An Overview of the XYZ Mesons:

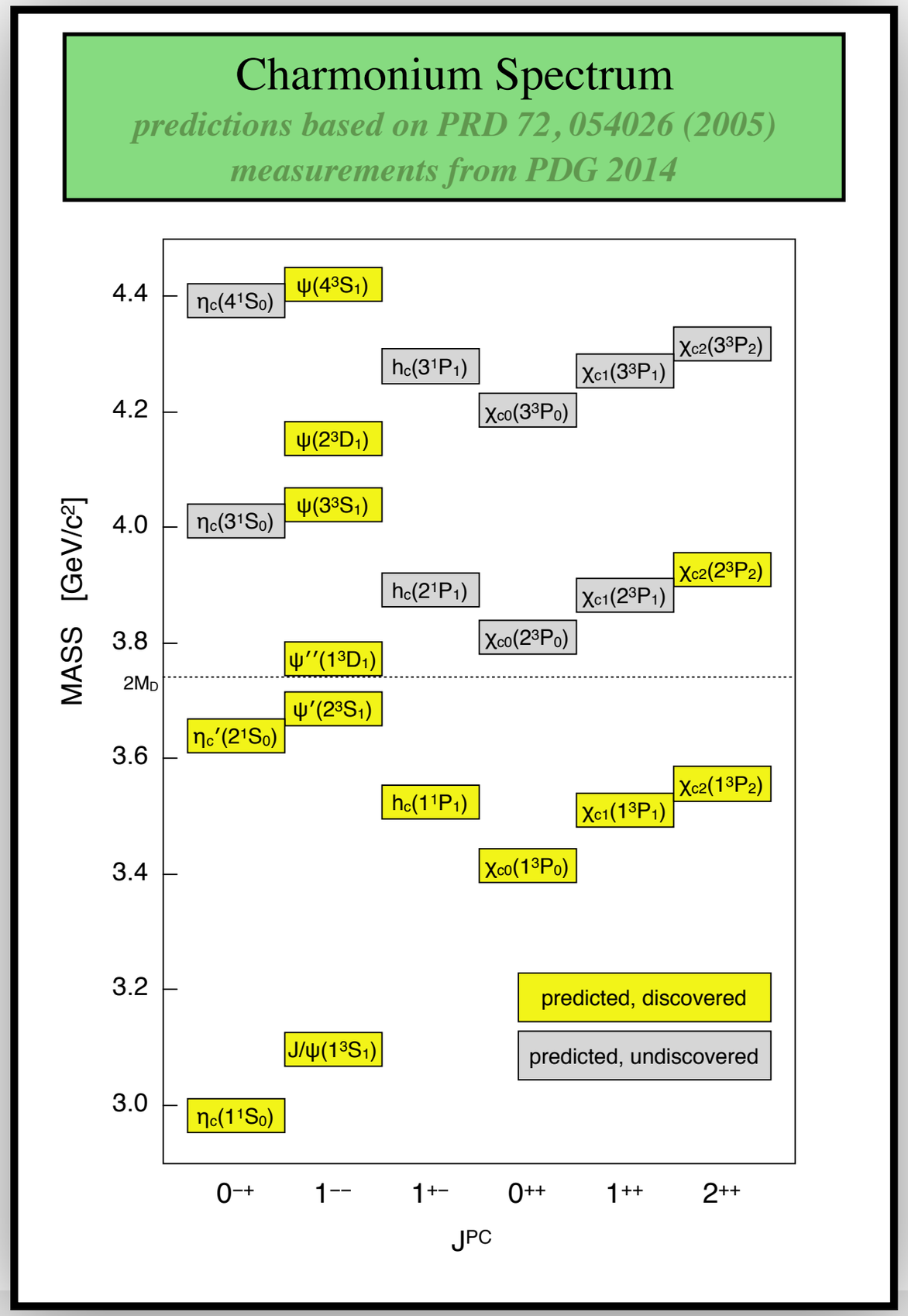
Experimental Issues

Ryan Mitchell
Indiana University

INT Workshop

November 2, 2015

Introductory Notes on the XYZ Mesons



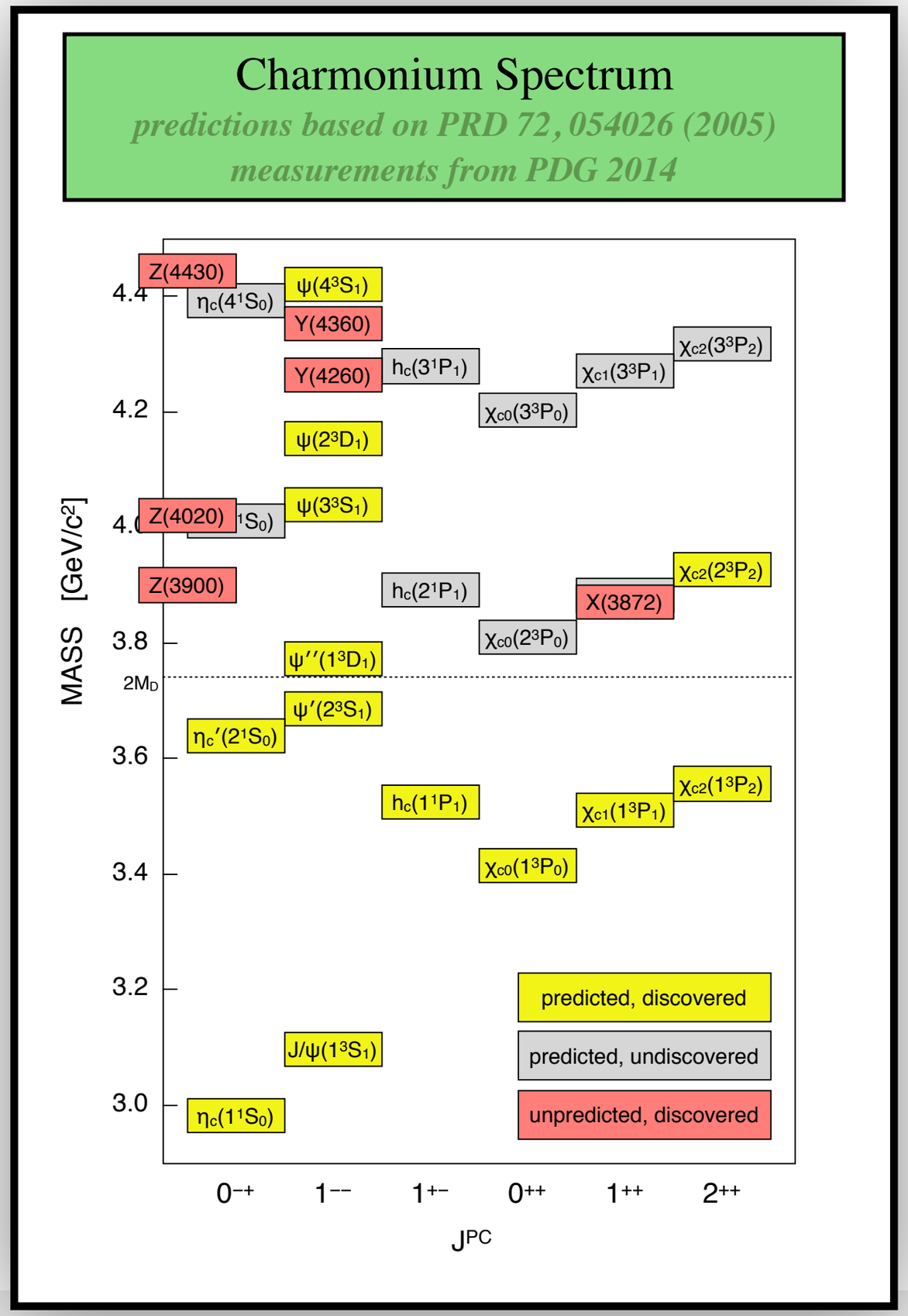
The charmonium and bottomonium systems are relatively simple.

The quark model description of these states has been enormously successful *(with a few anomalies, e.g., the ϱπ puzzle)*.

This talk briefly outlines the spectroscopy in these regions.

There are other interesting regions:
light quark mesons and baryons,
the D_s system, charmed baryons…

Introductory Notes on the XYZ Mesons



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

There is some order:

- the naming scheme reveals some;
- there are definite analogies between charmonium and bottomonium;
- there are apparent correlations between some structures and some thresholds, etc.

But there seems to be more disorder.

This talk:

I. The Experimental Landscape
II. Connections and Complexities
III. Theory and Experiment Coordination

Missing: a coherent framework.
Hopefully this workshop will help.

Part I: 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-factories
CLEO
BaBar
Belle

τ-charm
CLEO-c
BESIII

hadron
CDF
D0
LHCb
ATLAS
CMS

p-pbar
PANDA

Part I: The Experimental Landscape

BOTTOMONIUM:

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

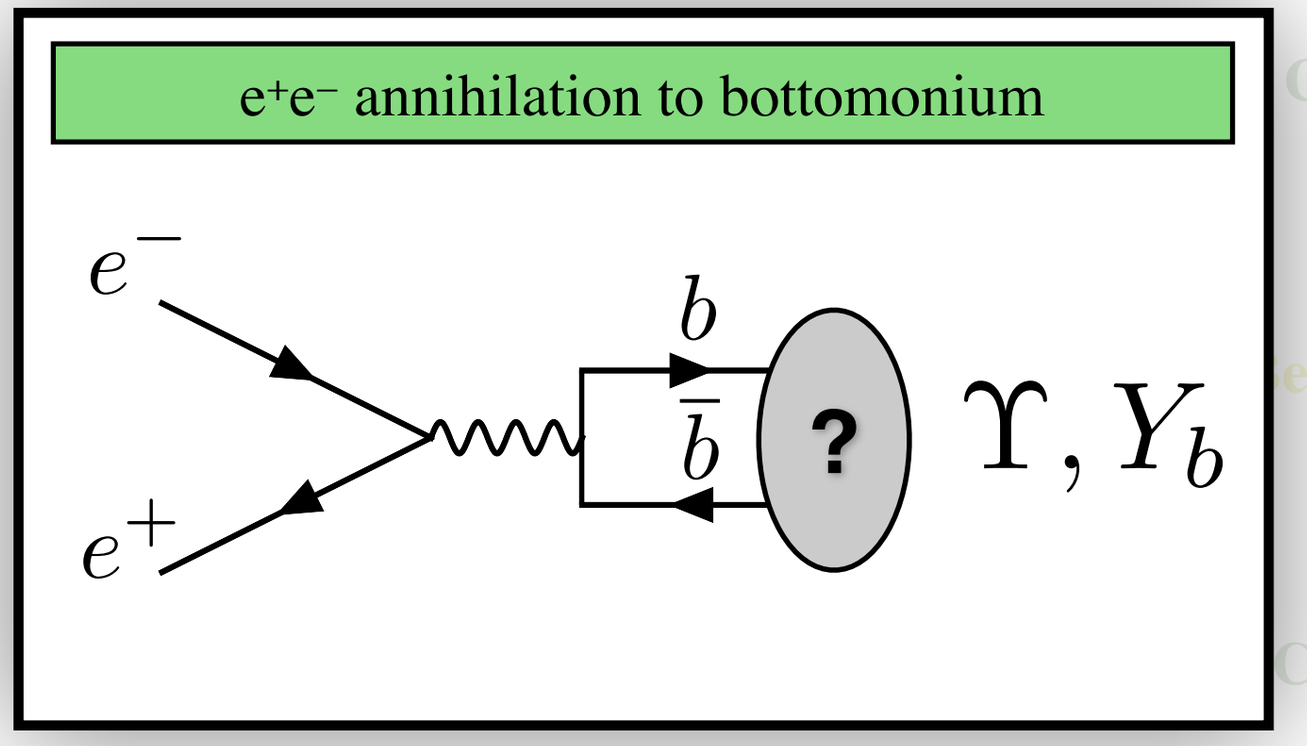
CHARMONIUM:

- 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?!?!)*

Part I: The Experimental Landscape

BOTTOMONIUM:

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



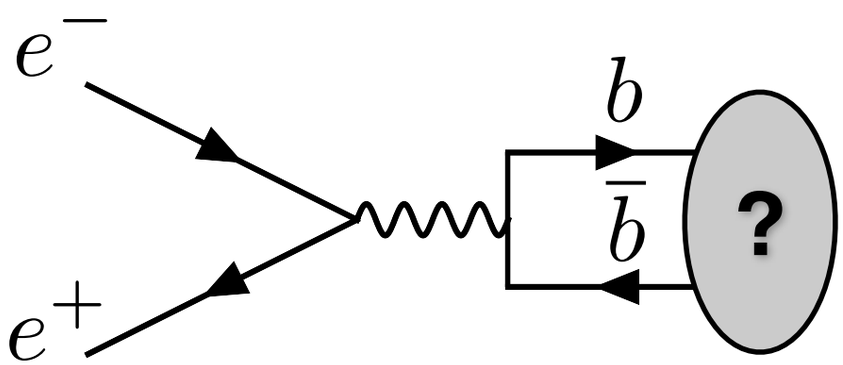
- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)
- $\gamma\gamma$ collisions (CLEO, BaBar, **Belle**)
- double charmonium production (CLEO, BaBar, **Belle**)
- *proton anti-proton annihilation (PANDA?!?!)*

Part I: The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, Belle)
- proton collisions (CDF, D0, LHCb, ATLAS, CMS)
- $\gamma\gamma$ collisions (CLEO, BaBar, Belle)
- double charmonium production (CLEO, BaBar, Belle)
- *proton anti-proton annihilation (PANDA?!?!)*

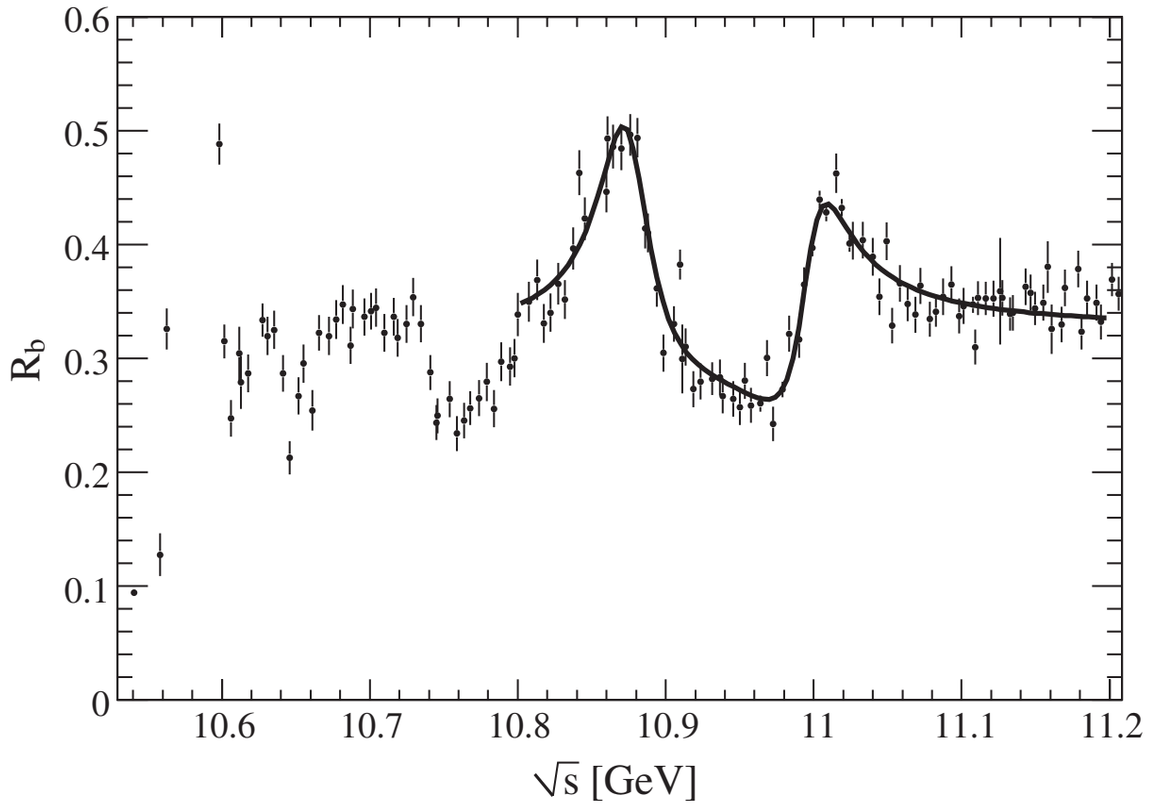
e^+e^- annihilation to bottomonium



Υ, X

R_b above the $\Upsilon(4S)$ from BaBar

PRL 102, 012001 (2009)



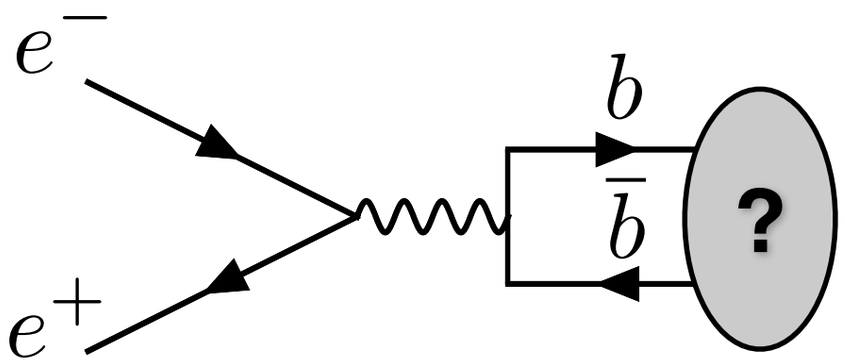
- the "$\Upsilon(5S)$" and "$\Upsilon(6S)$" in the inclusive cross section

Part I: The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, Belle)
- proton collisions (CDF, D0, LHCb, ATLAS)
- $\gamma\gamma$ collisions (CLEO, BaBar, Belle)
- double charmonium production (CLEO, BaBar, Belle)
- *proton anti-proton annihilation (PANDA?!?!)*

e^+e^- annihilation to bottomonium

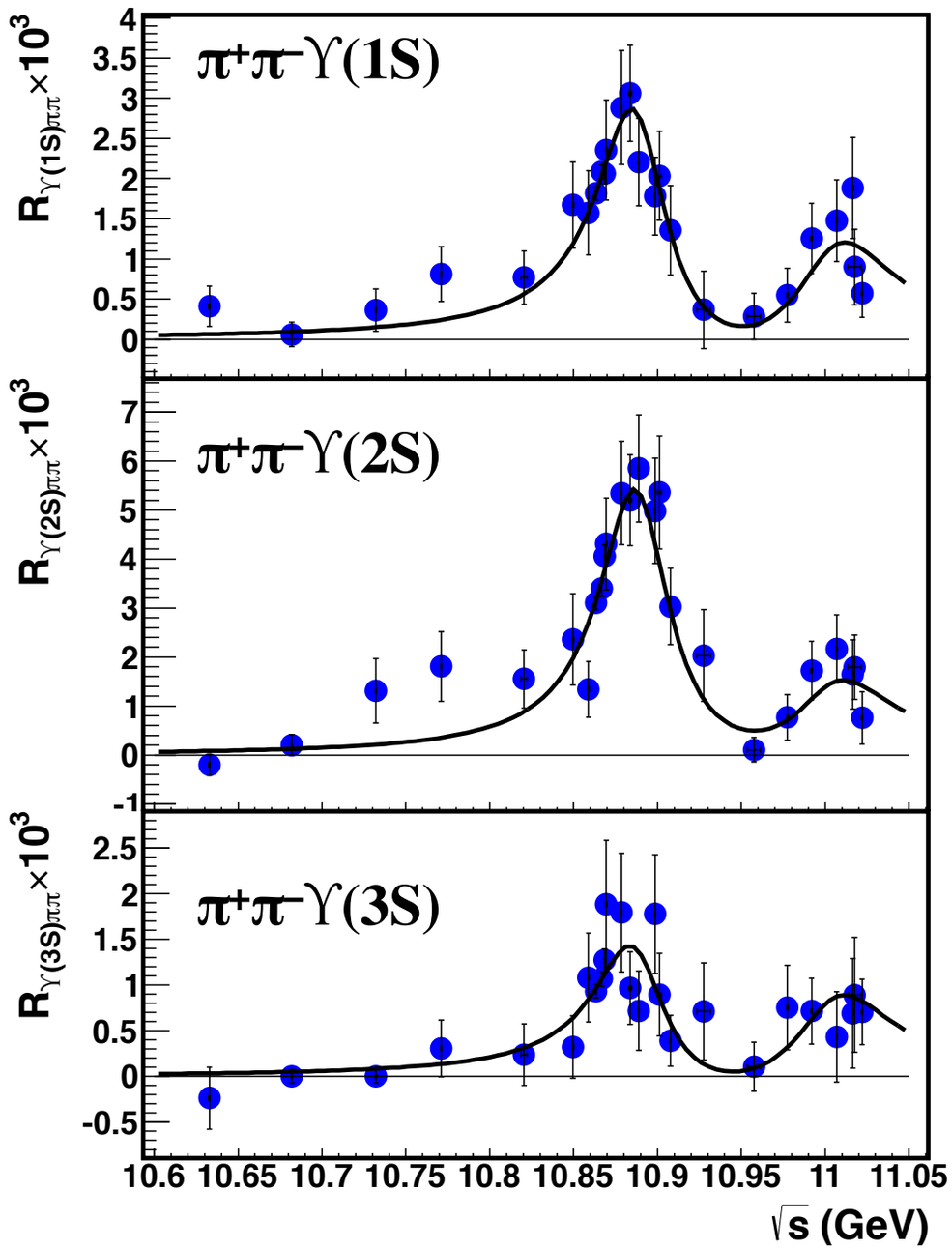


Υ, X

R_b

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

arXiv:1501.01137



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

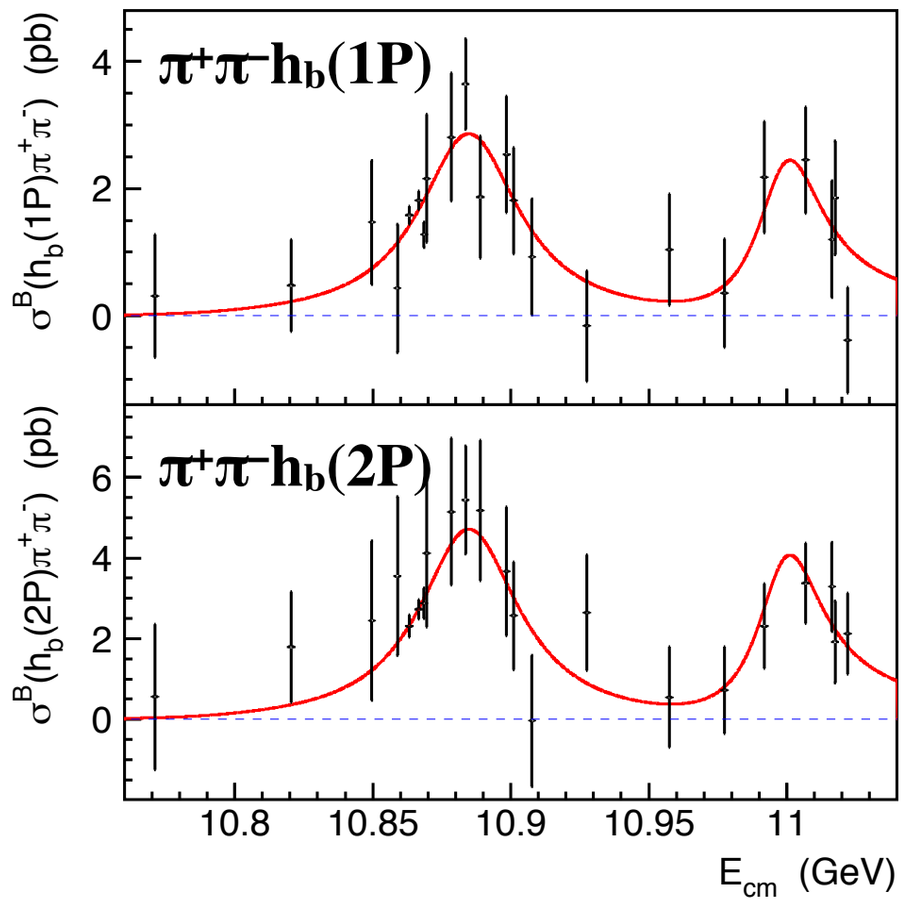
Part I: The Experimental Landscape

BOTTOMONIUM:

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

$e^+e^- \to \pi^+\pi^- h_b(1P,2P)$ at Belle

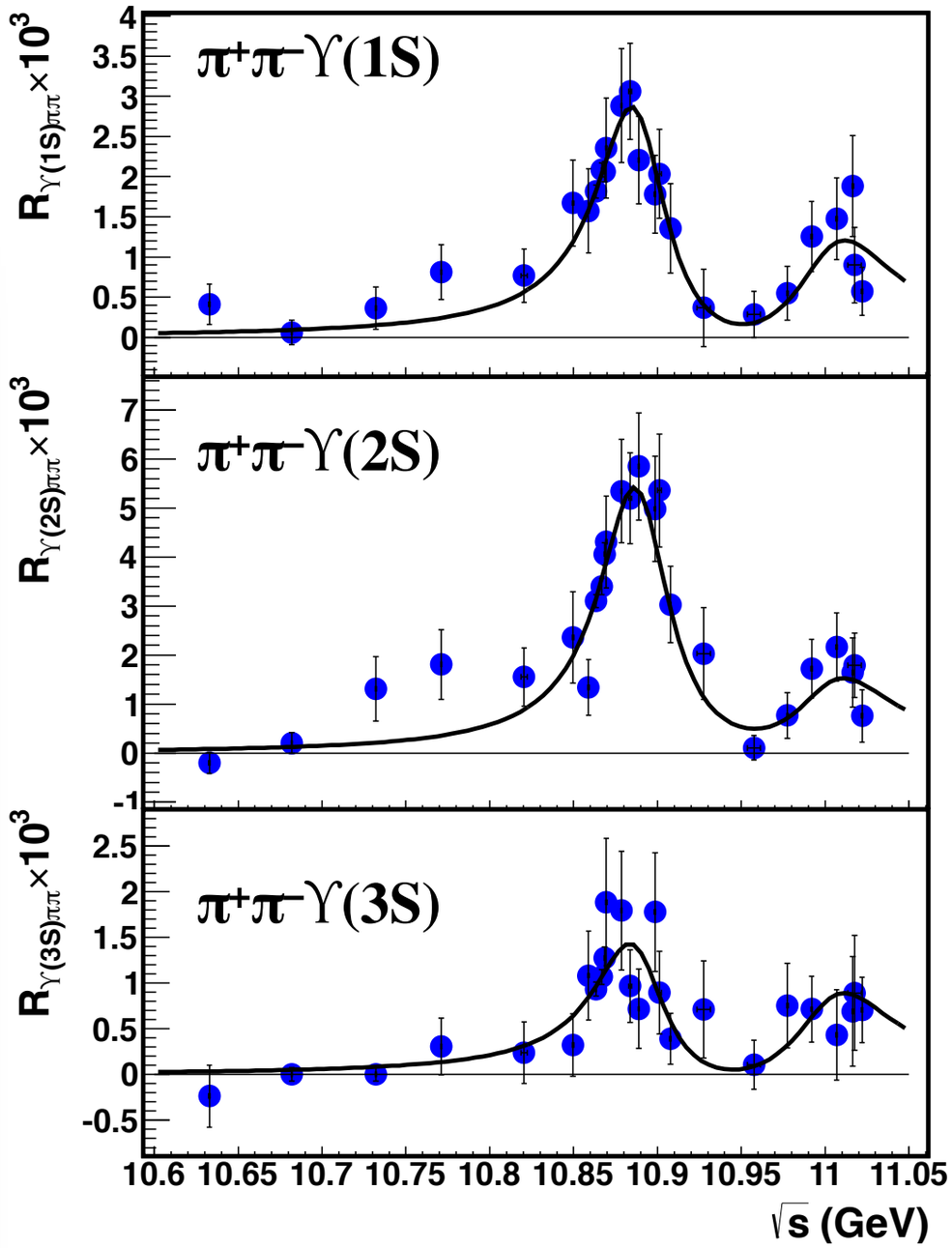
arXiv:1508.06562



- similar rates and shapes for $\pi^+\pi^- h_b(nP)$.

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

arXiv:1501.01137



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

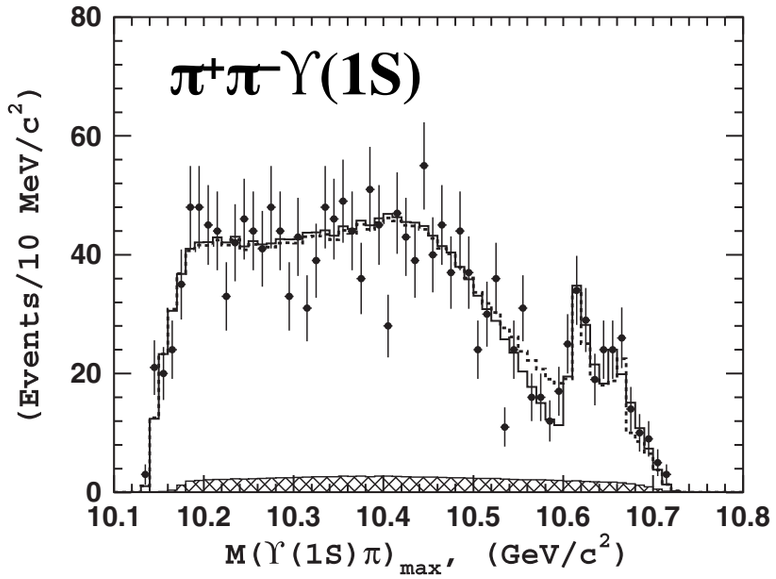
Part I: The Experimental Landscape

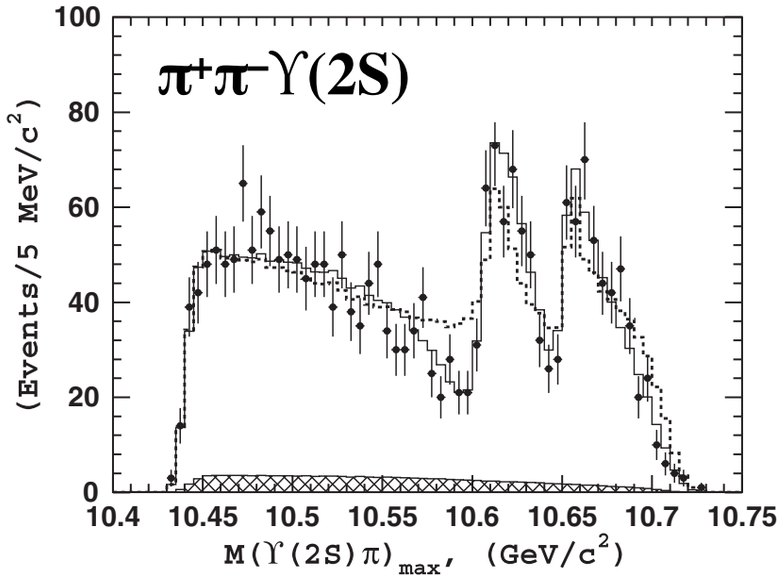
$e^+e^- \to \pi^+\pi^-\Upsilon(1S,2S,3S)$ at Belle

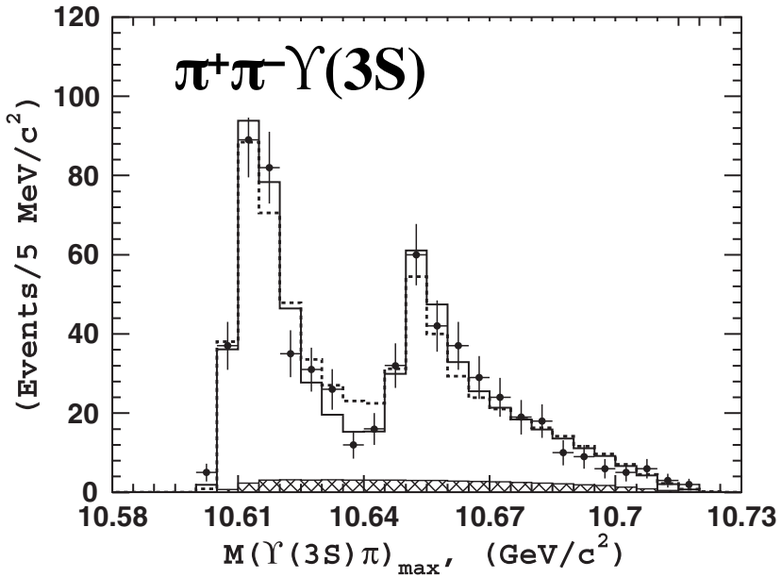
arXiv:1501.01137

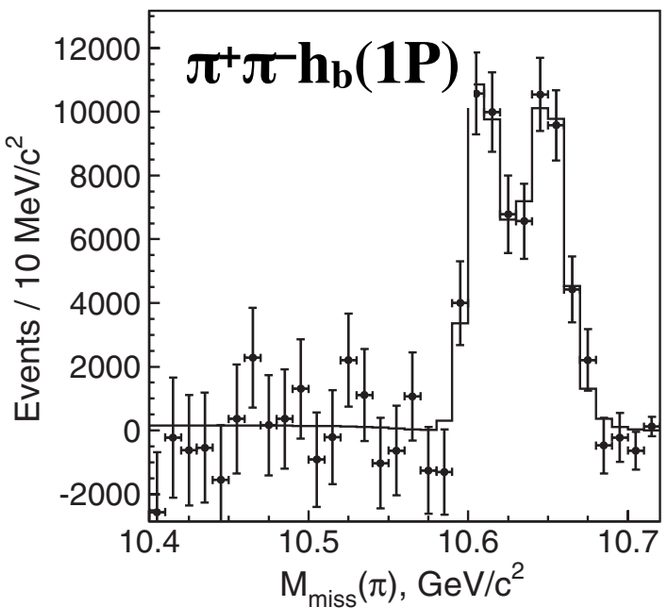
$e^+e^- \to \pi^+\pi^-\Upsilon(1S,2S,3S)$ and $\pi^+\pi^- h_b(1P,2P)$ at $E_{CM} \sim \Upsilon(5S)$ Mass at Belle

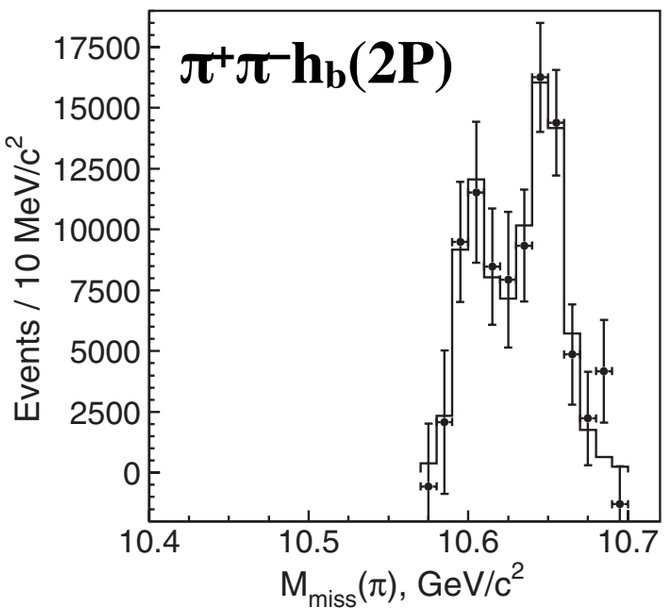
PRD 91, 072003 (2015), PRL 108, 122001 (2012)











- two peaks, Z_b and Z_b', are found in the substructure of all five reactions, close to BB* and B*B* thresholds.

similar rates and shapes for Υ's & h_b(nP)!

Part I: The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, **Belle**) ⟶ "$\Upsilon(5S)$", "$\Upsilon(6S)$", Z_b, Z_b'
- 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?!?!)*

Part I: 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?!?!)*

Part I: The Experimental Landscape

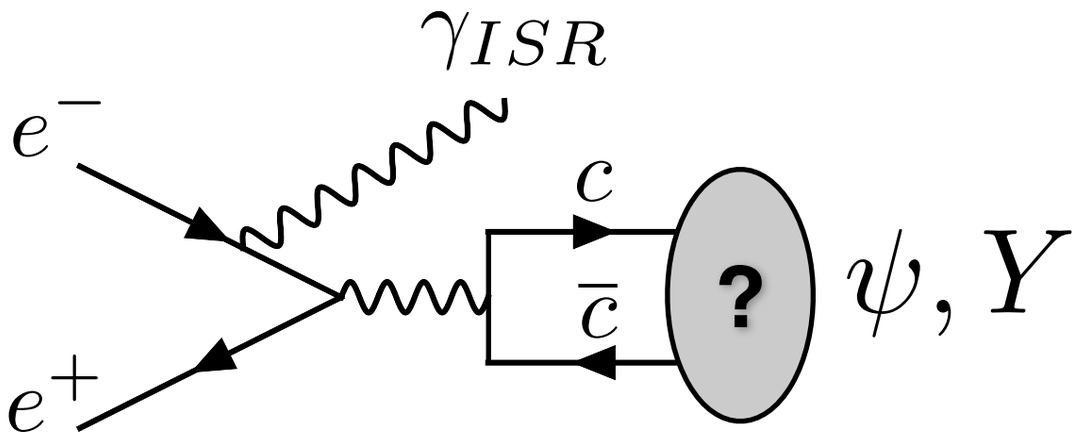
BOTTOMONIUM:

- 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 to charmonium (via ISR)



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

Part I: The Experimental Landscape

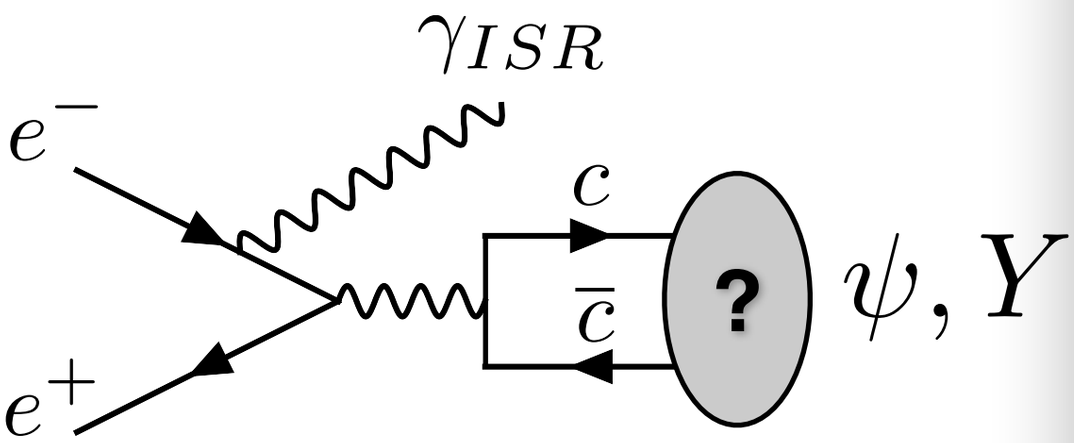
BOTTOMONIUM:

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

CHARMONIUM:

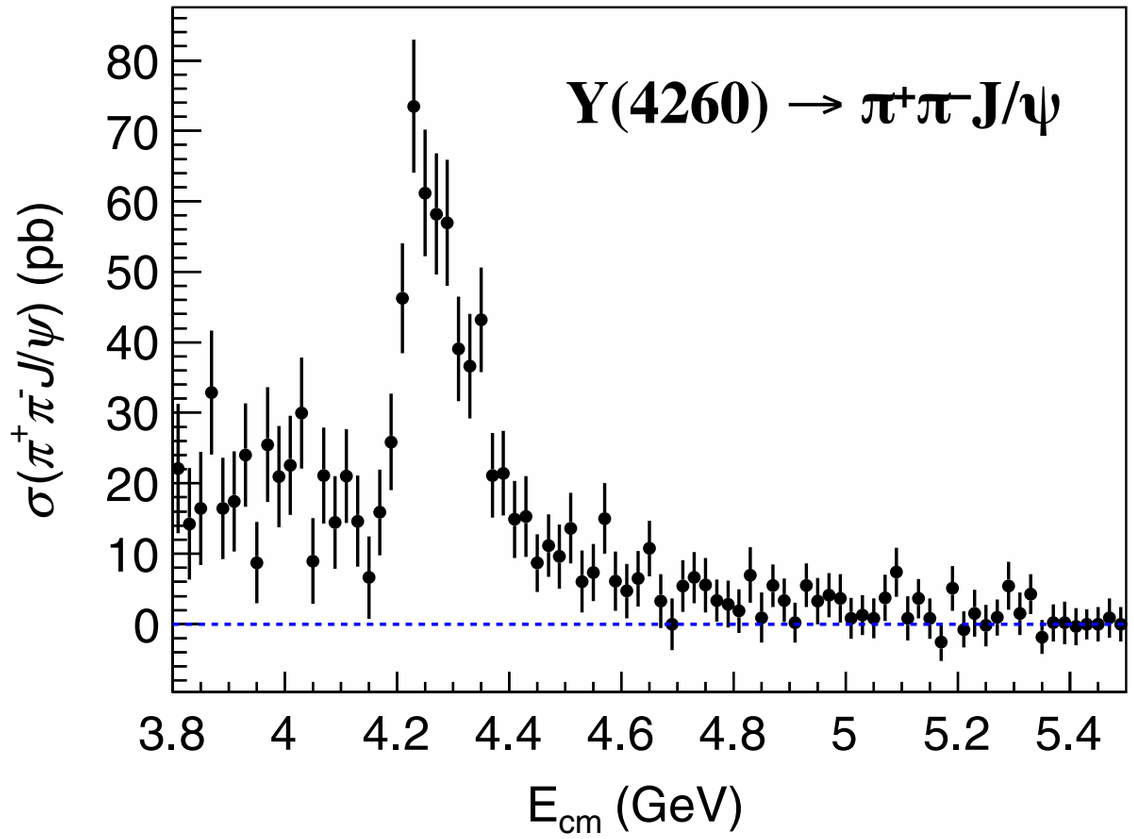
- e^+e^- annihilation using ISR (CLEO, BaBar
- *proton anti-proton annihilation (PANDA?!*

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



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

PRL 110, 252002 (2013)

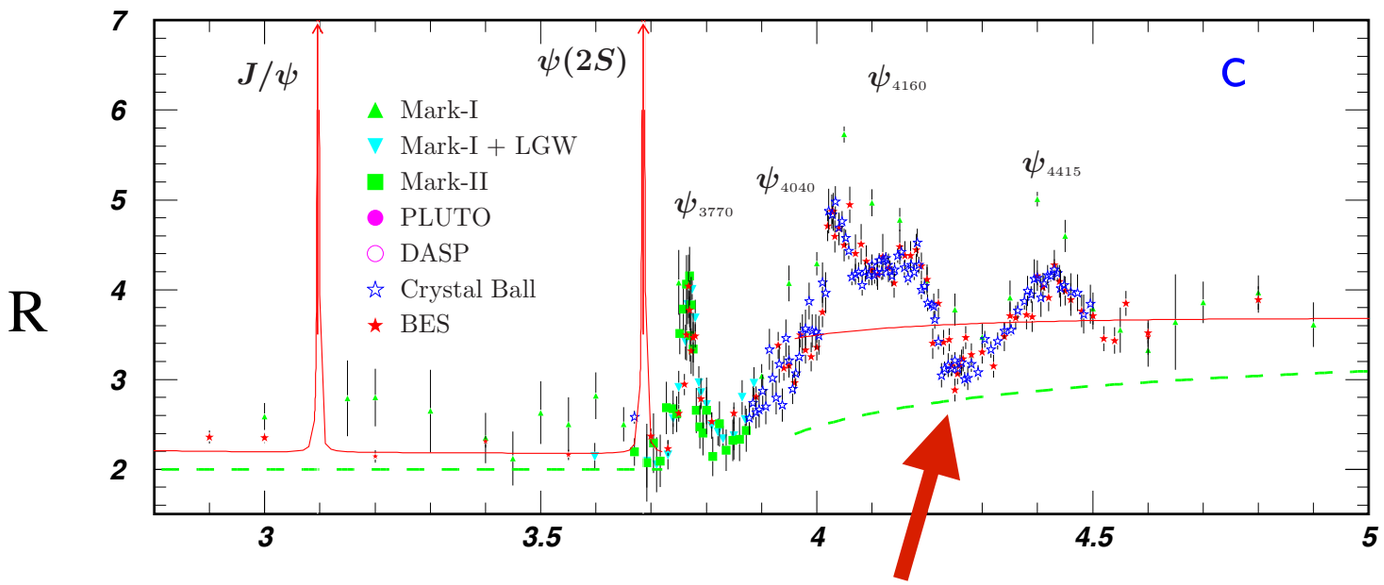


- the Y(4260) has no place in the quark model

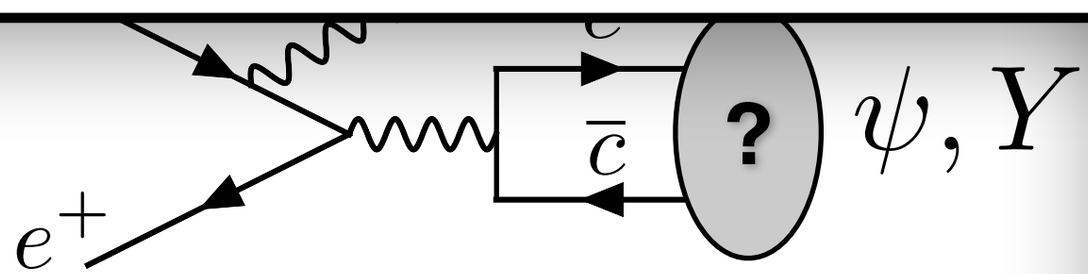
Part I: The Experimental Landscape

R in the Charmonium Region

PDG 2014



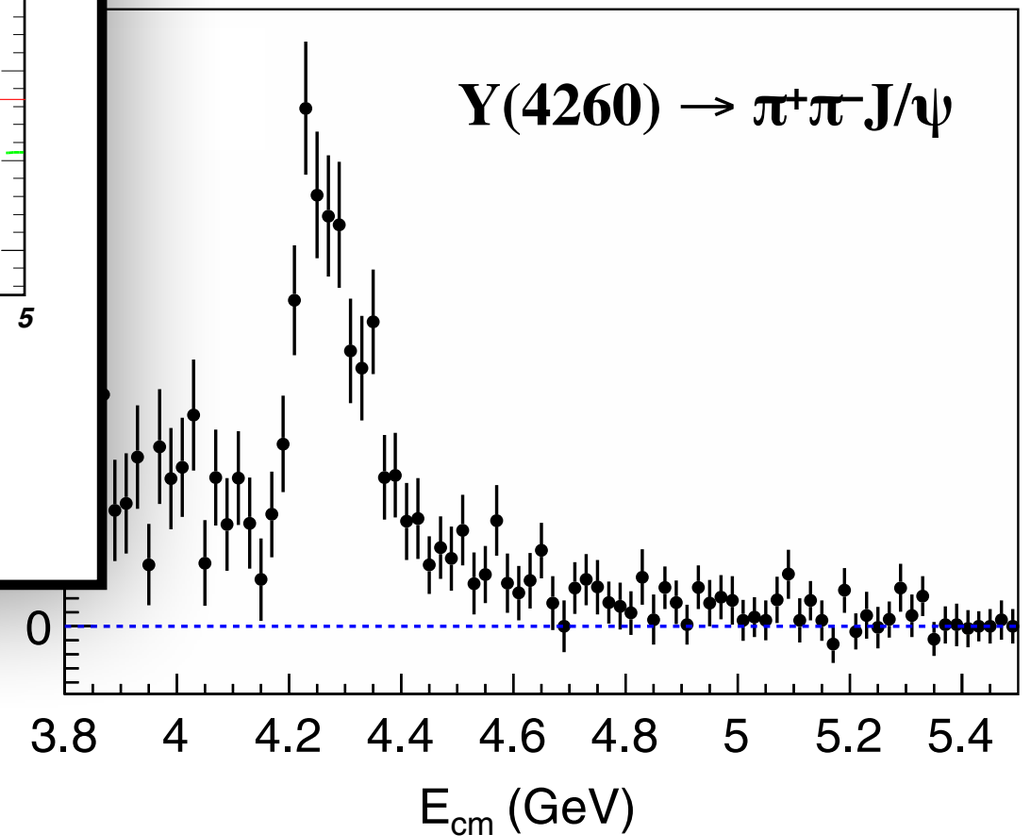
- the Y(4260) does not appear in R *(except possibly as a dip?)*



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

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

PRL 110, 252002 (2013)

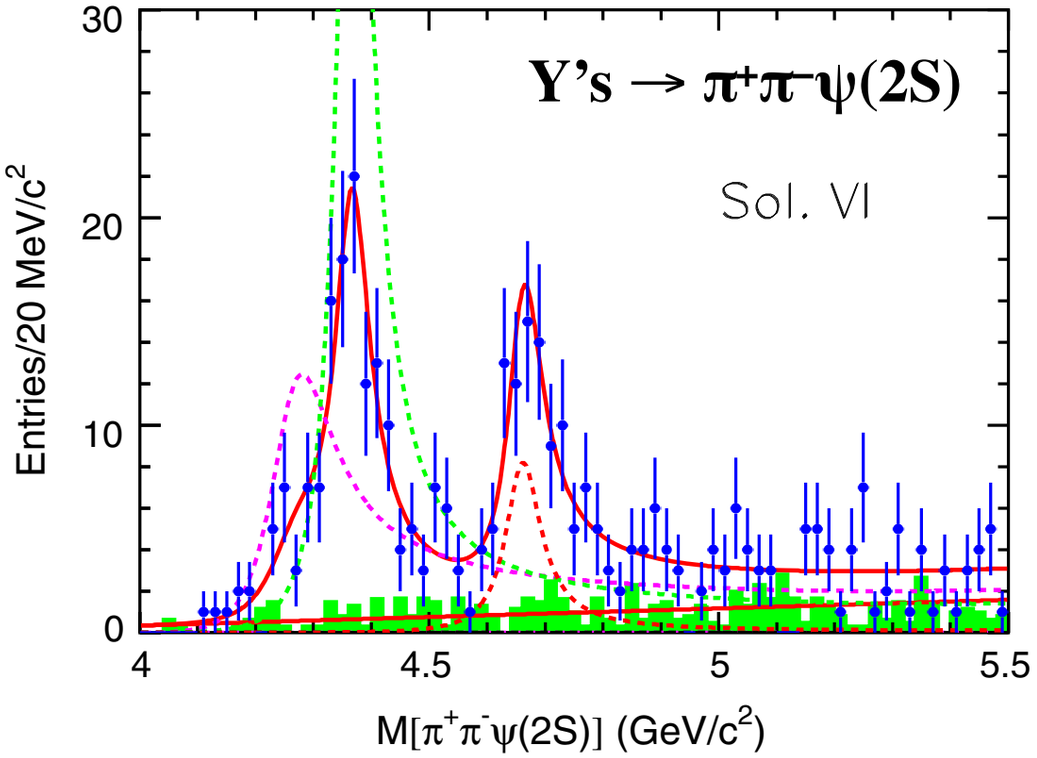


- the Y(4260) has no place in the quark model

Part I: The Experimental Landscape

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

PRD 91, 112007 (2015)

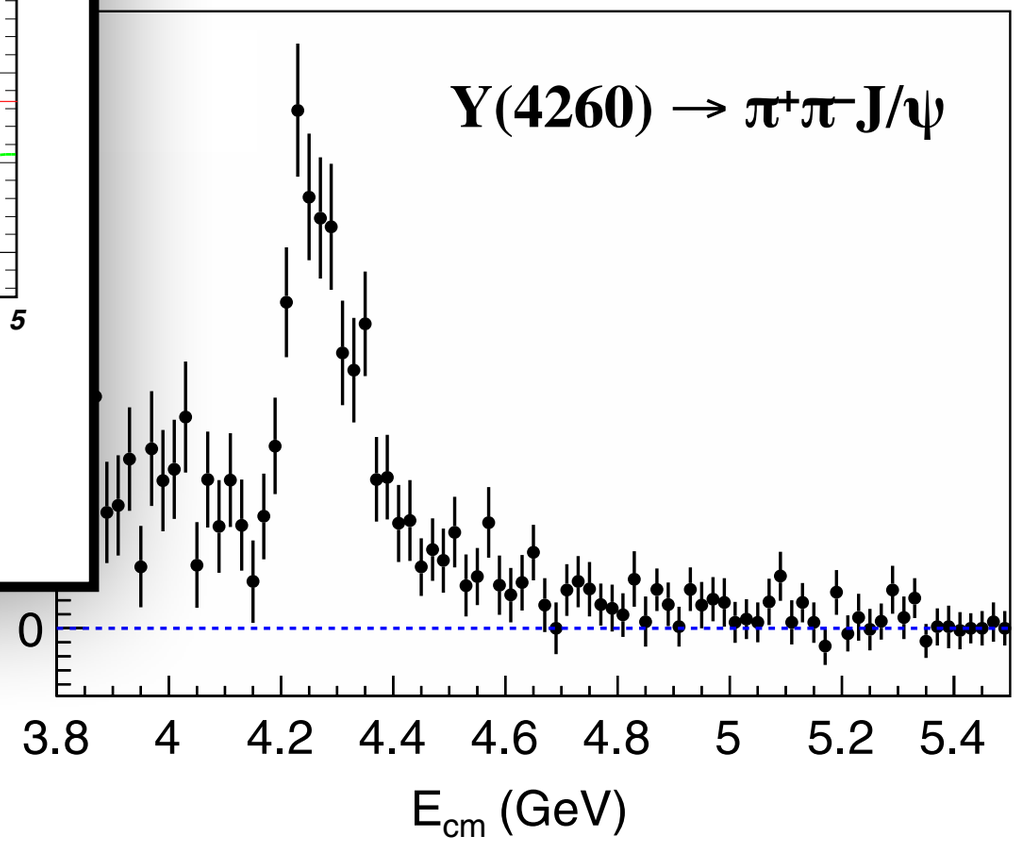


- there are also the Y(4360) and a Y(4660)

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

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

PRL 110, 252002 (2013)



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

Part I: 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**) ⟶ Y(4260), Y(4360), Y(4660), …
- 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?!?!)*

Part I: 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?!?!)*

Part I: The Experimental Landscape

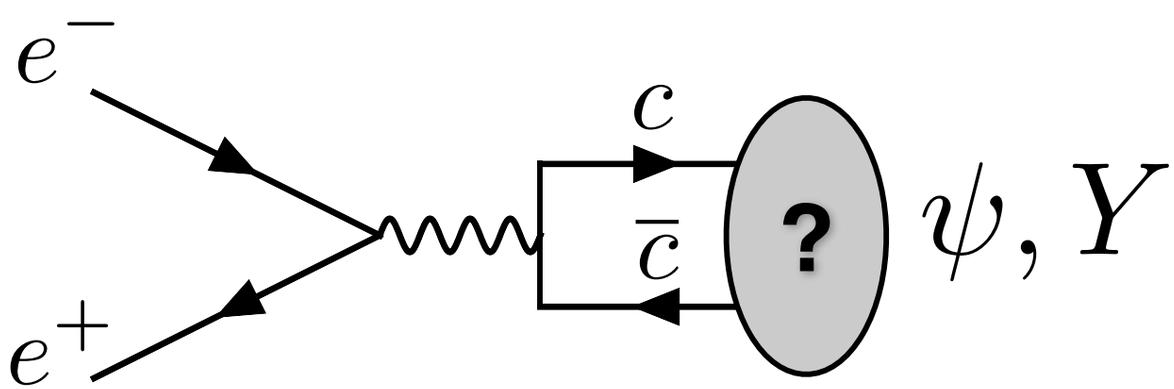
BOTTOMONIUM:

- 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



Part I: The Experimental Landscape

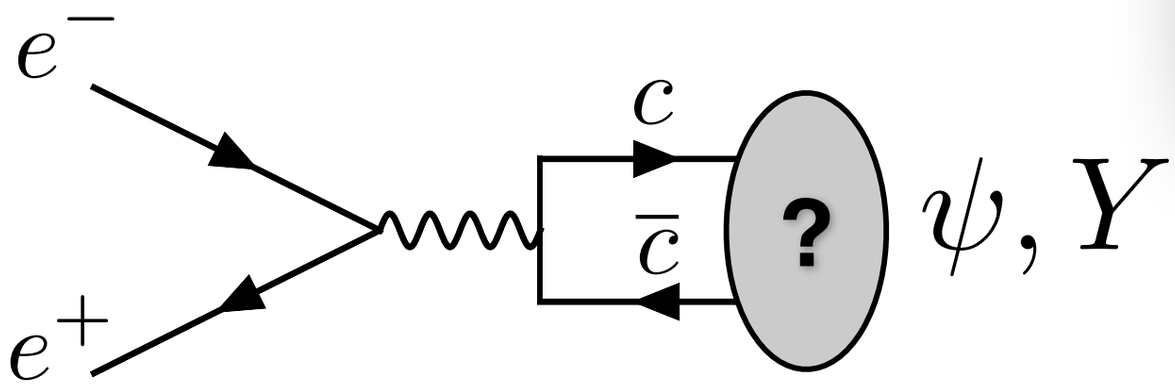
BOTTOMONIUM:

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

CHARMONIUM:

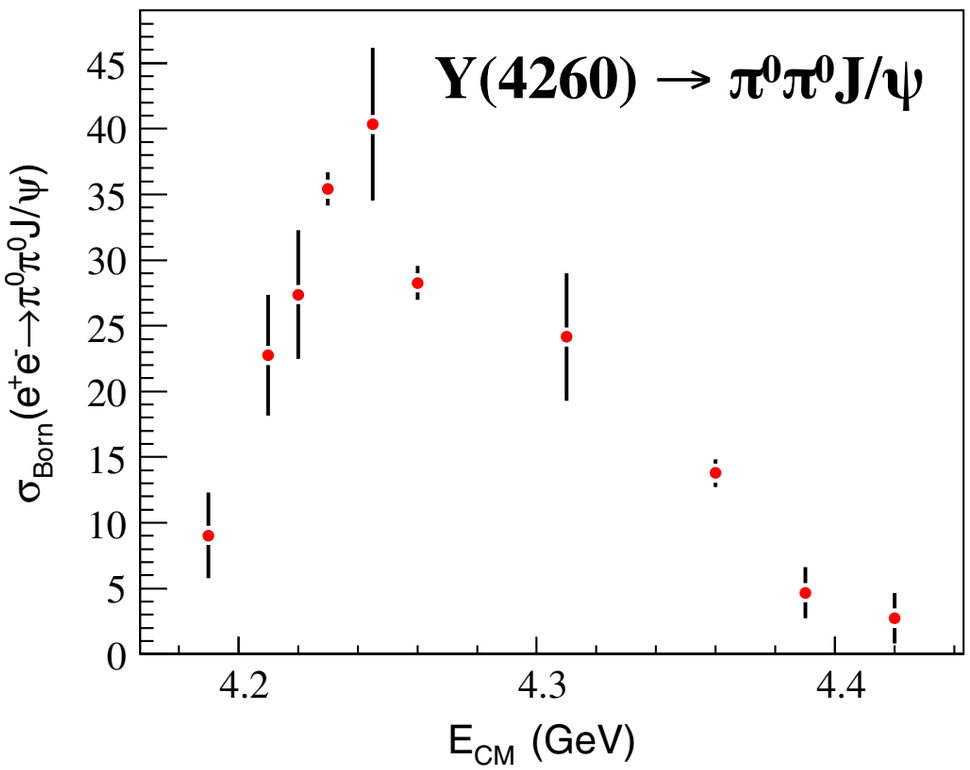
- e^+e^- annihilation using ISR (CLEO, BaBar, Be
- e^+e^- annihilation (CLEO-c, **BESIII**)

e^+e^- annihilation to charmonium



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

PRL 115, 112003 (2015)



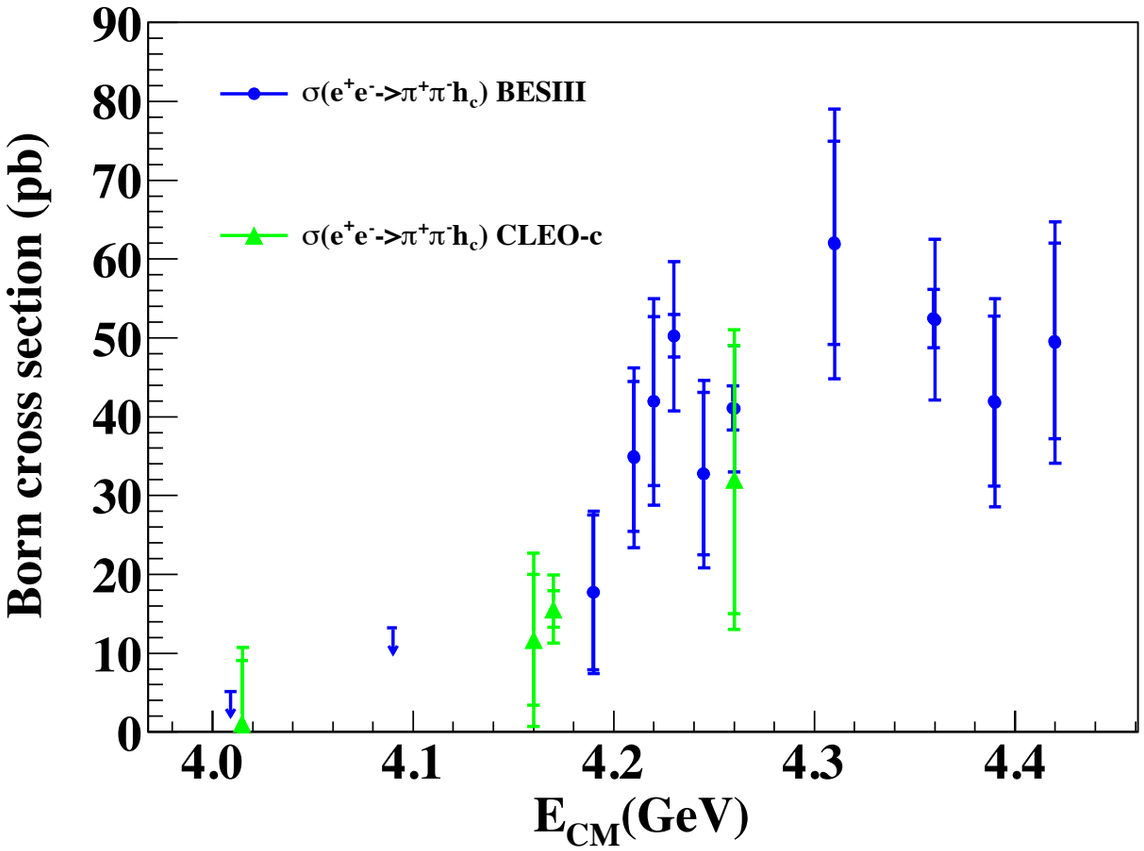
- another view of the Y(4260).

, Belle)

Part I: The Experimental Landscape

$e^+e^- \to \pi^+\pi^- h_c(1P)$ at BESIII

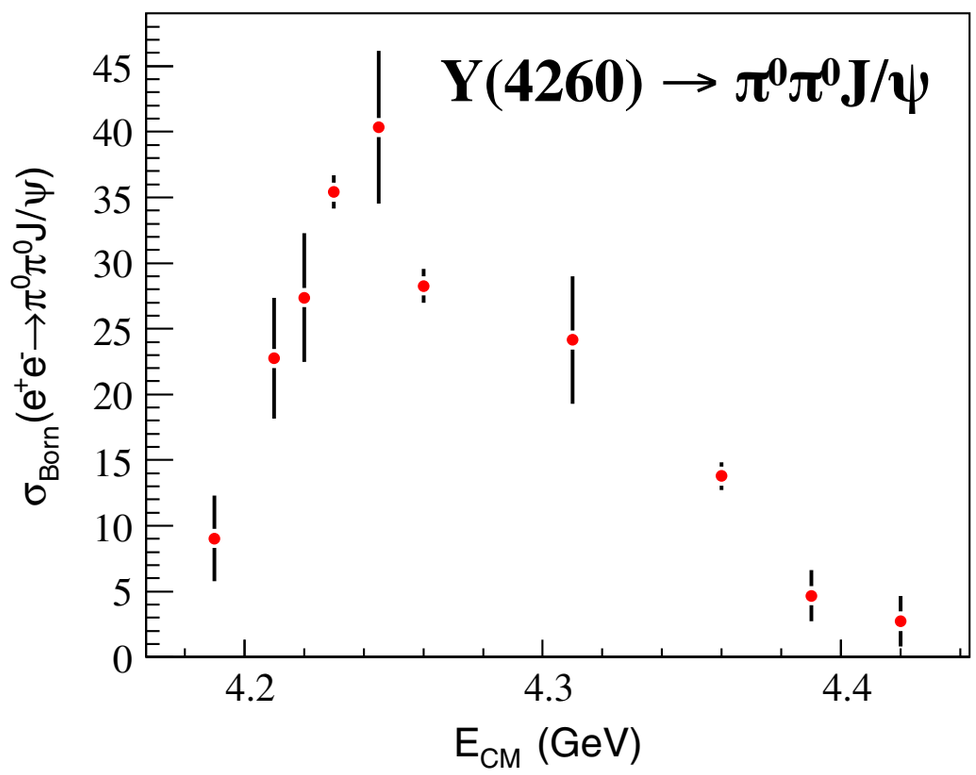
PRL 111, 242001 (2013)



- the $\pi^+\pi^- h_c(1P)$ shape is different.

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

PRL 115, 112003 (2015)

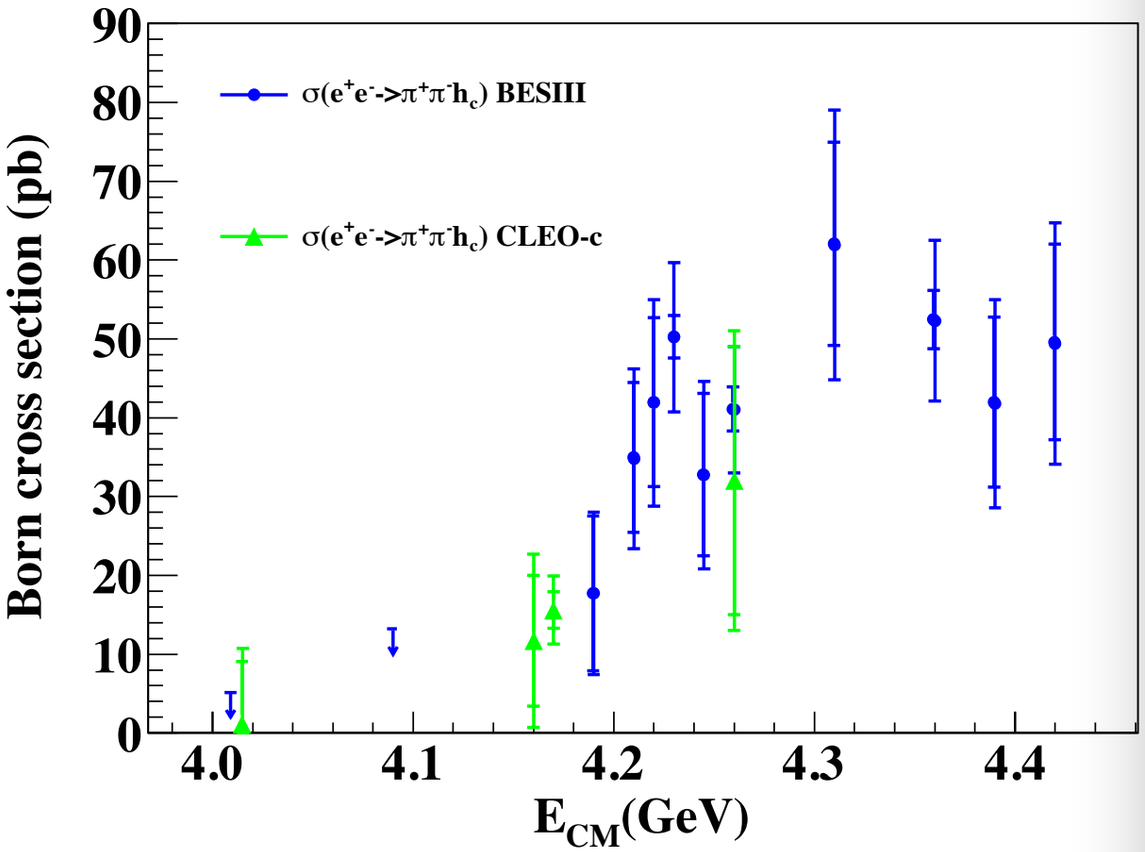


- another view of the Y(4260).

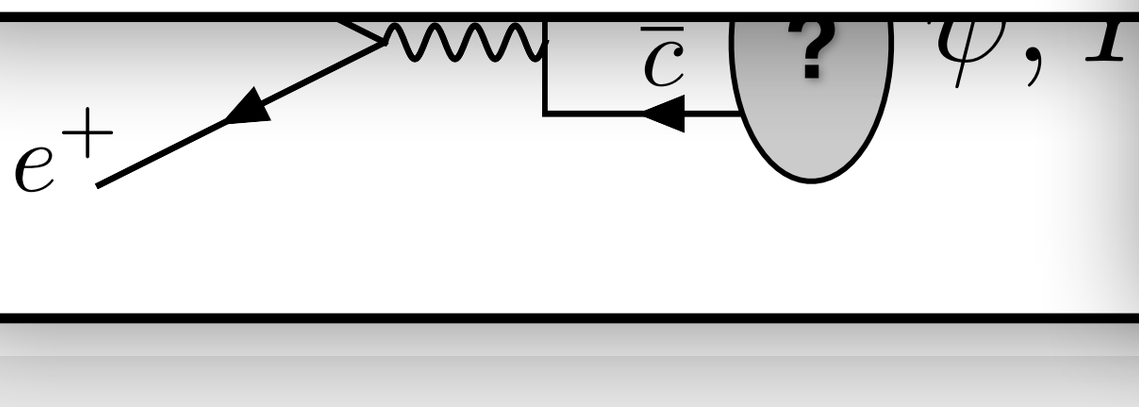
Part I: The Experimental Landscape

$e^+e^- \to \pi^+\pi^- h_c(1P)$ at BESIII

PRL 111, 242001 (2013)



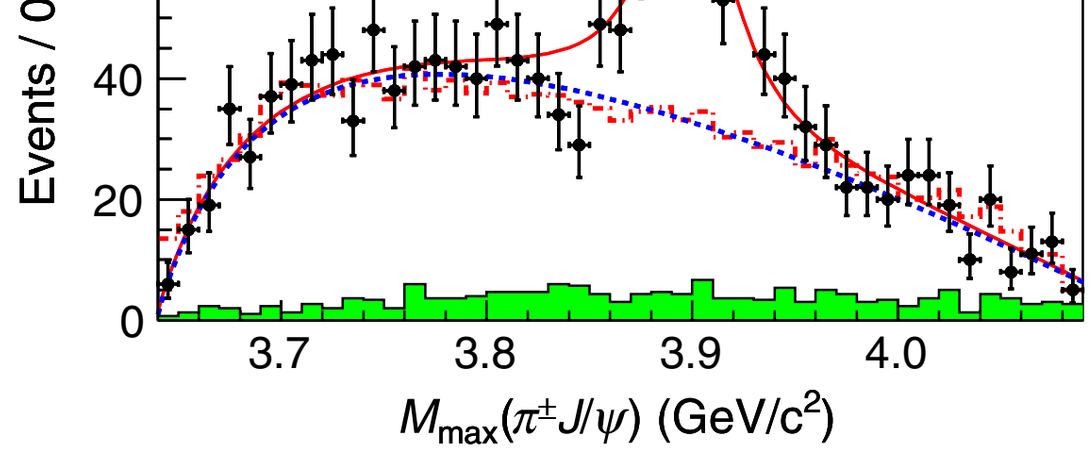
- the $\pi^+\pi^- h_c(1P)$ shape is different.



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

$e^+e^- \to \pi^\pm Z_c \to \pi^+\pi^- J/\psi$ at BESIII

PRL 110, 252001 (2013)



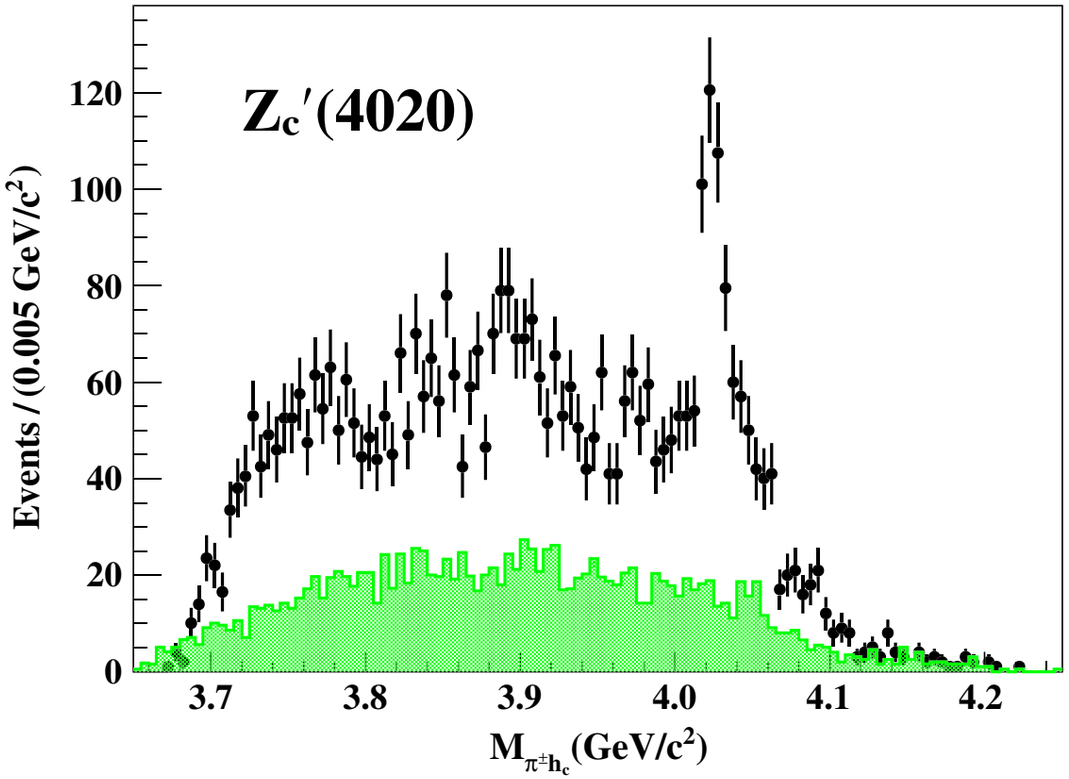
- substructure in $Y(4260) \to \pi^+\pi^- J/\psi$ *(similar substructure in $Y(4260) \to \pi^0\pi^0 J/\psi$)*, close to DD* threshold

Part I: The Experimental Landscape

$e^+e^- \to \pi^+\pi^- h_c(1P)$ at BESIII

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

PRL 111, 242001 (2013)

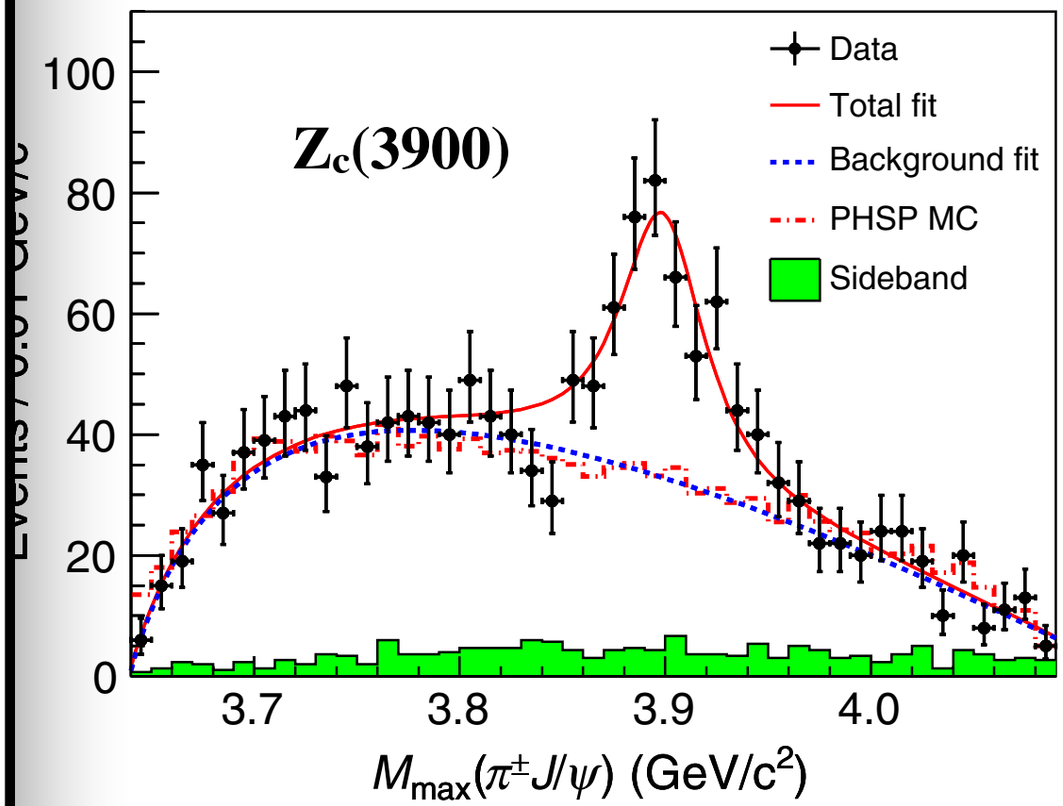


- substructure in $e^+e^- \to \pi^+\pi^- h_c(1P)$
  (similar substructure in $e^+e^- \to \pi^0\pi^0 h_c(1P)$),
  close to D*D* threshold

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

$e^+e^- \to \pi^\pm Z_c \to \pi^+\pi^- J/\psi$ at BESIII

PRL 110, 252001 (2013)



- substructure in $Y(4260) \to \pi^+\pi^- J/\psi$
  (similar substructure in $Y(4260) \to \pi^0\pi^0 J/\psi$),
  close to DD* threshold

Part I: 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**) → $Y(4260), Y(4360), \ldots$ $Z_c(3900), Z_c'(4020), \ldots$
- 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?!?!)*

Part I: The Experimental Landscape

BOTTOMONIUM:

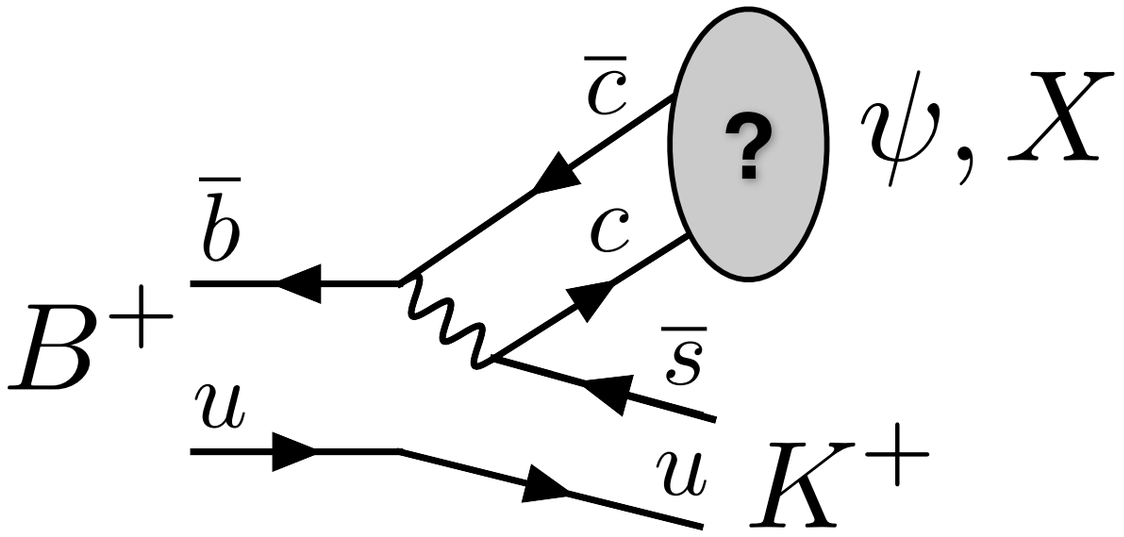
- e^+e^- annihilation (CLEO, BaBar, **Belle**)
- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

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?!?!)*

Part I: The Experimental Landscape

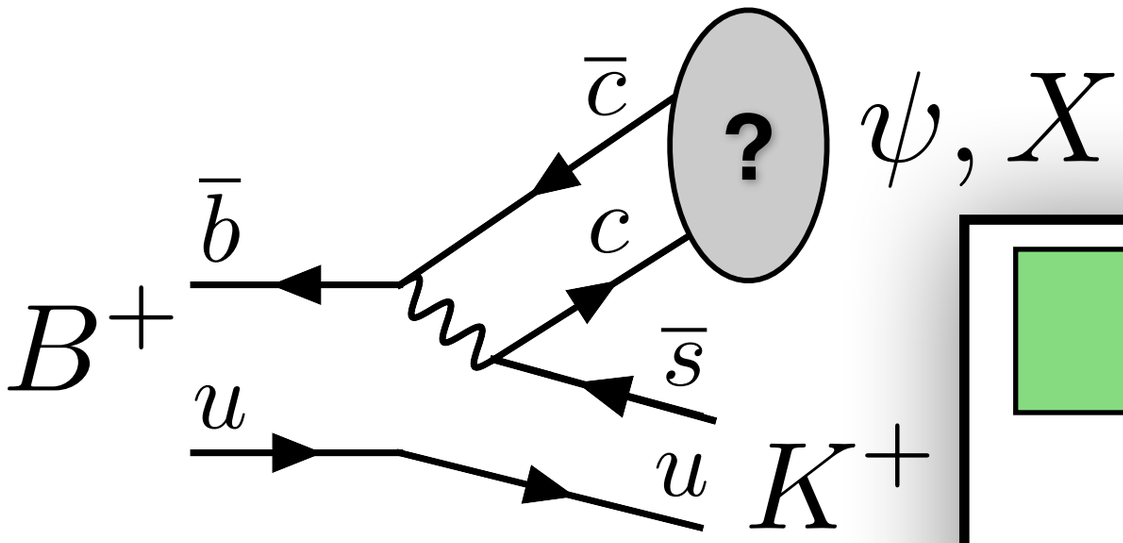
B decays to charmonium



- e^+e^- annihilation (CLEO-c, BESIII)
- B decay (CDF, D0, CLEO, BaBar, Belle, LHCb, ATLAS, CMS)
- proton collisions (CDF, D0, LHCb, ATLAS, CMS)
- $\gamma\gamma$ collisions (CLEO, BaBar, Belle)
- double charmonium production (CLEO, BaBar, Belle)
- *proton anti-proton annihilation (PANDA?!?!)*

Part I: The Experimental Landscape

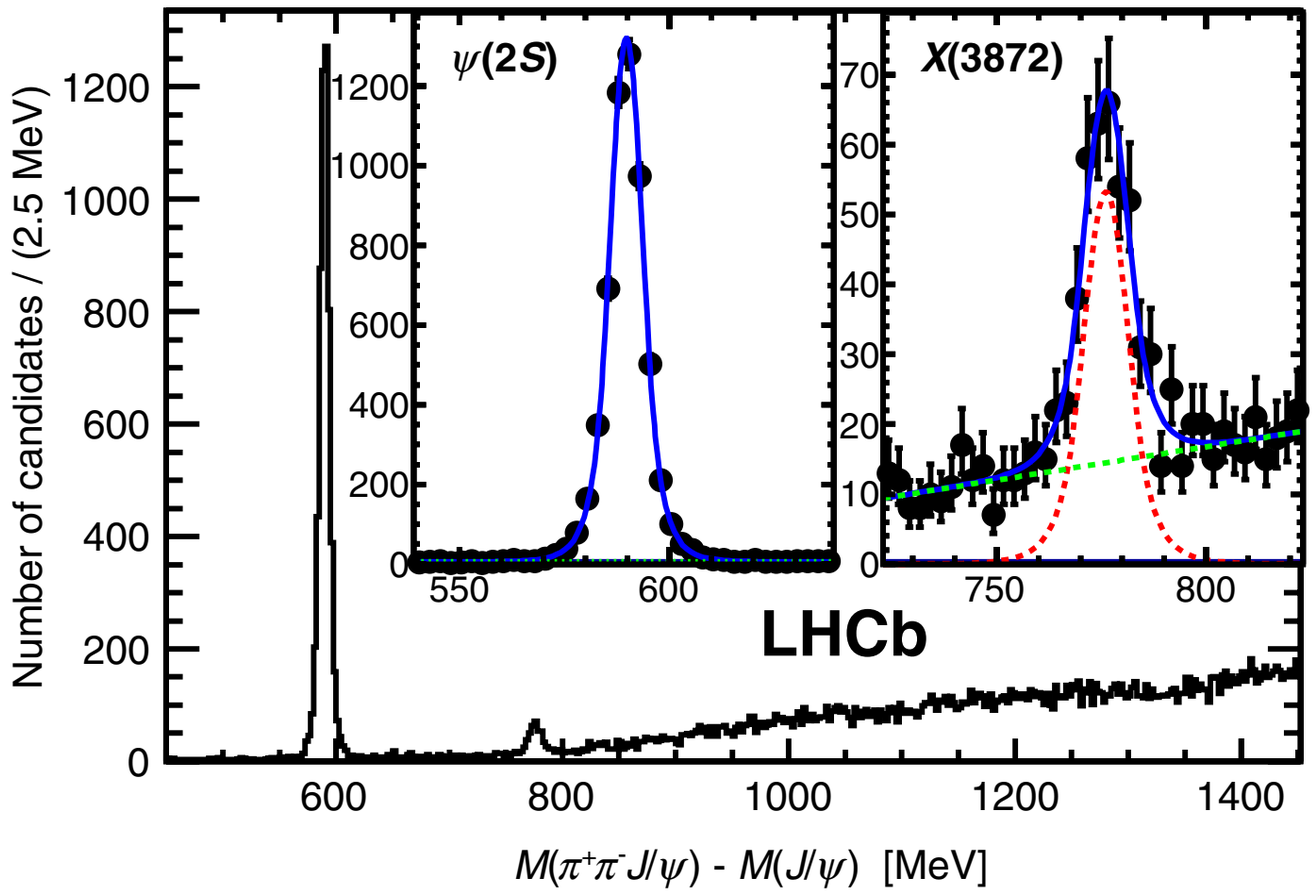
B decays to charmonium



- e^+e^- annihilation (CLEO-c, BESI
- B decay (CDF, D0, CLEO, BaBar
- proton collisions (CDF, D0, LHC
- $\gamma\gamma$ collisions (CLEO, BaBar, Bell
- double charmonium production (
- *proton anti-proton annihilation (*

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

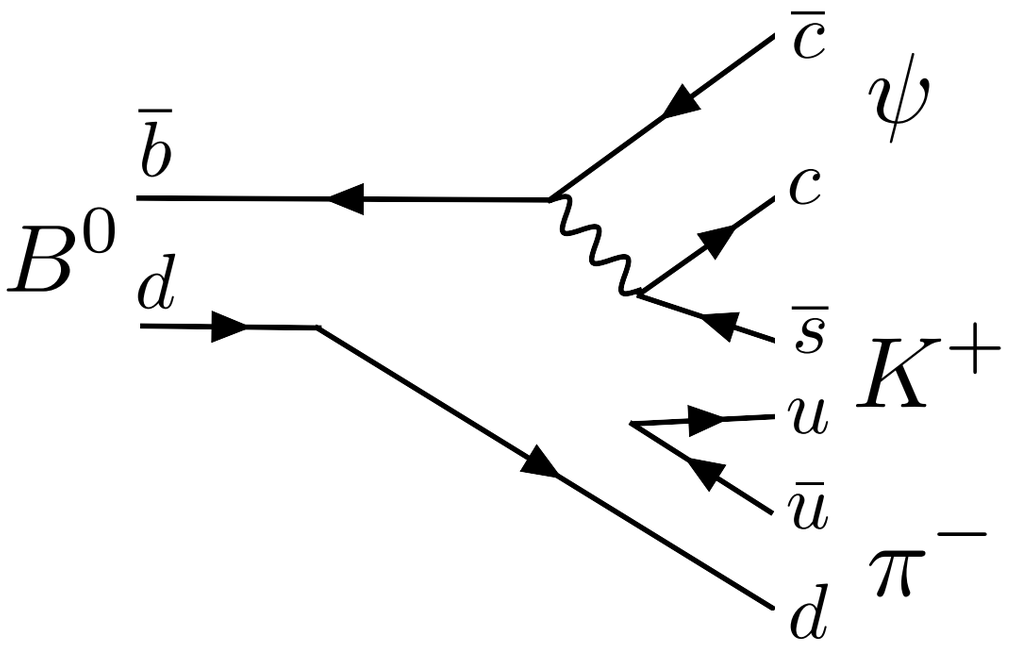
PRL 110, 222001 (2013)



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

Part I: The Experimental Landscape

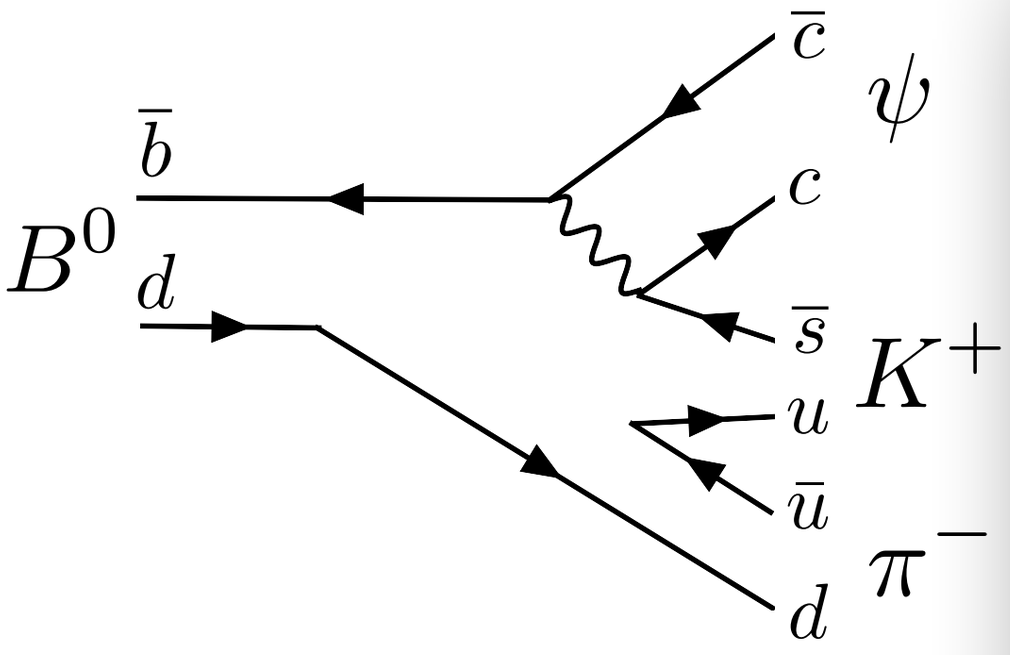
B decays to charmonium



- 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?!?!)*

Part I: The Experimental Landscape

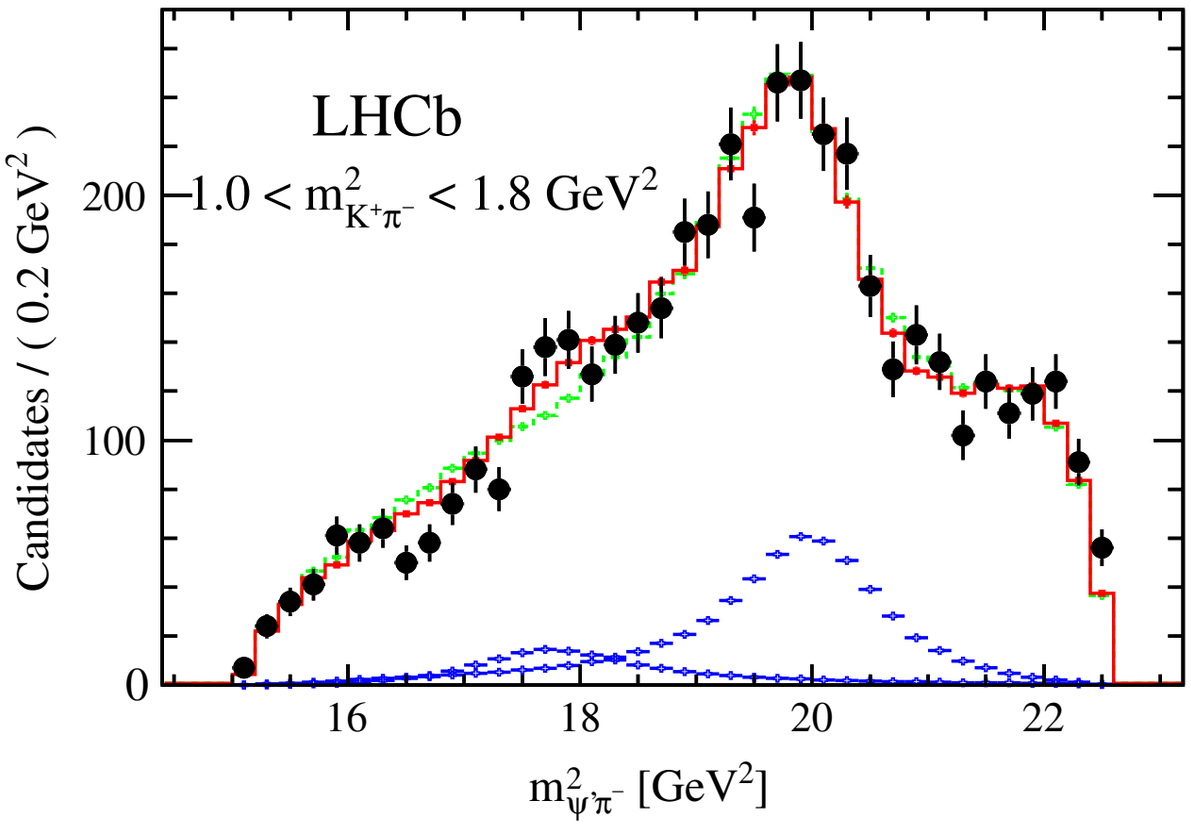
B decays to charmonium



- B decay (CDF, D0, CLEO, BaBar, Be
- proton collisions (CDF, D0, LHCb, A
- $\gamma\gamma$ collisions (CLEO, BaBar, Belle)
- double charmonium production (CLE
- *proton anti-proton annihilation (PANDA?!?!)*

$B^0 \to K^+(\pi^-\psi(2S))$ at LHCb

PRL 112, 222002 (2014)

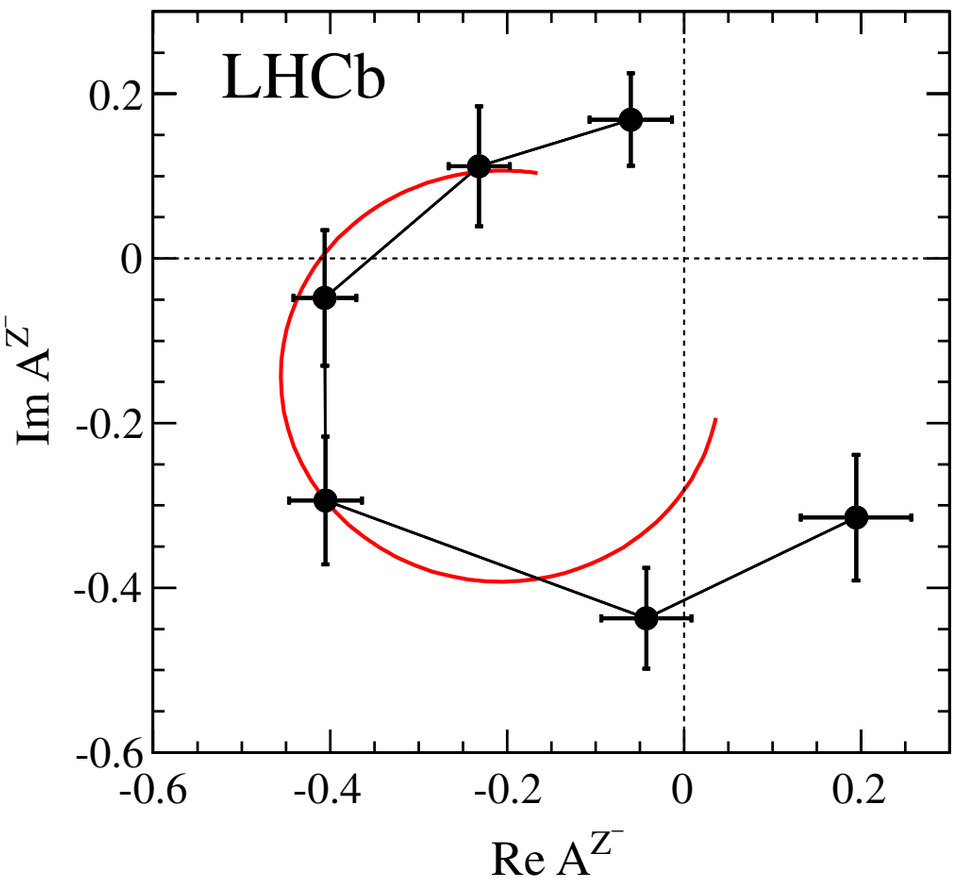


- there are also charged Z states in B decays, e.g., the $Z_1(4430)$ [and the $Z_0(4240)$]

Part I: The Experimental Landscape

$B^0 \to K^+(\pi^-\psi(2S))$ at LHCb

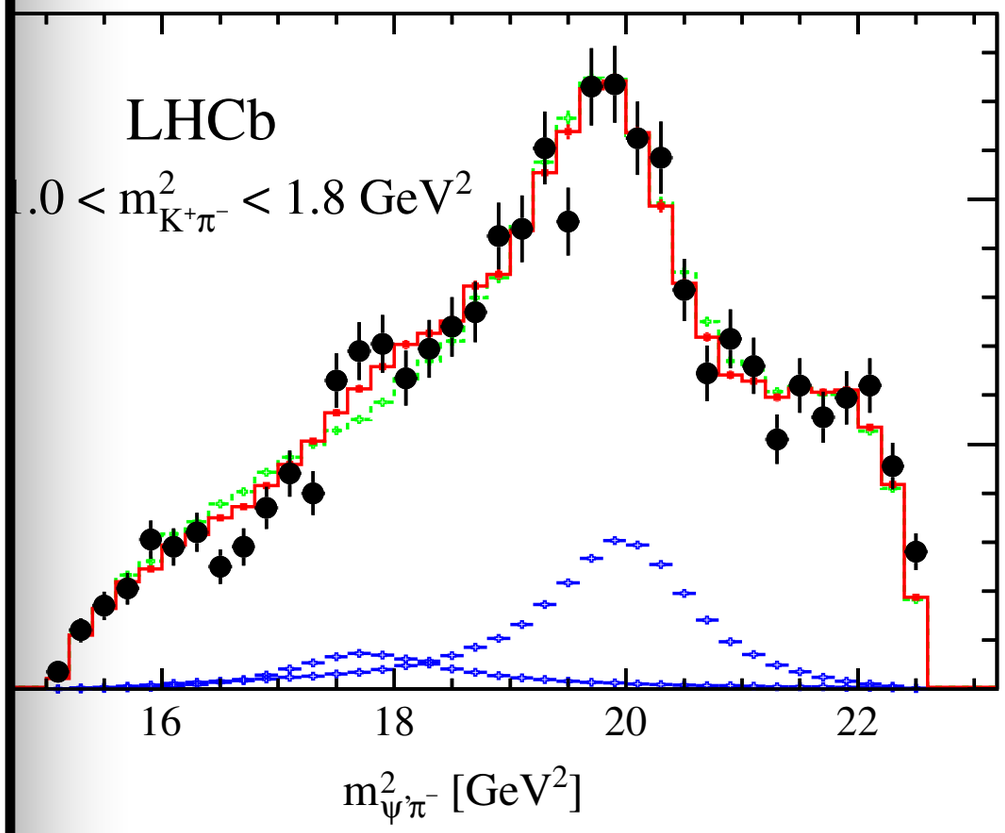
PRL 112, 222002 (2014)



- phase motion of $Z_1(4430)$ decay

$B^0 \to K^+(\pi^-\psi(2S))$ at LHCb

PRL 112, 222002 (2014)



are also charged Z states in B decays,
e.g., the $Z_1(4430)$ [and the $Z_0(4240)$]

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

Part I: 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**) → X(3872), $Z_1(4430)$, $Z_0(4240)$, …
- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)
- $\gamma\gamma$ collisions (CLEO, BaBar, **Belle**)
- double charmonium production (CLEO, BaBar, **Belle**)
- *proton anti-proton annihilation (PANDA?!?!)*

Part I: The Experimental Landscape

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, **Belle**) → "ϒ(5S)", "ϒ(6S)", Z_b, Z_b'
- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

CHARMONIUM:

- e^+e^- annihilation using ISR (CLEO, BaBar, **Belle**) → Y(4260), Y(4360), Y(4660), …
- e^+e^- annihilation (CLEO-c, **BESIII**) → Y(4260), Y(4360), … $Z_c(3900)$, $Z_c'(4020)$, …
- B decay (CDF, D0, CLEO, BaBar, **Belle**, **LHCb**, **ATLAS**, **CMS**) → X(3872), $Z_1(4430)$, $Z_0(4240)$, …
- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)
- γγ collisions (CLEO, BaBar, **Belle**)
- double charmonium production (CLEO, BaBar, **Belle**)
- *proton anti-proton annihilation (PANDA?!?!)*

Part I: 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?!?!)*

Part I: The Experimental Landscape

BOTTOMONIUM:

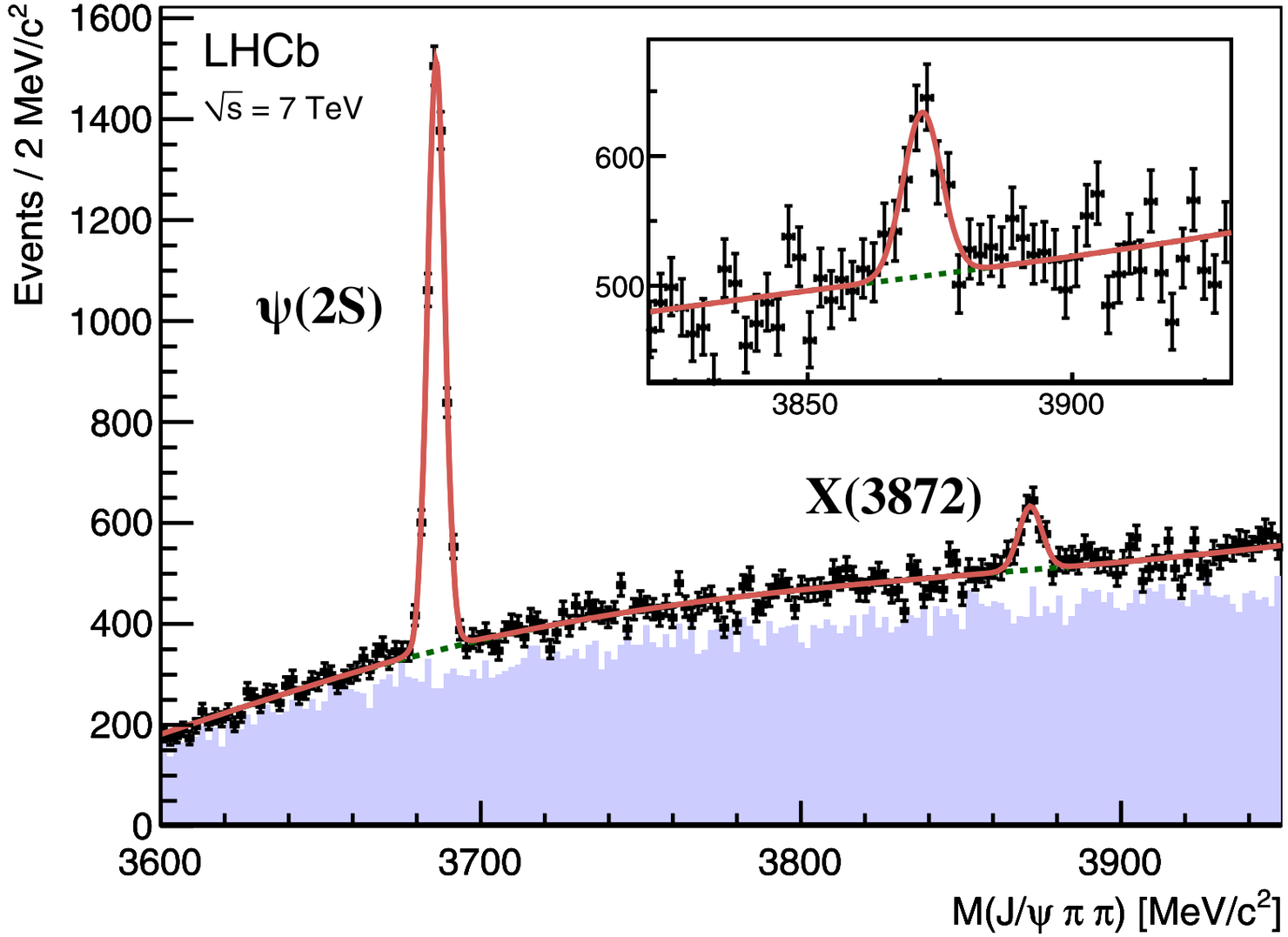
- e^+e^- annihilation (CLEO
- proton collisions (CDF,

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 proc
- *proton anti-proton annih*

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

EPJ C72, 1972 (2012)



- another view of the X(3872)

Part I: 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?!?!)*

Part I: The Experimental Landscape

BOTTOMONIUM:

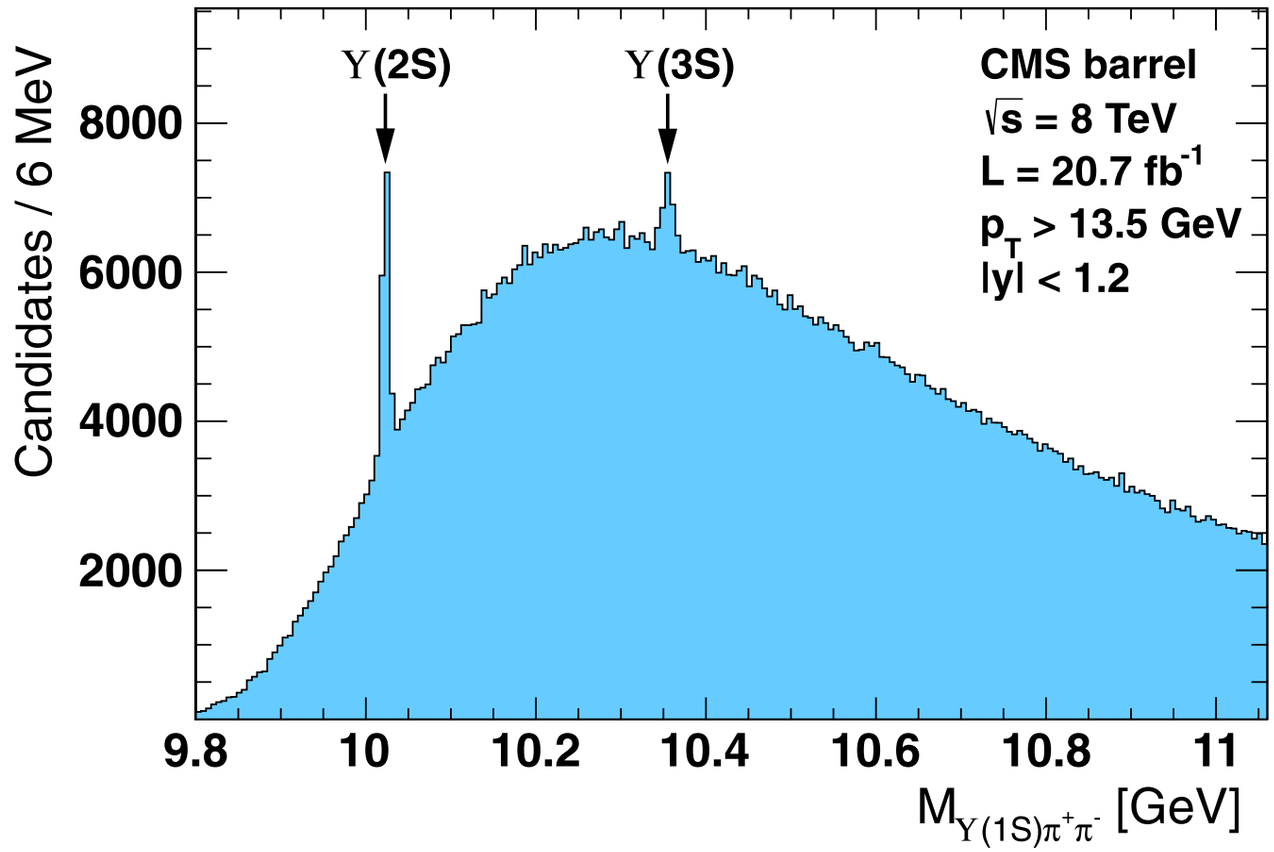
- e^+e^- annihilation (CLEO, BaBa
- proton collisions (CDF, D0, LH

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?!?!)*

$pp \rightarrow \pi^+\pi^-\Upsilon(1S) + X$ at CMS

PLB 727, 57 (2013)



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

Part I: The Experimental Landscape

BOTTOMONIUM:

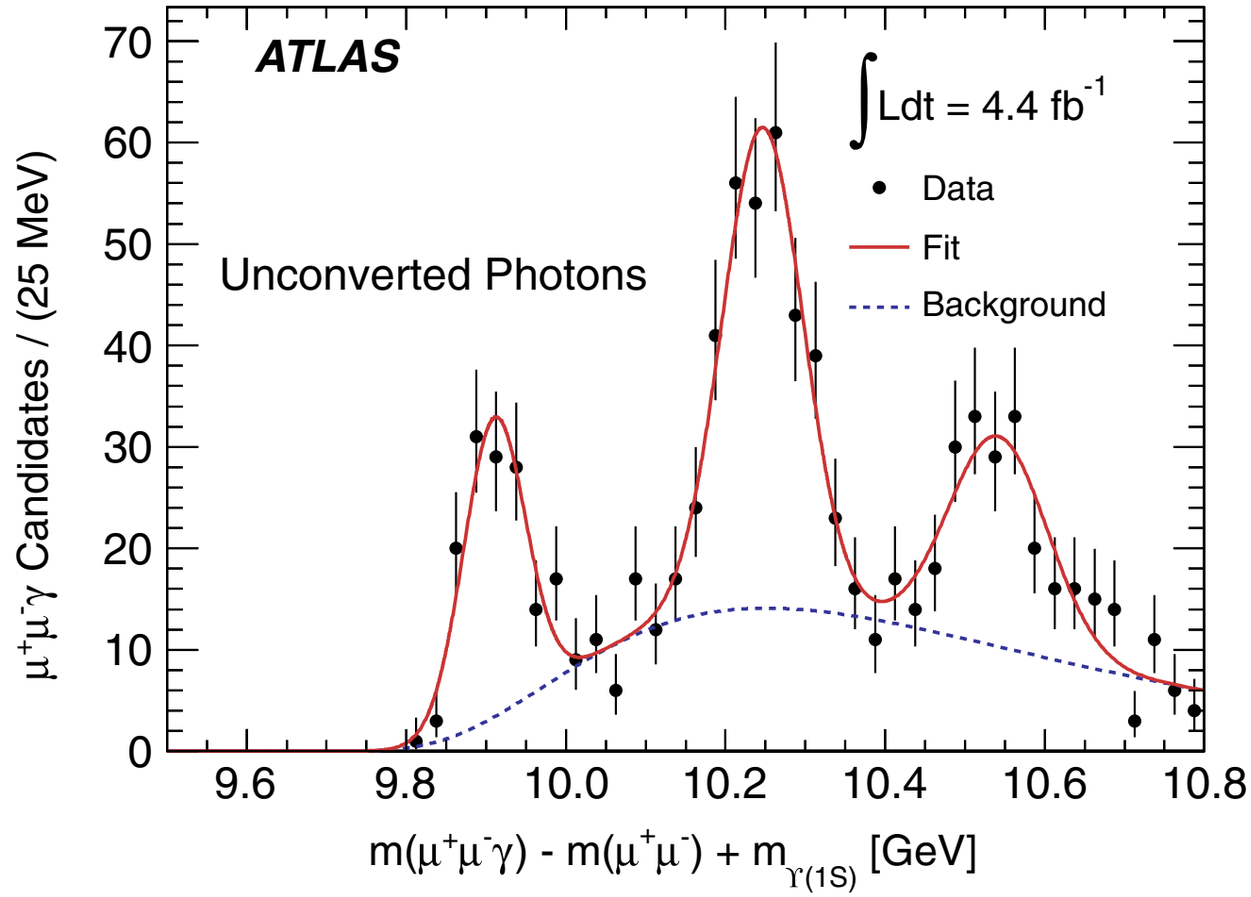
- e^+e^- annihilation (CLEO, B
- proton collisions (CDF, D0

CHARMONIUM:

- e^+e^- annihilation using ISR
- e^+e^- annihilation (CLEO-c
- B decay (CDF, D0, CLEO
- proton collisions (CDF, D0
- $\gamma\gamma$ collisions (CLEO, BaB
- double charmonium produ
- *proton anti-proton annihilation (PANDA?!?!)*

$pp \rightarrow \gamma\Upsilon(1S) + X$ at ATLAS

PRL 108, 152001 (2012)



- discovery of the $\chi_b(3P)$ states

Part I: The Experimental Landscape

BOTTOMONIUM:

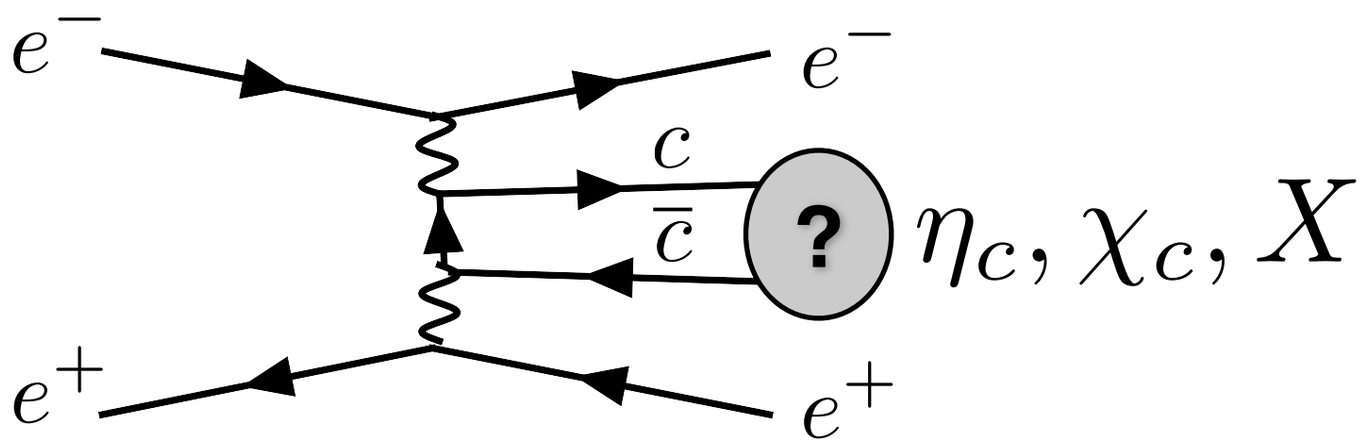
- e^+e^- annihilation (CLEO, BaBar, **Belle**)
- proton collisions (CDF, D0, **LHCb**, **ATLAS**, **CMS**)

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?!?!)*

Part I: The Experimental Landscape

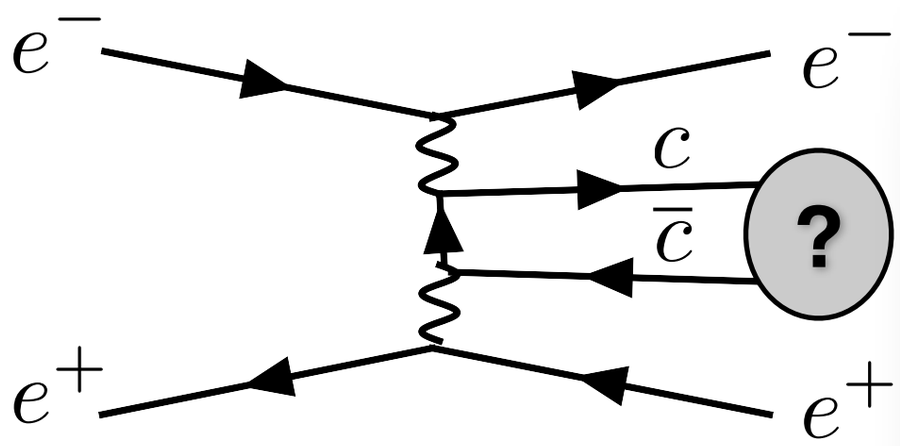
γγ collisions to charmonium



- 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?!?!)*

Part I: The Experimental Landscape

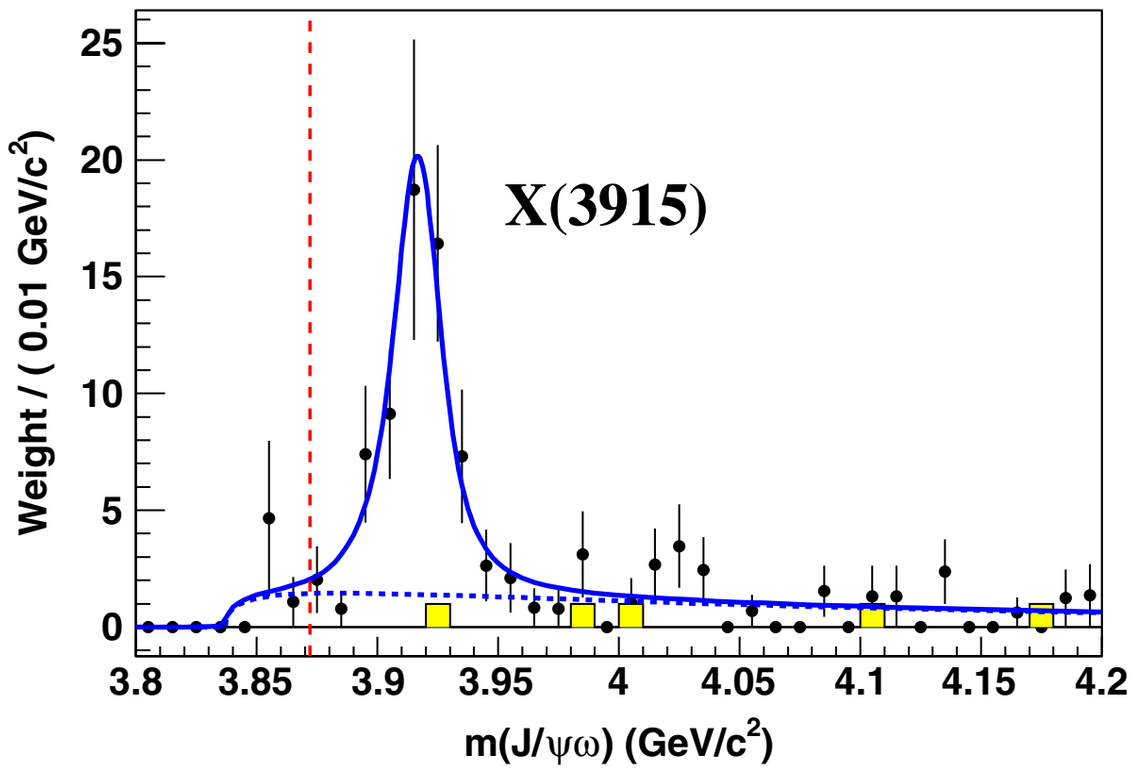
γγ collisions to charmonium



- 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)



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

Part I: 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?!?!)*

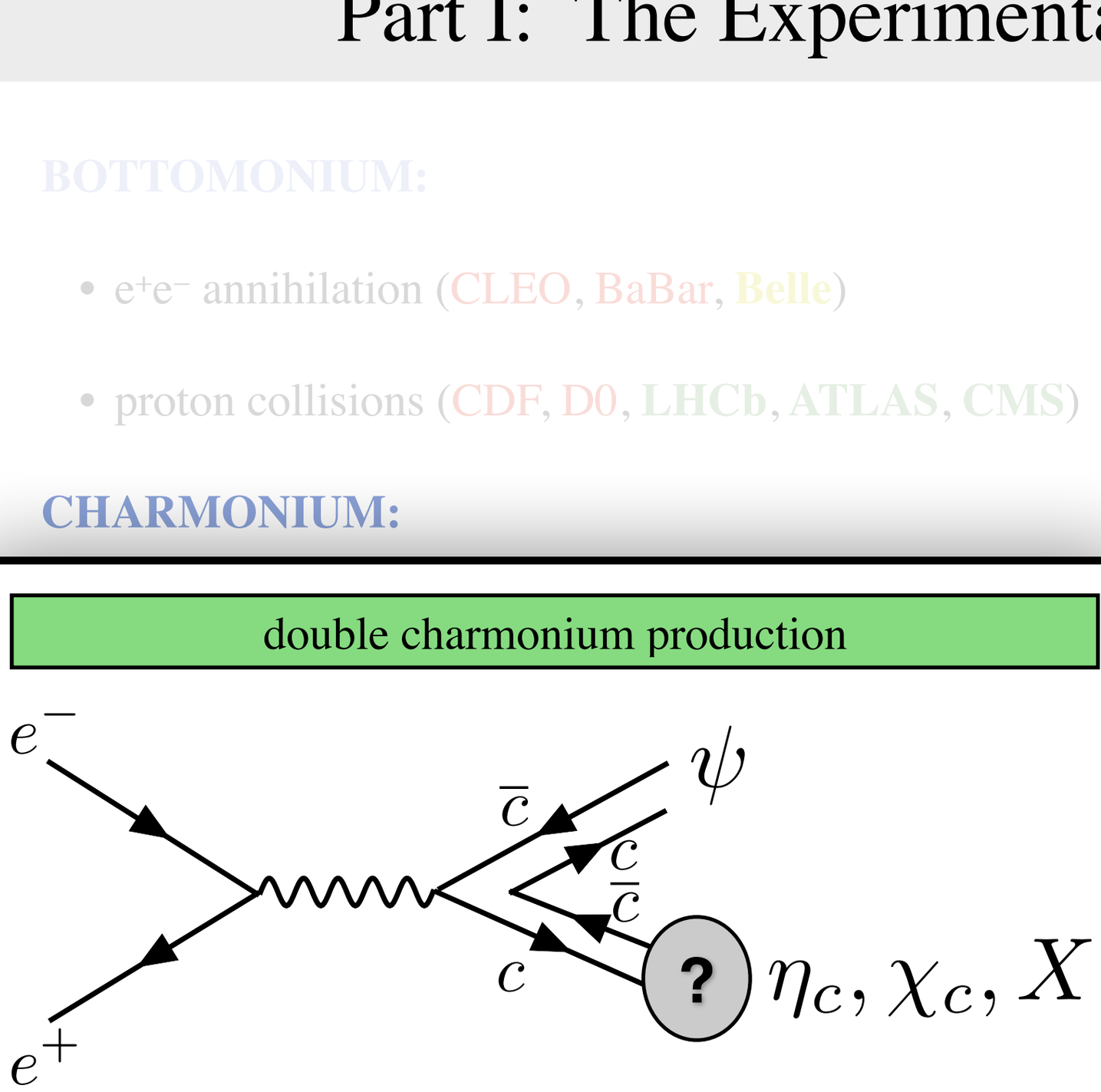
Part I: The Experimental Landscape

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?!?!)*

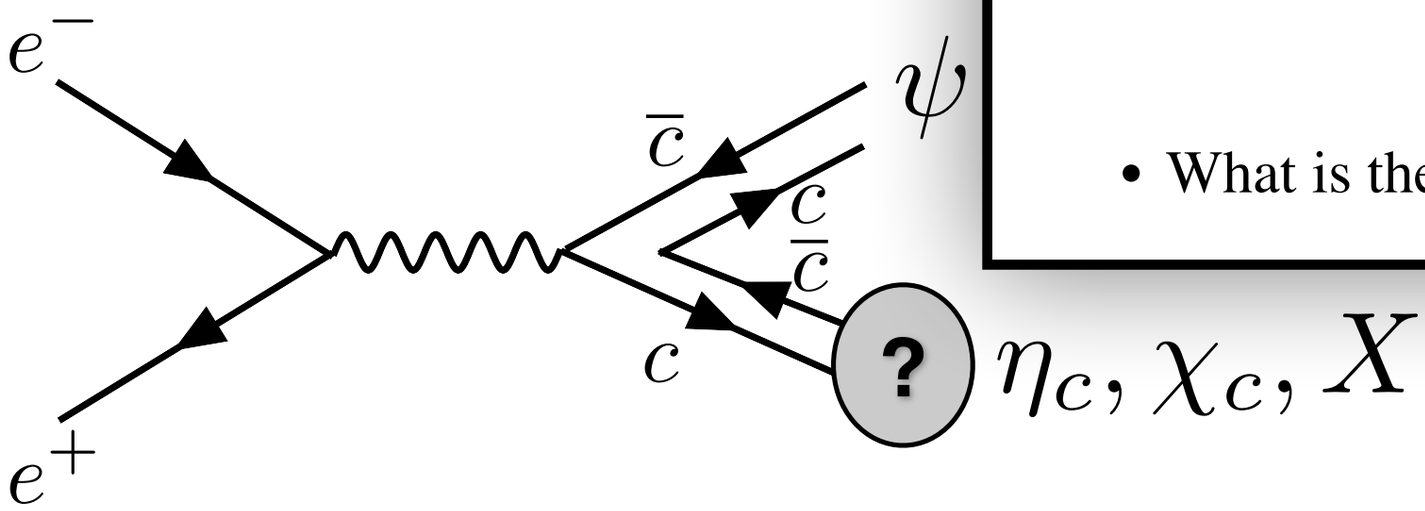
Part I: The E

BOTTOMONIUM:

- e^+e^- annihilation (CLEO, BaBar, B
- proton collisions (CDF, D0, LHCb

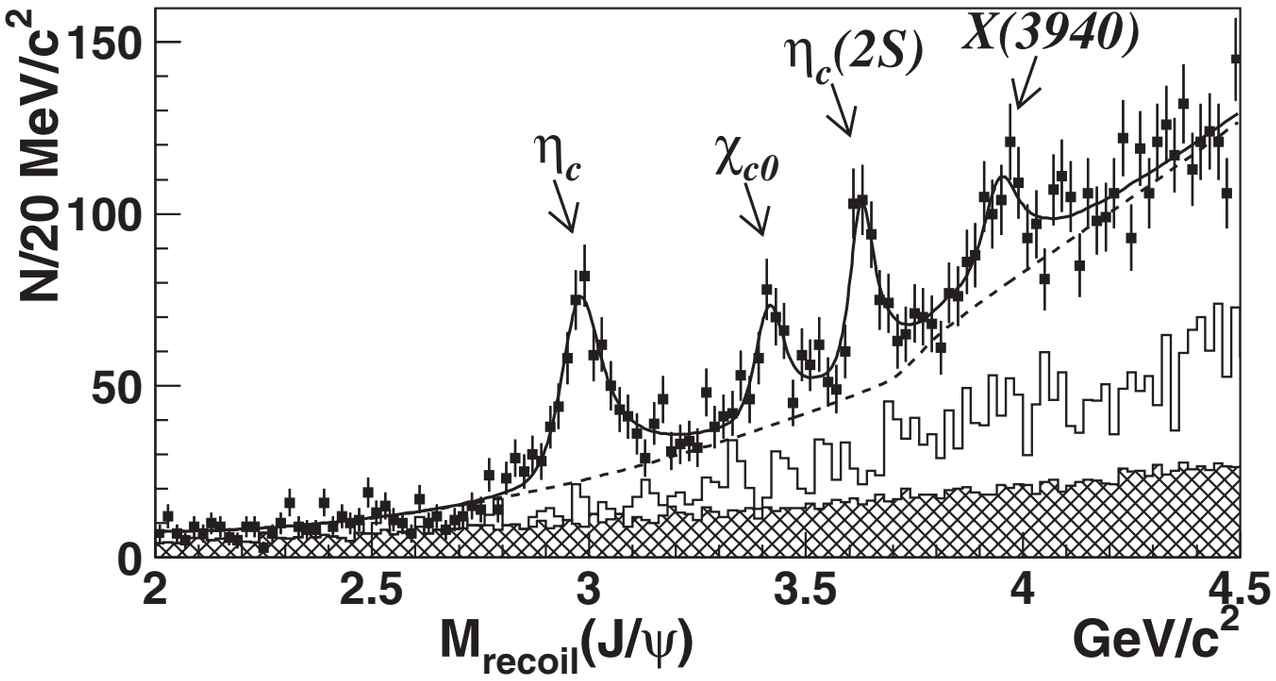
CHARMONIUM:

double charmonium produ



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

PRL 98, 082001 (2007)



- What is the X(3940)?

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

Part I: 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?!?!)*

Part I: 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?!?!)*

Part II: Connections and Complexities

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

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

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

Part II: Connections and Complexities

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

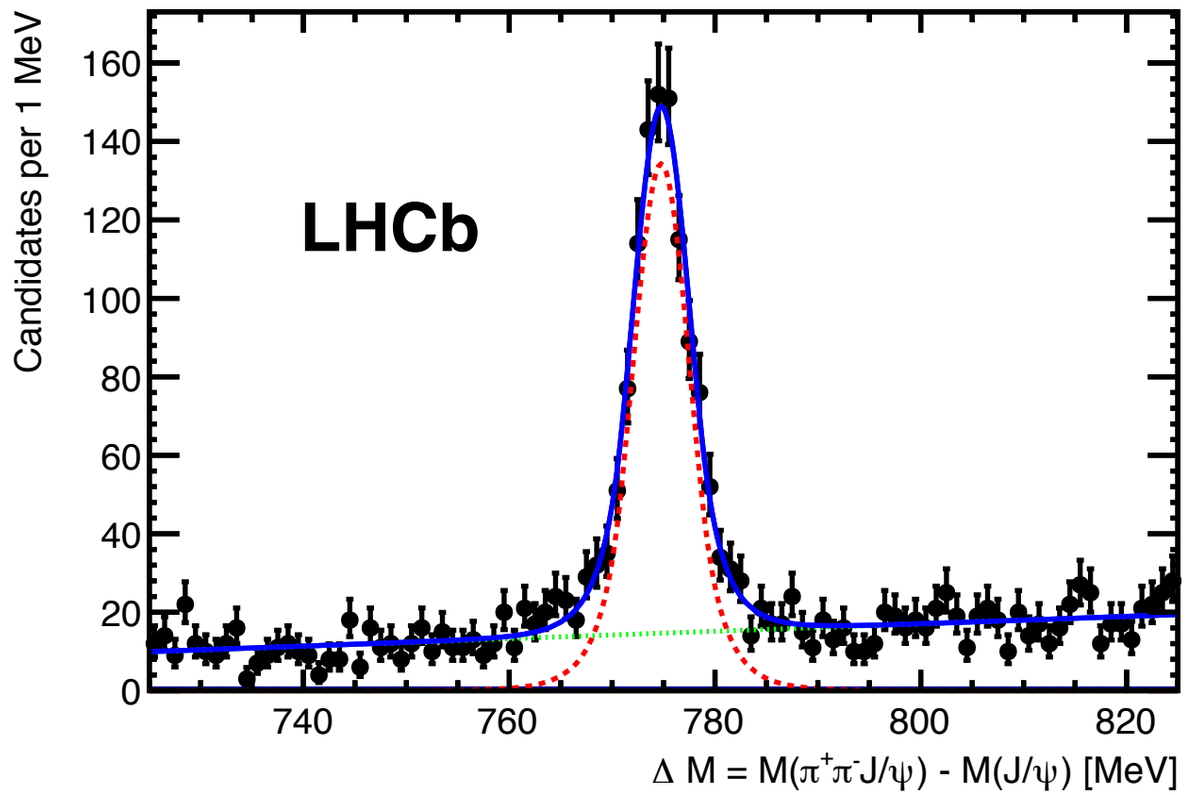
Connections II: The Z_c and Z_c' and the Z_b and Z_b'.

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

Overview of the X(3872)

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

PRD 92, 011102 (2015)

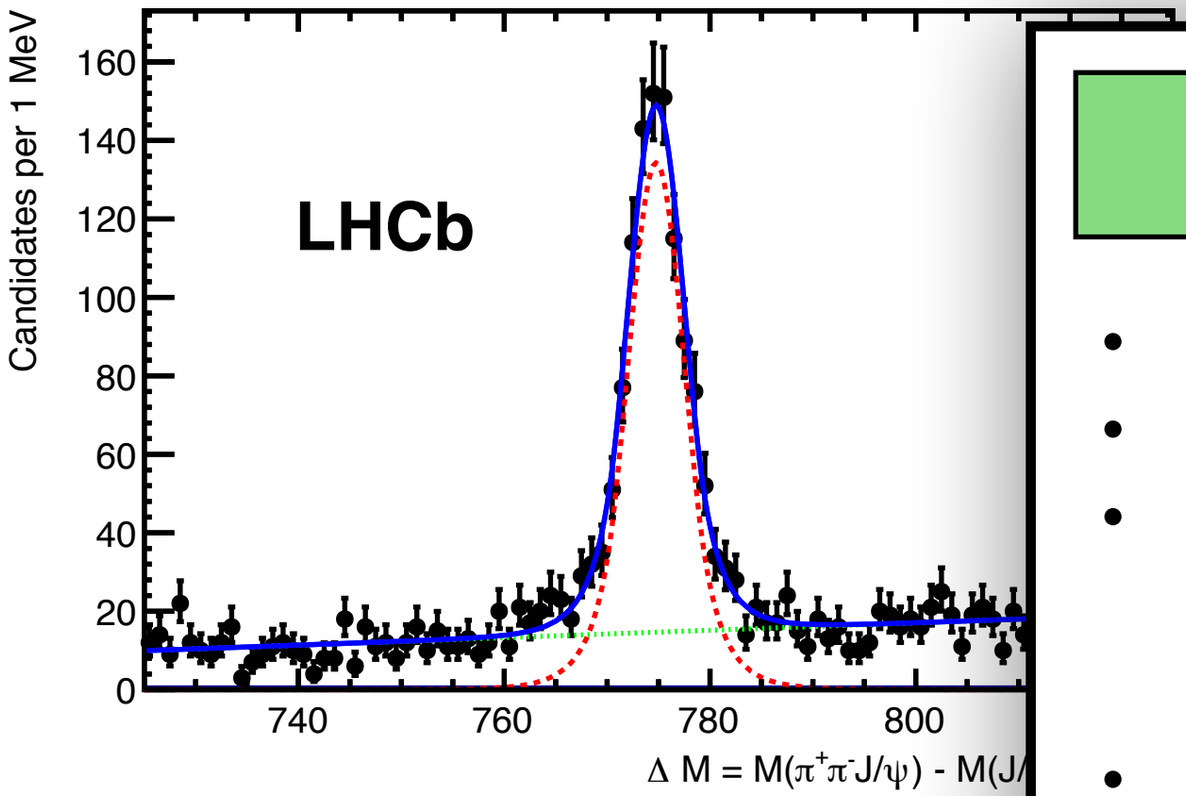


- latest observation of the X(3872) and confirmation of $J^{PC} = 1^{++}$

Overview of the X(3872)

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

PRD 92, 011102 (2015)



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

Properties of the X(3872)

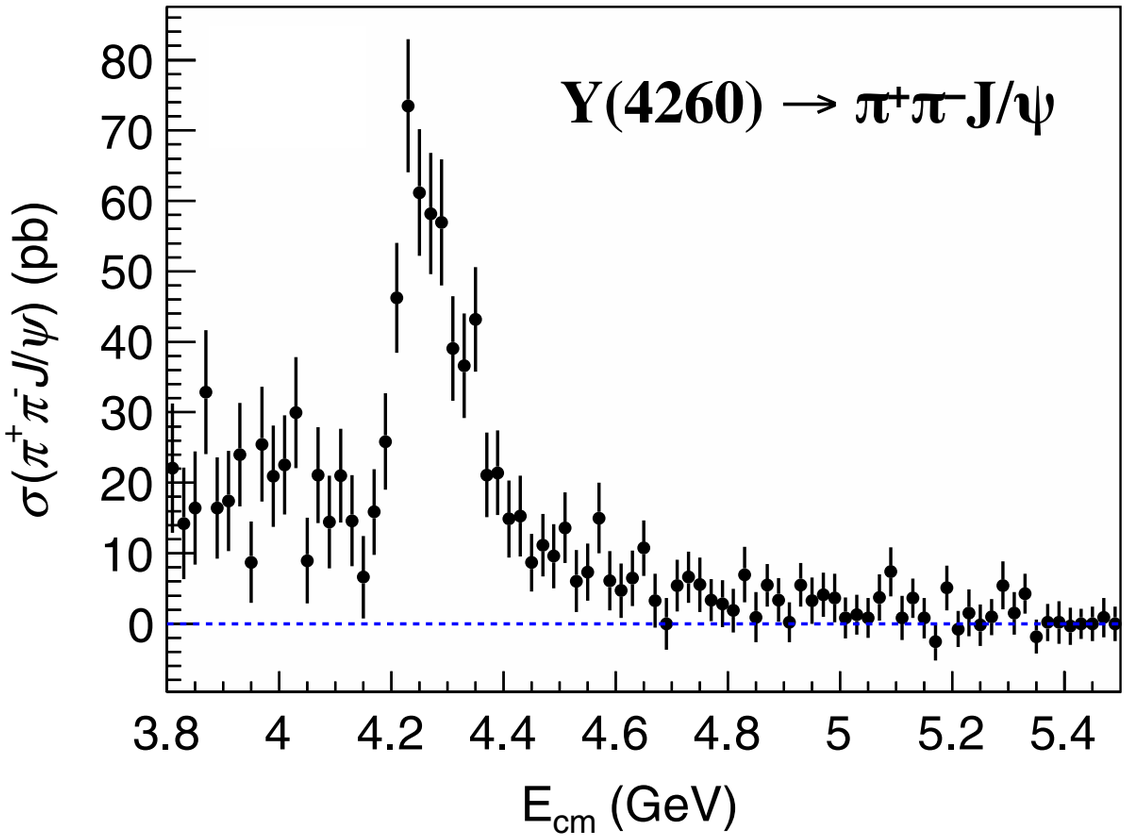
2014 PDG

- 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
- a popular interpretation: DD* molecule or tetraquark

Overview of the Y(4260)

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

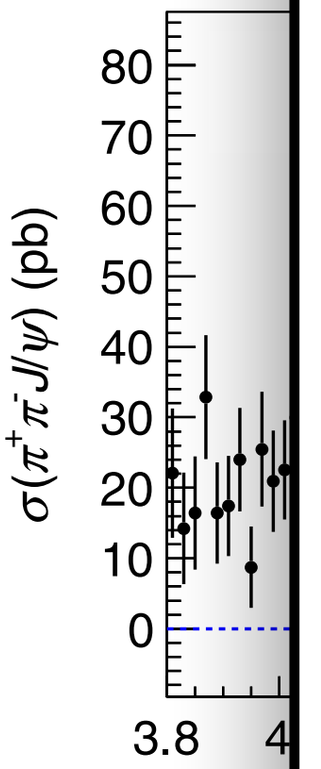
PRL 110, 252002 (2013)



- latest observation of the Y(4260)

Overview of the Y(4260)

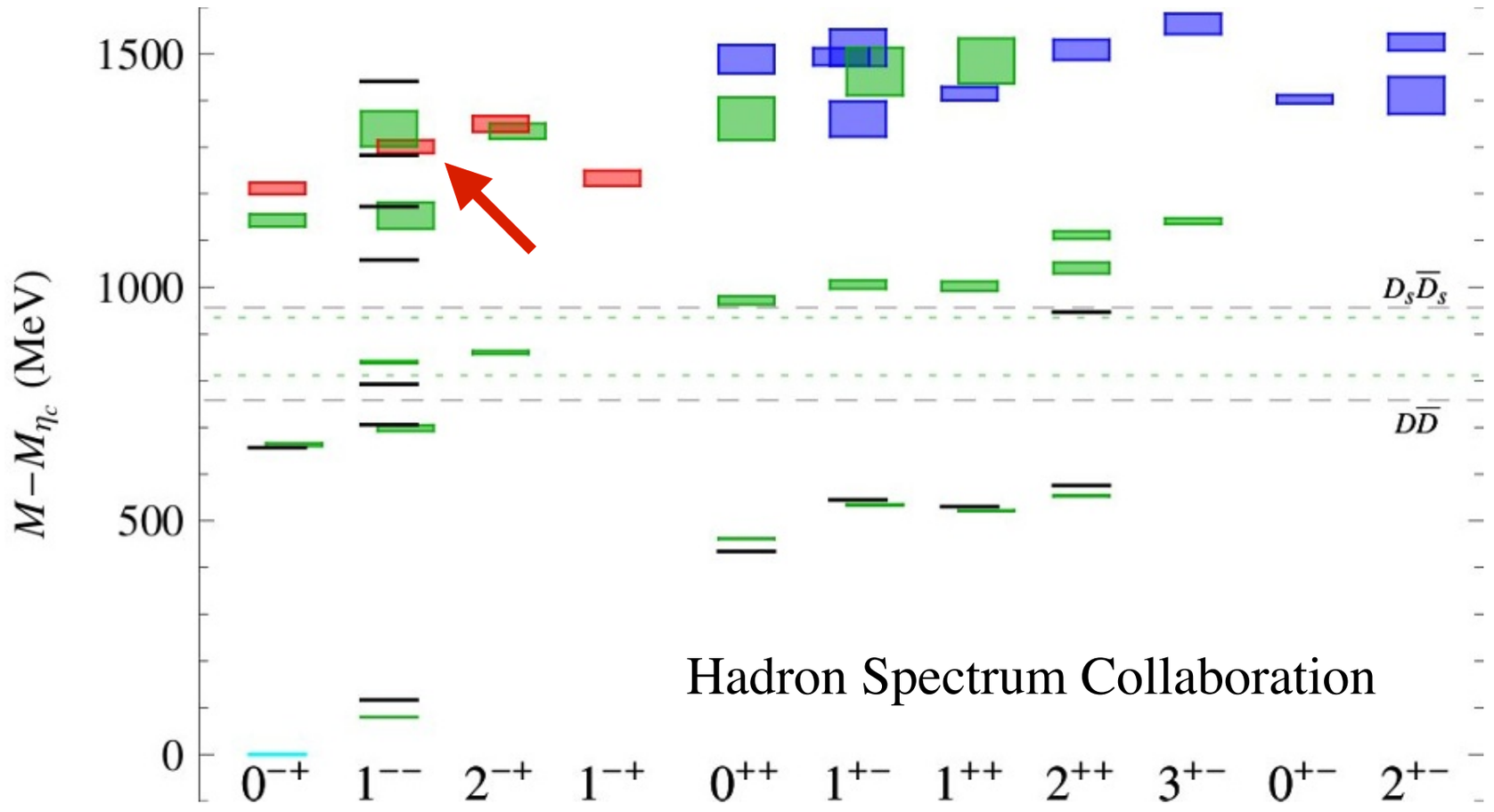
e+e



- latest ob

Lattice Calculations of the Charmonium Spectrum

JHEP 07, 126 (2012)

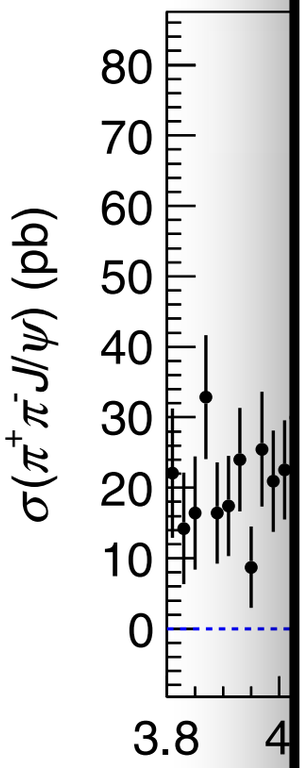


Hadron Spectrum Collaboration

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

Overview of the Y(4260)

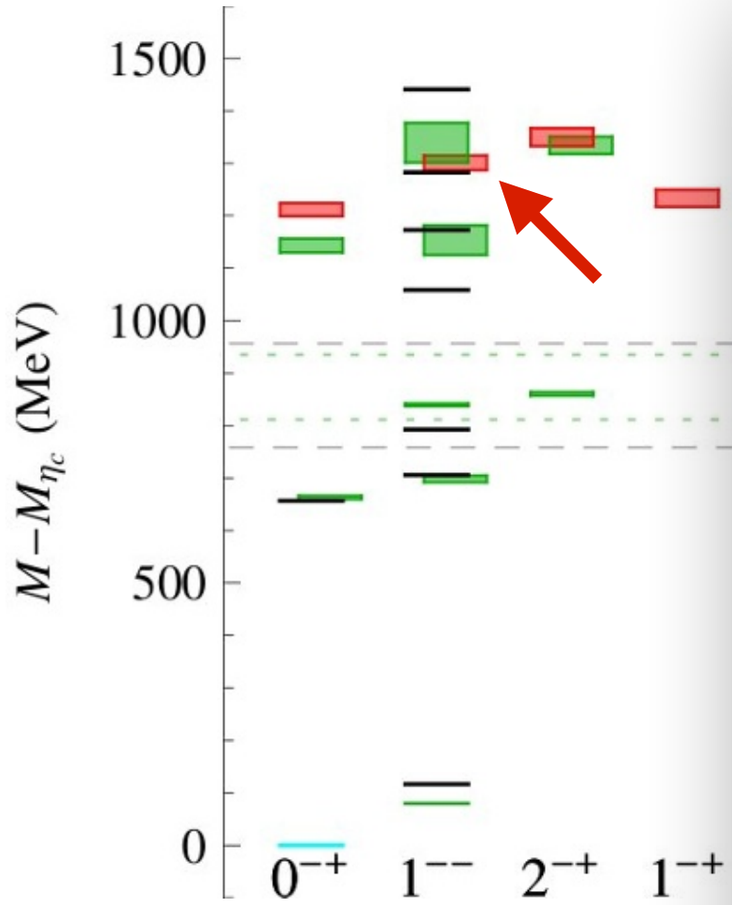
e^+e^-



- latest ob

Lattice Calculations of the Charmonium Spectrum

JHEP 07, 126 (2012)



- a "hybrid-like state" is

Properties of the Y(4260)

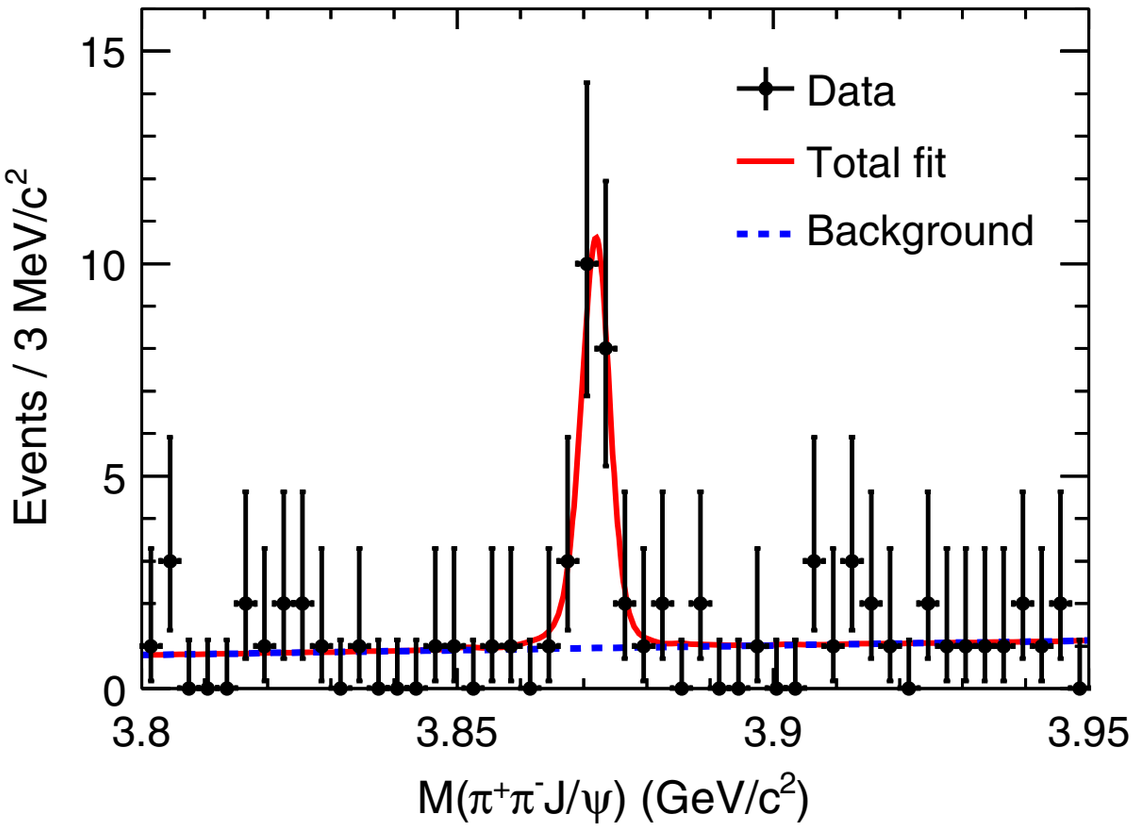
2014 PDG

- 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?
- a popular interpretation: hybrid meson

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)

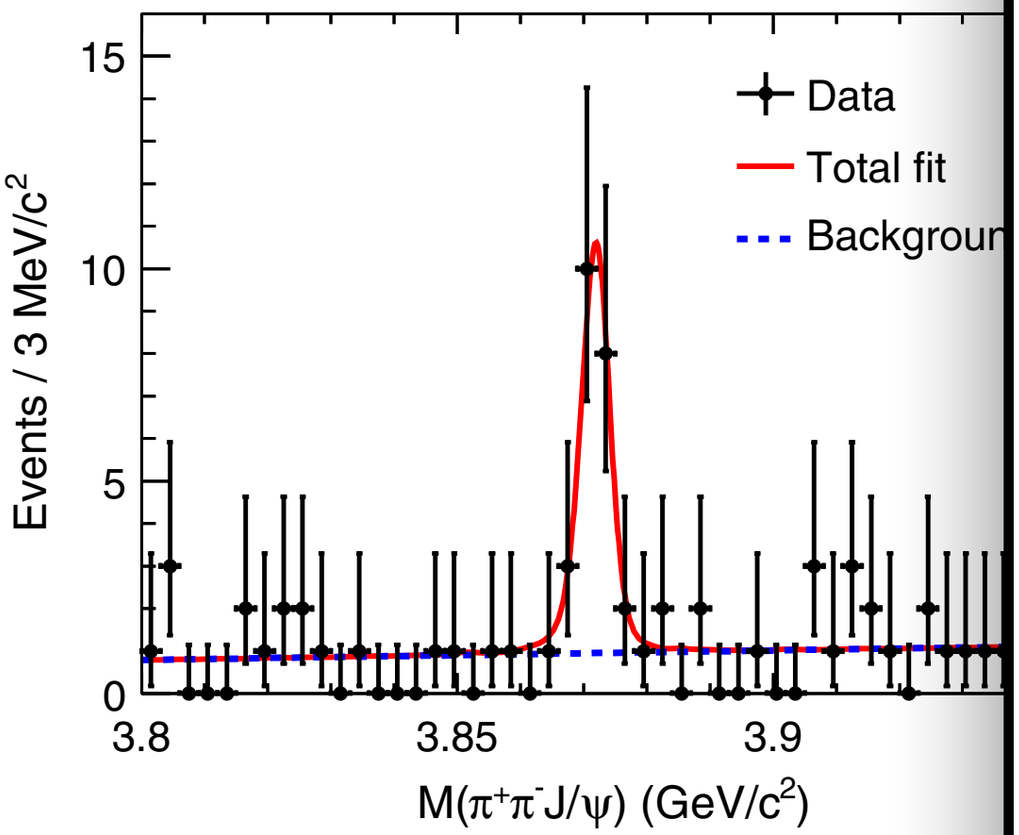


- observation of the X(3872) in a radiative transition

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

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

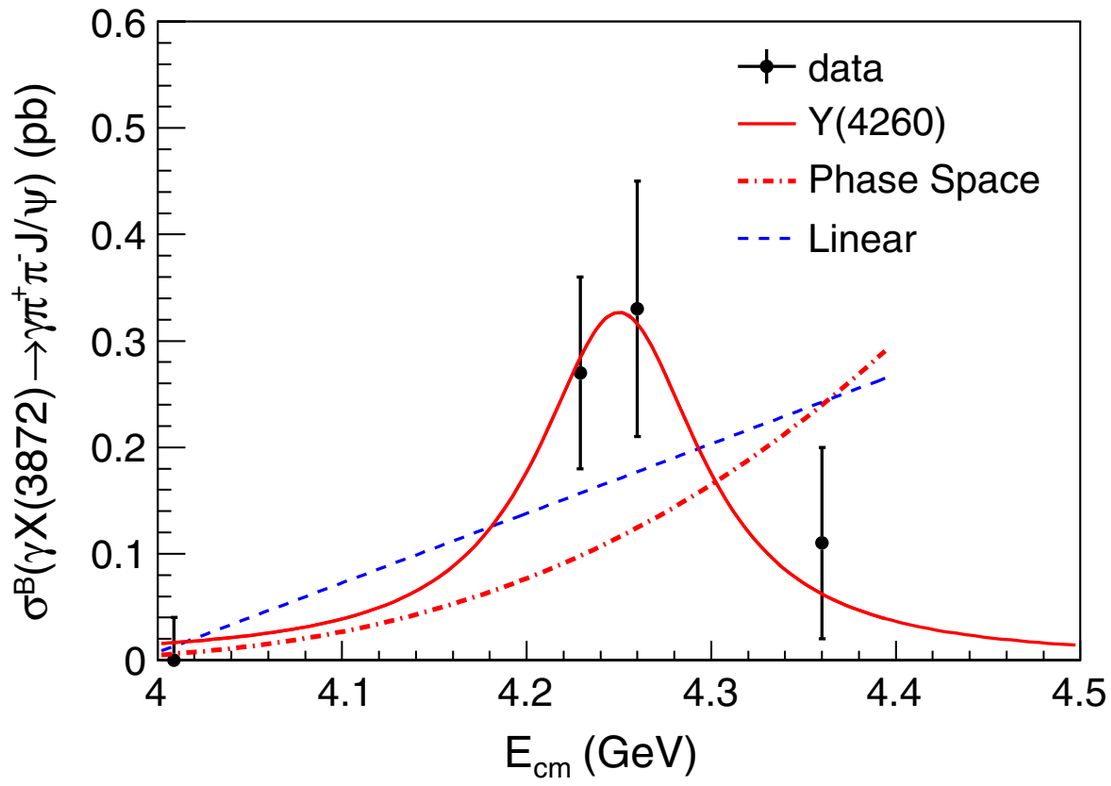
PRL 112, 092001 (2014)



- observation of the X(3872) in a radiative

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

PRL 112, 092001 (2014)

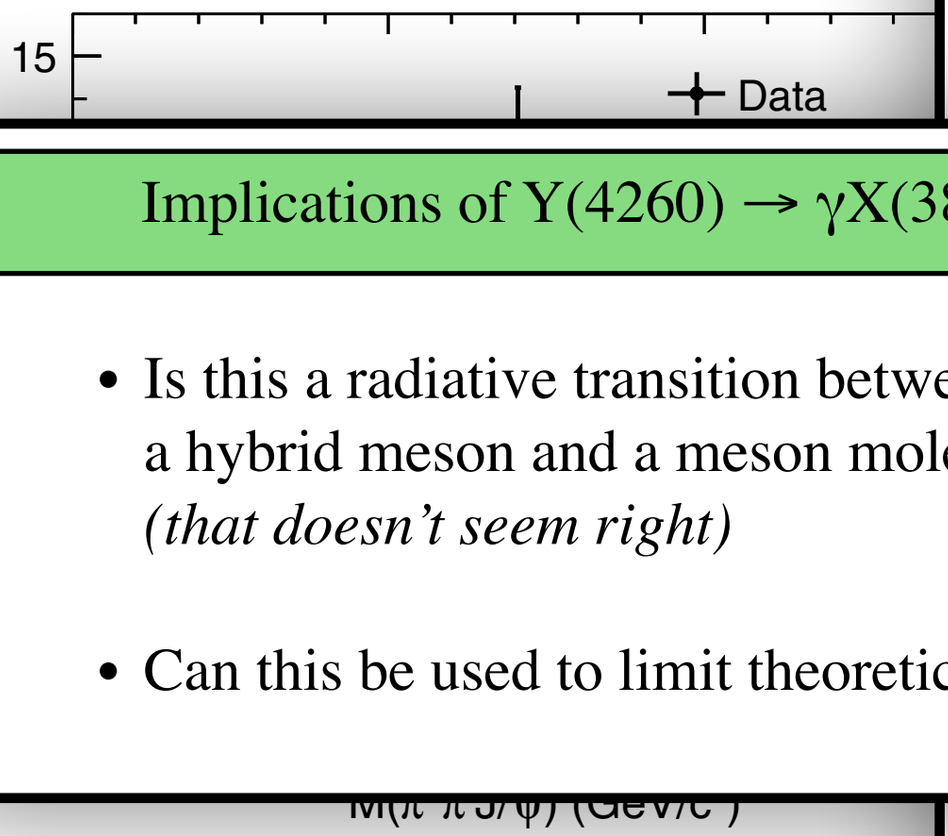


- is this Y(4260) → γX(3872)??

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

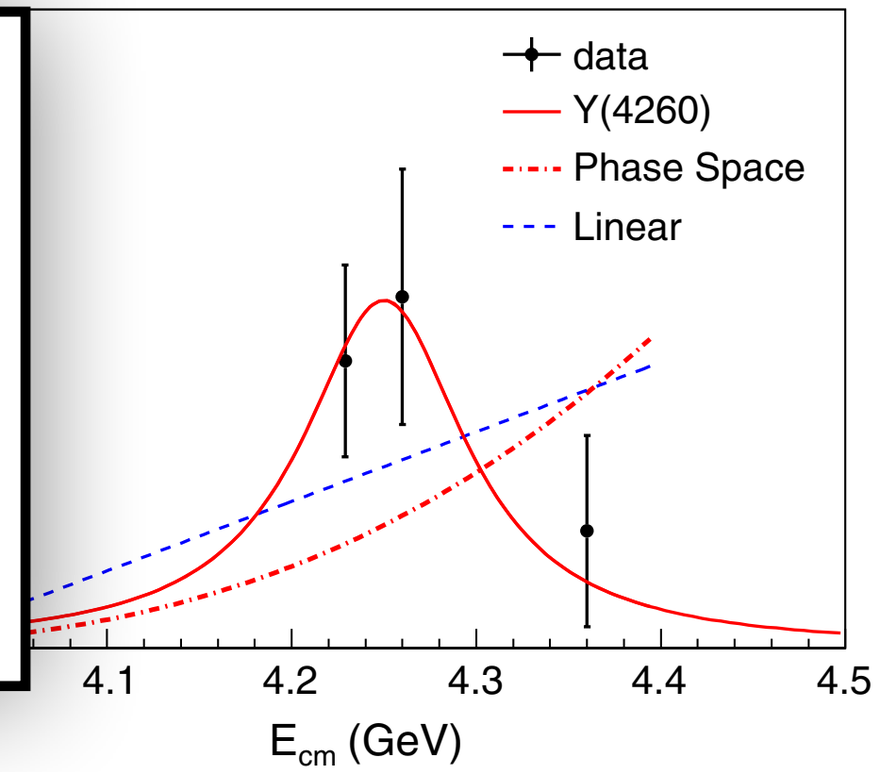
$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$ at $E_{CM} \sim 4.26$ GeV at BESIII

PRL 112, 092001 (2014)



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

PRL 112, 092001 (2014)



- is this $Y(4260) \to \gamma X(3872)$??

Implications of $Y(4260) \to \gamma X(3872)$?

- 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?

- observation of the X(3872) in a radiative

Part II: Connections and Complexities

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

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

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

Part II: Connections and Complexities

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

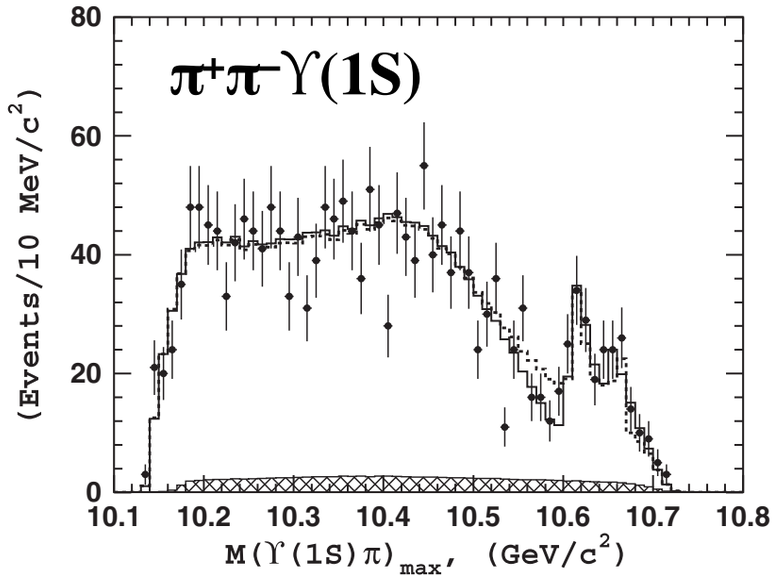
Connections II: The Z_c and Z_c' and the Z_b and Z_b'.

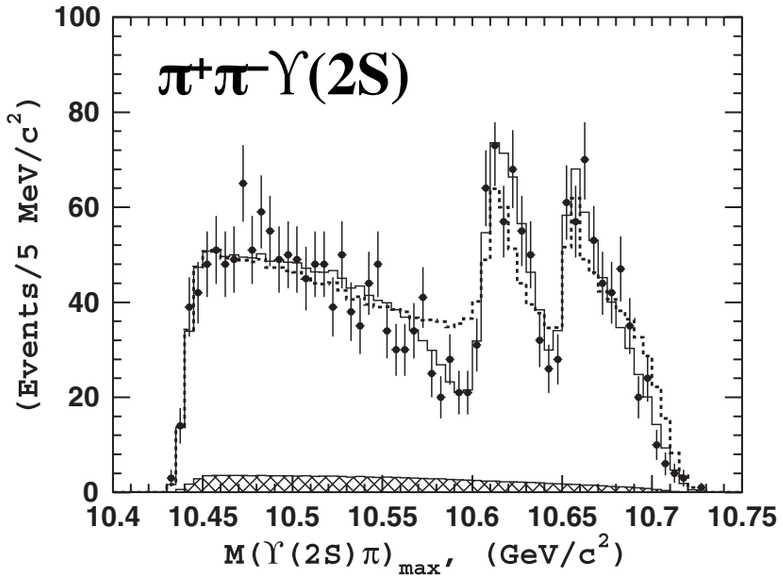
Complexities: A Collection of e^+e^- Cross Sections.

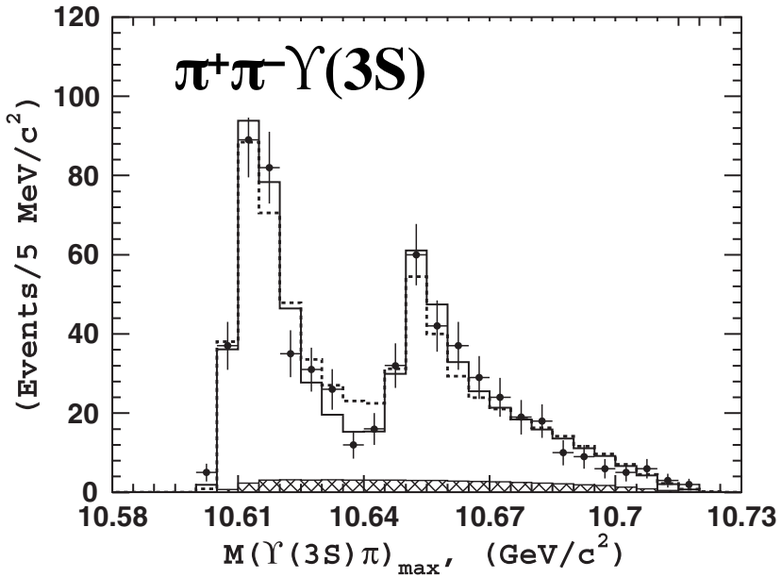
Observation of the Z_b and Z_b'

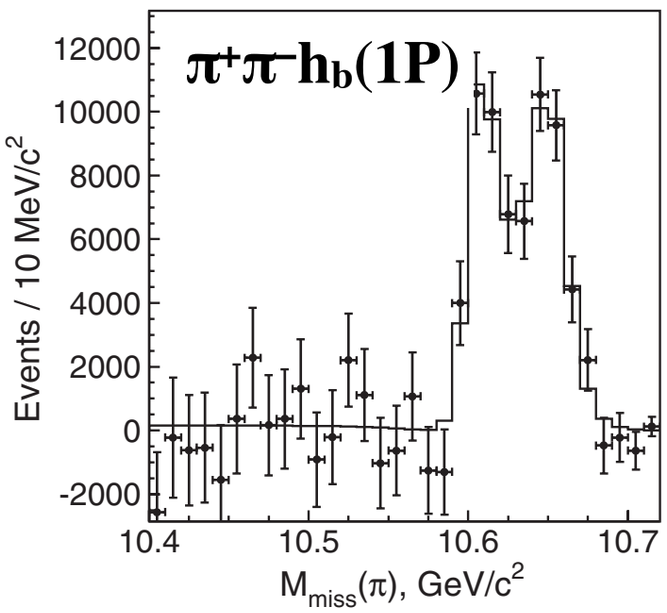
$e^+e^- \to \pi^+\pi^-\Upsilon(1S,2S,3S)$ and $\pi^+\pi^- h_b(1P,2P)$ at $E_{CM} \sim \Upsilon(5S)$ Mass at Belle

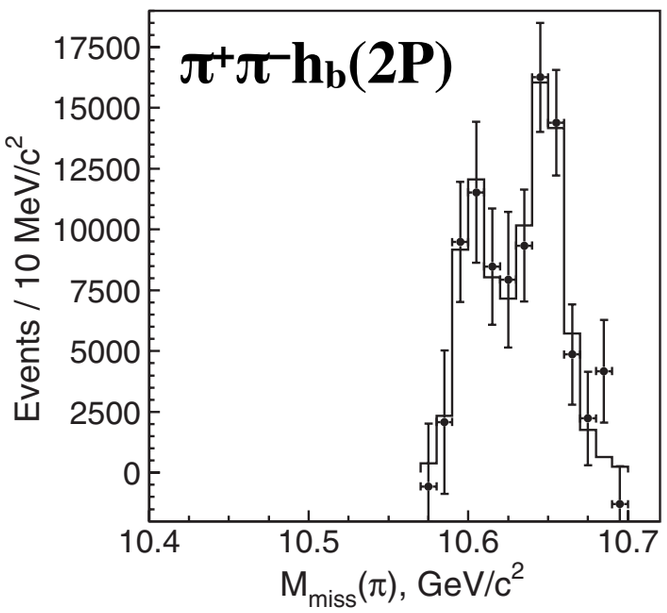
PRD 91, 072003 (2015), PRL 108, 122001 (2012)









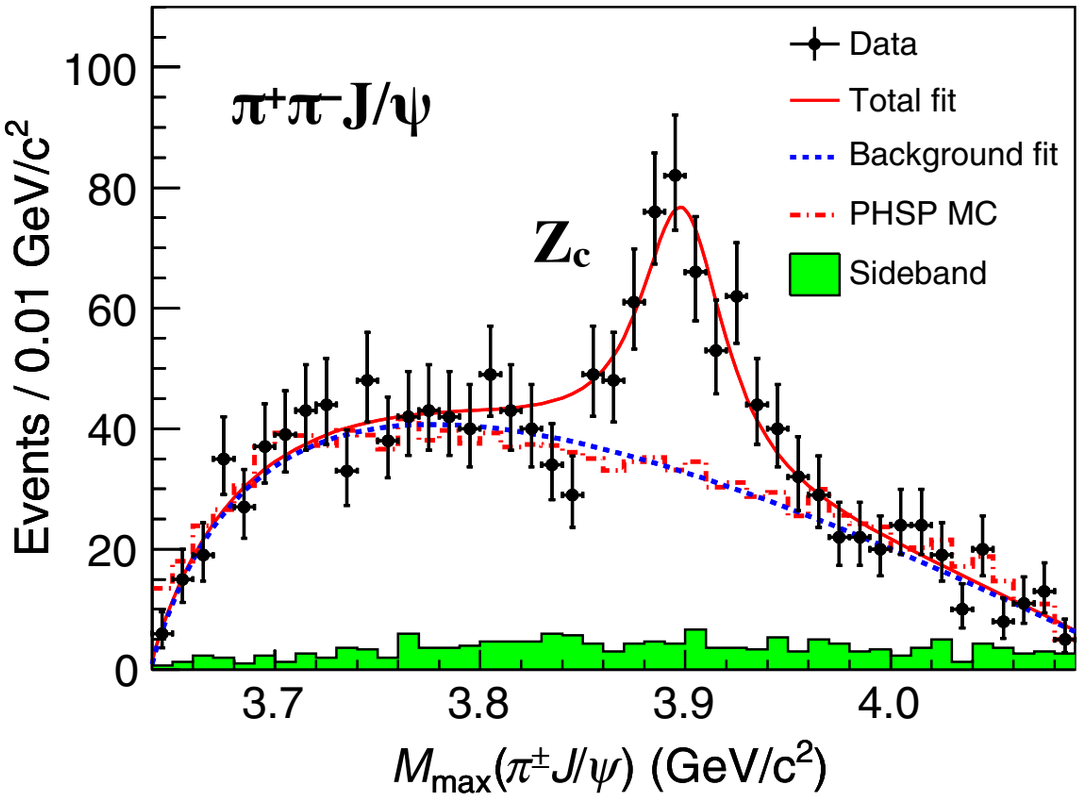


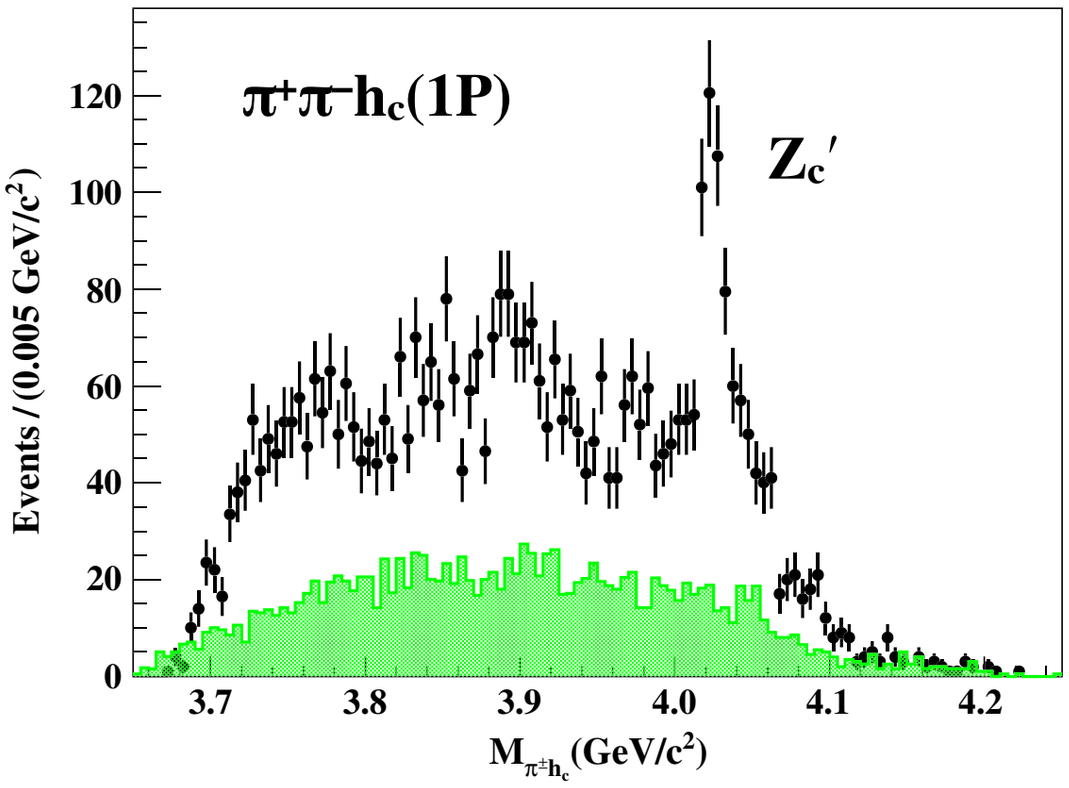
- two peaks, Z_b and Z_b', are found in the substructure of all five reactions, close to BB* and B*B* thresholds.

Observation of the Z_c and Z_c'

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

PRL 110, 252001 (2013), PRL 111, 242001 (2013)



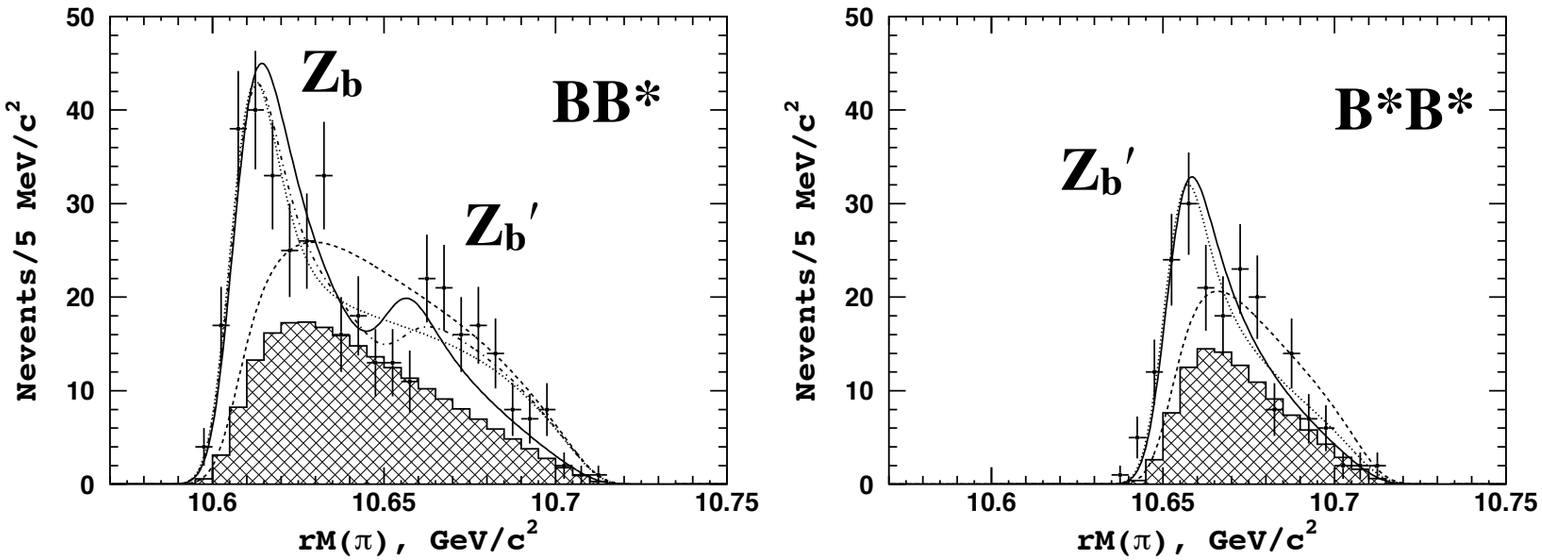


- a Z_c peak is found in $\pi J/\psi$ and a Z_c' peak is found in $\pi h_c(1P)$, close to the DD* and D*D* thresholds.

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

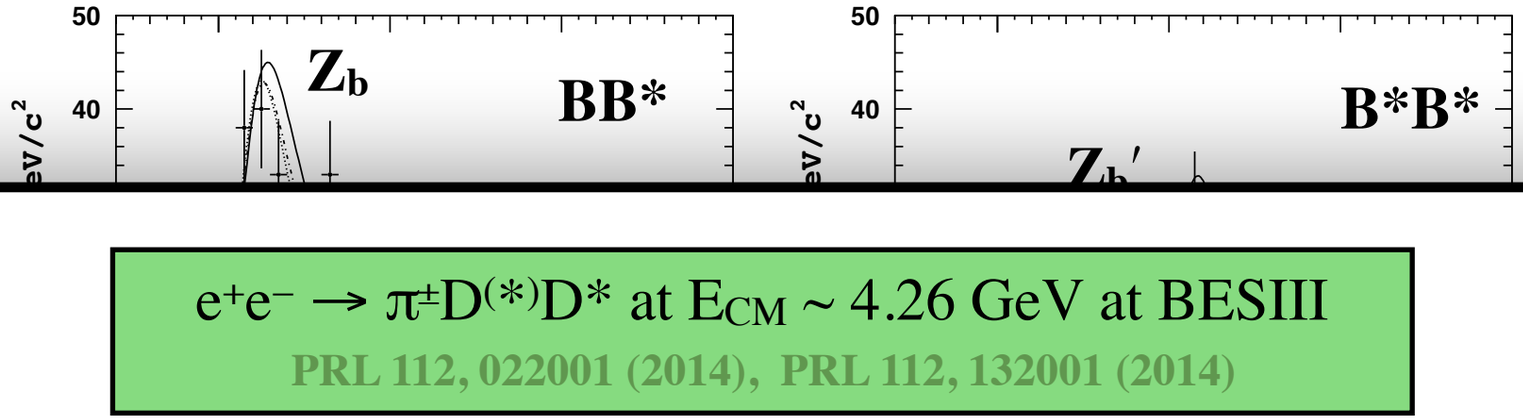
arXiv:1209.6450



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

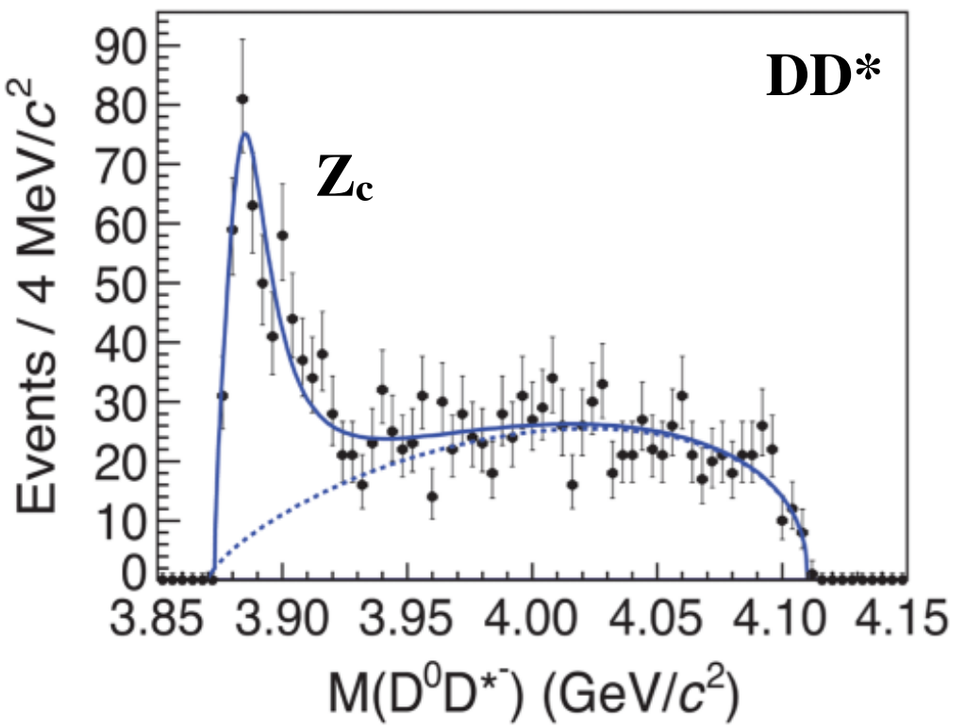
$e^+e^- \to \pi^\pm B^{(*)}B^*$ at $E_{CM} \sim \Upsilon(5S)$ Mass at Belle

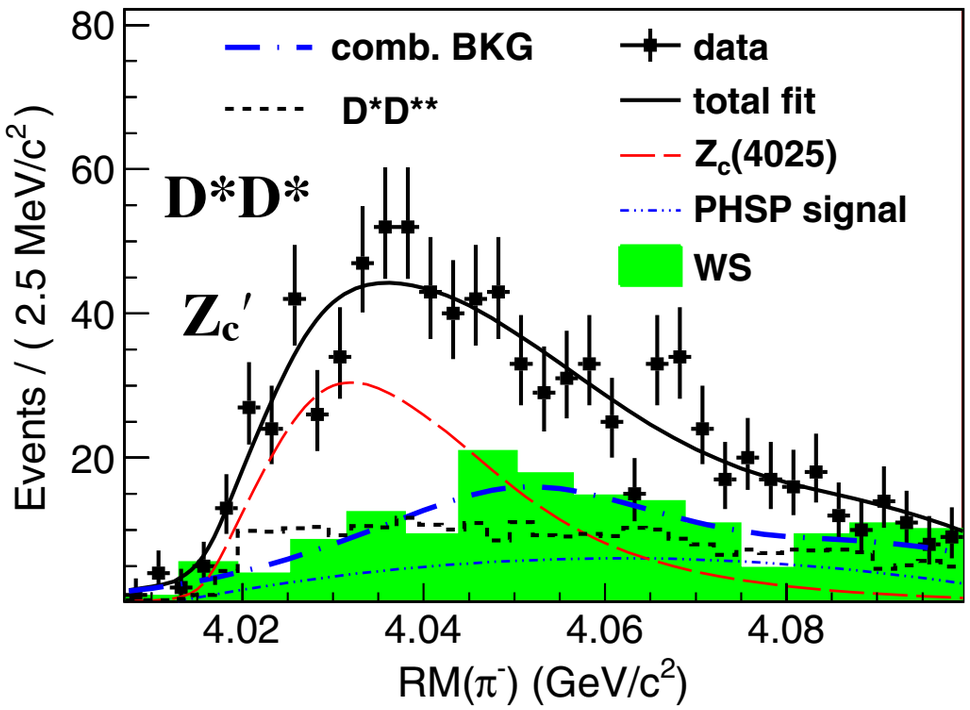
arXiv:1209.6450



$e^+e^- \to \pi^\pm D^{(*)}D^*$ 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 "$\Upsilon(5S)$".

Part II: Connections and Complexities

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

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

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

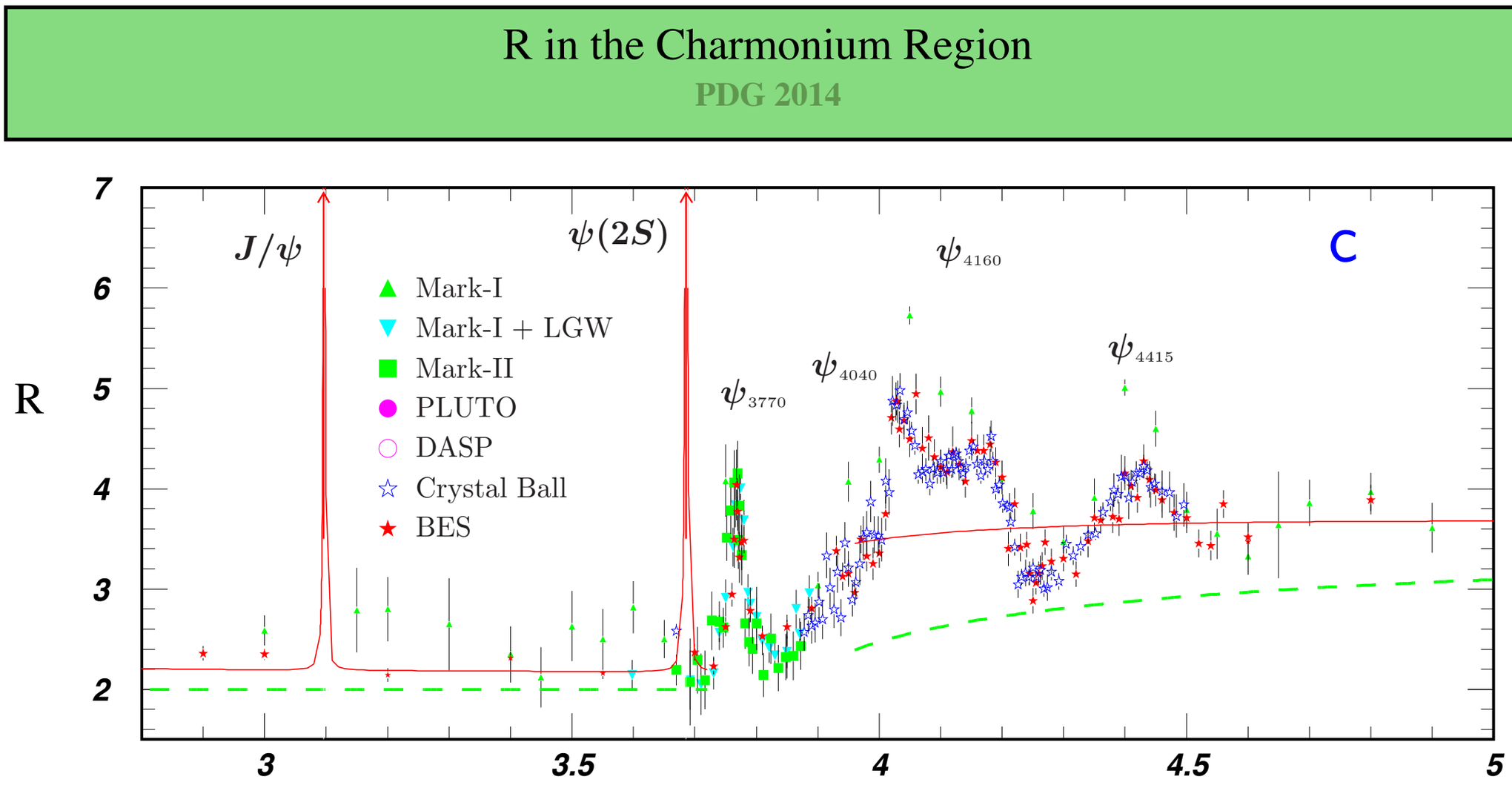
Part II: Connections and Complexities

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

Connections II: 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



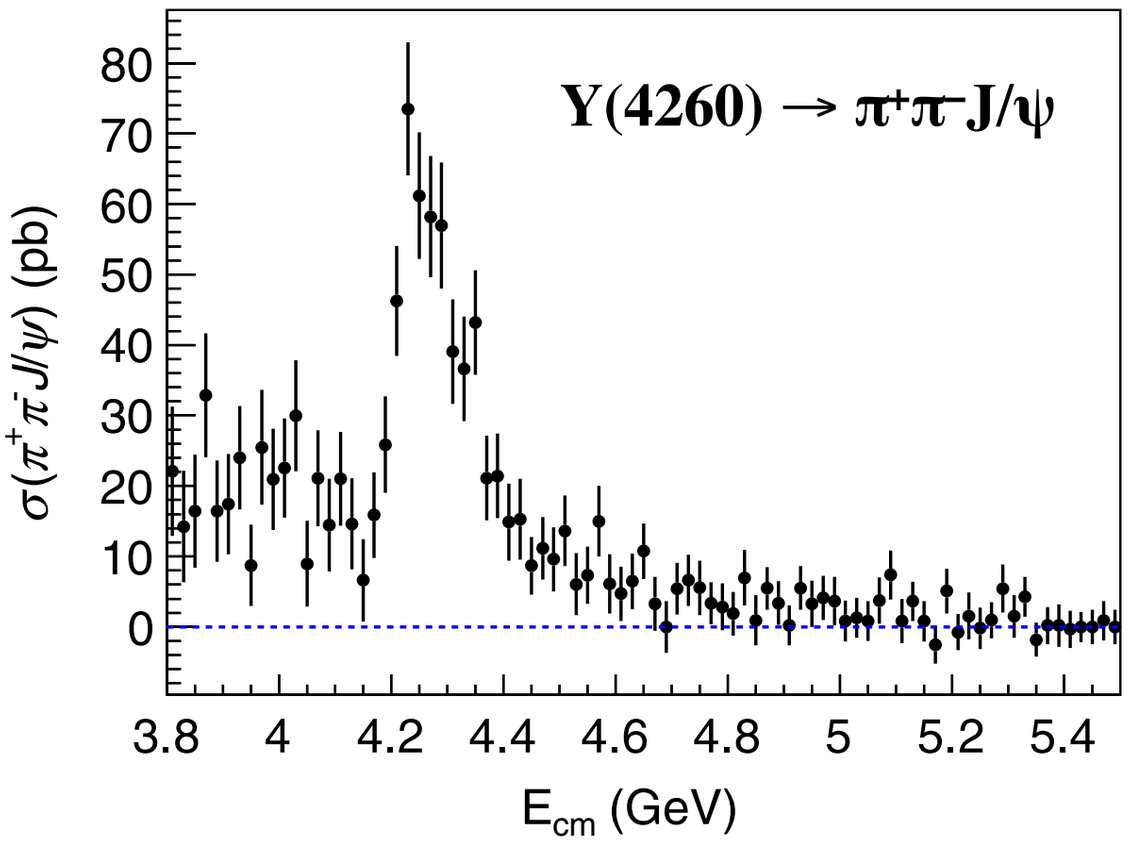
- R suggests a tidy quark model picture:

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

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

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

PRL 110, 252002 (2013)

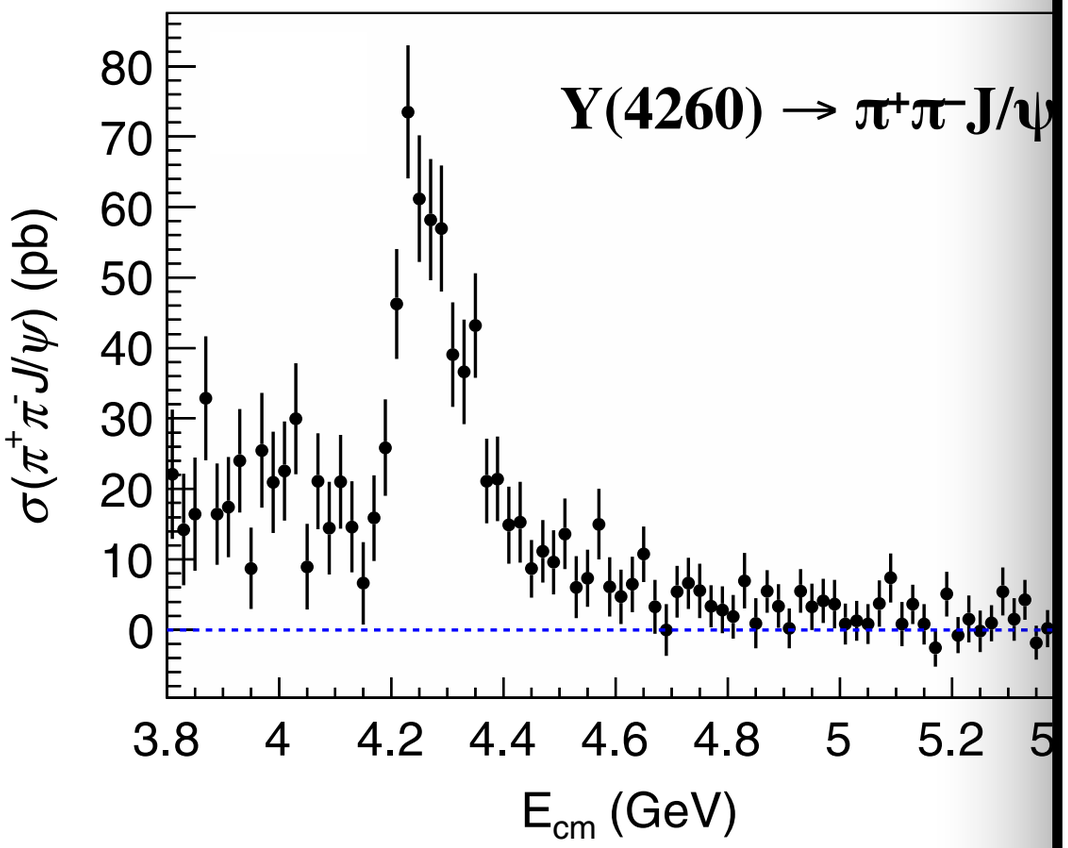


- the Y(4260) has no place in the quark model

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

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

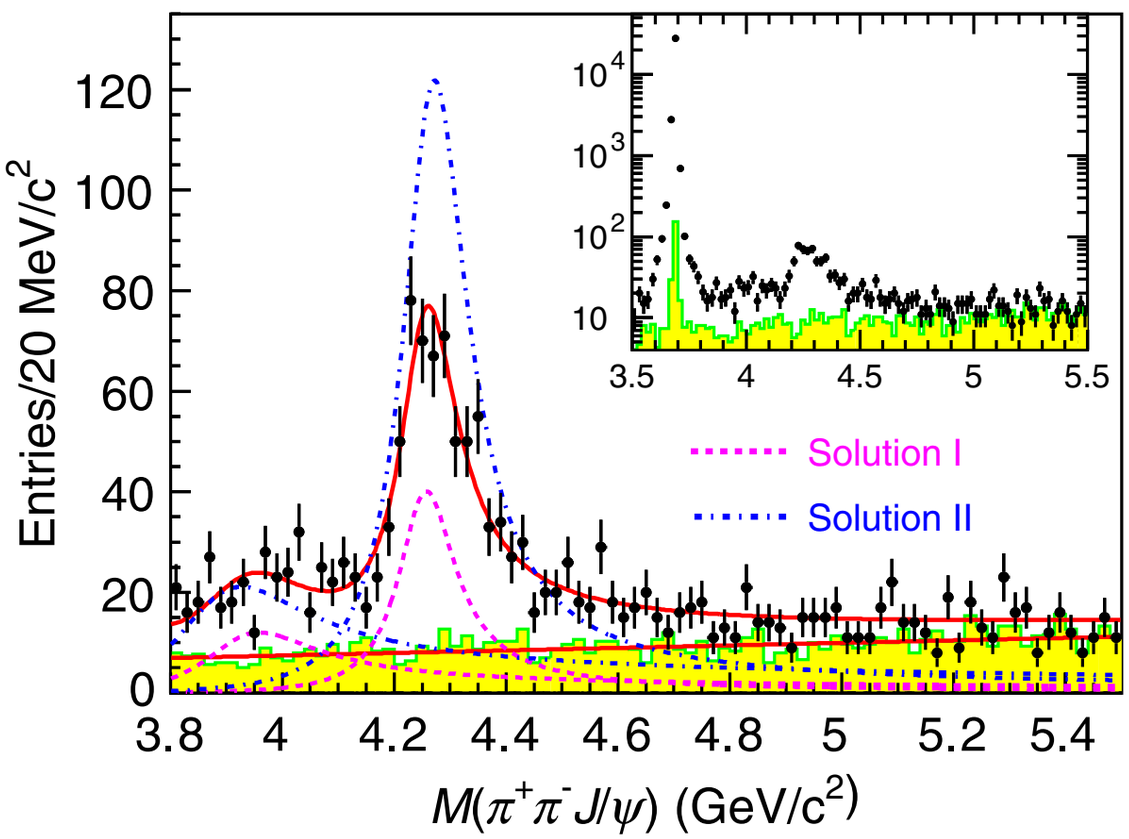
PRL 110, 252002 (2013)



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

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

PRL 110, 252002 (2013)

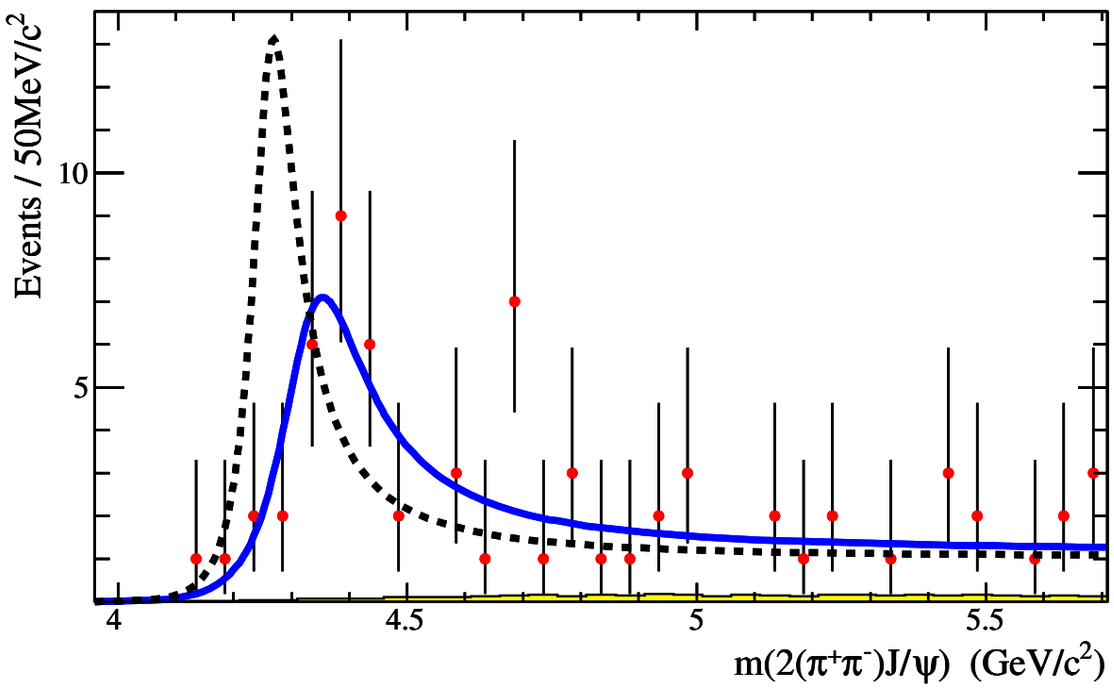


- is this really two resonances??

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

$e^+e^-(\gamma_{ISR}) \to \pi^+\pi^-\psi(2S)$ at BaBar

PRL 98, 212001 (2007)

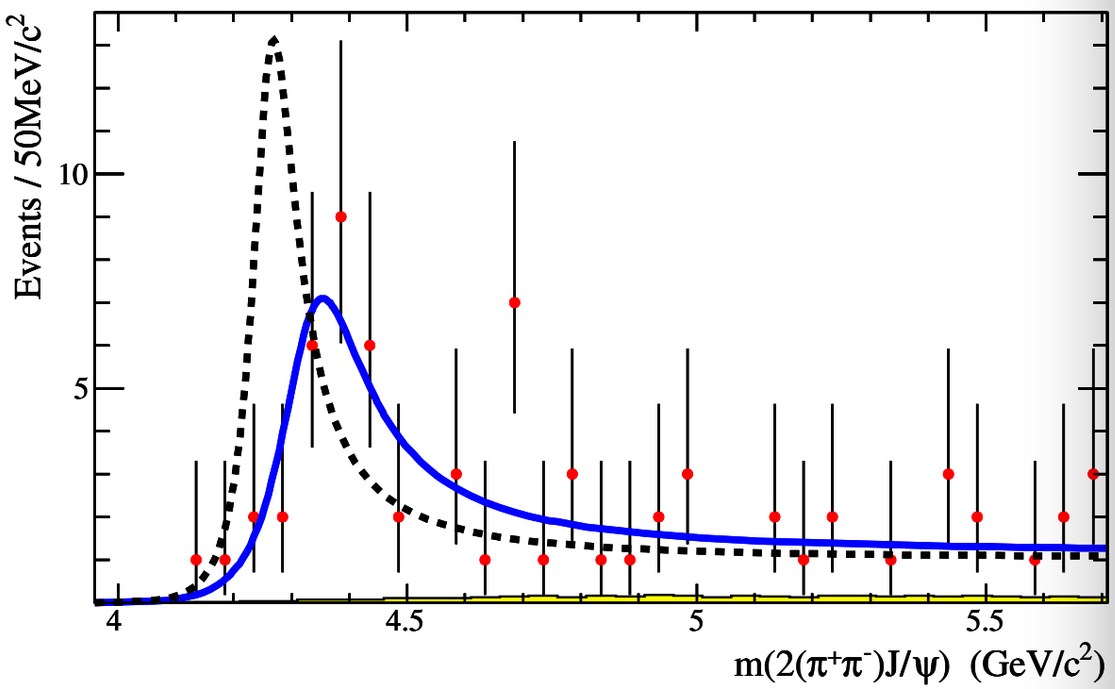


- there is a Y(4360) instead of a Y(4260)?

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

$e^+e^-(\gamma_{ISR}) \to \pi^+\pi^-\psi(2S)$ at BaBar

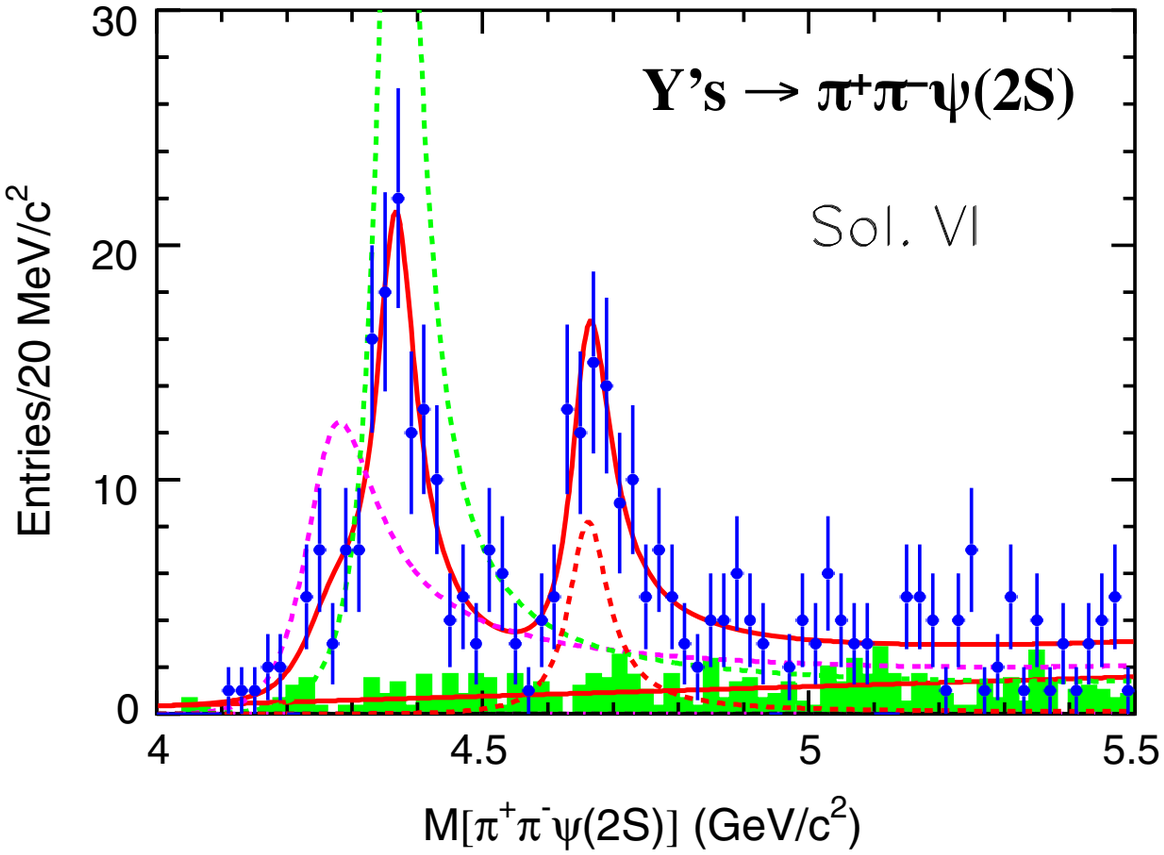
PRL 98, 212001 (2007)



- there is a Y(4360) instead of a Y(4260)?

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

PRD 91, 112007 (2015)

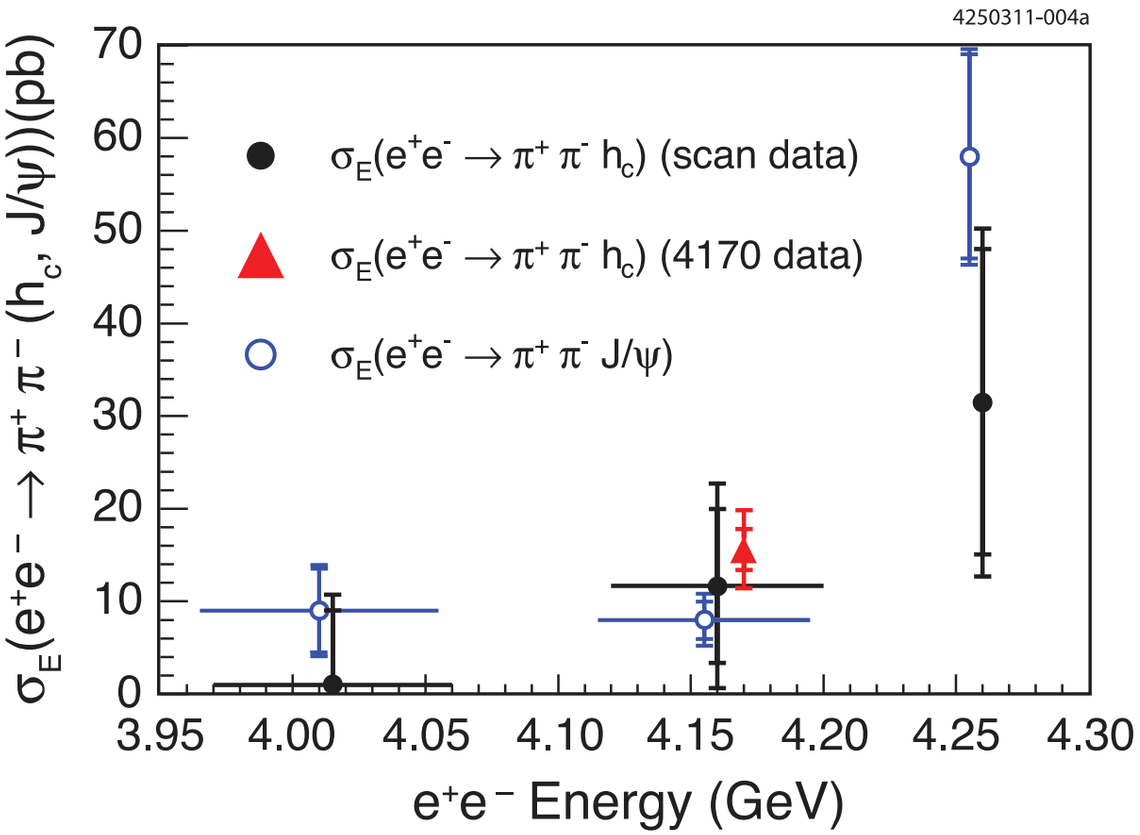


- actually, there is a Y(4360) and a Y(4660)

Overview of $e^+e^- \to \pi^+\pi^- h_c(1P)$

$e^+e^- \to \pi^+\pi^- h_c(1P)$ at CLEO-c

PRL 107, 041803 (2011)

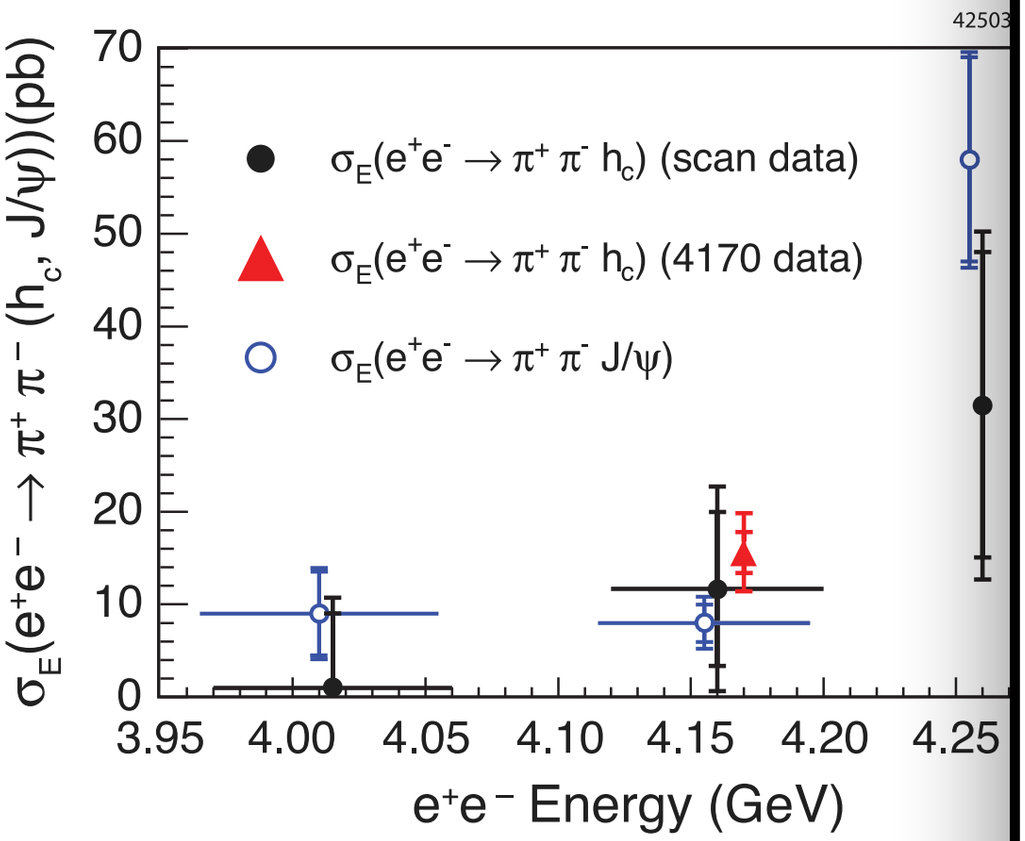


- is this a hint of $Y(4260) \to \pi^+\pi^- h_c(1P)$?

Overview of $e^+e^- \to \pi^+\pi^- h_c(1P)$

$e^+e^- \to \pi^+\pi^- h_c(1P)$ at CLEO-c

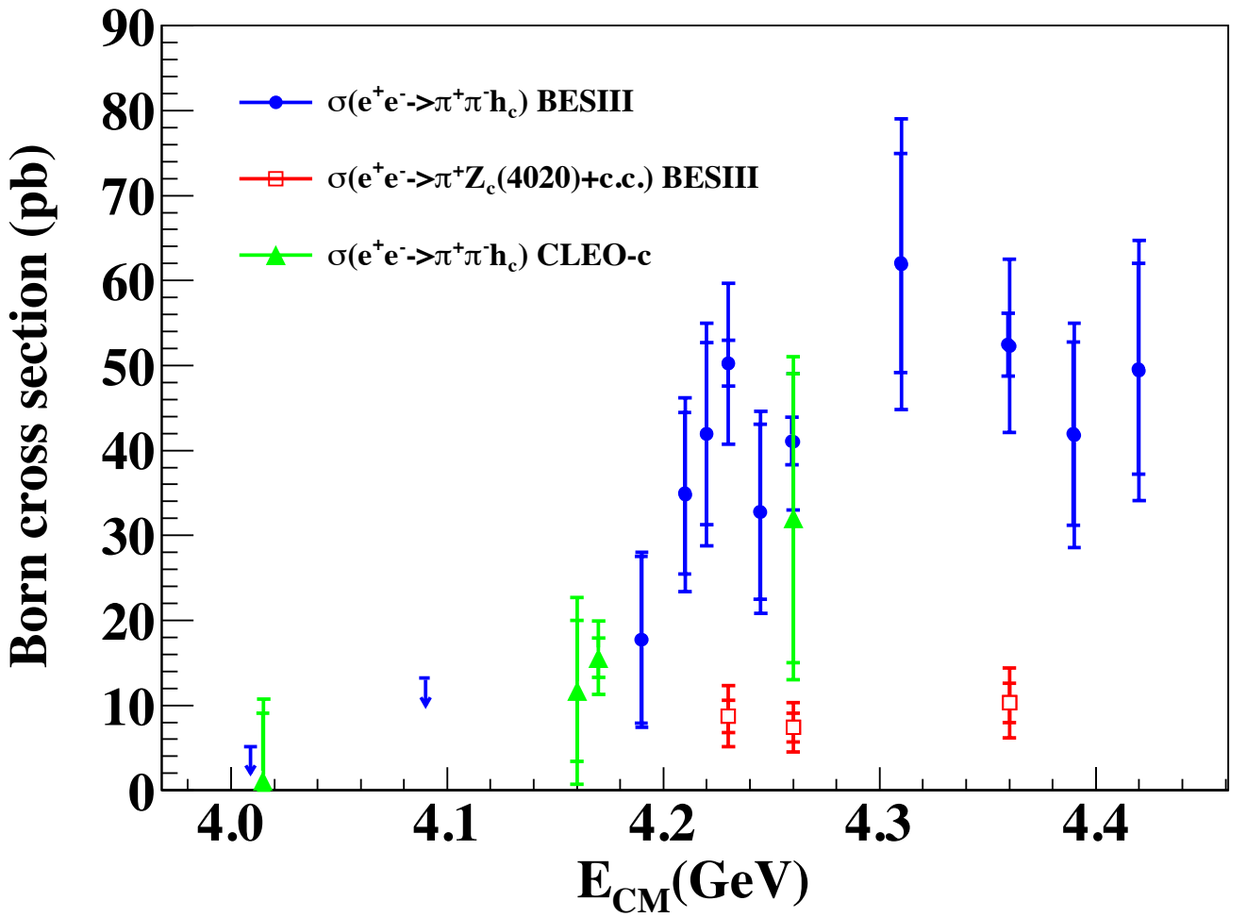
PRL 107, 041803 (2011)



- is this a hint of $Y(4260) \to \pi^+\pi^- h_c(1$

$e^+e^- \to \pi^+\pi^- h_c(1P)$ at BESIII

PRL 111, 242001 (2013)

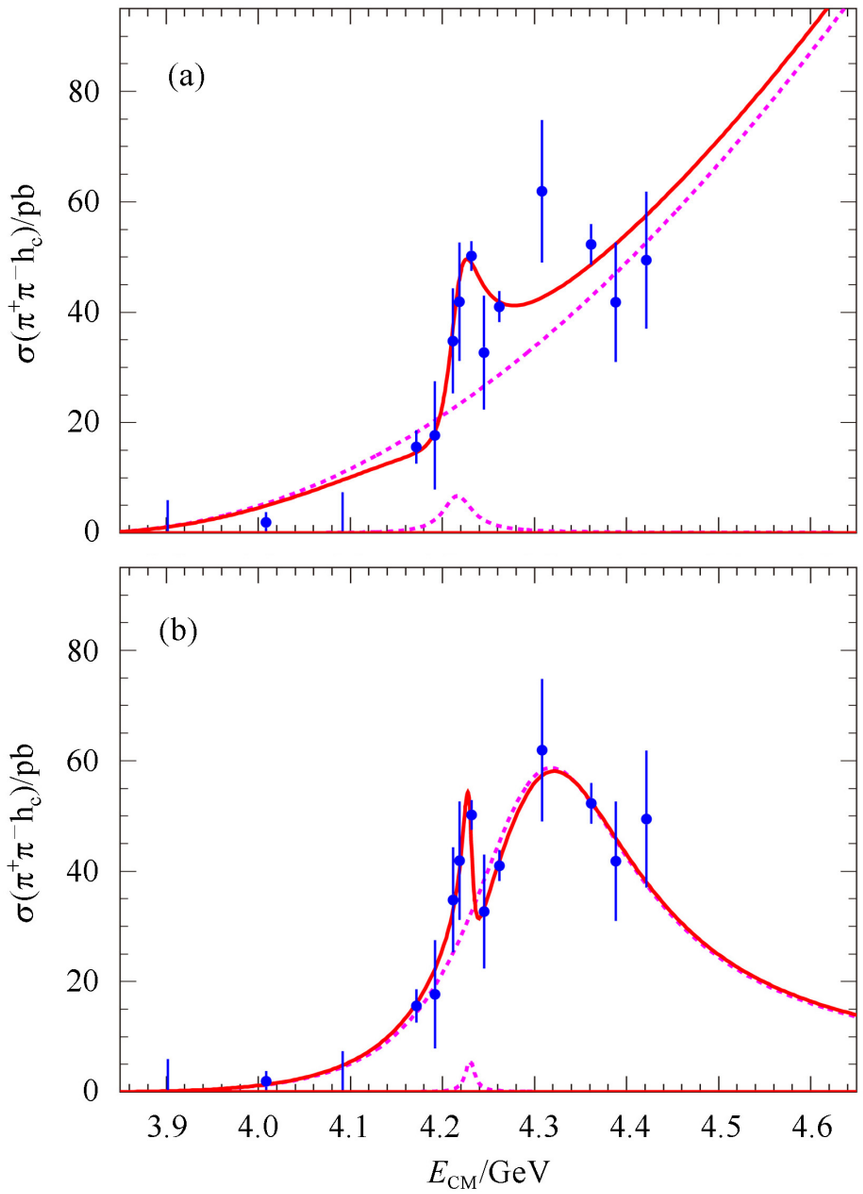


- it is more complicated than just $Y(4260) \to \pi^+\pi^- h_c(1P)$

$e^+e^- \to \pi^+\pi^- h_c(1P)$

Fitting $e^+e^- \to \pi^+\pi^- h_c(1P)$ by C. Z. Yuan

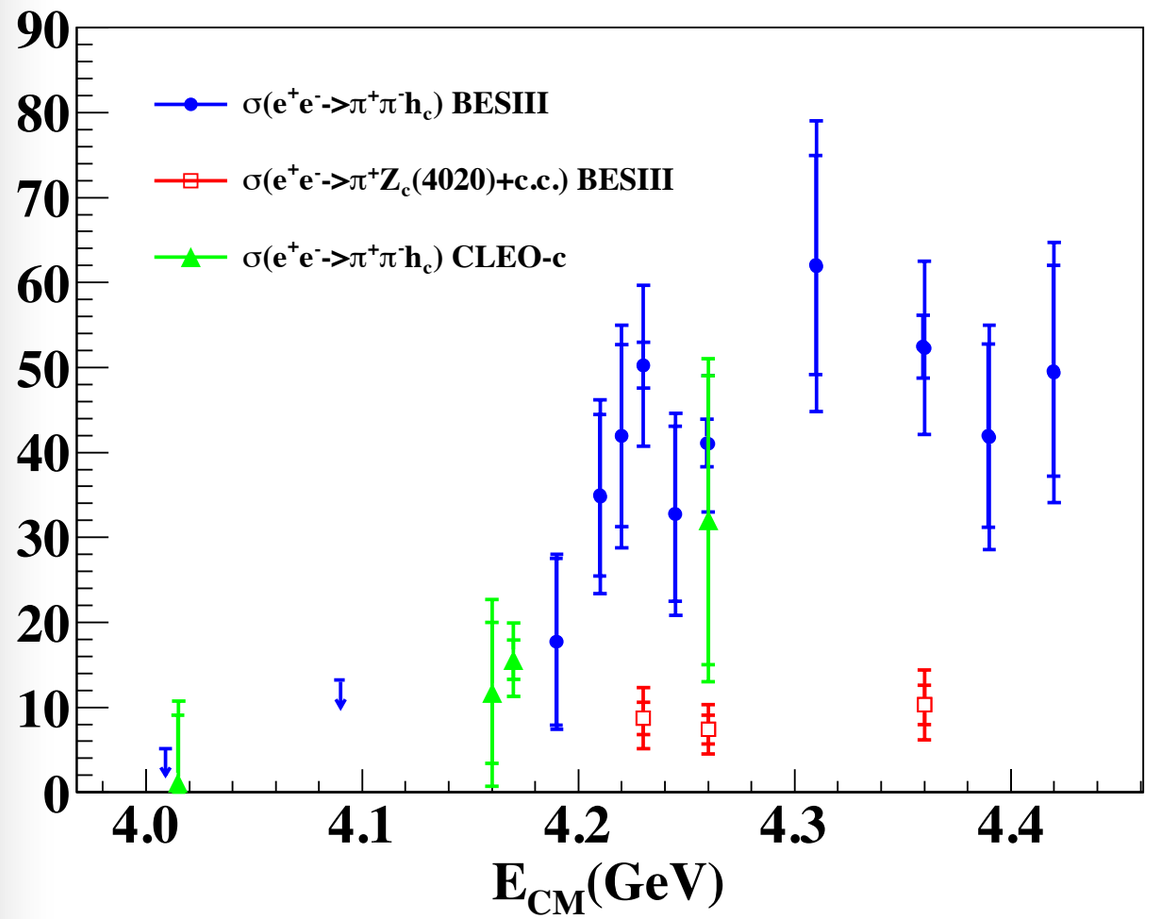
CPC 38, 043001 (2014)



- the $\pi^+\pi^- h_c(1P)$ shape is difficult.

$e^+e^- \to \pi^+\pi^- h_c(1P)$ at BESIII

PRL 111, 242001 (2013)

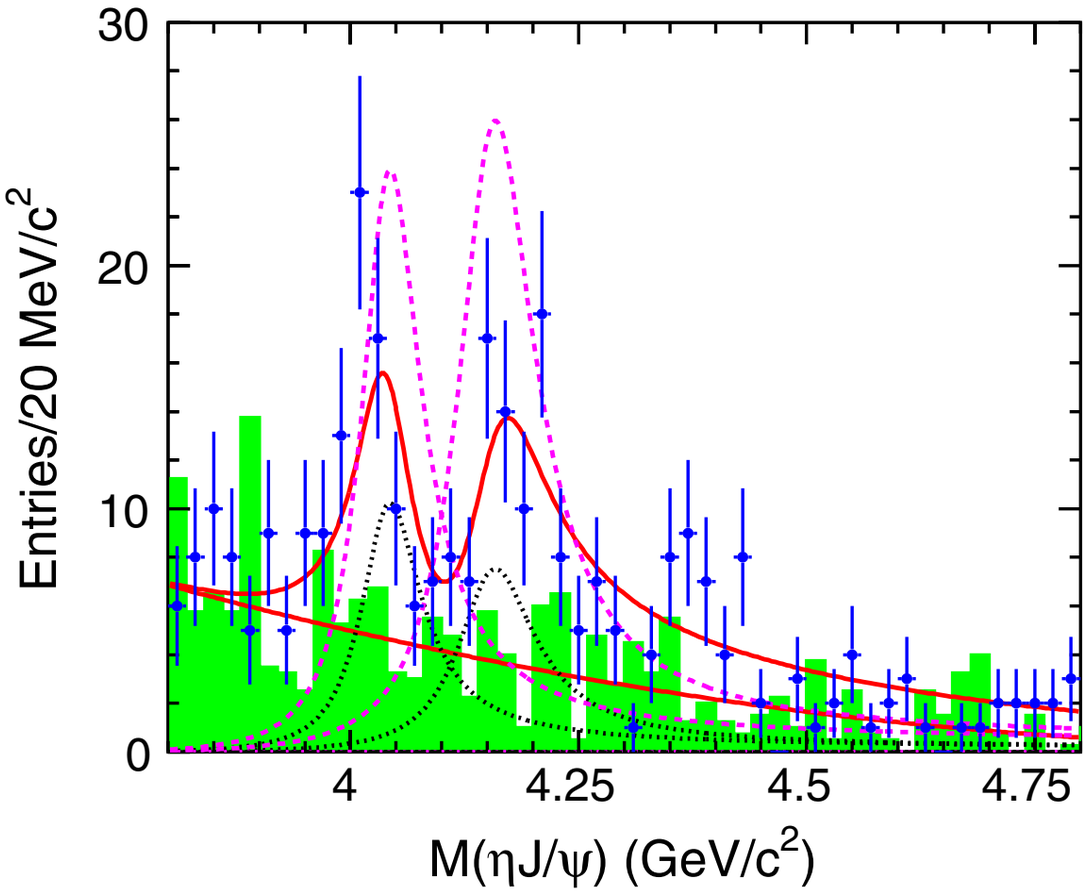


- it is more complicated than just $Y(4260) \to \pi^+\pi^- h_c(1P)$

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

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

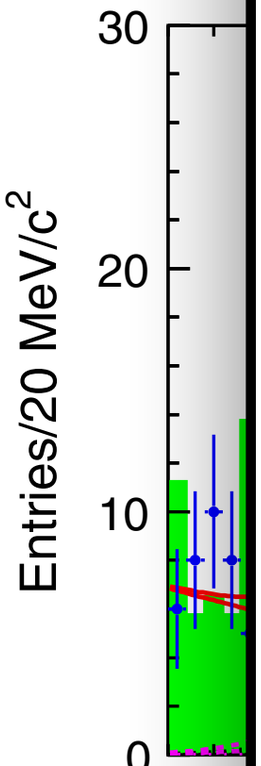
PRD 87, 051101(R) (2013)



- fit with conventional $\psi(4040)$ and $\psi(4160)$ states

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

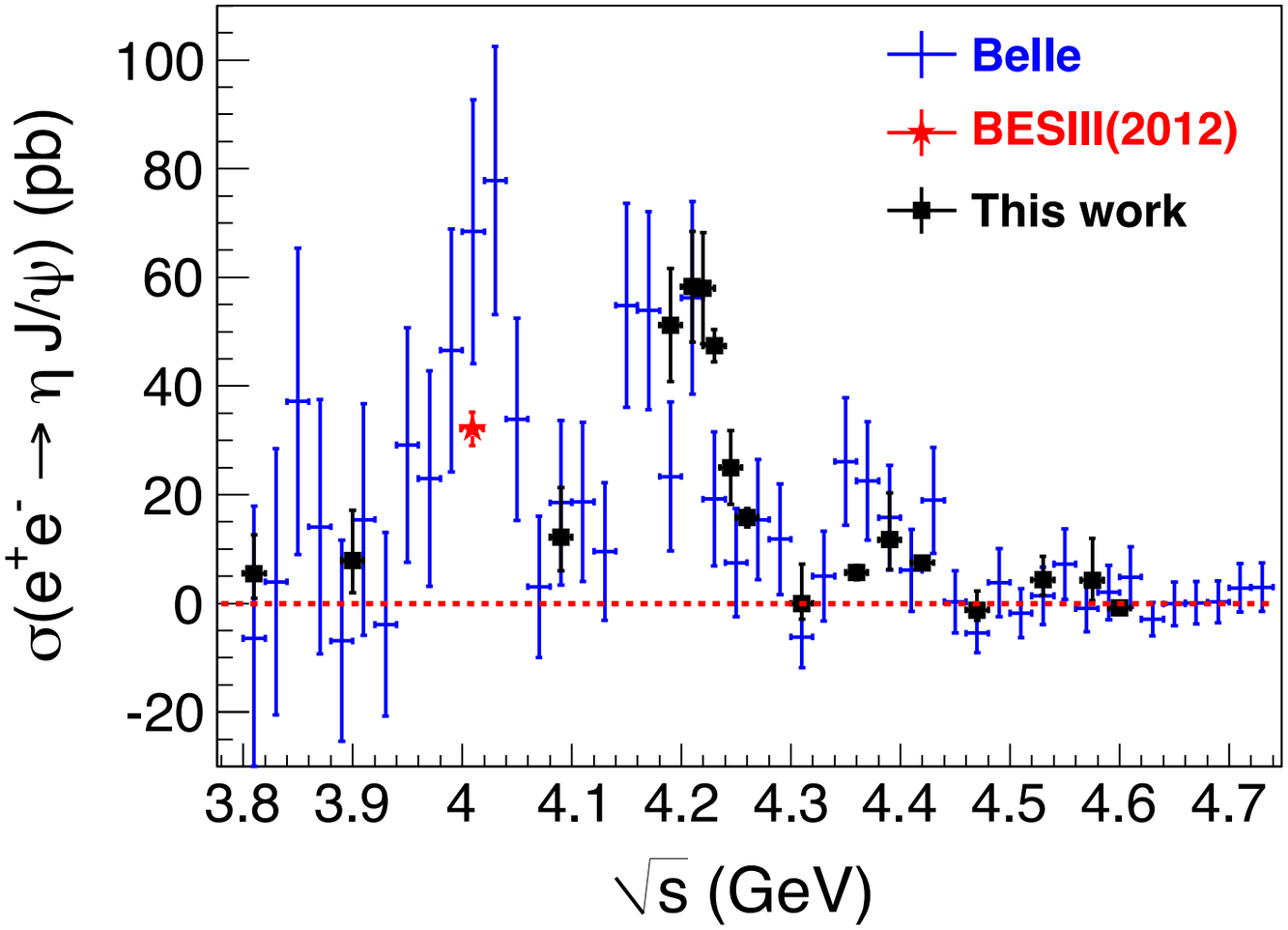
$e^+e^-(\gamma_{ISR}) \to \eta J/\psi$ at Belle



- fit with
states

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

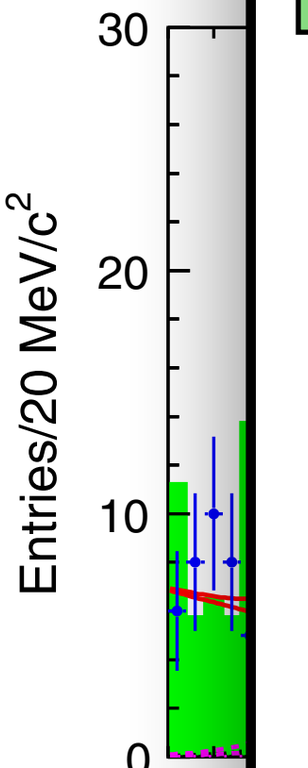
PRD 91, 112005 (2015)



- BESIII confirms there is nontrivial structure

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

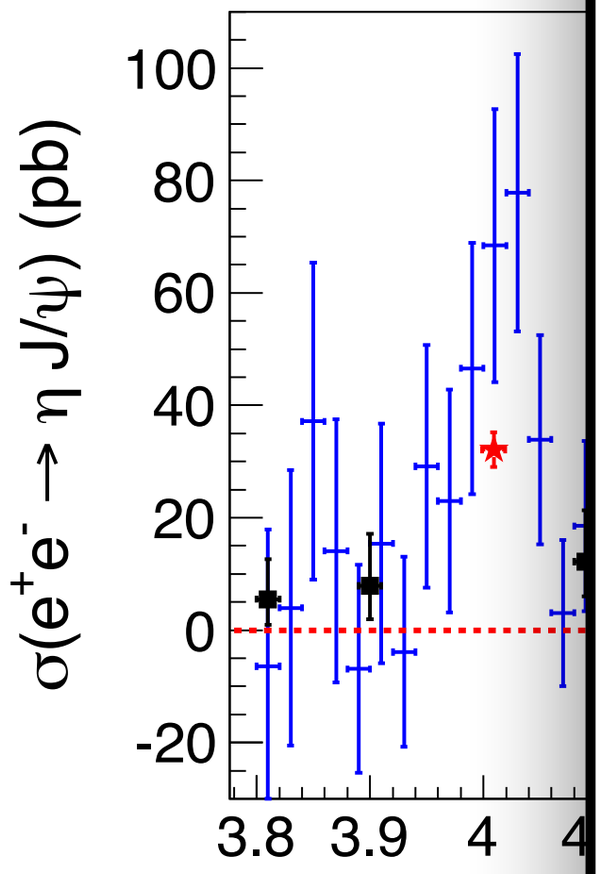
$e^+e^-(\gamma_{ISR}) \to \eta J/\psi$ at Belle



- fit with
states

$e^+e^- \to$

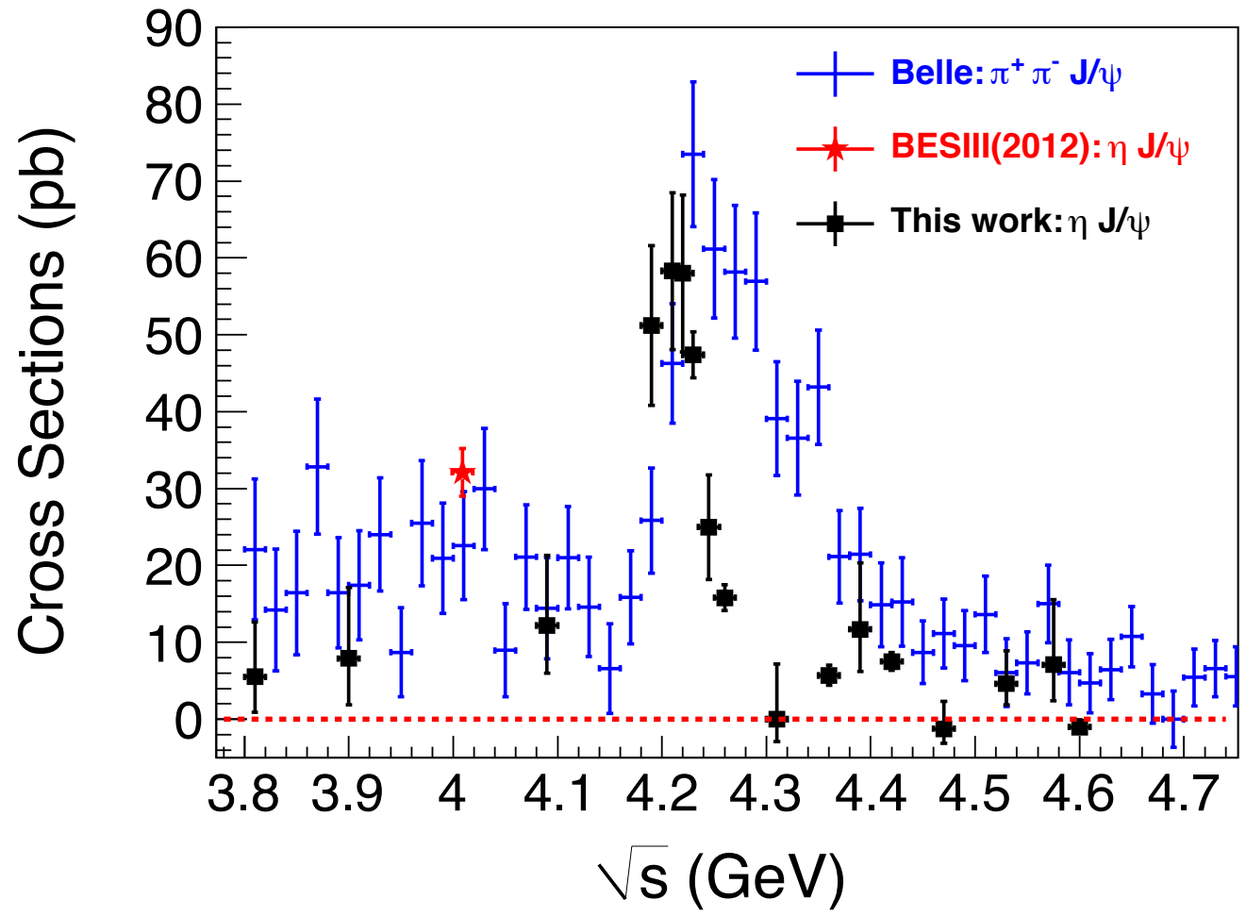
PRD 9



- BESIII confirms th

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

PRD 91, 112005 (2015)

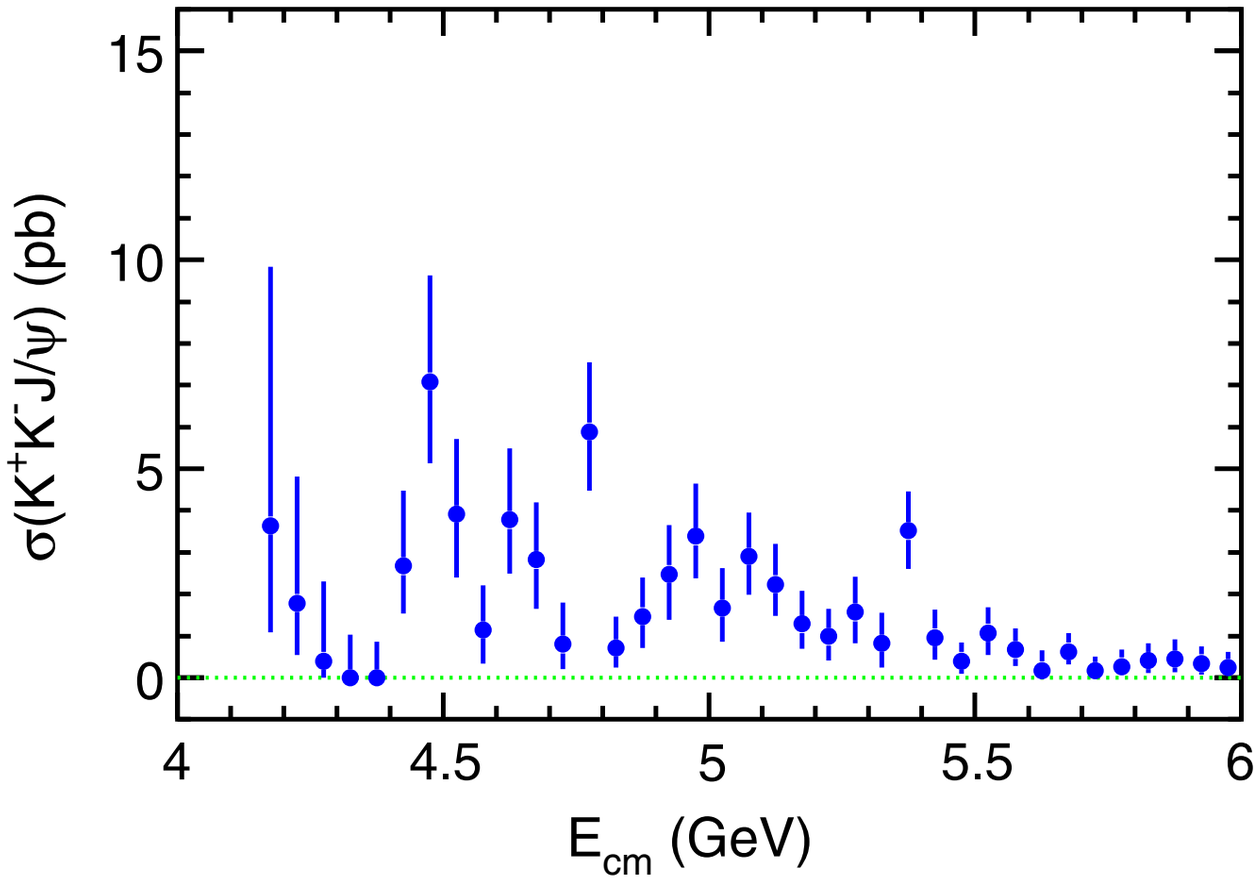


- the $\eta J/\psi$ cross section is inconsistent with Y(4260)

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

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

PRD 89, 072015 (2014)

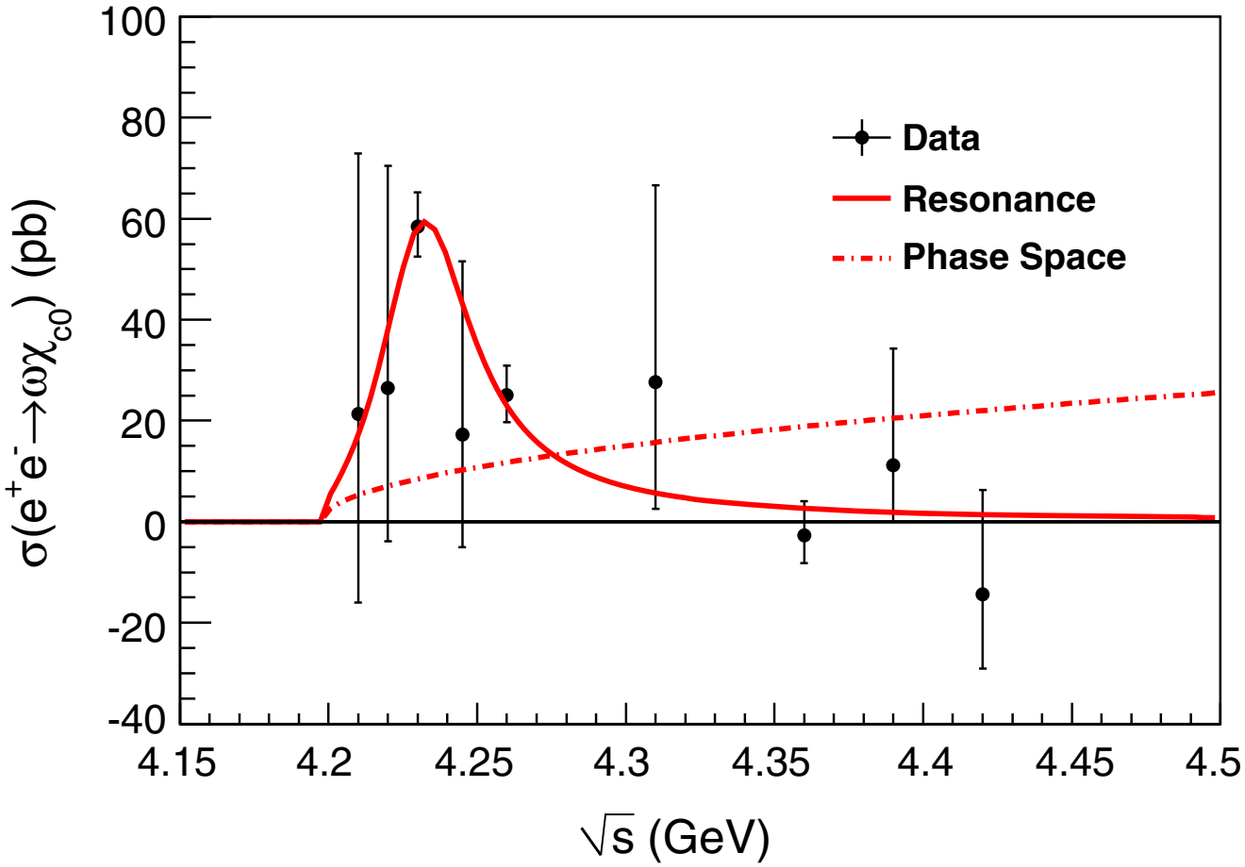


- there is surprising nontrivial structure in KKJ/ψ?

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

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

PRL 114, 092003 (2015)

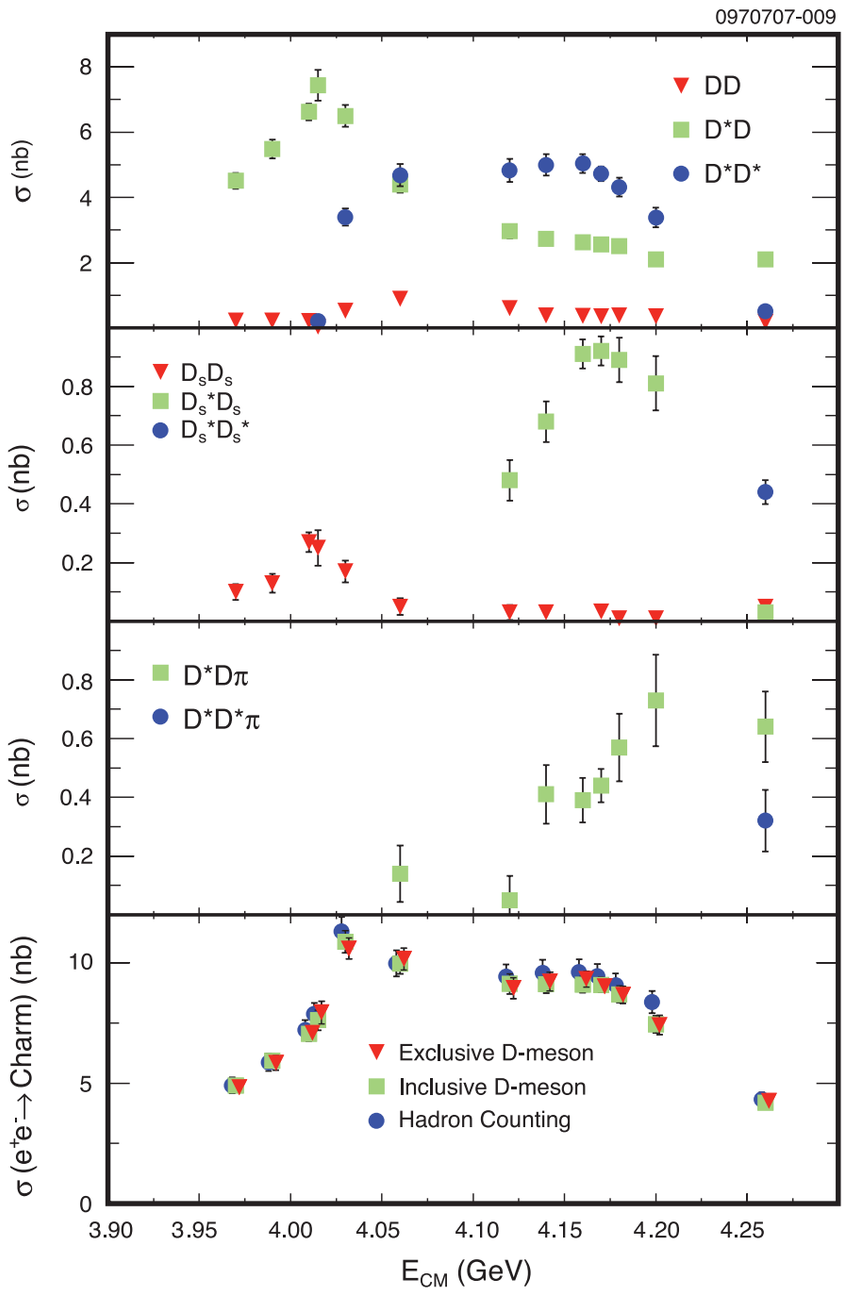


- this shows a Y(4230)??
  (it is inconsistent with Y(4260))

Overview of Open Charm Cross Sections

Open Charm Cross Sections at CLEO-c

PRD 80, 072001 (2009)



- there is no exclusive cross section that agrees with R??
- (precision data from BESIII is on its way)

Part II: Connections and Complexities

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

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

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

Part III: Theory and Experiment Coordination

A. Should experimental "data" be available to the community?

B. Should data always be published with interpretation?

C. Can experimentalists and theorists work together on data analysis?
(some successes, e.g. JPAC, some failures)

D. Is there a way to stimulate theoretical predictions that would be helpful to ongoing experimental analyses?

Part III: Theory and Experiment Coordination

A. Should experimental "data" be available to the community?

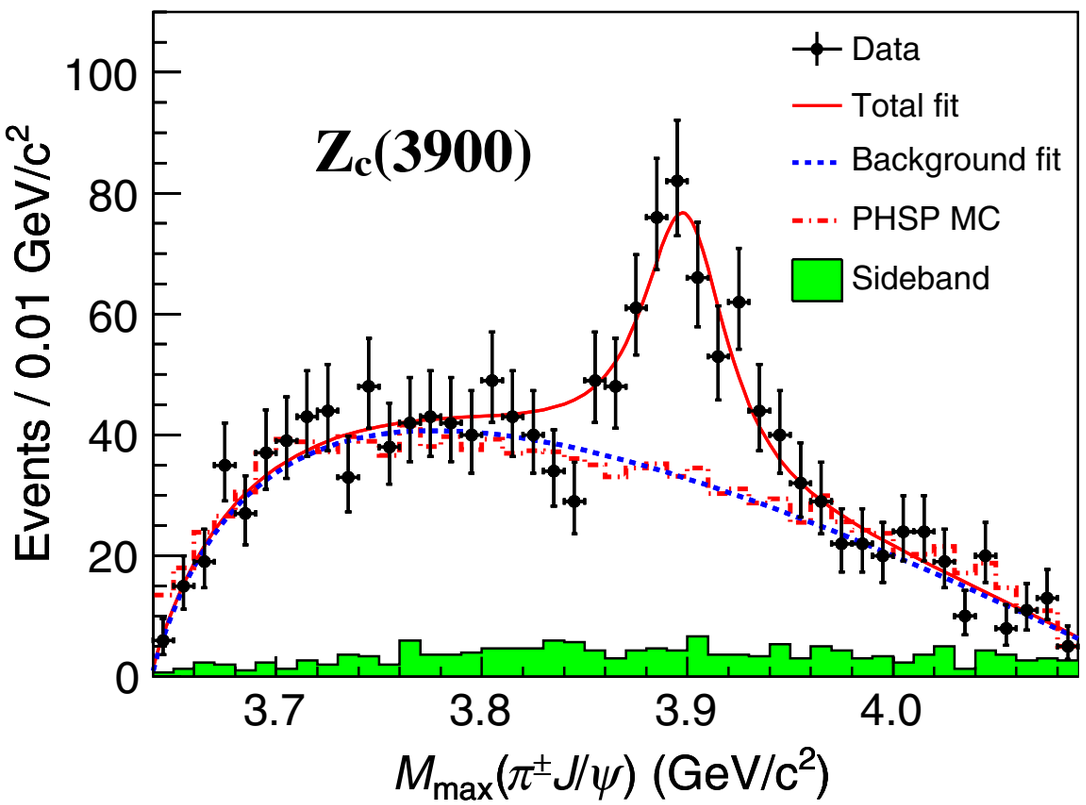
B. Should data always be published with interpr

C. Can experimentalists and theorists work toge
(some successes, e.g. JPAC, some failures)

D. Is there a way to stimulate theoretical predict
ongoing experimental analyses?

$e^+e^- \to \pi^\pm Z_c \to \pi^+\pi^- J/\psi$ at BESIII

PRL 110, 252001 (2013)



- substructure in $\Upsilon(4260) \to \pi^+\pi^- J/\psi$.

Part III: Theory and Experiment Coordination

A. Should experimental "data" be available to the community?

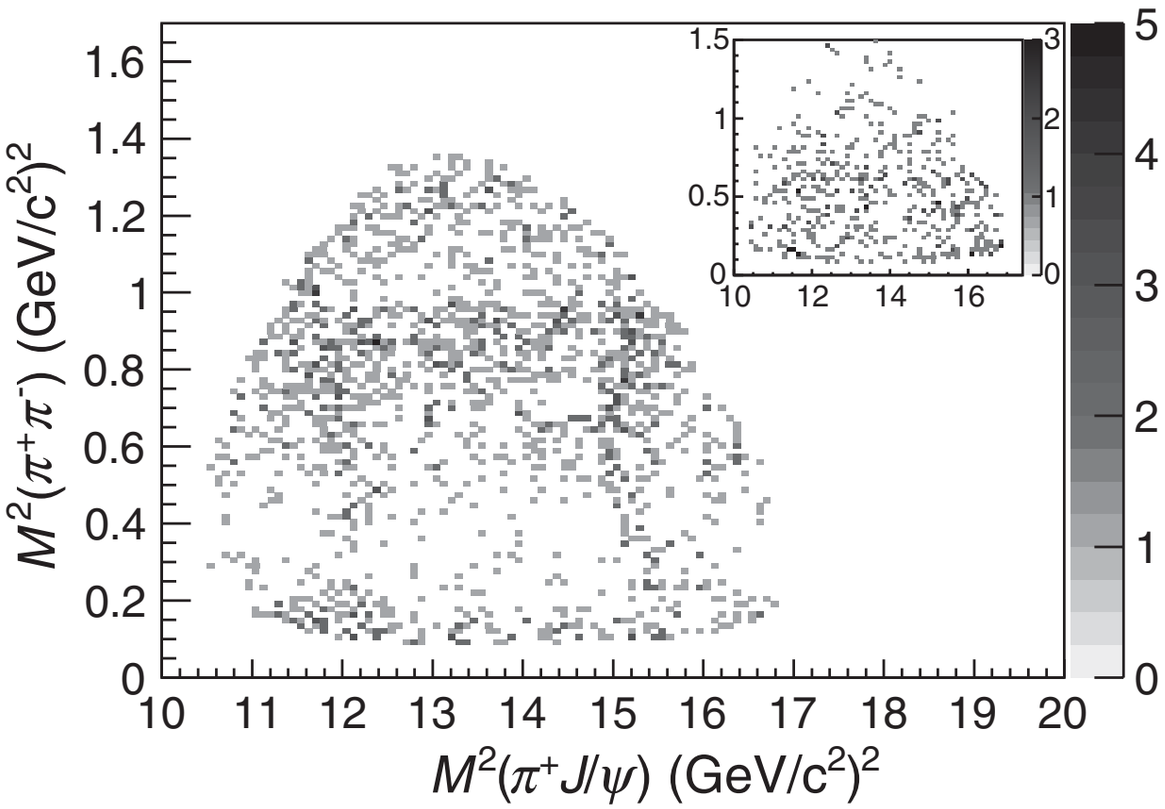
B. Should data always be published with inter

C. Can experimentalists and theorists work to
(some successes, e.g. JPAC, some failures)

D. Is there a way to stimulate theoretical pred
ongoing experimental analyses?

$e^+e^- \to \pi^\pm Z_c \to \pi^+\pi^- J/\psi$ at BESIII

PRL 110, 252001 (2013)



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

Part III: Theory and Experiment Coordination

A. Should experimental "data" be available to the community?

Can this data be shared with theorists?

BESIII: no.

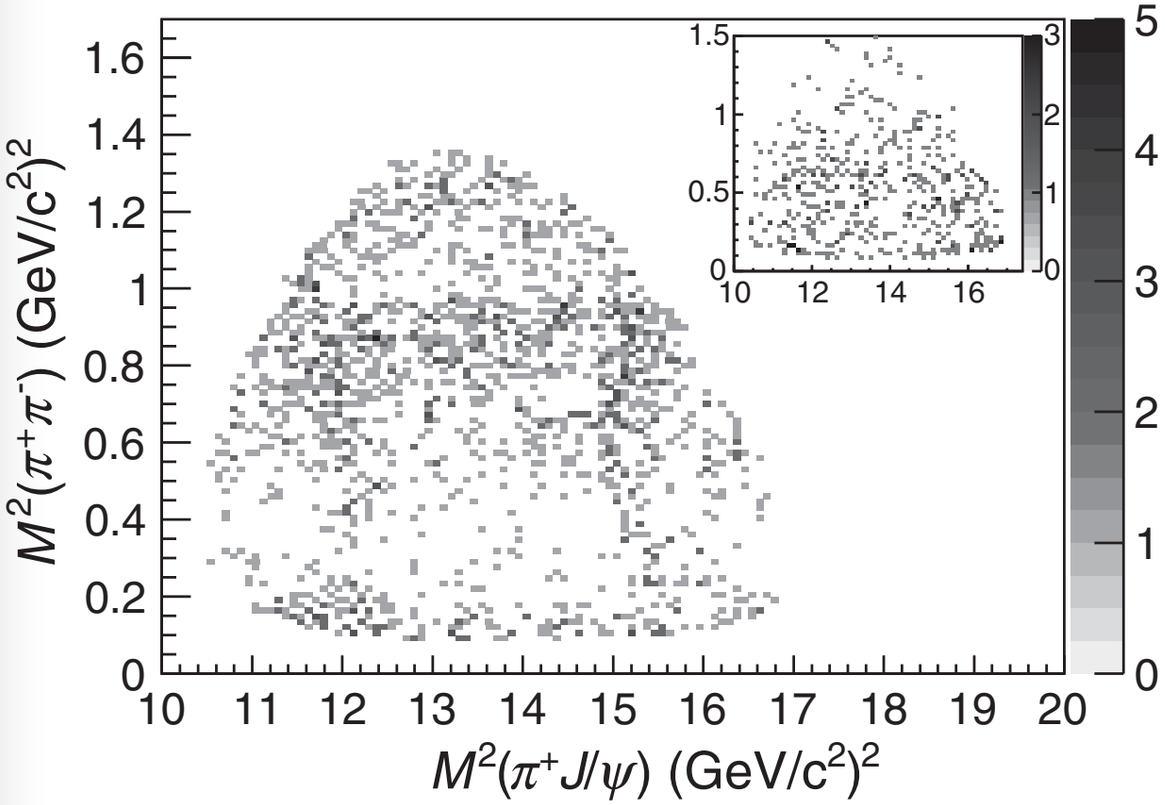
Why?

1. Experimental issues: the data is not acceptance-corrected, there are resolution effects, also backgrounds. (Sharing the data would give implicit consent to fitting and publishing the fits.)

2. Priority issues: if theorists fit the data and make a "discovery" then it is not a BESIII discovery.

$e^+e^- \to \pi^\pm Z_c \to \pi^+\pi^- J/\psi$ at BESIII

PRL 110, 252001 (2013)



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

Part III: Theory and Experiment Coordination

A. Should experimental "data" be available to

Can this data be shared with theorists?

BESIII: no.

Why?

1. Experimental issues: the data is not acceptance-corrected, there are resolution effects, also backgrounds. (Sharing the data would give implicit consent to fitting and publishing the fits.)

2. Priority issues: if theorists fit the data and make a "discovery" then it is not a BESIII discovery.

Should data always be published with interpretation?

BESIII: yes.

Why?

1. Experimental issues: only experimentalists have the proper tools to handle acceptance issues, etc.

2. Priority issues: same as previous.

3. On principle. We are physicists and we should make physics conclusions, not just measure numbers.

What if we don't know how to fit the data?
This is currently an important issue…

Part III: Theory and Experiment Coordination

A. Should experimental "data" be available to the community?

B. Should data always be published with interpretation?

C. Can experimentalists and theorists work together on data analysis?
(some successes, e.g. JPAC, some failures)

D. Is there a way to stimulate theoretical predictions that would be helpful to ongoing experimental analyses?

Part III: Theory and Experiment Coordination

A. Should experimental "data" be available to the community?

B. Should data always be published with interpretation?

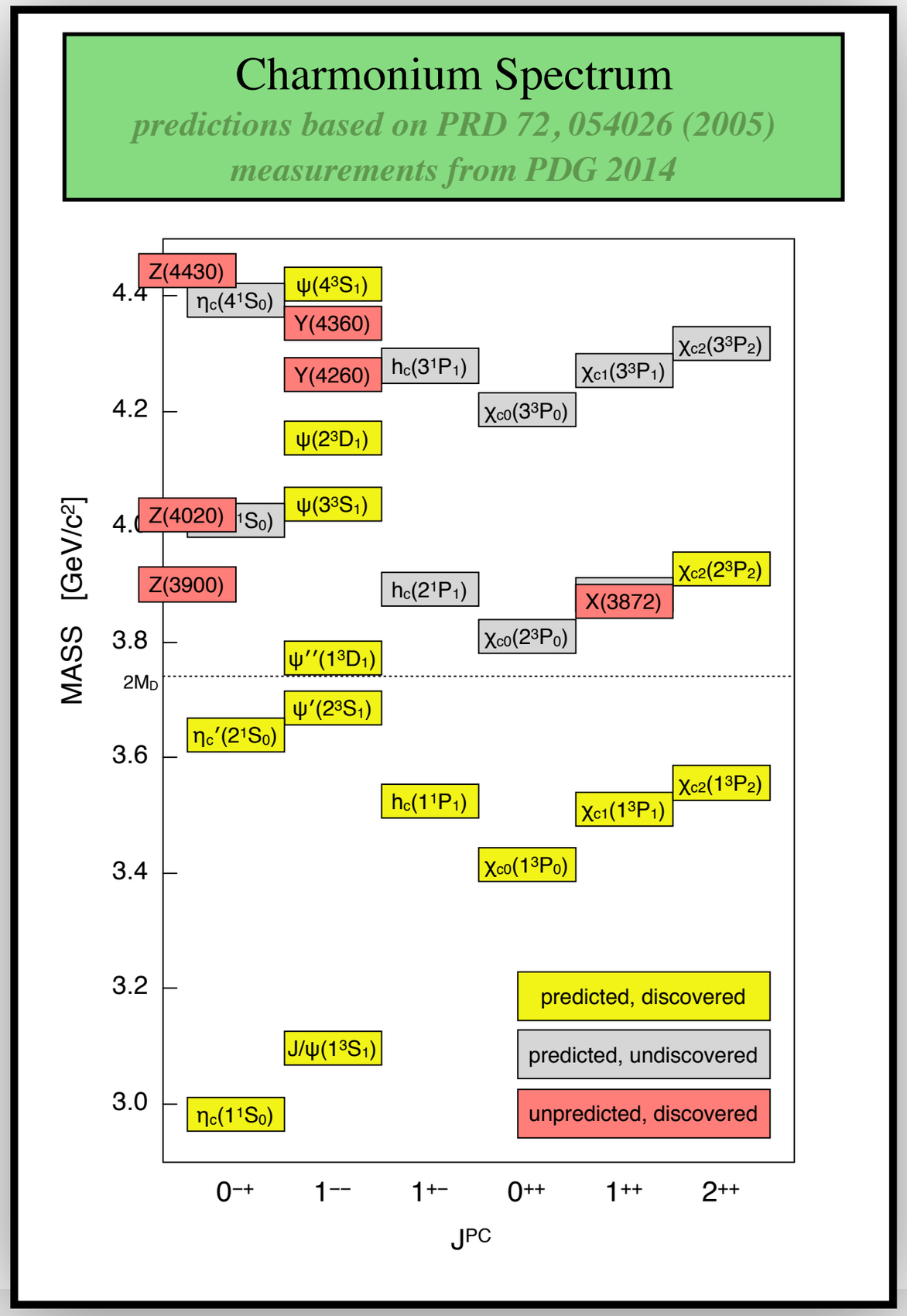
C. Can experimentalists and theorists work together on data analysis?
(some successes, e.g. JPAC, some failures)

D. Is there a way to stimulate theoretical predictions that would be helpful to ongoing experimental analyses?

Example:

1. Predict how the $e^+e^- \to \pi^+\pi^- J/\psi$ Dalitz plot changes as a function of center-of-mass energy.

Concluding Thoughts on the XYZ Mesons



Many experimental results are waiting to be synthesized.

[There are also many experimental results struggling to reach publication stage.]

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

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

Some complexities (e.g., e^+e^- cross sections) *may* resolve themselves with more data?

We need to consider ways to push forward towards a more global understanding of these phenomena.

It is an interesting time…