Mysteries in the Meson System at the BESIII Experiment

Ryan Mitchell
Indiana University

Bormio 2019

January 21, 2019

Beijing, China

BESIII (Beijing Spectrometer)
at **BEPCII** (Beijing Electron-Positron Collider)
at **IHEP** (Institute for High Energy Physics)

son System

ment

BEPCII: e^+e^- Collisions at E_{CM} between 2.0 and 4.6 GeV

BESIII (Beijing Spectrometer)
at **BEPCII** (Beijing Electron-Positron Collider)
at **IHEP** (Institute for High Energy Physics)

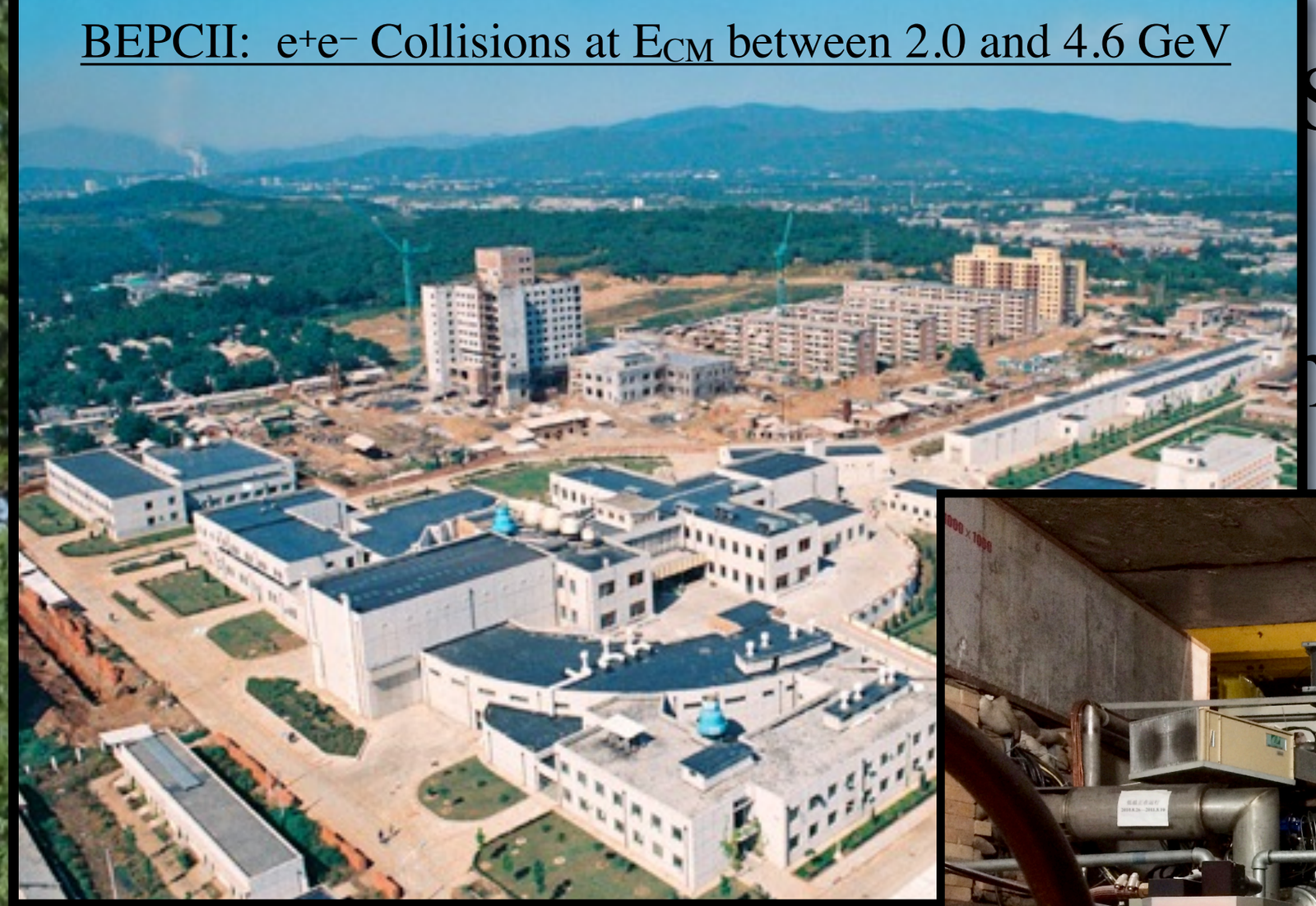
son System

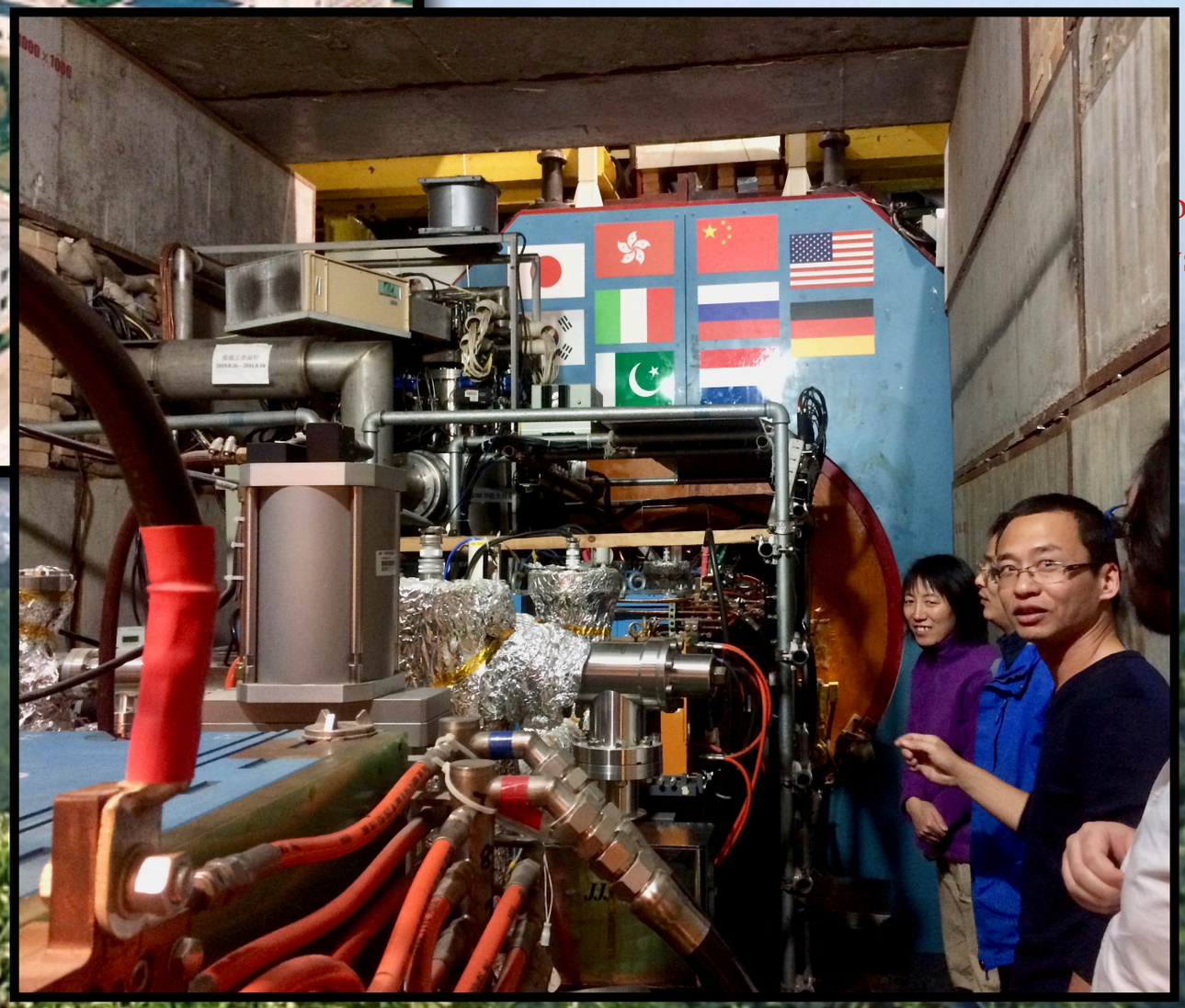
ment

llider)

sics)

BEPCII: e^+e^- Collisions at E_{CM} between 2.0 and 4.6 GeV





son System

ment

Collider)
ysics)

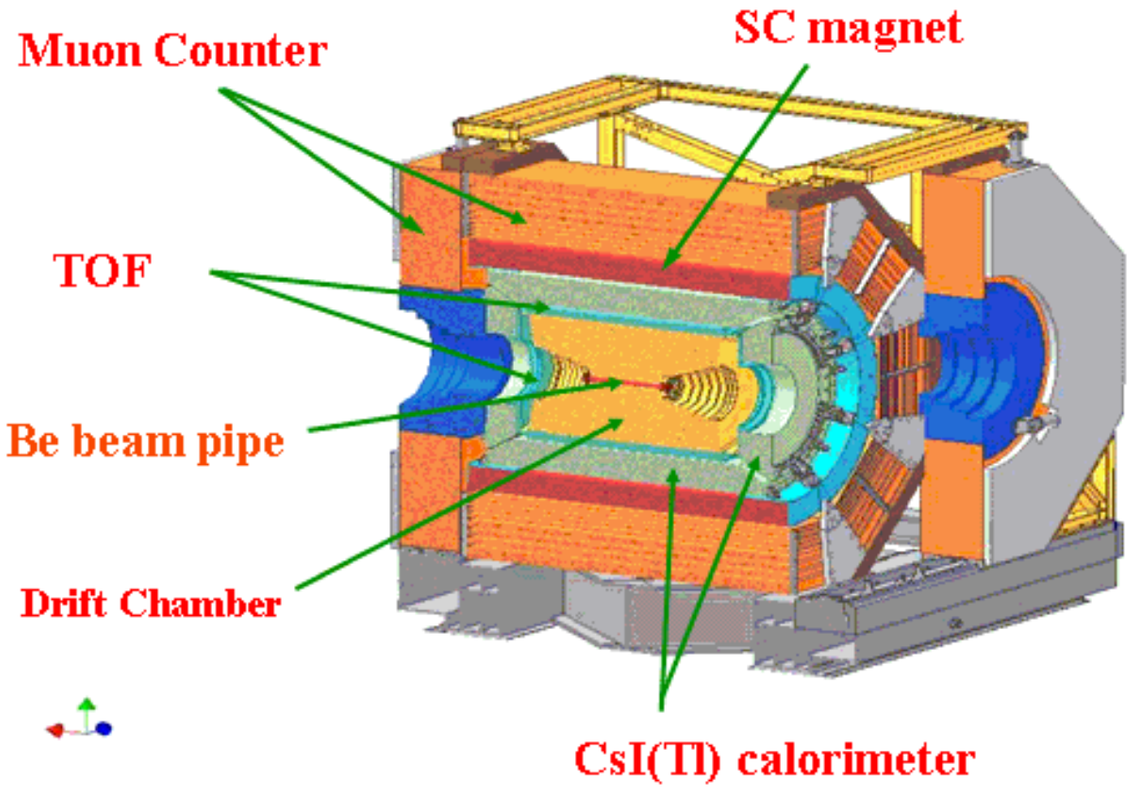
BEPCII: e^+e^- Collisions at E_{CM} between 2.0 and 4.6 GeV

BESIII Detector *(a standard high-energy physics experiment)*

(1) Calorimeter: photon energy and direction

(2) Drift Chamber and Magnet: charged particle momentum

(3) Time-of-Flight (TOF): charged particle mass



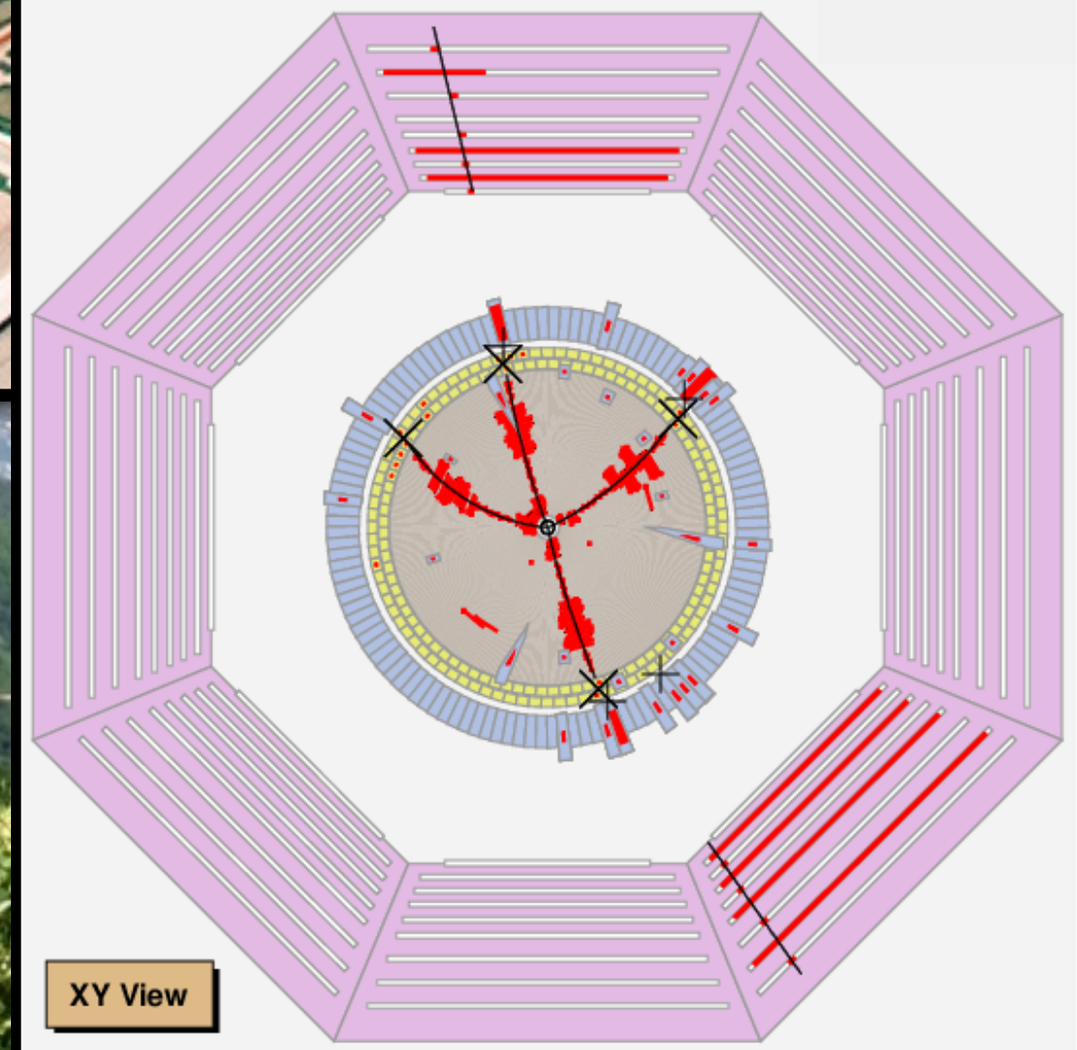
son System

ment

eter)
on Collider)
y Physics)

BEPCII: e^+e^- Collisions at E_{CM} between 2.0 and 4.6 GeV

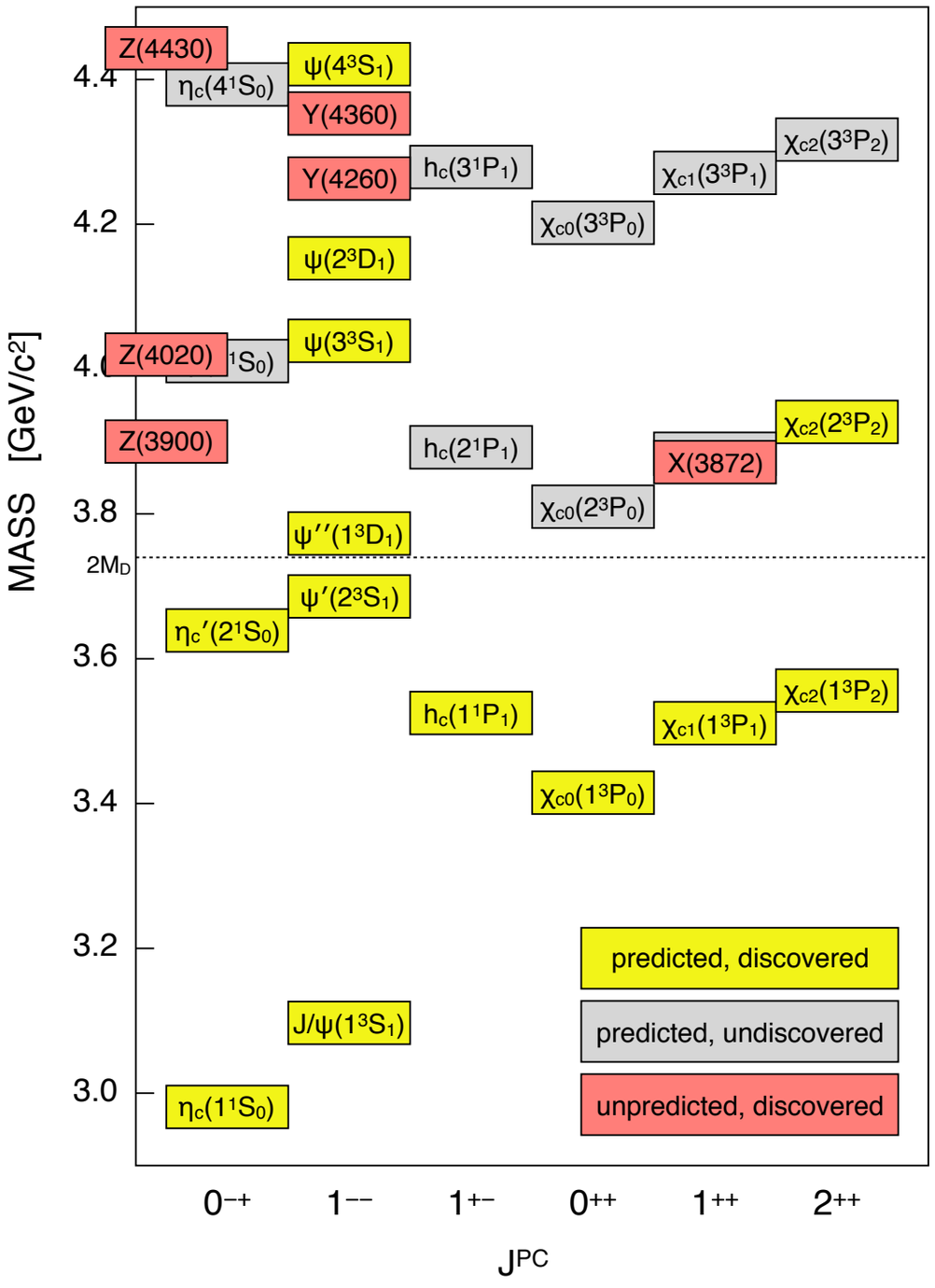
$e^+e^- \to \pi^+\pi^- J/\psi; \quad J/\psi \to \mu^+\mu^-$

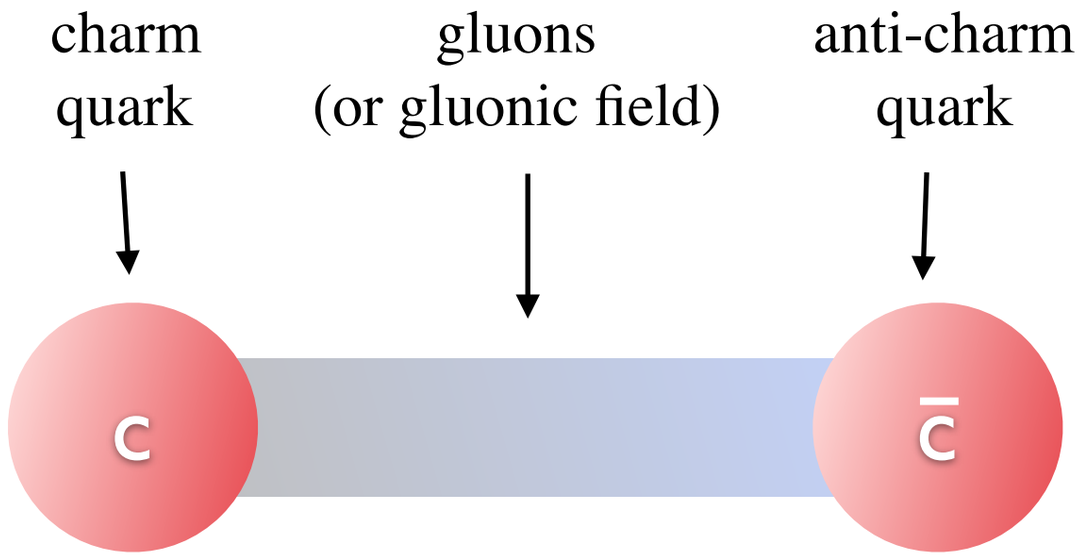


Charmonium as a Model System *(almost)*

Charmonium Spectrum

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





Experimentally accessible quantum numbers:

$$\mathbf{J^{PC}}$$

Derived quantum numbers:

$$\mathbf{n^{2S+1}L_J}$$

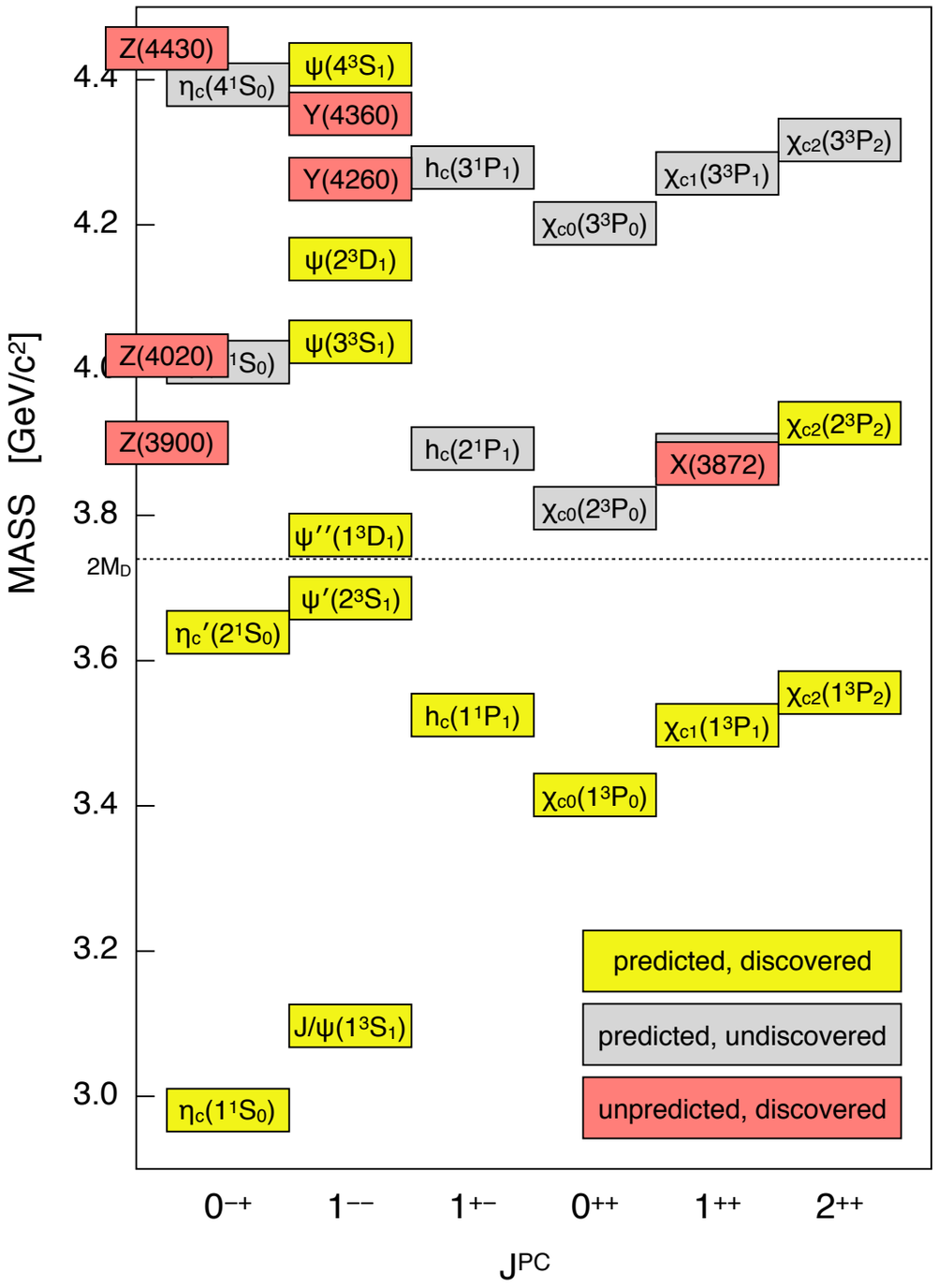
Relationships:

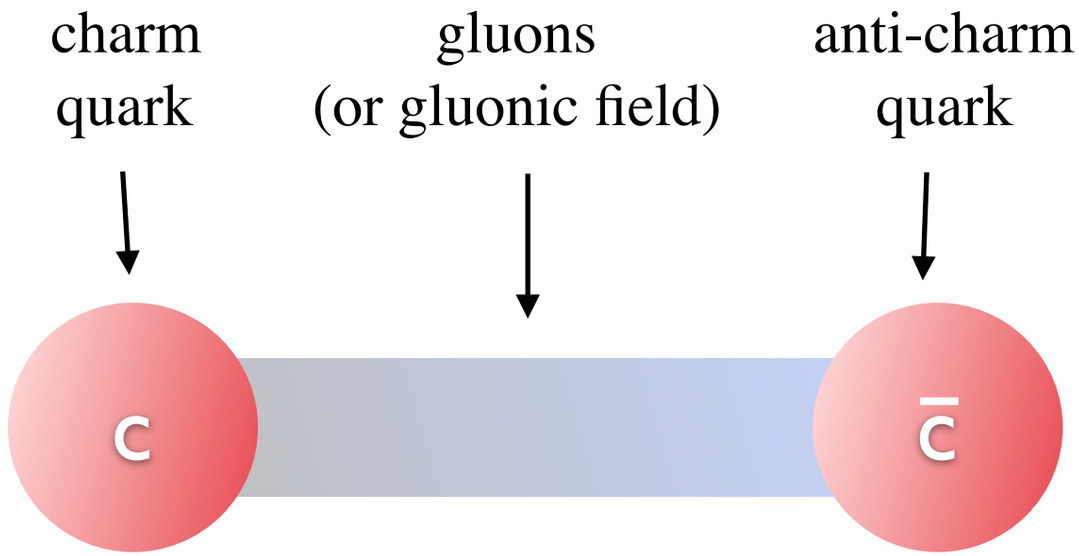
$$P = (-1)^{L+1} \qquad C = (-1)^{L+S}$$

Charmonium as a Model System *(almost)*

Charmonium Spectrum

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





Experimentally accessible quantum numbers:

JPC

$$J^{PC} = \begin{cases} 0^{-+} & 1^{+-} & 1^{--} & 0^{++} \\ 2^{-+} & 3^{+-} & 2^{--} & 1^{++} \\ \vdots & \vdots & \vdots & \vdots \end{cases}$$

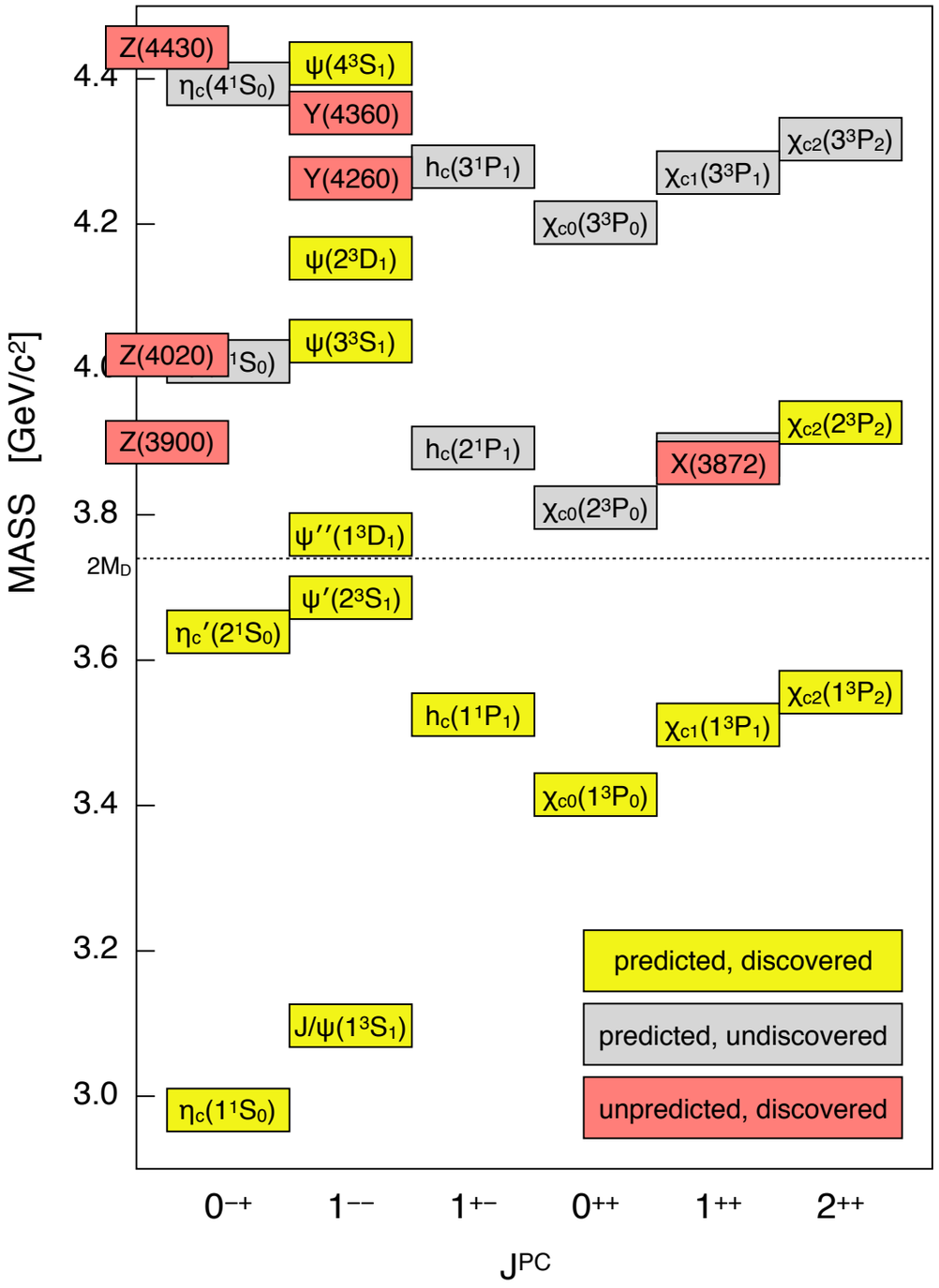
Minimal quark content				
$u\bar{d}, u\bar{u} - d\bar{d}, d\bar{u}$ $(I=1)$	π	b	ρ	a
$d\bar{d} + u\bar{u}$ $(I=0)$	η, η'	h, h'	ω, ϕ	f, f'
and/or $s\bar{s}$				
$c\bar{c}$	η_c	h_c	$\psi^\dagger$	χ_c
$b\bar{b}$	η_b	h_b	Υ	χ_b
$I=1$ with $c\bar{c}$	(Π_c)	Z_c	R_c	(W_c)
$I=1$ with $b\bar{b}$	(Π_b)	Z_b	(R_b)	(W_b)

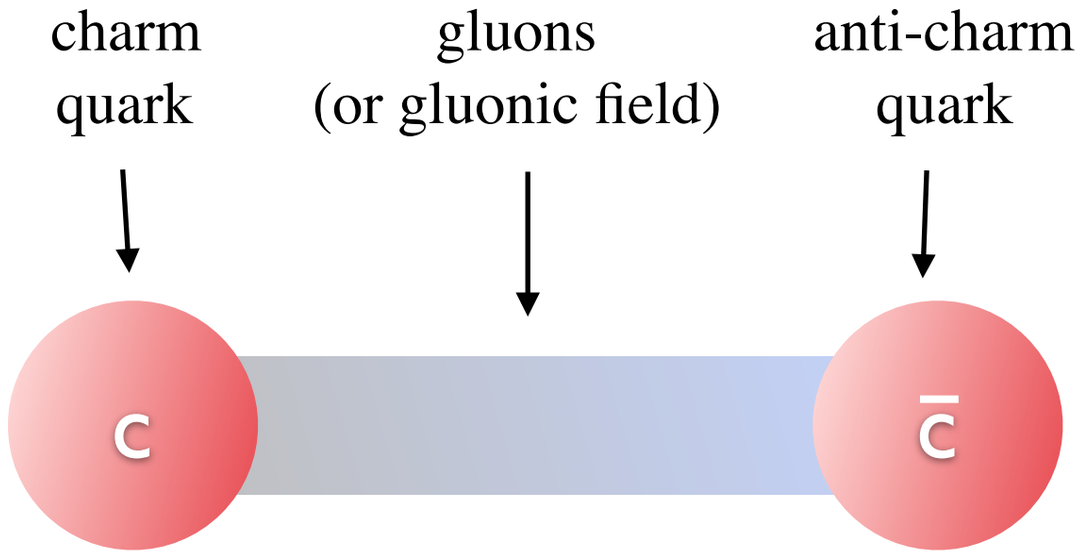
†The J/ψ remains the J/ψ.

Charmonium as a Model System *(almost)*

Charmonium Spectrum

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





Potential models:

Example from Barnes, Godfrey, Swanson:

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

(Coulomb + Confinement + Contact)

$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

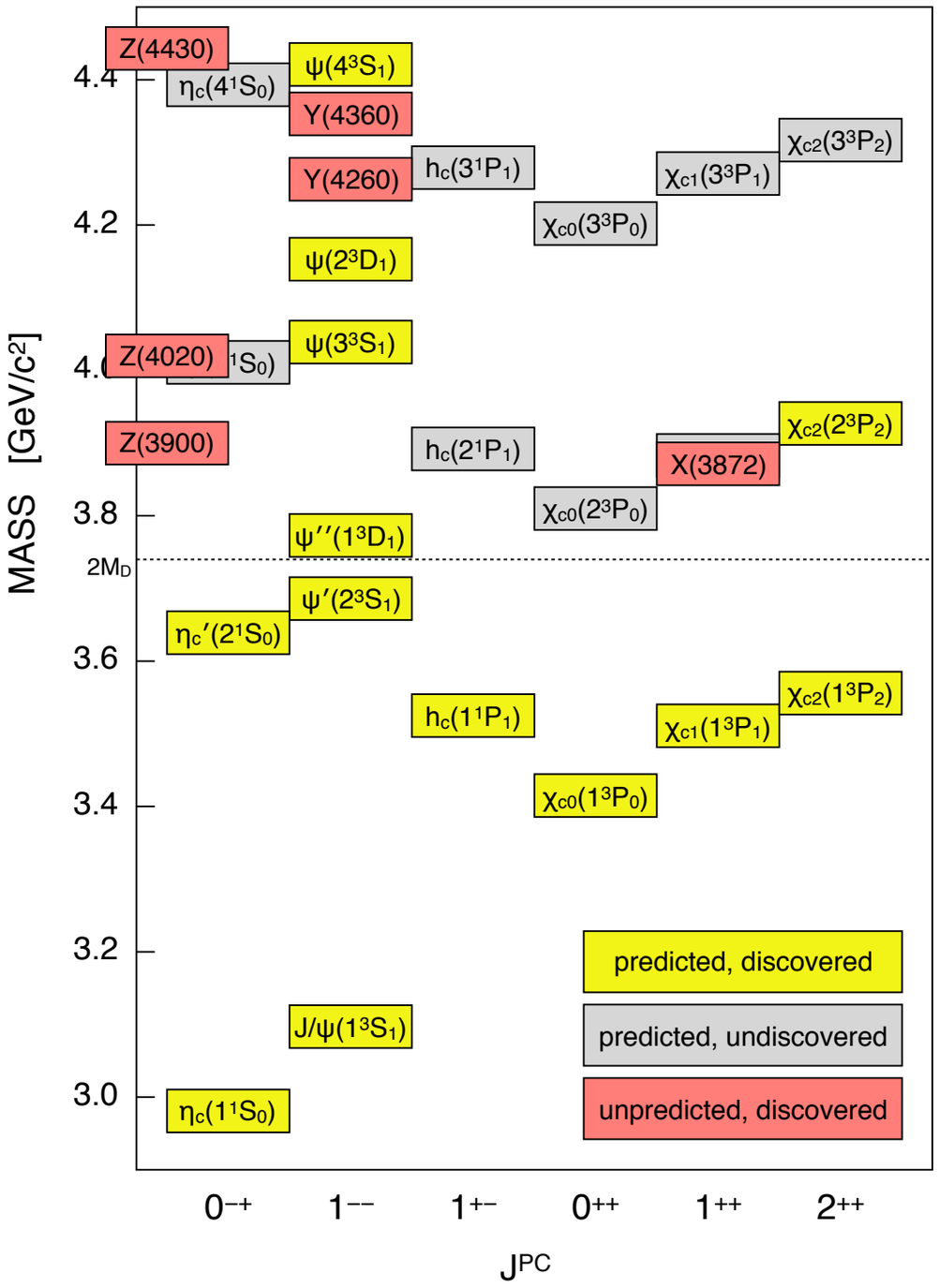
(Spin-Orbit + Tensor)

PRD72, 054026 (2005)

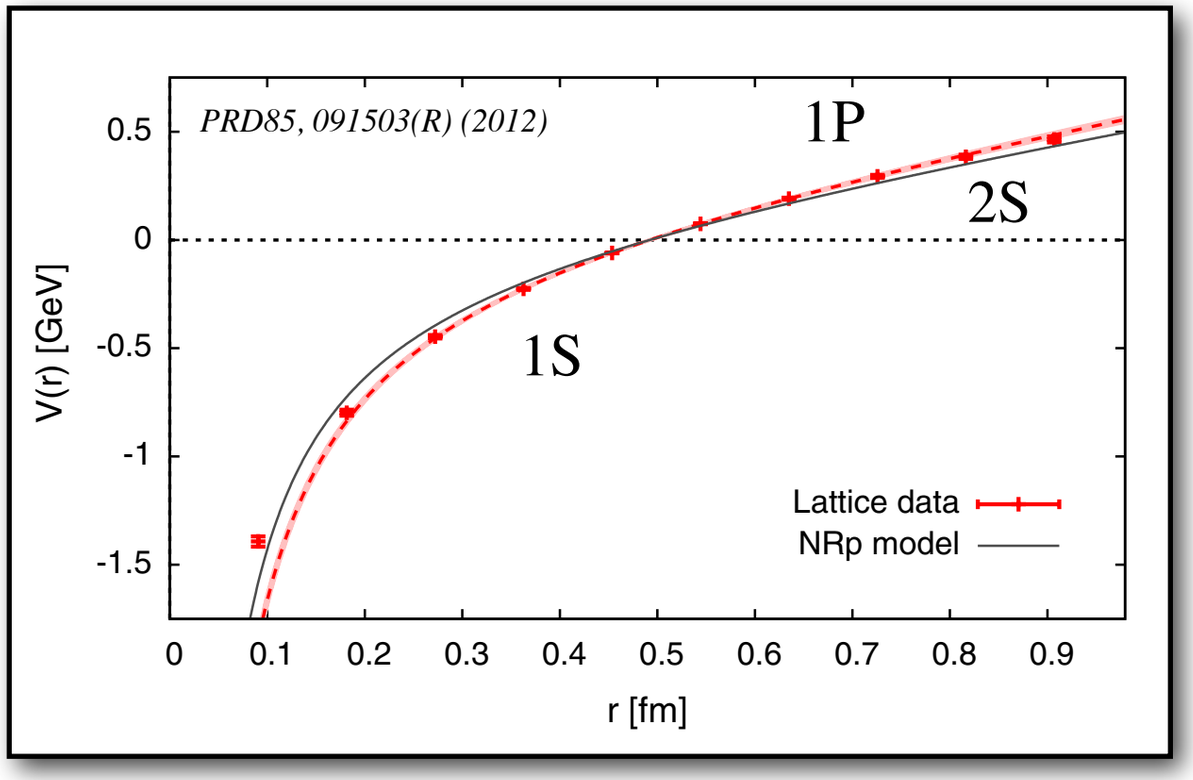
Charmonium as a Model System *(almost)*

Charmonium Spectrum

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



Potential models and Lattice QCD:



Potential models:

Example from Barnes, Godfrey, Swanson:

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

(Coulomb + Confinement + Contact)

$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

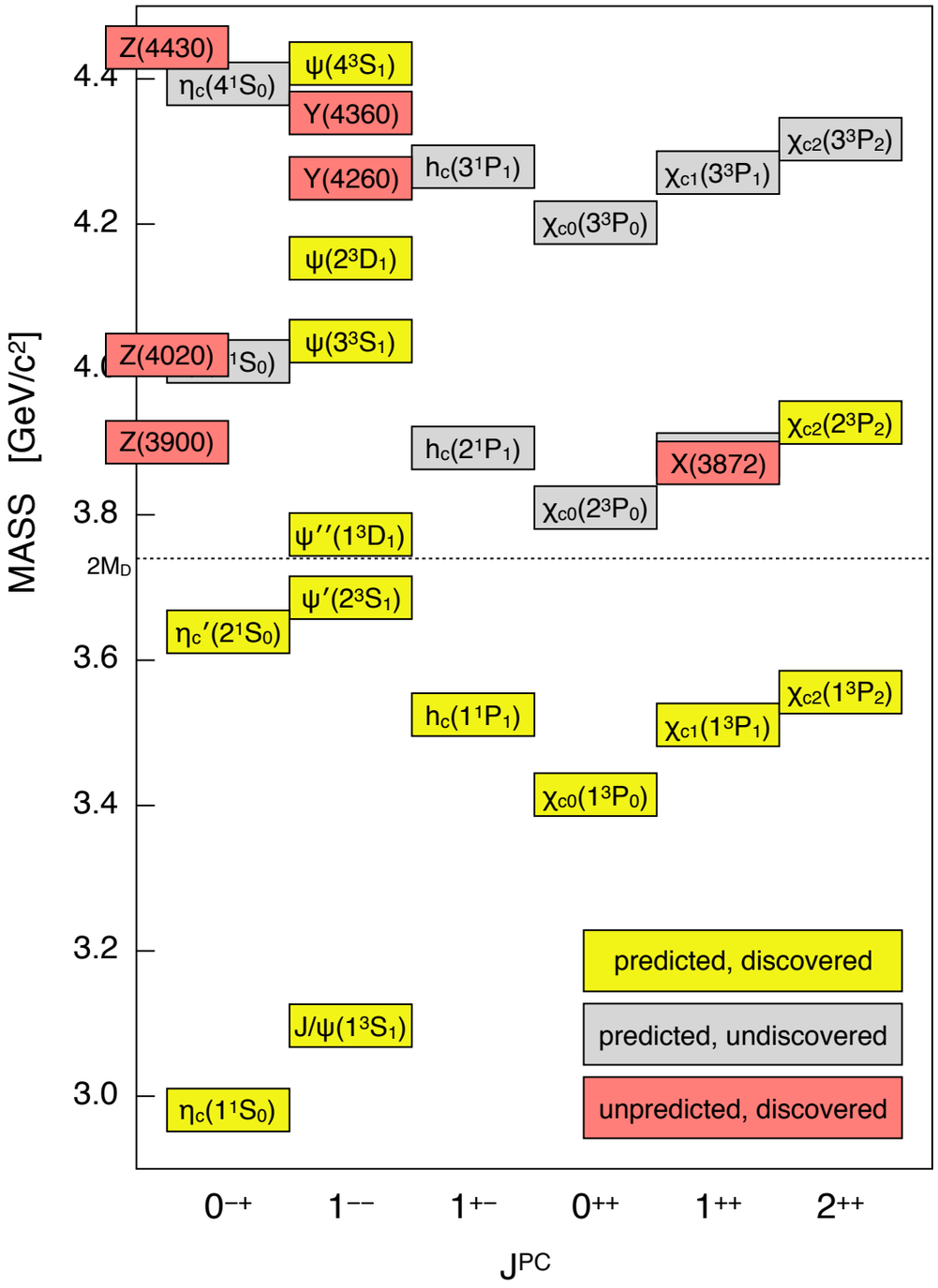
(Spin-Orbit + Tensor)

PRD72, 054026 (2005)

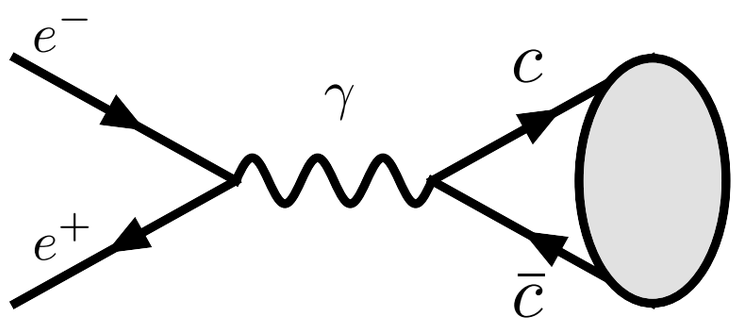
Charmonium as a Model System *(almost)*

Charmonium Spectrum

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



Charmonium at BESIII:



$$J/\psi, \psi', \psi'', \ldots$$

Potential models:

Example from Barnes, Godfrey, Swanson:

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

(Coulomb + Confinement + Contact)

$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

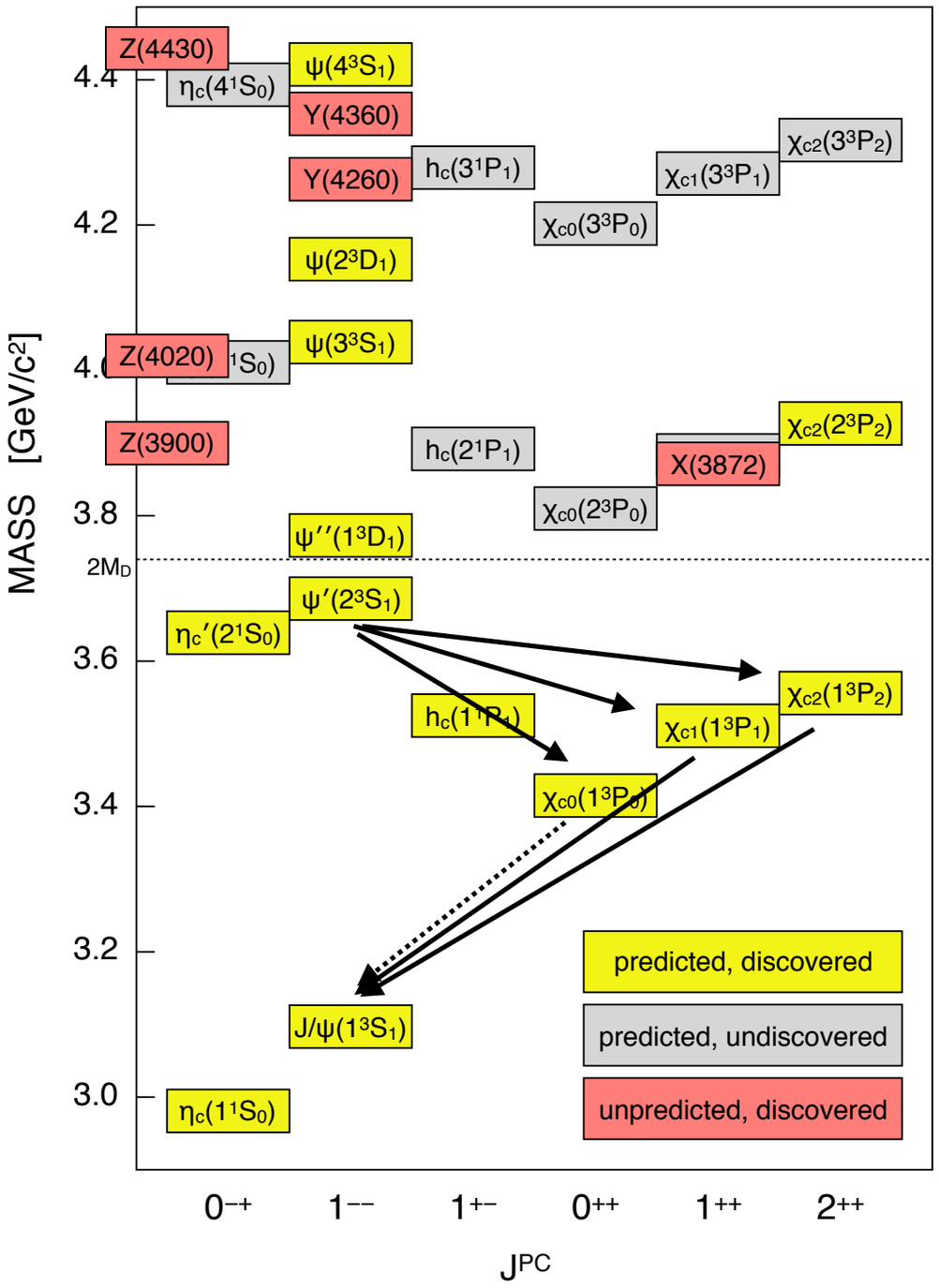
(Spin-Orbit + Tensor)

PRD72, 054026 (2005)

Charmonium as a Model System *(almost)*

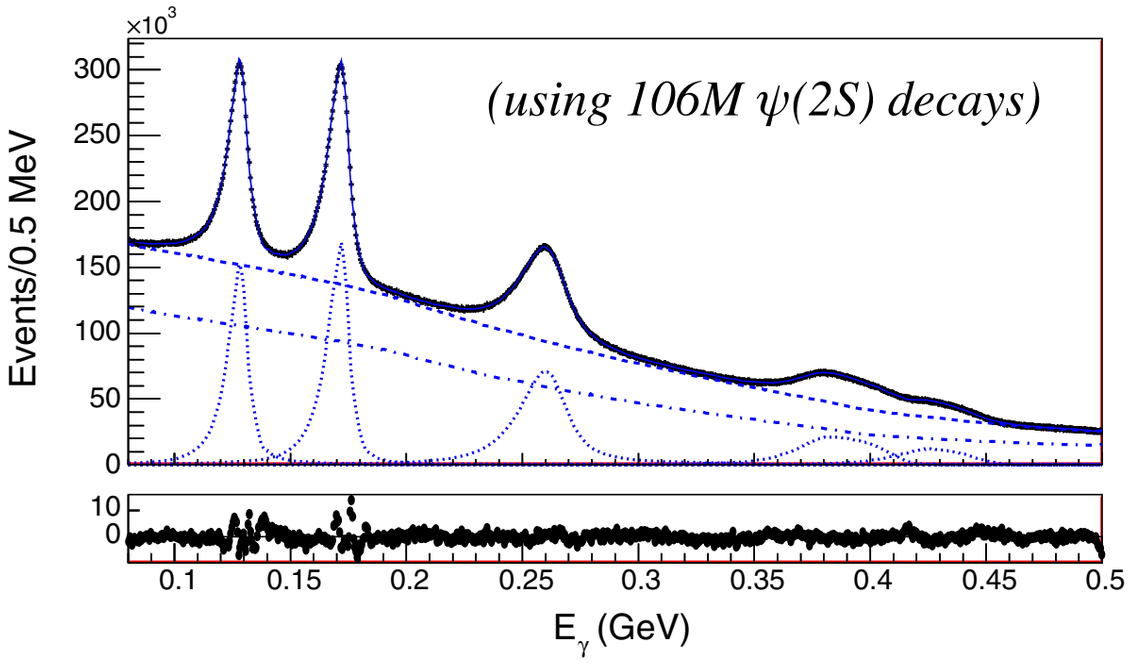
Charmonium Spectrum

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



$\psi(2S) \to \gamma +$ anything

[PRD 96, 032001 (2017)]



Potential models:

Example from Barnes, Godfrey, Swanson:

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

(Coulomb + Confinement + Contact)

$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

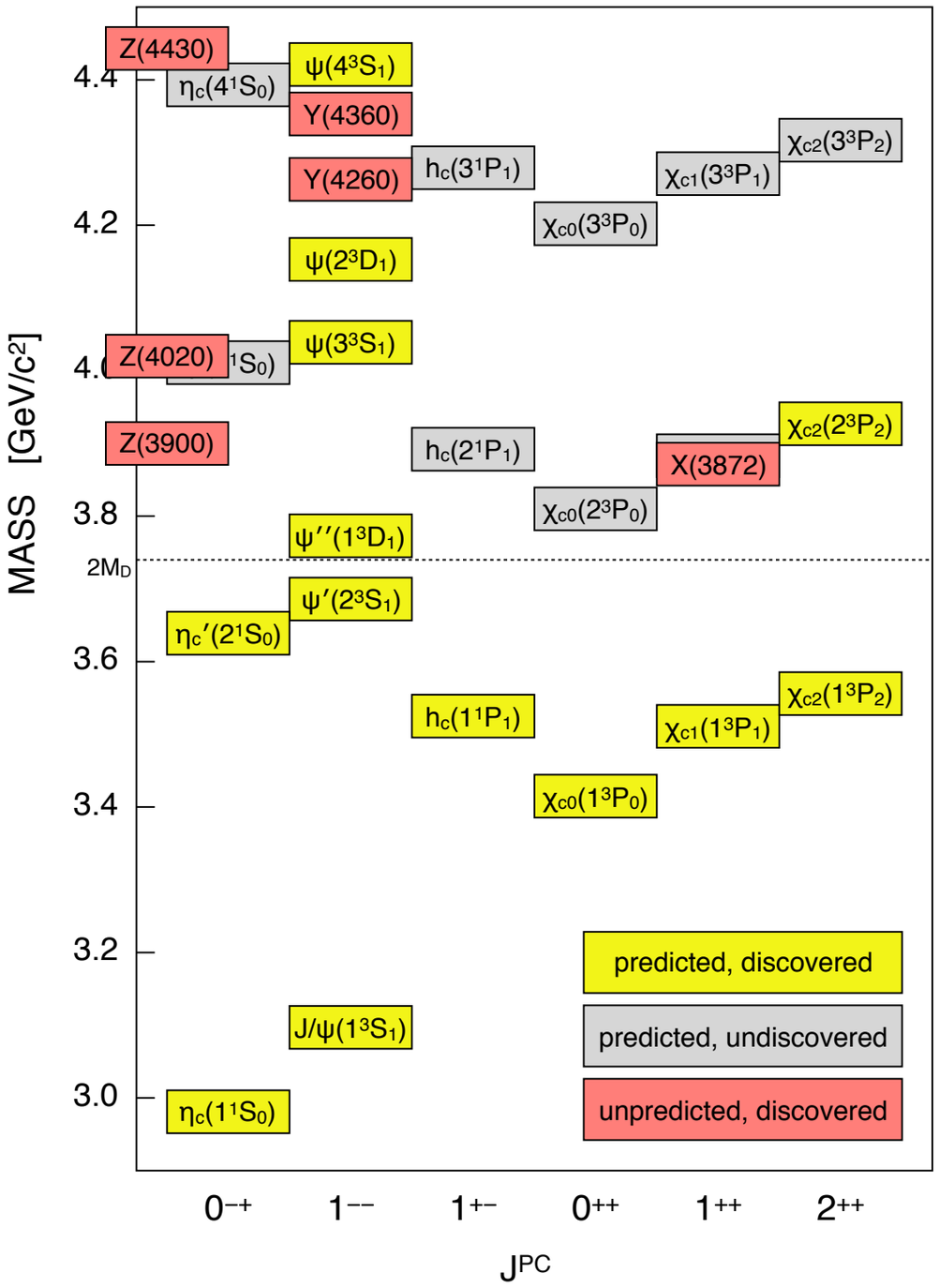
(Spin-Orbit + Tensor)

PRD72, 054026 (2005)

The Broad Physics Reach of BESIII

Charmonium Spectrum

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



BESIII Data Sets (primary):

(e^+e^- collisions at E_{CM} between 2.0 and 4.6 GeV)

2009: 106M ψ(2S)
225M J/ψ
2010: 975 pb^{-1} at ψ(3770)
2011: 2.9 fb^{-1} at **ψ(3770)** *(total)*
482 pb^{-1} at **4.01 GeV**
2012: 0.45B **ψ(2S)** *(total)*
1.3B **J/ψ** *(total)*
2013: 1092 pb^{-1} at **4.23 GeV**
826 pb^{-1} at **4.26 GeV**
540 pb^{-1} at **4.36 GeV**
~50 pb^{-1} at **3.81, 3.90, 4.09, 4.19, 4.21, 4.22, 4.245, 4.31, 4.39, 4.42 GeV**
2014: 1029 pb^{-1} at **4.42 GeV**
110 pb^{-1} at **4.47 GeV**
110 pb^{-1} at **4.53 GeV**
48 pb^{-1} at **4.575 GeV**
567 pb^{-1} at **4.6 GeV**
0.8 fb^{-1} **R-scan** from 3.85 to 4.59 GeV (104 points)
2015: **R-scan** from 2-3 GeV + **2.175 GeV** data
2016: ~3fb^{-1} at 4.18 GeV (for **D_s**)
2017: 7 × 500 pb^{-1} between **4.19** and **4.27 GeV**
2018: **J/ψ** *(and tuning new RF cavity)*

+ Initial State Radiation (ISR)

(data sets from BESII are much smaller (e.g. 58M J/ψ decays))

(1) The **proton antiproton** Question

What is the X(1835)?

(2) The **ϱπ** Question

Why are there anomalous differences between J/ψ and ψ(2S) decays?

(3) The **Y** Question

Why are there so many different peaks in exclusive e^+e^- cross sections?
e.g. Y(4230), Y(4260), Y(4360), Y(4660), etc.

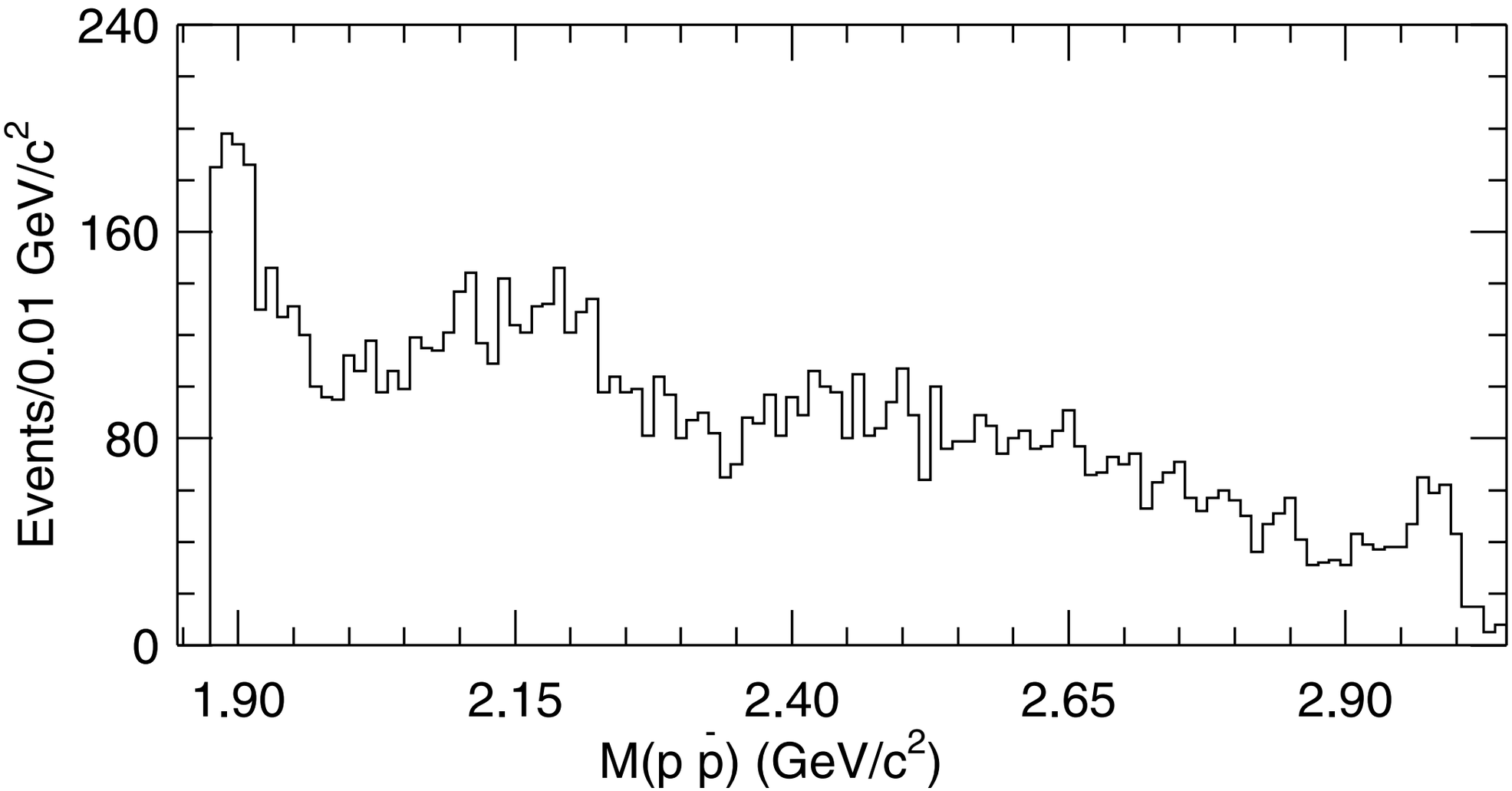
(4) The **Z** Question

What are the electrically charged "charmoniumlike" peaks?
e.g. Z_c(3900), Z_c(4020), Z_c(4055), etc.

(1) The **proton antiproton** Question

$J/\psi \to \gamma p\bar{p}$

[BESII, PRL 91, 022001 (2003)]

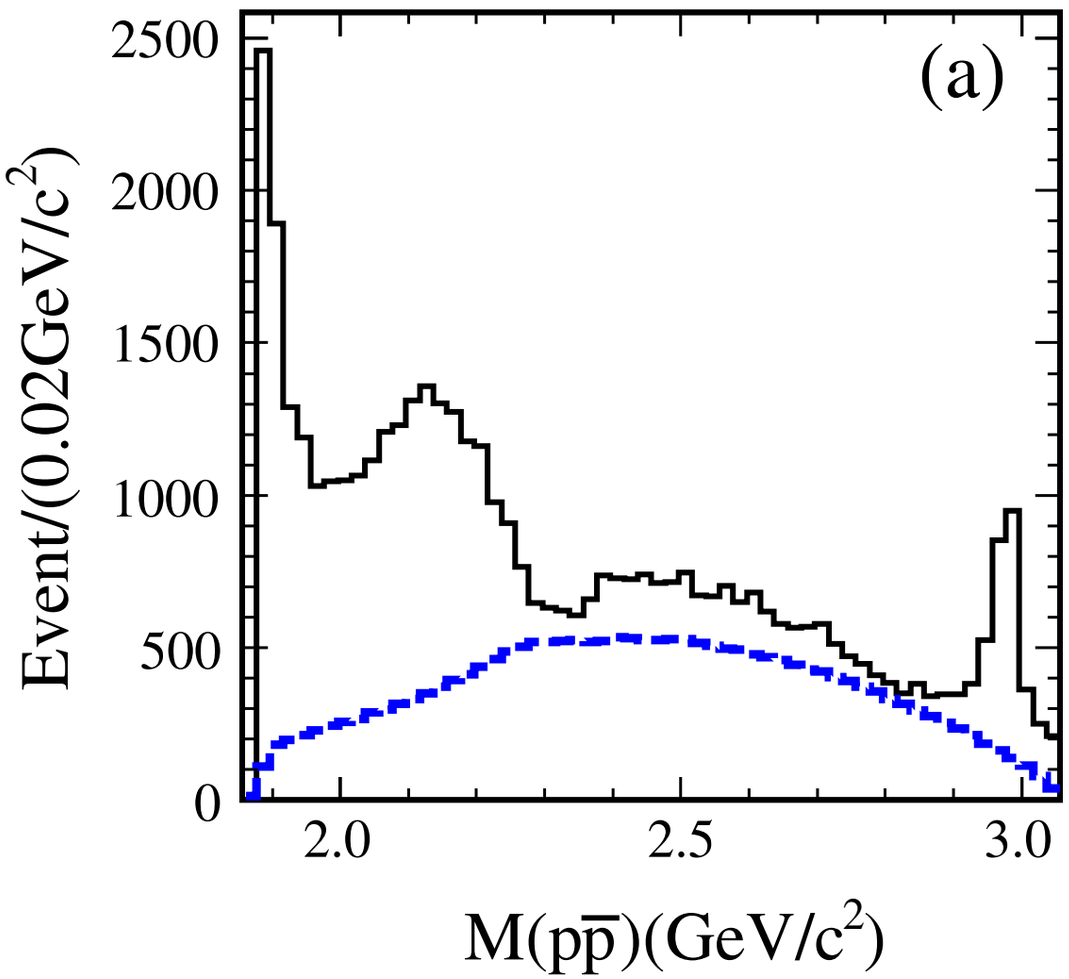


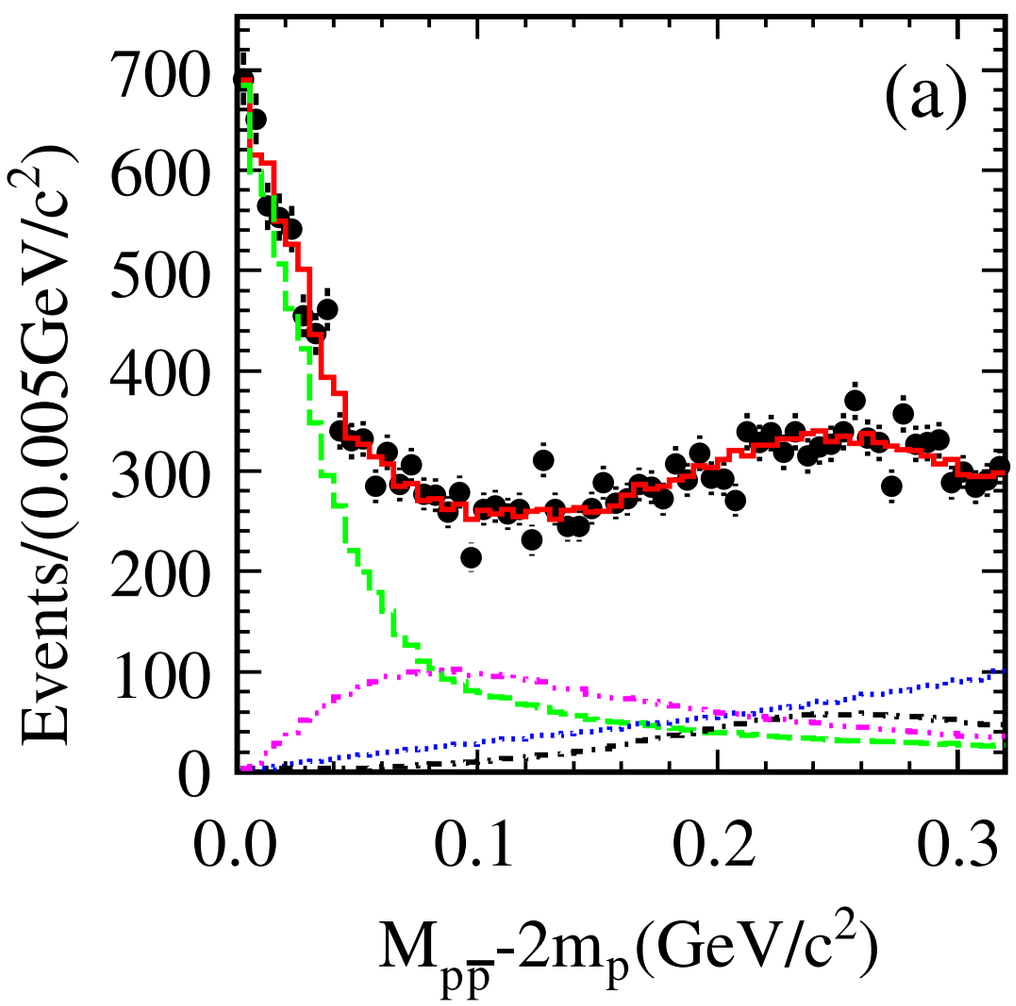
(using 58M J/ψ decays at BESII)

(1) The **proton antiproton** Question

$$J/\psi \to \gamma p\bar{p}$$

[PRL 108, 112003 (2012)]





(using 225M J/ψ decays)

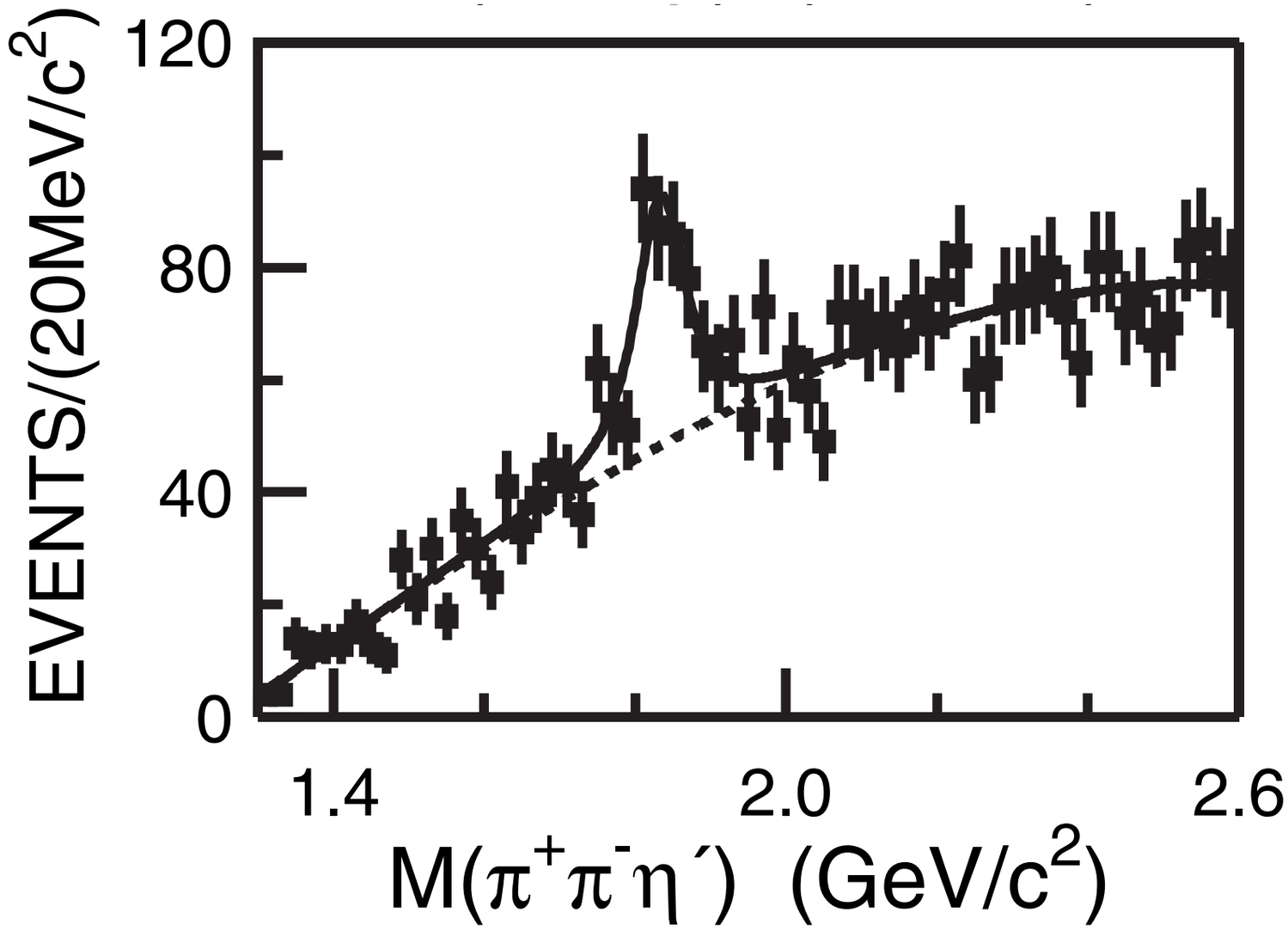
Fit Components: X(1835), 0^{++} phase space, $f_0(2100)$, $f_2(1910)$

$$M = 1832^{+19}_{-5}(\text{stat})^{+18}_{-17}(\text{syst})\pm 19(\text{model});\ \Gamma < 76\ \text{MeV}/c^2;\ J^{PC} = 0^{-+}$$

(1) The **proton antiproton** Question

$$J/\psi \to \gamma\pi^+\pi^-\eta'$$

[BESII, PRL 95, 262001 (2005)]



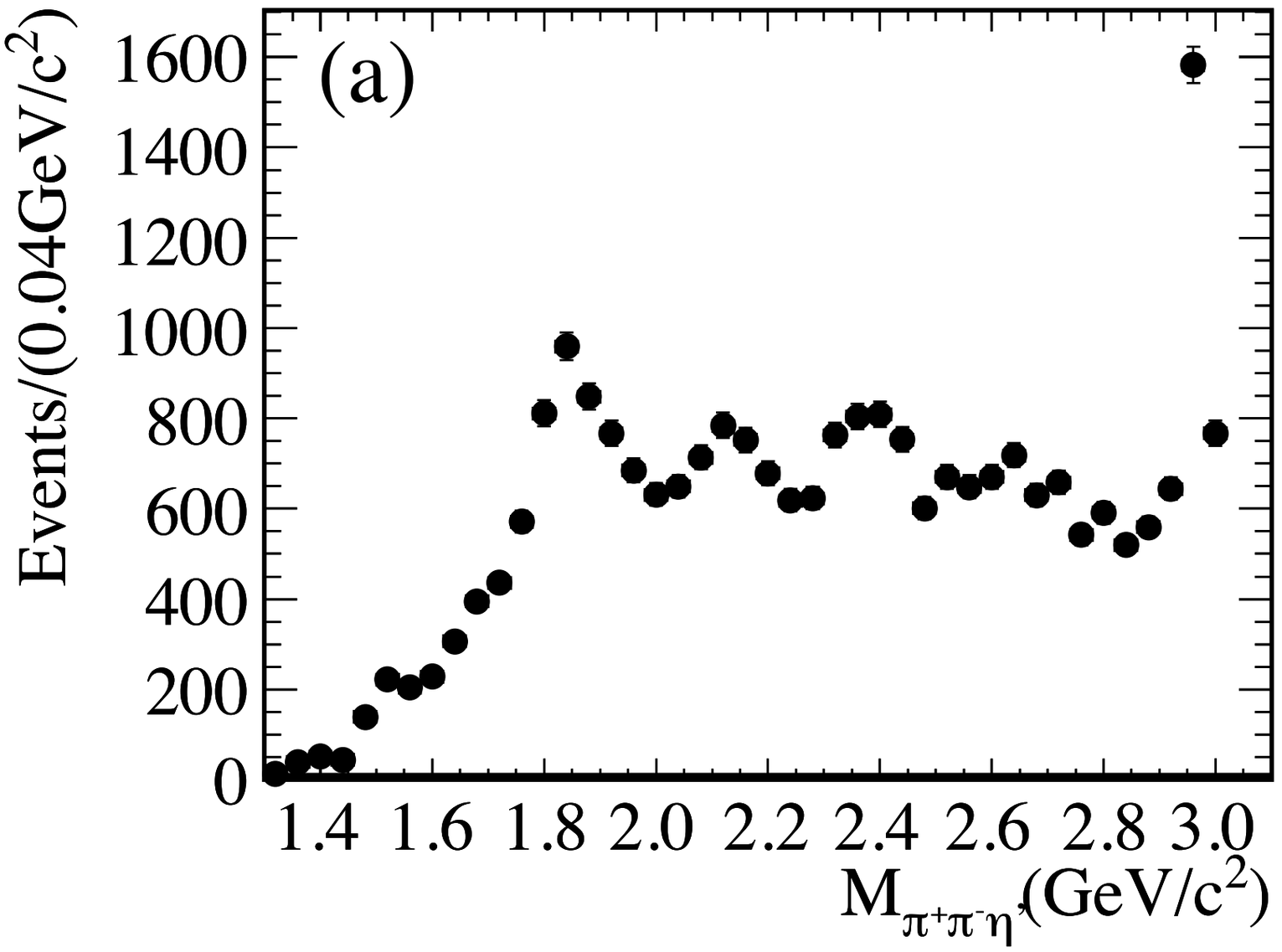
(using 58M J/ψ decays at BESII)

$M = 1833.7 \pm 6.1(\text{stat}) \pm 2.7(\text{syst})\ \text{MeV}/c^2;\ \Gamma = 67.7 \pm 20.3(\text{stat}) \pm 7.7(\text{syst})\ \text{MeV}/c^2;$

(1) The **proton antiproton** Question

$J/\psi \to \gamma\pi^+\pi^-\eta'$

[PRL 106, 072002 (2011)]

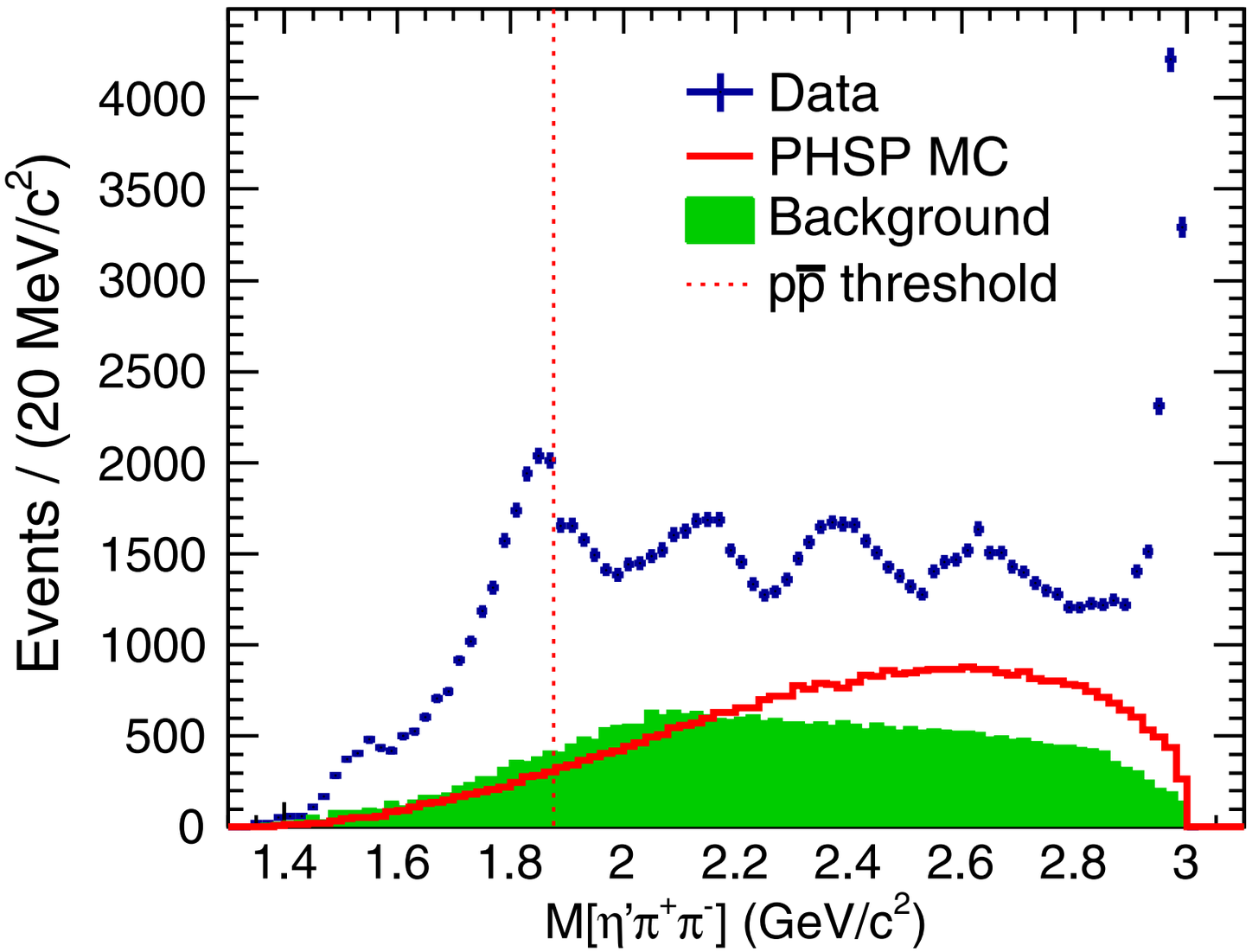


(using 225M J/ψ decays)

(1) The **proton antiproton** Question

$$J/\psi \to \gamma\pi^+\pi^-\eta'$$

[PRL 117, 042002 (2016)]



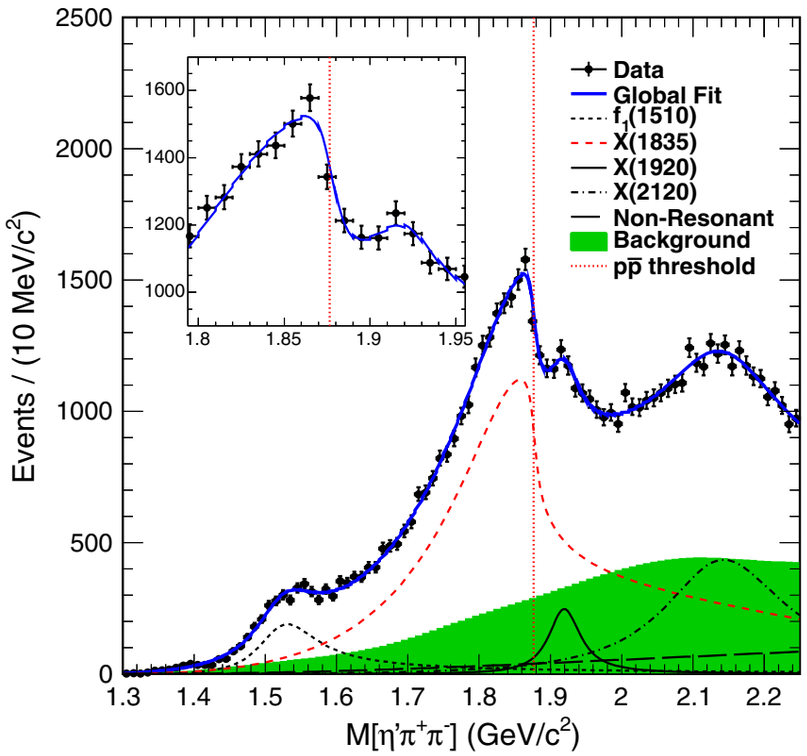
$f_1(1510)$
X(1835)??
X(2120)
X(2370)
??(2600)

(using 1.1B J/ψ decays)

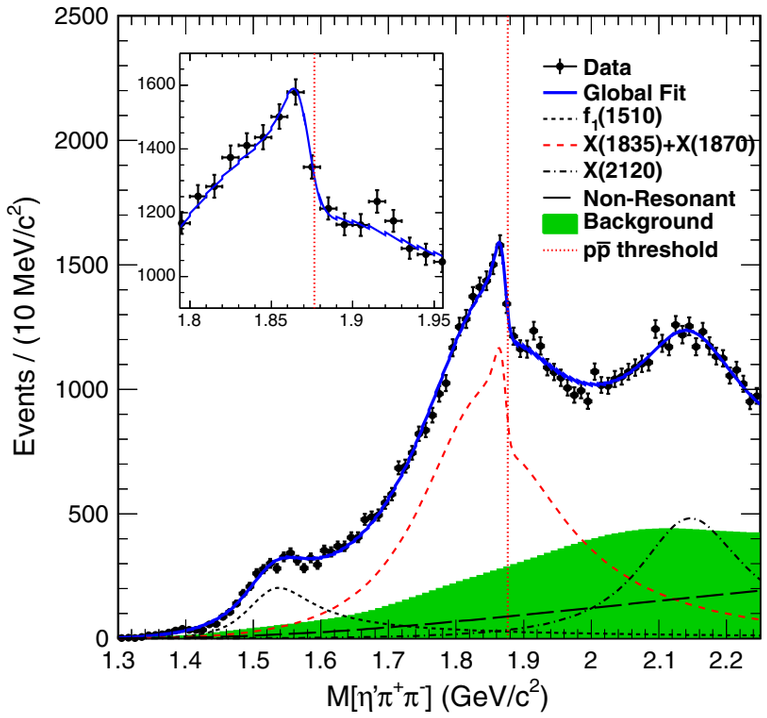
(1) The **proton antiproton** Question

$$J/\psi \to \gamma\pi^+\pi^-\eta'$$

[PRL 117, 042002 (2016)]



The state around 1.85 GeV/c^2	
$\mathcal{M}$ (MeV/c^2)	$1638.0 \pm 121.9^{+127.8}_{-254.3}$
g_0^2 [(GeV/c^2)^2]	$93.7 \pm 35.4^{+47.6}_{-43.9}$
$g_{p\bar{p}}^2/g_0^2$	$2.31 \pm 0.37^{+0.83}_{-0.60}$
$M_{\rm pole}$ (MeV/c^2)	$1909.5 \pm 15.9^{+9.4}_{-27.5}$
$\Gamma_{\rm pole}$ (MeV/c^2)	$273.5 \pm 21.4^{+6.1}_{-64.0}$
Branching ratio	$(3.93 \pm 0.38^{+0.31}_{-0.84}) \times 10^{-4}$



$X(1835)$	
Mass (MeV/c^2)	$1825.3 \pm 2.4^{+17.3}_{-2.4}$
Width (MeV/c^2)	$245.2 \pm 13.1^{+4.6}_{-9.6}$
B.R. (constructive interference)	$(3.01 \pm 0.17^{+0.26}_{-0.28}) \times 10^{-4}$
B.R. (destructive interference)	$(3.72 \pm 0.21^{+0.18}_{-0.35}) \times 10^{-4}$

$X(1870)$	
Mass (MeV/c^2)	$1870.2 \pm 2.2^{+2.3}_{-0.7}$
Width (MeV/c^2)	$13.0 \pm 6.1^{+2.1}_{-3.8}$
B.R. (constructive interference)	$(2.03 \pm 0.12^{+0.43}_{-0.70}) \times 10^{-7}$
B.R. (destructive interference)	$(1.57 \pm 0.09^{+0.49}_{-0.86}) \times 10^{-5}$

(1) The **proton antiproton** Question

What is the X(1835)?

(2) The **ϱπ** Question

Why are there anomalous differences between J/ψ and ψ(2S) decays?

(3) The **Y** Question

Why are there so many different peaks in exclusive e^+e^- cross sections?
e.g. Y(4230), Y(4260), Y(4360), Y(4660), etc.

(4) The **Z** Question

What are the electrically charged "charmoniumlike" peaks?
e.g. Z_c(3900), Z_c(4020), Z_c(4055), etc.

(2) The ϱπ Question

The "12% Rule": Once the charm quarks of the J/ψ or ψ(2S) annihilate, the rest of the process should proceed independently of the origin. So, after taking out transitions,

$$\frac{\mathcal{B}(\psi(2S) \to X)}{\mathcal{B}(J/\psi \to X)} \approx 12\%$$

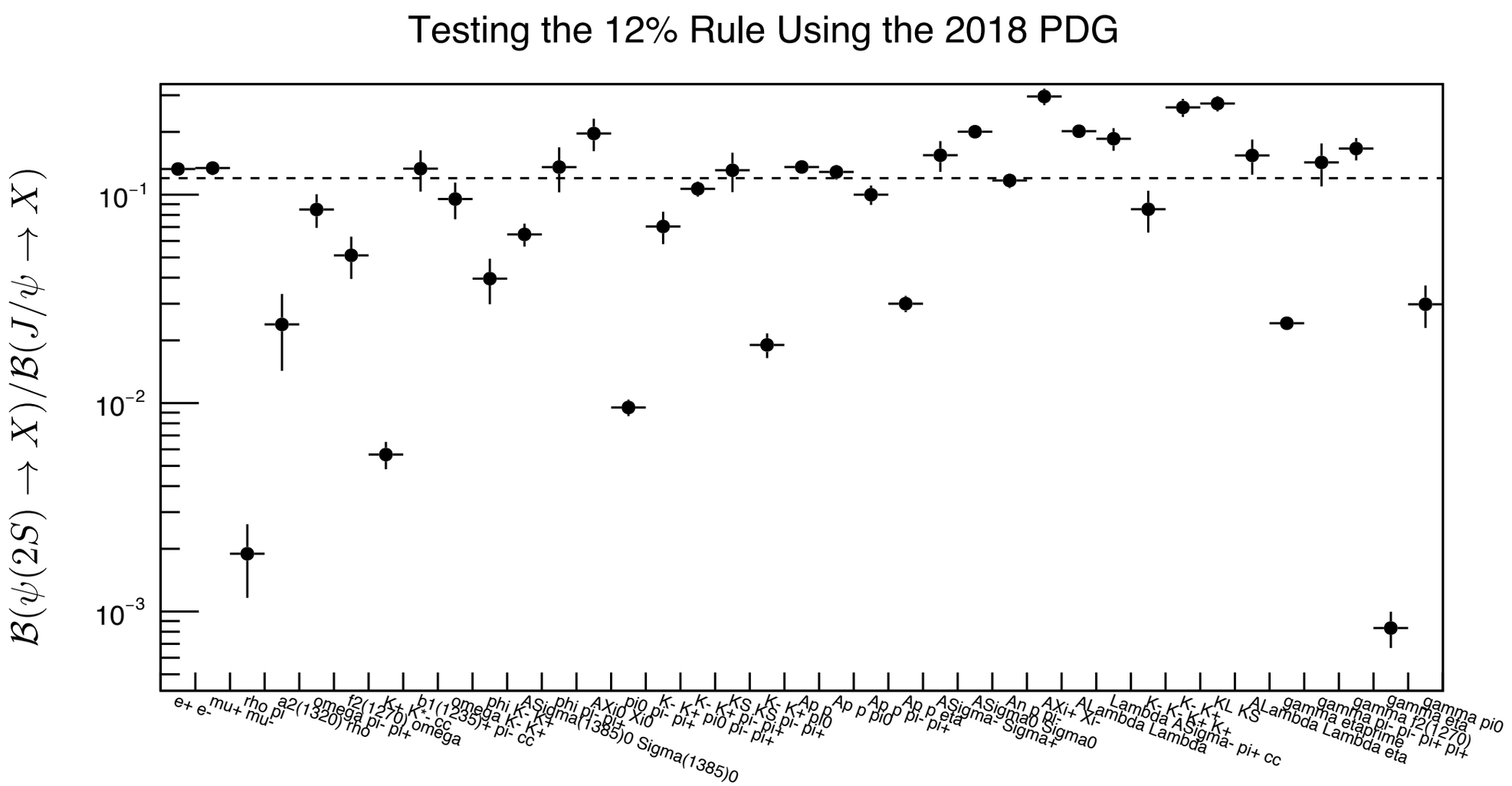
(2) The ϱπ Question

The "12% Rule": Once the charm quarks of the J/ψ or ψ(2S) annihilate, the rest of the process should proceed independently of the origin. So, after taking out transitions,

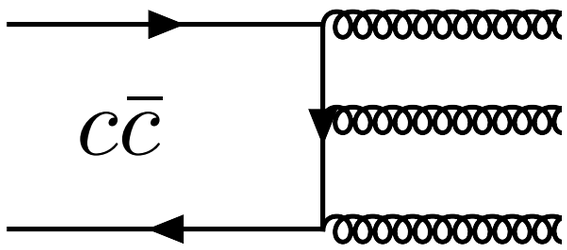
$$\frac{\mathcal{B}(\psi(2S) \to X)}{\mathcal{B}(J/\psi \to X)} \approx 12\%$$

Does it work?

Sort of.
But sometimes it fails spectacularly.



(2) The ϱπ Question



implies:

$$\frac{\mathcal{B}(\psi(2S) \to X)}{\mathcal{B}(J/\psi \to X)} \approx 12\%$$

but:

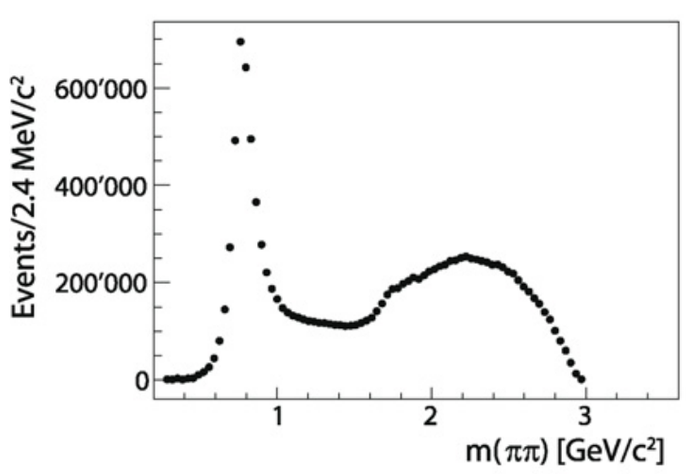
$$\frac{\mathcal{B}(\psi(2S) \to \pi^+\pi^-\pi^0)}{\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)}$$

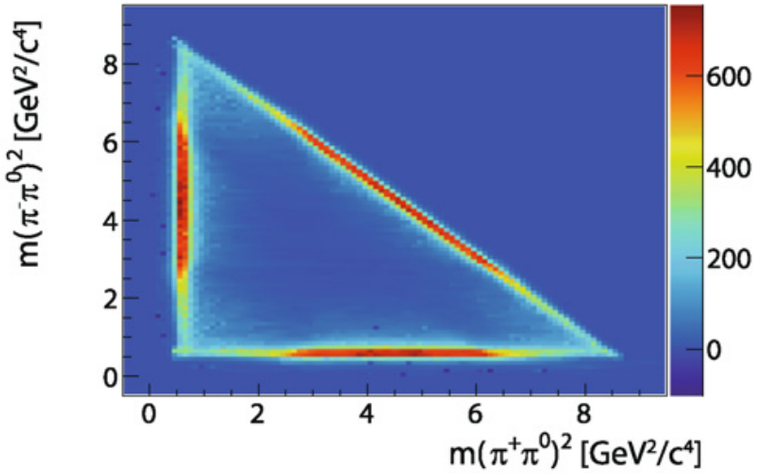
$$= \left(1.00 \pm 0.01\ (\text{stat.})^{+0.06}_{-0.05}\ (\text{syst.})\right)\%$$

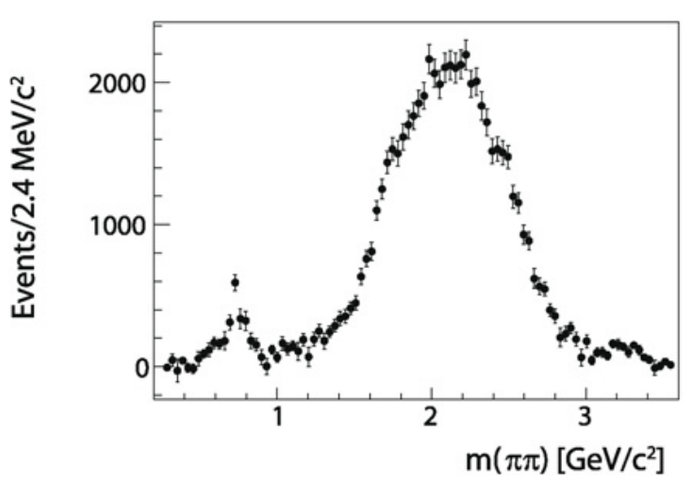
and ϱπ is ~ 2 × 10⁻³

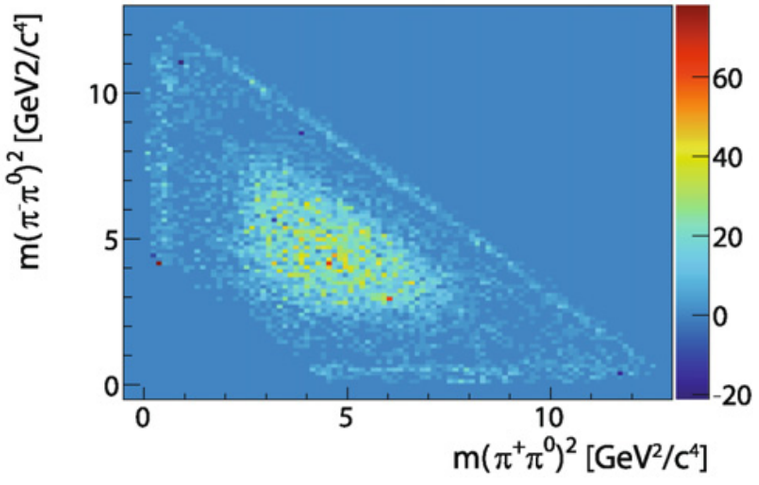
J/ψ and $\psi(2S) \to \pi^+\pi^-\pi^0$

[PLB 710, 594 (2012)]



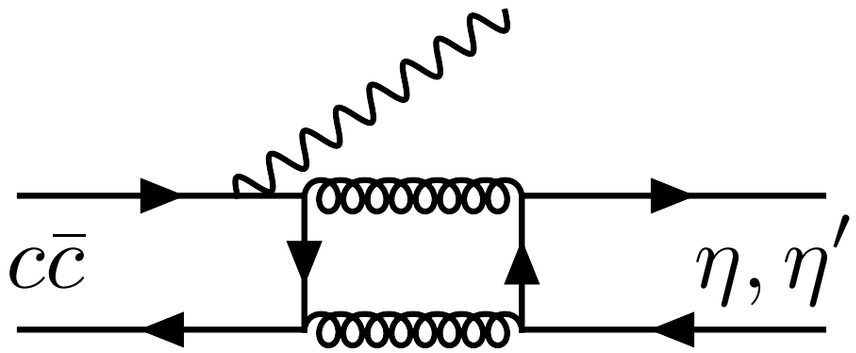






(using 225M J/ψ decays and 106M ψ(2S) decays)

(2) The ϱπ Question



implies:

$$\frac{\mathcal{B}(J/\psi \to \gamma\eta)}{\mathcal{B}(J/\psi \to \gamma\eta')} \approx \frac{\mathcal{B}(\psi(2S) \to \gamma\eta)}{\mathcal{B}(\psi(2S) \to \gamma\eta')}$$

but:

$$\frac{\mathcal{B}(J/\psi \to \gamma\eta)}{\mathcal{B}(J/\psi \to \gamma\eta')} = (21.4 \pm 0.9)\%$$

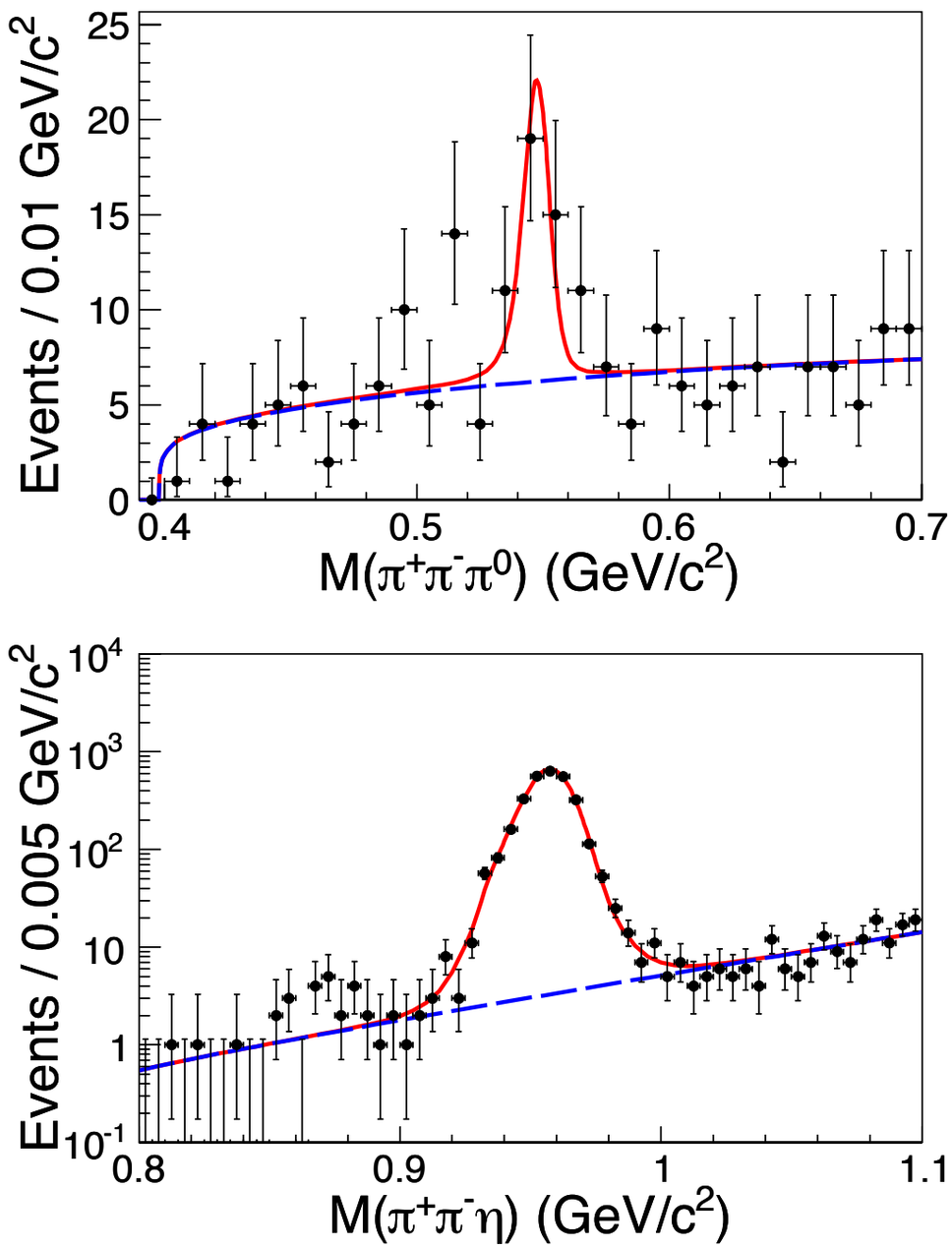
and:

$$\frac{\mathcal{B}(\psi(2S) \to \gamma\eta)}{\mathcal{B}(\psi(2S) \to \gamma\eta')}$$

$$= (0.66 \pm 0.13 \pm 0.02)\%$$

$\psi(2S) \to \gamma\eta$ and $\gamma\eta'$

[PRD 96, 052003 (2017)]



(using 448M ψ(2S) decays)

(1) The **proton antiproton** Question

What is the X(1835)?

(2) The **ϱπ** Question

Why are there anomalous differences between J/ψ and ψ(2S) decays?

(3) The **Y** Question

Why are there so many different peaks in exclusive e^+e^- cross sections?
e.g. Y(4230), Y(4260), Y(4360), Y(4660), etc.

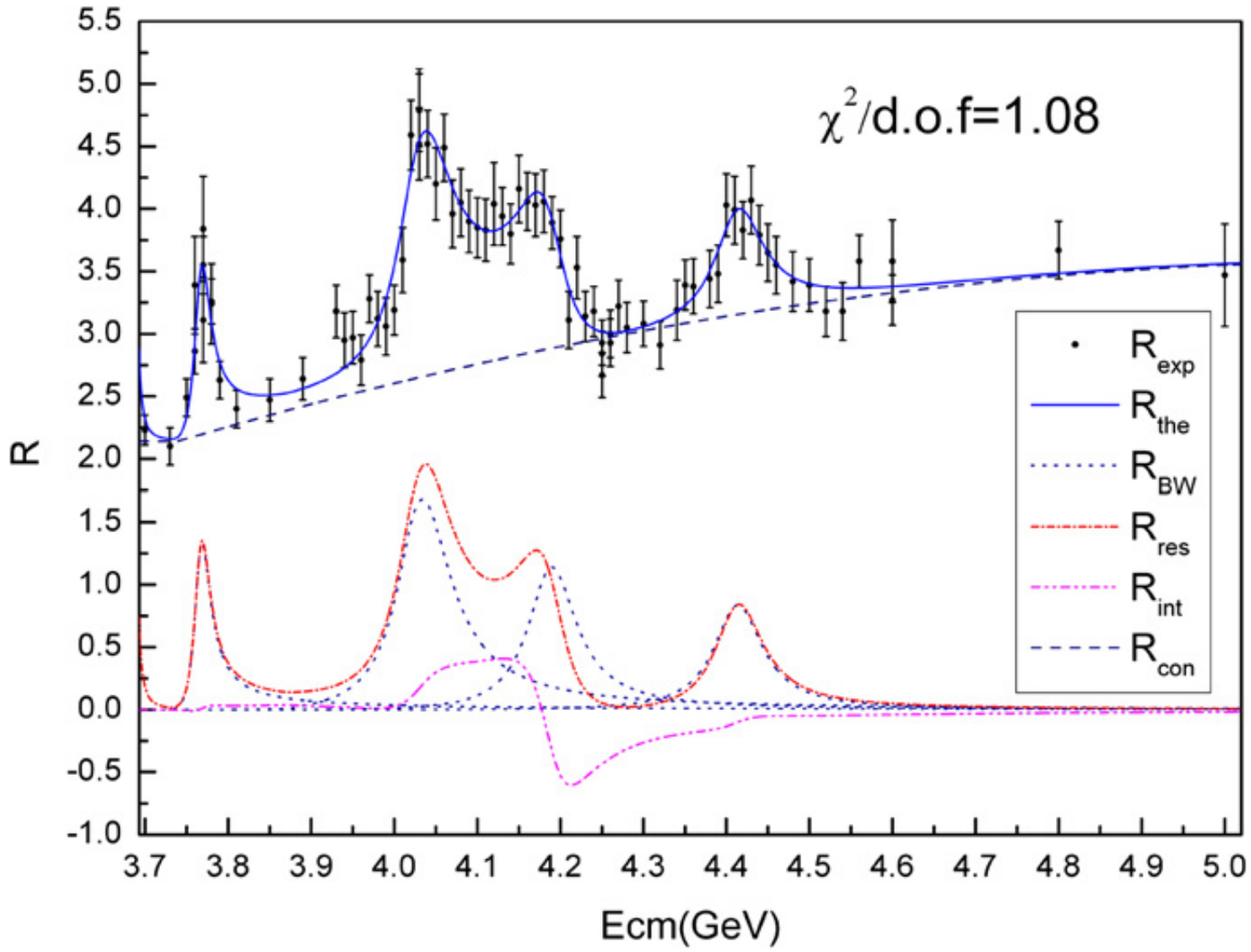
(4) The **Z** Question

What are the electrically charged "charmoniumlike" peaks?
e.g. Z_c(3900), Z_c(4020), Z_c(4055), etc.

(3) The **Y** Question

$e^+e^- \to$ hadrons

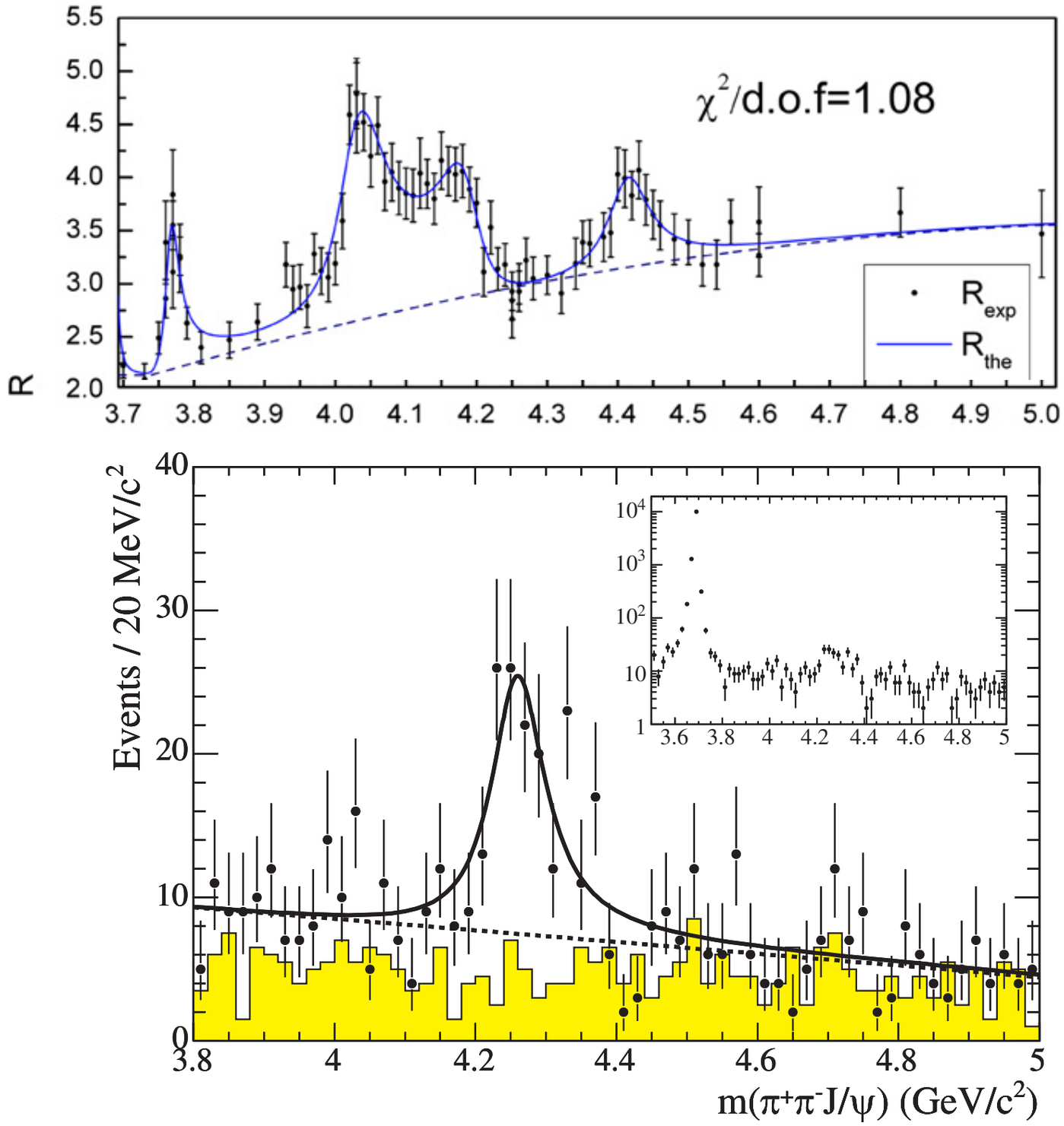
[BESII, PLB 660, 315 (2008)]



J/ψ = 1^3S_1	ψ(3770) = 1^3D_1	ψ(4160) = 2^3D_1
ψ(2S) = 2^3S_1	ψ(4040) = 3^3S_1	ψ(4415) = 4^3S_1

(3) The **Y** Question

$e^+e^- \to$ hadrons [BESII, PLB 660, 315 (2008)] vs. $e^+e^- \to \pi^+\pi^- J/\psi$ [BaBar, PRL 95, 142001 (2005)]

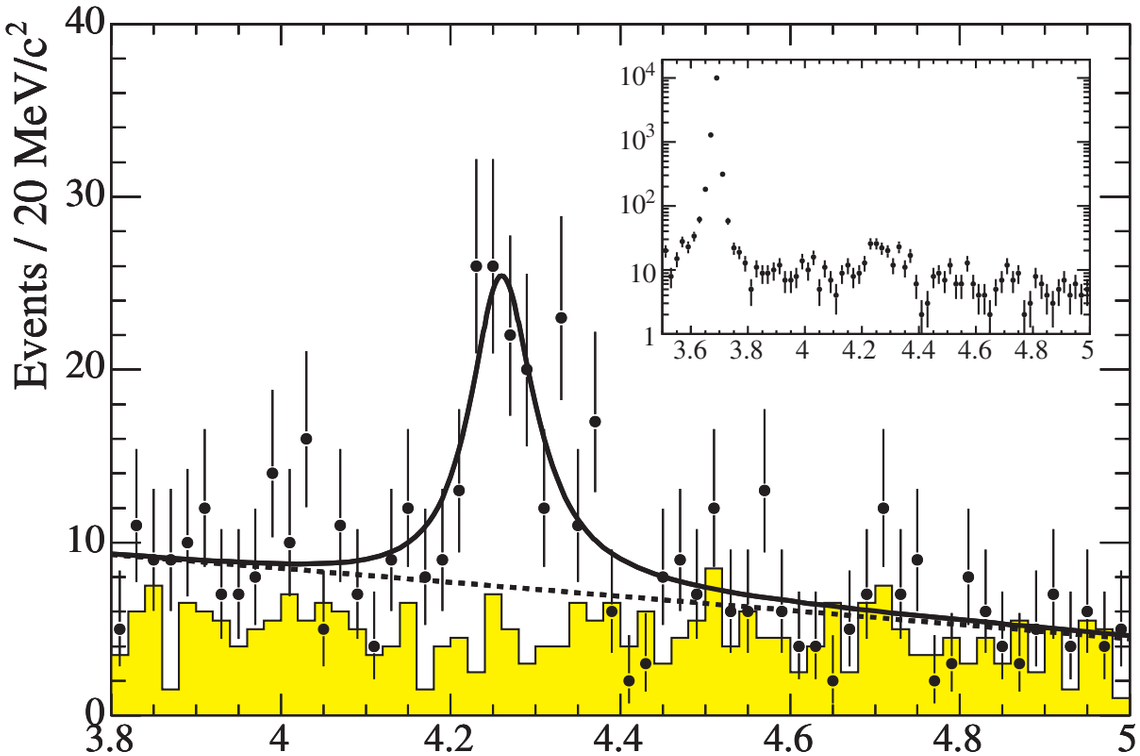


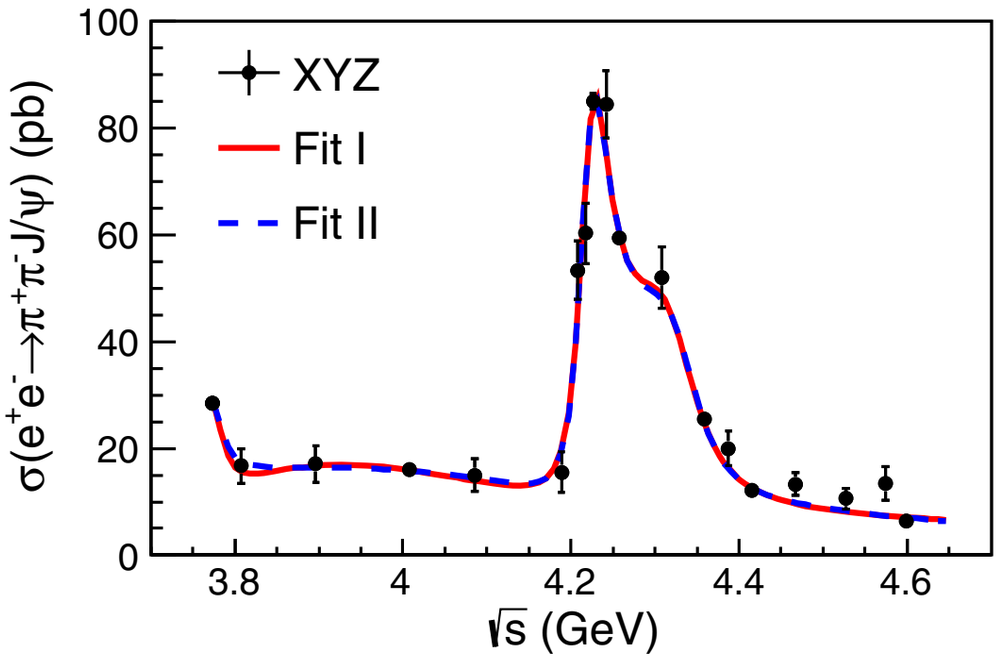
(3) The **Y** Question

$e^+e^- \to \pi^+\pi^- J/\psi$
[BaBar, PRL 95, 142001 (2005)]

vs.

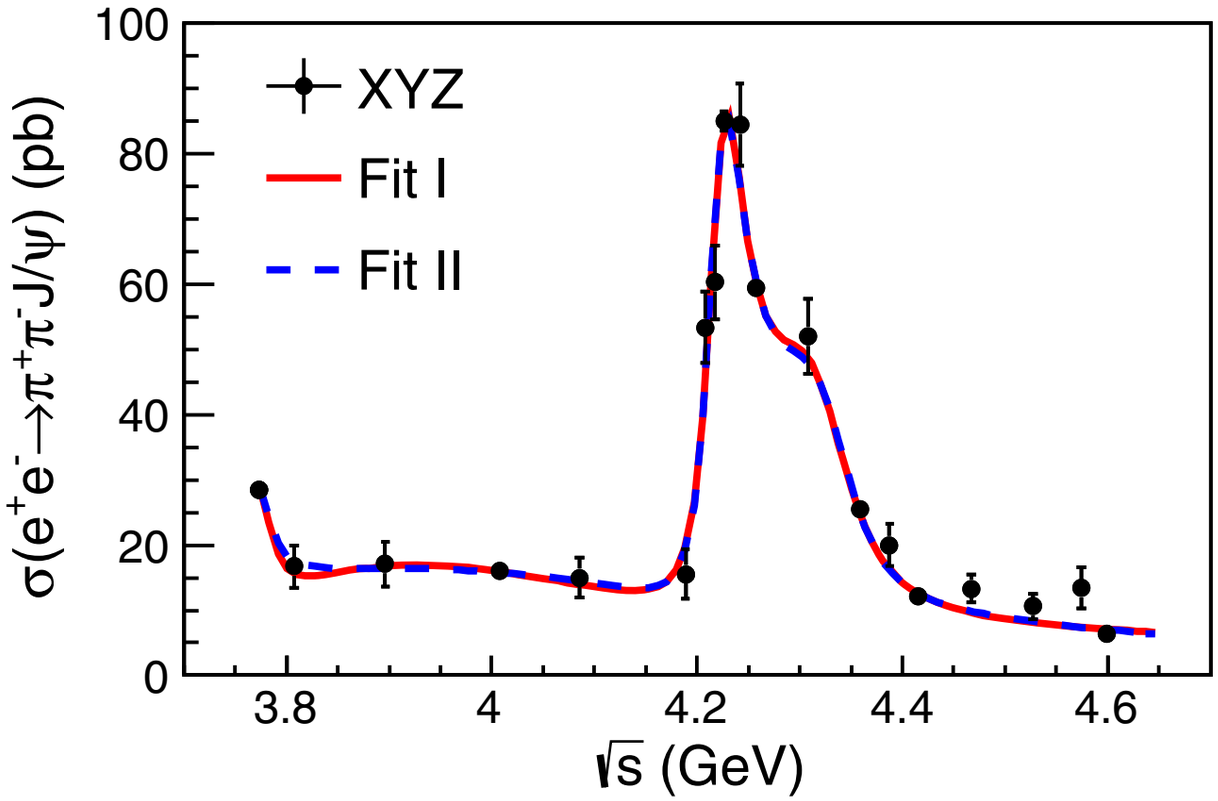
$e^+e^- \to \pi^+\pi^- J/\psi$
[PRL 118, 092001 (2017)]

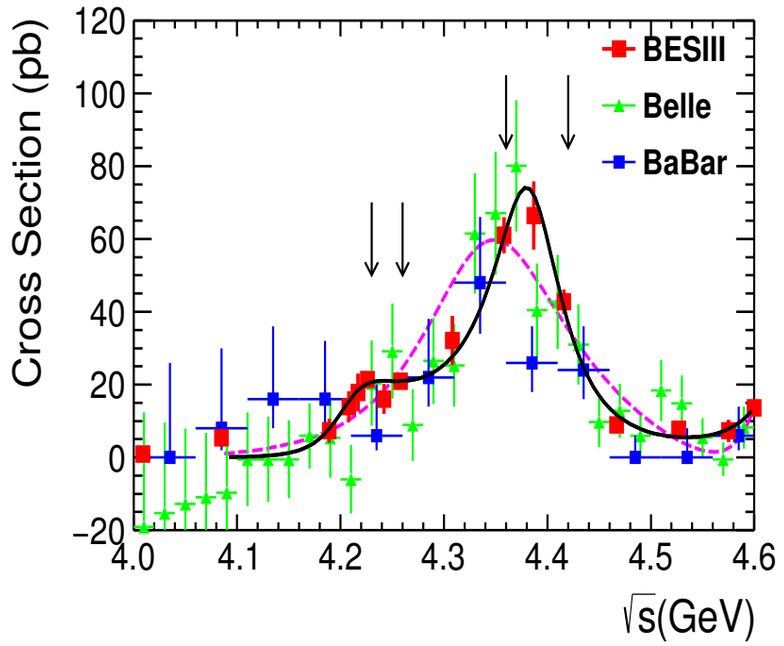




(3) The **Y** Question

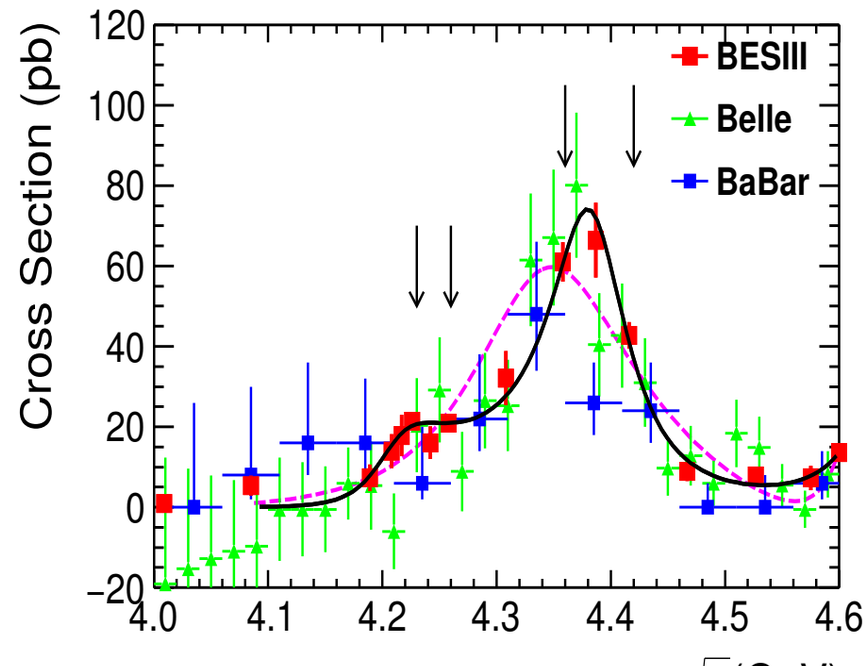
$e^+e^- \to \pi^+\pi^- J/\psi$ [PRL 118, 092001 (2017)] vs. $e^+e^- \to \pi^+\pi^-\psi(2S)$ [PRD 96, 032004 (2017)]

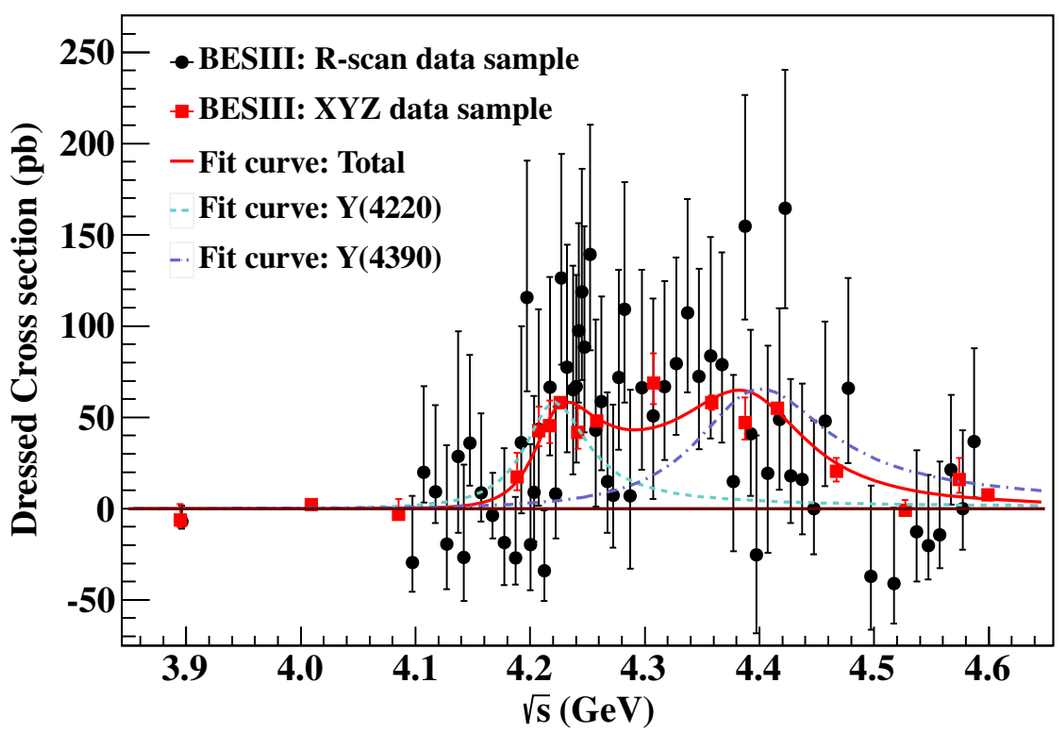




(3) The **Y** Question

$e^+e^- \to \pi^+\pi^-\psi(2S)$ [PRD 96, 032004 (2017)] vs. $e^+e^- \to \pi^+\pi^- h_c(1P)$ [PRL 118, 092002 (2017)]



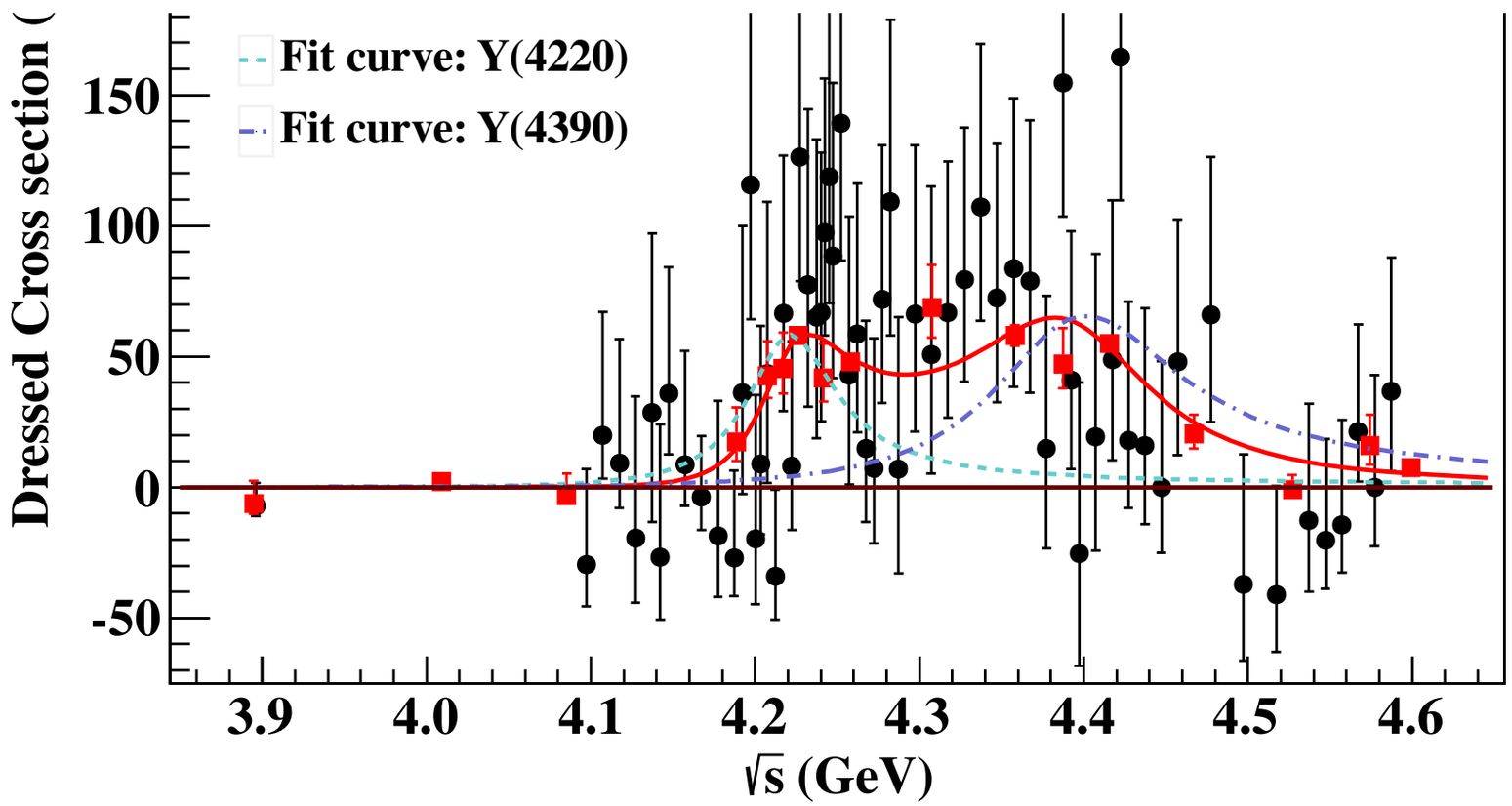


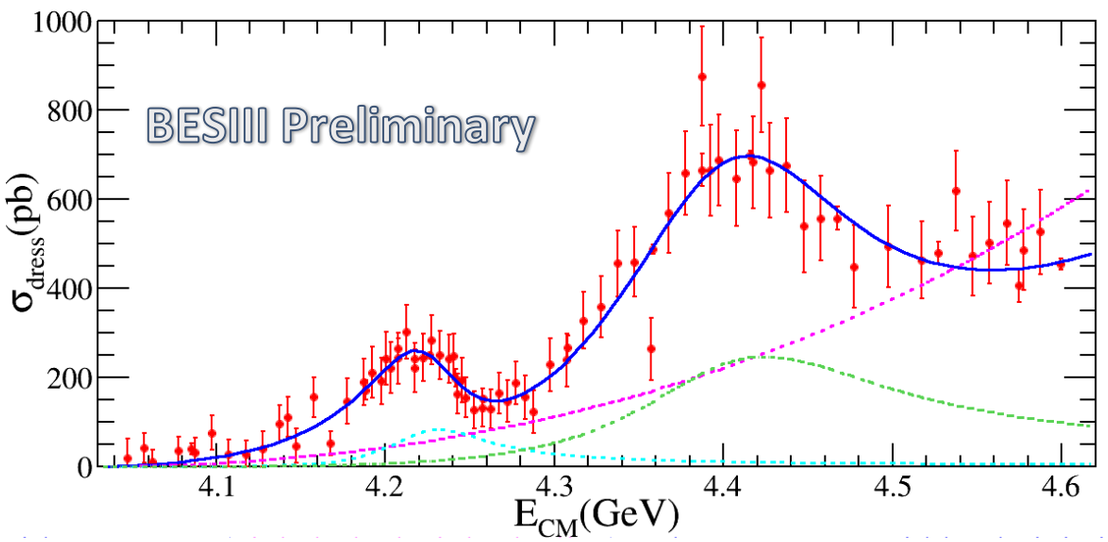
(3) The **Y** Question

$e^+e^- \to \pi^+\pi^- h_c(1P)$
[PRL 118, 092002 (2017)]

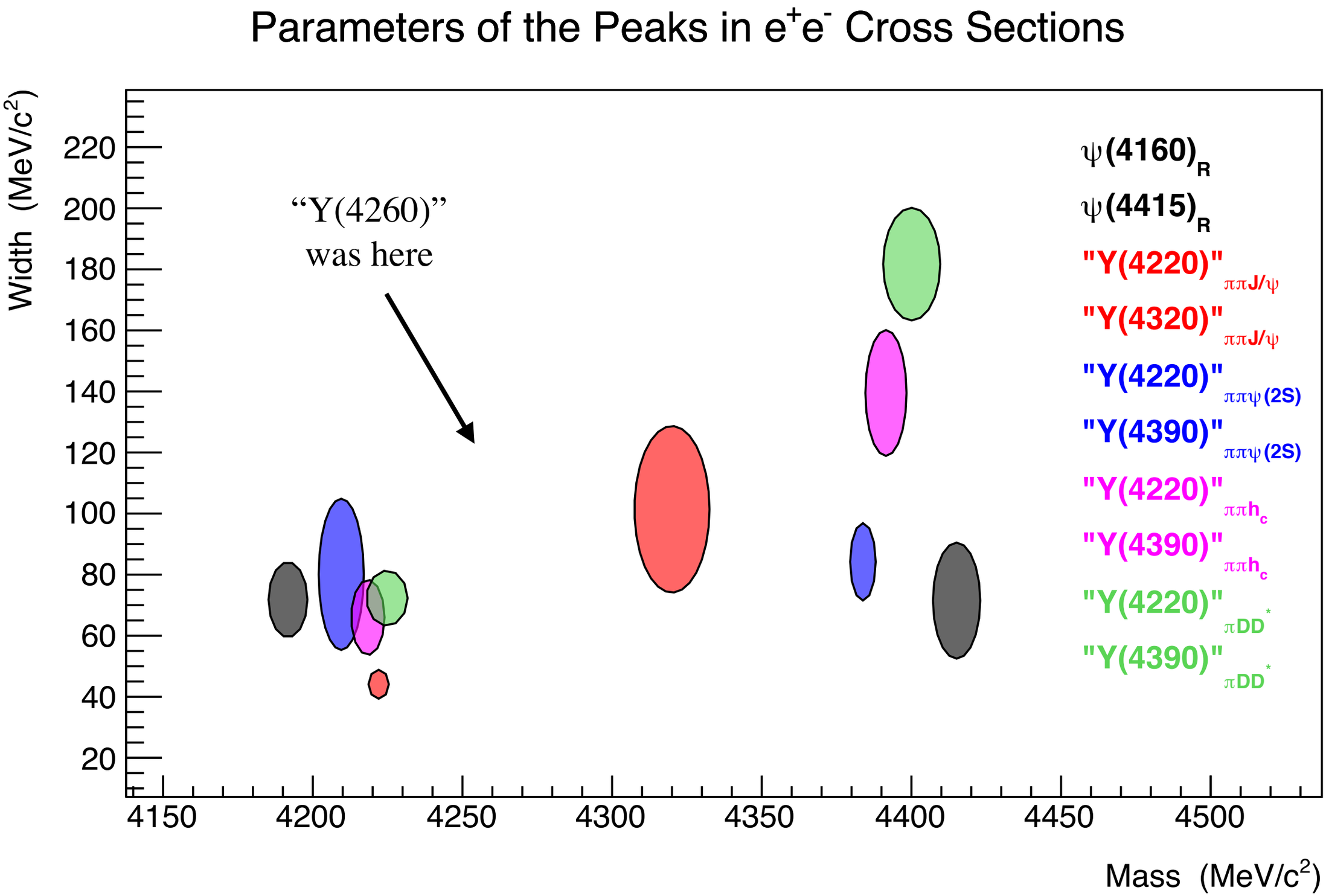
vs.

$e^+e^- \to \pi^+ D^0 D^{*-} + c.c.$
[preliminary (2017)]





(3) The **Y** Question



(1) The **proton antiproton** Question

What is the X(1835)?

(2) The **ϱπ** Question

Why are there anomalous differences between J/ψ and ψ(2S) decays?

(3) The **Y** Question

Why are there so many different peaks in exclusive e^+e^- cross sections?
e.g. Y(4230), Y(4260), Y(4360), Y(4660), etc.

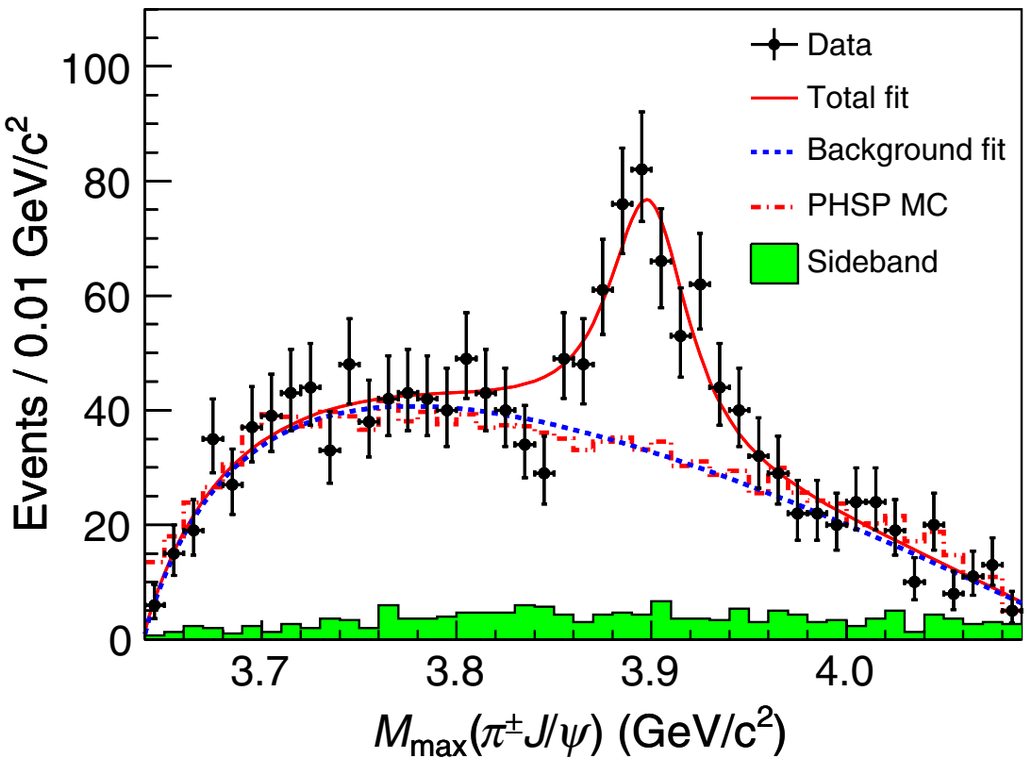
(4) The **Z** Question

What are the electrically charged "charmoniumlike" peaks?
e.g. Z_c(3900), Z_c(4020), Z_c(4055), etc.

(4) The **Z** Question

$e^+e^- \to \pi^\pm(\pi^\mp J/\psi)$

[PRL 110, 252001 (2013)]

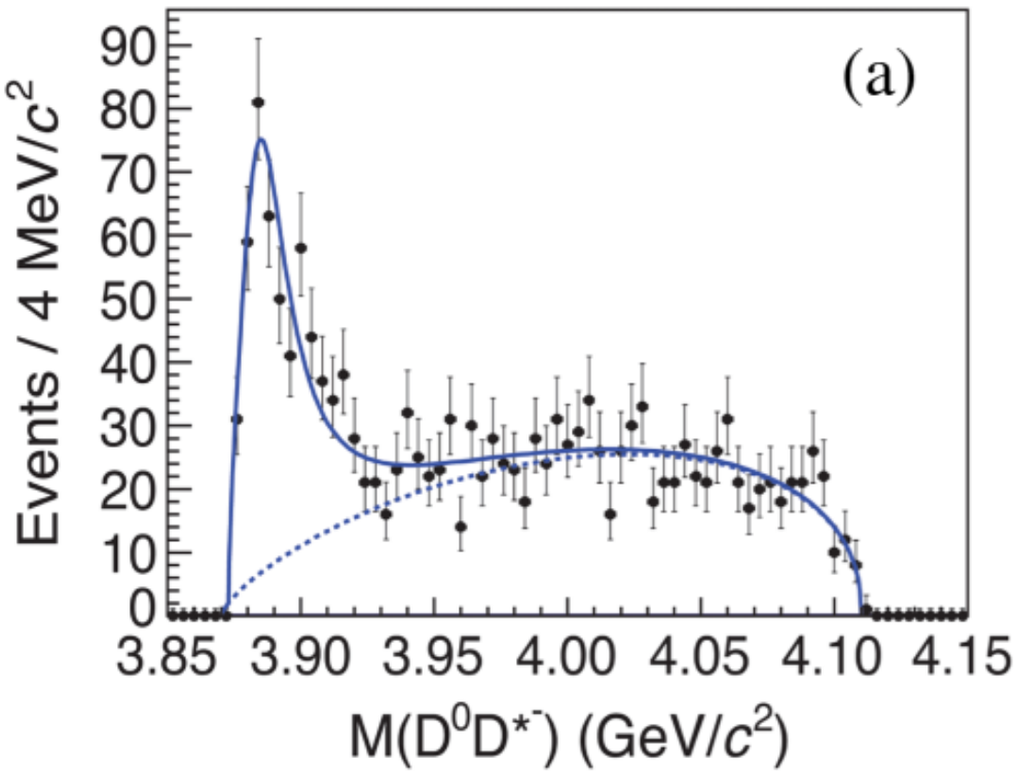


(using 525 pb^{-1} at 4.26 GeV)

$M = (3899.0 \pm 3.6 \pm 4.9)\ \mathrm{MeV}/c^2;$
$\Gamma = (46 \pm 10 \pm 20)\ \mathrm{MeV}/c^2$

$e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$

[PRL 112, 022001 (2014)]



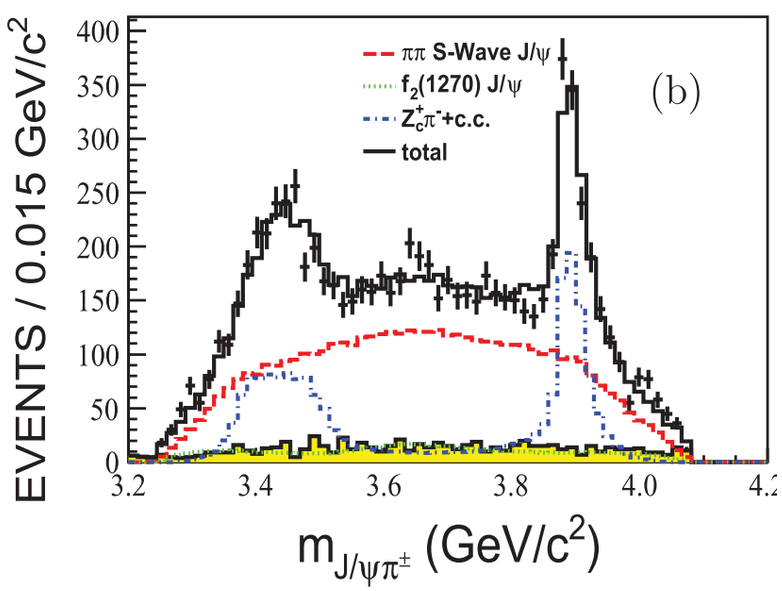
(using 525 pb^{-1} at 4.26 GeV)

$M = (3883.9 \pm 1.5 \pm 4.2)\ \mathrm{MeV}/c^2;$
$\Gamma = (24.8 \pm 3.3 \pm 11.0)\ \mathrm{MeV}/c^2;$
$J^P = 1^+$

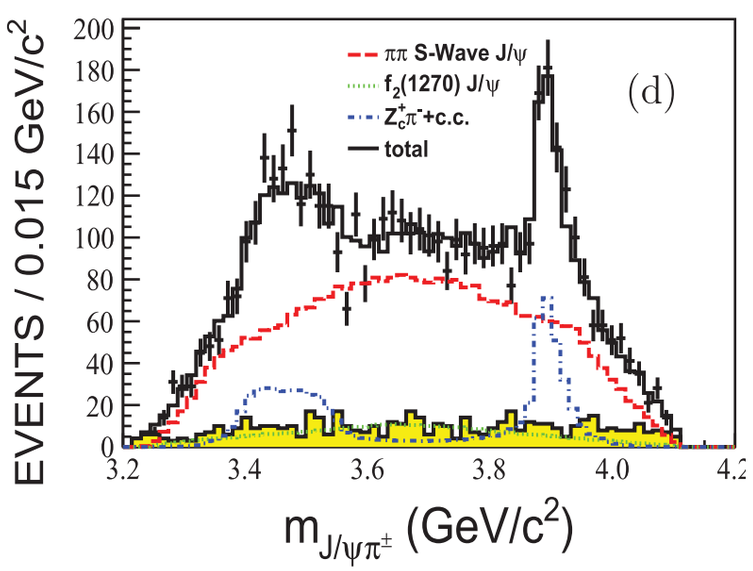
(4) The **Z** Question

$$e^+e^- \to \pi^\pm(\pi^\mp J/\psi)$$

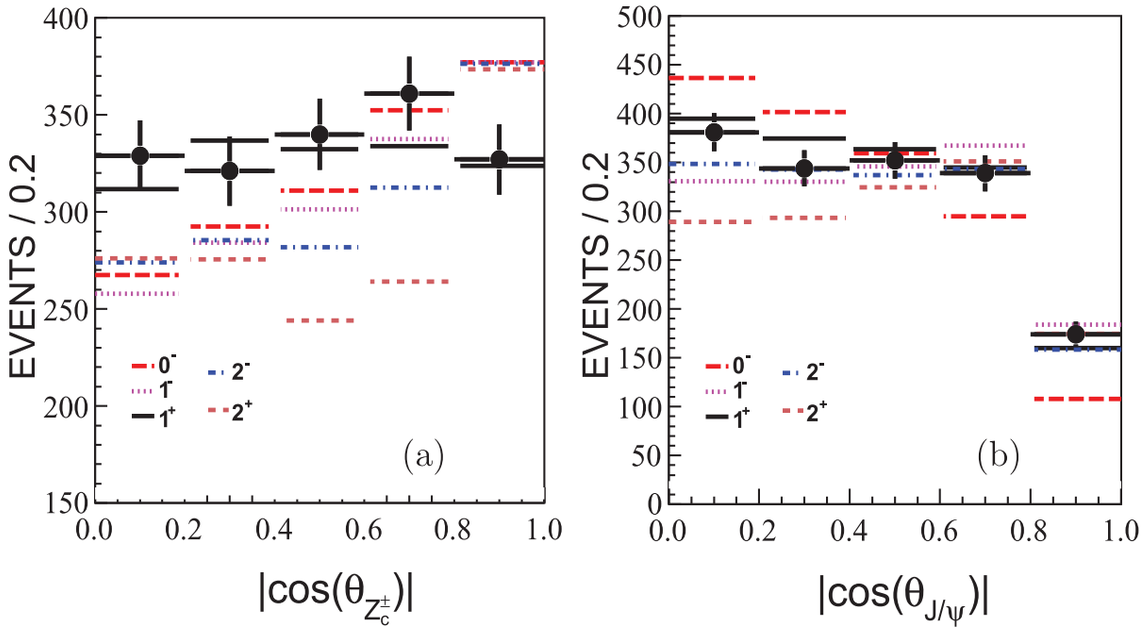
[PRL 119, 072001 (2017) (Aug. 16)]



(using 1092 pb^{-1} at 4.23 GeV)



(using 827 pb^{-1} at 4.26 GeV)

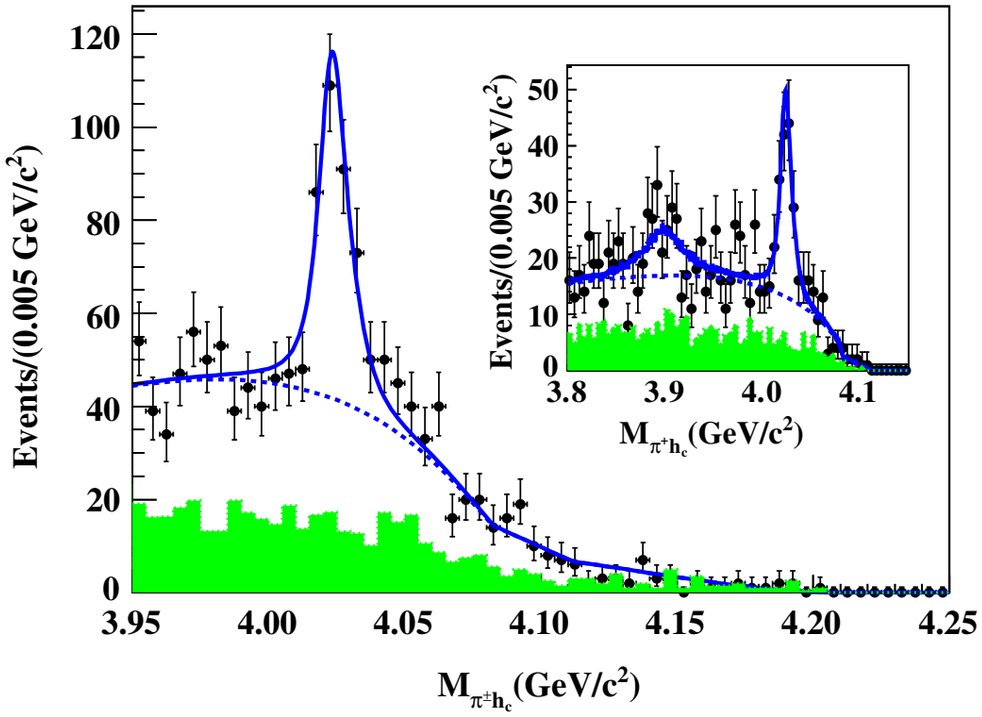


$$M = (3881.2 \pm 4.2 \pm 52.7)\ \mathrm{MeV}/c^2;$$
$$\Gamma = (51.8 \pm 4.6 \pm 36.0)\ \mathrm{MeV}/c^2;$$
$$J^P = 1^+$$

(4) The **Z** Question

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

[PRL 111, 242001 (2013)]

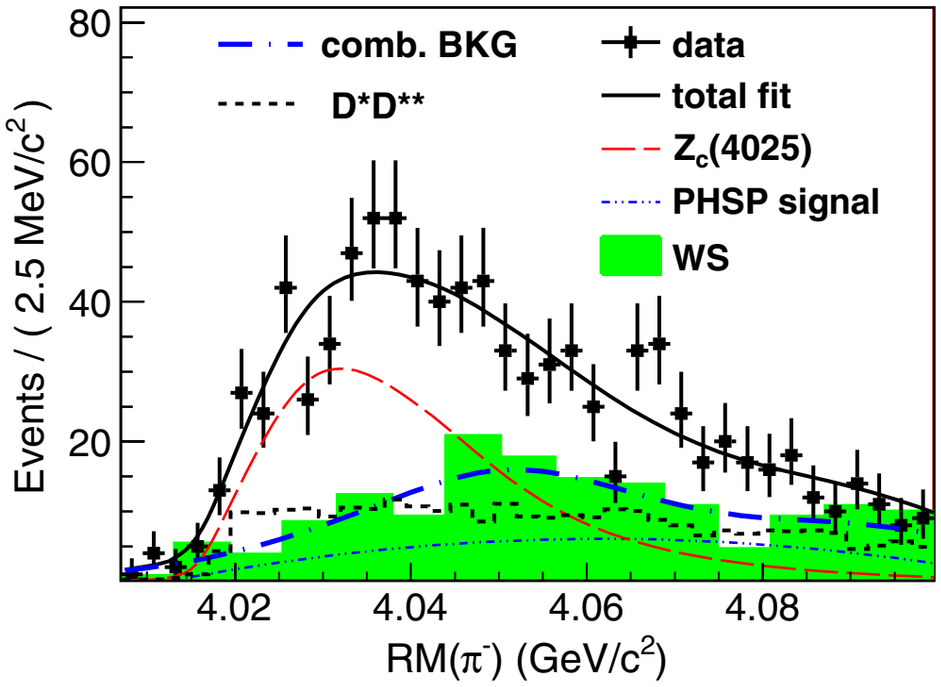


(using 1090 pb^{-1} at 4.23 GeV,
827 pb^{-1} at 4.26 GeV,
545 pb^{-1} at 4.36 GeV)

$M = (4022.9 \pm 0.8 \pm 2.7)\ \mathrm{MeV}/c^2;$
$\Gamma = (7.9 \pm 2.7 \pm 2.6)\ \mathrm{MeV}/c^2$

$e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp$

[PRL 112, 132001 (2014)]



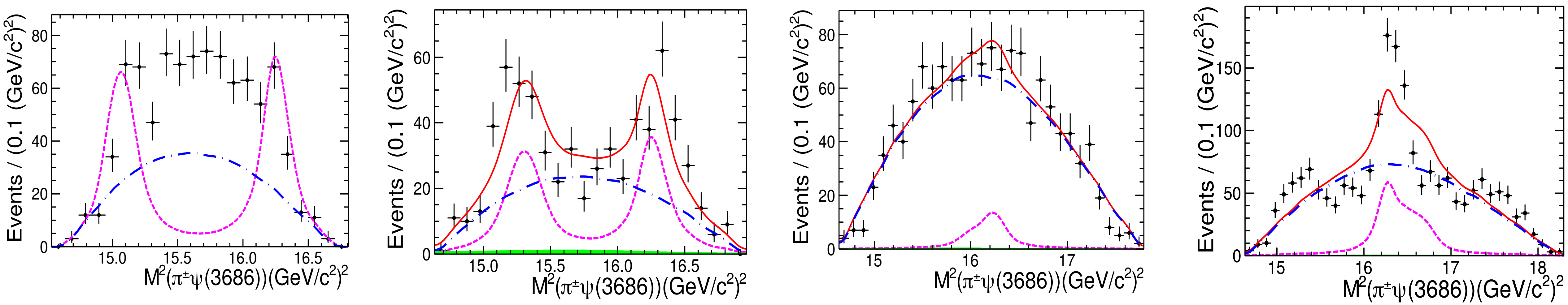
(using 827 pb^{-1} at 4.26 GeV)

$M = (4026.3 \pm 2.6 \pm 3.7)\ \mathrm{MeV}/c^2;$
$\Gamma = (24.8 \pm 5.6 \pm 7.7)\ \mathrm{MeV}/c^2$

(4) The **Z** Question

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

[PRD 96, 032004 (2017)]



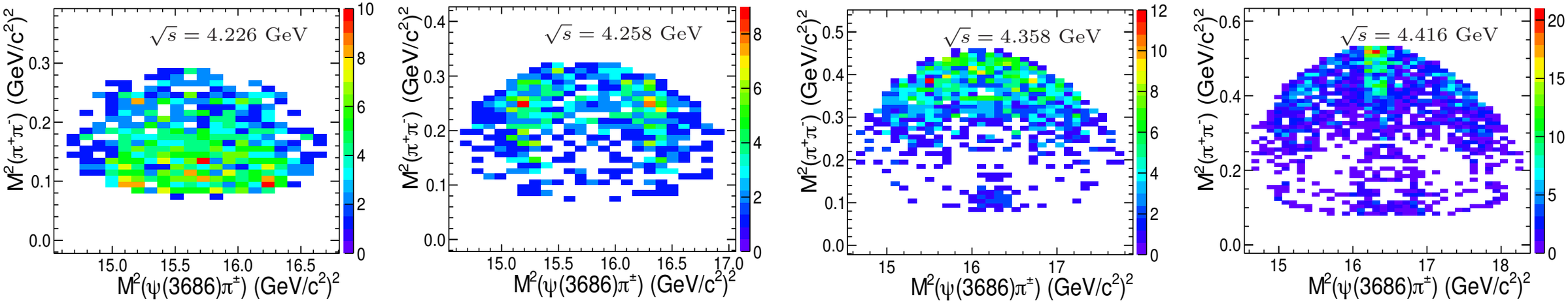
(1092 pb⁻¹ at 4.23 GeV; 826 pb⁻¹ at 4.26 GeV; 540 pb⁻¹ at 4.36 GeV; 1074 pb⁻¹ at 4.42 GeV)

$$M = (4032.1 \pm 2.4)\ \mathrm{MeV}/c^2;$$
$$\Gamma = (26.1 \pm 5.3)\ \mathrm{MeV}/c^2$$

(4) The **Z** Question

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

[PRD 96, 032004 (2017)]



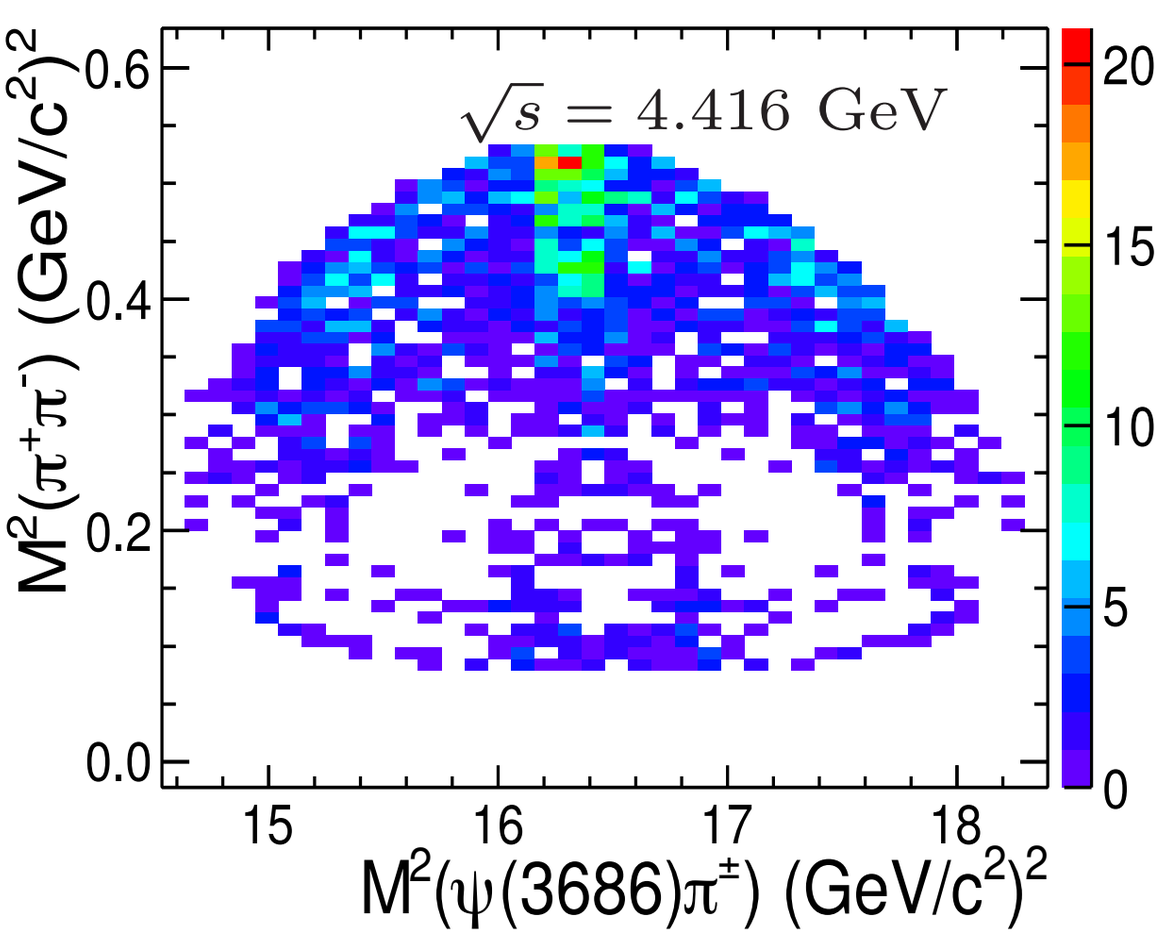
(1092 pb^{-1} at 4.23 GeV; 826 pb^{-1} at 4.26 GeV; 540 pb^{-1} at 4.36 GeV; 1074 pb^{-1} at 4.42 GeV)

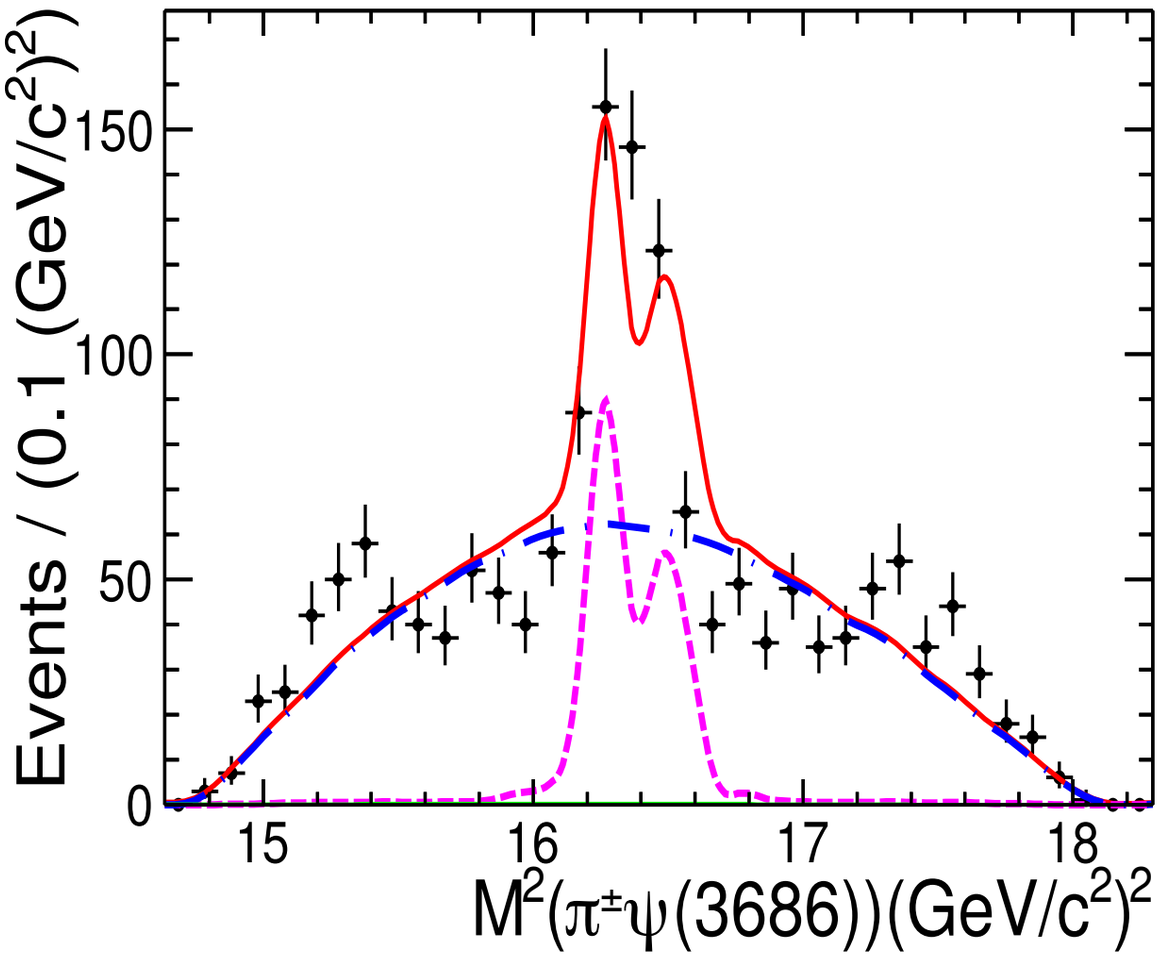
$$M = (4032.1 \pm 2.4)\ \mathrm{MeV}/c^2;$$
$$\Gamma = (26.1 \pm 5.3)\ \mathrm{MeV}/c^2$$

(4) The **Z** Question

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

[PRD 96, 032004 (2017)]





For $M^2(\pi^+\pi^-) > 0.3$ GeV$^2/c^4$:

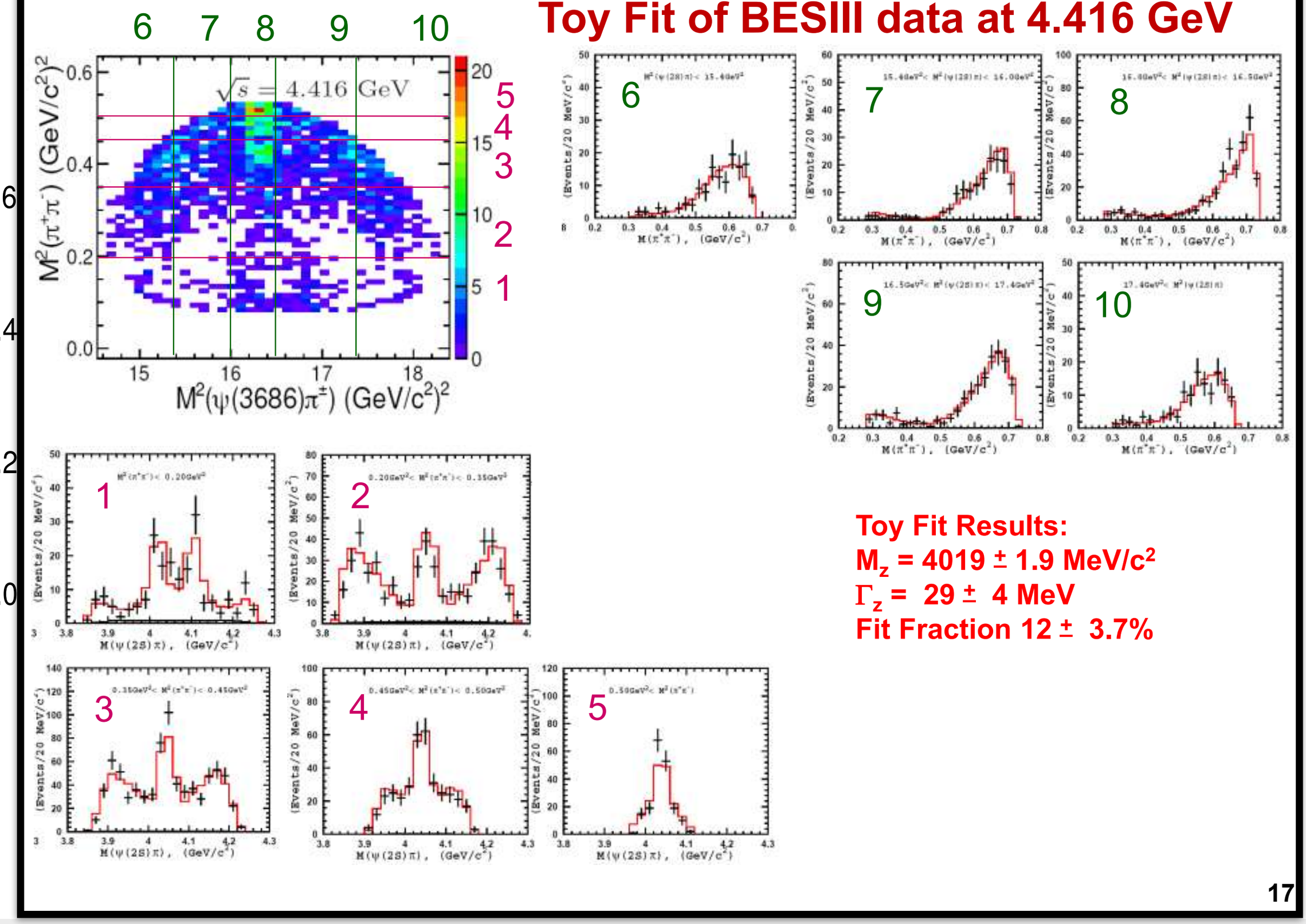
$M = (4030.3 \pm 0.1)$ MeV$/c^2$;

$\Gamma = (5.1 \pm 0.2)$ MeV$/c^2$

(4) The **Z** Question

Alex Bondar, CHARM 2018

Toy Fit of BESIII data at 4.416 GeV



Toy Fit Results:

M_z = 4019 ± 1.9 MeV/c²

Γ_z = 29 ± 4 MeV

Fit Fraction 12 ± 3.7%

17

(1) The **proton antiproton** Question

What is the X(1835)?

(2) The **ϱπ** Question

Why are there anomalous differences between J/ψ and ψ(2S) decays?

(3) The **Y** Question

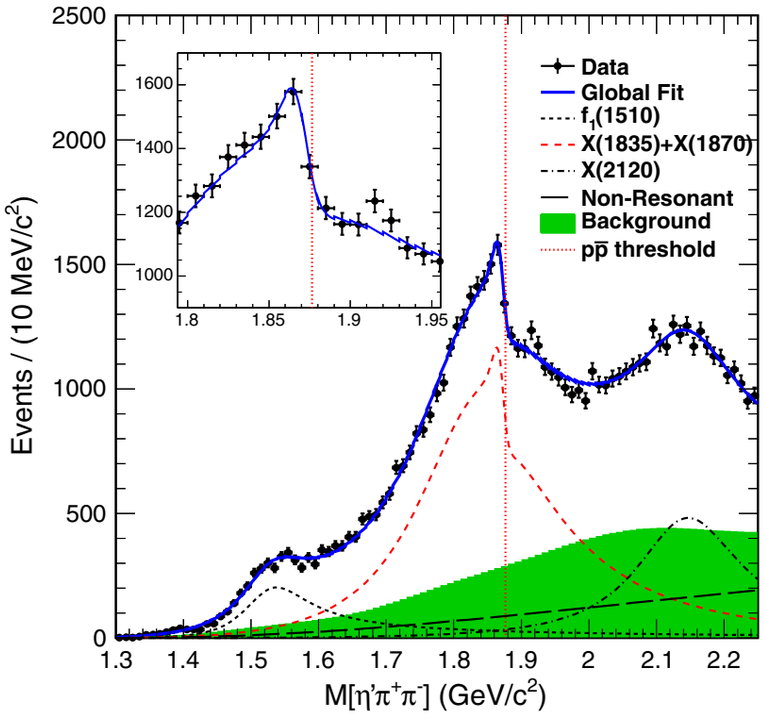
Why are there so many different peaks in exclusive e^+e^- cross sections?
e.g. Y(4230), Y(4260), Y(4360), Y(4660), etc.

(4) The **Z** Question

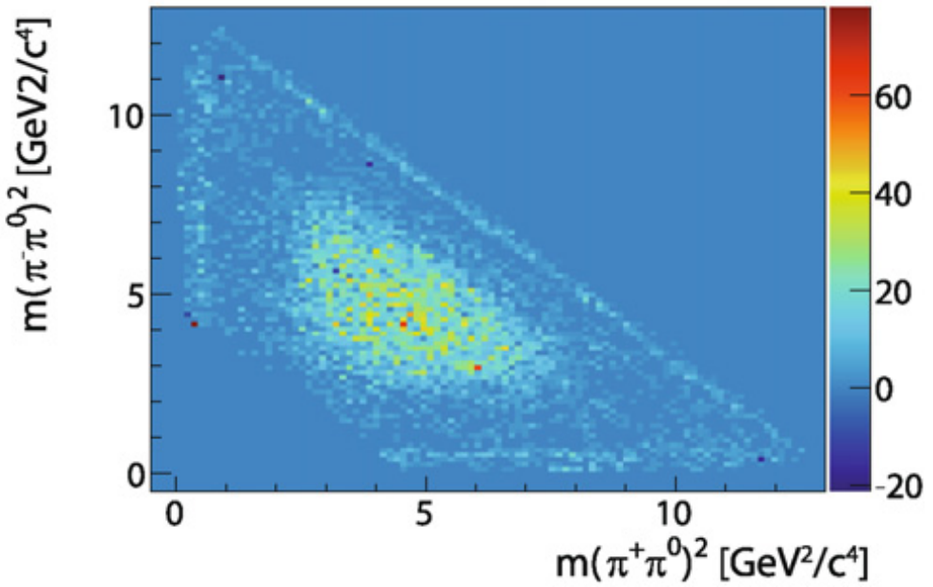
What are the electrically charged "charmoniumlike" peaks?
e.g. Z_c(3900), Z_c(4020), Z_c(4055), etc.

Mysteries in the Meson System at BESIII

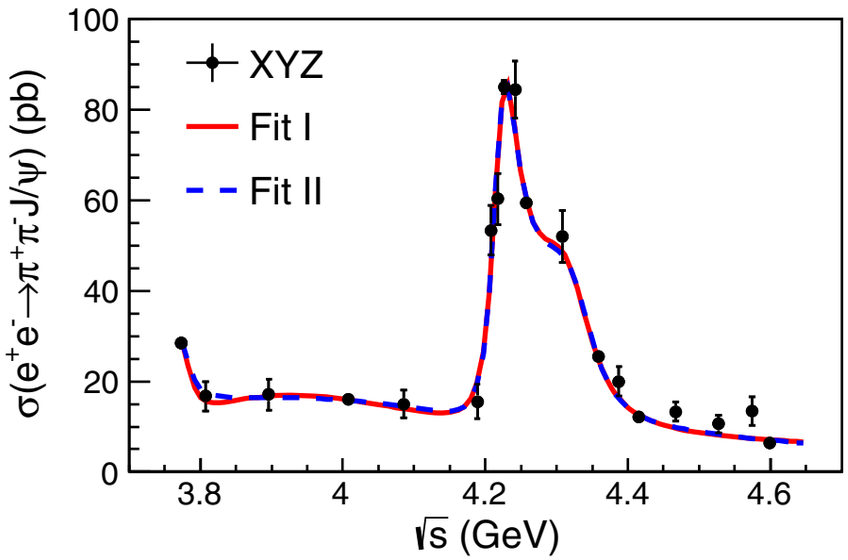
(1) The proton antiproton Question



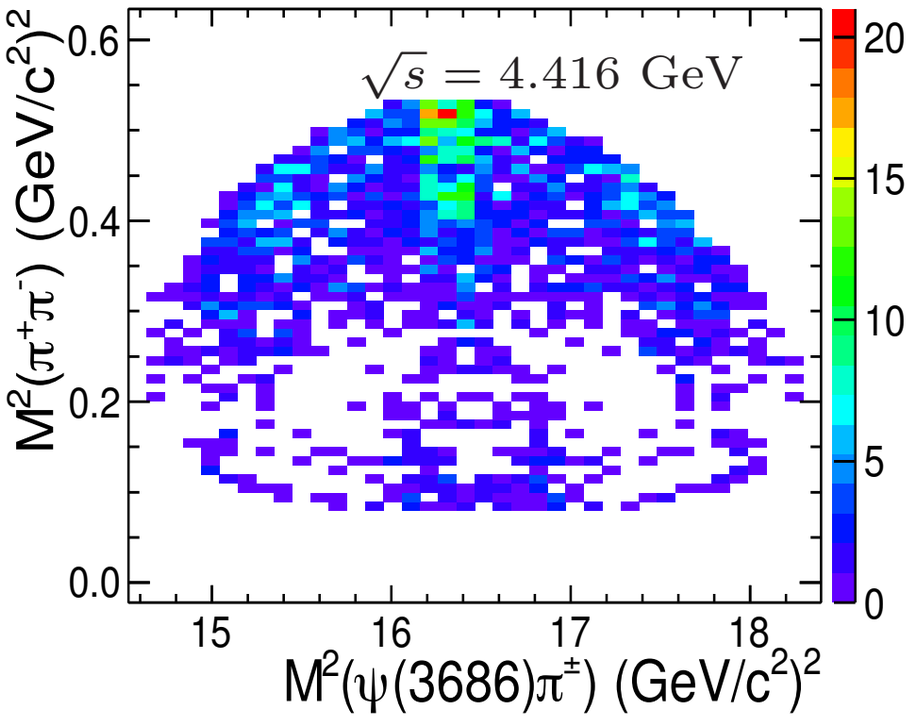
(2) The ϱπ Question



(3) The Y Question

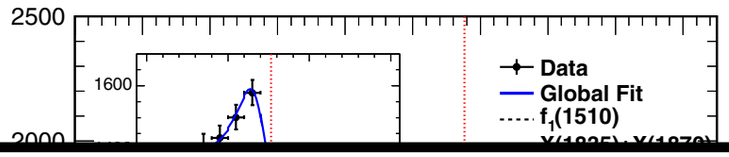


(4) The Z Question



Mysteries in the Meson System at BESIII

(1) The proton antiproton Question



(2) The ϱπ Question

Conclusions:

⇒ There is much still to learn about mesons (and more) at BESIII.

⇒ We are in an era where experiment-theory collaboration has become crucial.

⇒ We will soon have 10 billion J/ψ decays and more data in the XYZ region…

We look forward to new discoveries!