Experimental Status of the XYZ Mesons:
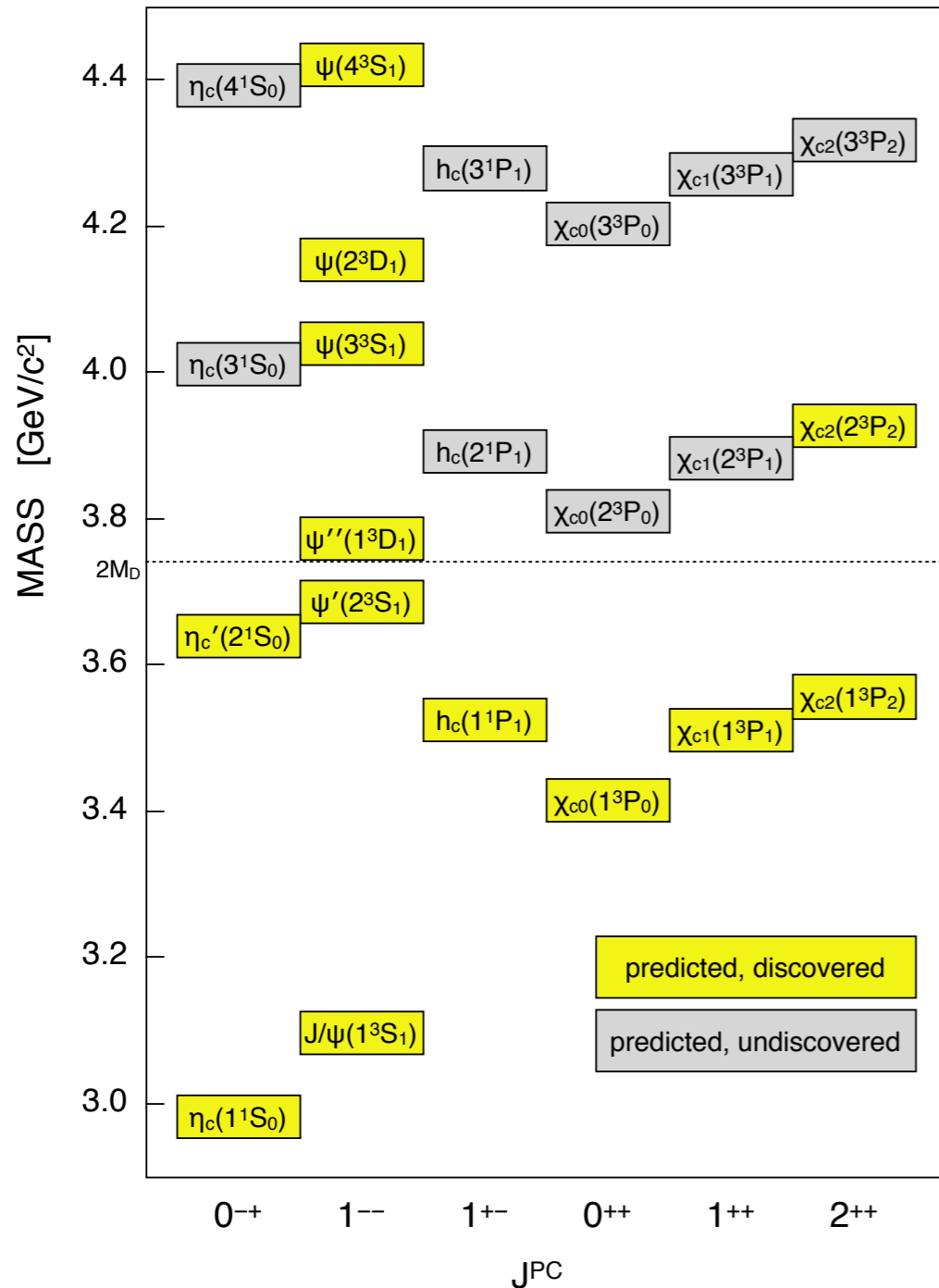
Connections and Complexities

Ryan Mitchell

Indiana University

CIPANP 2015

May 22, 2015

Introductory Notes on the XYZ Mesons

Charmonium Spectrum
predictions based on PRD 72, 054026 (2005)
measurements from PDG 2014

The charmonium and bottomonium systems arguably represent the simplest bound states of QCD.
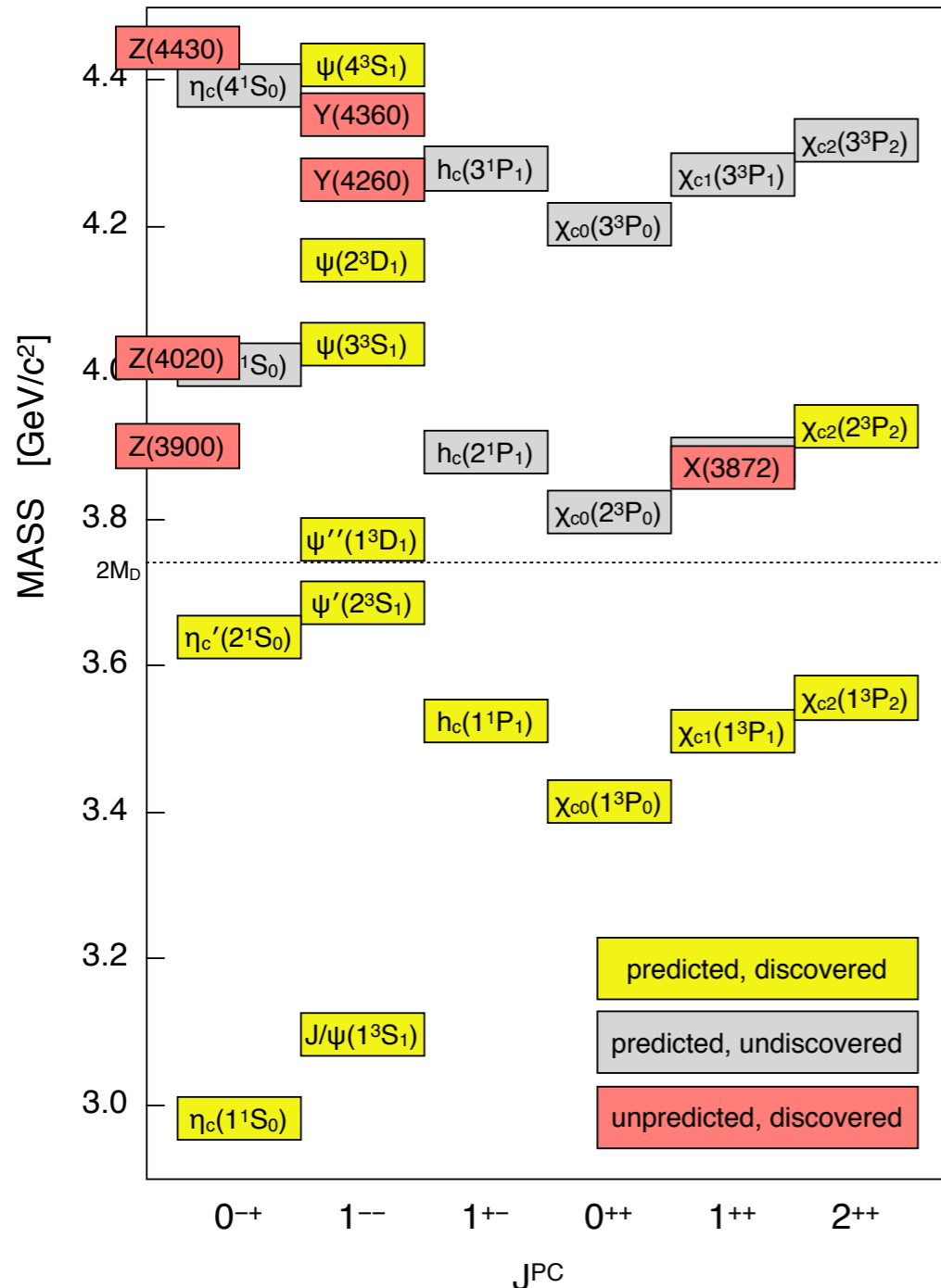
The quark model description of these states has been enormously successful *(with a few anomalies)*.

But QCD is more complicated than the quark model, and we are now taking firm steps beyond it *(e.g., lattice QCD)*.

Charmonium Spectrum
predictions based on PRD 72, 054026 (2005)
measurements from PDG 2014

The "XYZ states" cannot be accommodated in the quark model. Beyond that, their interpretation is still unclear.

Three misconceptions:
1. This is hopelessly complicated.
2. These are experimental artifacts.
3. Everything is/isn't resonant (a "particle").

Theoretical tasks:
1. Develop a theoretical framework.
2. Develop theoretical tools for amplitude analysis.

Experimental tasks:
1. Keep adding information.
2. Start making connections.

This talk:
    Connections and Complexities

The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, **Belle**)

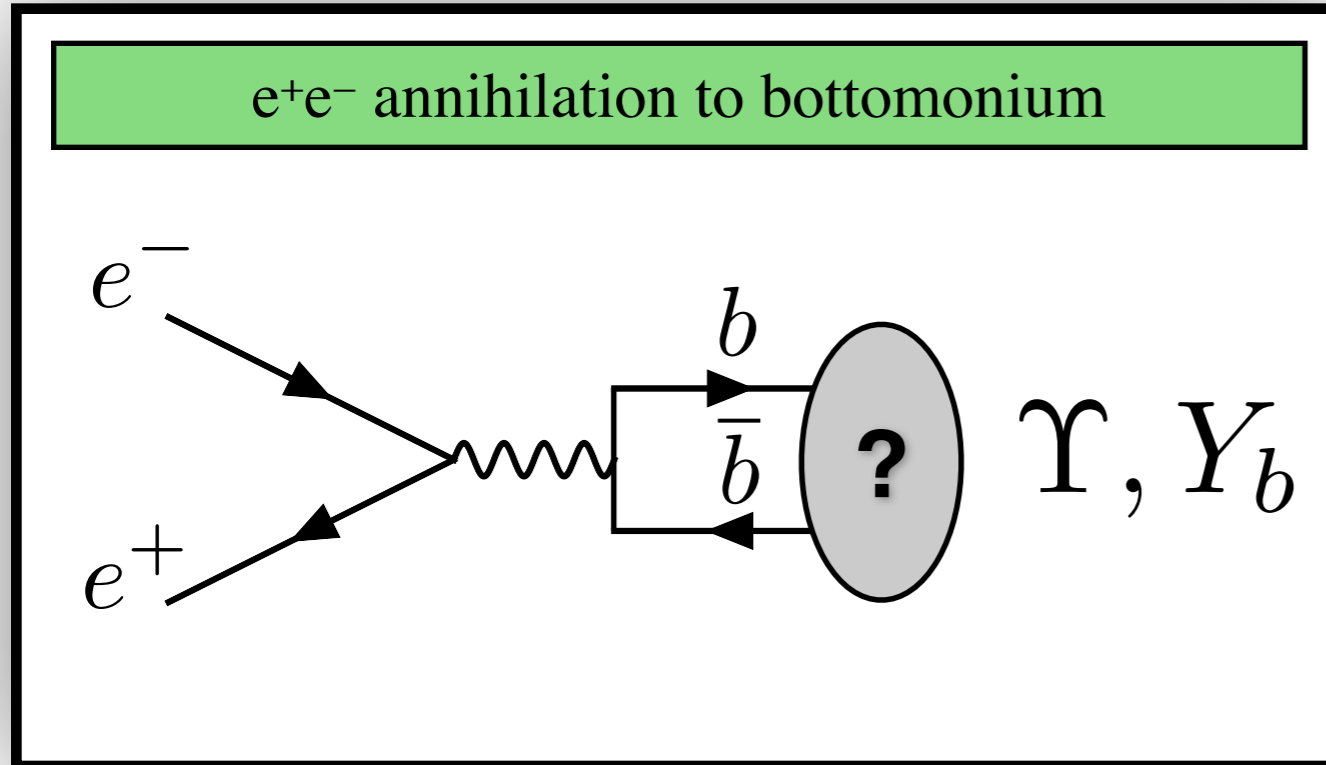- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e^+e^- annihilation using ISR (CLEO, BaBar, **Belle**)

- e^+e^- annihilation (CLEO-c, **BESIII**)

- B decay (CDF, D0, CLEO, BaBar, **Belle**, **LHCb**, **ATLAS**, **CMS**)

- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

- $\gamma\gamma$ collisions (CLEO, BaBar, **Belle**)

- double charmonium production (CLEO, BaBar, **Belle**)

- *proton anti-proton annihilation (PANDA?!?!)*

The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, **Belle**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e^+e^- annihilation using ISR (CLEO, BaBar, **Belle**)

- e^+e^- annihilation (CLEO-c, **BESIII**)

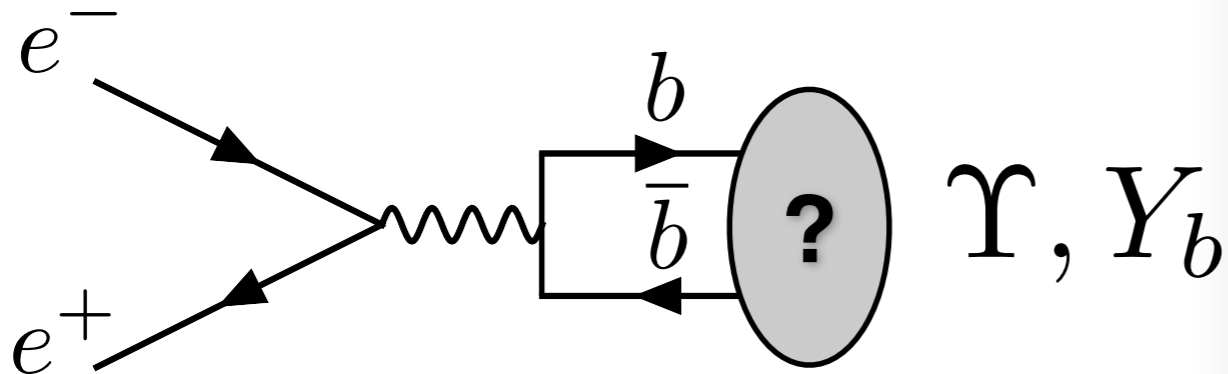- B decay (CDF, D0, CLEO, BaBar, **Belle**, **LHCb**, **ATLAS**, **CMS**)

- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

- $\gamma\gamma$ collisions (CLEO, BaBar, **Belle**)

- double charmonium production (CLEO, BaBar, **Belle**)

- *proton anti-proton annihilation (PANDA?!?!)*

The Experimental Landscape

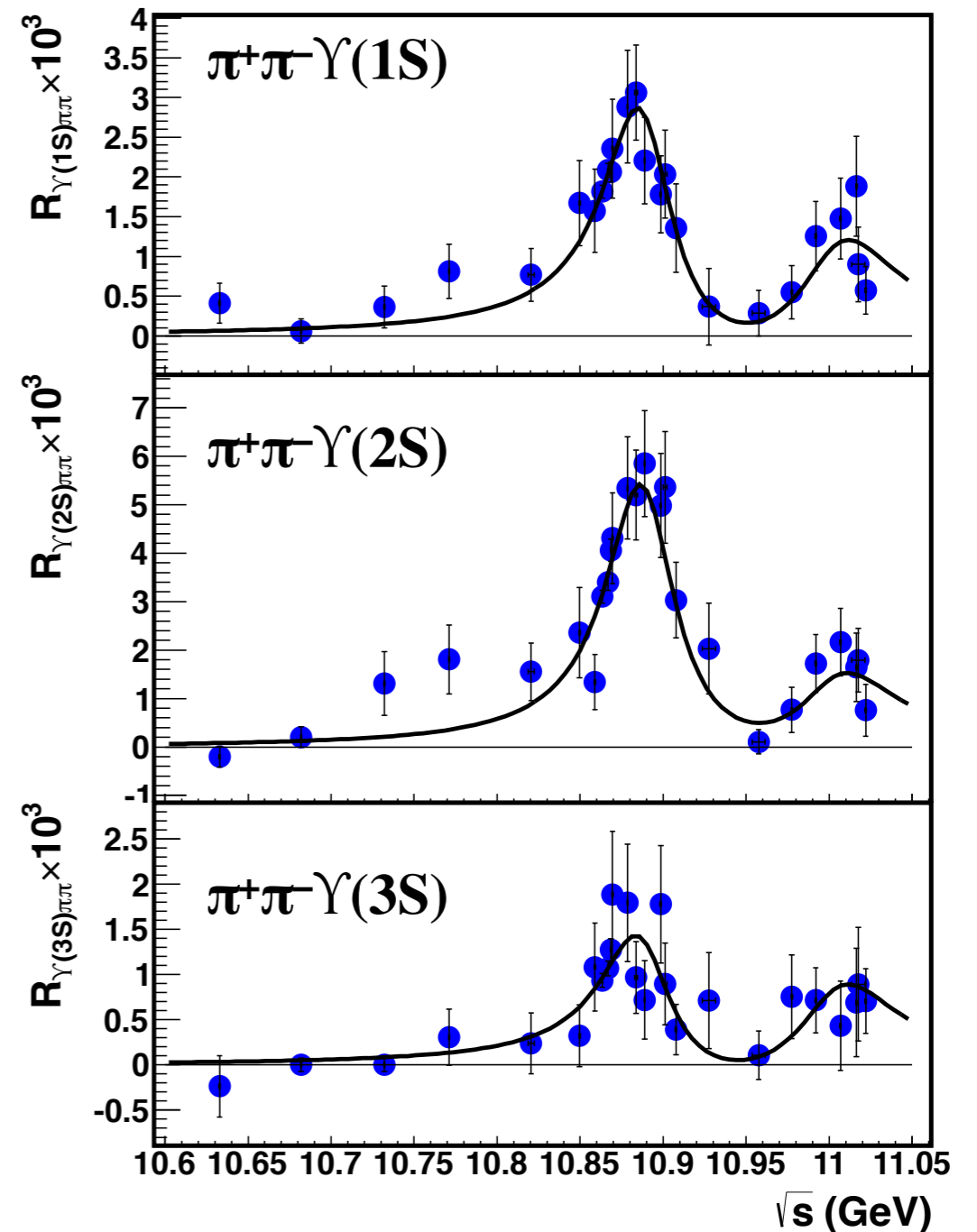**BOTTOMONIUM:**

- e^+e^- annihilation (**CLEO**, BaBar, **Belle**)

$$\Upsilon, Y_b$$

- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

- $\gamma\gamma$ collisions (CLEO, BaBar, **Belle**)

- double charmonium production (CLEO, BaBar, **Belle**)

- *proton anti-proton annihilation (PANDA?!?!)*

γ_{ISR}

e^-

BOTTOMONIUM:

c

$\bar{c}$

? ψ, Y

- e^+e^- annihilation (CLEO, BaBar, **Belle**)

e^+

| e^+e^- annihilation to bottomonium |

e^-

b

$\bar{b}$

? Υ, Y_b

e^+

- proton collisions (CDF, D0, **LHCb**, **ATLAS**, CMS)

- $\gamma\gamma$ collisions (CLEO, BaBar, **Belle**)

- double charmonium production (CLEO, BaBar, Belle)
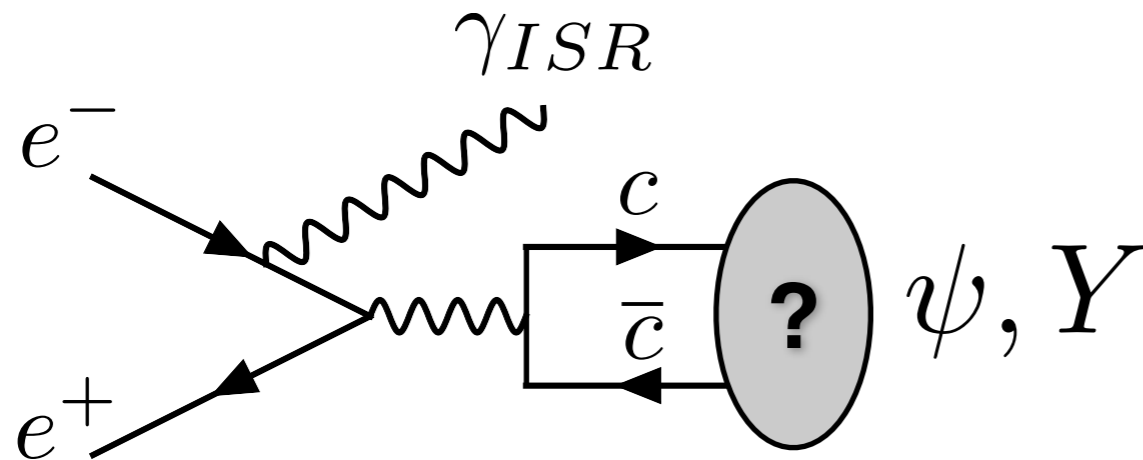
- *proton anti-proton annihilation (PANDA?!?!)*

| $e^+e^- \to \pi^+\pi^-\Upsilon(1S,2S,3S)$ at Belle |
| arXiv:1501.01137 |

- anomalously large $\pi^+\pi^-\Upsilon(nS)$ rates — indication for something exotic? a Y_b?

The Experimental Landscape

BOTTOMONIUM:

- e⁺e⁻ annihilation (**CLEO**, BaBar, **Belle**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e⁺e⁻ annihilation using ISR (**CLEO**, BaBar, **Belle**)

- e⁺e⁻ annihilation (**CLEO-c**, **BESIII**)

- B decay (**CDF**, **D0**, **CLEO**, BaBar, **Belle**, **LHCb**, **ATLAS**, **CMS**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

- γγ collisions (**CLEO**, BaBar, **Belle**)

- double charmonium production (**CLEO**, BaBar, **Belle**)

- *proton anti-proton annihilation (PANDA?!?!)*

BOTTOMONIUM:

- e^+e^- annihilation (**CLEO**, **BaBar**, **Belle**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e^+e^- annihilation using ISR (**CLEO**, **BaBar**, **Belle**)

e^+e^- annihilation to charmonium (via ISR)

γ_{ISR}

e^-

c

$\bar{c}$

e^+

ψ, Y

proton anti-proton annihilation (PANDA?!?!)

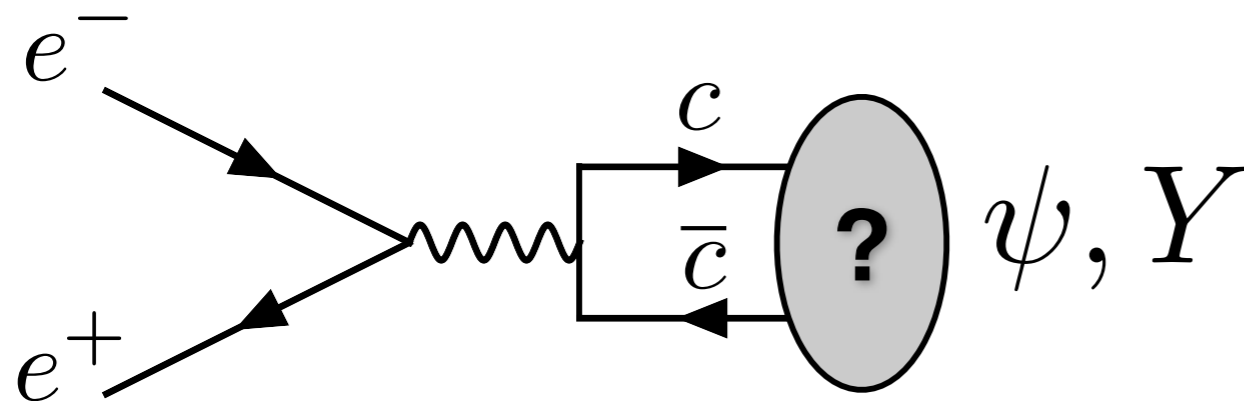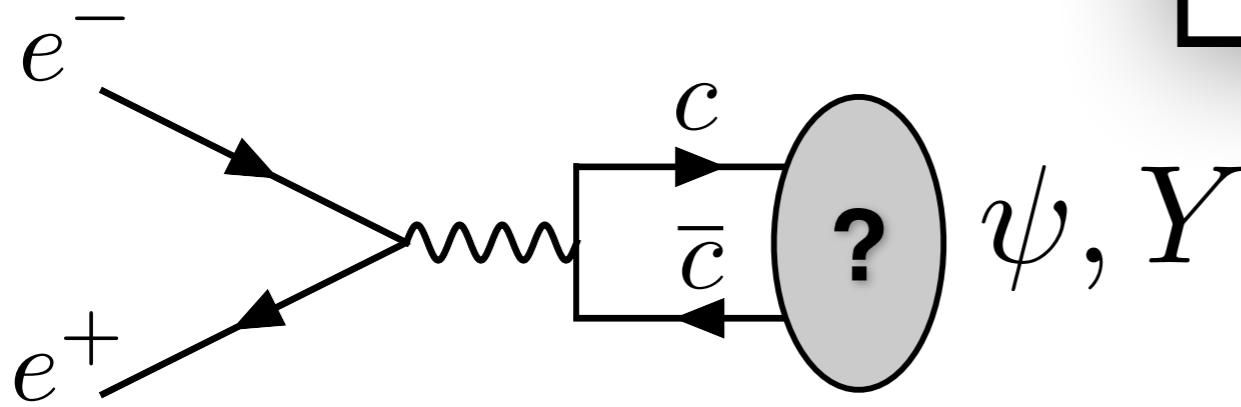# The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, **Belle**)

- proton collisions (CDF, D0, **LHCb**, **ATLAS**)

CHARMONIUM:

- e^+e^- annihilation using ISR (CLEO, BaBar)

e^+e^- annihilation to charmonium (via ISR)

γ_{ISR}

e^-

e^+

c

$\bar{c}$

? ψ, Y

e^- *proton anti-proton annihilation (PANDA?!?!)*

b

$e^+e^-(\gamma_{ISR}) \rightarrow \pi^+\pi^-J/\psi$ at Belle

PRL 110, 252002 (2013)

$Y(4260) \rightarrow \pi^+\pi^-J/\psi$

- the Y(4260) has no place in the quark model

The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, **Belle**)

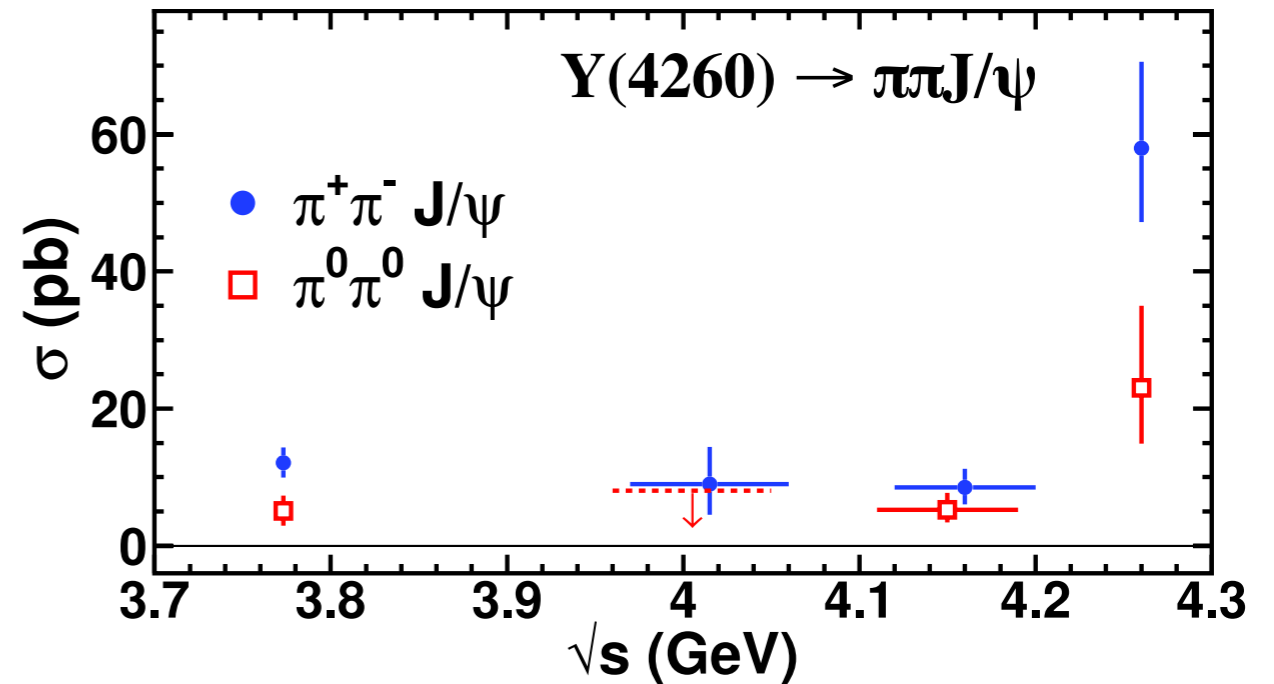- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e^+e^- annihilation using ISR (CLEO, BaBar, **Belle**)

- e^+e^- annihilation (CLEO-c, **BESIII**)

- B decay (**CDF**, **D0**, CLEO, BaBar, **Belle**, **LHCb**, **ATLAS**, **CMS**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

- $\gamma\gamma$ collisions (CLEO, BaBar, **Belle**)

- double charmonium production (CLEO, BaBar, **Belle**)

- *proton anti-proton annihilation (PANDA?!?!)*

The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (**CLEO**, BaBar, **Belle**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e^+e^- annihilation using ISR (**CLEO**, BaBar, **Belle**)

- e^+e^- annihilation (**CLEO-c**, **BESIII**)

e^+e^- annihilation to charmonium

e^-

c

$\bar{c}$

?

ψ, Y

e^+

γ_{ISR}

The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, **Belle**)
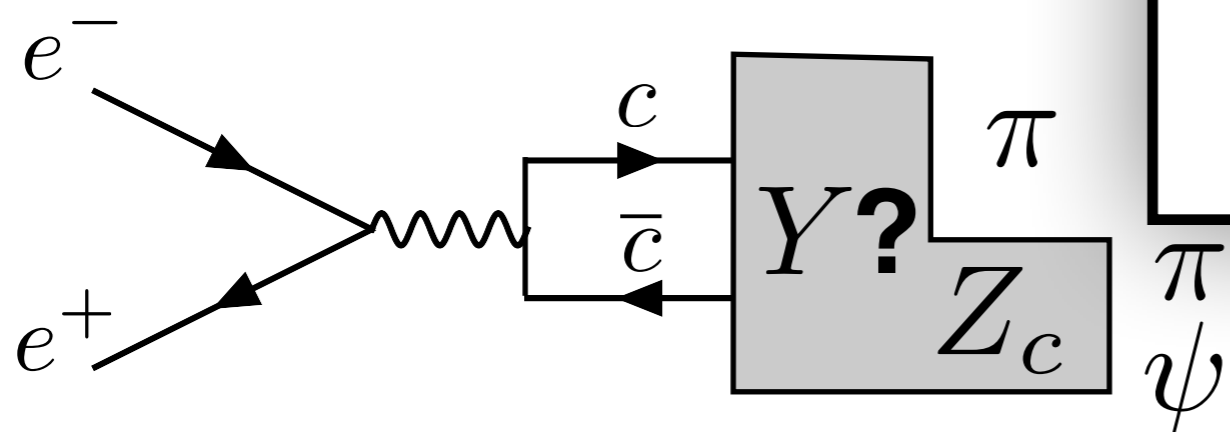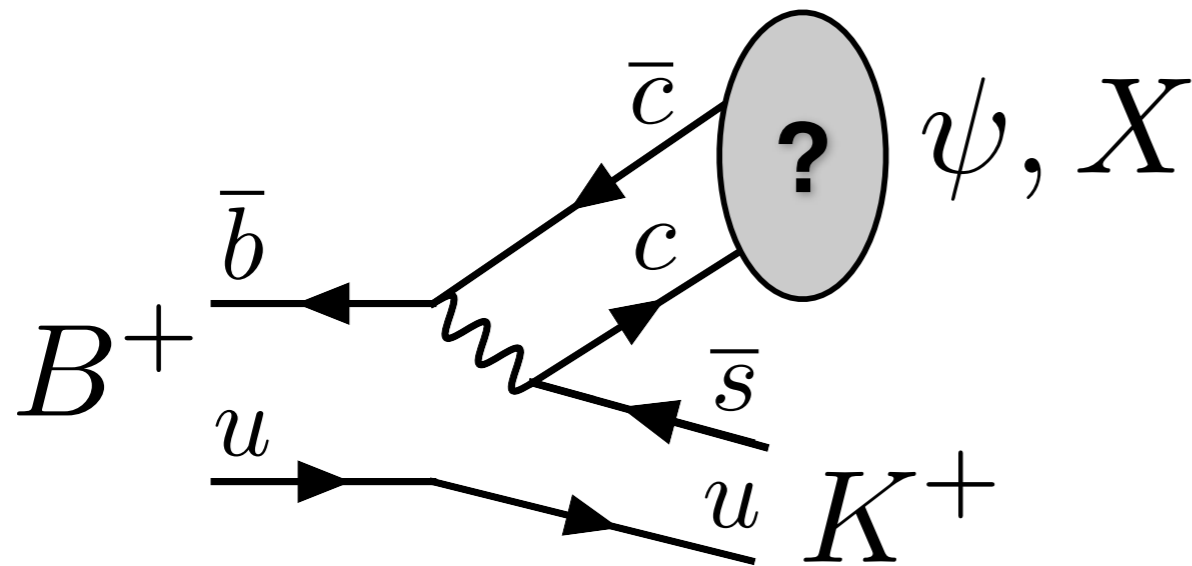
- proton collisions (CDF, D0, LHCb, ATLAS)

CHARMONIUM:

- e^+e^- annihilation using ISR (CLEO, BaBar)

- e^+e^- annihilation (CLEO-c, **BESIII**)

e^+e^- annihilation to charmonium

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at CLEO-c

PRL 96, 162003 (2006)

- another view of the Y(4260)

BOTTOMONIUM:

- e⁺e⁻ annihilation (**CLEO**, **BaBar**, **Belle**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

$\bar{c}$

ψ, X

?

$\bar{b}$

c

B^+

e⁺e⁻ annihilation using ISR (**CLEO**, **BaBar**, **Belle**)

$\bar{s}$

u

- e⁺e⁻ annihilation (**CLEO**-c, **BESIII**)

u

K^+

LHCb, **ATLAS**, **CMS**)

CMS)

e⁺e⁻ annihilation to charmonium

e^-

c

π

$\bar{c}$

Y **?**

Z_c

π

ψ

e^+

Belle)

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, Belle)

- proton collisions (CDF, D0, LHCb, ATLAS)

CHARMONIUM:

- e^+e^- annihilation using ISR (CLEO, BaBar)

- e^+e^- annihilation (CLEO-c, BESIII)

ψ, X

$\bar{c}$

$\bar{b}$

B^+

c

$\bar{s}$

u

$\bar{u}$

K^+

?
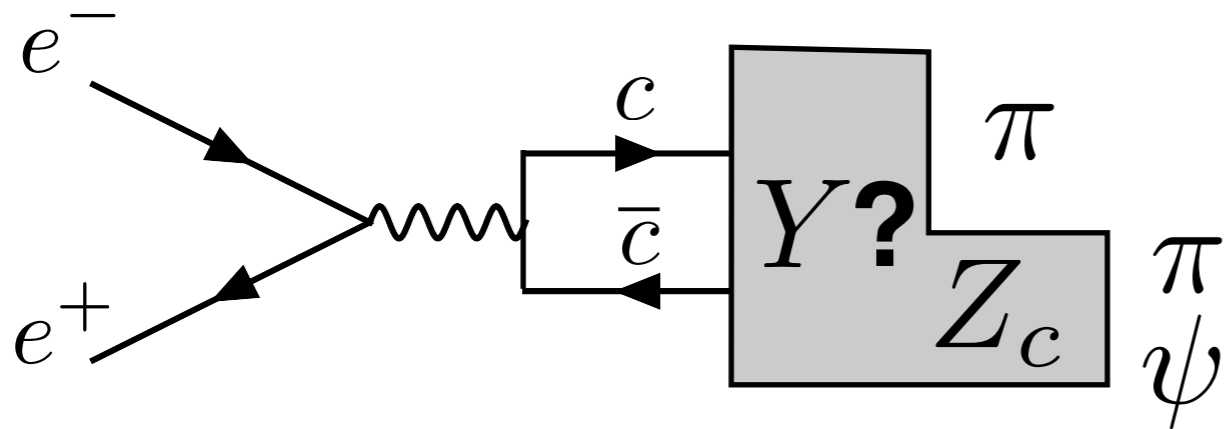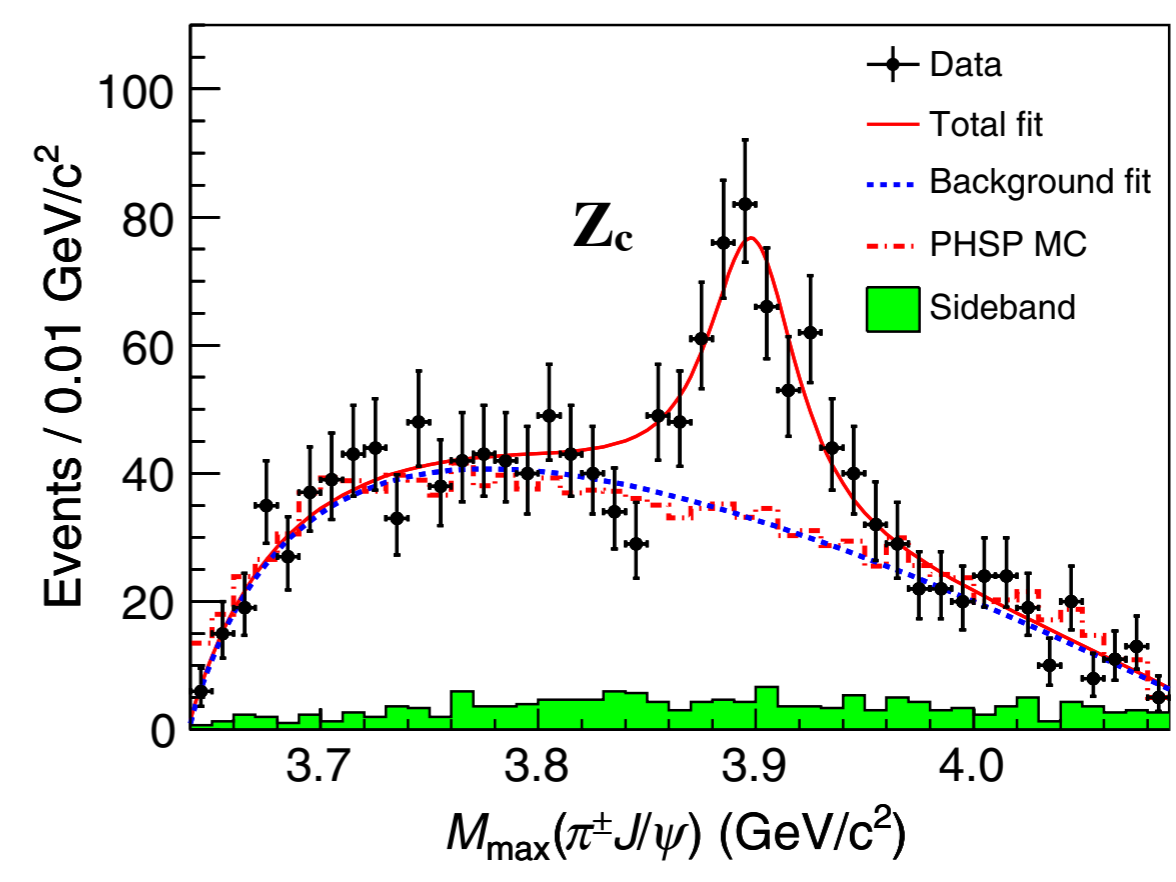
- substructure in $Y(4260) \to \pi^+\pi^- J/\psi$

e^+e^- annihilation to charmonium

e^-

e^+

c

$\bar{c}$

Y**?**

Z_c

π

π

ψ

(, Belle)

The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, **Belle**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e^+e^- annihilation using ISR (CLEO, BaBar, **Belle**)

- e^+e^- annihilation (CLEO-c, **BESIII**)

- B decay (CDF, D0, CLEO, BaBar, **Belle**, **LHCb**, **ATLAS**, **CMS**)

- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

- $\gamma\gamma$ collisions (CLEO, BaBar, **Belle**)

- double charmonium production (CLEO, BaBar, **Belle**)
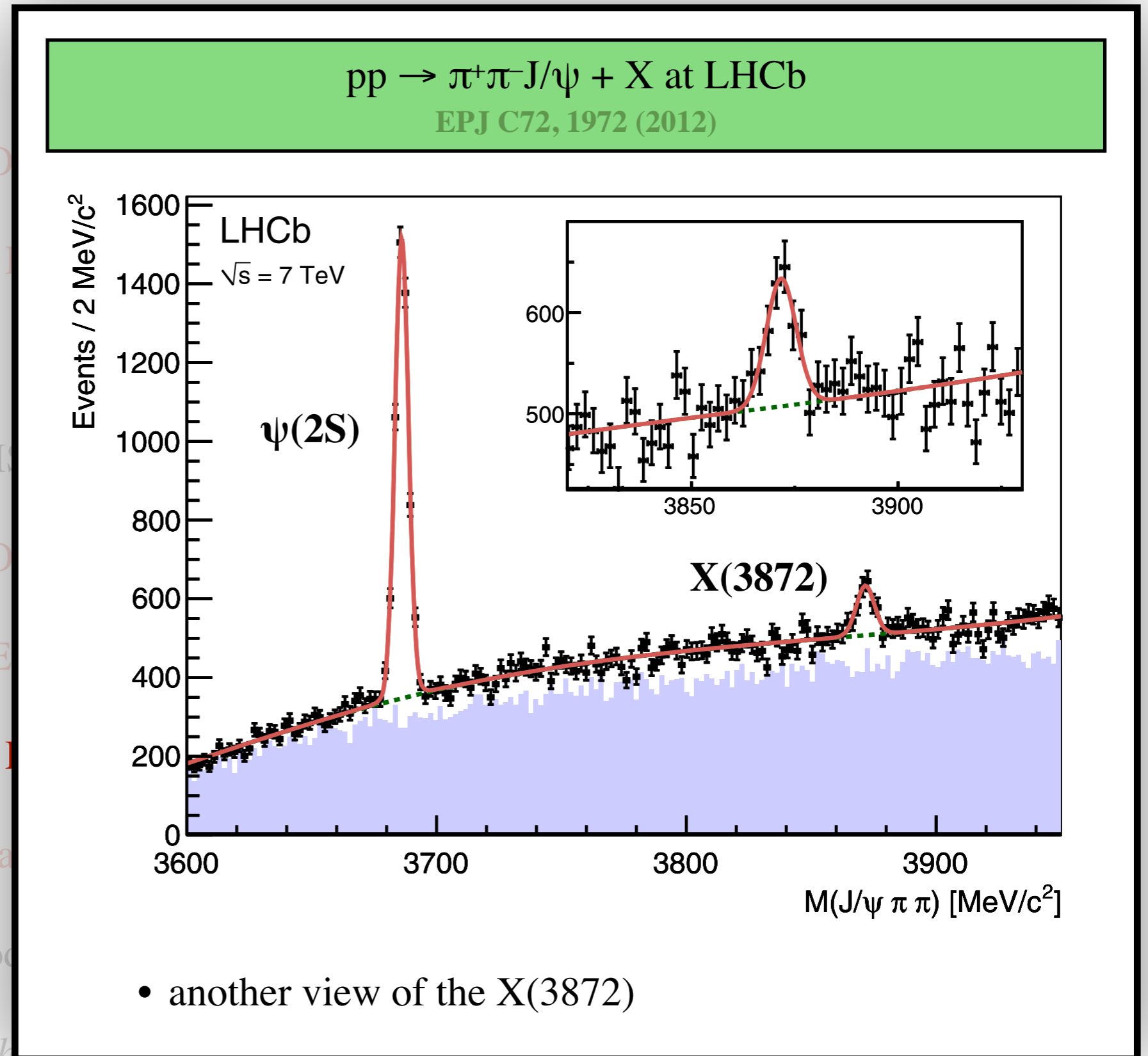
- *proton anti-proton annihilation (PANDA?!?!)*

B decays to charmonium

$\bar{c}$

$?$

ψ, X

$\bar{b}$

c

B^+

$\bar{s}$

u

u K^+

- e⁺e⁻ annihilation (CLEO-c, BESIII)

- B decay (CDF, D0, CLEO, BaBar, **Belle**, **LHCb**, **ATLAS**, **CMS**)

- proton collisions (CDF, D0, LHCb, ATLAS, CMS)

- γγ collisions (CLEO, BaBar, Belle)

- double charmonium production (CLEO, BaBar, **Belle**)

- proton anti-proton annihilation (PANDA?!?!)

e^-
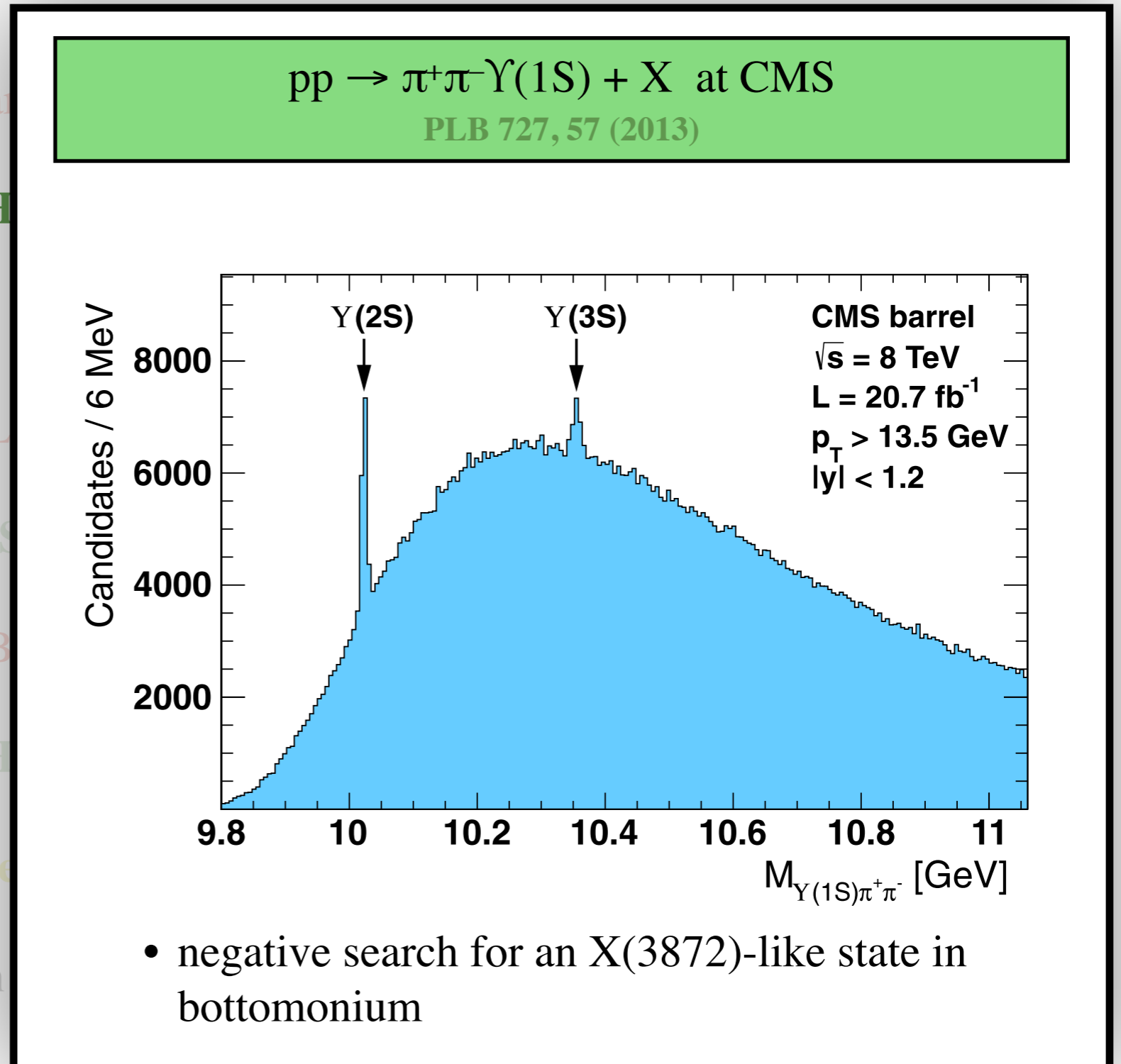
c

π

$?$

$\bar{c}$

Z_c

π

e^+

ψ

e^-

c

B decays to charmonium

B^+ ... $\bar{c}$, c ... ψ, X ... $\bar{b}$ ... $\bar{s}$ ... u ... u K^+

- e⁺e⁻ annihilation (CLEO-c, BES...)

- B decay (CDF, D0, CL... BaBar...)

- proton collisions (CDF... LHC...)

- γγ collisions (CLEO, ...)

- double charmonium production (...)

- proton anti-proton annihilation (...)

e^- ... e^+ ... c ... $\bar{c}$ ... π ... Z_c

B⁺ → K⁺(π⁺π⁻J/ψ) at LHCb
PRL 110, 222001 (2013)
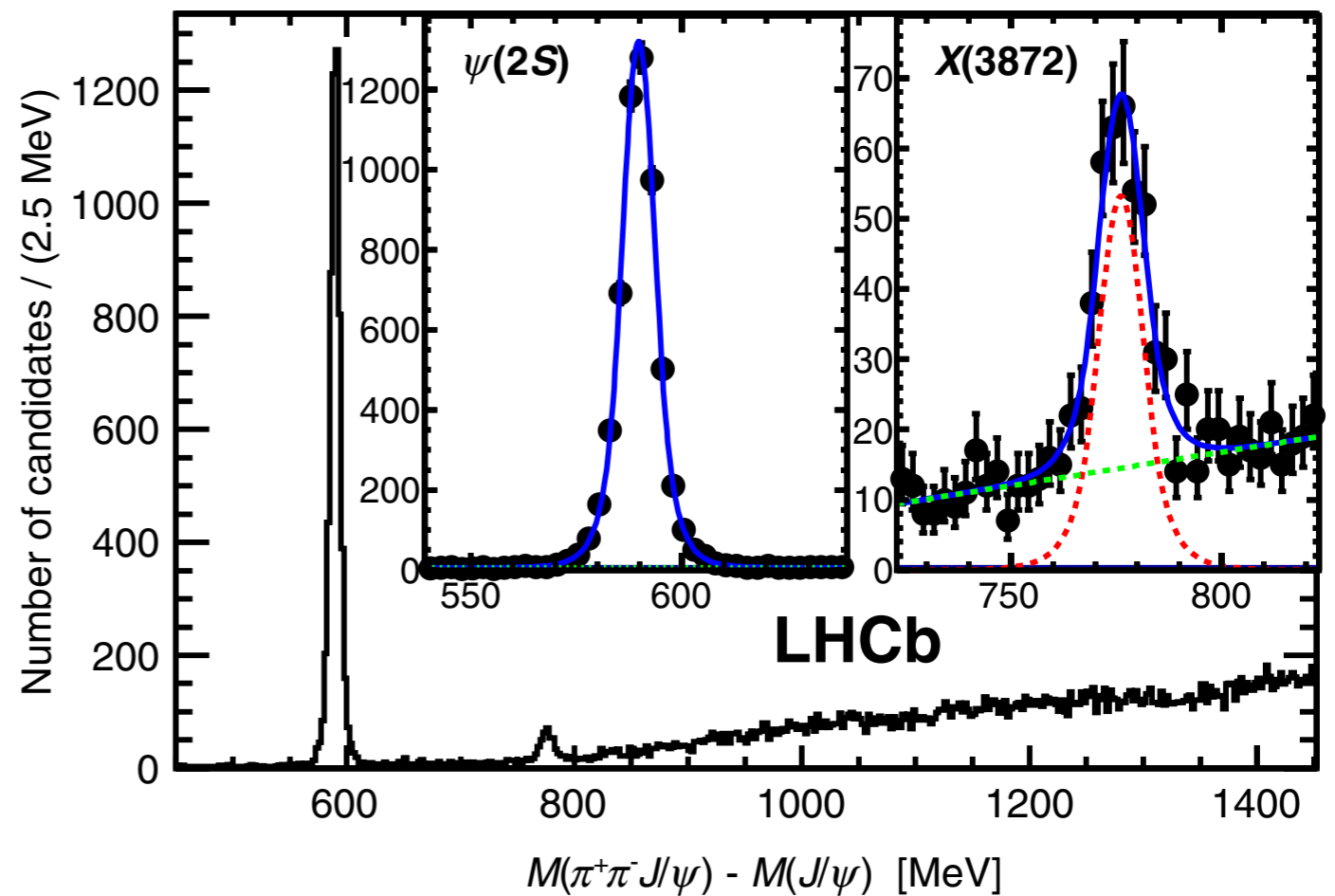
ψ(2S) X(3872)

LHCb

$M(\pi^+\pi^- J/\psi) - M(J/\psi)$ [MeV]

Number of candidates / (2.5 MeV)

- the X(3872) is also hard to accommodate in the quark model
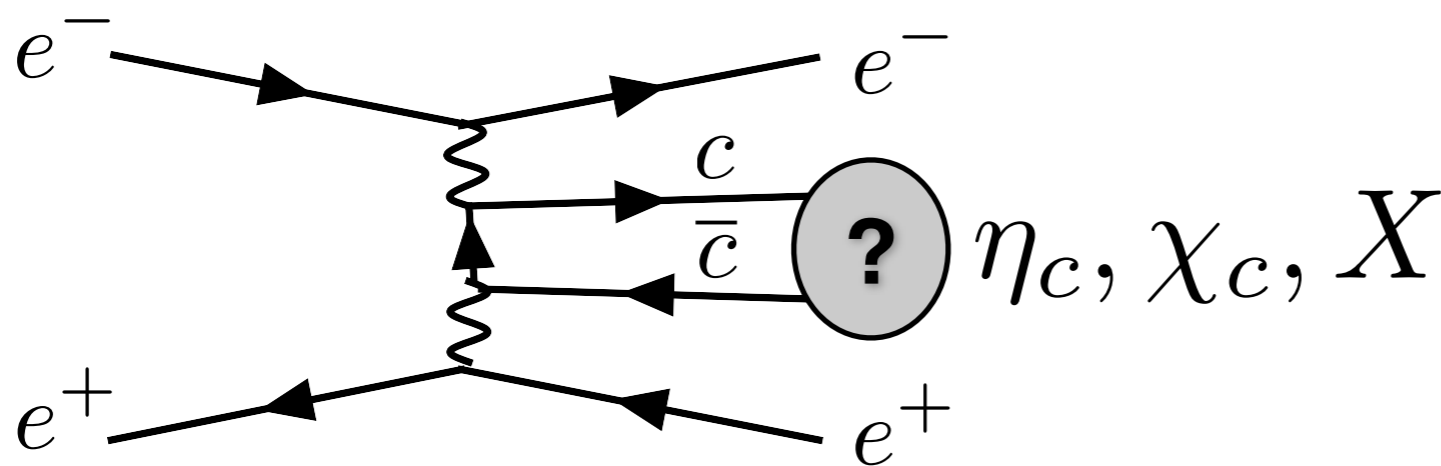
BOTTOMONIUM:

- e$^+$e$^-$ annihilation (CLEO, BaBar, **Belle**)

- proton collisions (CDF, D0, LHCb, ATLAS, CMS)

CHARMONIUM:

- e$^+$e$^-$ annihilation using ISR (CLEO, BaBar, **Belle**)

- e$^+$e$^-$ annihilation (CLEO-c, **BESIII**)

- B decay (CDF, D0, CLEO, BaBar, **Belle**, **LHCb**, **ATLAS**, **CMS**)

- proton collisions (CDF, D0, LHCb, ATLAS, CMS)

- γγ collisions (CLEO, BaBar, **Belle**)

- double charmonium production (CLEO, BaBar, **Belle**)

- *proton anti-proton annihilation (PANDA?!?!)*

The Experimental Landscape

BOTTOMONIUM:

- e+e− annihilation (CLEO, BaBar, **Belle**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e+e− annihilation using ISR (CLEO, BaBar, **Belle**)

- e+e− annihilation (CLEO-c, **BESIII**)

- B decay (CDF, D0, CLEO, BaBar, **Belle**, **LHCb**, **ATLAS**, **CMS**)

- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

- γγ collisions (CLEO, BaBar, **Belle**)

- double charmonium production (CLEO, BaBar, **Belle**)

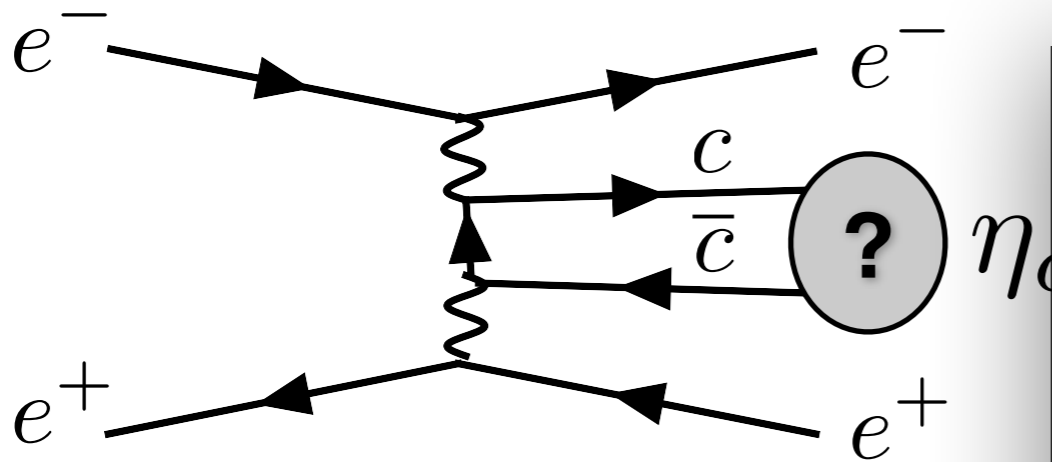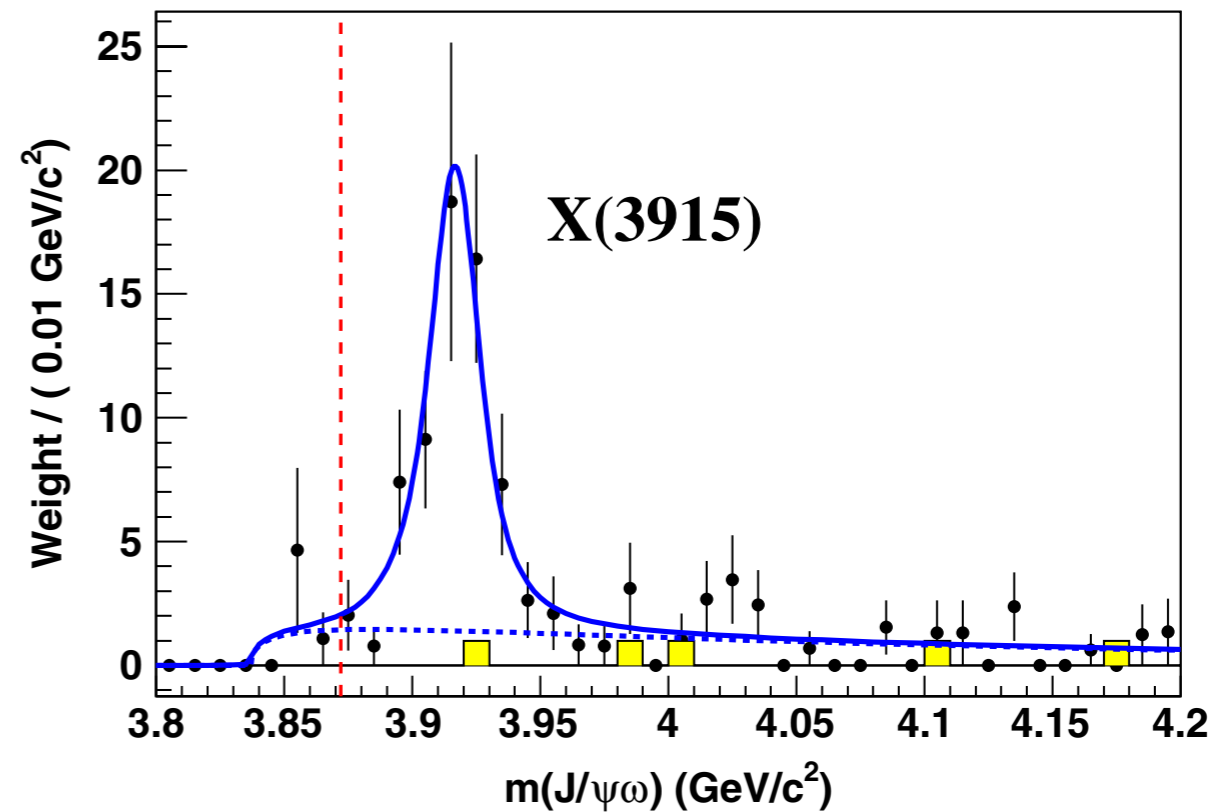- *proton anti-proton annihilation (PANDA?!?!)*

The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO
- proton collisions (CDF,

CHARMONIUM:

- e^+e^- annihilation using I
- e^+e^- annihilation (CLEO
- B decay (CDF, D0, CLE
- proton collisions (CDF,
- $\gamma\gamma$ collisions (CLEO, Ba
- double charmonium prod
- proton anti-proton annihilation

$pp \rightarrow \pi^+\pi^- J/\psi + X$ at LHCb

EPJ C72, 1972 (2012)

- another view of the X(3872)

The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, **Belle**)

- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e^+e^- annihilation using ISR (CLEO, BaBar, **Belle**)

- e^+e^- annihilation (CLEO-c, **BESIII**)

- B decay (CDF, D0, CLEO, BaBar, **Belle**, **LHCb**, **ATLAS**, **CMS**)

- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

- $\gamma\gamma$ collisions (CLEO, BaBar, **Belle**)

- double charmonium production (CLEO, BaBar, **Belle**)

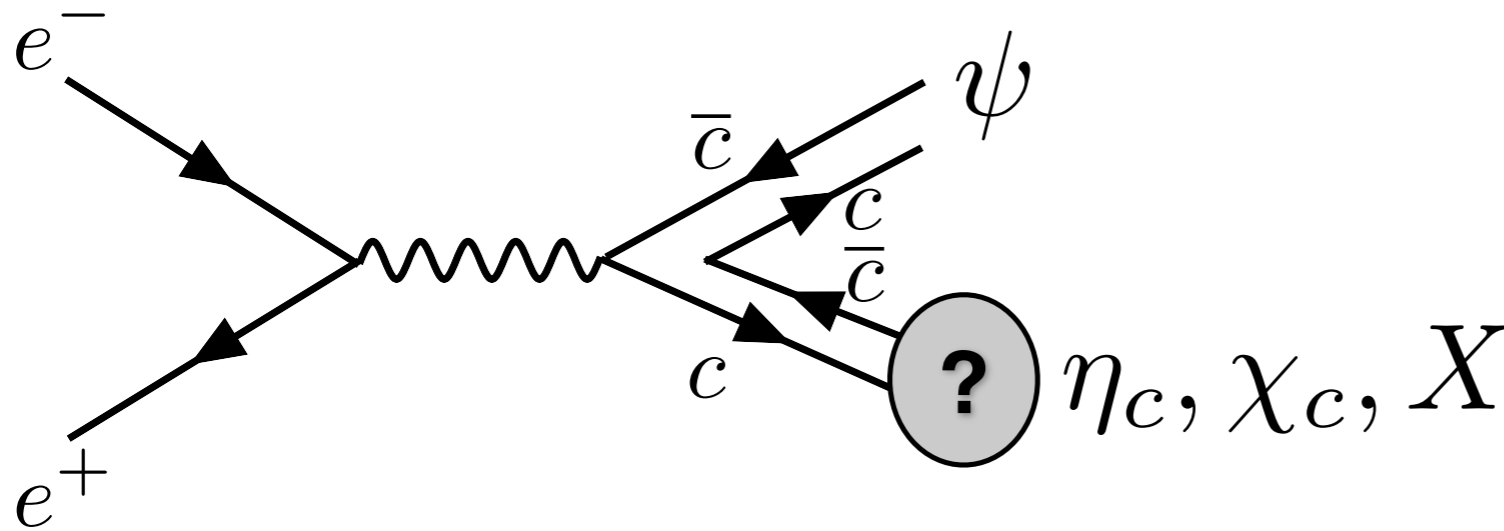- *proton anti-proton annihilation (PANDA?!?!)*

The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar

- proton collisions (CDF, D0, LH

CHARMONIUM:

- e^+e^- annihilation using ISR (CL

- e^+e^- annihilation (CLEO-c, BES

- B decay (CDF, D0, CLEO, BaB

- proton collisions (CDF, D0, LH

- $\gamma\gamma$ collisions (CLEO, BaBar, Be

- double charmonium production

- *proton anti-proton annihilation (PANDA?!?!)*

pp → $\pi^+\pi^-\Upsilon$(1S) + X at CMS
PLB 727, 57 (2013)

- negative search for an X(3872)-like state in bottomonium

The Experimental Landscape

BOTTOMONIUM:

- e⁺e⁻ annihilation (CLEO, E
- **proton collisions (CDF, D0**

CHARMONIUM:

- e⁺e⁻ annihilation using ISR
- e⁺e⁻ annihilation (CLEO-c
- B decay (CDF, D0, CLEO,
- proton collisions (CDF, D0
- γγ collisions (CLEO, BaBa
- double charmonium produc
- *proton anti-proton annihilation (PANDA?!?!)*

pp → γϒ(1S) + X at ATLAS
PRL 108, 152001 (2012)
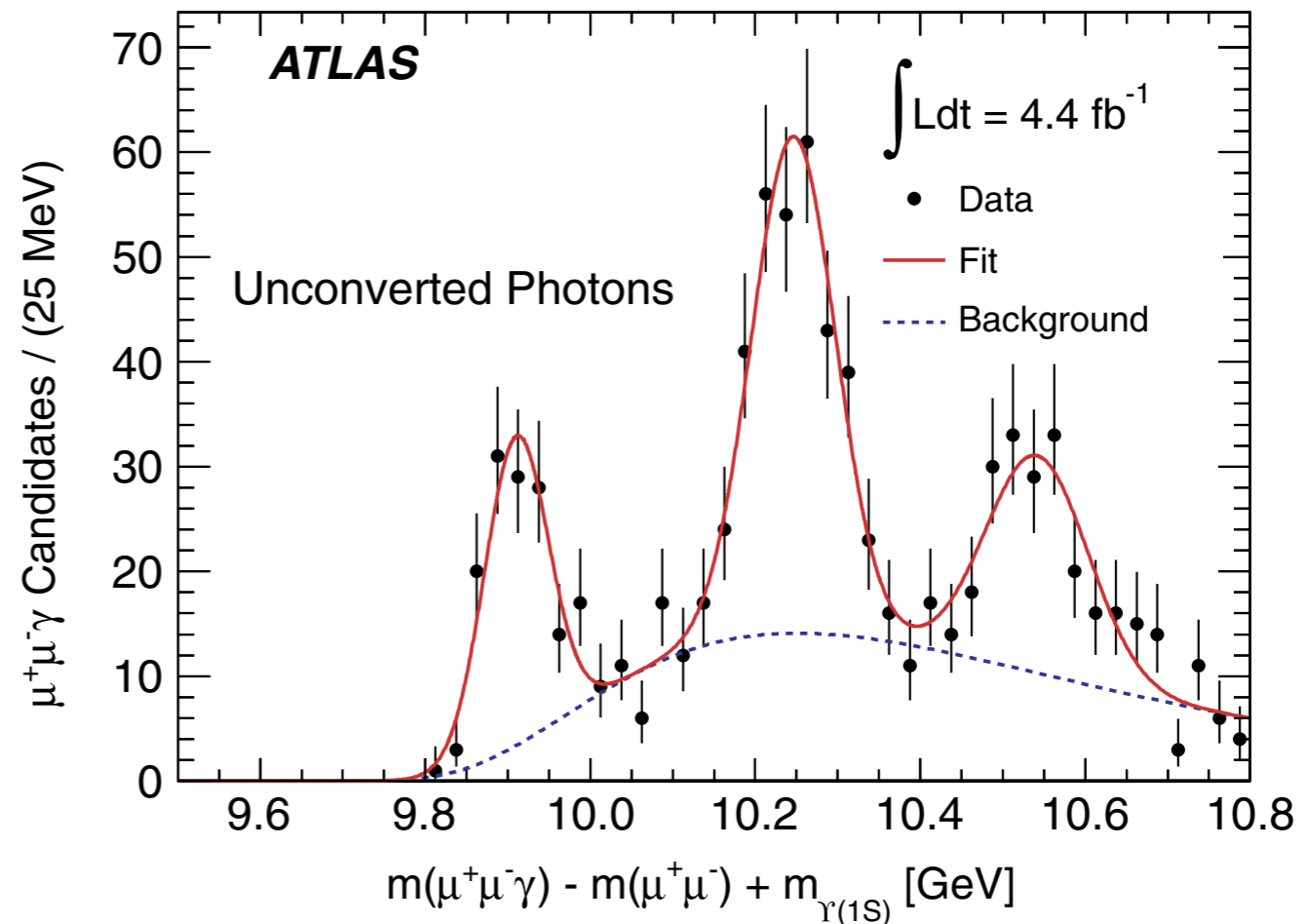
- discovery of the χ_b(3P) states

The Experimental Landscape

BOTTOMONIUM:

- e⁺e⁻ annihilation (**CLEO**, **BaBar**, **Belle**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e⁺e⁻ annihilation using ISR (**CLEO**, **BaBar**, **Belle**)

- e⁺e⁻ annihilation (**CLEO-c**, **BESIII**)

- B decay (**CDF**, **D0**, **CLEO**, **BaBar**, **Belle**, **LHCb**, **ATLAS**, **CMS**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

- γγ collisions (**CLEO**, **BaBar**, **Belle**)

- double charmonium production (**CLEO**, **BaBar**, **Belle**)

- *proton anti-proton annihilation (PANDA?!?!)*

γγ collisions to charmonium

- e⁺e⁻ annihilation (CLEO-c, BESIII)

- B decay (CDF, D0, CLEO, BaBar, Belle, LHCb, ATLAS, CMS)

- proton collisions (CDF, D0, LHCb, ATLAS, CMS)

- γγ collisions (CLEO, BaBar, Belle)

- double charmonium production (CLEO, BaBar, Belle)

- *proton anti-proton annihilation (PANDA?!?!)*

e^+

Y?

Z_c

π

π

ψ

γγ collisions to charmonium

e^- e^-

c

$\bar{c}$ **?** η_c

e^+ e^+

- e^+e^- annihilation (CLEO-c, BESIII)

- B decay (CDF, D0, CLEO, BaBar, **Be**

- proton collisions (CDF, D0, **LHCb**, A

- **γγ collisions (CLEO, BaBar, Belle)**

- double charmonium production (CLE

- *proton anti-proton annihilation (PAN*

γγ → ωJ/ψ at BaBar
PRD 86, 072002 (2012)

X(3915)

m(J/ψω) (GeV/c²)

- maybe the X(3915) is the $\chi_{c0}(2P)$, but there are strong arguments against it

The Experimental Landscape

BOTTOMONIUM:

- e$^+$e$^-$ annihilation (**CLEO**, **BaBar**, **Belle**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e$^+$e$^-$ annihilation using ISR (**CLEO**, **BaBar**, **Belle**)

- e$^+$e$^-$ annihilation (**CLEO-c**, **BESIII**)

- B decay (**CDF**, **D0**, **CLEO**, **BaBar**, **Belle**, **LHCb**, **ATLAS**, **CMS**)

- proton collisions (**CDF**, **D0**, **LHCb**, **ATLAS**, **CMS**)

- γγ collisions (**CLEO**, **BaBar**, **Belle**)

- double charmonium production (**CLEO**, **BaBar**, **Belle**)

- *proton anti-proton annihilation (PANDA?!?!)*

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, **Belle**)

- proton collisions (CDF, D0, LHCb, ATLAS, CMS)

CHARMONIUM:

double charmonium production

- double charmonium production (CLEO, BaBar, **Belle**)

- *proton anti-proton annihilation (PANDA?!?!)*

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, B...)

- proton collisions (CDF, D0, LHCb...)

CHARMONIUM:

double charmonium production
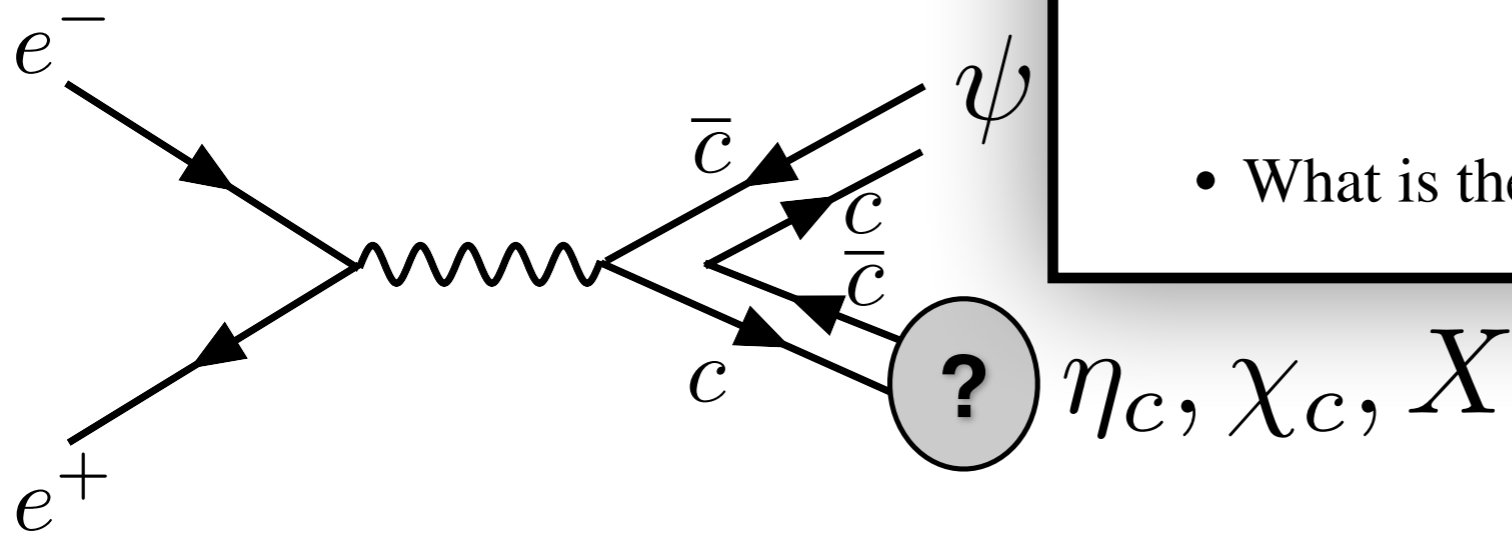
$e^+e^- \rightarrow J/\psi + X$ at Belle

PRL 98, 082001 (2007)
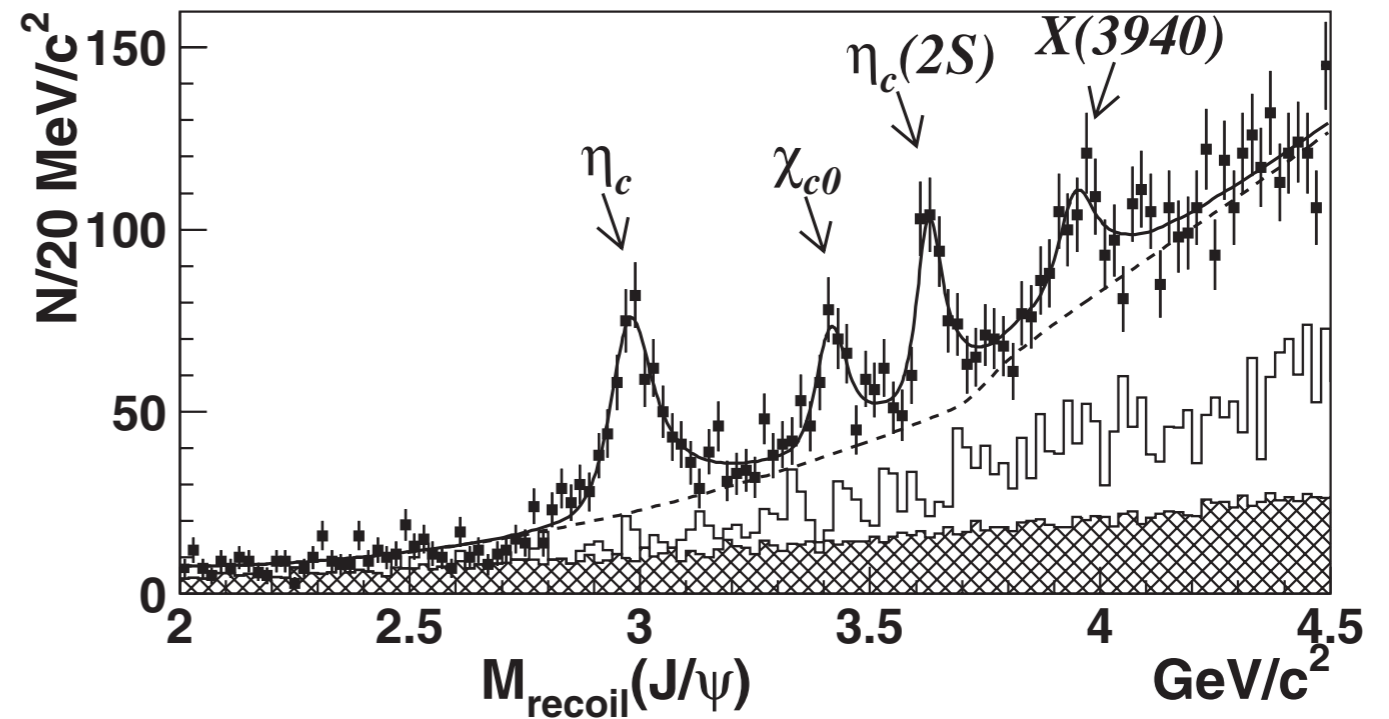
- What is the X(3940)?

- double charmonium production (CLEO, BaBar, **Belle**)

- *proton anti-proton annihilation (PANDA?!?!)*

The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, Belle)

- proton collisions (CDF, D0, LHCb, ATLAS, CMS)

CHARMONIUM:

- e^+e^- annihilation using ISR (CLEO, BaBar, Belle)

- e^+e^- annihilation (CLEO-c, BESIII)

- B decay (CDF, D0, CLEO, BaBar, Belle, LHCb, ATLAS, CMS)

- proton collisions (CDF, D0, LHCb, ATLAS, CMS)

- $\gamma\gamma$ collisions (CLEO, BaBar, Belle)

- double charmonium production (CLEO, BaBar, Belle)

- *proton anti-proton annihilation (PANDA?!?!)*

The Experimental Landscape

BOTTOMONIUM:

- e$^+$e$^-$ annihilation (CLEO, BaBar, **Belle**)

- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e$^+$e$^-$ annihilation using ISR (CLEO, BaBar, **Belle**)

- e$^+$e$^-$ annihilation (CLEO-c, **BESIII**)

- B decay (CDF, D0, CLEO, BaBar, **Belle**, **LHCb**, **ATLAS**, **CMS**)

- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

- γγ collisions (CLEO, BaBar, **Belle**)

- double charmonium production (CLEO, BaBar, **Belle**)

- *proton anti-proton annihilation (PANDA?!?!)*

Connections and Complexities

Connections I: The X(3872) and the Y(4260).

Connections II: The Y(4260) and the "Υ(5S)".

Connections III: The Z_c and $Z_c{}'$ and the Z_b and $Z_b{}'$.

Complexities: A Collection of e^+e^- Cross Sections.

Connections and Complexities

Connections I: The X(3872) and the Y(4260).

Connections II: The Y(4260) and the "Υ(5S)".

Connections III: The Z_c and $Z_c{}'$ and the Z_b and $Z_b{}'$.

Complexities: A Collection of e^+e^- Cross Sections.

Overview of the X(3872)

$B^+ \rightarrow K^+(\pi^+\pi^-J/\psi)$ at Belle

PRL 91, 262001 (2003)
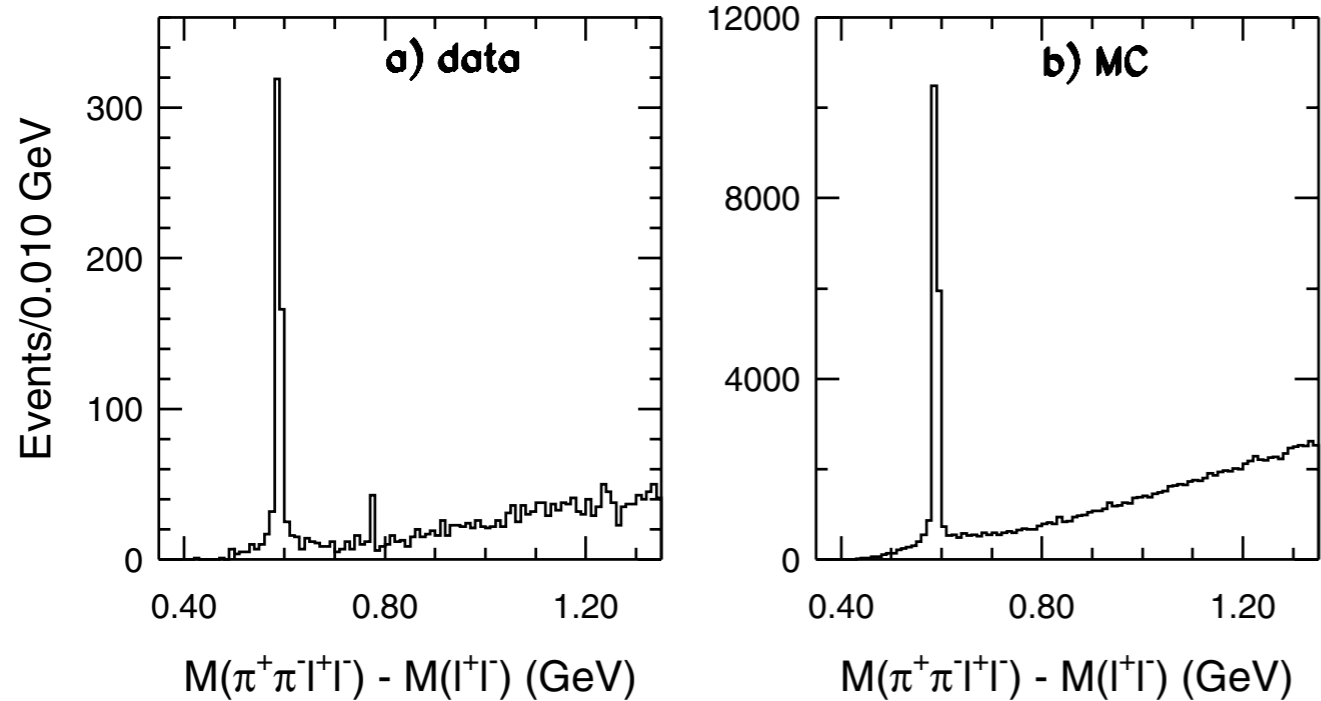
- first observation of the X(3872)

Overview of the X(3872)

$B^+ \to K^+(\pi^+\pi^- J/\psi)$ at Belle

PRL 91, 262001 (2

a) data
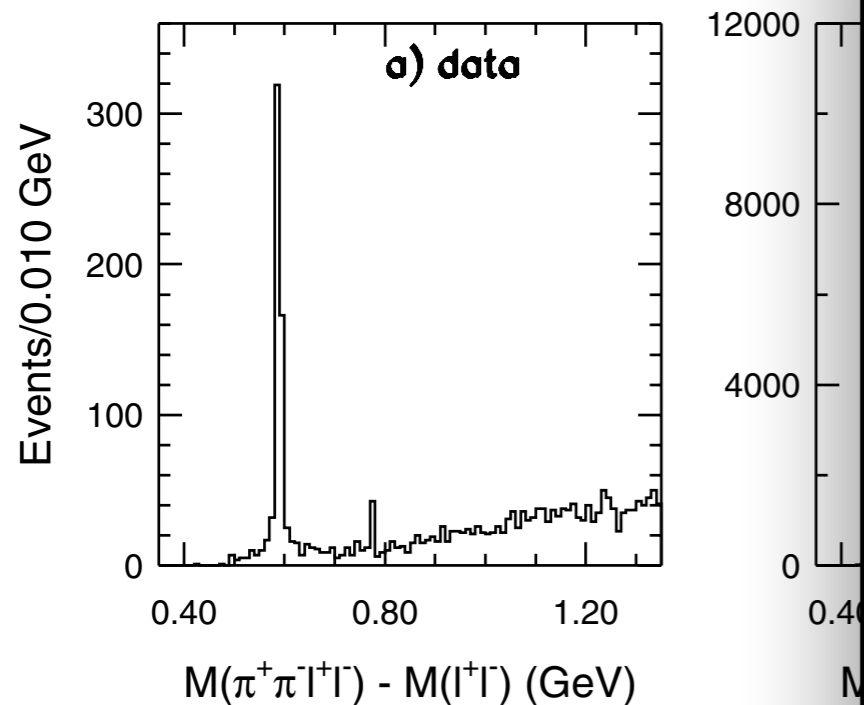
• first observation of the X(38

$B^+ \to K^+(\pi^+\pi^- J/\psi)$ at LHCb

arXiv:1504.06339

LHCb
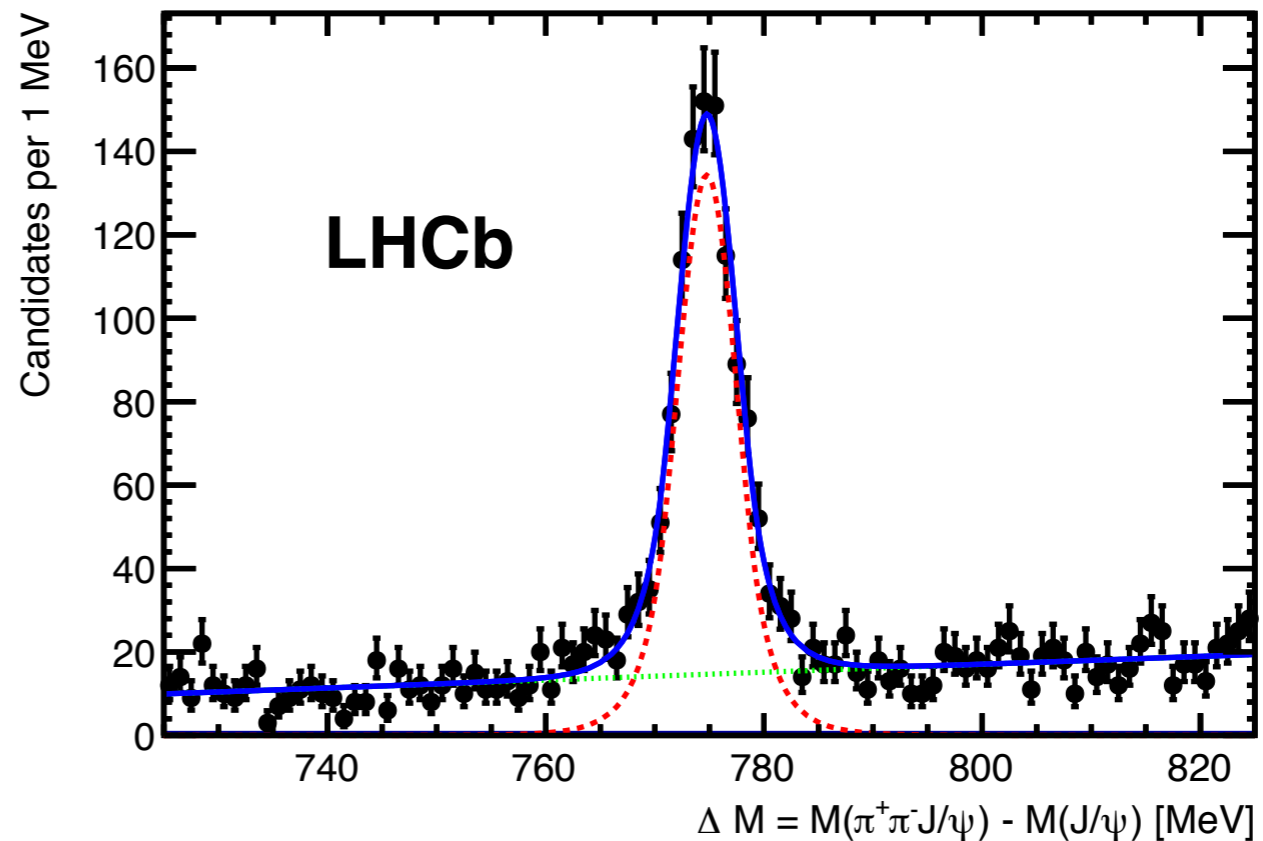
• latest observation of the X(3872) and confirmation of $J^{PC} = 1^{++}$

Overview of the X(3872)

B⁺ → K⁺(π⁺π⁻J/ψ) at Belle

PRL. 91, 262001 (

a) d

Events/0.010 GeV

300

200

100

0

0.40   0.80

M(π⁺π⁻l⁺l⁻) - M(l

• first observa

HCb
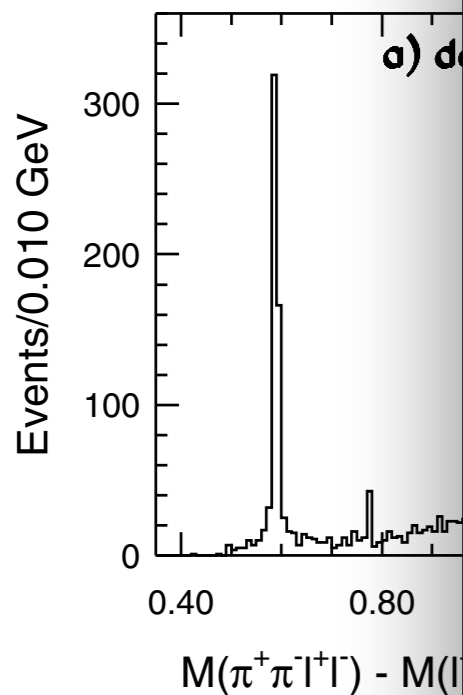
Properties of the X(3872)

2014 PDG

- Mass = **3871.69 ± 0.17 MeV**
- Width < **1.2 MeV**
- $M(D^0) + M(D^{0*})$ - Mass = **0.11 ± 0.23 MeV**
  (using $M(D^0) = 1864.84$ +- 0.07 MeV and $M(D^{0*}) - M(D^0) = 142.12$ +- 0.07 MeV)
- $J^{PC} = 1^{++}$
- too light and too narrow to be the $\chi_{c1}(2P)$
- also seen in other decay modes
- popular interpretation: DD* molecule or tetraquark

800   820

/ψ) - M(J/ψ) [MeV]

) and
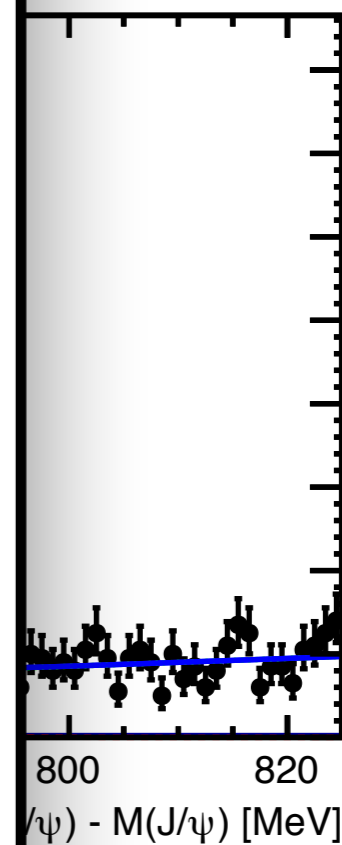
confirmation of J = 1

Overview of the Y(4260)

$e^+e^-(\gamma_{ISR}) \rightarrow \pi^+\pi^- J/\psi$ at BaBar

PRL 95, 142001 (2005)

- first observation of the Y(4260)

Overview of the Y(4260)

e⁺e⁻(γ_ISR) → π⁺π⁻J/ψ at BaBar
PRL 95, 142001 (2005)
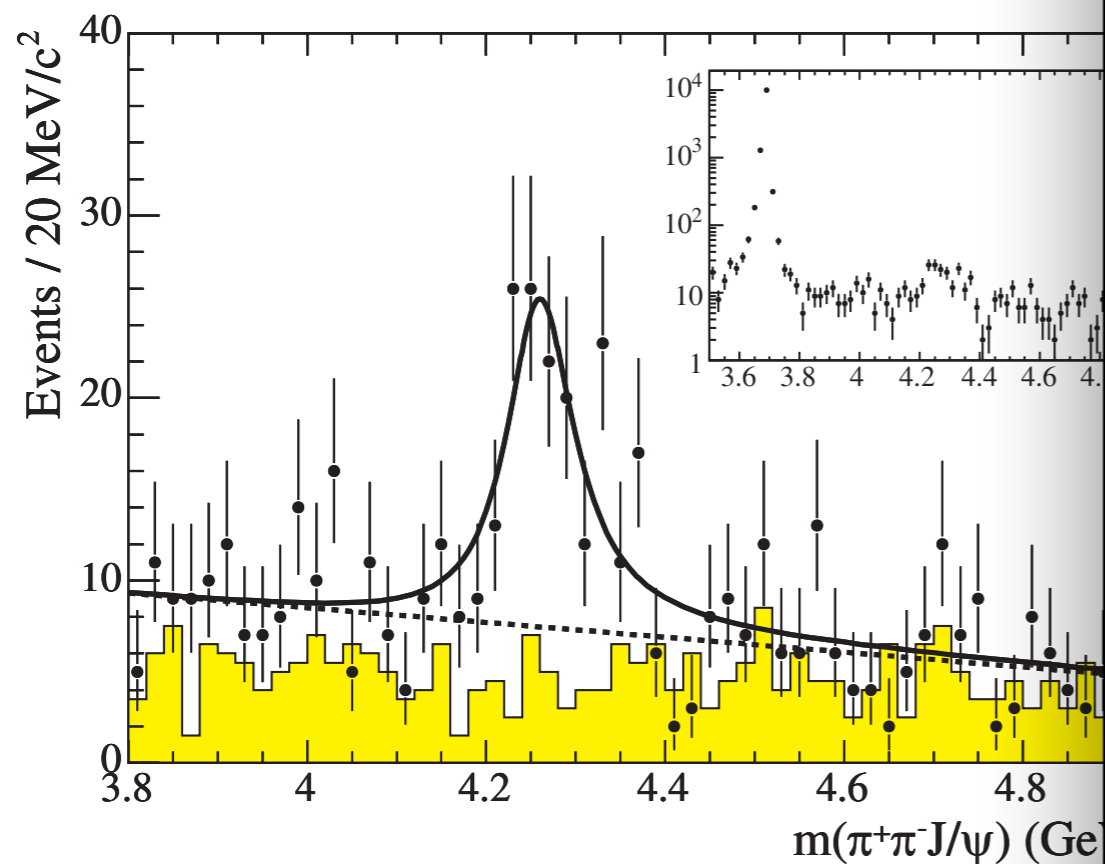
• first observation of the Y(4260)

e⁺e⁻(γ_ISR) → π⁺π⁻J/ψ at Belle
PRL 110, 252002 (2013)
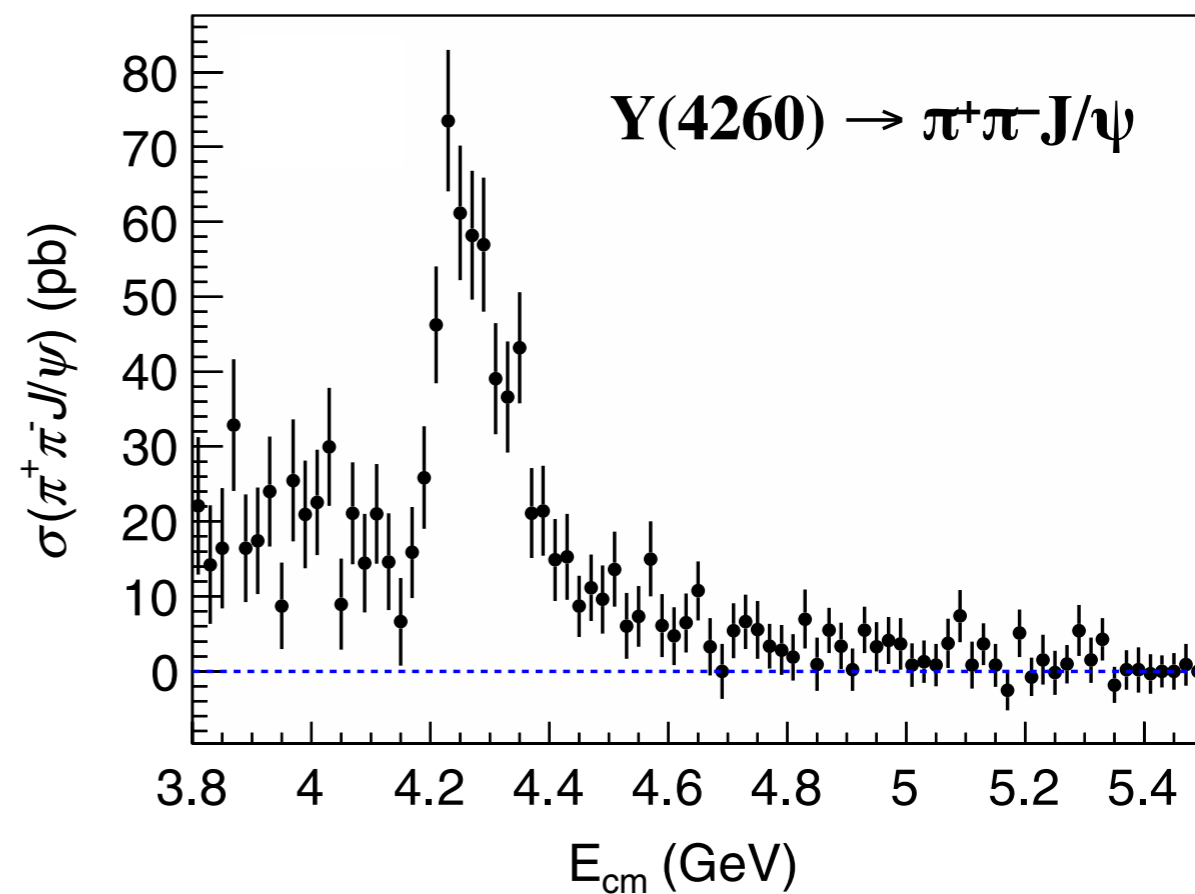
Y(4260) → π⁺π⁻J/ψ

• latest observation of the Y(4260)

Overview of the Y(4260)

Lattice Calculations of the Charmonium Spectrum

JHEP 07, 126 (2012)

Hadron Spectrum Collaboration
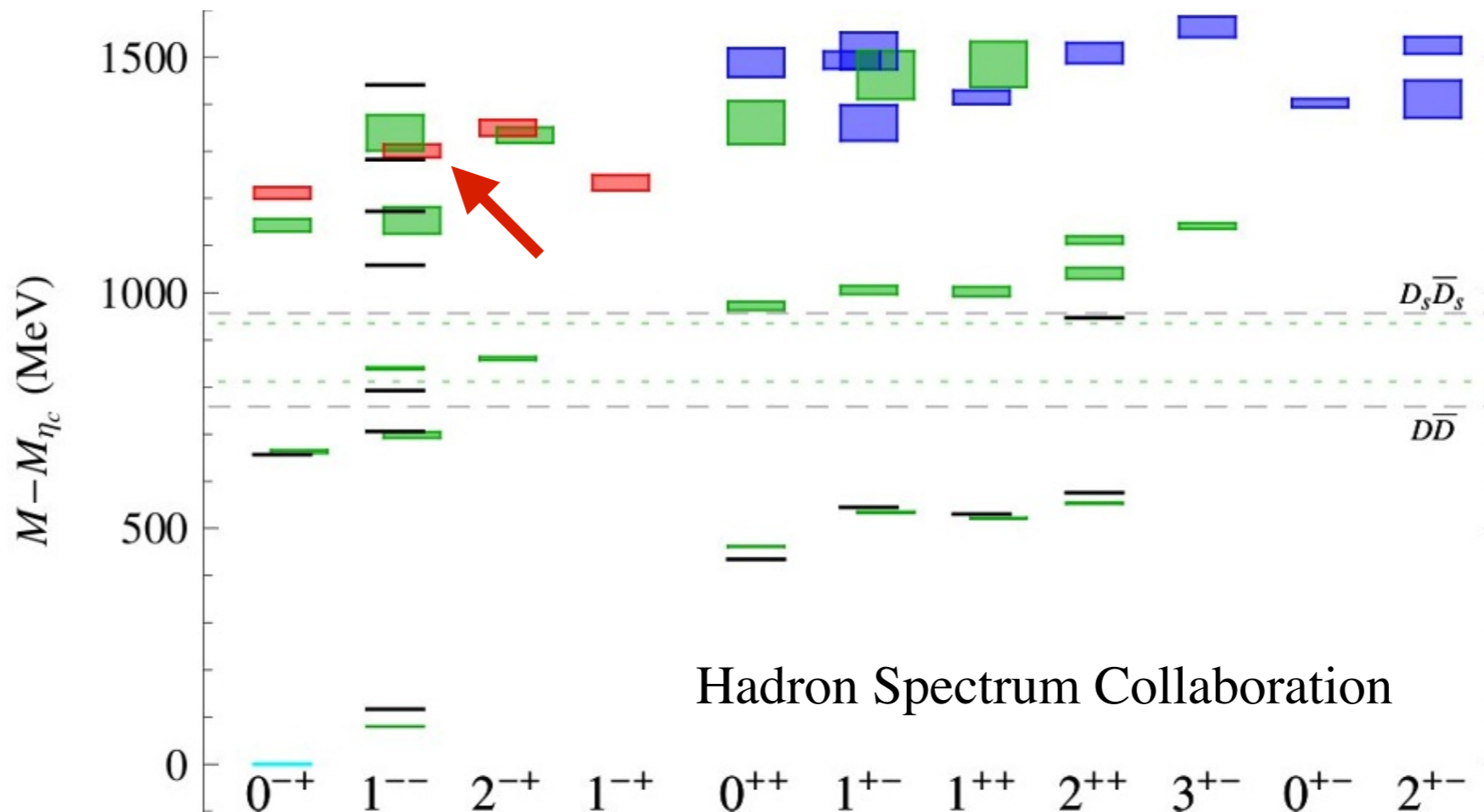
- a "hybrid-like state" is predicted to be near the Y(4260)
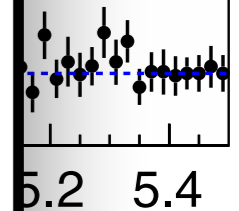
Overview of the Y(4260)

Lattice Calculations of the Charmonium Spectrum
JHEP 07, 126 (2012)
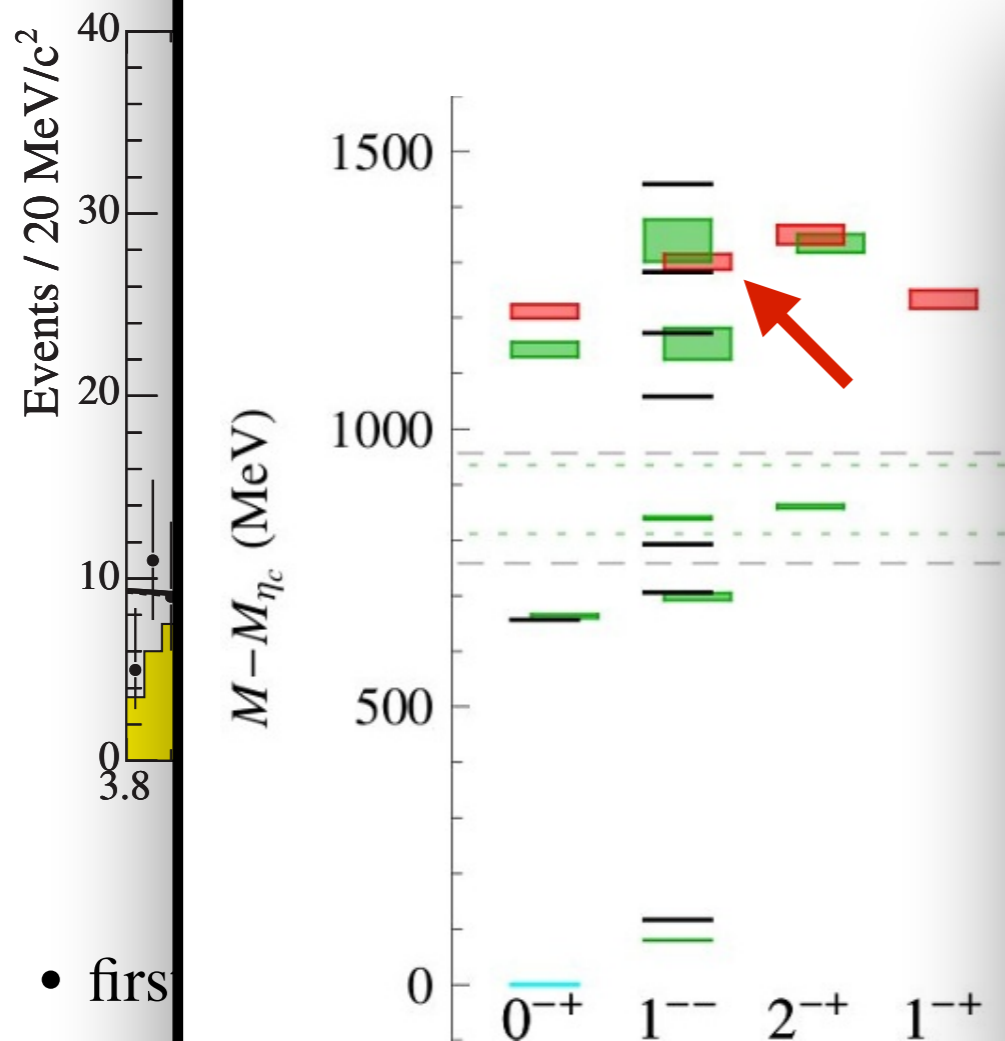
Properties of the Y(4260)
2014 PDG

- Mass = **4251 ± 9 MeV**
- Width = **120 ± 12 MeV**
- $J^{PC} = 1^{--}$
- no place for it in the quark model
- no strong signals in other decay modes (besides $\pi^0\pi^0 J/\psi$)
- distorted line shape?
- popular interpretation: hybrid meson

- first

- a "hybrid-like state" is predicted to be near the Y(4260)

Connecting the Y(4260) and the X(3872)?

$e^+e^- \to \gamma(\pi^+\pi^-J/\psi)$ at $E_{CM} \sim 4.26$ GeV at BESIII
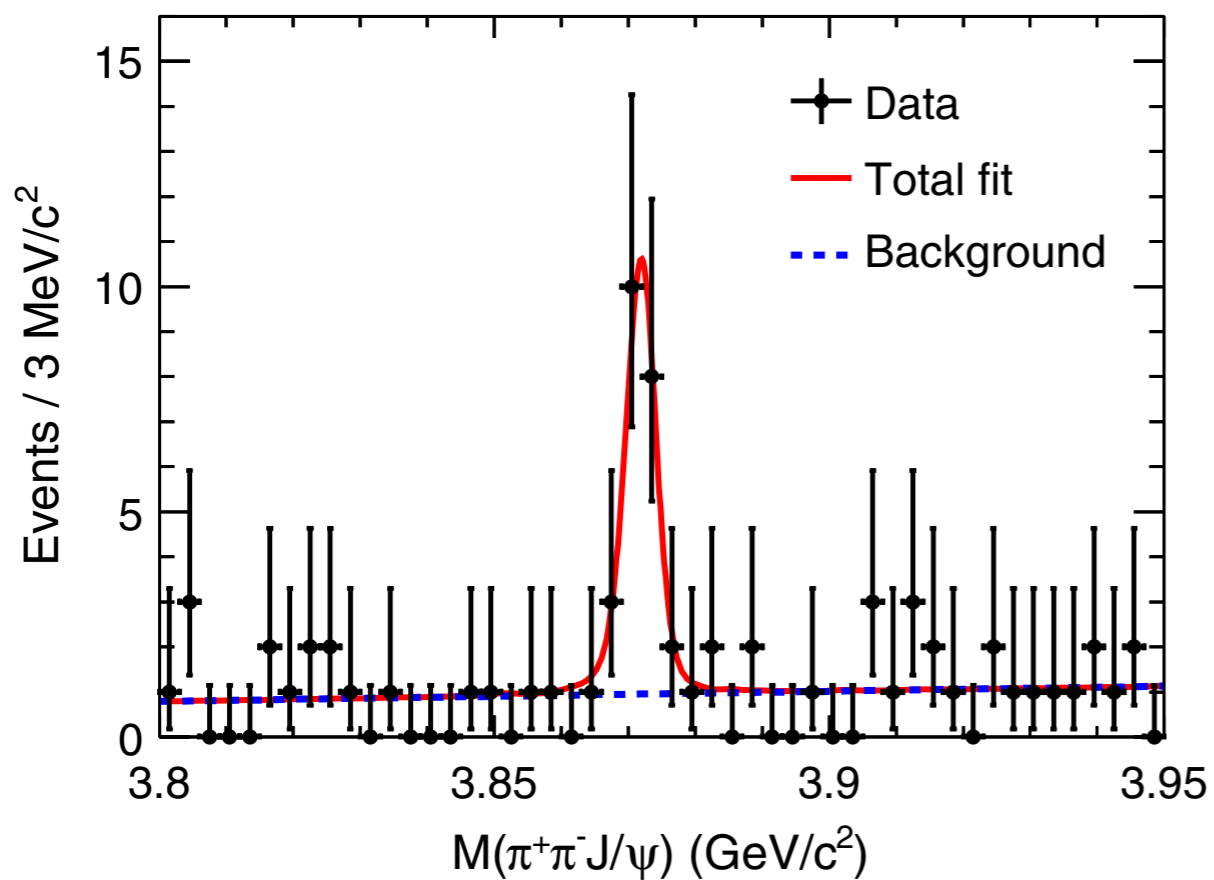
PRL 112, 092001 (2014)

- observation of the X(3872) in a radiative transition

Connecting the Y(4260) and the X(3872)?

$e^+e^- \rightarrow \gamma(\pi^+\pi^-J/\psi)$ at $E_{CM} \sim 4.26$ GeV at BESIII
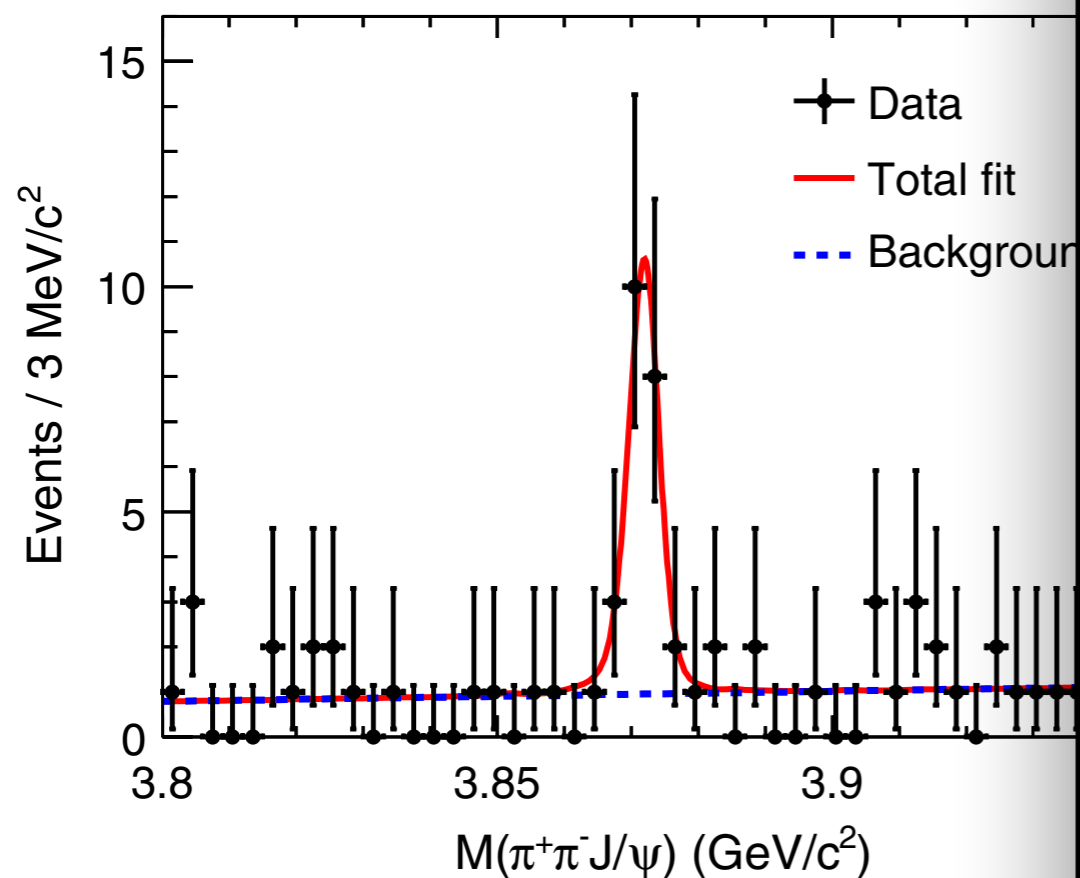
PRL 112, 092001 (2014)

• observation of the X(3872) in a radiative

$e^+e^- \rightarrow \gamma(\pi^+\pi^-J/\psi)$ at $E_{CM} \sim 4.26$ GeV at BESIII
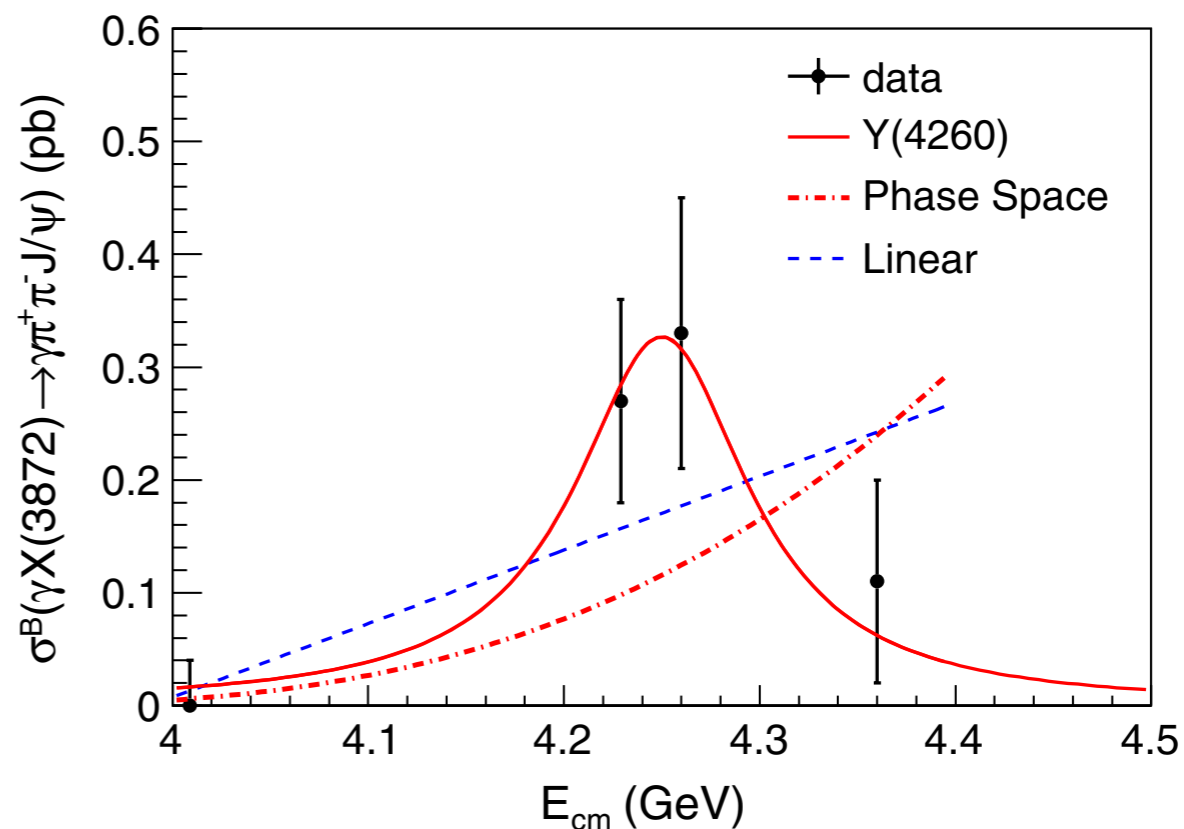
PRL 112, 092001 (2014)

• is this Y(4260) $\rightarrow \gamma$X(3872)??

Connecting the Y(4260) and the X(3872)?

e⁺e⁻ → γ(π⁺π⁻J/ψ) at E_CM ~ 4.26 GeV at BESIII

PRL 112, 092001 (2014)

15

Data

e⁺e⁻ → γ(π⁺π⁻J/ψ) at E_CM ~ 4.26 GeV at BESIII

PRL 112, 092001 (2014)

data
Y(4260)
Phase Space
Linear

Implications of Y(4260) → γX(3872)?

- Is this a radiative transition between a hybrid meson and a meson molecule? *(that doesn't seem right)*

- Can this be used to limit theoretical ideas?

M(π⁺π⁻J/ψ) (GeV/c²)

4.1   4.2   4.3   4.4   4.5

E_cm (GeV)
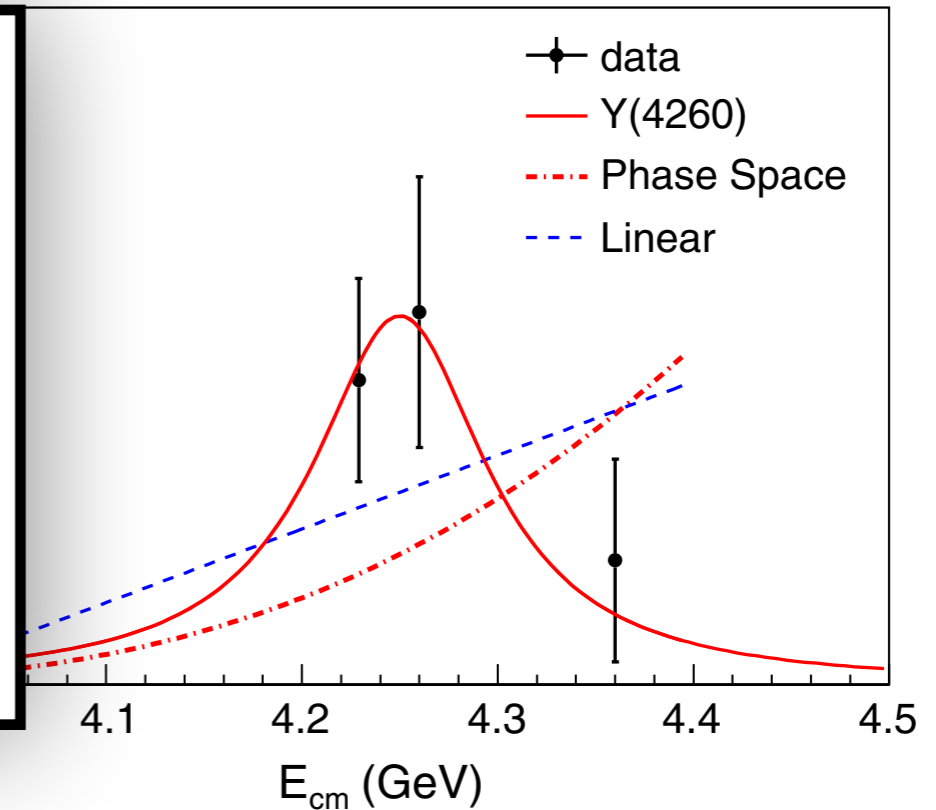
- observation of the X(3872) in a radiative

- is this Y(4260) → γX(3872)??

Connections I: The X(3872) and the Y(4260).

Connections II: The Y(4260) and the "Υ(5S)".

Connections III: The Z_c and Z_c' and the Z_b and Z_b'.

Complexities: A Collection of e⁺e⁻ Cross Sections.

Connections and Complexities

*Connections I:* The X(3872) and the Y(4260).

Connections II: The Y(4260) and the "Υ(5S)".

Connections III: The Z_c and $Z_c{}'$ and the Z_b and $Z_b{}'$.

*Complexities:* A Collection of e$^+$e$^-$ Cross Sections.

The Y(4260) and the "ϒ(5S)"

$e^+e^-(\gamma_{ISR}) \rightarrow \pi^+\pi^- J/\psi$ at Belle
PRL 110, 252002 (2013)

$Y(4260) \rightarrow \pi^+\pi^- J/\psi$

$e^+e^- \rightarrow \pi^+\pi^- \Upsilon(1S,2S,3S)$ at Belle
arXiv:1501.01137

$\pi^+\pi^-\Upsilon(1S)$

$\pi^+\pi^-\Upsilon(2S)$

$\pi^+\pi^-\Upsilon(3S)$
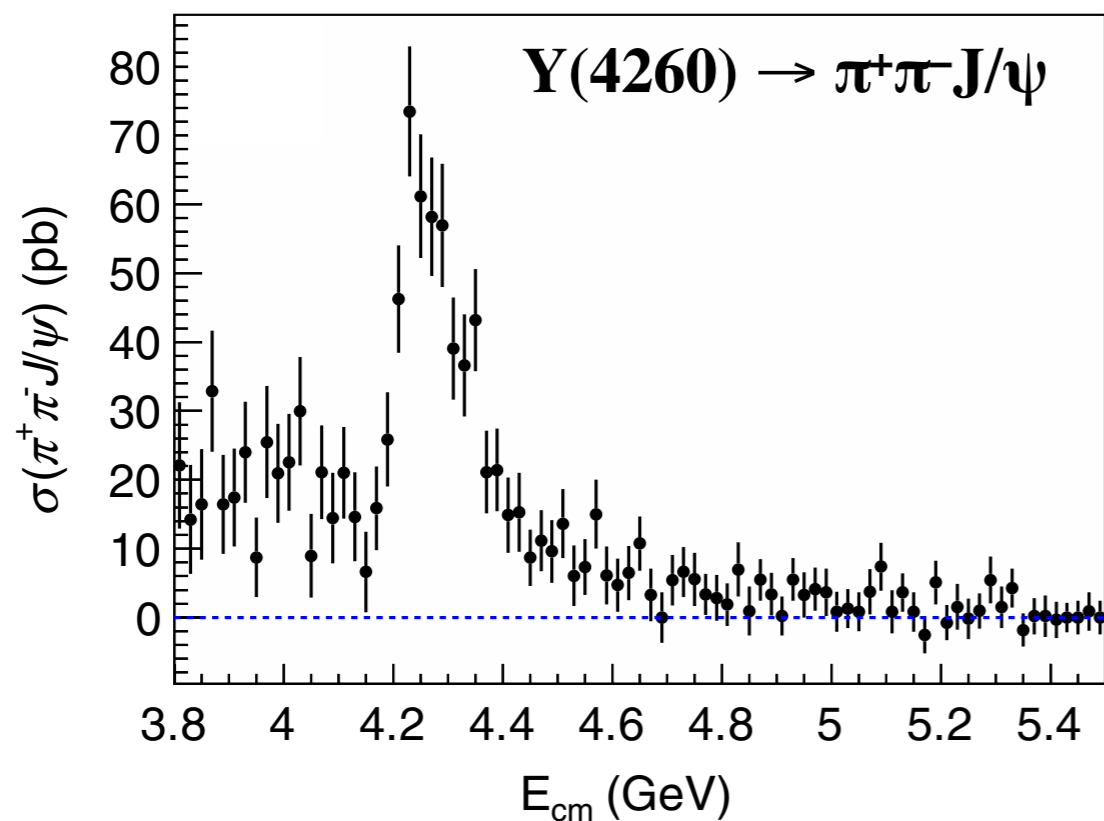
Similarity: Large rates to $\pi\pi J/\psi$ and $\pi\pi\Upsilon$, but no observed decays to open charm or open bottom.
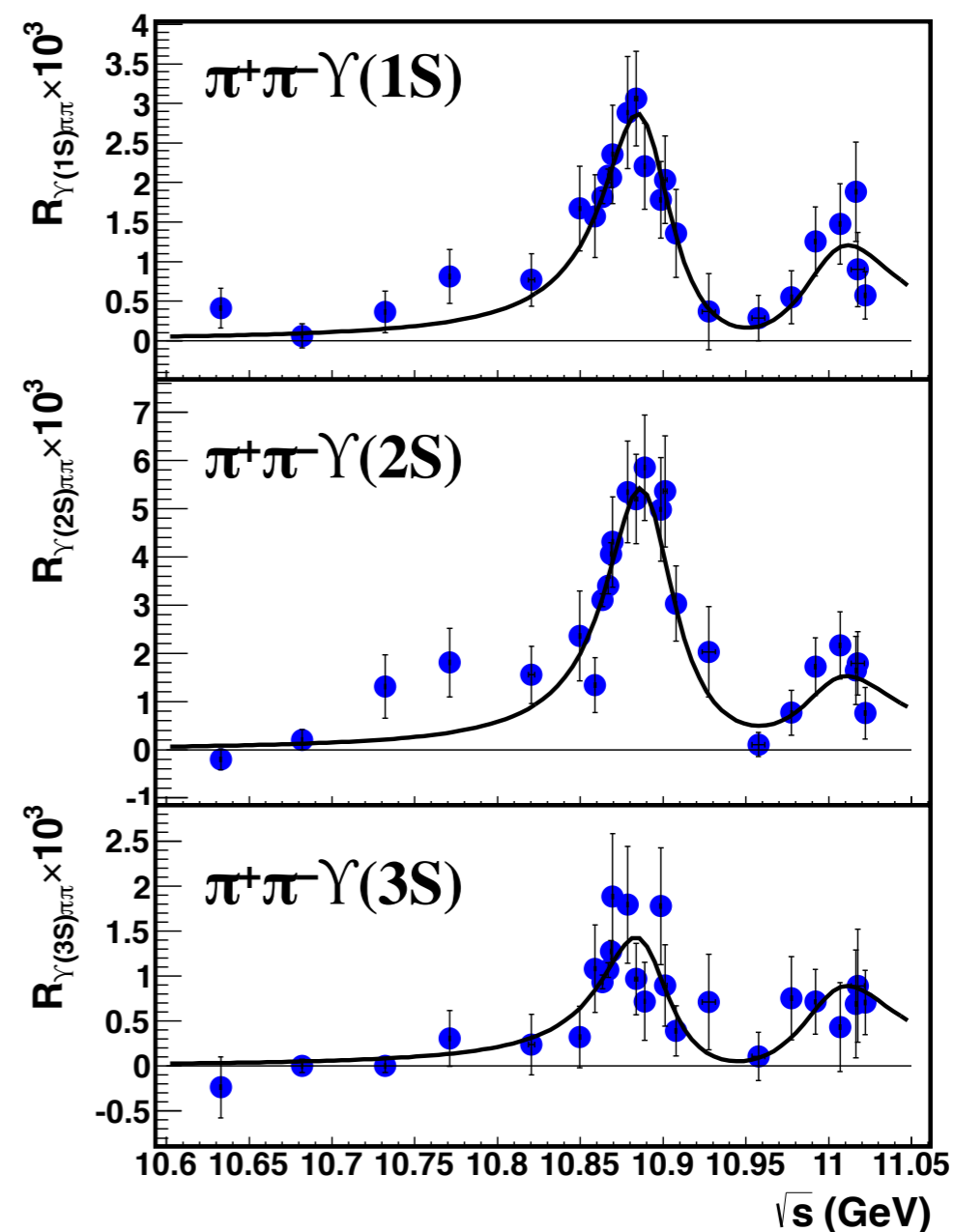
The Y(4260) and the "ϒ(5S)"

R in the Charmonium Region
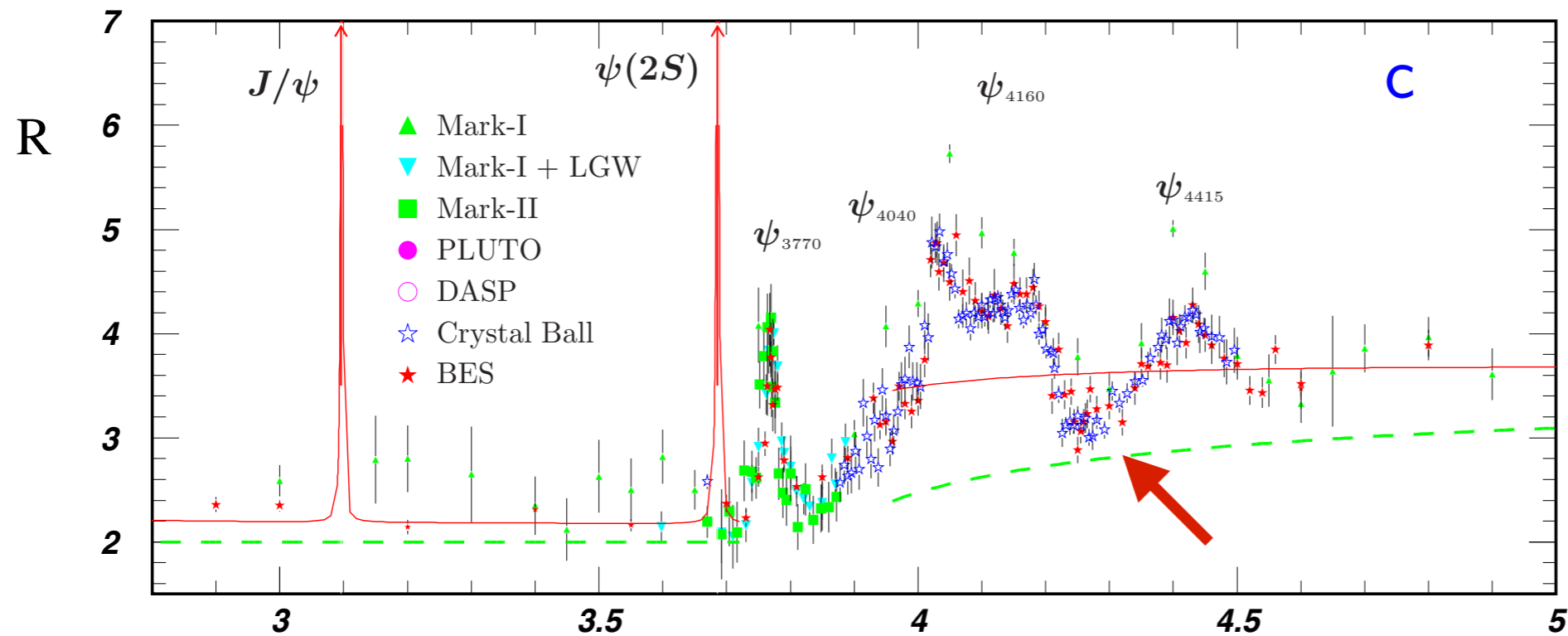
PDG 2014

- the Y(4260) does not appear.

The Y(4260) and the "ϒ(5S)"

R in the Charmonium Region

PDG 2014
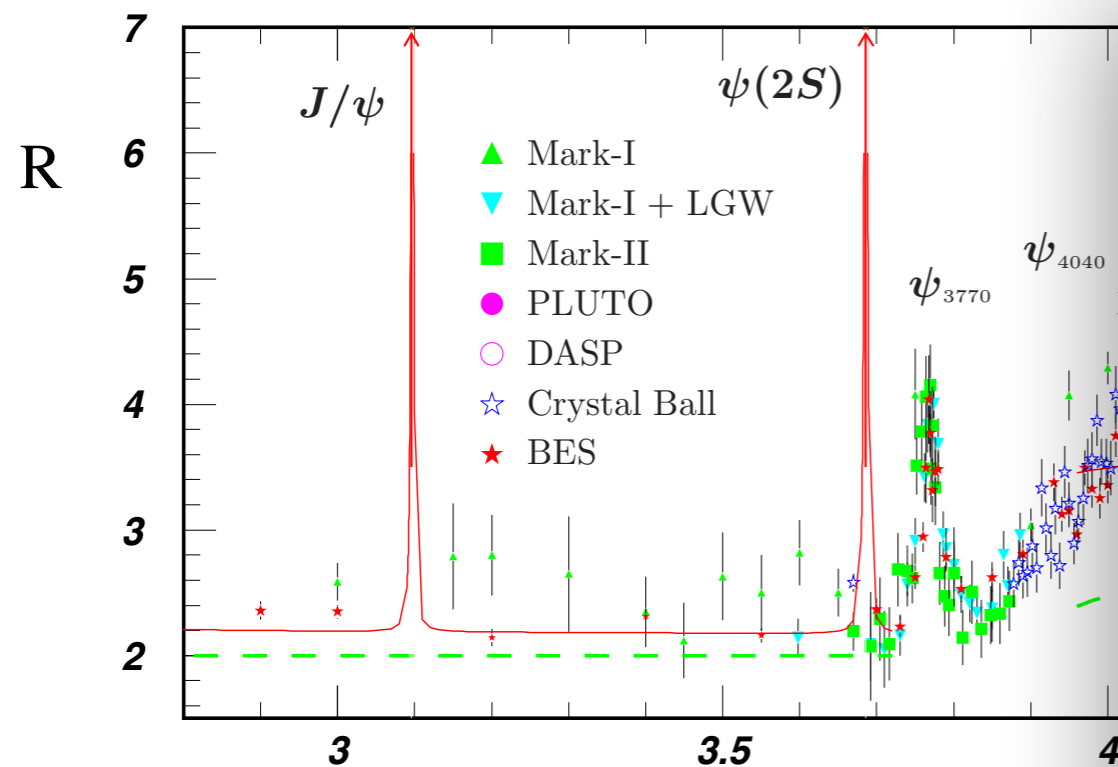
- the Y(4260) does not appear.

Dissimilarity in R.

R_b above the ϒ(4S) from BaBar

PRL 102, 012001 (2009)
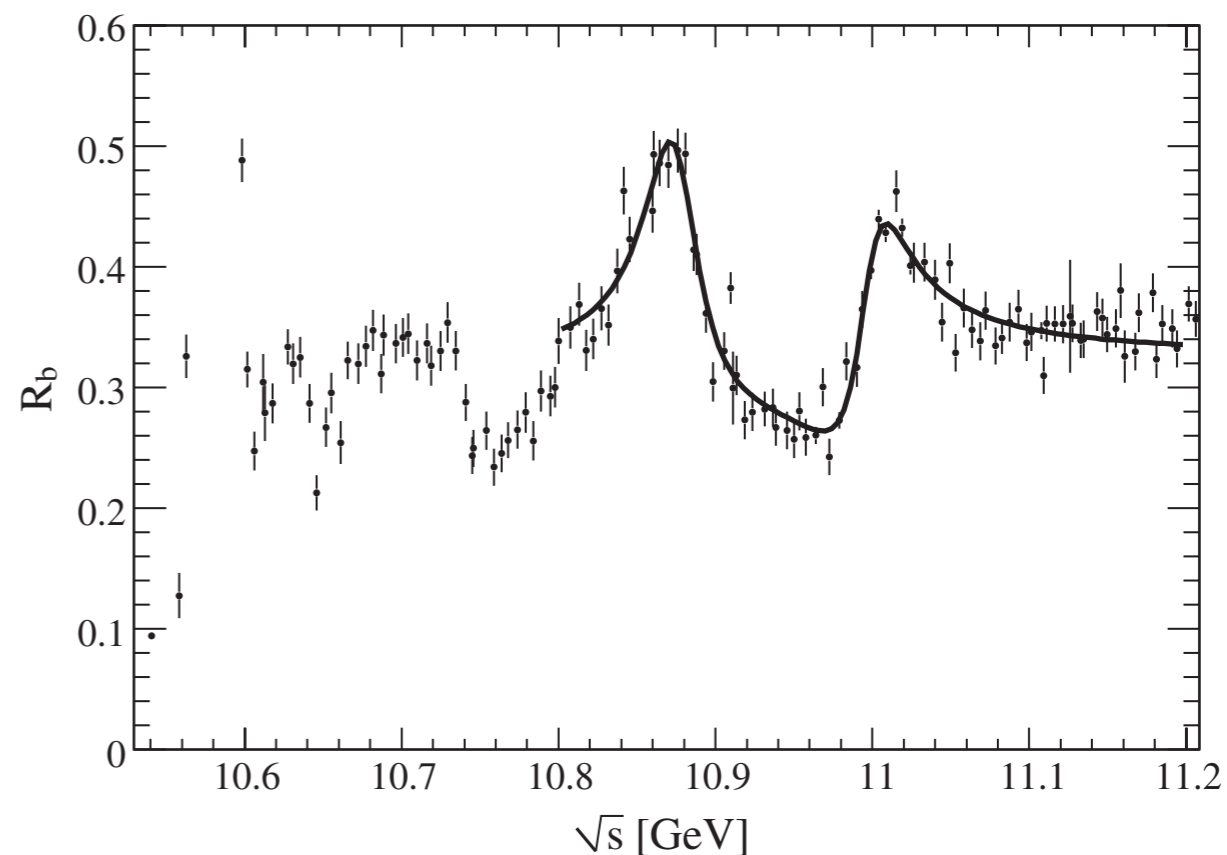
- the "ϒ(5S)" in $\pi\pi\Upsilon(nS)$ and in R_b are (more or less) consistent.

The Y(4260) and the "ϒ(5S)"

$e^+e^- \rightarrow \pi^+\pi^-h_c(1P)$ at $E_{CM} = 4.26$ GeV at BESIII
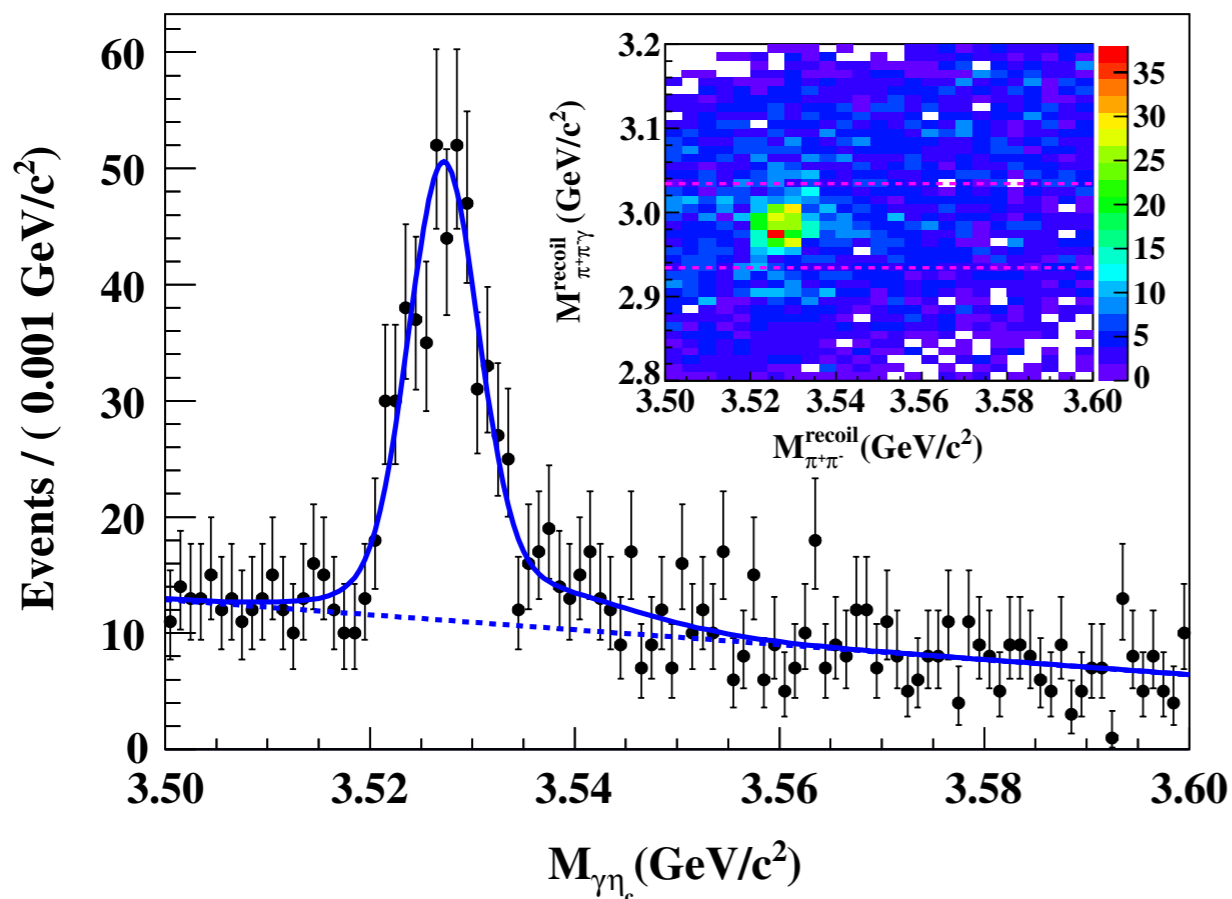
PRL 111, 242001 (2013)

- $\sigma(e^+e^- \rightarrow \pi^+\pi^-h_c(1P))$ is comparable to $\sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi)$ around the Y(4260).

The Y(4260) and the "Υ(5S)"

$e^+e^- \rightarrow \pi^+\pi^-h_c(1P)$ at E_{CM} = 4.26 GeV at BESIII

PRL 111, 242001 (2013)

$e^+e^- \rightarrow \pi^+\pi^-(\Upsilon(nS),h_b(nP))$ at $E_{CM} \sim \Upsilon$(5S) Mass at Belle

PRL 108, 032001 (2012)

- $\sigma(e^+e^- \rightarrow \pi^+\pi^-h_c(1P))$ is co[m]...
  $\sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi)$ around t...
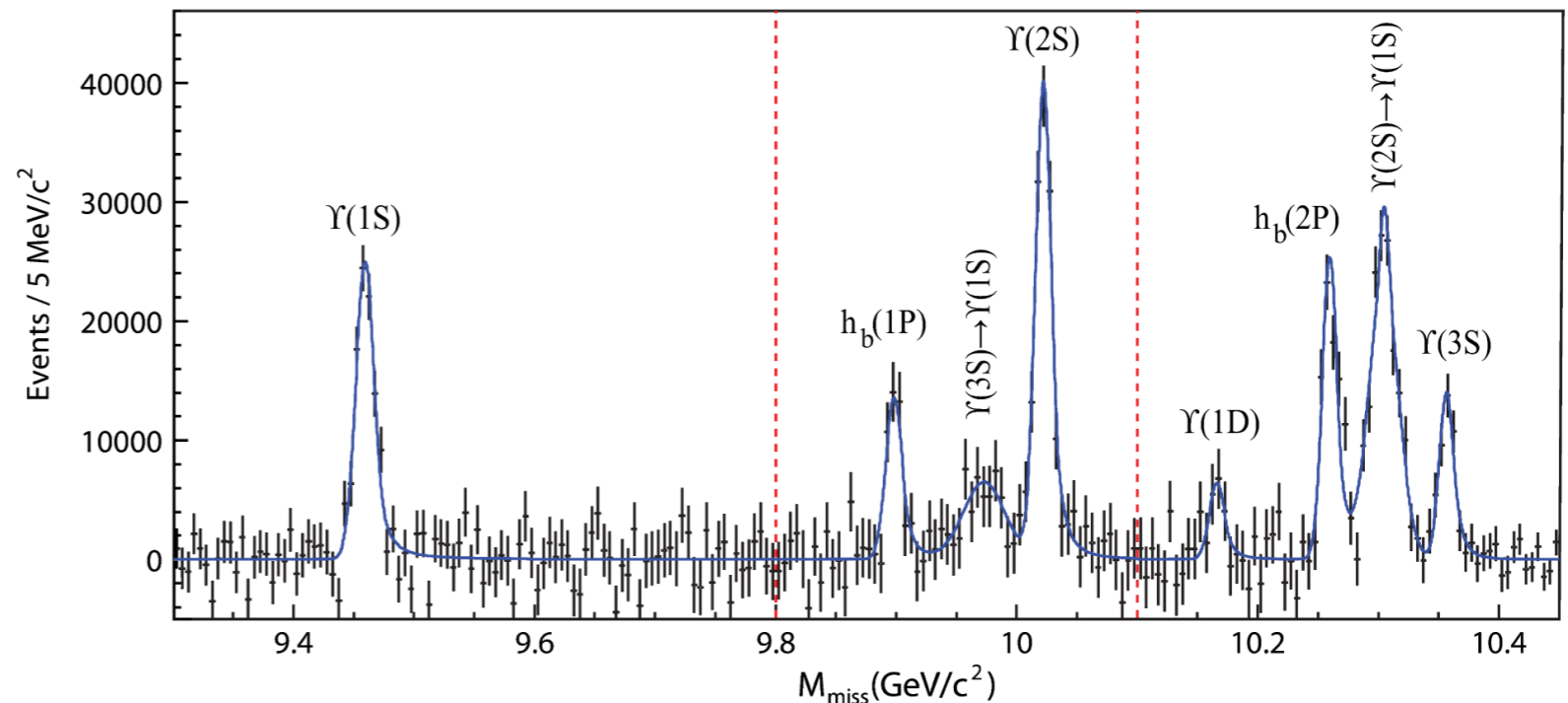
- $\sigma(e^+e^- \rightarrow \pi^+\pi^-h_b(nP))$ is comparable to $\sigma(e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS))$ around the "Υ(5S)".

Similar pattern in h_c and h_b production around the Y(4260) and "Υ(5S)".

Connections and Complexities

Connections I: The X(3872) and the Y(4260).

Connections II: The Y(4260) and the "Υ(5S)".

Connections III: The Z_c and Z_c' and the Z_b and Z_b'.

Complexities: A Collection of e^+e^- Cross Sections.

Connections I: The X(3872) and the Y(4260).

Connections II: The Y(4260) and the "Υ(5S)".

*Connections III:* The Z_c and $Z_c{}'$ and the Z_b and $Z_b{}'$.

Complexities: A Collection of e^+e^- Cross Sections.

Observation of the Z_b and Z_b'

$e^+e^- \rightarrow \pi^+\pi^-\Upsilon(1S,2S,3S)$ and $\pi^+\pi^- h_b(1P,2P)$ at $E_{CM} \sim \Upsilon(5S)$ Mass at Belle

PRD 91, 072003 (2015), PRL 108, 122001 (2012)
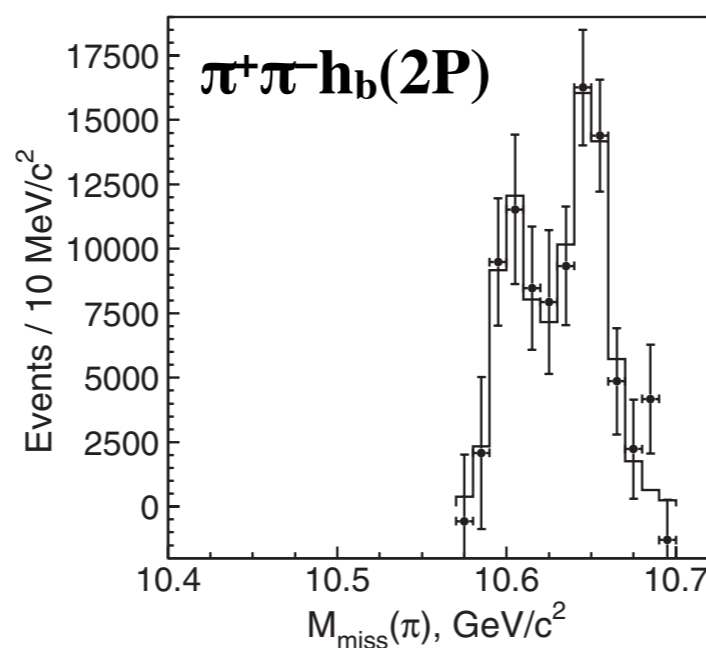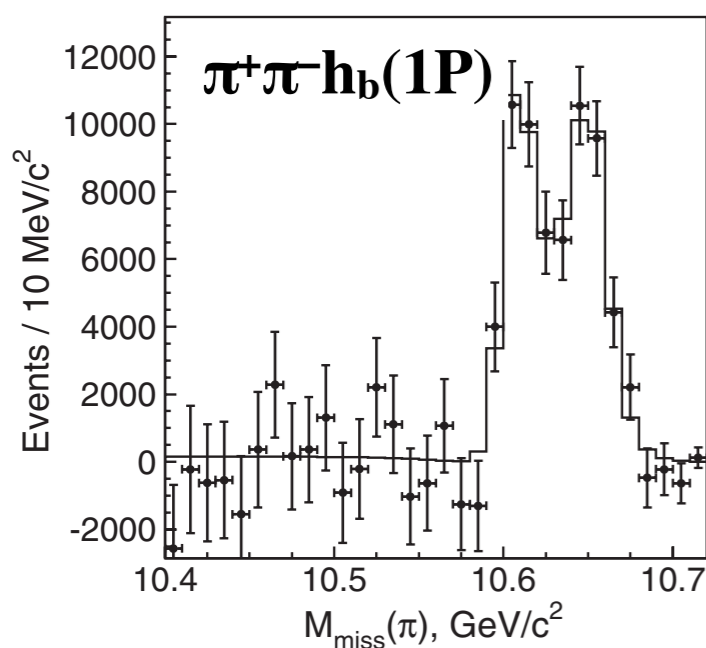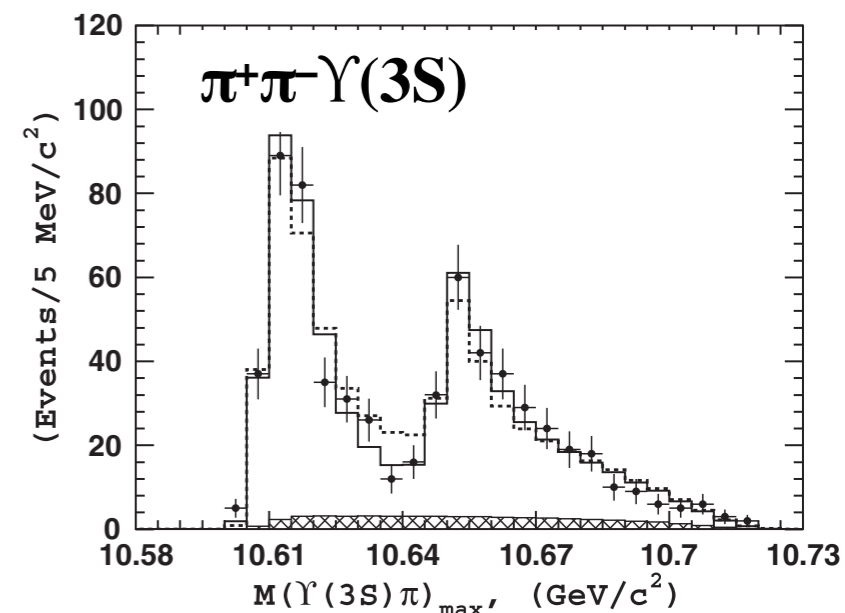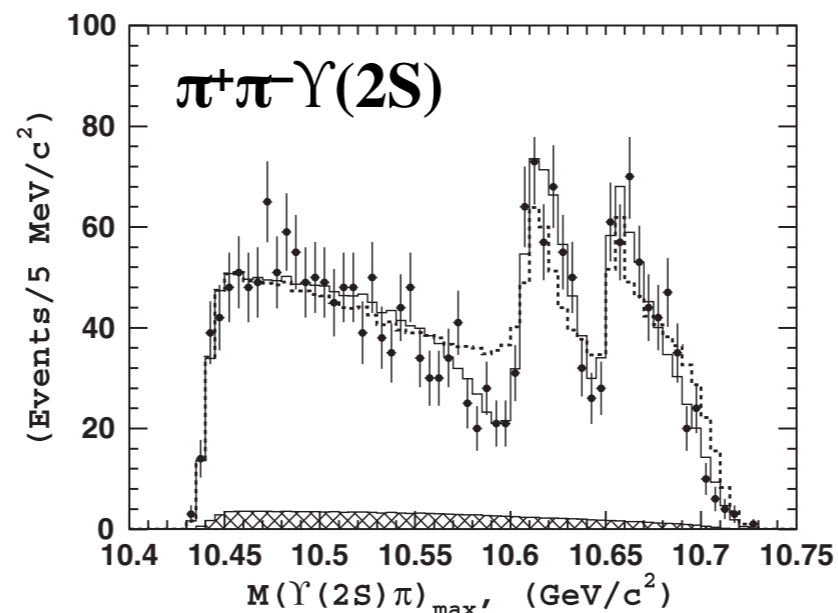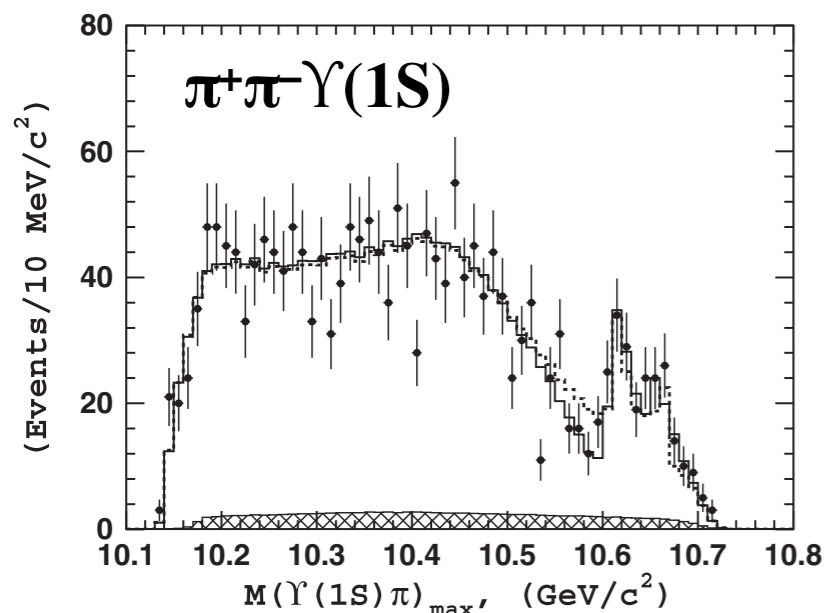
- two peaks, Z_b and Z_b', are found in the substructure of all five reactions, close to BB* and B*B* thresholds.

Observation of the Z_c and Z_c'

$e^+e^- \rightarrow \pi^+\pi^-J/\psi$ and $\pi^+\pi^-h_c(1P)$ at $E_{CM} \sim 4.26$ GeV at BESIII

PRL 110, 252001 (2013), PRL 111, 242001 (2013)
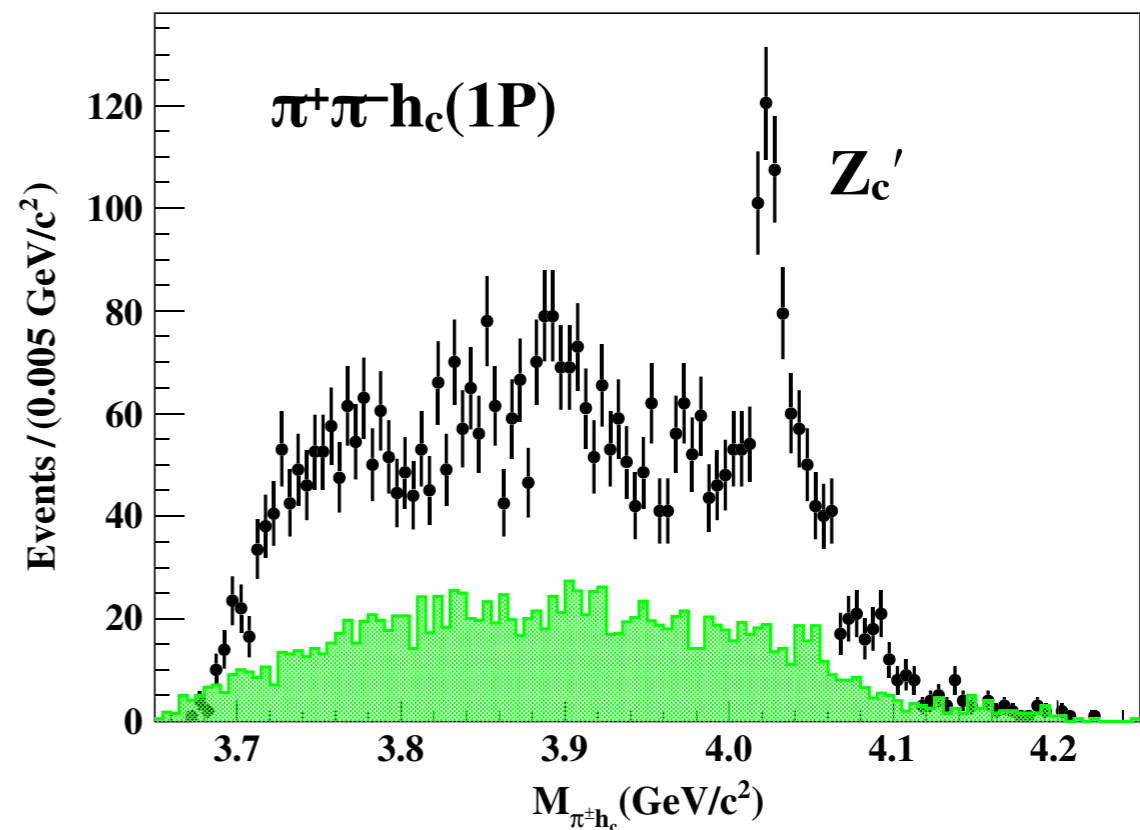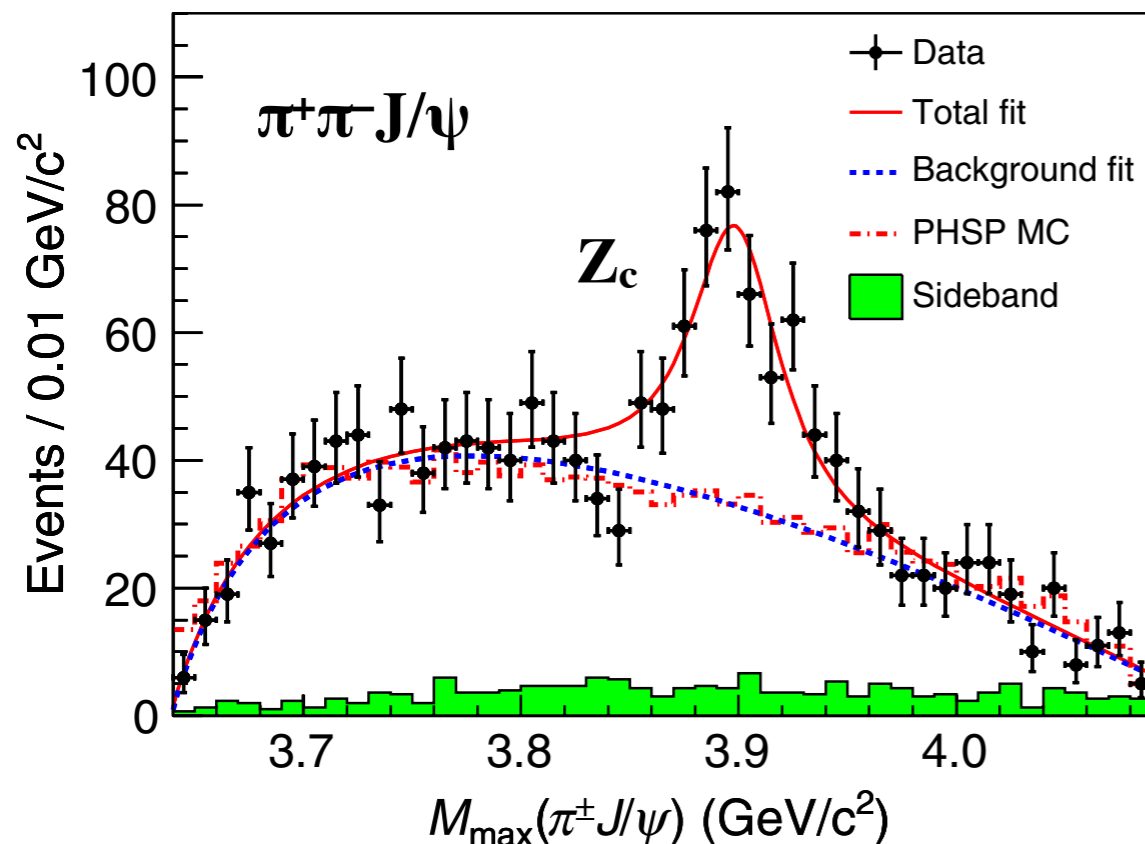
- a Z_c peak is found in $\pi J/\psi$ and a Z_c' peak is found in $\pi h_c(1P)$, close to the DD* and D*D* thresholds.

Open Flavor Decays of the Z_c and Z_c' and the Z_b and Z_b'

$e^+e^- \rightarrow \pi^\pm B^{(*)}B^*$ at $E_{CM} \sim \Upsilon(5S)$ Mass at Belle
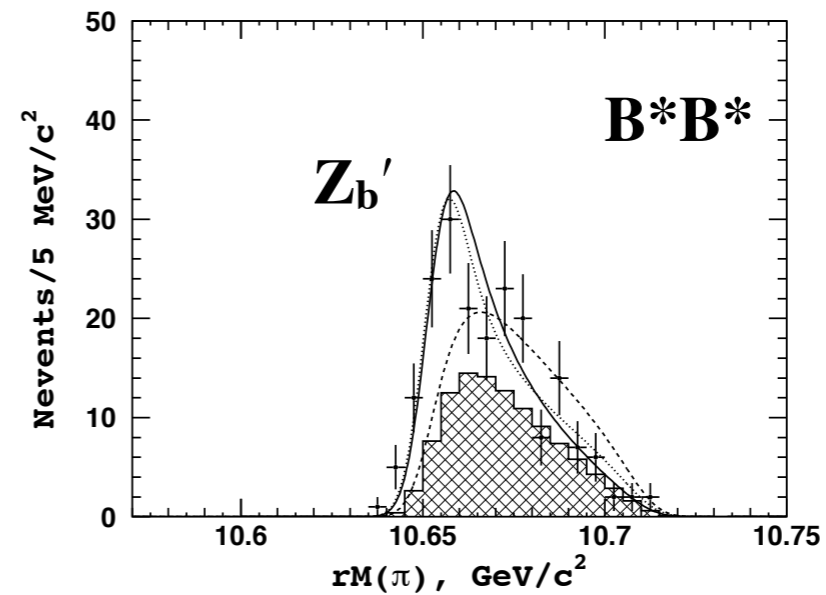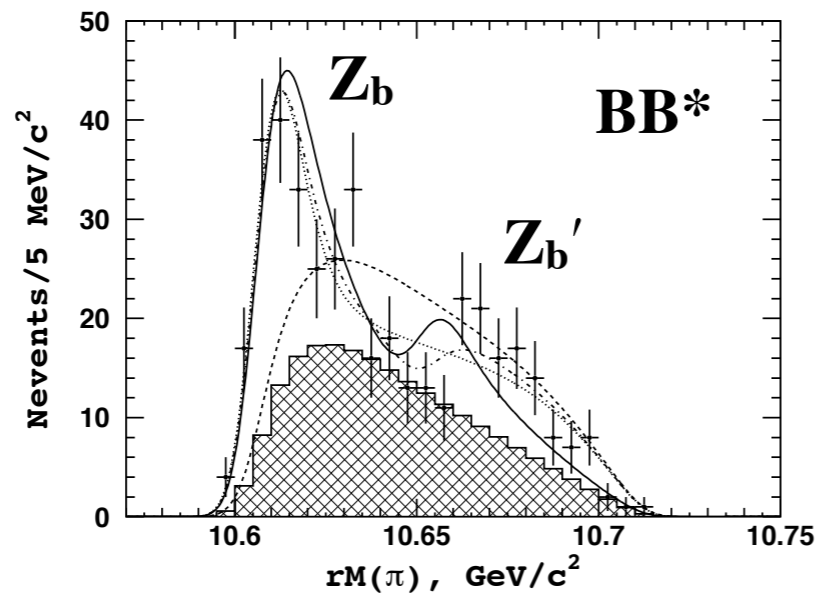
arXiv:1209.6450

Open Flavor Decays of the Z_c and $Z_c{'}$ and the Z_b and $Z_b{'}$

$e^+e^- \rightarrow \pi^{\pm}B^{(*)}B^*$ at $E_{CM} \sim \Upsilon(5S)$ Mass at Belle

arXiv:1209.6450
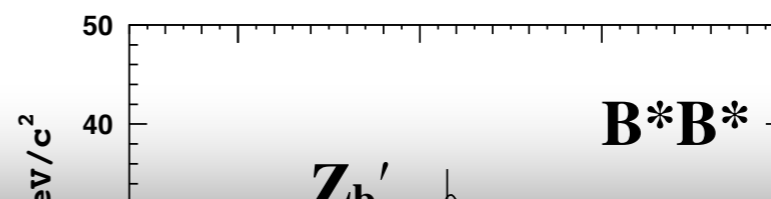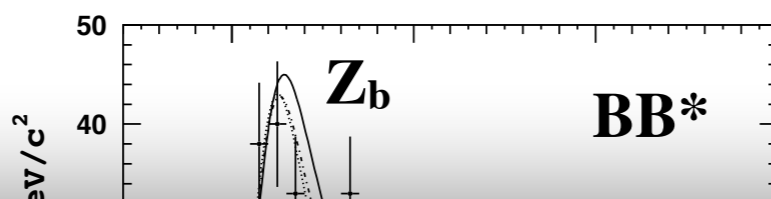
$e^+e^- \rightarrow \pi^{\pm}D^{(*)}D^*$ at $E_{CM} \sim 4.26$ GeV at BESIII

PRL 112, 022001 (2014), PRL 112, 132001 (2014)
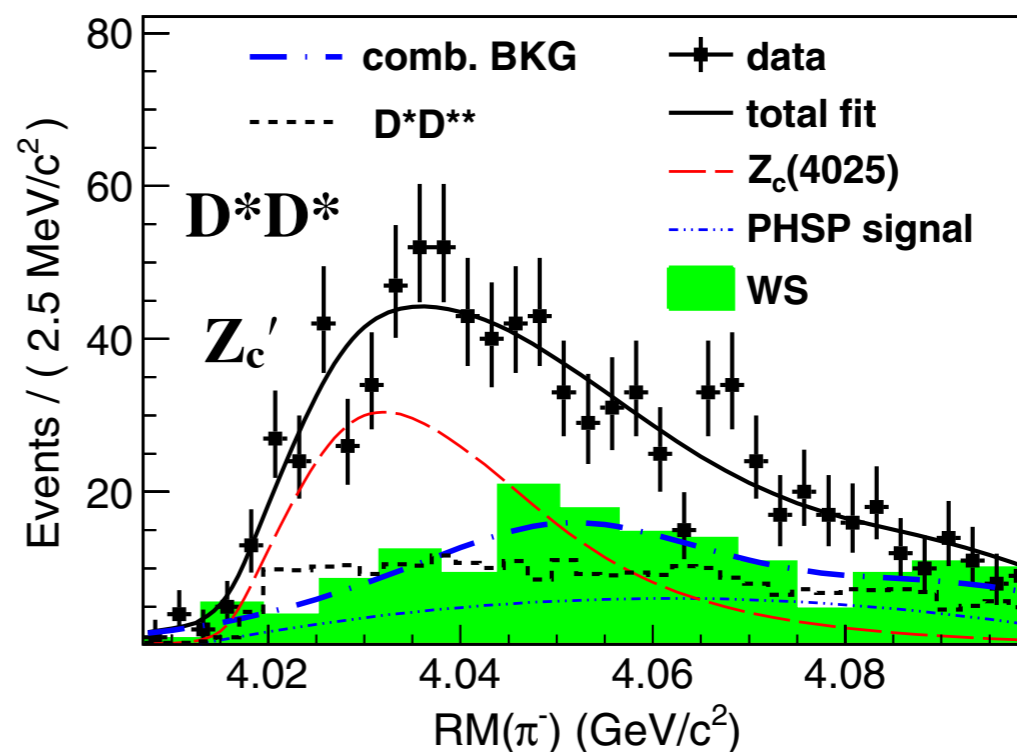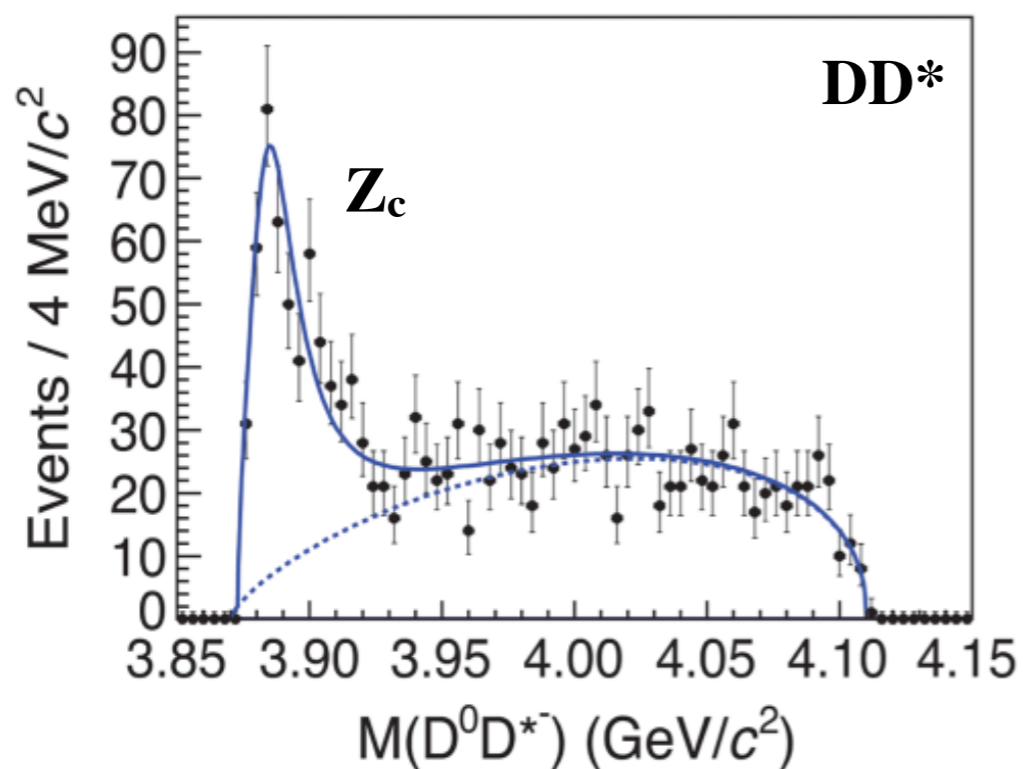
Parallels between the Z_c and Z_c' and the Z_b and Z_b'

Possible Parallels

Z_c and Z_c':

at the DD* and D*D* thresholds;

decaying to $\pi J/\psi$ and $\pi h_c(1P)$;

decaying to DD* and D*D*;

produced in e^+e^- collisions near the Y(4260).

Z_b and Z_b':

at the BB* and B*B* thresholds;

decaying to $\pi\Upsilon(nS)$ and $\pi h_b(nP)$;

decaying to BB* and B*B*;

produced in e^+e^- collisions near the "$\Upsilon(5S)$".

Connections and Complexities

Connections I: The X(3872) and the Y(4260).

Connections II: The Y(4260) and the "Υ(5S)".

Connections III: The Z_c and $Z_c{}'$ and the Z_b and $Z_b{}'$.

Complexities: A Collection of e^+e^- Cross Sections.

Connections and Complexities

Connections I: The X(3872) and the Y(4260).

Connections II: The Y(4260) and the "Υ(5S)".

Connections III: The Z_c and $Z_c{}'$ and the Z_b and $Z_b{}'$.

Complexities: A Collection of e⁺e⁻ Cross Sections.

Overview of e⁺e⁻ Cross Sections

R in the Charmonium Region
PDG 2014
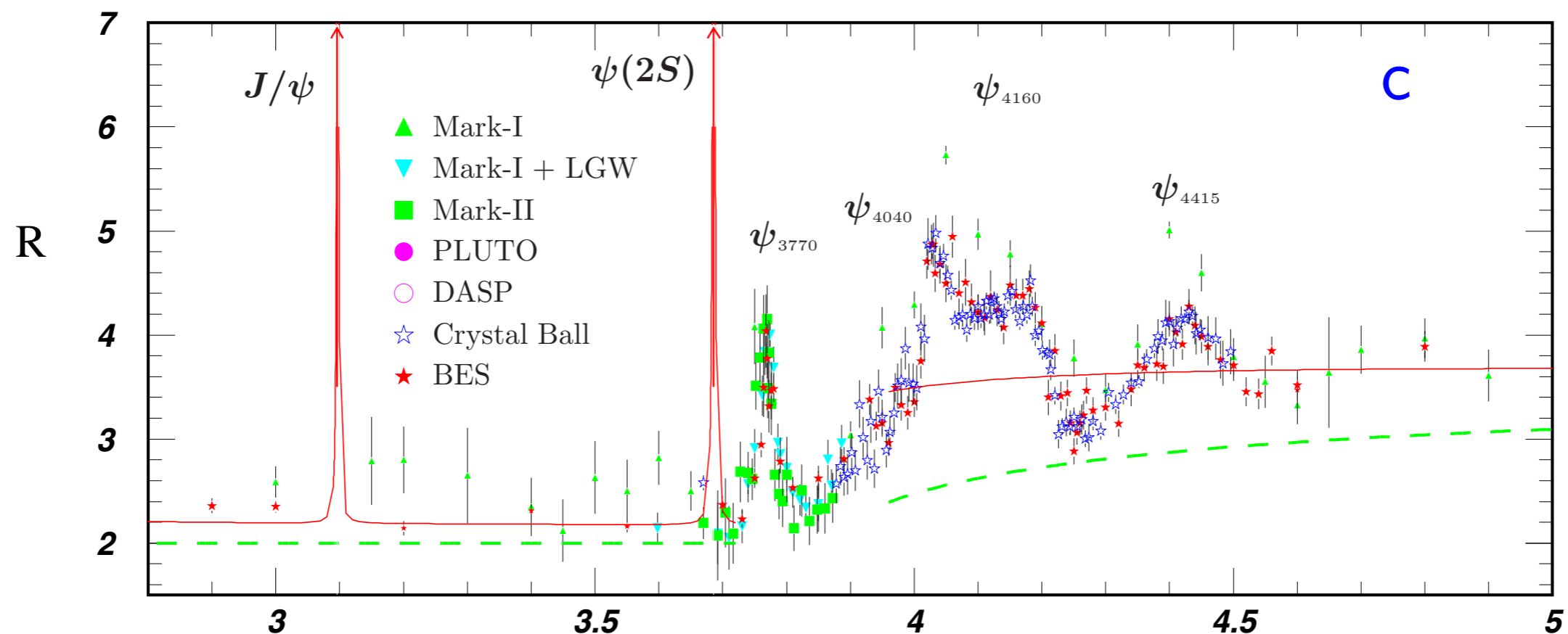
- R suggests a tidy quark model picture:

$$\psi(3770) = 1^3D_1$$
$$\psi(4040) = 3^3S_1$$
$$\psi(4160) = 2^3D_1$$
$$\psi(4415) = 4^3S_1$$

Overview of e⁺e⁻ → π⁺π⁻J/ψ

e⁺e⁻(γ_ISR) → π⁺π⁻J/ψ at Belle
PRL 110, 252002 (2013)

Y(4260) → π⁺π⁻J/ψ
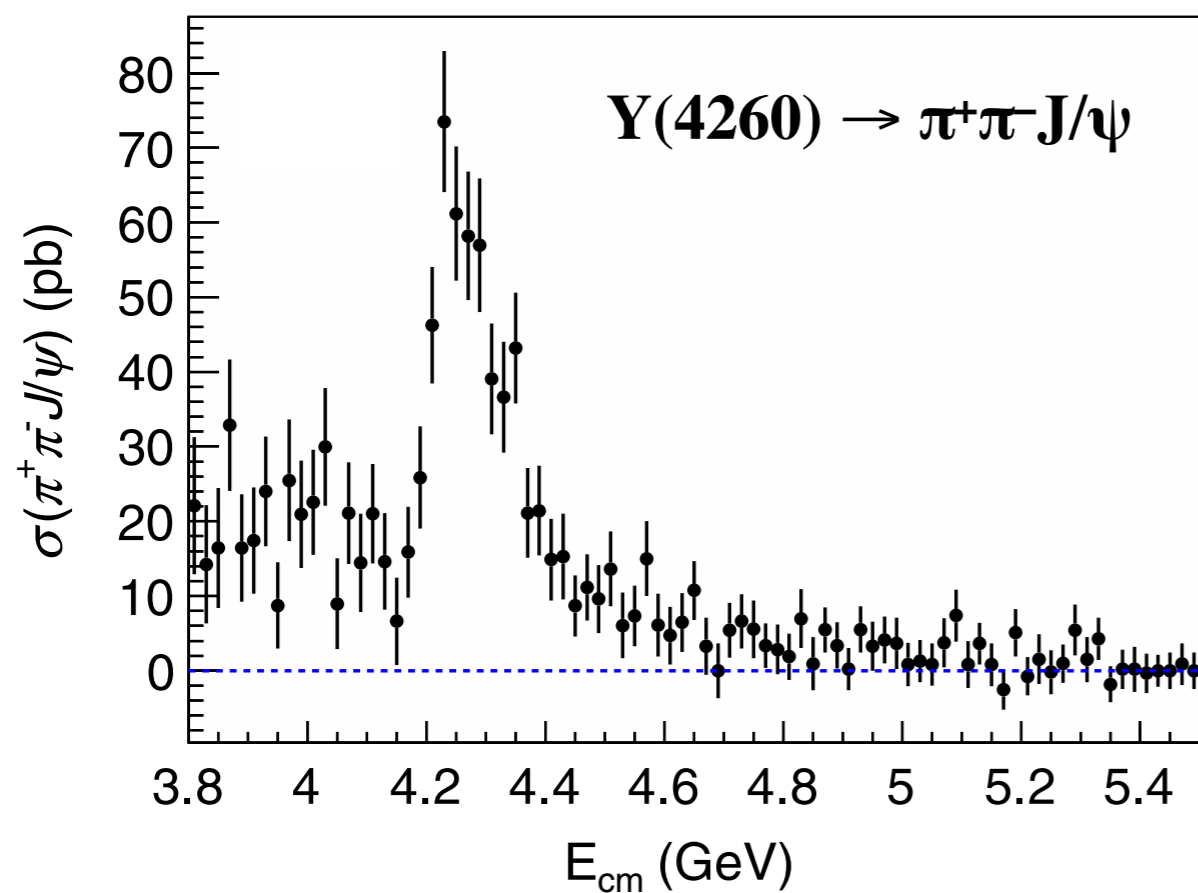
- the Y(4260) has no place in the quark model

Overview of e⁺e⁻ → π⁺π⁻J/ψ

Overview of e⁺e⁻ → π⁺π⁻J/ψ

e⁺e⁻(γ_ISR) → π⁺π⁻J/ψ at Belle
PRL 110, 252002 (2013)

e⁺e⁻(γ_ISR) → π⁺π⁻J/ψ at Belle
PRL 110, 252002 (2013)

e⁺e⁻(γ_ISR) → π⁺π⁻J/ψ at BaBar
PRD 86, 051102(R) (2012)
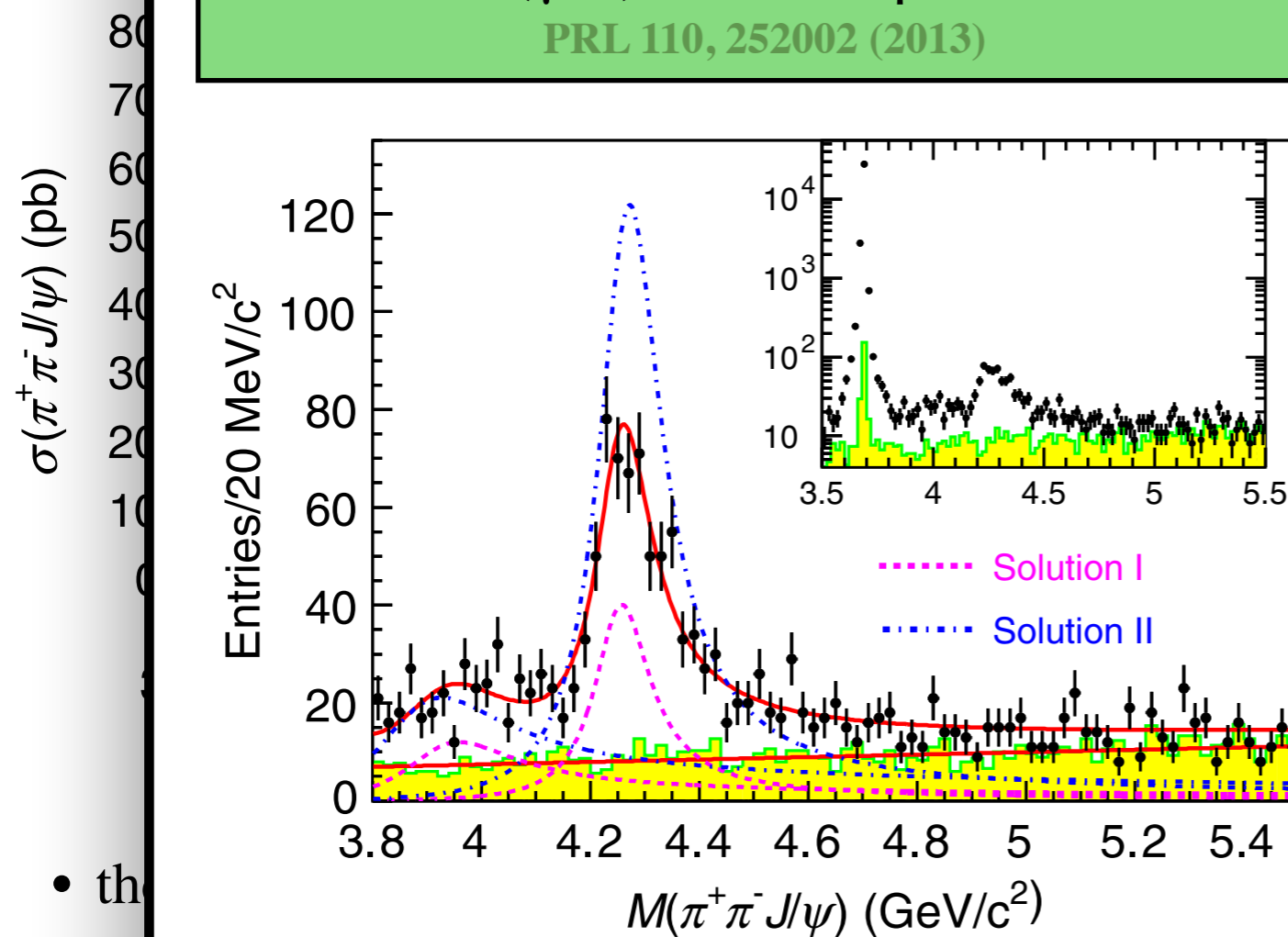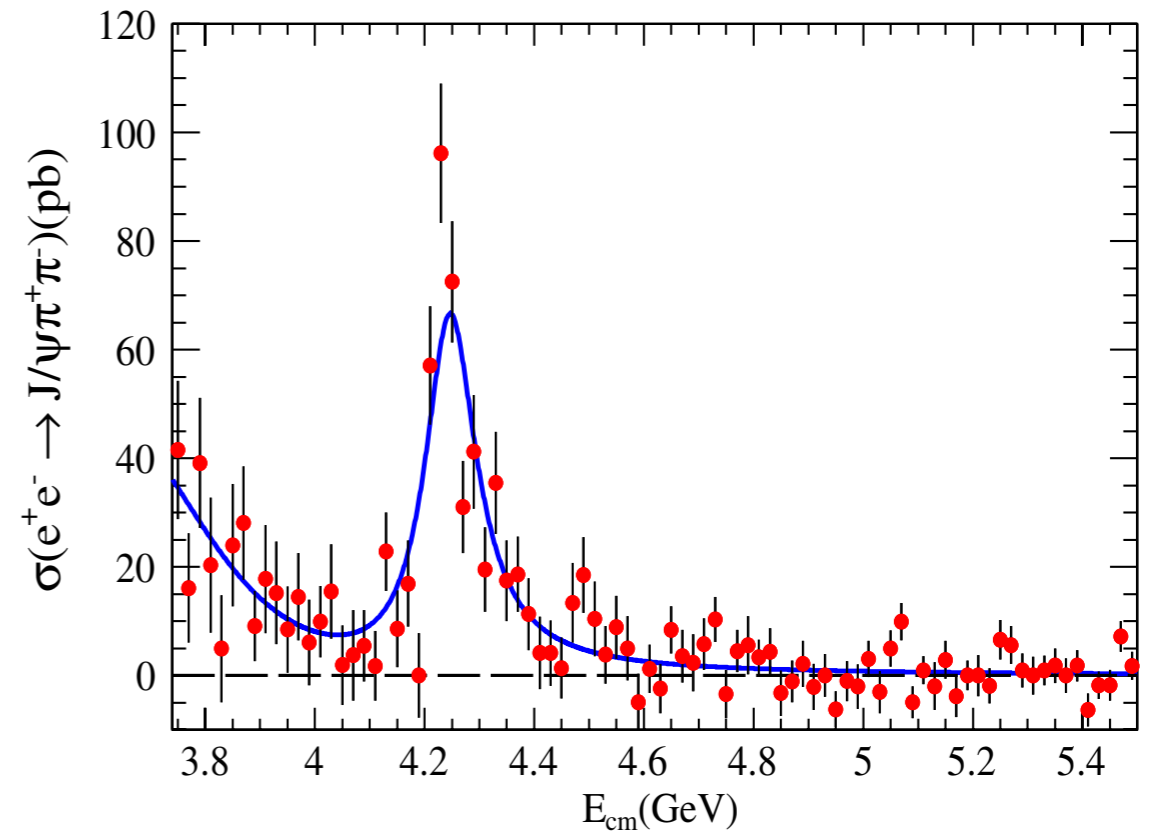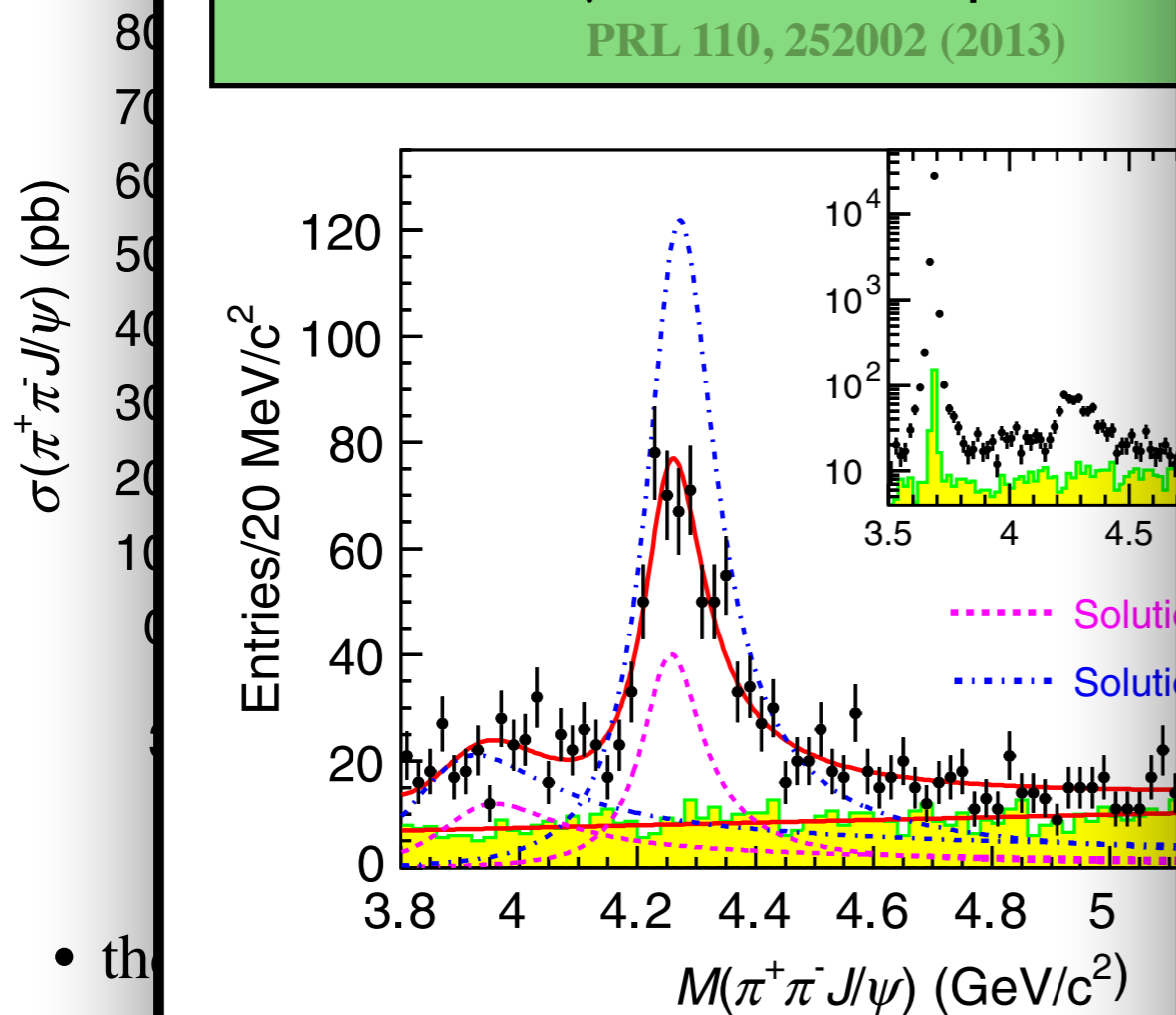
- is this really two resonances??

- BaBar doesn't need another resonance?

Overview of e⁺e⁻ → π⁺π⁻ψ(2S)

e⁺e⁻(γ$_{ISR}$) → π⁺π⁻ψ(2S) at BaBar
PRL 98, 212001 (2007)
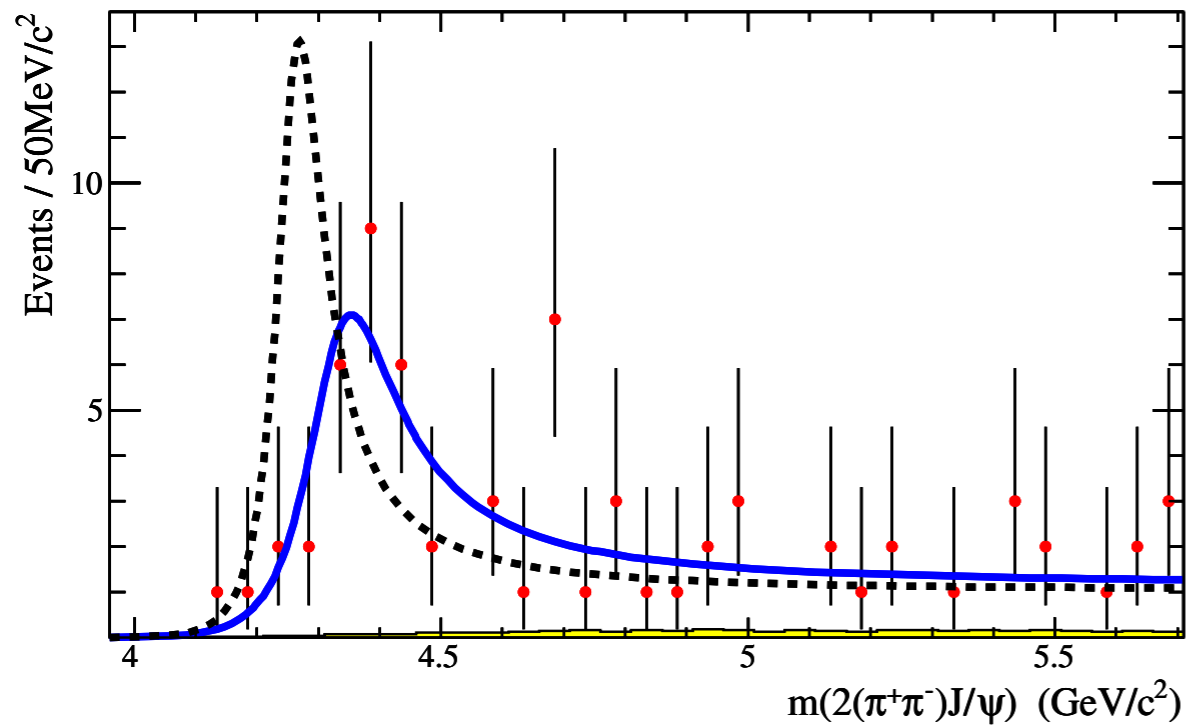
- there is a Y(4360) instead of a Y(4260)?

Overview of e⁺e⁻ → π⁺π⁻ψ(2S)

e⁺e⁻(γ_ISR) → π⁺π⁻ψ(2S) at BaBar

PR[...]

- there is a Y(4[...])

e⁺e⁻(γ_ISR) → π⁺π⁻ψ(2S) at BaBar (and Belle)
PRD 89, 111103(R) (2014)
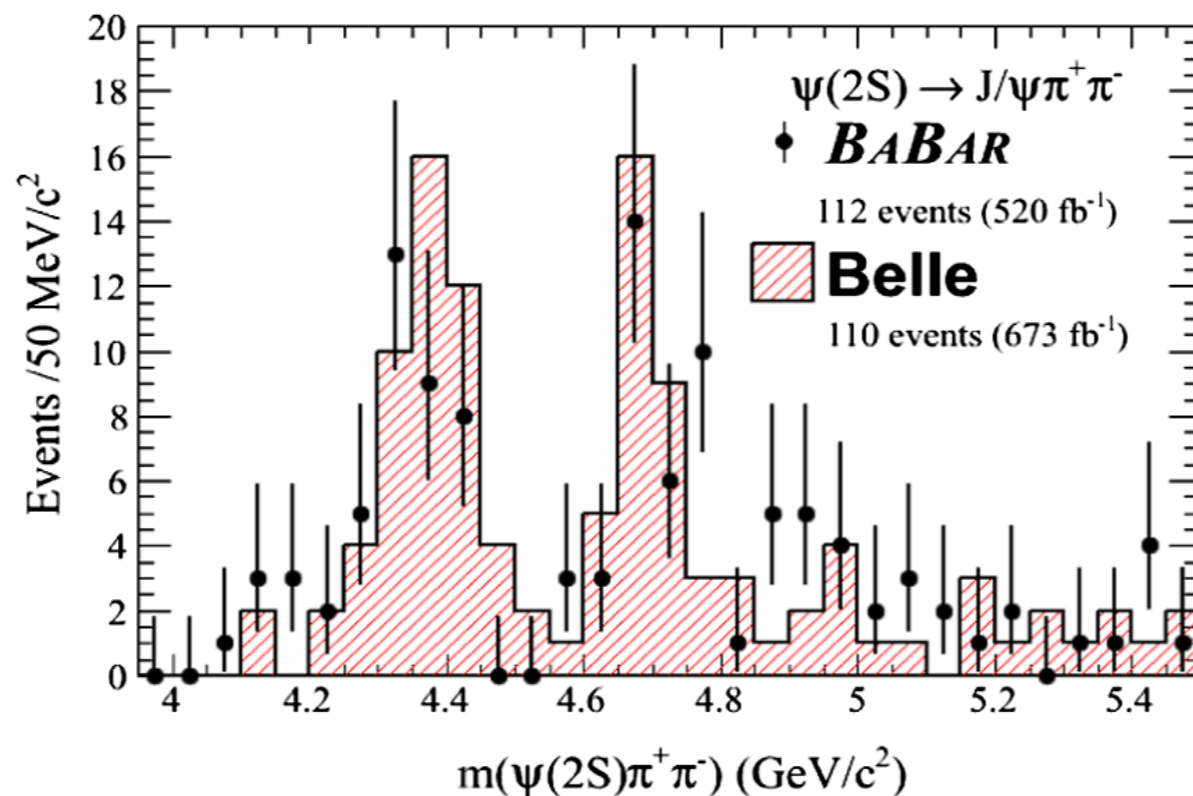
- actually, there is a Y(4360) and a Y(4660)?

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

$e^+e^-(\gamma_{ISR}) \to \pi^+\pi^-\psi(2S)$ at BaBar
PRD
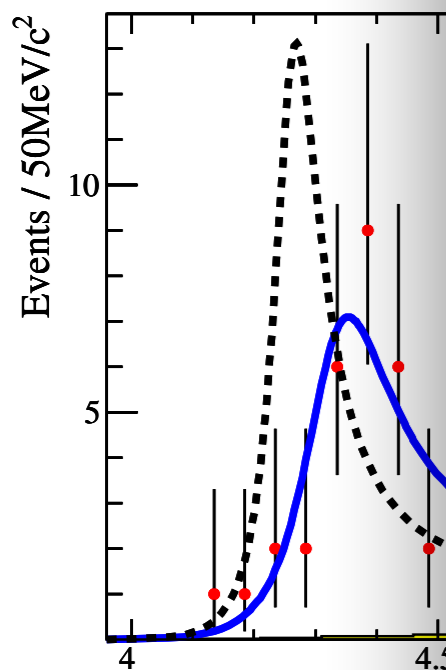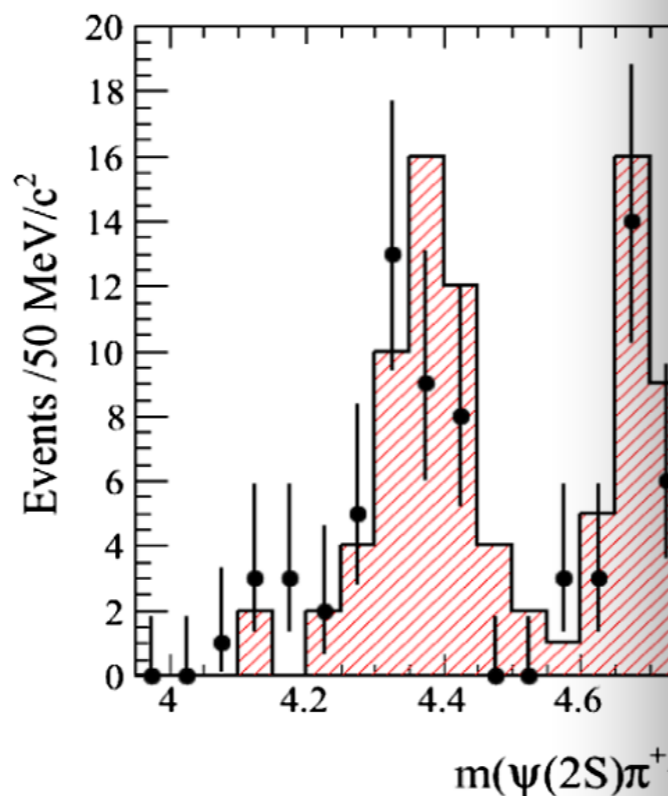
$e^+e^-(\gamma_{ISR}) \to \pi^+\pi^-\psi(2S)$ a
PRD 89, 111103

$e^+e^-(\gamma_{ISR}) \to \pi^+\pi^-\psi(2S)$ at Belle
arXiv:1410.7641

- there is a Y(4

- actually, there is a Y(4
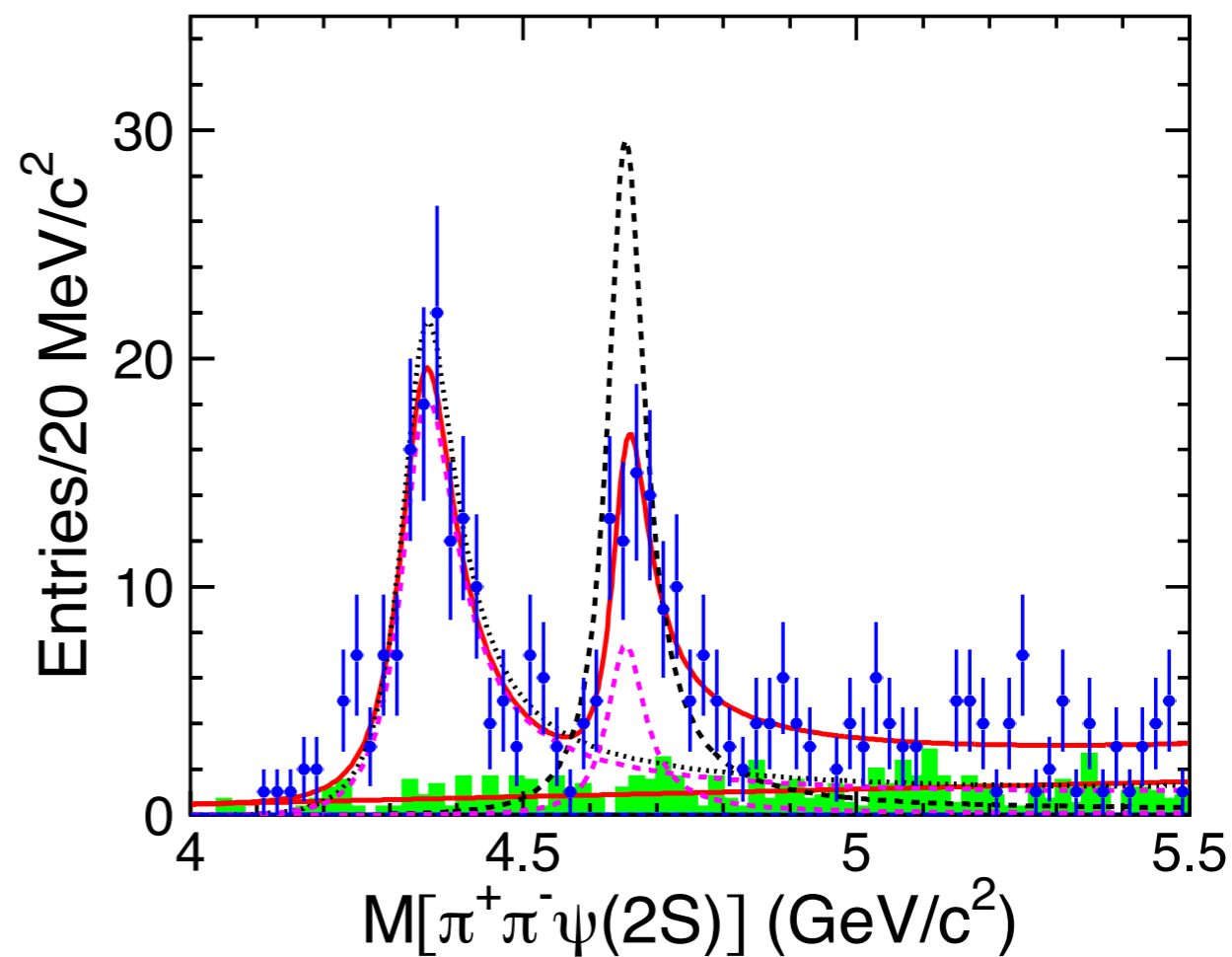
- actually, there is a Y(4360) and a Y(4660)?
(even more convincing with full Belle statistics)

Overview of e⁺e⁻ → π⁺π⁻h_c(1P)
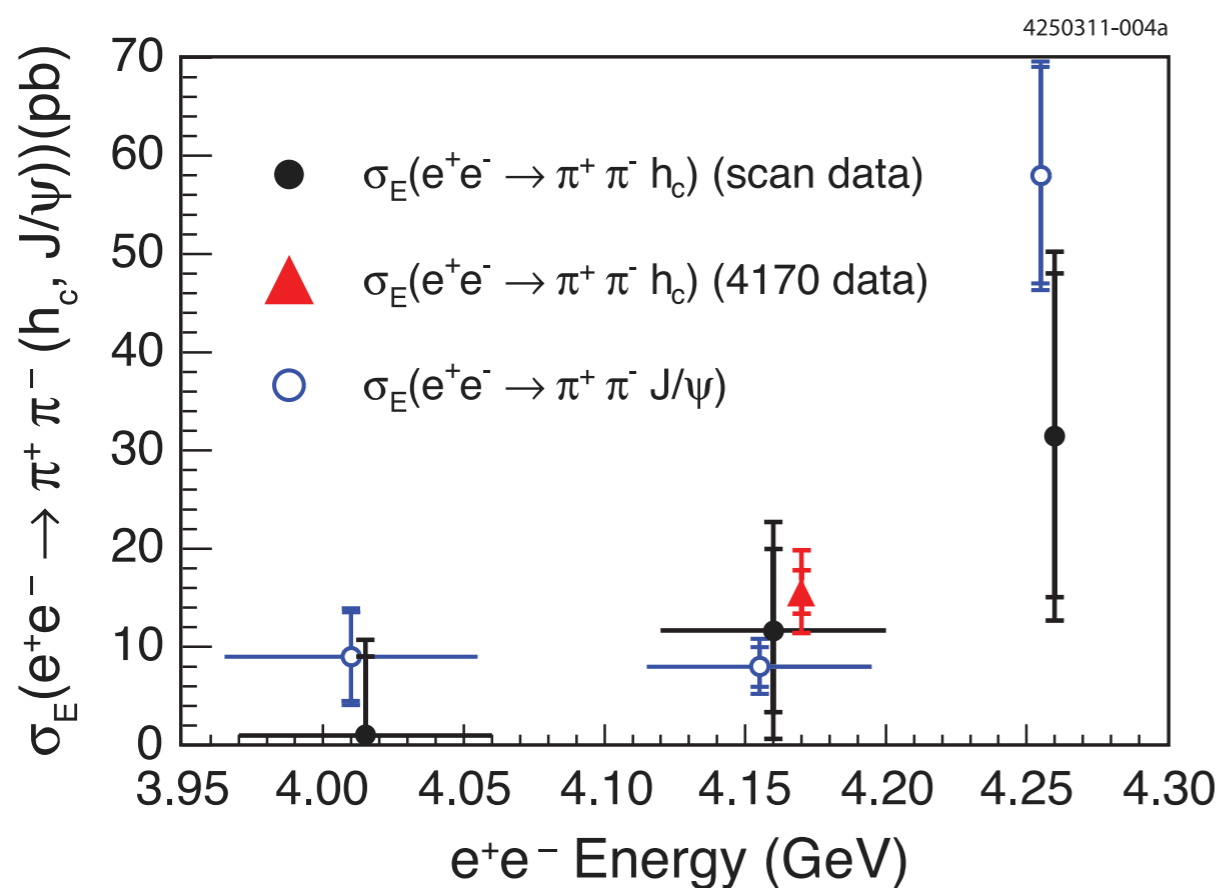
e⁺e⁻ → π⁺π⁻h_c(1P) at CLEO-c

PRL 107, 041803 (2011)

- is this a hint of Y(4260) → π⁺π⁻h_c(1P)?

Overview of e⁺e⁻ → π⁺π⁻h_c(1P)

e⁺e⁻ → π⁺π⁻h_c(1P) at CLEO-c
PRL 107, 041803 (2011)
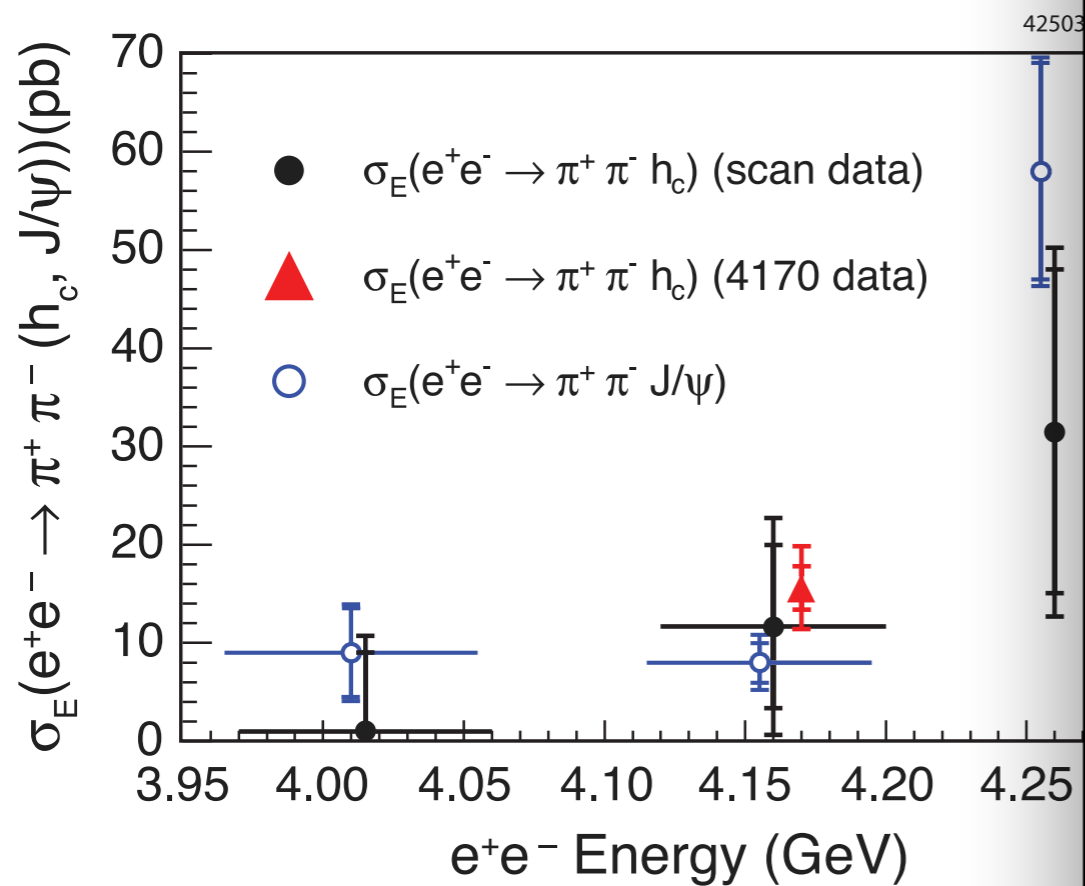
- is this a hint of Y(4260) → π⁺π⁻h_c(1

e⁺e⁻ → π⁺π⁻h_c(1P) at BESIII
PRL 111, 242001 (2013)
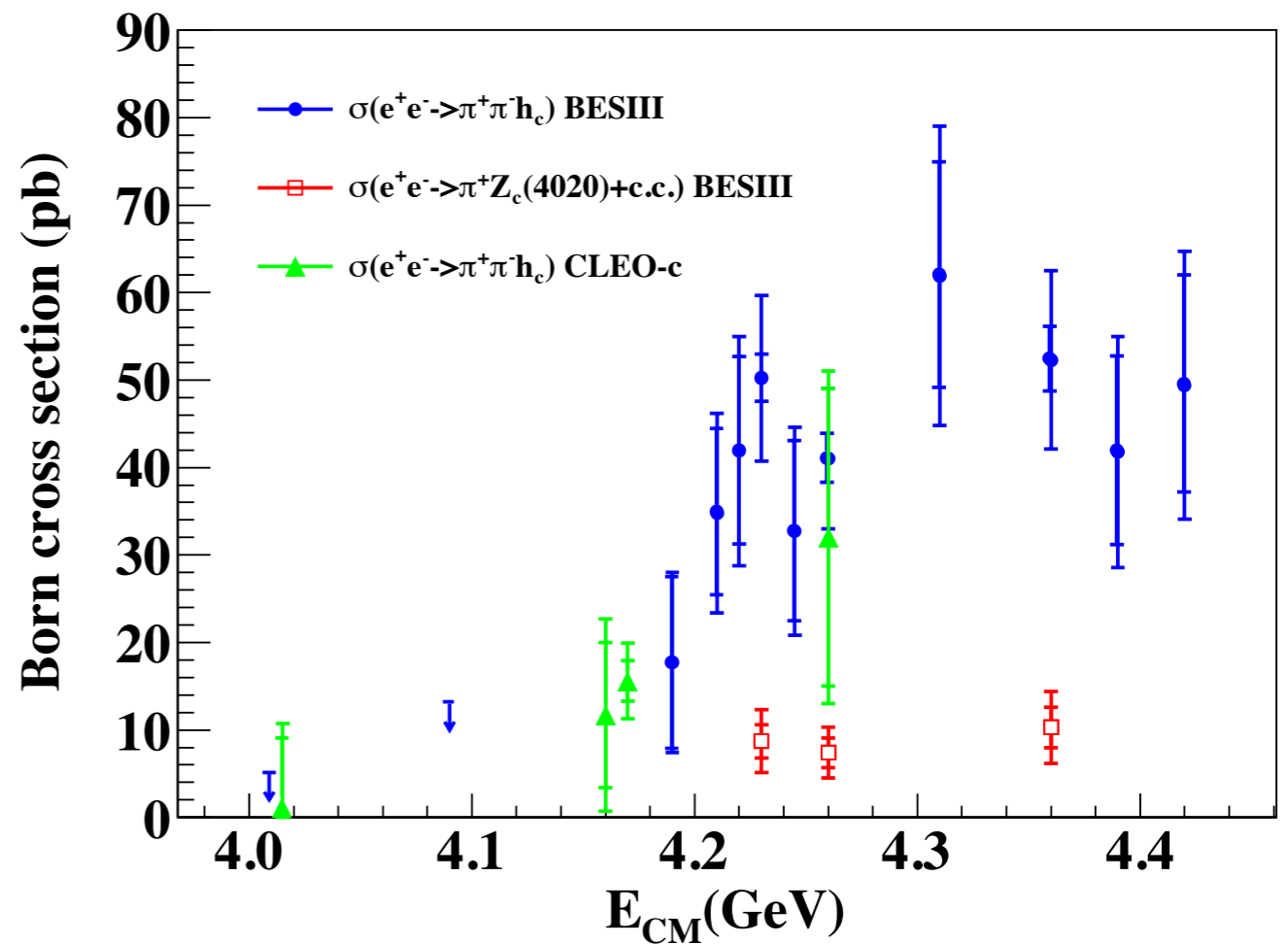
- it is more complicated than just
  Y(4260) → π⁺π⁻h_c(1P)

Overview of e⁺e⁻ → ηJ/ψ

e⁺e⁻(γ_ISR) → ηJ/ψ at Belle
PRD 87, 051101(R) (2013)
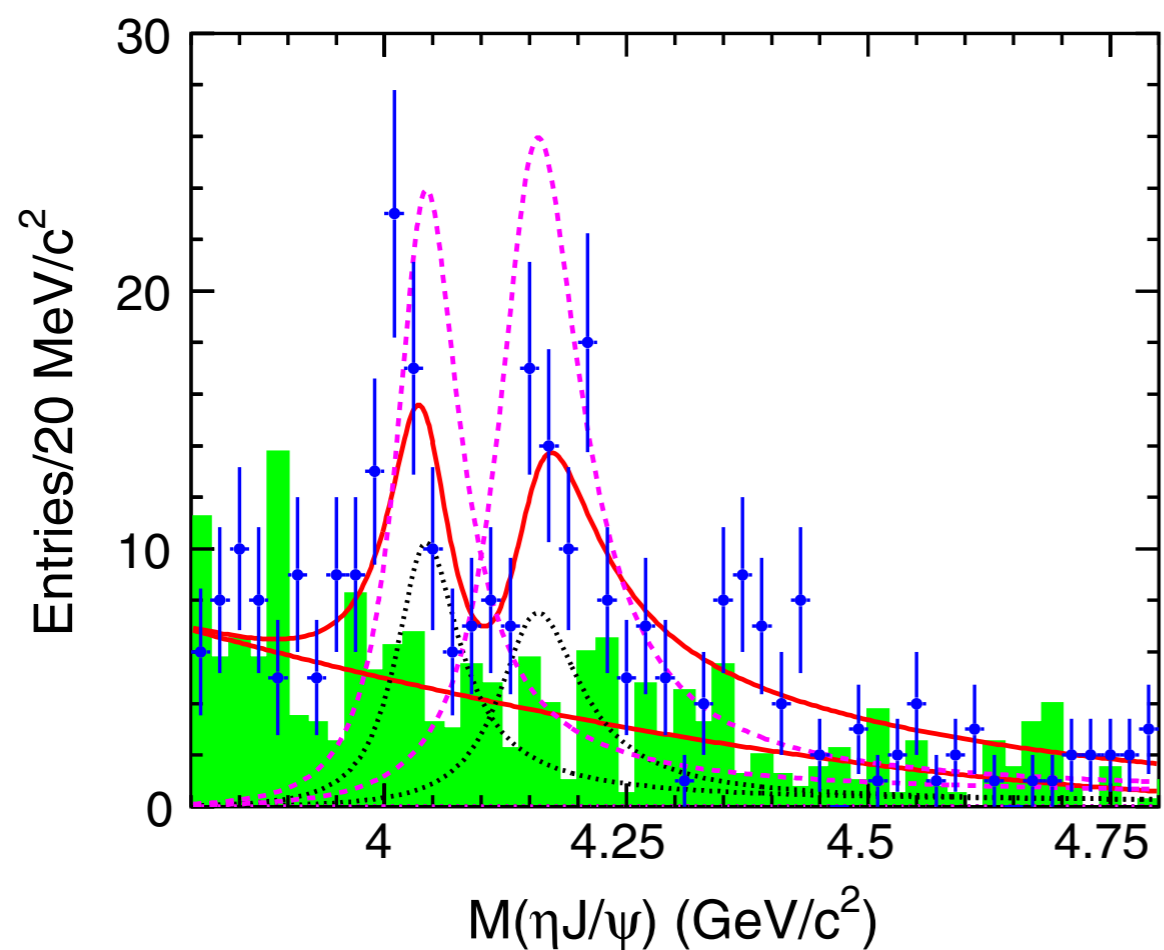
- fit with conventional ψ(4040) and ψ(4170) states

Overview of e⁺e⁻ → ηJ/ψ

e⁺e⁻(γ_ISR) → ηJ/ψ at Belle
PRD 8...
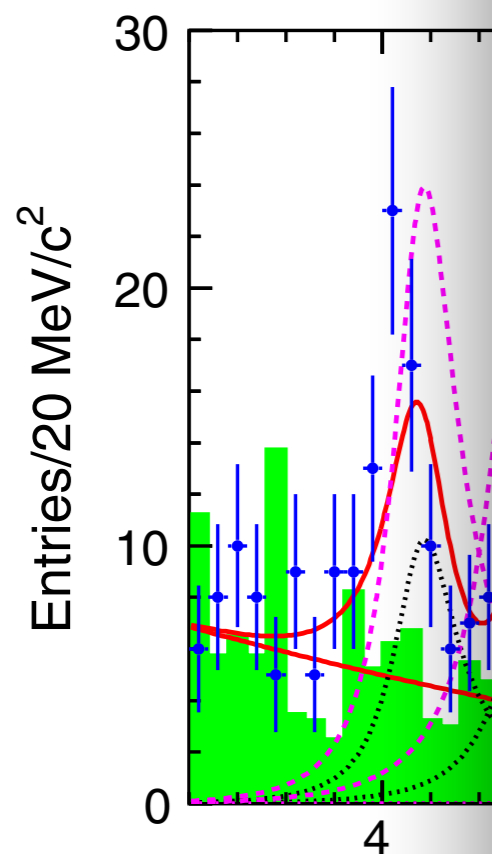
e⁺e⁻ → ηJ/ψ at BESIII
arXiv:1503.06644

- fit with conven... states
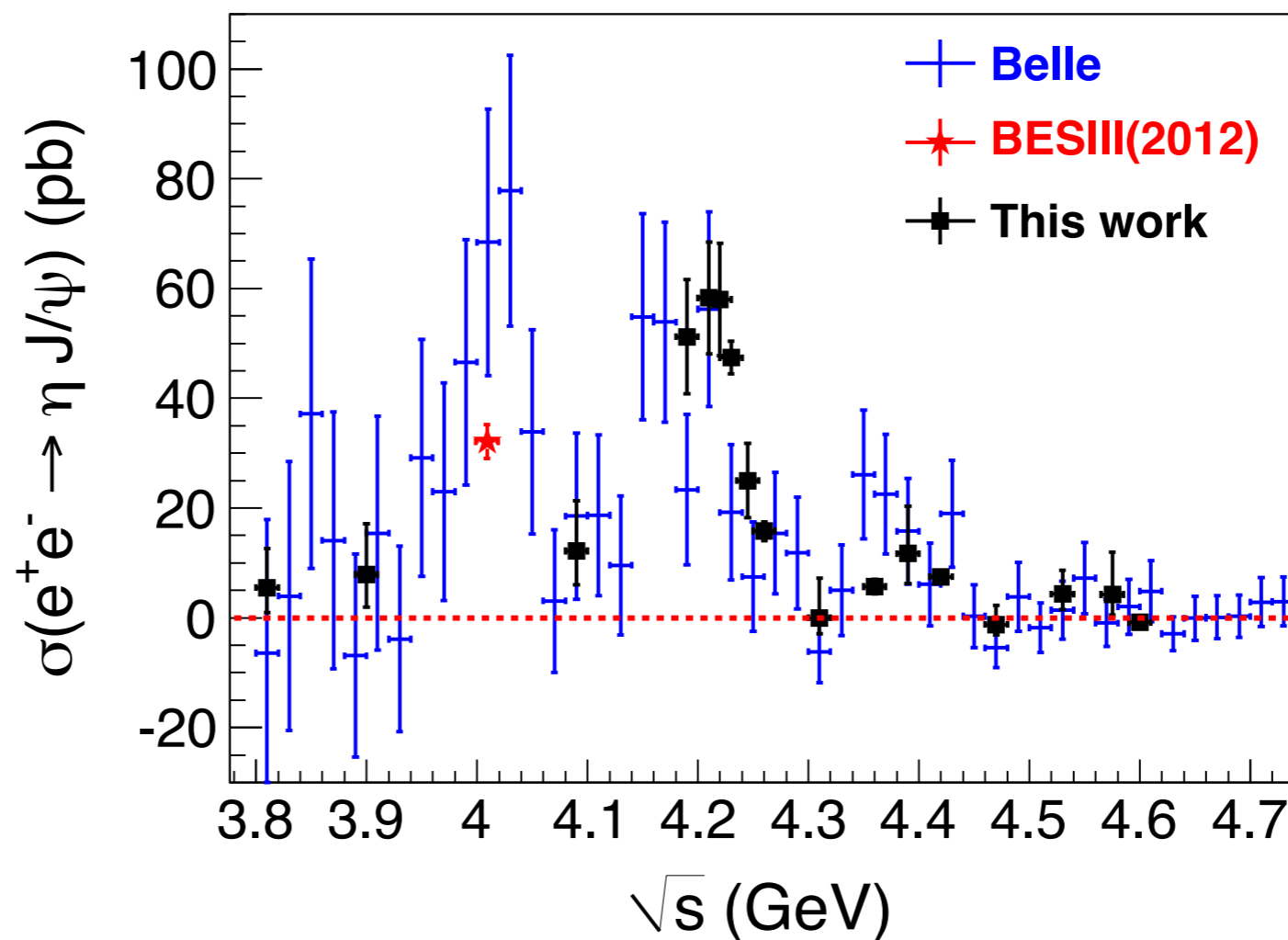
- BESIII confirms there is nontrivial structure

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

- the $\eta J/\psi$ cross section is inconsistent with Y(4260)

- fit with conven... states

- BESIII confirms there is nontrivial structure

36

Overview of e⁺e⁻ → K⁺K⁻J/ψ

e⁺e⁻(γ_ISR) → K⁺K⁻J/ψ at Belle
PRD 89, 072015 (2014)

- there is surprising nontrivial structure in KKJ/ψ?
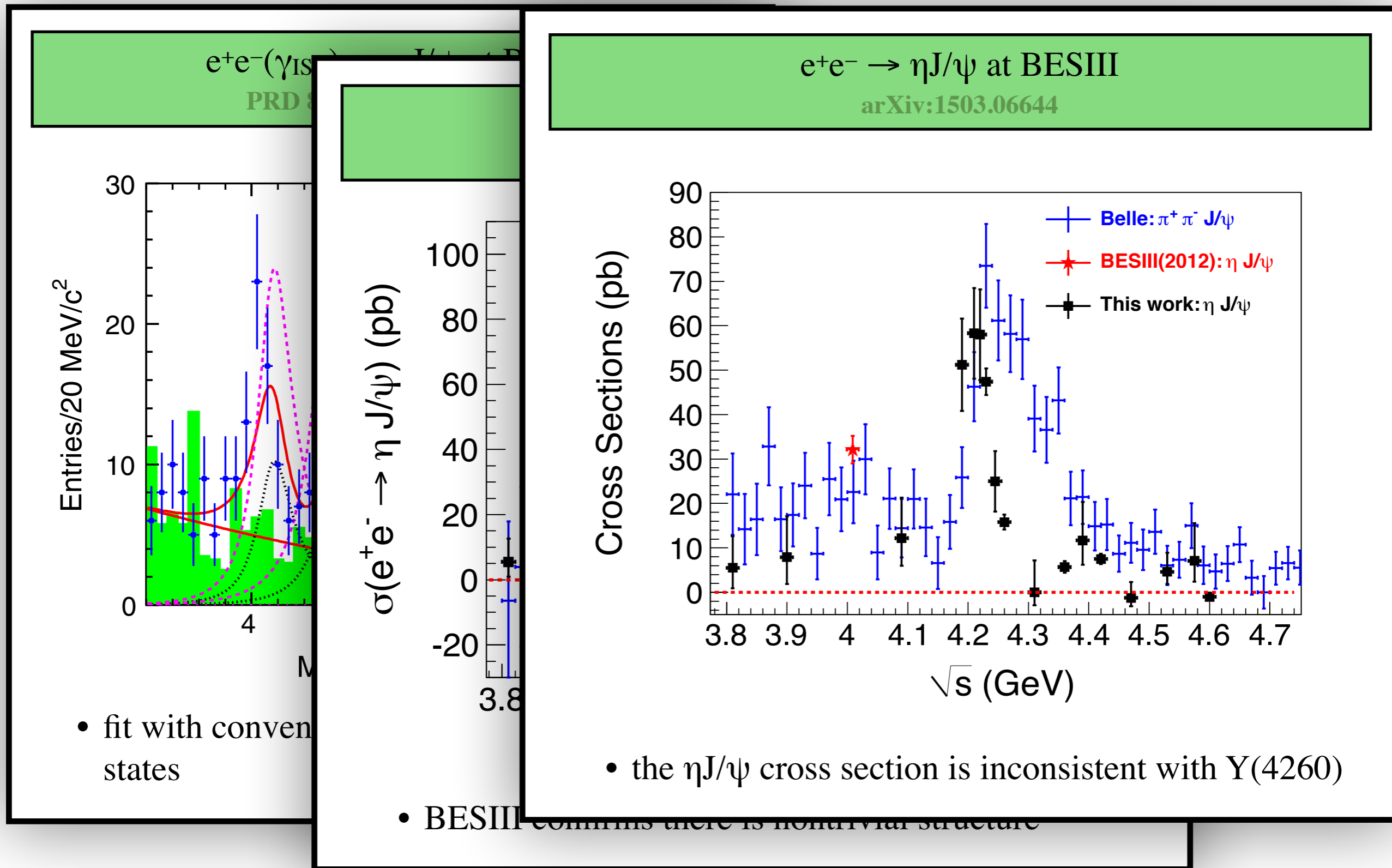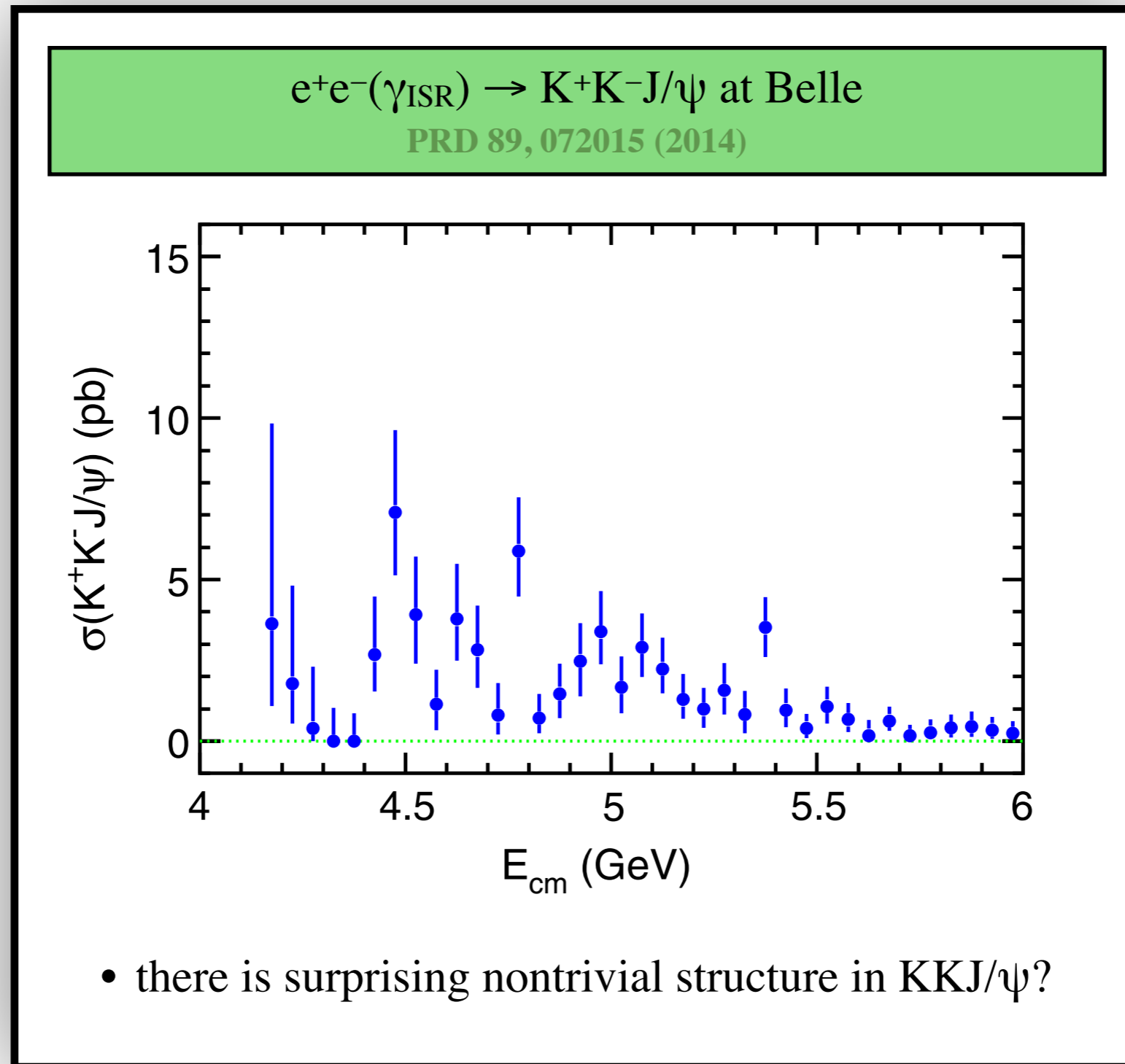
Overview of e⁺e⁻ → ωχ_{c0}

e⁺e⁻ → ωχ_{c0} at BESIII
PRL 114, 092003 (2015)
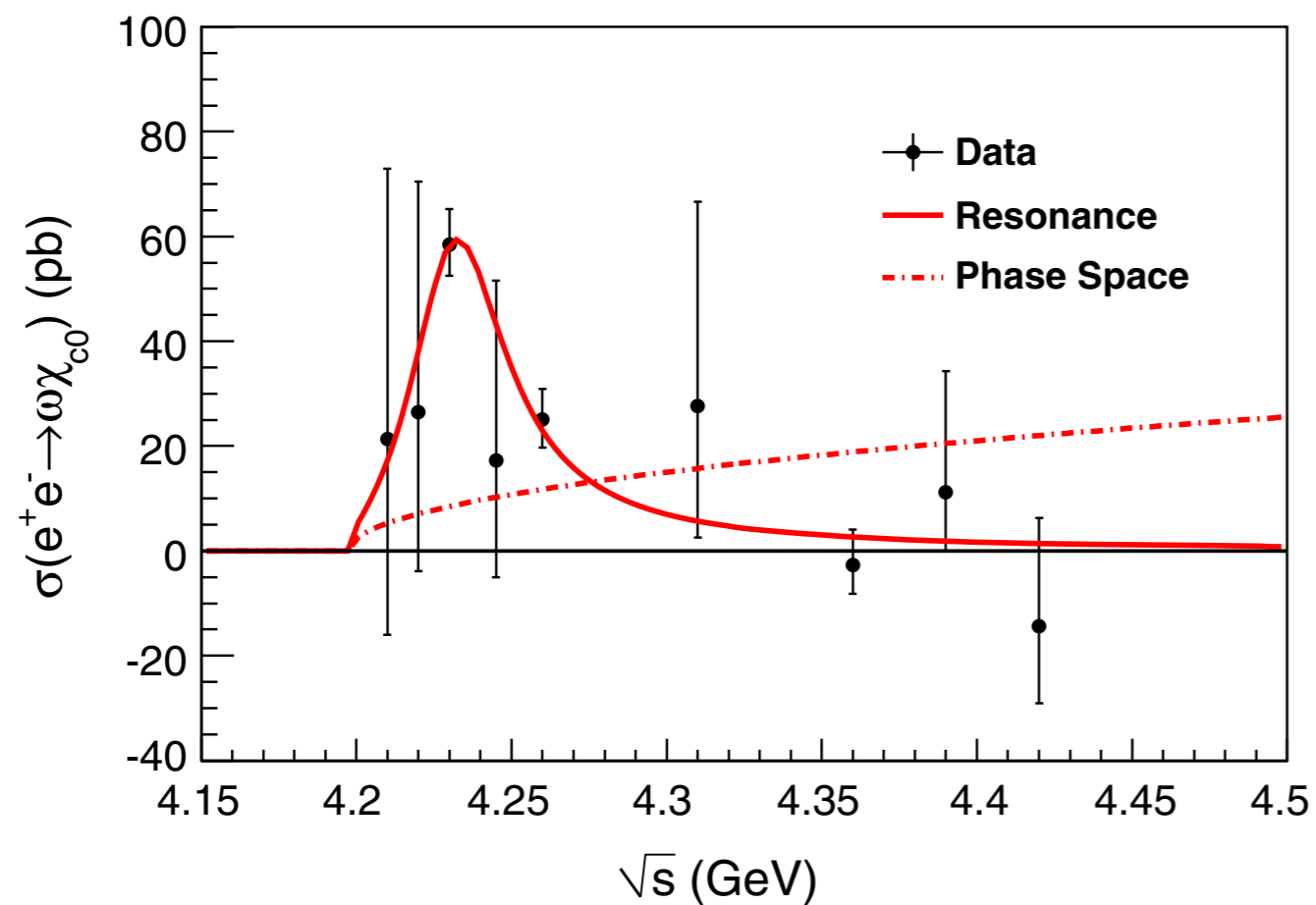
- this shows a Y(4230)??
  (it is inconsistent with Y(4260))

Overview of e⁺e⁻ → ωχ$_{c0}$

e⁺e⁻ → ωχ$_{c0}$ at BESIII
PRL 114, 092003 (2015)
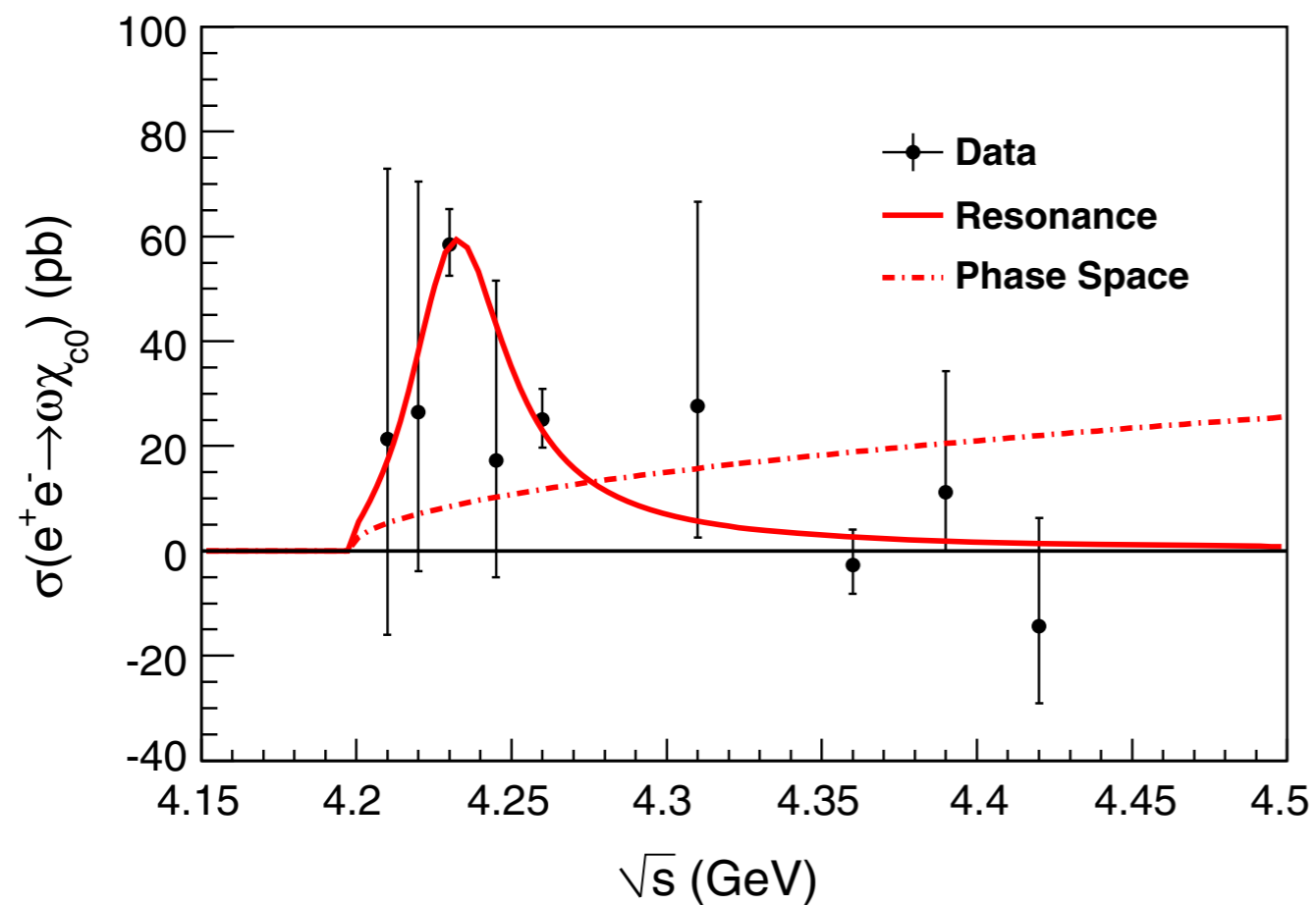
No obvious patterns are emerging in e⁺e⁻ cross sections!?!?

- this shows a Y(4230)??
  (it is inconsistent with Y(4260))

Connections and Complexities

Connections I: The X(3872) and the Y(4260).

Connections II: The Y(4260) and the "Υ(5S)".

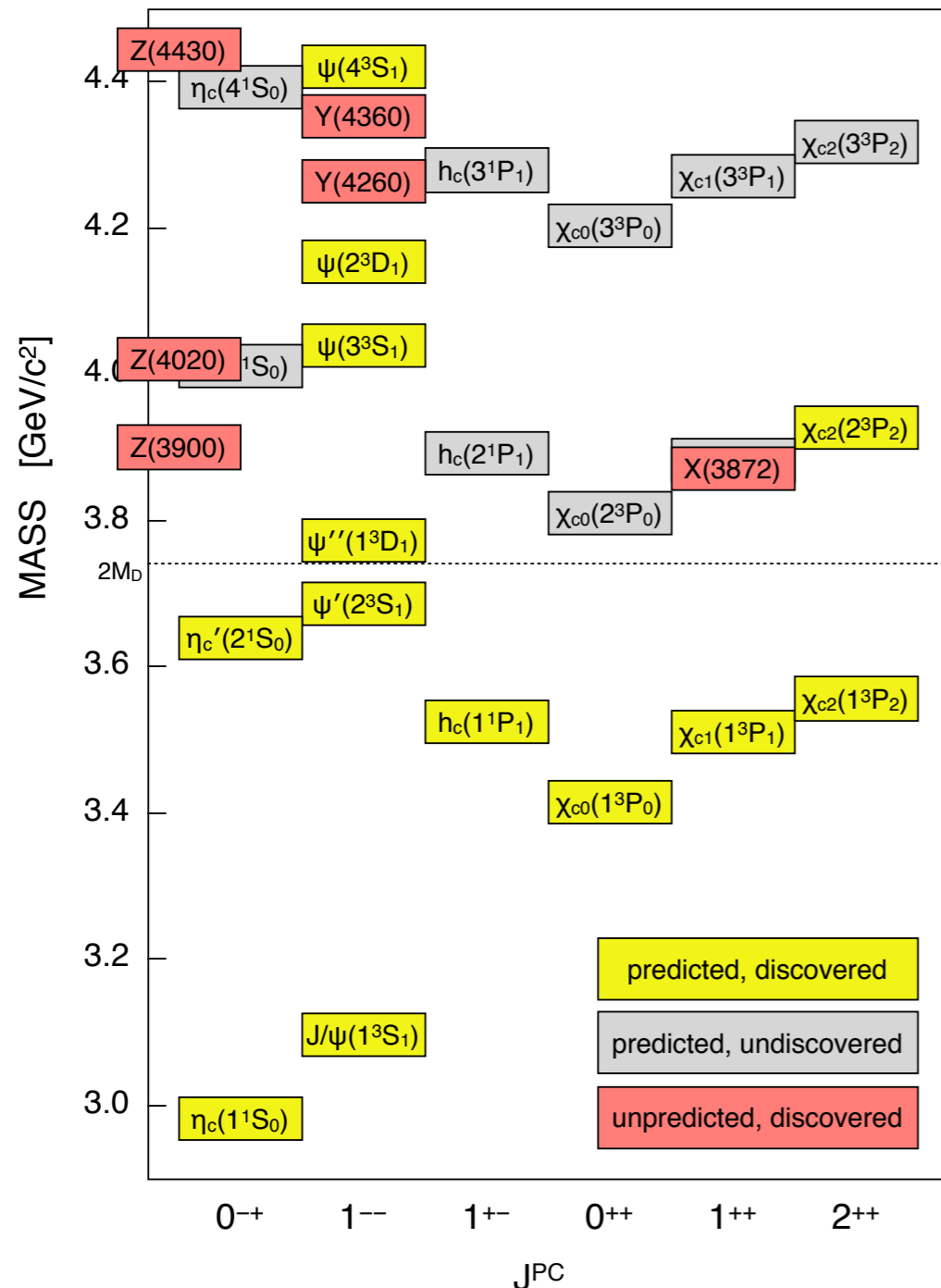*Connections III:* The Z_c and $Z_c{}'$ and the Z_b and $Z_b{}'$.

Complexities: A Collection of e^+e^- Cross Sections.

Charmonium Spectrum
predictions based on PRD 72, 054026 (2005)
measurements from PDG 2014

Loads of experimental results are waiting to be synthesized.

Many more results can be expected:
BESIII, Belle-II, LHC, Panda (hopefully)

A solution would greatly advance our understanding of QCD.

Connections are beginning to form, but there are still many complexities.

Three misconceptions:
1. This is hopelessly complicated.
2. These are experimental artifacts.
3. Everything is/isn't resonant (a "particle").

It is an interesting time…

Concluding Thoughts on the XYZ Mesons

Charmonium Spectrum
predictions based on PRD 72, 054026 (2005)
measurements from PDG 2014

Loads of experimental results are waiting to be synthesized.

Many more results can be expected:
BESIII, Belle-II, LHC, Panda (hopefully)

A solution would greatly advance our understanding of QCD.

Connections are beginning to form, but there are still many complexities.
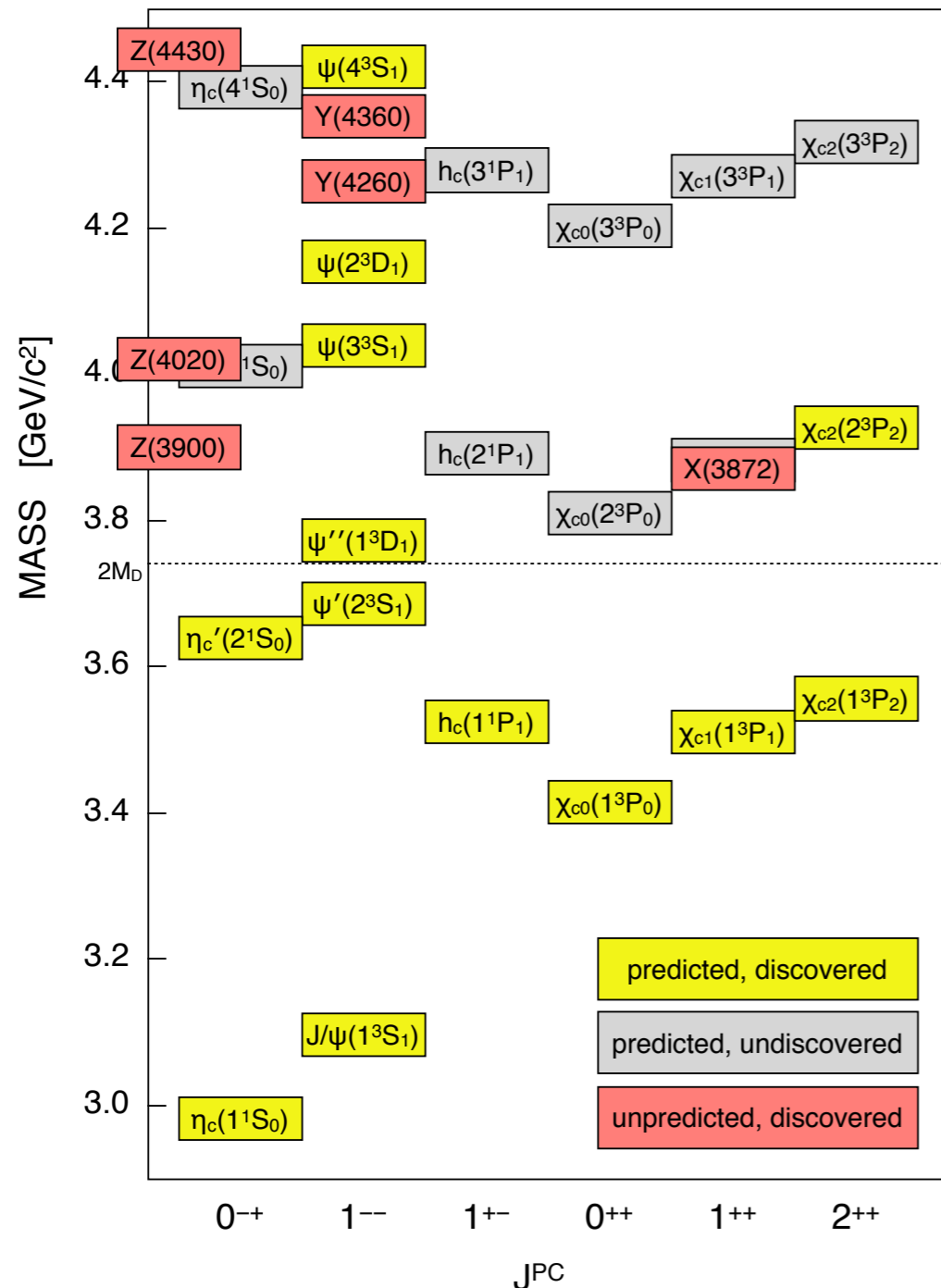
Three misconceptions:
1. This is hopelessly complicated.
2. These are experimental artifacts.
3. Everything is/isn't resonant (a "particle").

It is an interesting time…

Thanks.