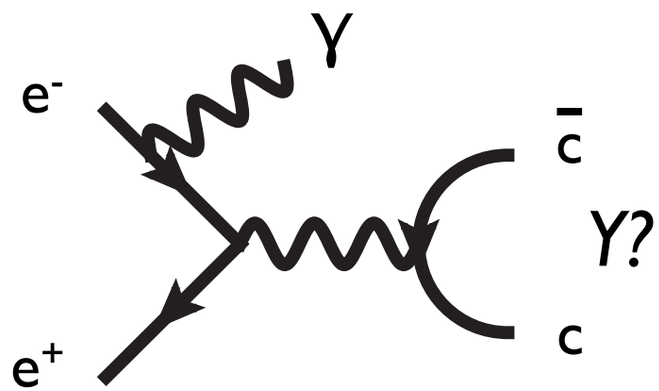
(Spectrum figures courtesy of R. Mitchell)



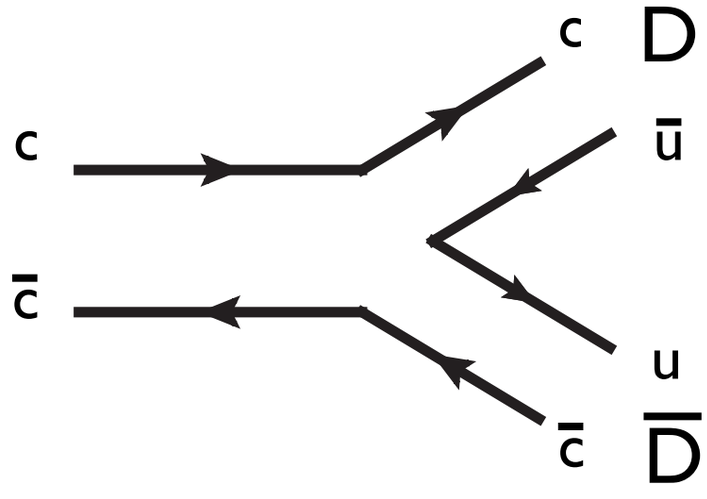
Prediction: Barnes, Swanson, and Godfrey, PRD 72, 054026 (2005)

The History: *Y*(4260)

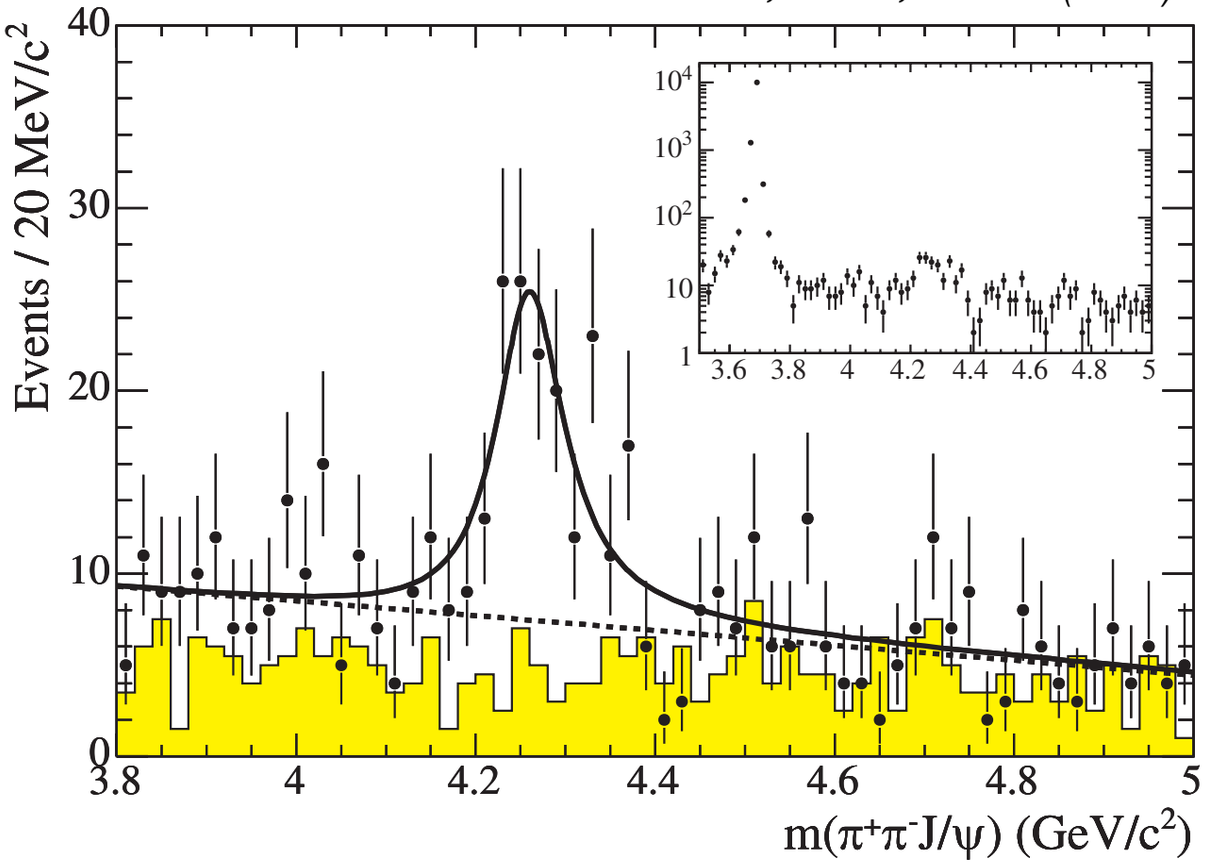
- 1^{--} state produced in e^+e^-



- mass greater than 2M(*D*) so we expect OZI favored decay:



The BaBar Collaboration, PRL 95, 142001 (2005)



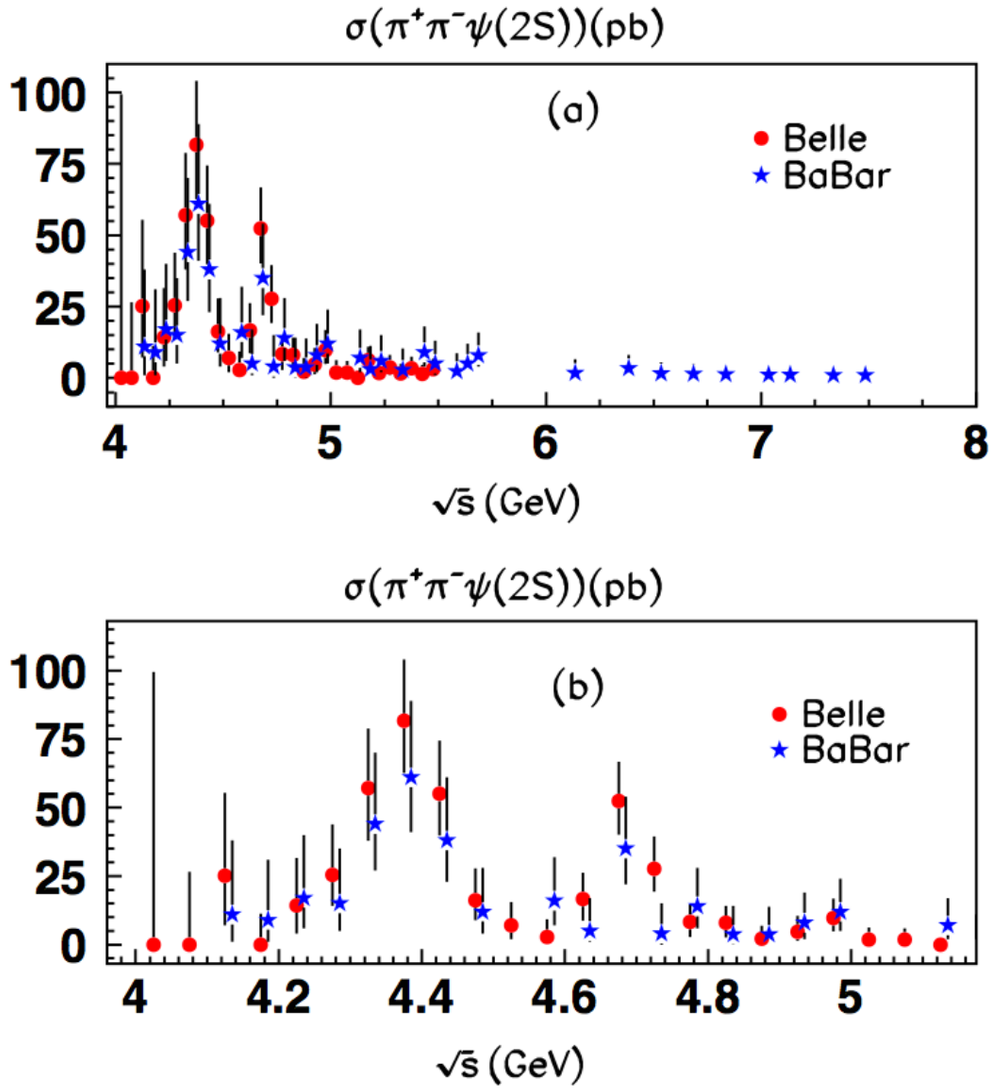
CLEO Collaboration, PRD 80, 072001 (2009)

$$\frac{\mathcal{B}(Y(4260) \to D\bar{D})}{\mathcal{B}(Y(4260) \to \pi\pi J/\psi)} < 4$$

compare with ≈500 for ψ(3770)

More History: *Y*(4360)

- similar to *Y*(4260) except dominantly decays to ππψ'
- additional state at 4660 MeV
- nature of *Y* states is unknown
- all produced in e^+e^- collisions
- perfect problem to study with e^+e^- collider in the charmonium region
  - motivation for dedicated running at BESIII starting in the winter of 2012-2013



Liu, Qin, and Yuan, PRD 78, 014032 (2008)
using data from:
BaBar Collaboration, PRL 98, 212001 (2007)
Belle Collaboration, PRL 99, 142002 (2007)

The Available Data

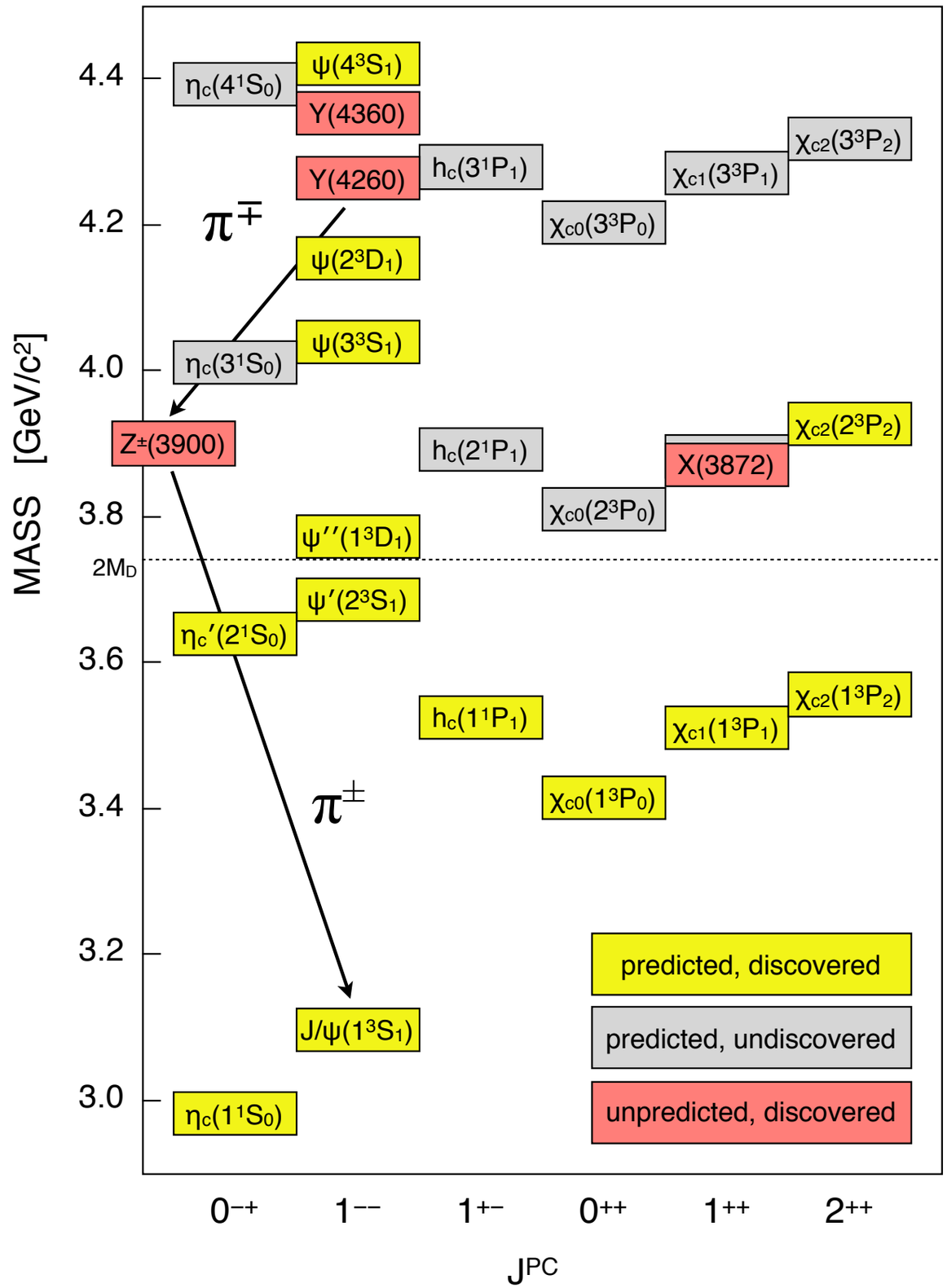
Data sets collected by BESIII since 2009

e^+e^- collision E_{cm}	L or N	Physics Topics
3097 MeV: J/ψ	1.3×10^9 J/ψ	light hadron spectroscopy
3686 MeV: ψ'	0.4×10^9 ψ'	charmonium transitions; light hadron spectroscopy
ψ(3770)	2.9 fb^{-1}	D decays; precision flavor physics
ψ(4040)	0.5 fb^{-1}	charmonium spectroscopy
3554 MeV	0.024 fb^{-1}	precision determination of τ mass
4230 MeV - 4260 MeV	1.9 fb^{-1}	charmonium spectroscopy; study of $Y(4260)$ and Z_c
4360 MeV	0.5 fb^{-1}	charmonium spectroscopy; study of $Y(4360)$
4100 MeV - 4400 MeV	0.5 fb^{-1}	coarse scan; Y spectroscopy
3850 MeV - 4590 MeV	0.8 fb^{-1}	fine scan; R measurement; Y spectroscopy
4600 MeV	0.5 fb^{-1}	charmonium spectroscopy

(Red: partial or full data sets for the analyses presented today)

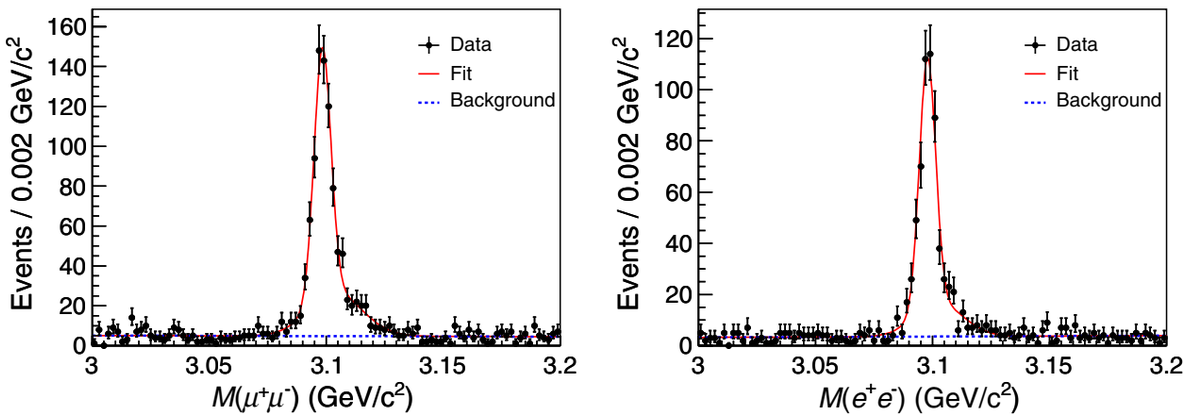
$e^+e^- \to \pi^+\pi^- J/\psi$

- $\pi\pi J/\psi$ is the only firmly established decay mode of *Y*(4260)
  - preliminary Belle result limits $\sigma(KKJ/\psi)$ to about 1/10 of $\pi\pi J/\psi$ (*arXiv:1402.6578*)
- natural starting place for study:
  - collide e^+e^- near 4260 MeV
  - examine $\pi\pi J/\psi$ Dalitz plot



$e^+e^- \to \pi^+\pi^- J/\psi$ at E_{cm} = 4260 MeV

- J/ψ is cleanly identified in dilepton decay modes



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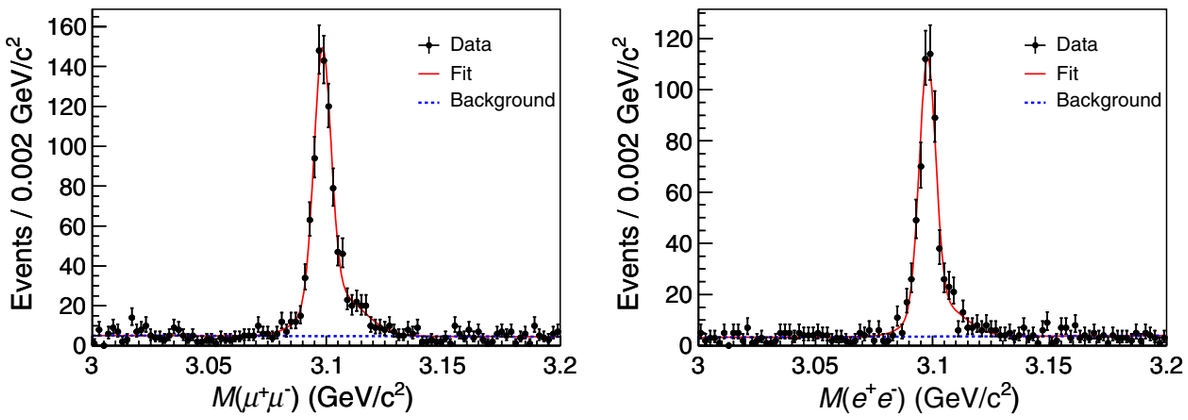
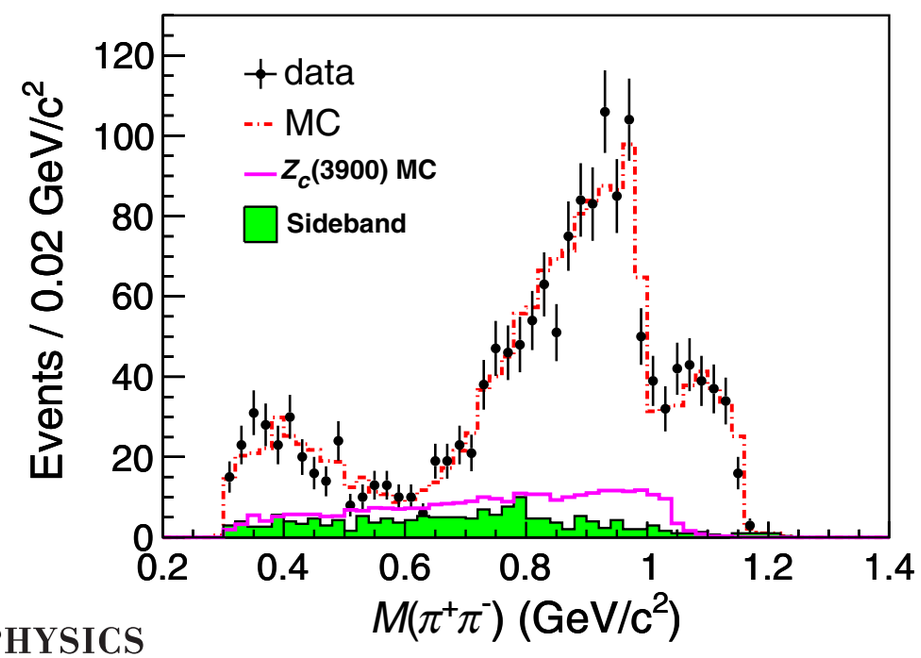
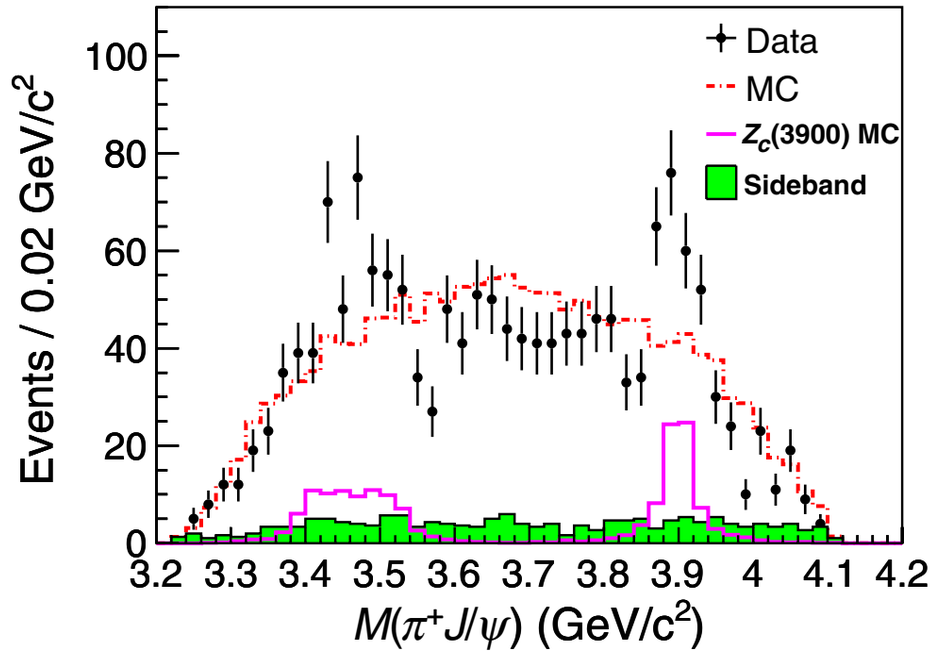
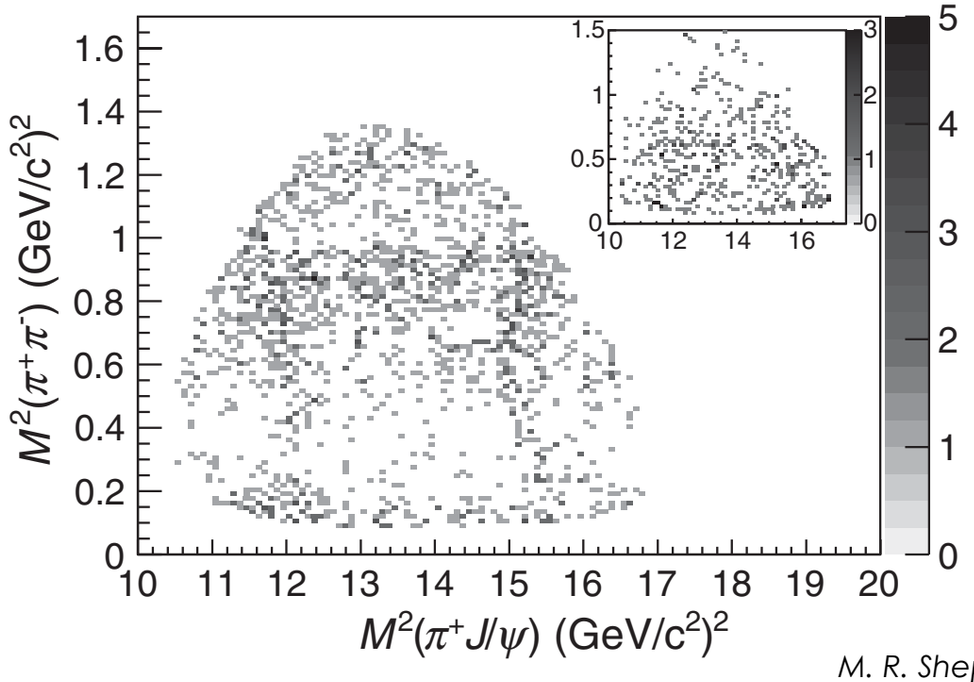


- Structure in $\pi^+ J/\psi$ mass that does not arise from $\pi^+\pi^-$ interactions

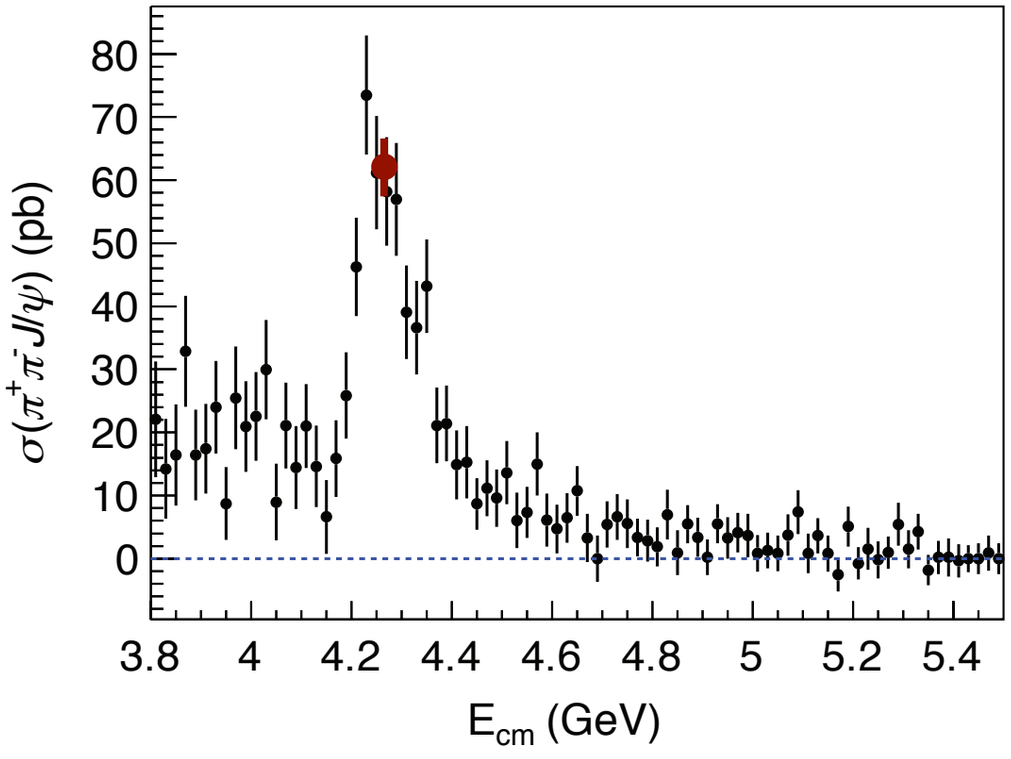


BESIII Collaboration, PRL 110, 252001 (2013)





Belle Collaboration, PRL 110, 252002 (2013)



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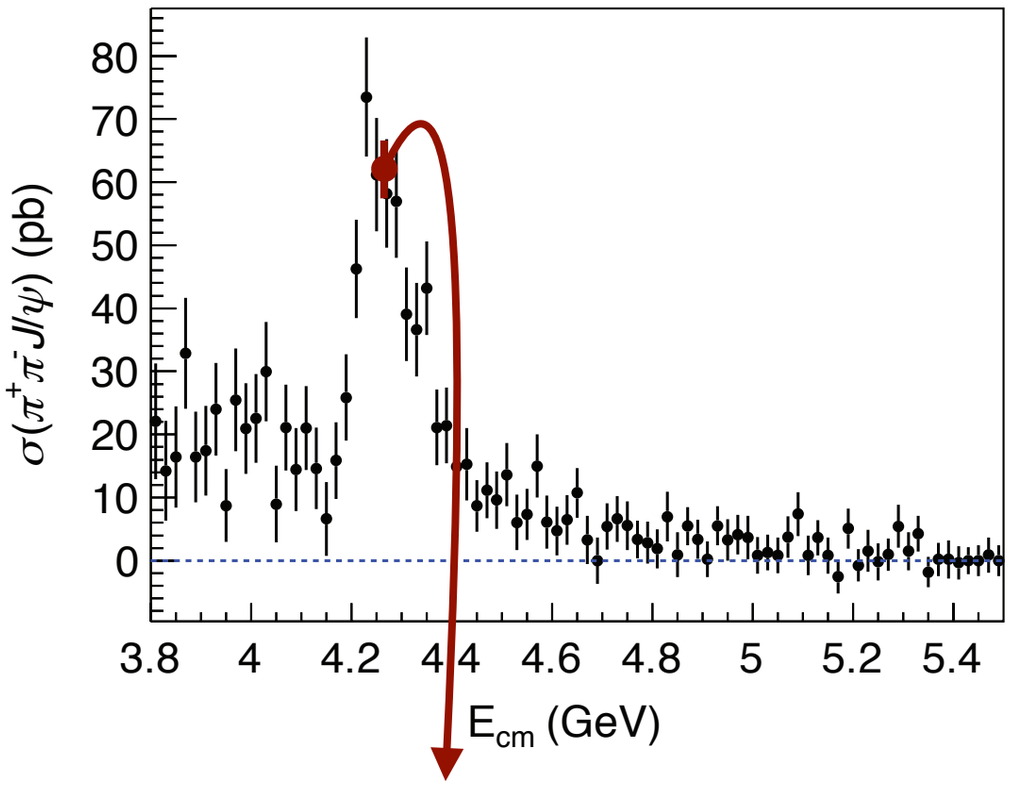

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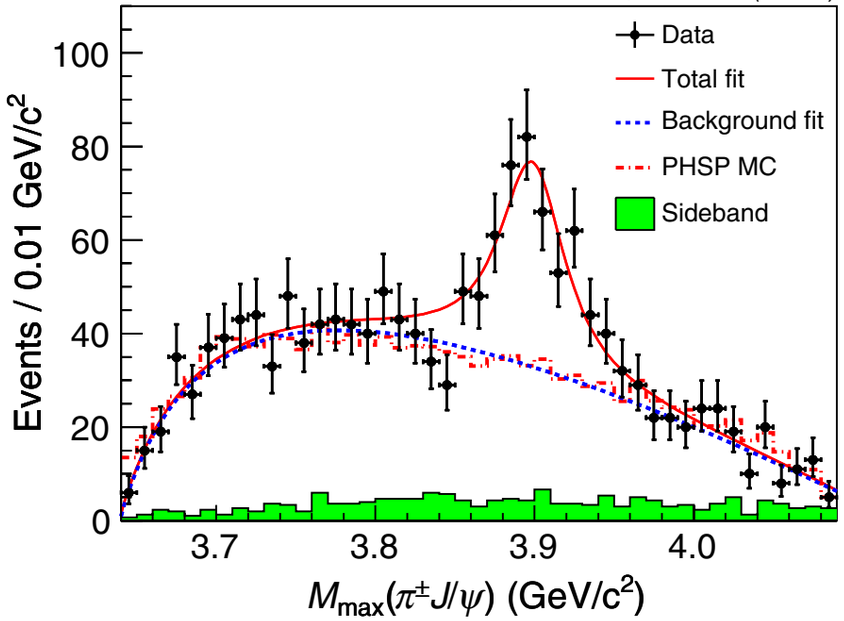

$M[Z_c(3900)] = 3899 \pm 6$ MeV

$\Gamma[Z_c(3900)] = 46 \pm 22$ MeV

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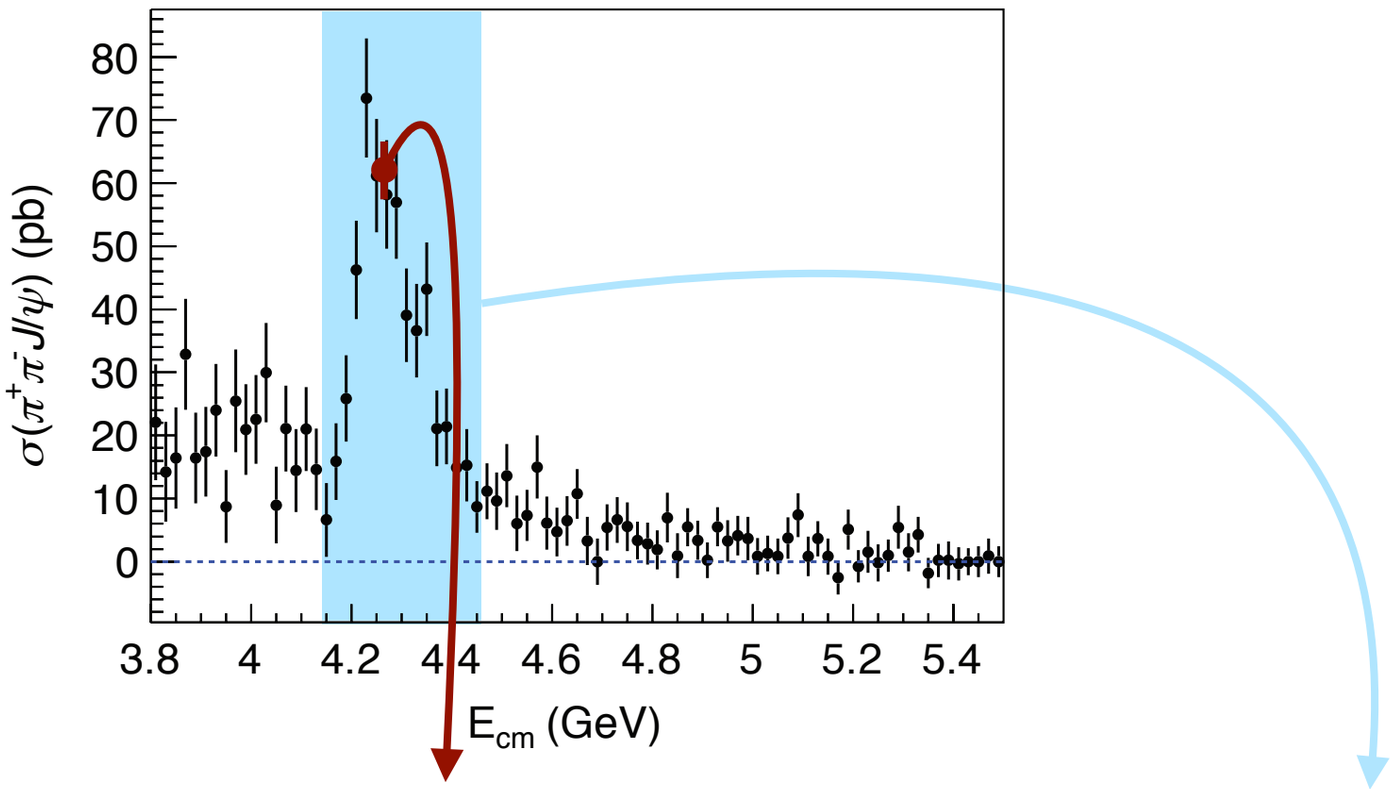

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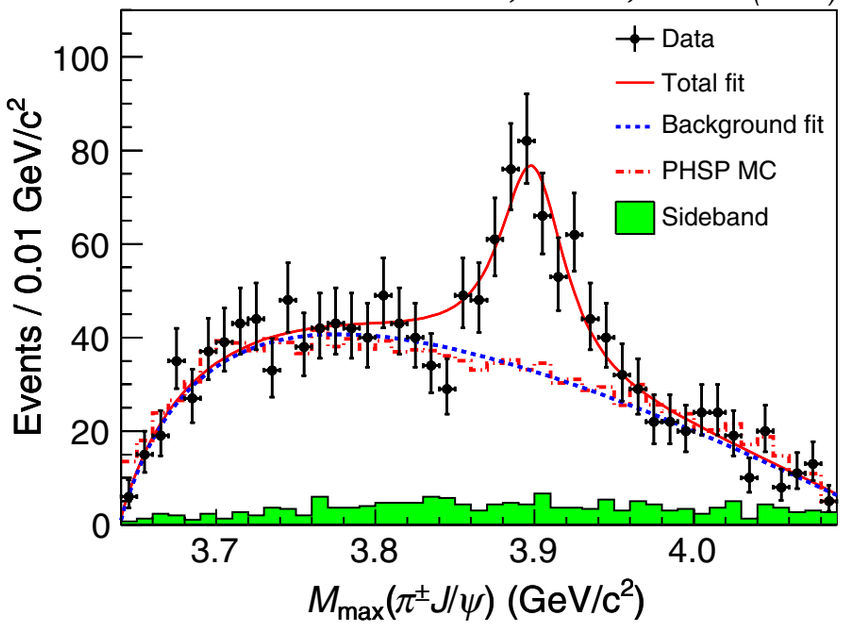

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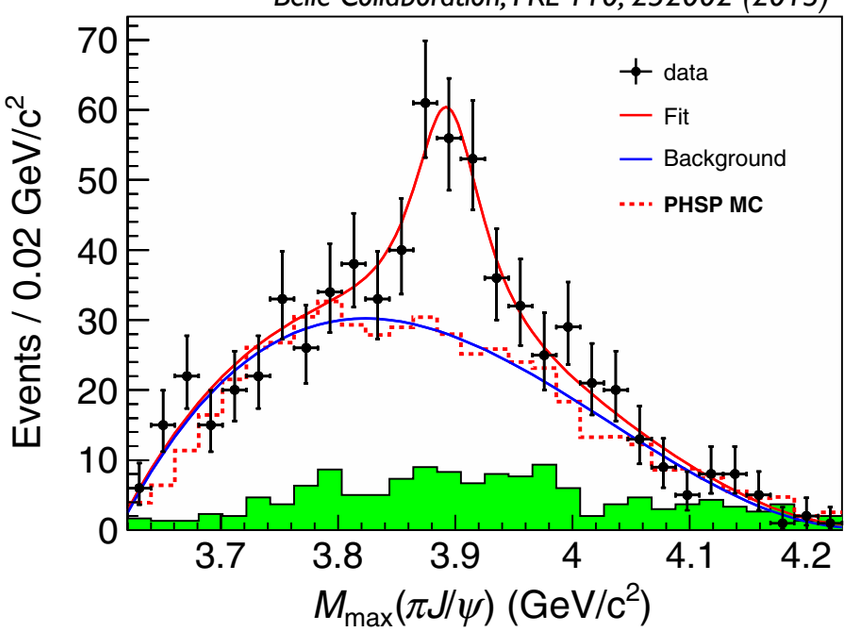

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$\Gamma[Z_c(3900)] = 63 \pm 35$ MeV

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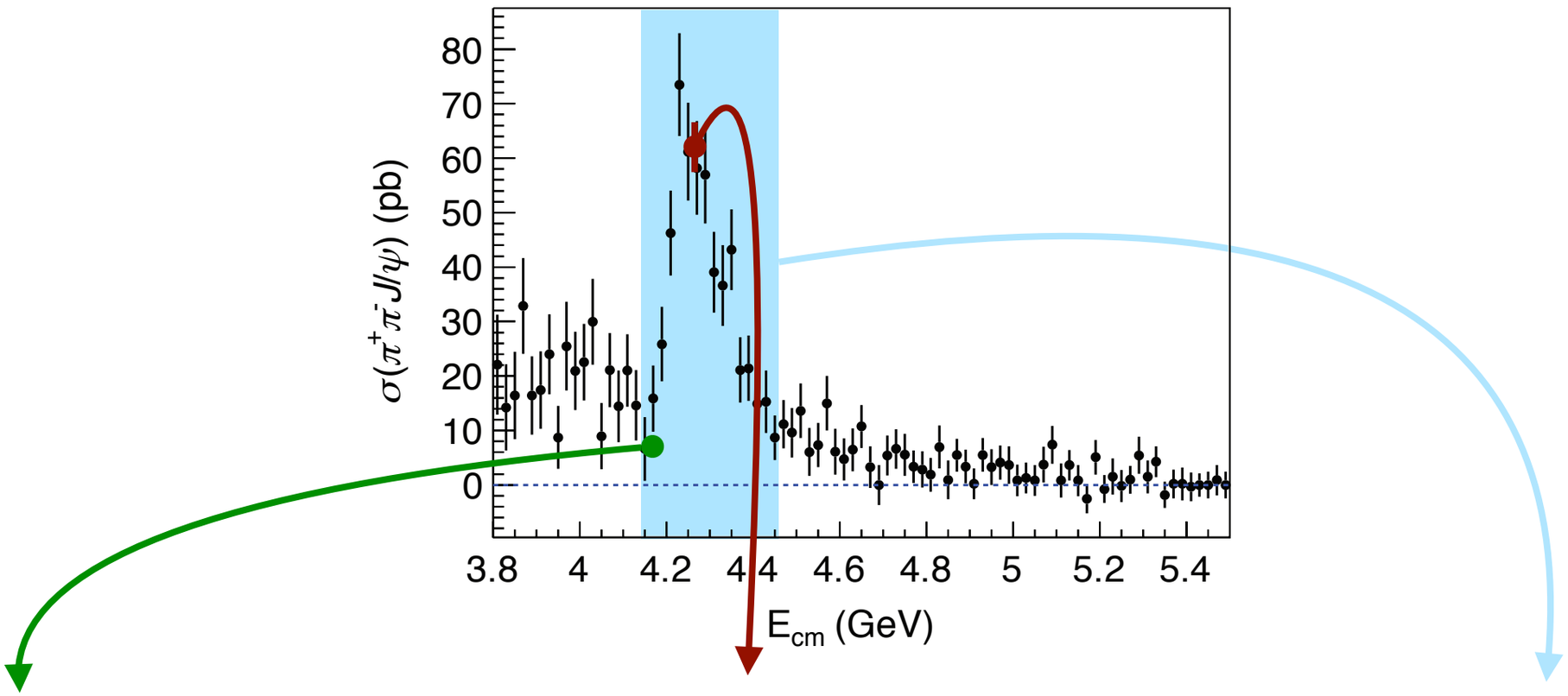
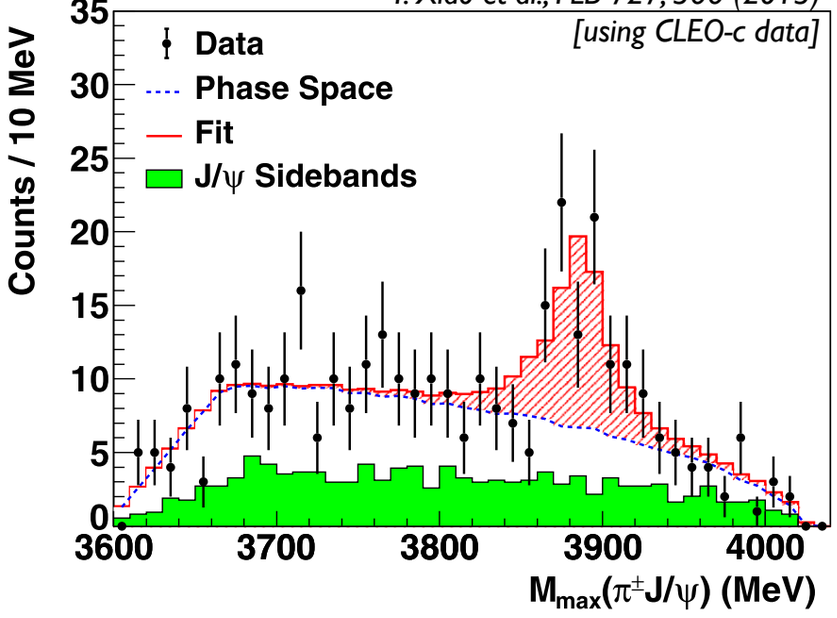
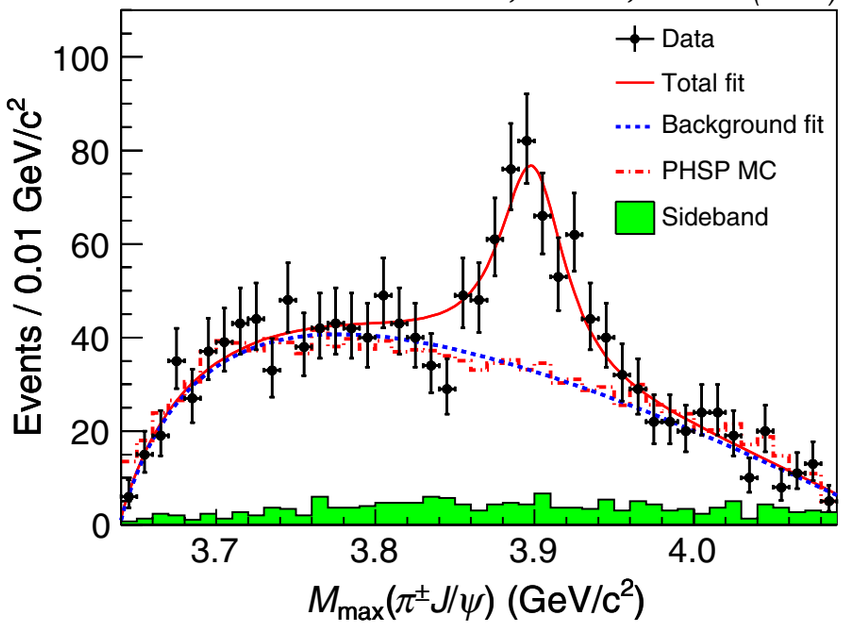


T. Xiao et al., PLB 727, 366 (2013)



$M[Z_c(3900)] = 3886 \pm 5$ MeV
$\Gamma[Z_c(3900)] = 33 \pm 9$ MeV

BESIII Collaboration, PRL 110, 252001 (2013)



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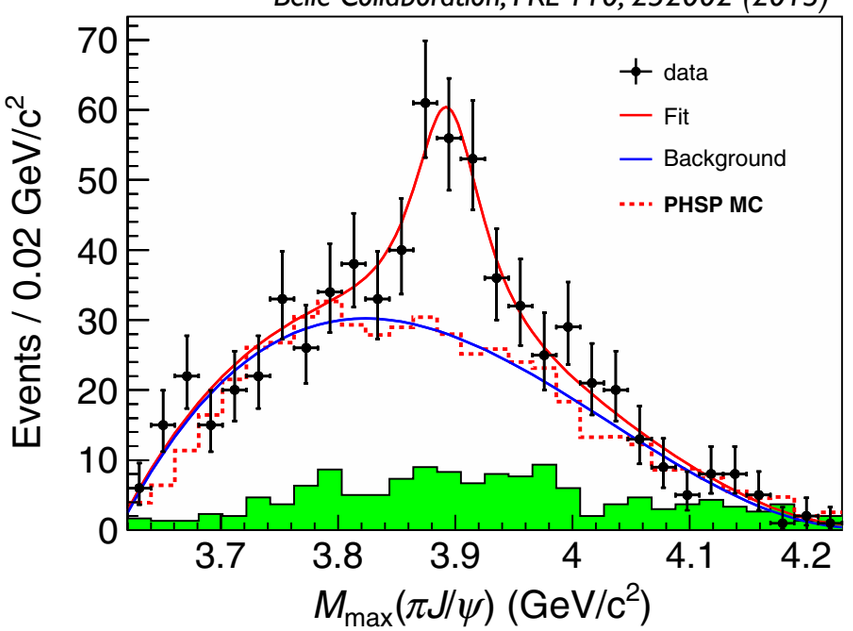


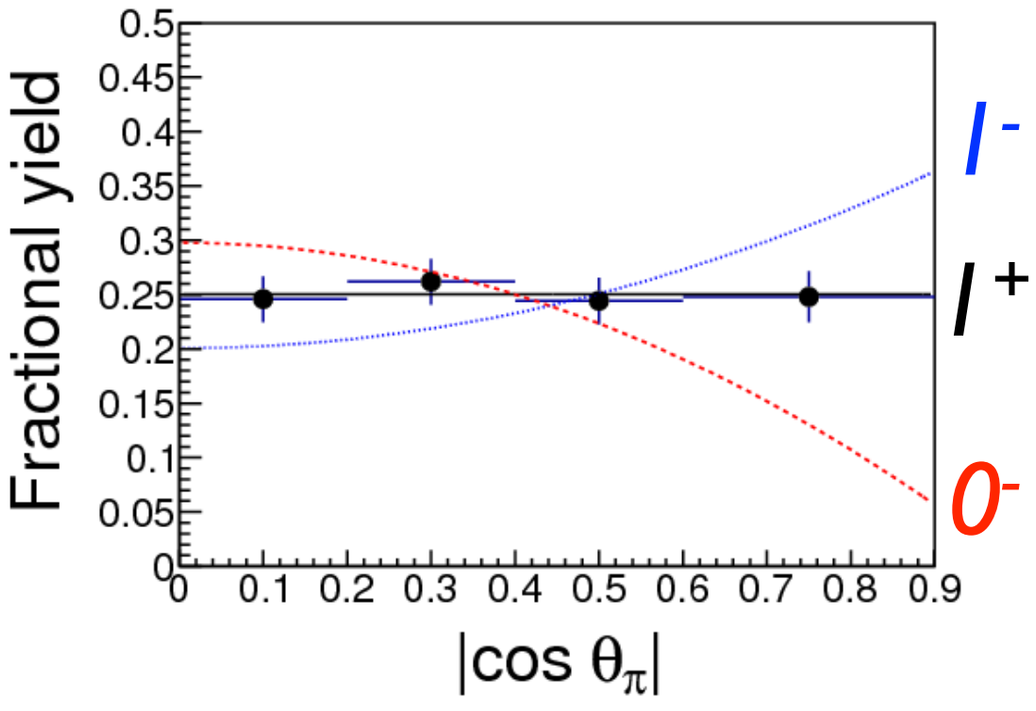
$M[Z_c(3900)] = 3895 \pm 9$ MeV
$\Gamma[Z_c(3900)] = 63 \pm 35$ MeV

$e^+e^- \to \pi^\pm (D\bar{D}^*)^\mp$ at E_{cm} = 4260 MeV

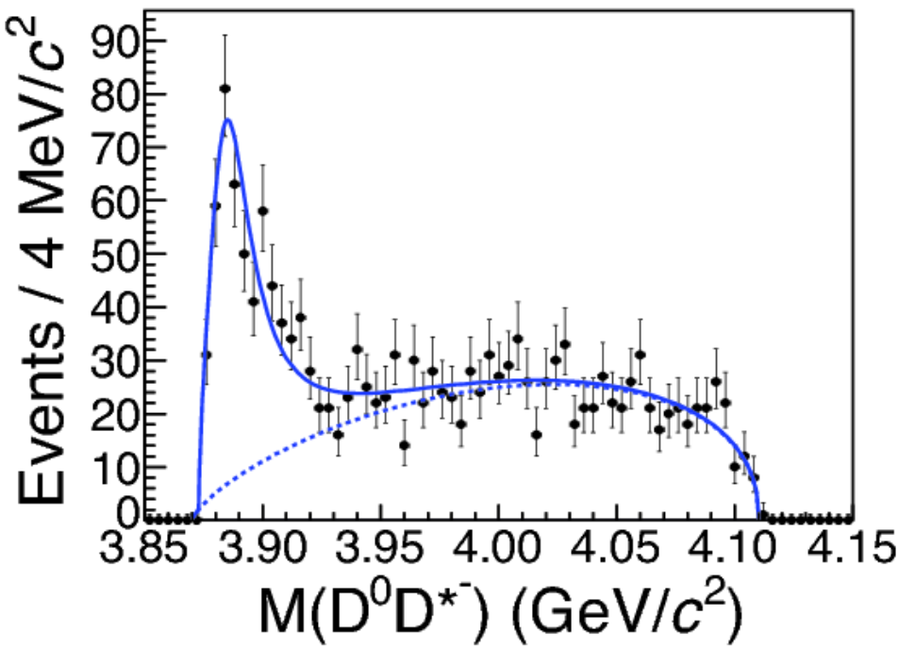
- If $Z_c(3885)$ is $Z_c(3900)$:

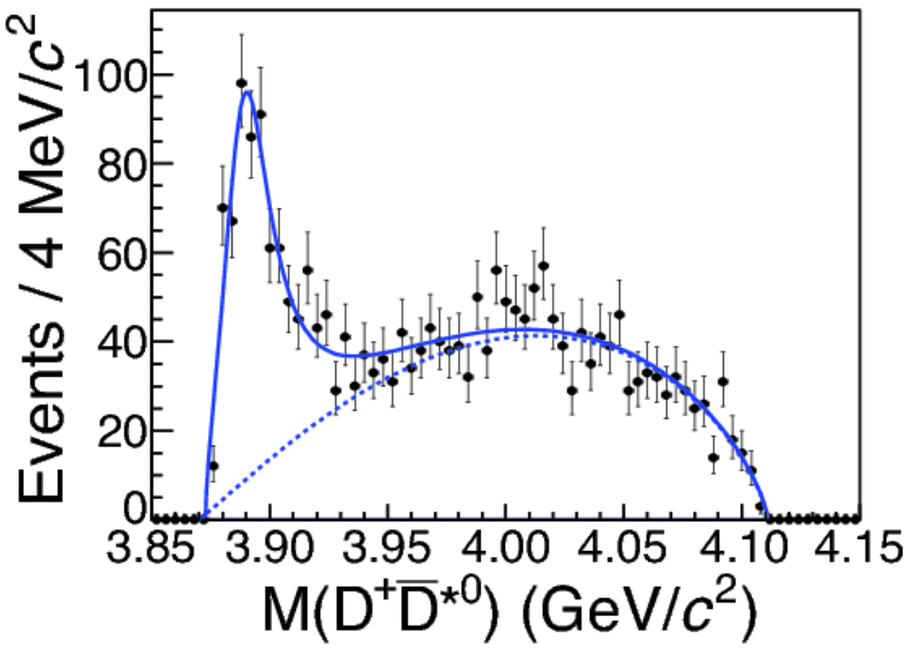
$$\frac{\Gamma(Z_c(3900) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 6.2 \pm 2.9$$

- π angular distribution establishes $J^P = 1^+$



BESIII Collaboration, PRL 112, 022001 (2013)



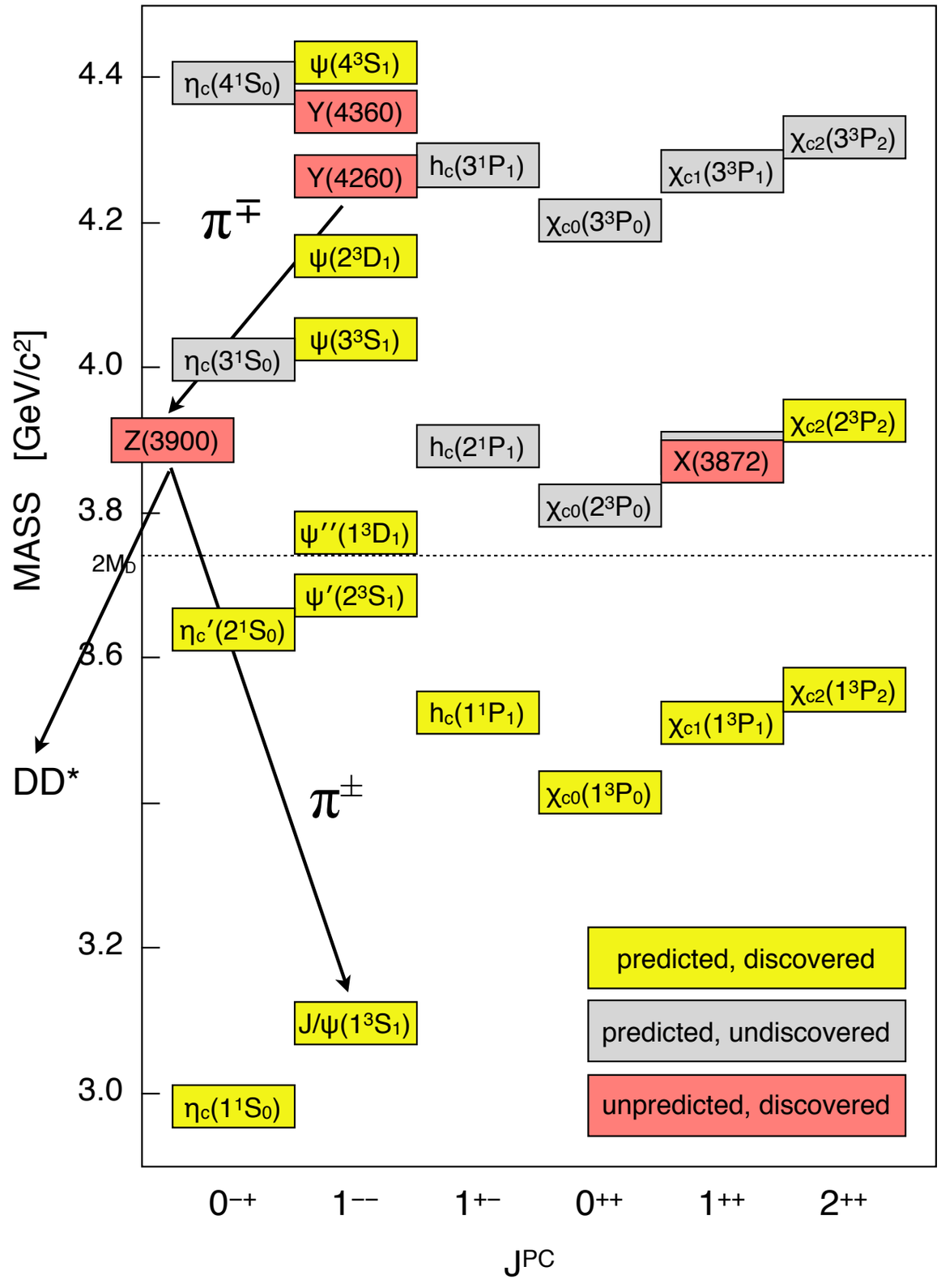


M[$Z_c(3885)$] = 3884 ± 4 MeV

Γ[$Z_c(3885)$] = 25 ± 11 MeV

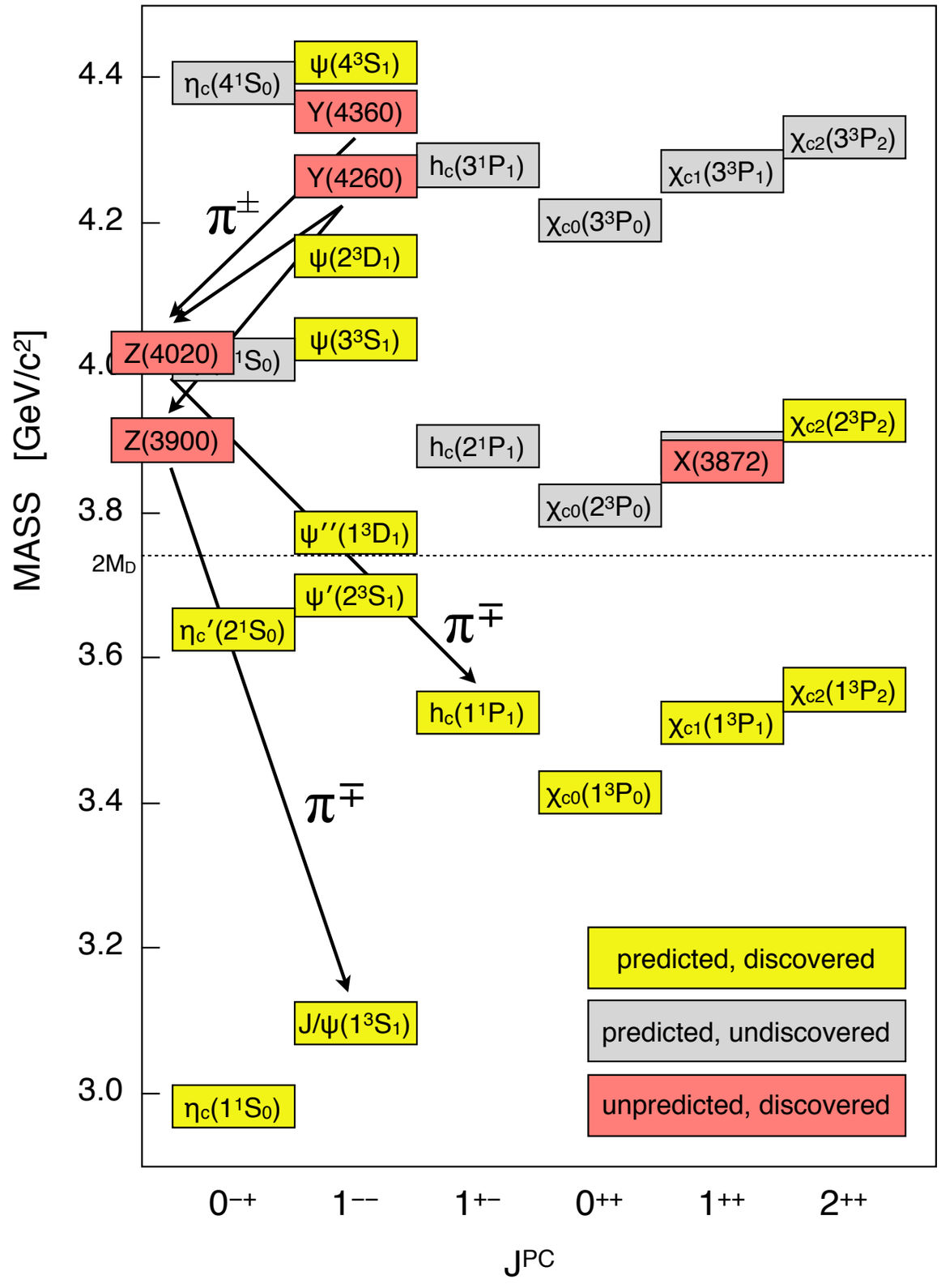
$Z_c(3900)^{\pm}$

- Charged charmonium-like structure above *DD** mass threshold
- Decays to $(DD^*)^{\pm}$ and $\pi^{\pm}J/\psi$ in ratio of 6±3 : 1
- Evidence for neutral isospin partner [T. Xiao *et al.*, PLB 727, 366 (2013)]
- $J^P = 1^+$
- Production seems correlated with *Y*(4260) decay



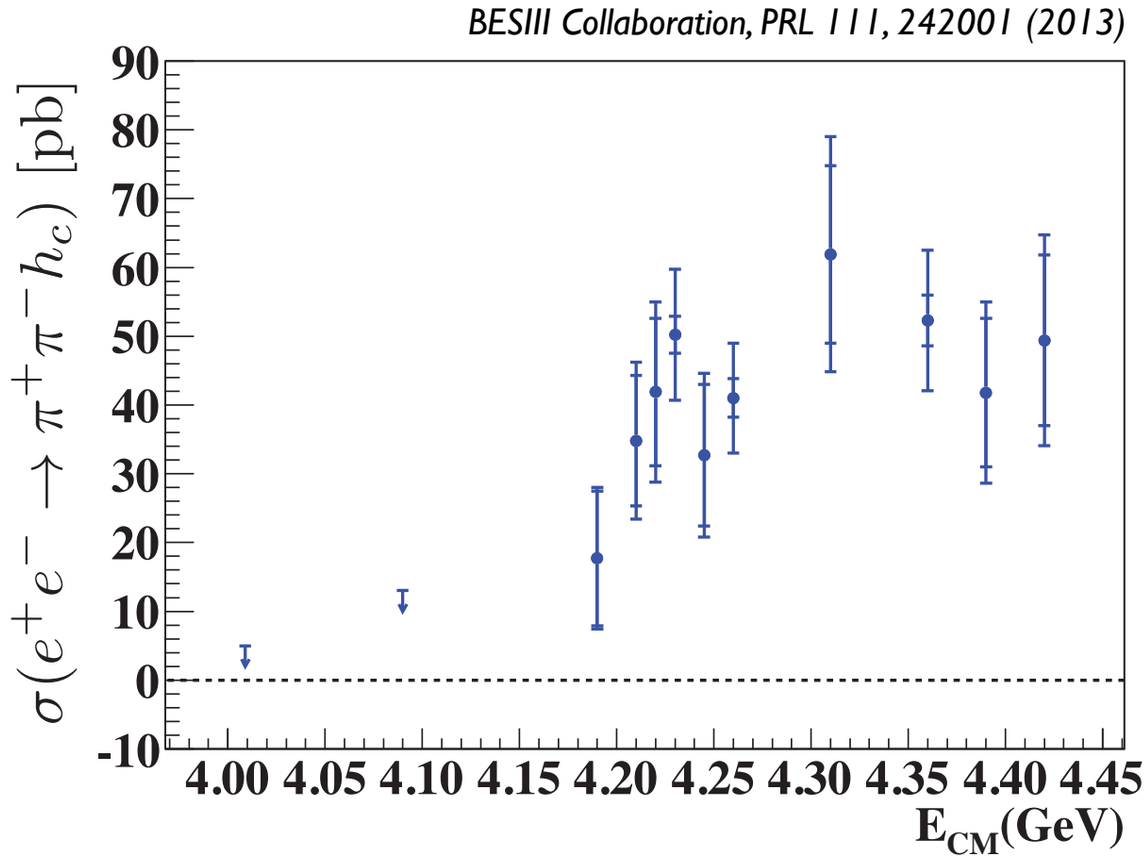
$e^+e^- \rightarrow \pi^+\pi^- h_c$

- significant $\pi^+\pi^- h_c$ production reported by CLEO at E_{cm} = 4170 MeV [PRL 107, 041803 (2011)]
- correlated with Y(4260)?
- h_c is spin singlet (S=0) state
  - different charm quark spin orientation than J/ψ
- explore $\pi^+\pi^-$ transitions to h_c as a function of E_{cm}
- search for $\pi^\pm h_c$ states



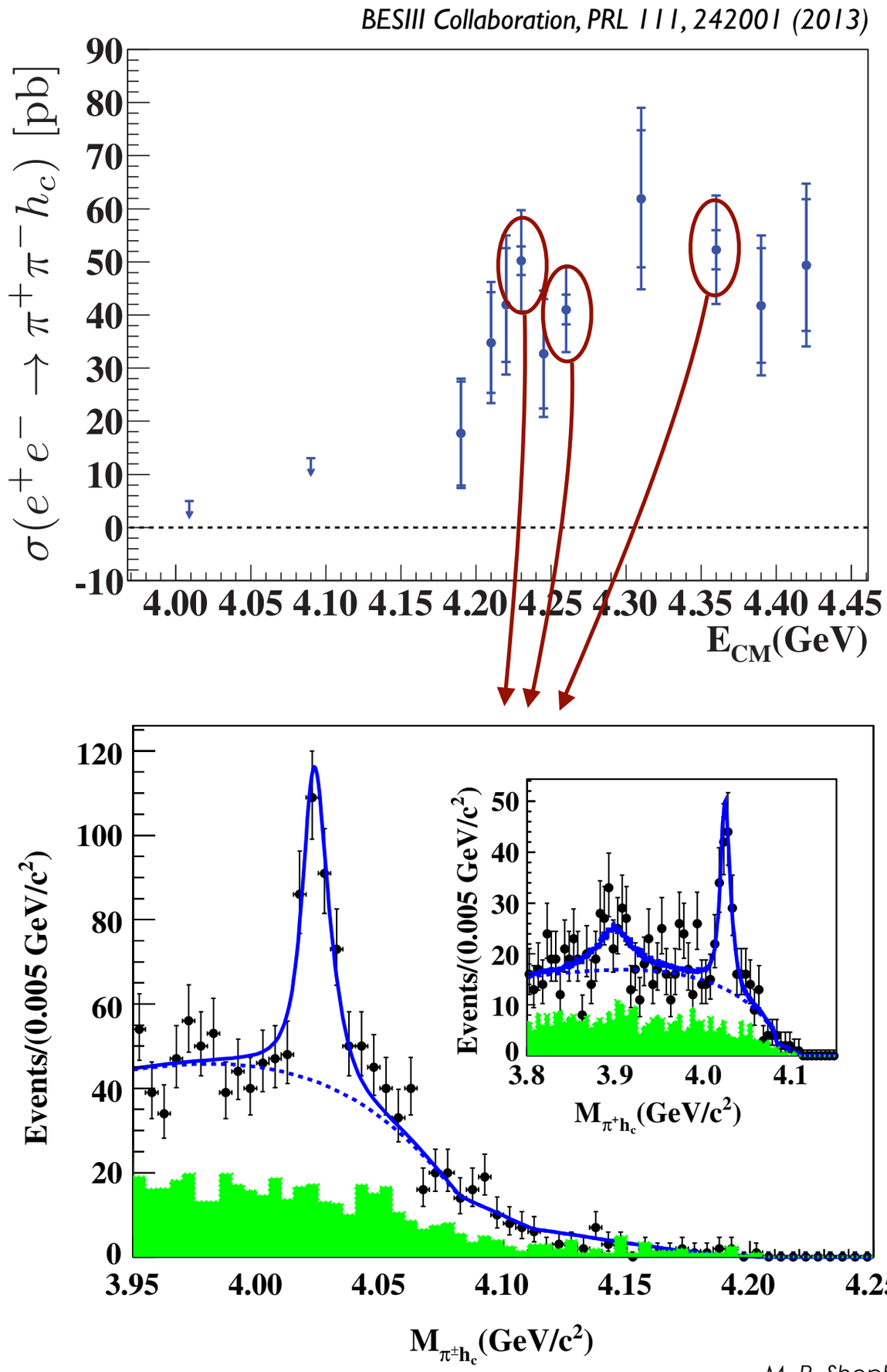
$e^+e^- \to \pi^+\pi^- h_c$

- no sharp structure in $\pi^+\pi^- h_c$ cross section
  - correlation with $Y(4260)$ or $Y(4360)$ unclear



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

- no sharp structure in $\pi^+\pi^- h_c$ cross section
  - correlation with $Y(4260)$ or $Y(4360)$ unclear
- narrow $\pi^\pm h_c$ structure observed
  - $M[Z_c(4020)] = 4023 \pm 3$ MeV
  - $\Gamma[Z_c(4020)] = 8 \pm 4$ MeV



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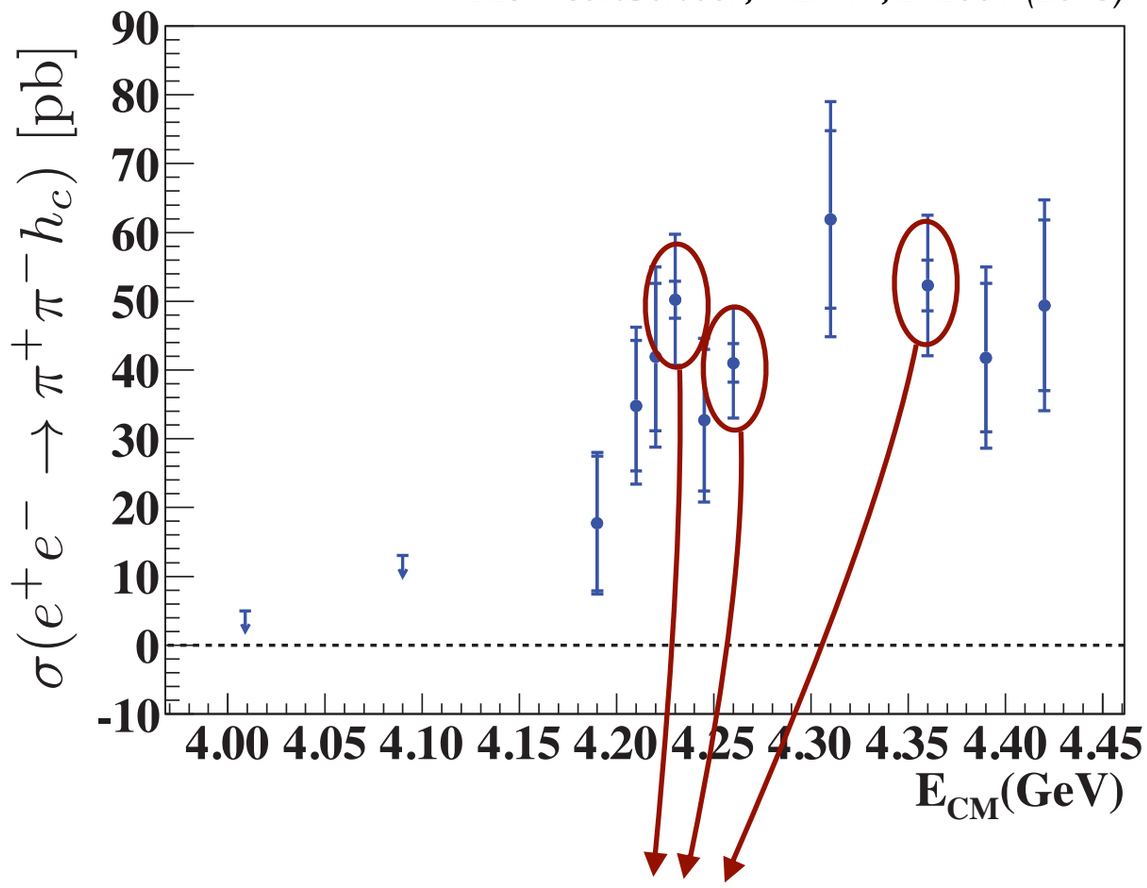
- narrow $\pi^\pm h_c$ structure observed
  - $M[Z_c(4020)] = 4023 \pm 3$ MeV
  - $\Gamma[Z_c(4020)] = 8 \pm 4$ MeV
- no significant evidence for $Z_c(3900) \rightarrow \pi^\pm h_c$
  - at $E_{cm} = 4260$ MeV:

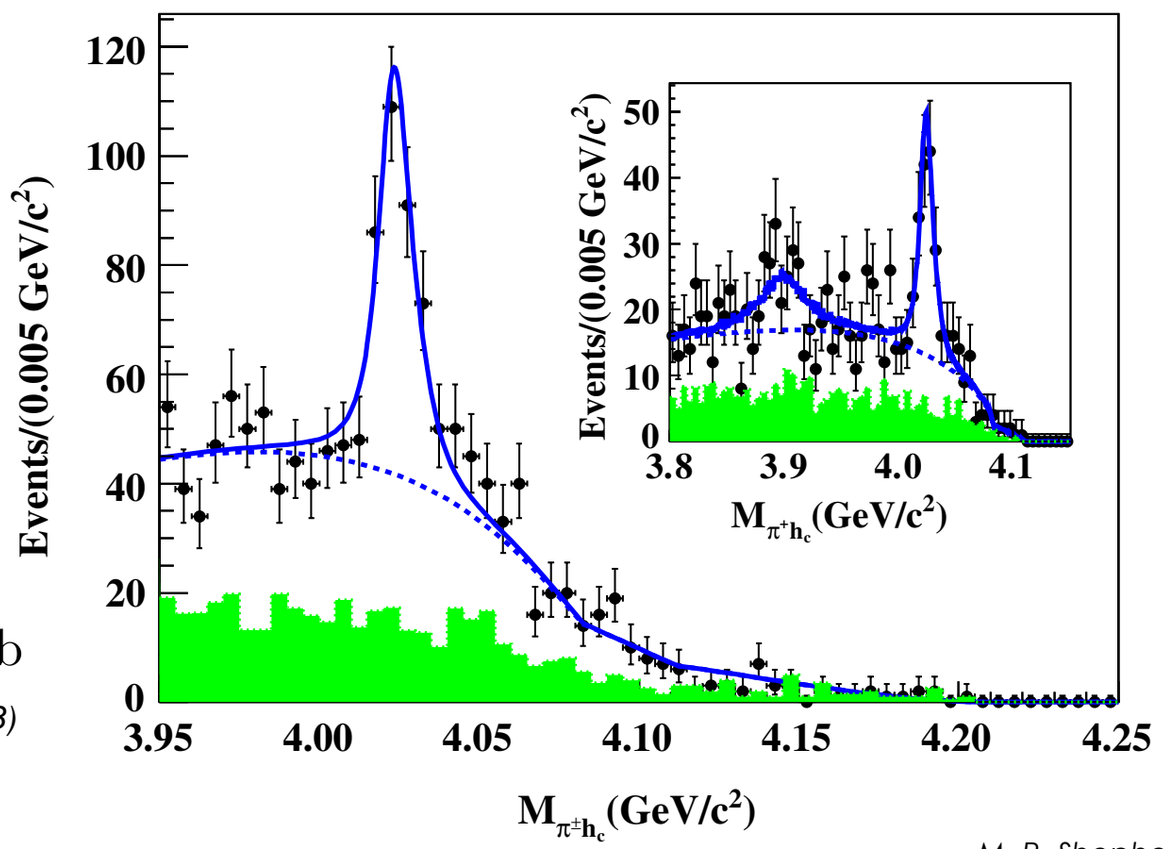
$$\sigma(e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^- h_c) < 11 \text{ pb}$$

$$\sigma(e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^- J/\psi) = 13 \pm 5 \text{ pb}$$

BESIII Collaboration, PRL 110, 252001 (2013)

BESIII Collaboration, PRL 111, 242001 (2013)





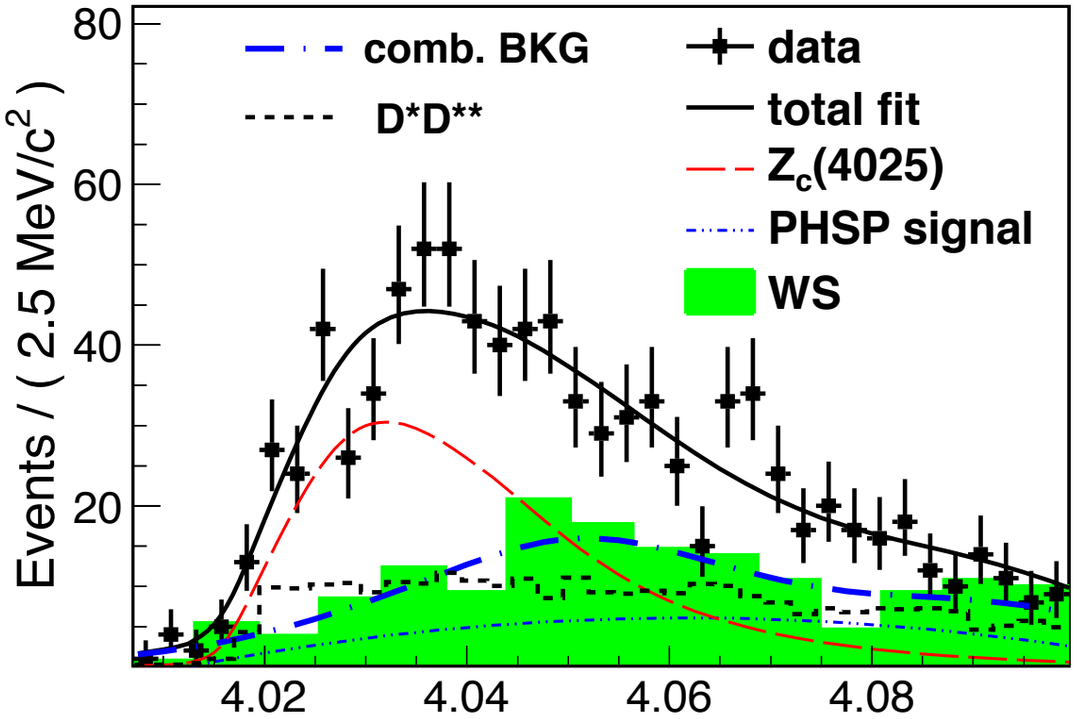
$e^+e^- \to \pi^\pm (D^*\bar{D}^*)^\mp$ at E_{cm} = 4260 MeV

- deviation from phase space decay
  - could be described by a charged state decaying to $D^*\bar{D}^*$
- if $Z_c(4025)^\pm$ is the $Z_c(4020)^\pm$ observed in the $\pi^\pm h_c$ spectrum:

$$\frac{\Gamma(Z_c(4020) \to D^*\bar{D}^*)}{\Gamma(Z_c(4020) \to \pi h_c)} = 12 \pm 5$$

- similar behavior to $Z_c(3900)^\pm$

BESIII Collaboration, PRL 112, 132001 (2014)



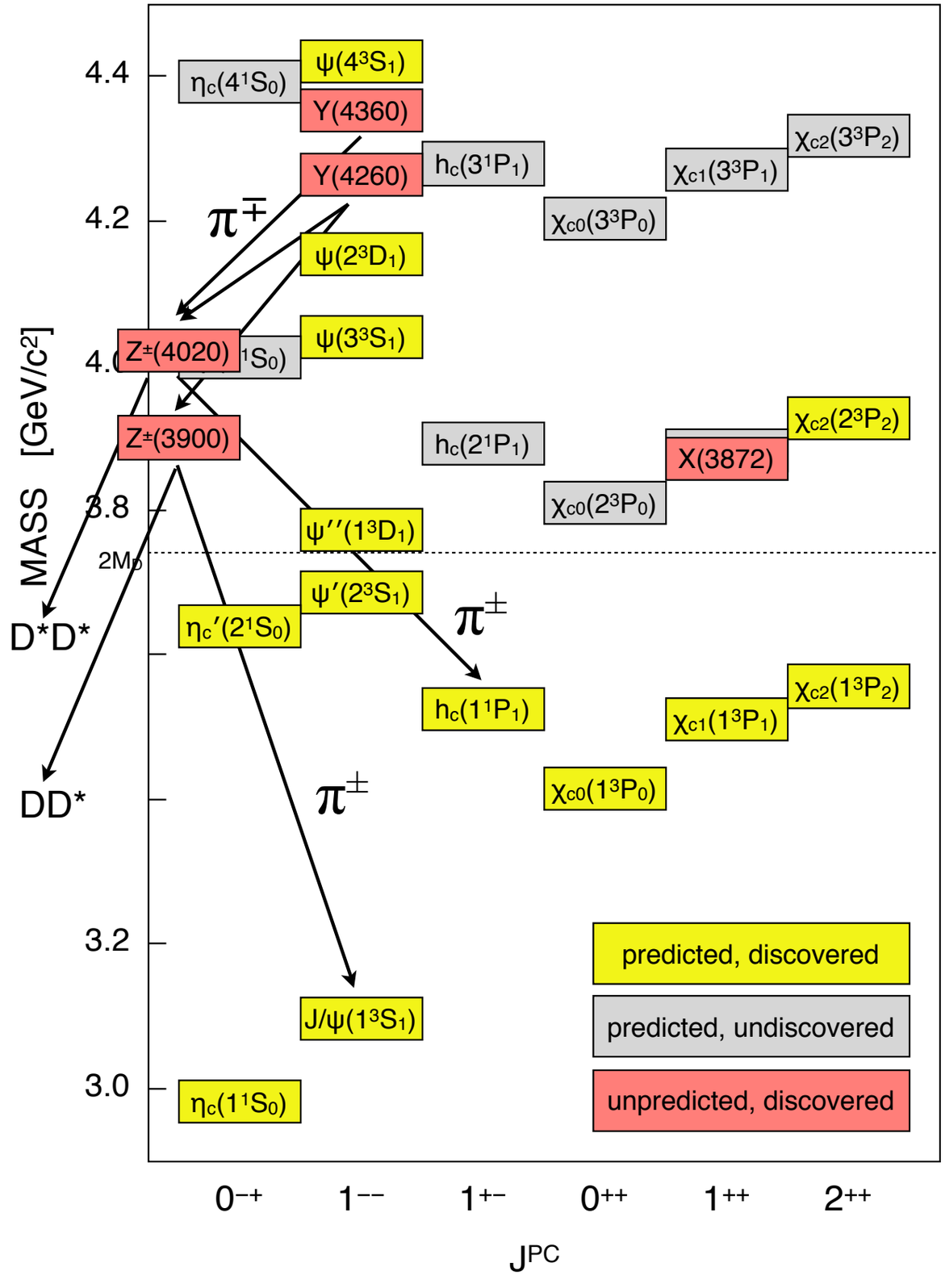
M[$Z_c(4025)$] = 4026 ± 3 MeV
Γ[$Z_c(4025)$] = 25 ± 6 MeV

compare with $\pi^\pm h_c$ structure:

M[$Z_c(4020)$] = 4023 ± 3 MeV
Γ[$Z_c(4020)$] = 8 ± 4 MeV

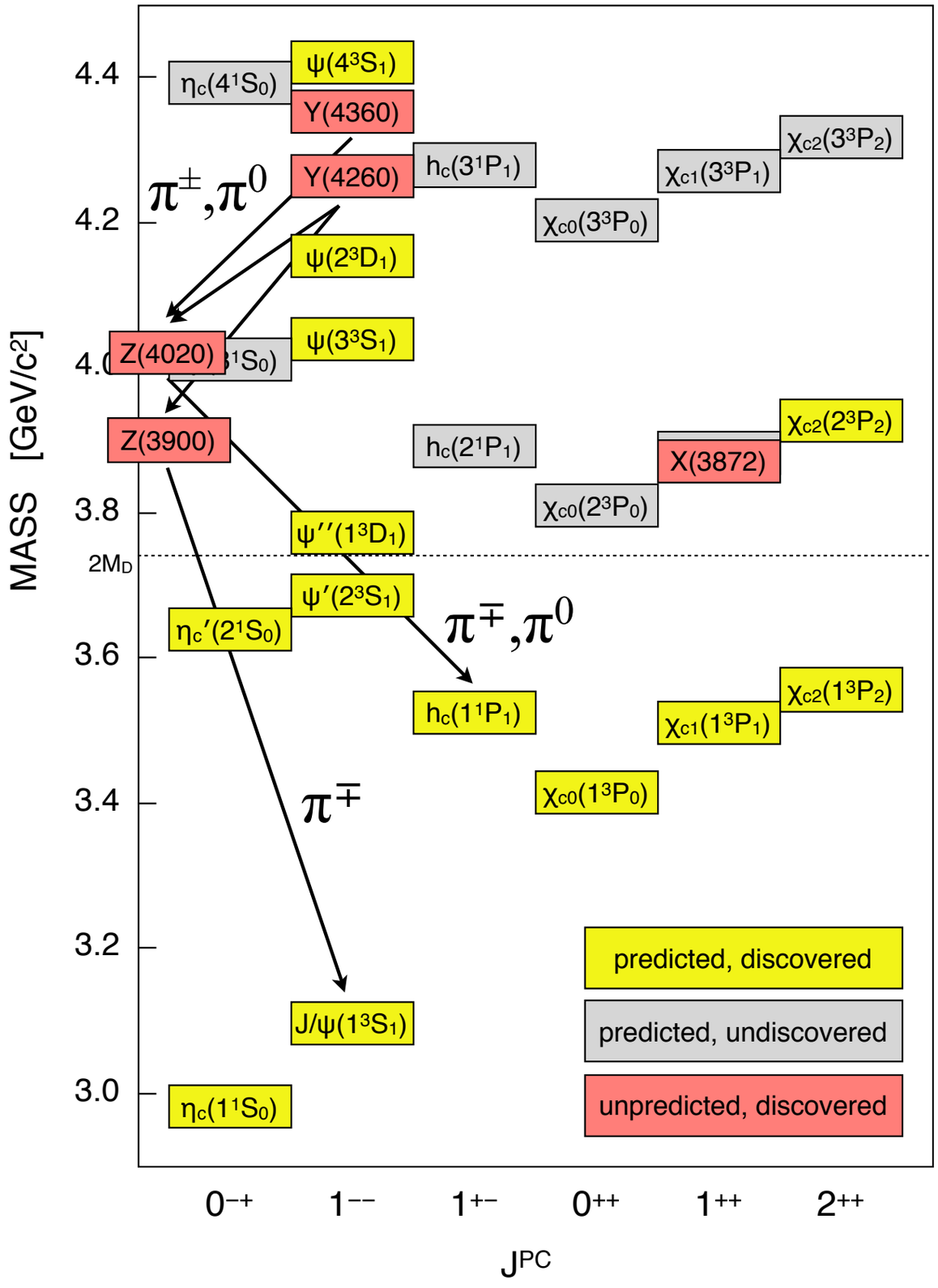
$Z_c(4020)^{\pm}$

- Charged charmonium-like structure above D^*D^* mass threshold
- Prefers to transition to charmonium spin singlet (h_c) over spin triplet (J/ψ)
- J^P unknown
- Correlation with $Y(4360)$ or $Y(4260)$ is unclear
- If structure in πh_c is the same as that in $D^*\overline{D}^*$, then ratio of $D^*\overline{D}^*$ to πh_c partial widths is 12±5 : 1
- Qualitatively similar to $Z_c(3900)$



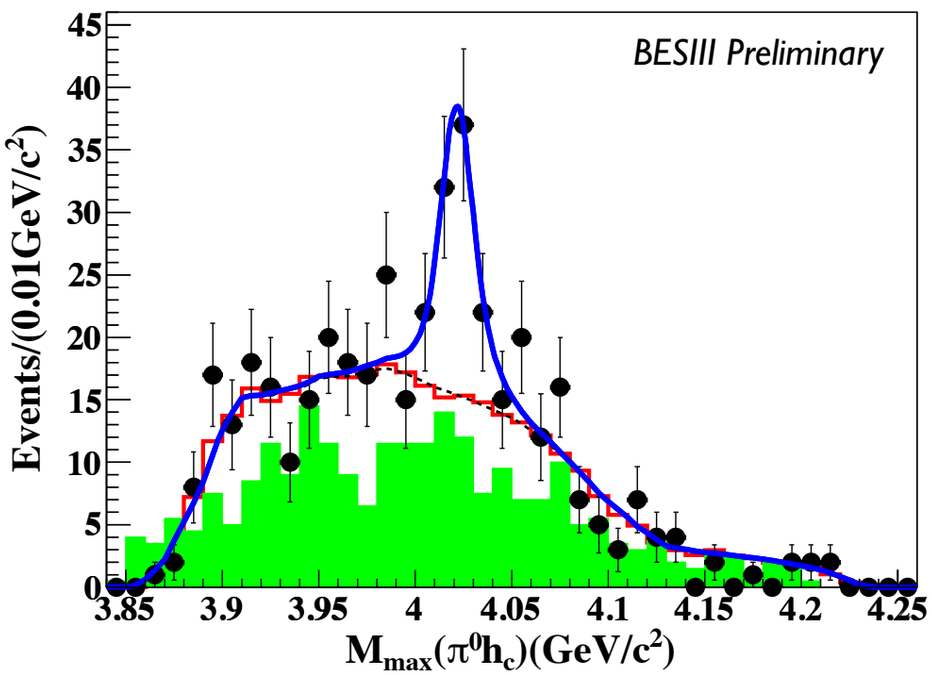
$e^+e^- \to \pi^0\pi^0 h_c$

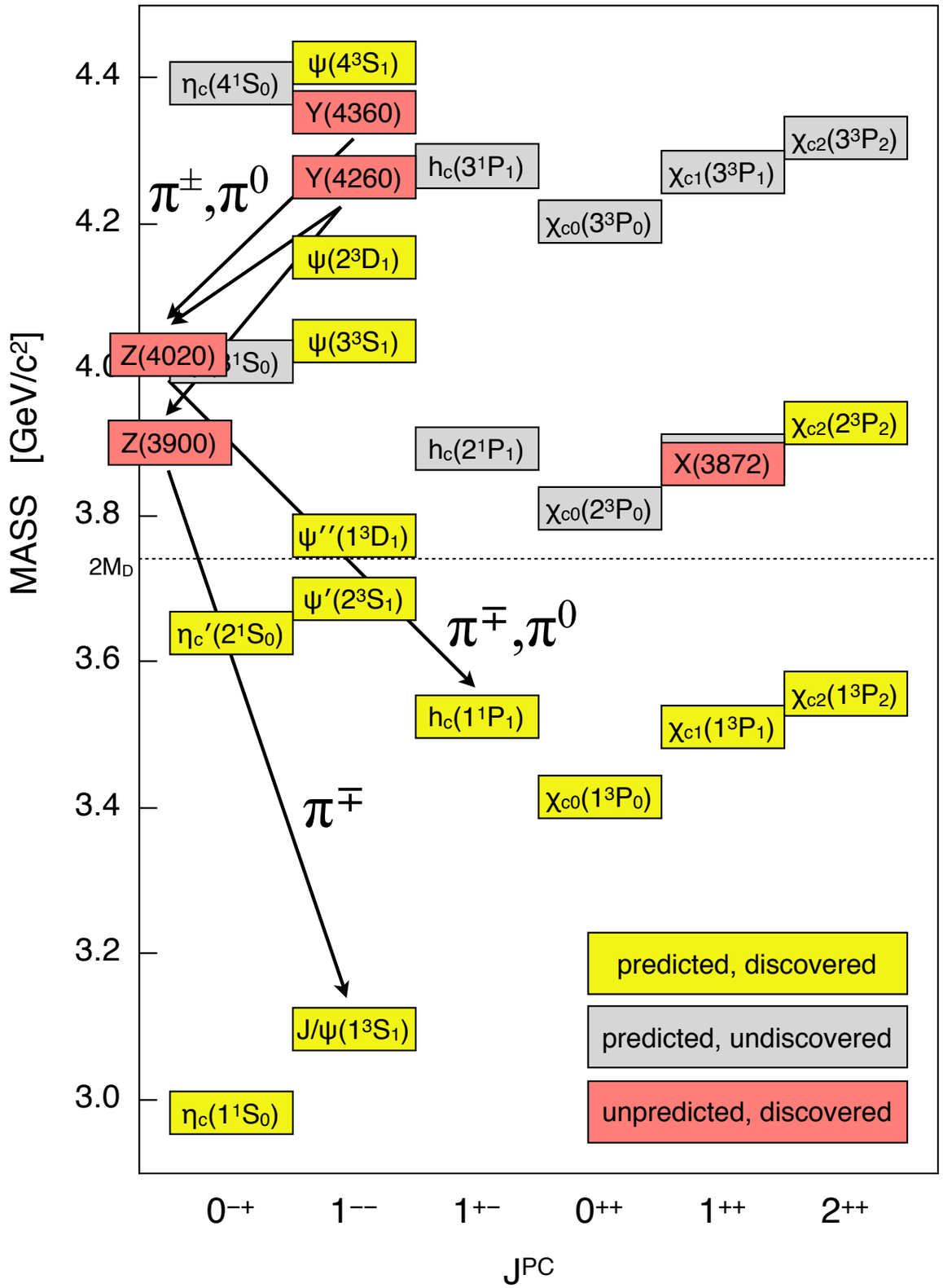
- Study $e^+e^- \to \pi^0\pi^0 h_c$ at 4.23, 4.26, and 4.36 GeV



$e^+e^- \to \pi^0\pi^0 h_c$

- Study $e^+e^- \to \pi^0\pi^0 h_c$ at 4.23, 4.26, and 4.36 GeV
- Observe $Z_c(4020)^0$ structure in $\pi^0 h_c$ mass distribution
- BESIII Preliminary result:
  - $M[Z_c(4020)^0] = 4023.6 \pm 4.5$ MeV
- Neutral isospin partner of the $Z_c(4020)^{\pm}$





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  - observe new structure in $\pi^{\pm}J/\psi$ mass spectrum
    - mass of about 3900 MeV; also decays to DD^*
    - heavy and charged: can't be charm anti-charm
- Try to establish $Y(4260) \rightarrow \pi^{\pm}\pi^{\mp}h_c$ and $Y(4260) \rightarrow \pi^0\pi^0h_c$
  - no clear $Y(4260)$-like structure in $e^+e^- \rightarrow \pi^{\pm}\pi^{\mp}h_c$ cross section

Intermission

- Confirm well-established decay of $Y(4260) \rightarrow \pi^{\pm}\pi^{\mp}J/\psi$
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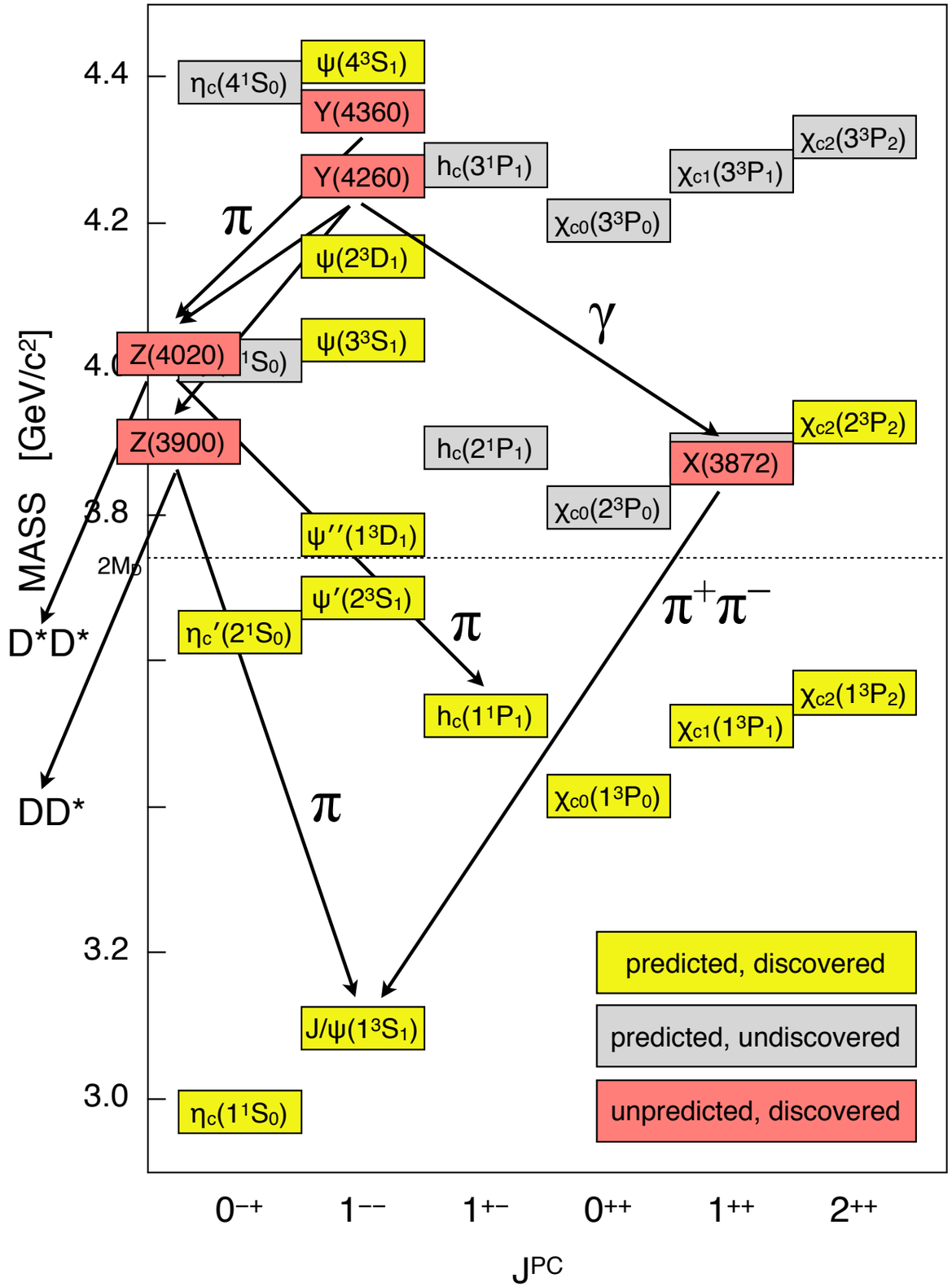
    - both have a mass of about 4020 MeV; consistent with isovector triplet of states; may decay to D^*D^*
    - heavy and charged: can't be charm anti-charm
- What does this tell us about $Y(4260)$? Don't know.
  - Search for more $Y(4260)$ decay modes, like transitions to (un)conventional charmonium.

X(3872)

- well-established neutral state just at or below D^0D^{*0} threshold
  - discovered by Belle in *B* decay [PRL 91, 262001 (2003)]
- decay to $(\pi^+\pi^-)_\rho$ J/ψ is atypical of conventional charmonium
- popular explanation: bound $D^0\overline{D}^{*0}$ "molecular" state
- recent developments:
  - $J^{PC} = 1^{++}$ firmly established by LHCb [PRL 110, 222001 (2013)]
  - LHCb observes radiative transition to ψ' (*arXiv:1404.0275*)
  - BESIII observes production in $e^+e^- \to \gamma X(3872)$

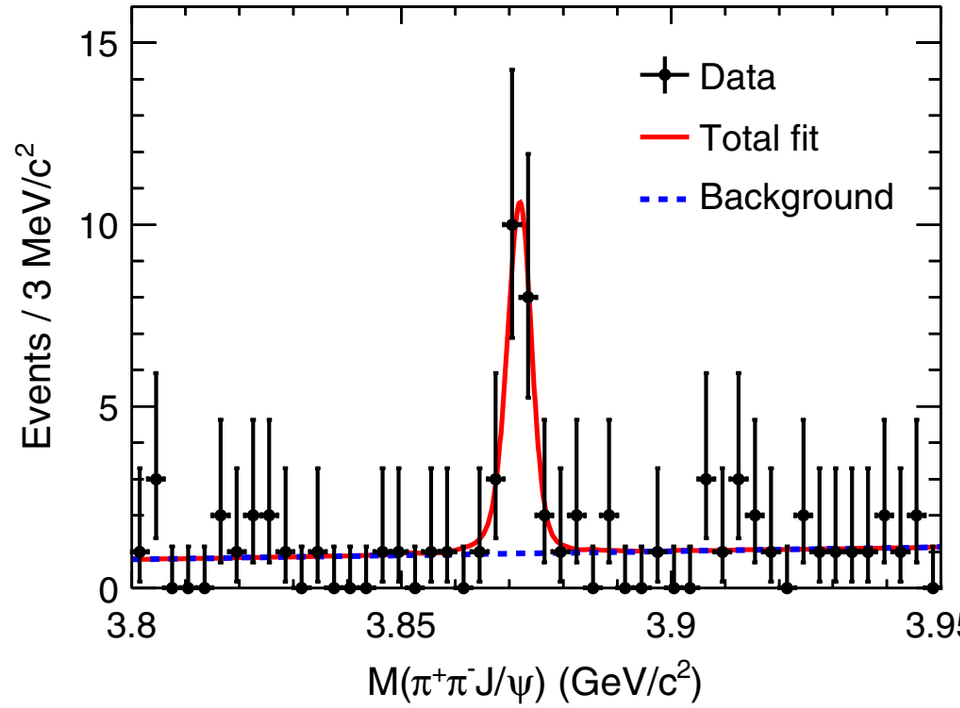


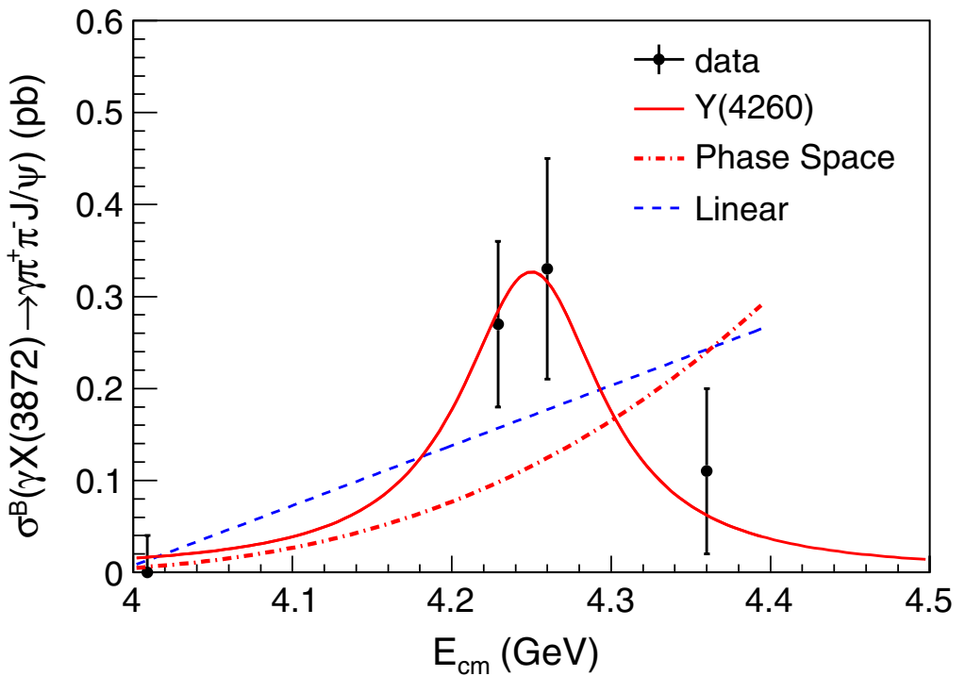
$e^+e^- \to \gamma X(3872)$

- search for $\gamma X(3872)$ with $X(3872) \to \pi\pi J/\psi$ at E_{cm} = 4.23 GeV, 4.26 GeV, and 4.36 GeV
- summed over all data $X(3872)$ significance: 6.3σ
- production in $Y(4260)$ decay suggestive but not conclusive
  - if from $Y(4260)$:

$$\frac{\mathcal{B}(Y(4260) \to \gamma X(3872))}{\mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi)} \approx 0.1$$

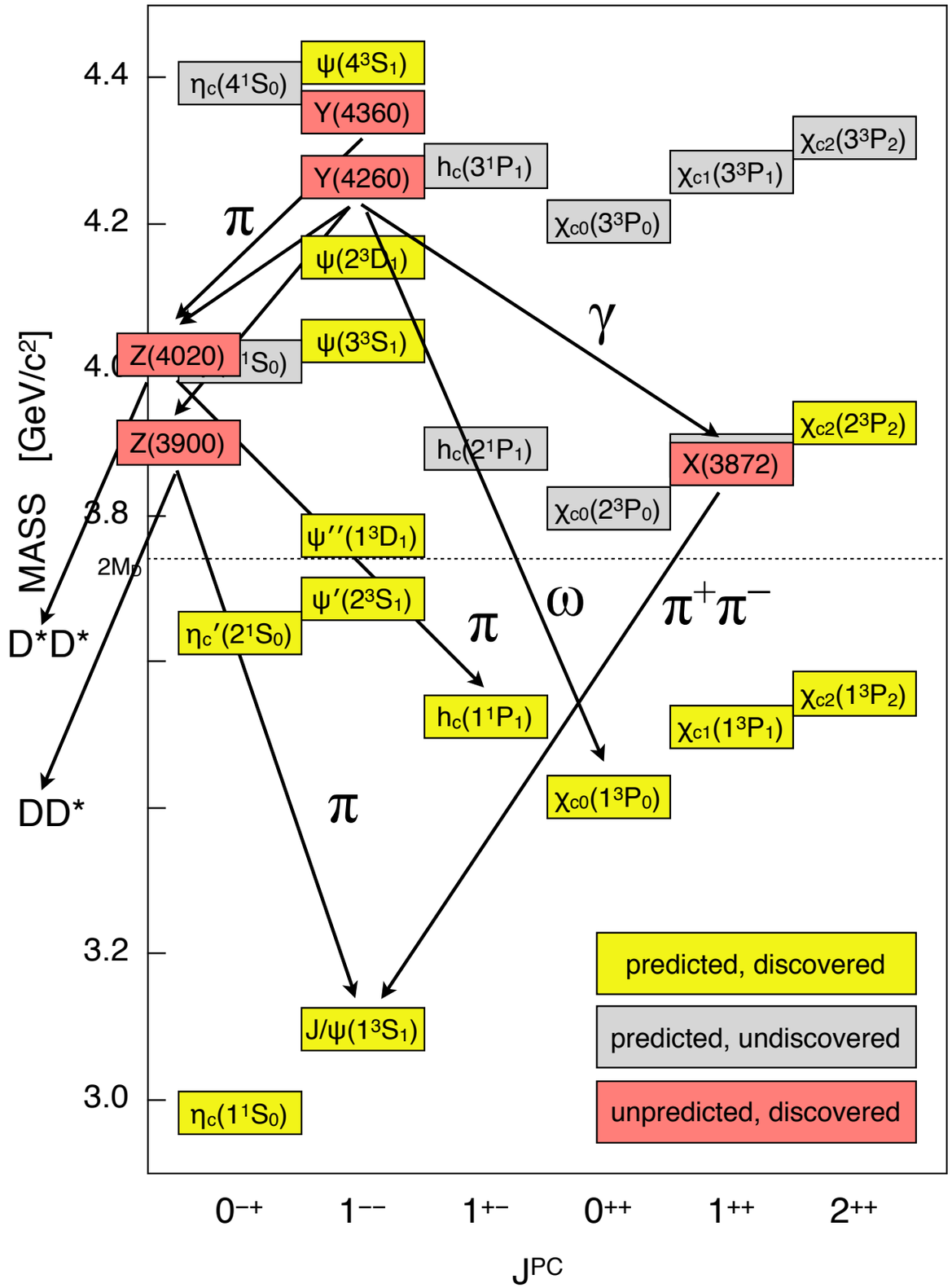
BESIII Collaboration, PRL 112, 092001 (2014)





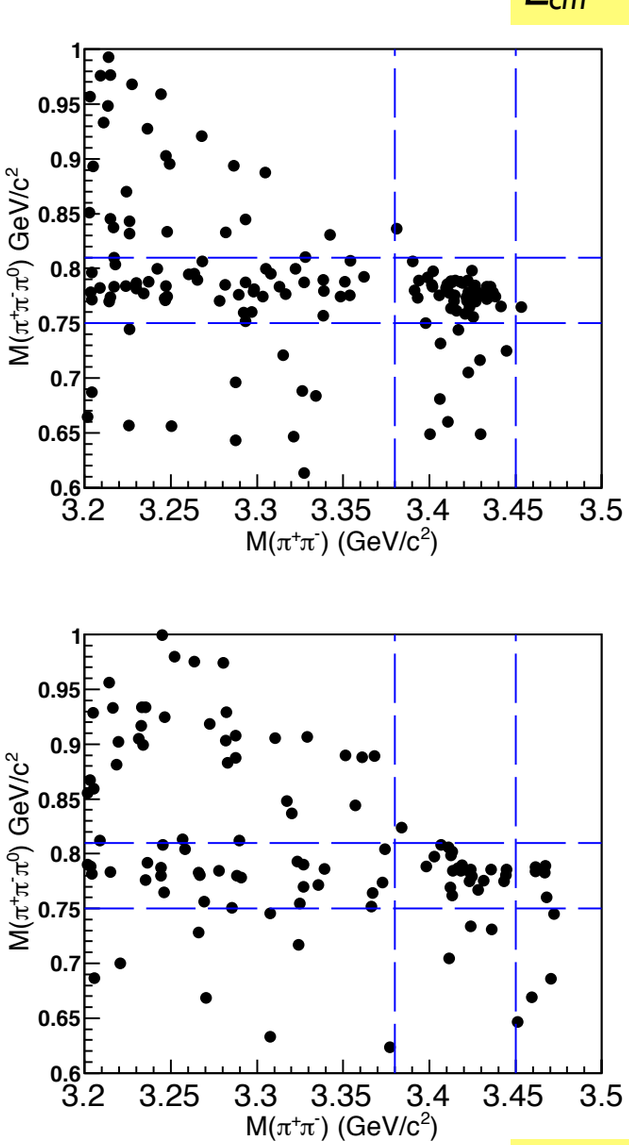
$e^+e^- \rightarrow \omega\chi_{c0}$

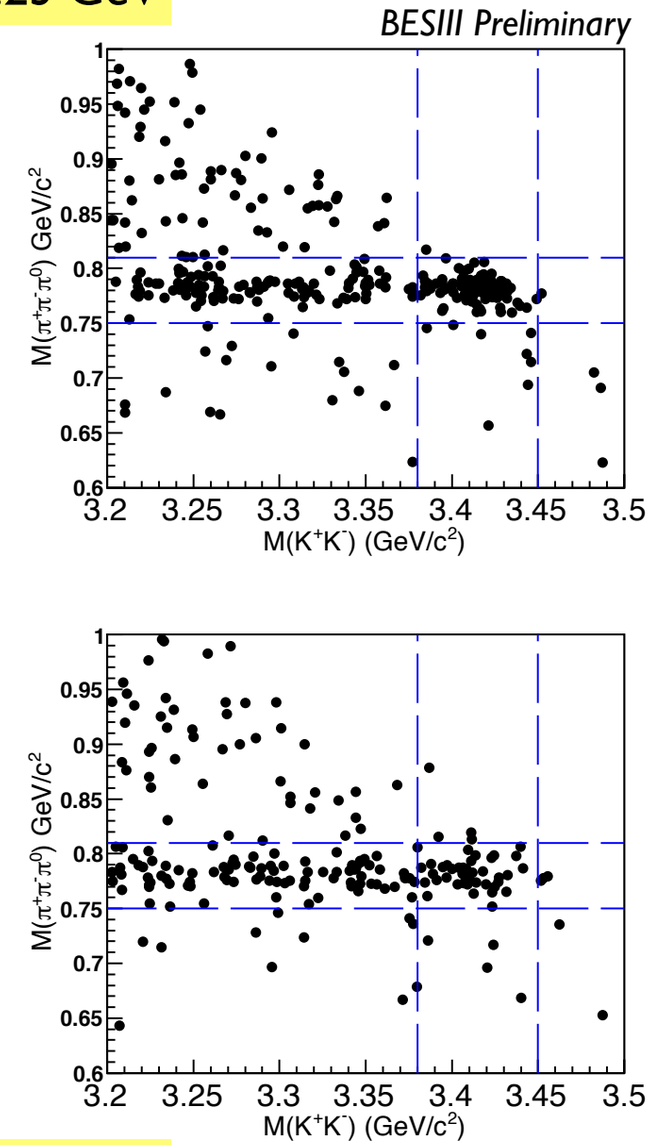
- Search for transitions of *Y*(4260) to the χ_{cJ} states via the emission of a vector meson
- Need to observe peak in the $e^+e^- \rightarrow \omega\chi_{c0}$ cross section that matches the *Y*(4260) lineshape



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

E_{cm} = 4.23 GeV





E_{cm} = 4.26 GeV

BESIII Preliminary

$\sqrt{s}$ (GeV)	σ (pb)
4.23	$59.2 \pm 6.4 \pm 6.3$
4.26	$25.0 \pm 5.6 \pm 3.2$

- observation of $\omega\chi_{c0}$ production at 4230 MeV and 4260 MeV
- no evidence for $\omega\chi_{c0}$ at 4360 MeV
- no evidence for $\omega\chi_{c1,2}$ at 4230 or 4260 MeV

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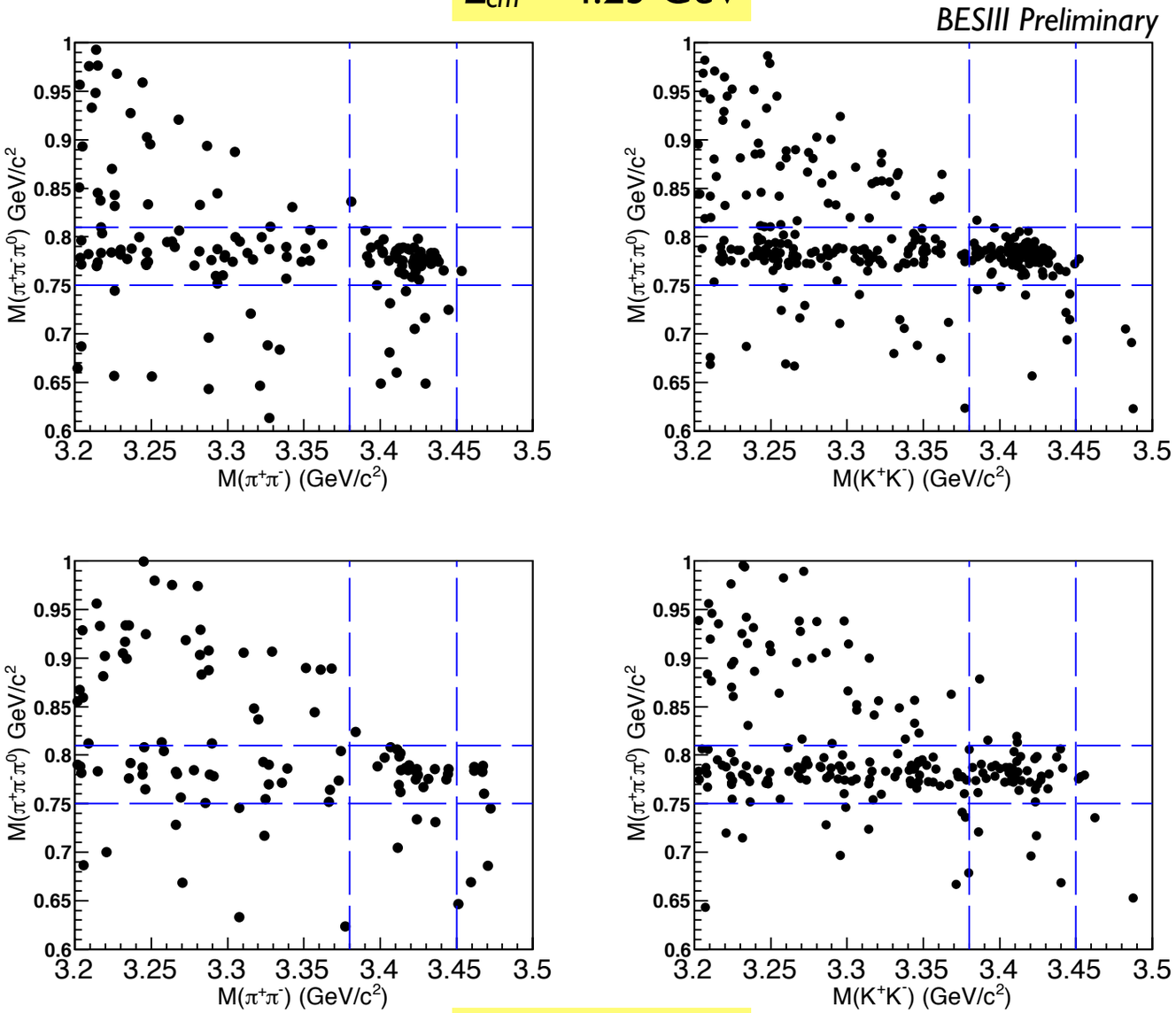

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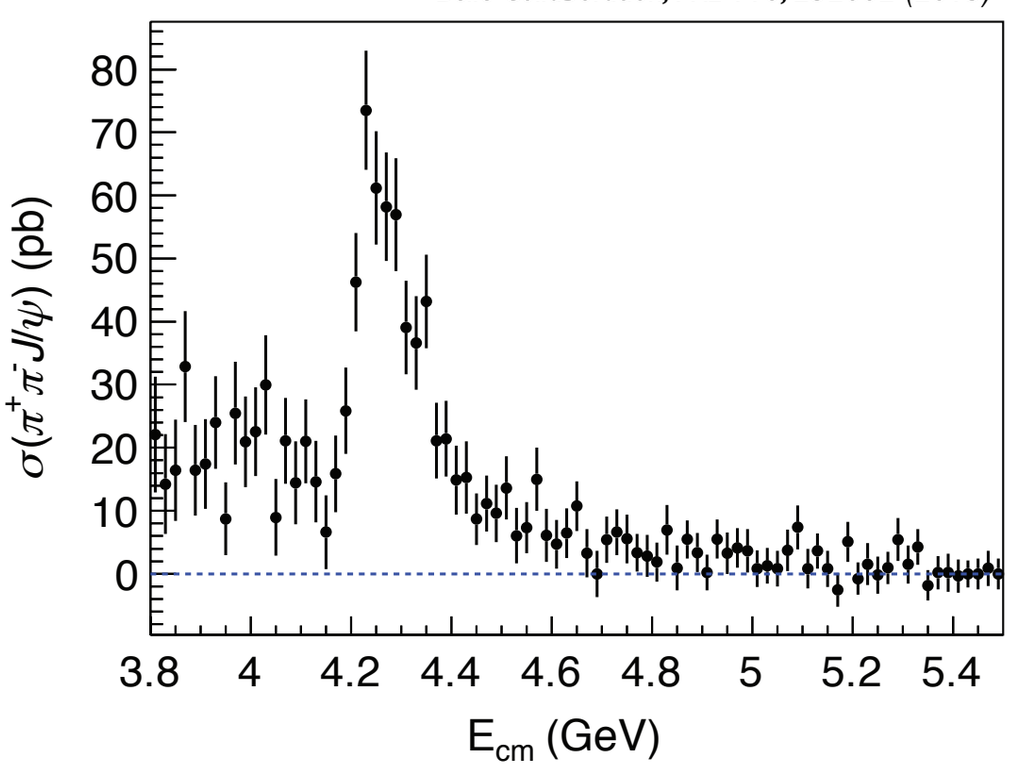
Belle Collaboration, PRL 110, 252002 (2013)



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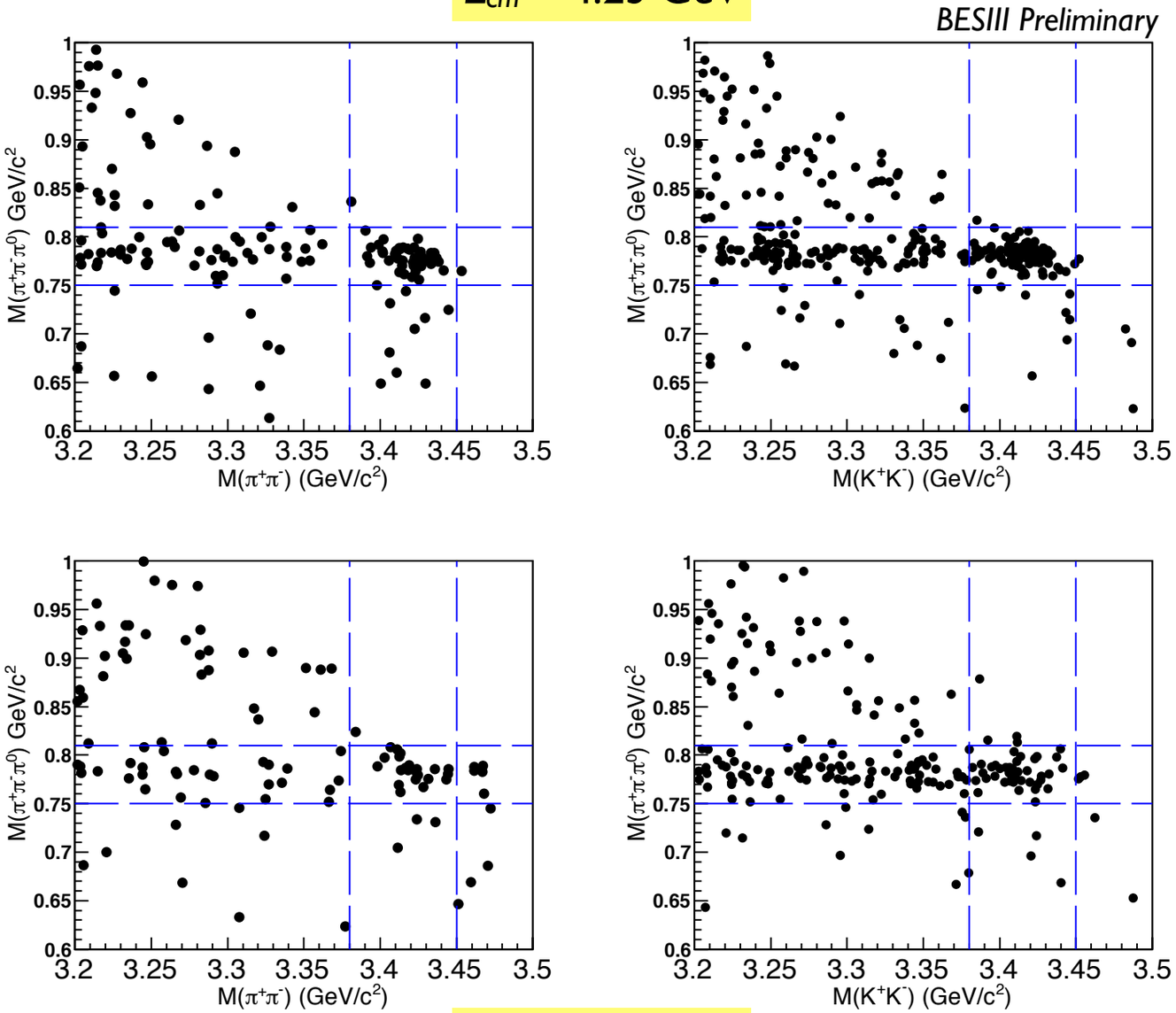

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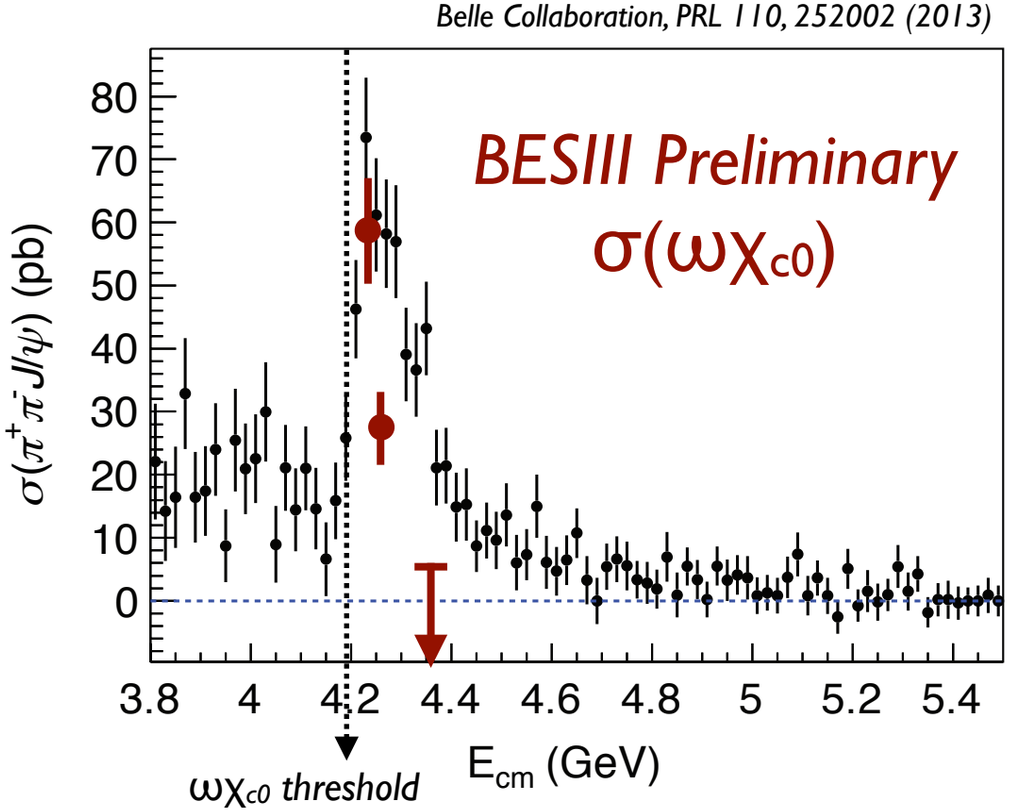
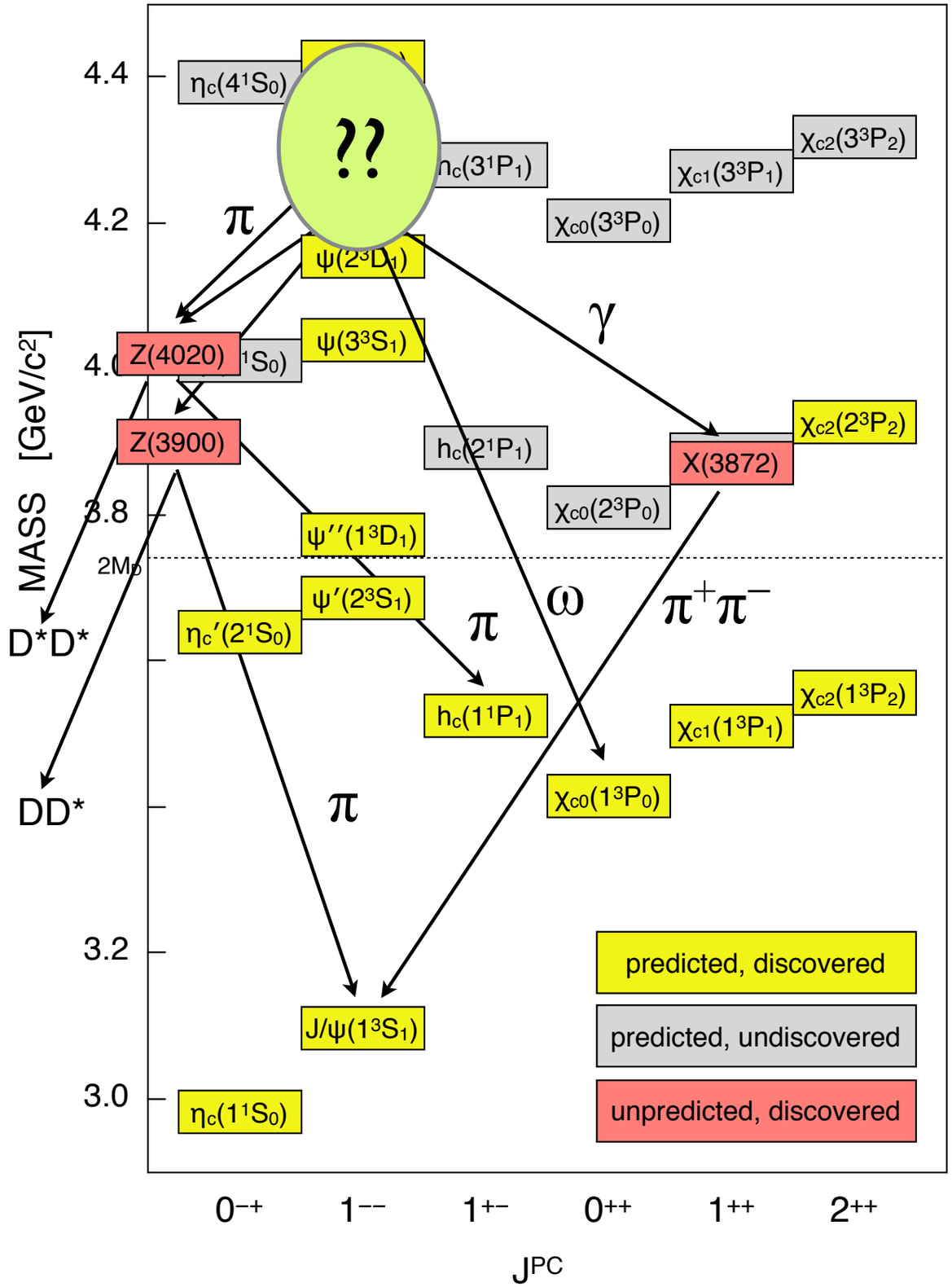
- shape seems inconsistent with $Y(4260)$

Belle Collaboration, PRL 110, 252002 (2013)



- Measuring (and understanding) transitions between states is essential
- Remaining experimental challenges:
  - explore all possible decay modes of new states
  - establish *Y*(4260) or *Y*(4360) as a definitive source of transition in e^+e^- collisions
- More data at a variety of E_{cm} may shed light on problem



Y(4260)
Y(4360)

- *Y*(4260) is a strong source of $\pi\pi J/\psi$ in e^+e^- collisions
  - about 1/4 of rate is through $\pi^\pm Z_c(3900)^\mp$
- source of $\pi\pi h_c$ in e+e- collisions not conclusive
  - about 1/5 of the rate is through $\pi^\pm Z_c(4020)^\mp$
- observation of $e^+e^- \to \gamma X(3872)$, perhaps via $Y(4260) \to \gamma X(3872)$
- observation of $e^+e^- \to \omega X_{c0}$, but likely not through *Y*(4260)

nature of Y states remains unclear

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nature of Y states remains unclear

newly observed structures:
presence of electric charge rules out
conventional charm anti-charm state

$Z_c(3900)^\pm$

- narrow charged charmonium-like structure above $(DD^*)^\pm$ mass threshold (3876 MeV)
- decays to $(D\overline{D}^*)^\pm$ and $\pi^\pm J/\psi$ in ratio of 6±3 : 1
- evidence for neutral isospin partner
- decay rate to $\pi^\pm h_c$ must be at or below the decay rate to $\pi^\pm J/\psi$
- $J^P = 1^+$
- production seems correlated with Y(4260) decay
- no production in $B^\pm \rightarrow K^\pm Z^\mp$ (in contrast to $B \rightarrow KX(3872)$)*

**BaBar Collaboration, PRD 79, 112001 (2009)*

$Z_c(4020)^\pm$

(assuming just one object)

- narrow charged charmonium-like structure above D^*D^* mass threshold (4017 MeV)
- decays to $(D^*\overline{D}^*)^\pm$ and $\pi^\pm h_c$ in ratio of 12±5 : 1
- observation of neutral isospin partner $Z_c(4020)^0$
- no apparent decay to $(DD^*)^\pm$
- decay rate to $\pi^\pm h_c$ must dominate $\pi^\pm J/\psi$ if it exists
- J^P unknown
- production correlated with Y(4260) and/or Y(4360) decay?

Global Context

- Other charged charmonium-like states:
  - $Z_c(4430)^{\pm} \rightarrow \psi' \pi^{\pm}$ discovered by Belle in 2008, not confirmed by BaBar, but recently confirmed by LHCb (arXiv:1404.1903)
  - $Z_c(4050)^{\pm}$ and $Z_c(4250)^{\pm}$ reported by Belle to decay to $\chi_{c1}\pi^{\pm}$ but not confirmed by BaBar
- Parallels to the bottomonium system:
(studied by the Belle Collaboration [PRL 108, 122001 (2012)])
  - An apparent analogue of the $Y(4260)$ exists for b quarks with a mass around 10.865 GeV with large decays to $\pi\pi\Upsilon(n\mathrm{S})$ and $\pi\pi h_b(m\mathrm{P})$
  - Observed: $Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$
    - decays to both $\pi h_b(m\mathrm{P})$ and $\pi\Upsilon(n\mathrm{S})$
    - heavy and charged: not just bottom anti-bottom

Summary of Observations

- Clear evidence for narrow structures in $\pi^{\pm}J/\psi$ and $\pi^{\pm}h_c$ spectra whose origin is unknown
  - conspicuously close to $D\overline{D}^*$ and $D^*\overline{D}^*$ thresholds
  - new type of QCD state or dynamically generated structure?
  - one certainty: not conventional charmonium
- Data are slightly suggestive of transitions between mysterious structures
  - $Z_c(3900)^{\pm}$ appears to be correlated with $Y(4260)$ decay
  - …but source of $\pi\pi h_c$ and $Z_c(4020)^{\pm,0}$ is not clear
  - possible radiative transition: $Y(4260) \rightarrow \gamma X(3872)$
  - …but $\omega\chi_{c0}$ does not seem to be a product of $Y(4260)$ decay
- Strong similarities between charmonium and bottomonium system
- Expect to hear more from BESIII in the near future!