Spectroscopy at BESIII:
Open Questions

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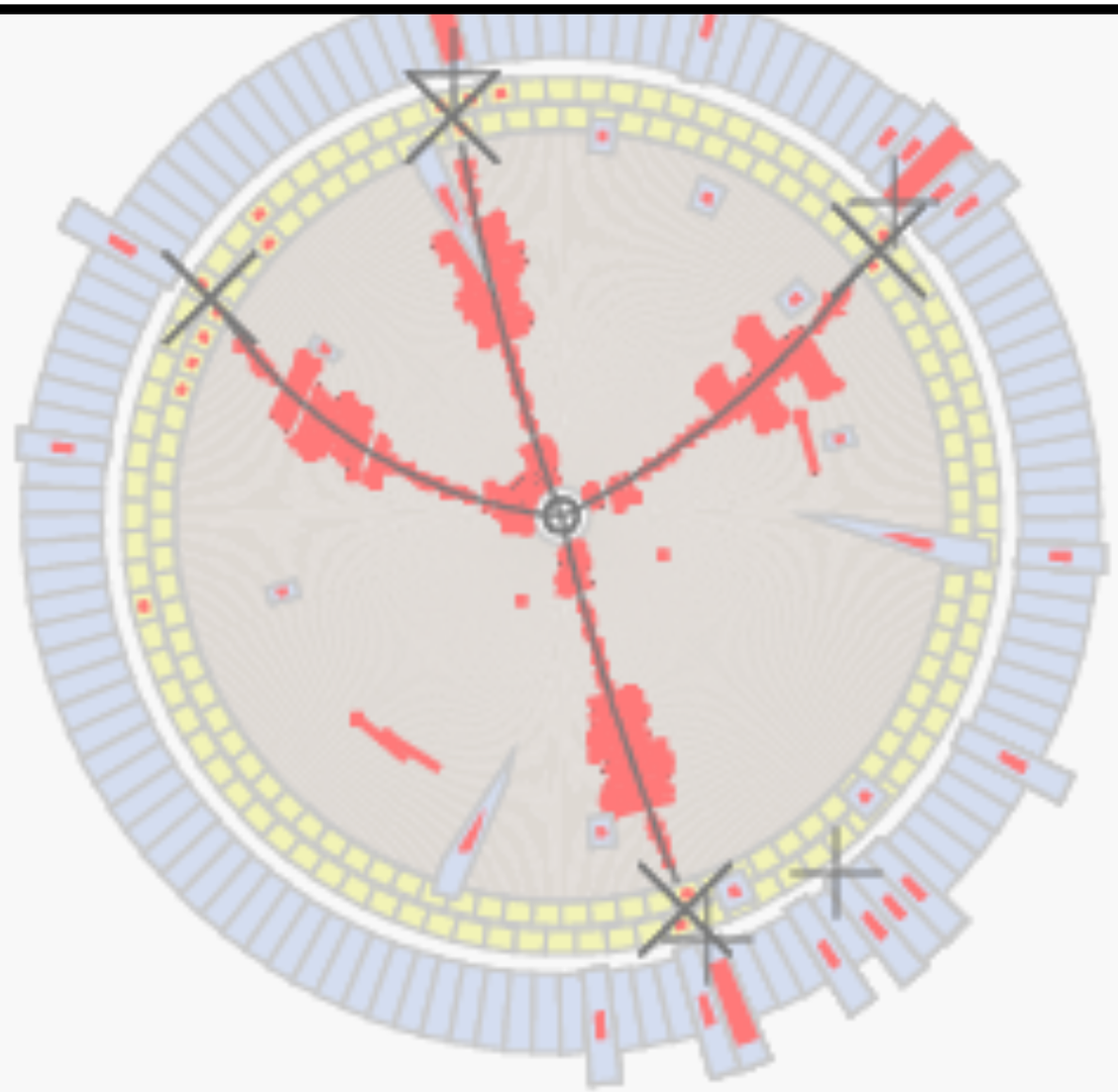


$e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$

Spectroscopy at BESIII:

BESIII Data Sets and Physics Reach

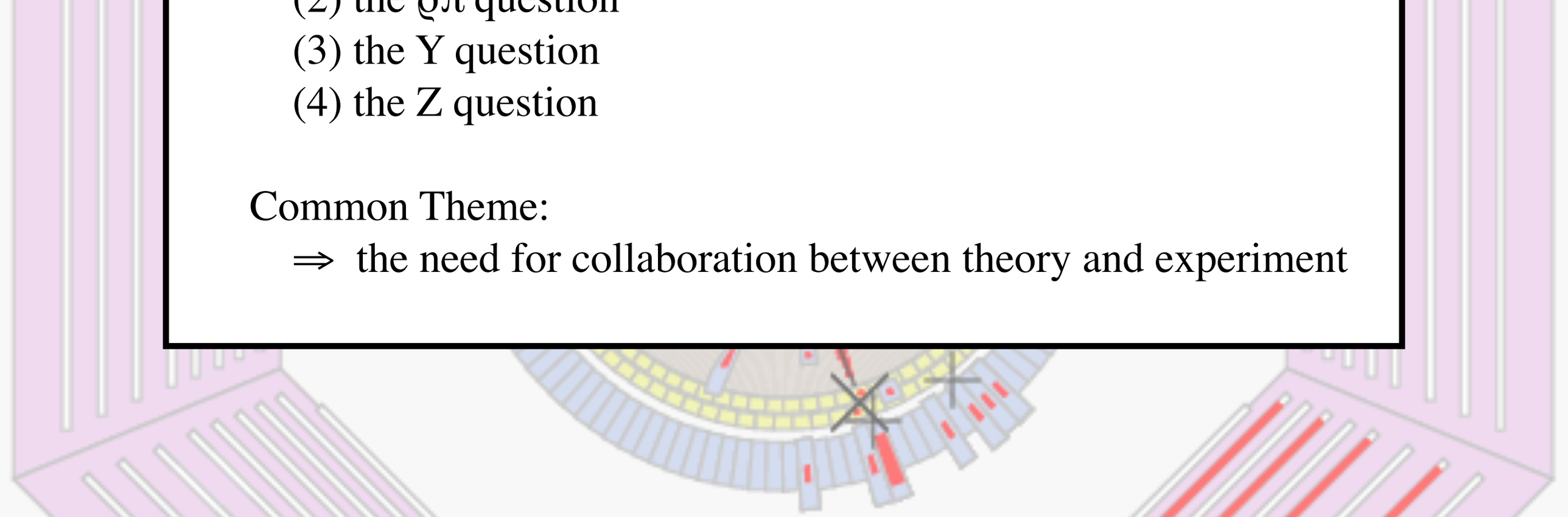
Examples of Precision Spectroscopy

Examples of Open Questions in Spectroscopy:

(1) the proton antiproton question
(2) the $\varrho\pi$ question
(3) the Y question
(4) the Z question

Common Theme:

$\Rightarrow$ the need for collaboration between theory and experiment

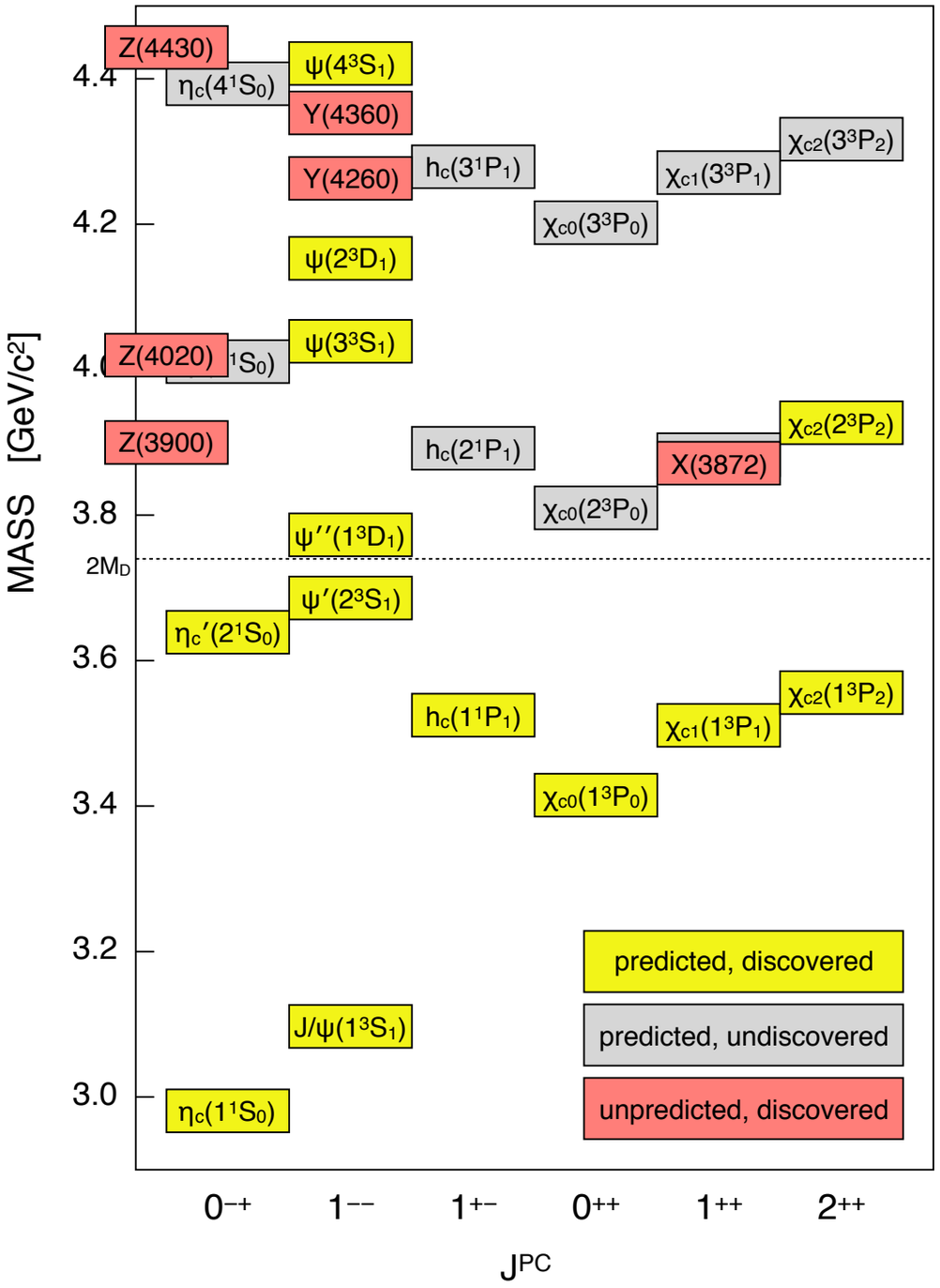


$e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$

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))

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Common Theme:

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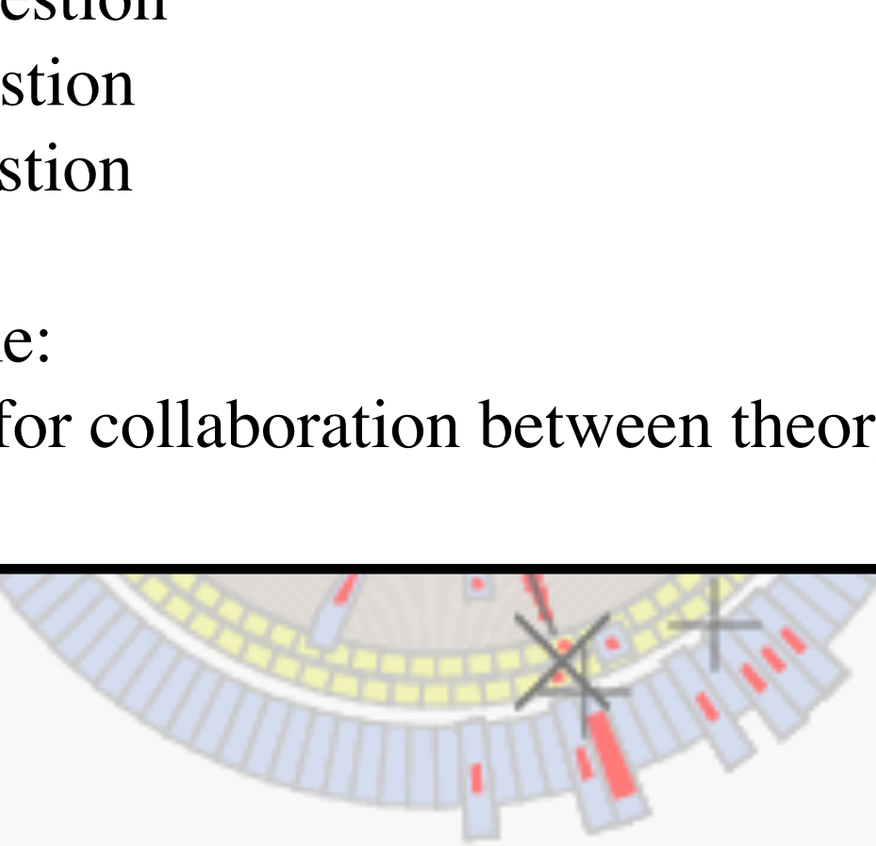
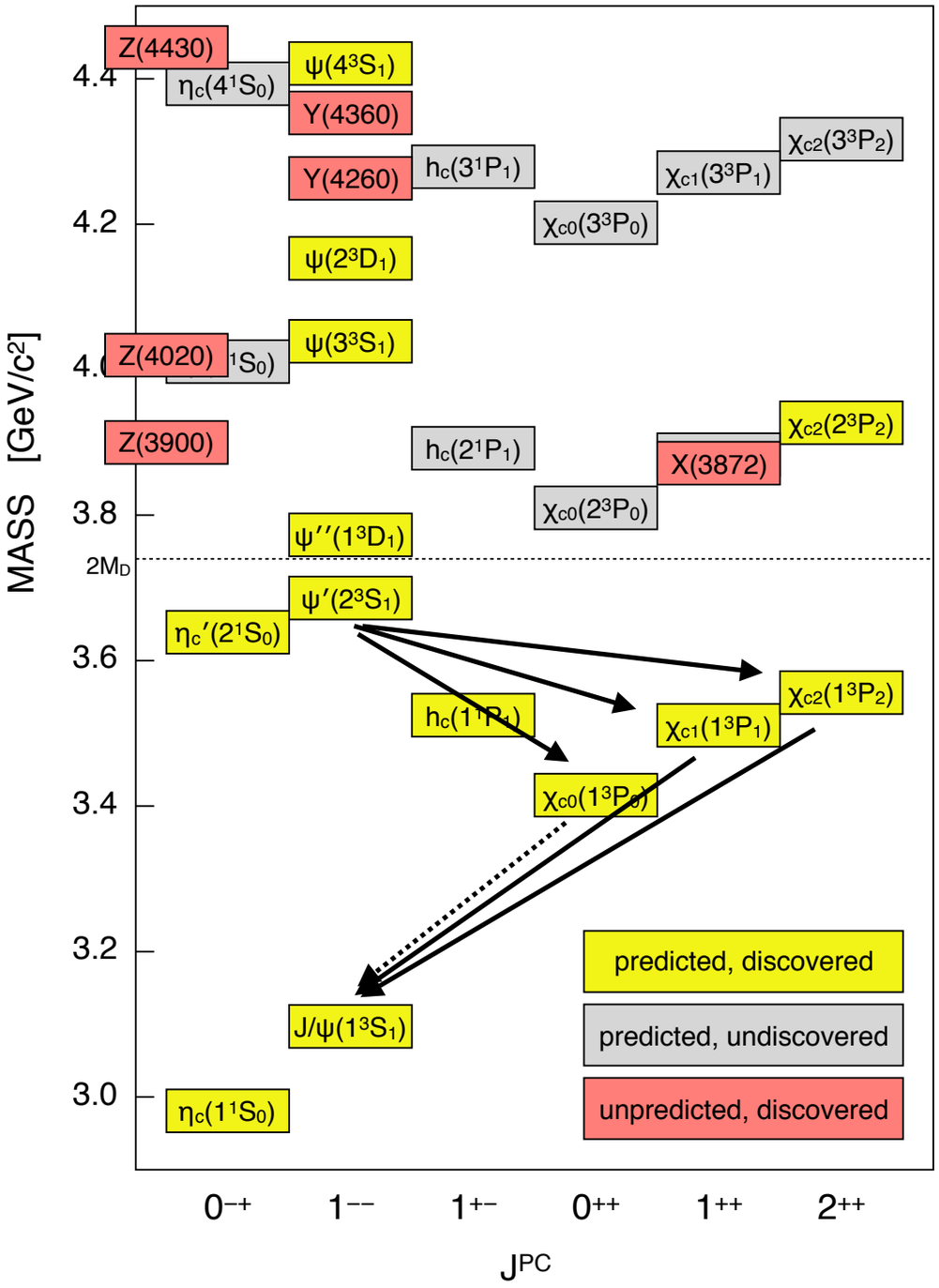


$e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$

Precision Studies in Charmonium (I)

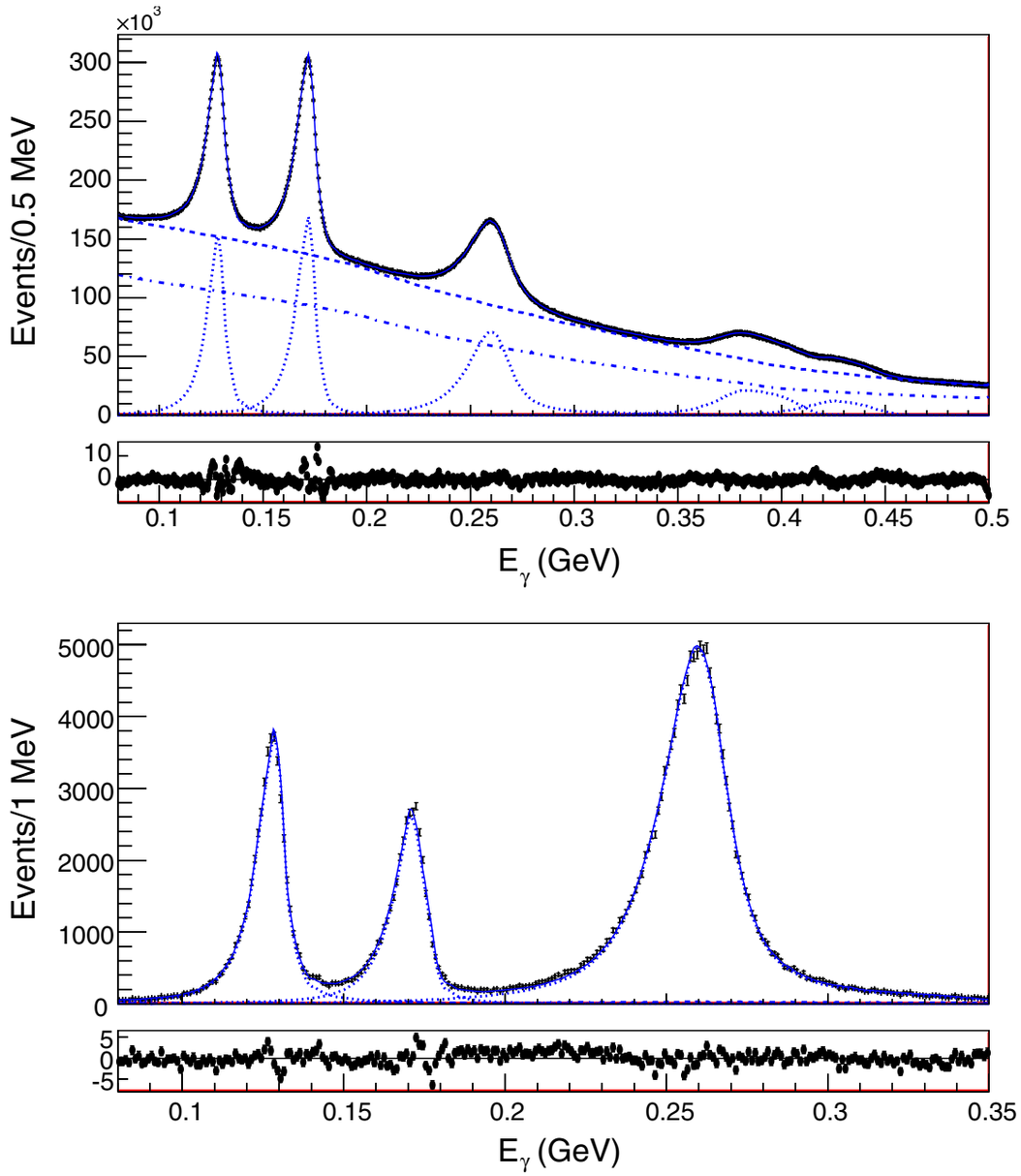
Charmonium Spectrum

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



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

[PRD 96, 032001 (2017)]



(using 106M ψ(2S) decays)

Precision Studies in Charmonium (I)

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

[PRD 96, 032001 (2017)]

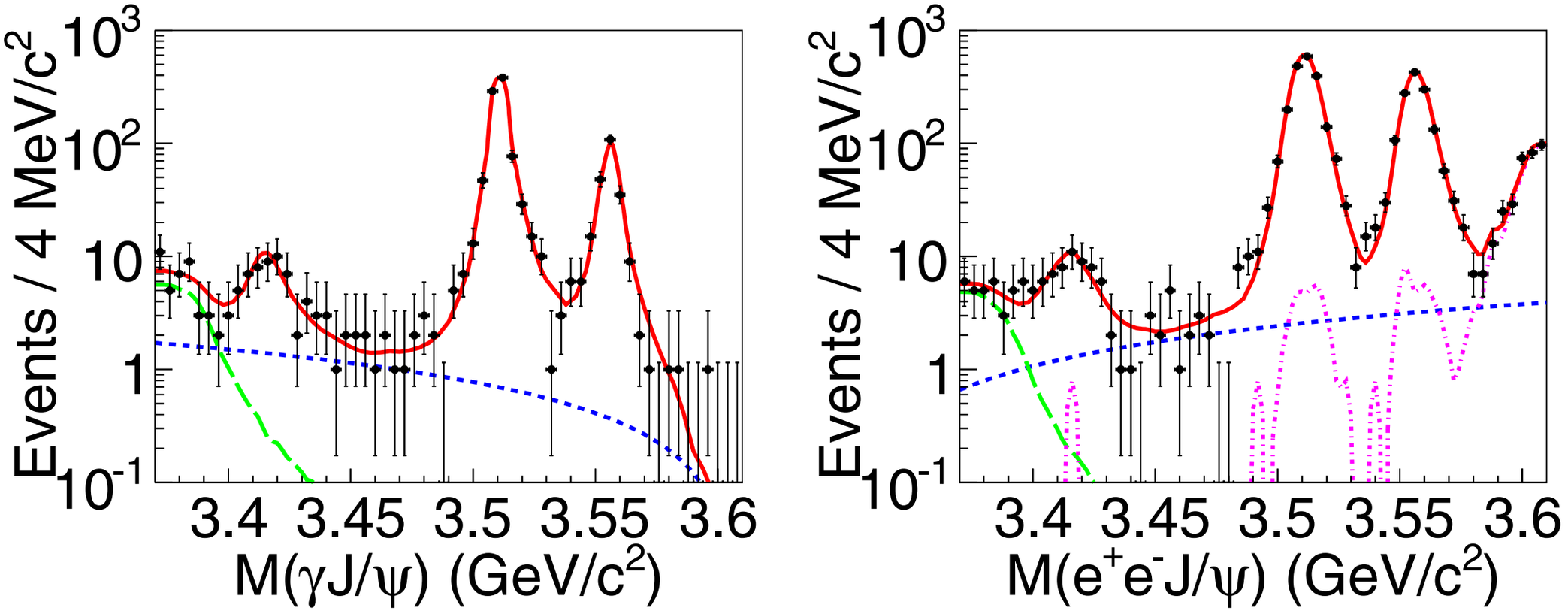
Branching Fraction	This analysis (%)	Other (%)	PDG [7] (%) Average	PDG [7] (%) Fit
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c0})$	$9.389 \pm 0.014 \pm 0.332$	$9.22 \pm 0.11 \pm 0.46$ [9]	9.2 ± 0.4	9.99 ± 0.27
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c1})$	$9.905 \pm 0.011 \pm 0.353$	$9.07 \pm 0.11 \pm 0.54$ [9]	8.9 ± 0.5	9.55 ± 0.31
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c2})$	$9.621 \pm 0.013 \pm 0.272$	$9.33 \pm 0.14 \pm 0.61$ [9]	8.8 ± 0.5	9.11 ± 0.31
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c0}) \times \mathcal{B}(\chi_{c0} \to \gamma J/\psi)$	$0.024 \pm 0.015 \pm 0.205$	$0.125 \pm 0.007 \pm 0.013$ [31] $0.151 \pm 0.003 \pm 0.010$ [15] $0.158 \pm 0.003 \pm 0.006$ [16]	0.131 ± 0.035	0.127 ± 0.006
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c1}) \times \mathcal{B}(\chi_{c1} \to \gamma J/\psi)$	$3.442 \pm 0.010 \pm 0.132$	$3.56 \pm 0.03 \pm 0.12$ [31] $3.377 \pm 0.009 \pm 0.183$ [15] $3.518 \pm 0.01 \pm 0.120$ [16]	2.93 ± 0.15	3.24 ± 0.07
$\mathcal{B}(\psi(3686) \to \gamma\chi_{c2}) \times \mathcal{B}(\chi_{c2} \to \gamma J/\psi)$	$1.793 \pm 0.008 \pm 0.163$	$1.95 \pm 0.02 \pm 0.07$ [31] $1.874 \pm 0.007 \pm 0.102$ [15] $1.996 \pm 0.008 \pm 0.070$ [16]	1.52 ± 0.15	1.75 ± 0.04
$\mathcal{B}(\chi_{c0} \to \gamma J/\psi)$	$0.25 \pm 0.16 \pm 2.15$	$2 \pm 0.2 \pm 0.2$ [32]		1.27 ± 0.06
$\mathcal{B}(\chi_{c1} \to \gamma J/\psi)$	$34.75 \pm 0.11 \pm 1.70$	$37.9 \pm 0.8 \pm 2.1$ [32]		33.9 ± 1.2
$\mathcal{B}(\chi_{c2} \to \gamma J/\psi)$	$18.64 \pm 0.08 \pm 1.69$	$19.9 \pm 0.5 \pm 1.2$ [32]		19.2 ± 0.7

		Γ_{E1} (keV)					Γ_{EM} (keV)		
Initial State	Final State	RQM [33]	NR/GI [34]	$SNR_{0/1}$ [35]	LP [8]	SP [8]	LP [8]	SP [8]	This Analysis
$\psi(3686)$	χ_{c0}	26.3	63/26	74/25	27	26	22	22	26.9 ± 1.8
	χ_{c1}	22.9	54/29	62/36	45	48	42	45	28.3 ± 1.9
	χ_{c2}	18.2	38/24	43/34	36	44	38	46	27.5 ± 1.7
χ_{c0}	J/ψ	121	152/114	167/117	141	146	172	179	
χ_{c1}		265	314/239	354/244	269	278	306	319	306 ± 23
χ_{c2}		327	424/313	473/309	327	338	284	292	363 ± 41

Precision Studies in Charmonium (II)

$\psi(2S) \to e^+e^-\chi_{cJ}$ and $\chi_{cJ} \to e^+e^- J/\psi$

[PRL 118, 221802 (2017)]



(using 448M $\psi(2S)$ decays; reconstruct $\psi(2S) \to \gamma e^+e^- J/\psi$)

Mode	Yields	Efficiency(%)	Branching fraction	$\mathcal{B}(\psi(3686) \to e^+e^-\chi_{cJ})/\mathcal{B}(\psi(3686) \to \gamma\chi_{cJ})$	$\mathcal{B}(\chi_{cJ} \to e^+e^- J/\psi)/\mathcal{B}(\chi_{cJ} \to \gamma J/\psi)$
$\psi(3686) \to e^+e^-\chi_{c0}$	48 ± 10	6.06	$(11.7 \pm 2.5 \pm 1.0) \times 10^{-4}$	$(9.4 \pm 1.9 \pm 0.6) \times 10^{-3}$	$\cdots$
$\psi(3686) \to e^+e^-\chi_{c1}$	873 ± 30	5.61	$(8.6 \pm 0.3 \pm 0.6) \times 10^{-4}$	$(8.3 \pm 0.3 \pm 0.4) \times 10^{-3}$	$\cdots$
$\psi(3686) \to e^+e^-\chi_{c2}$	227 ± 16	3.19	$(6.9 \pm 0.5 \pm 0.6) \times 10^{-4}$	$(6.6 \pm 0.5 \pm 0.4) \times 10^{-3}$	$\cdots$
$\chi_{c0} \to e^+e^- J/\psi$	56 ± 11	6.95	$(1.51 \pm 0.30 \pm 0.13) \times 10^{-4}$	$\cdots$	$(9.5 \pm 1.9 \pm 0.7) \times 10^{-3}$
$\chi_{c1} \to e^+e^- J/\psi$	1969 ± 46	10.35	$(3.73 \pm 0.09 \pm 0.25) \times 10^{-3}$	$\cdots$	$(10.1 \pm 0.3 \pm 0.5) \times 10^{-3}$
$\chi_{c2} \to e^+e^- J/\psi$	1354 ± 39	11.23	$(2.48 \pm 0.08 \pm 0.16) \times 10^{-3}$	$\cdots$	$(11.3 \pm 0.4 \pm 0.5) \times 10^{-3}$

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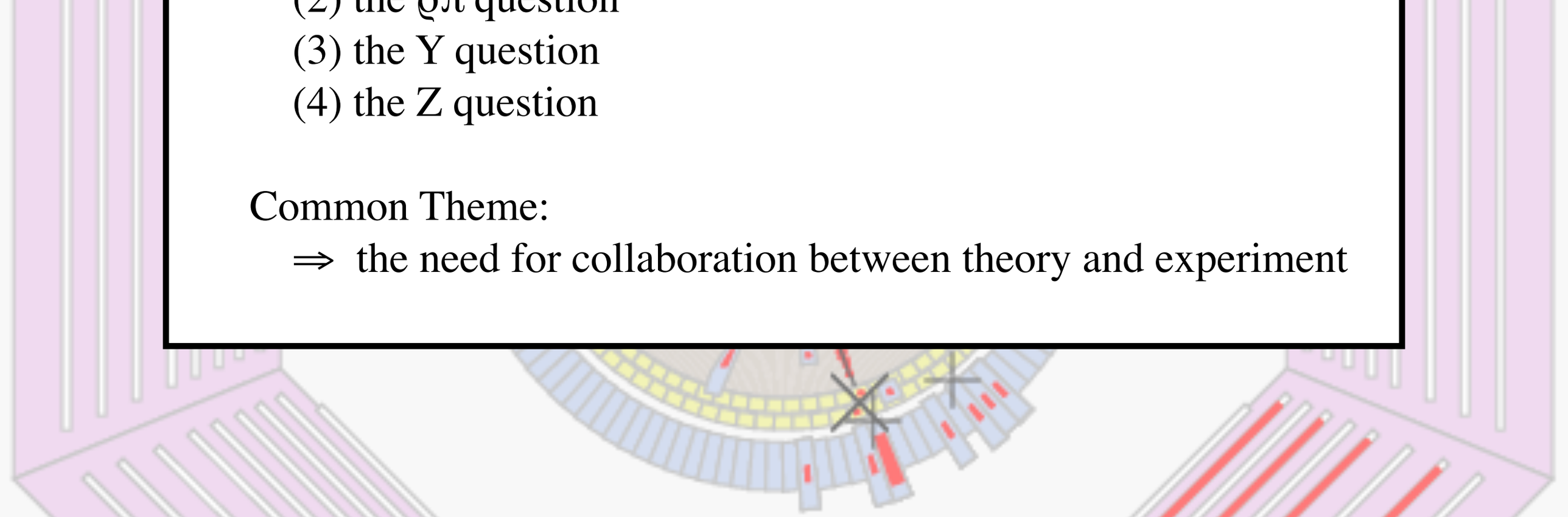
(4) the Z question

Common Theme:

$\Rightarrow$ the need for collaboration between theory and experiment



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

Examples of Open Questions in Spectroscopy at BESIII

(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.

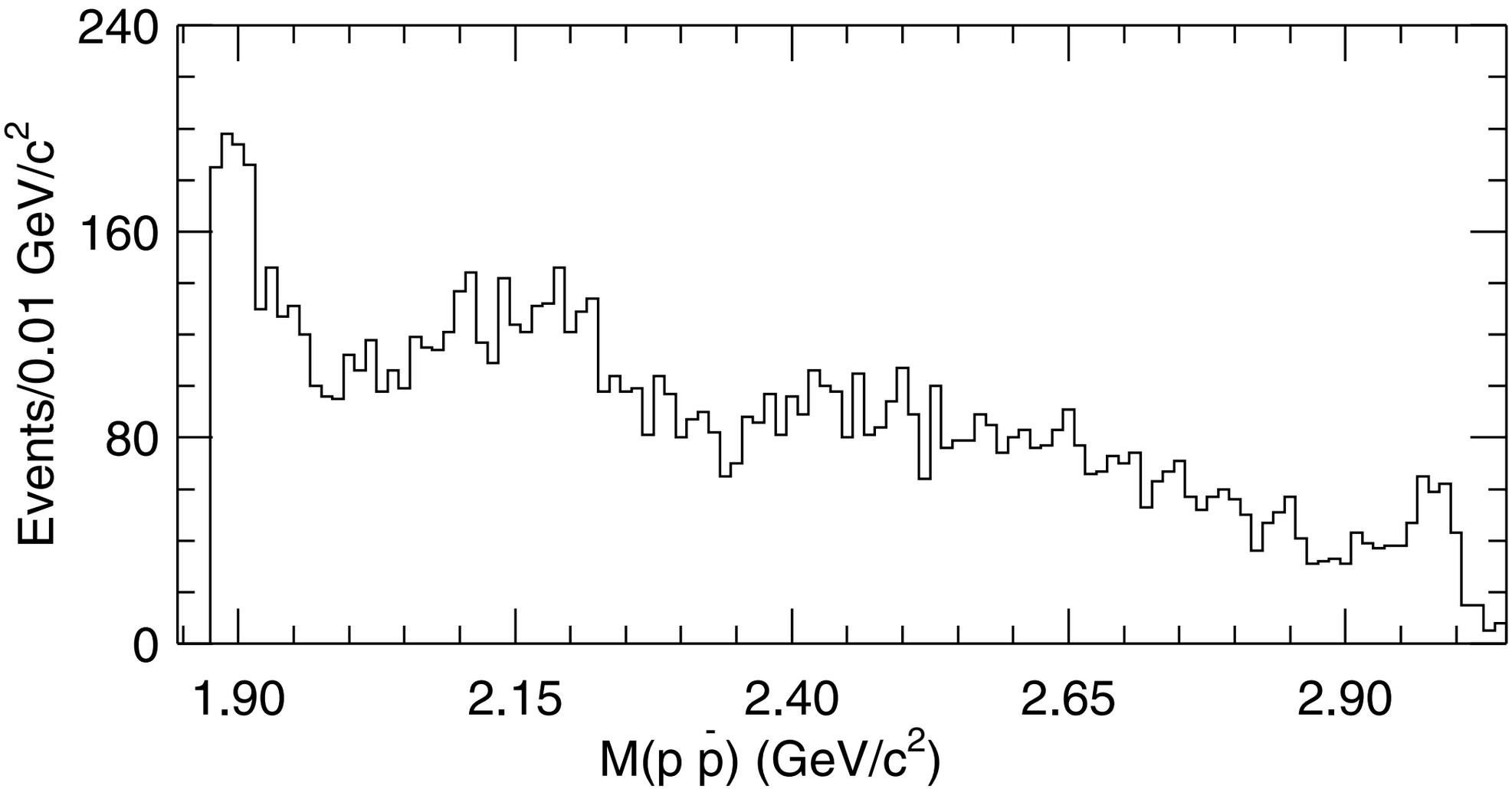
(4) The **Z** Question

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)]

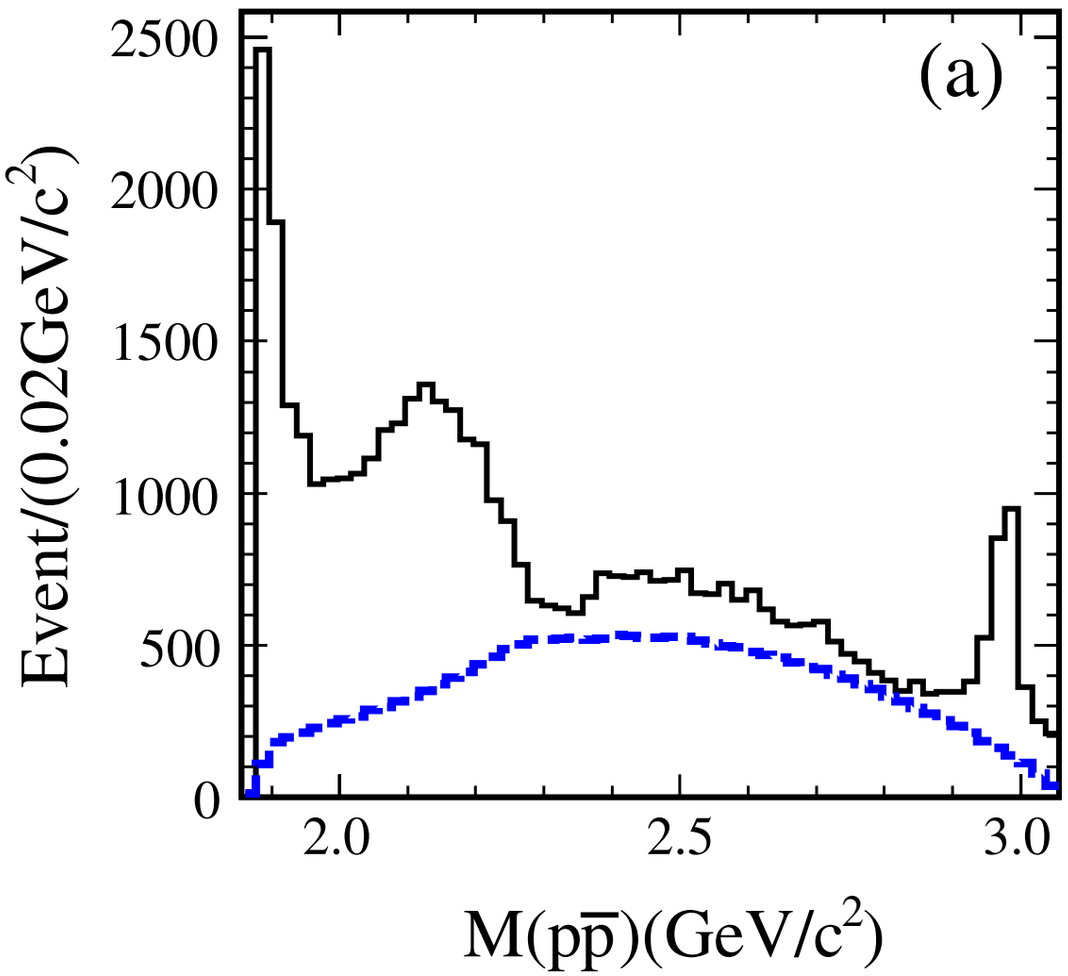


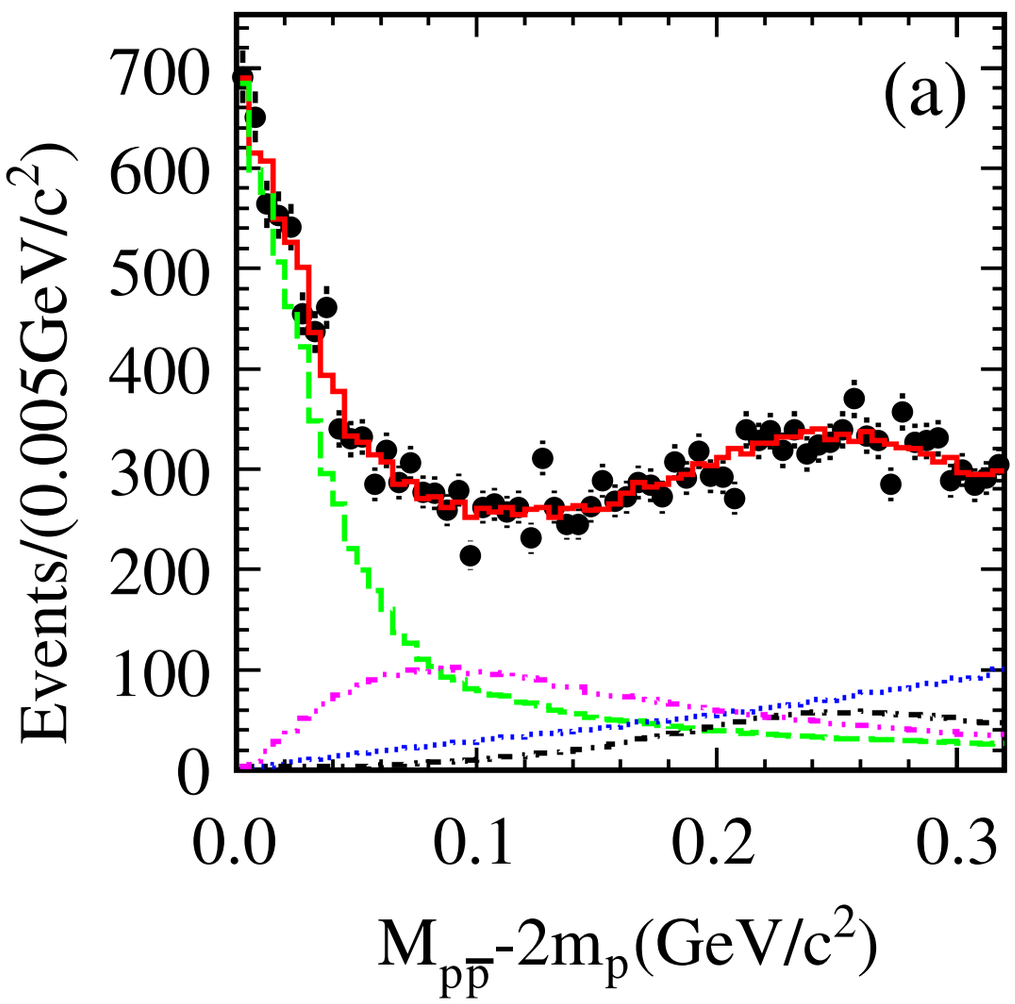
(using 58M J/ψ decays)

(1) The **proton antiproton** Question

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

[PRL 108, 112003 (2012)]





(using 225M J/ψ decays)

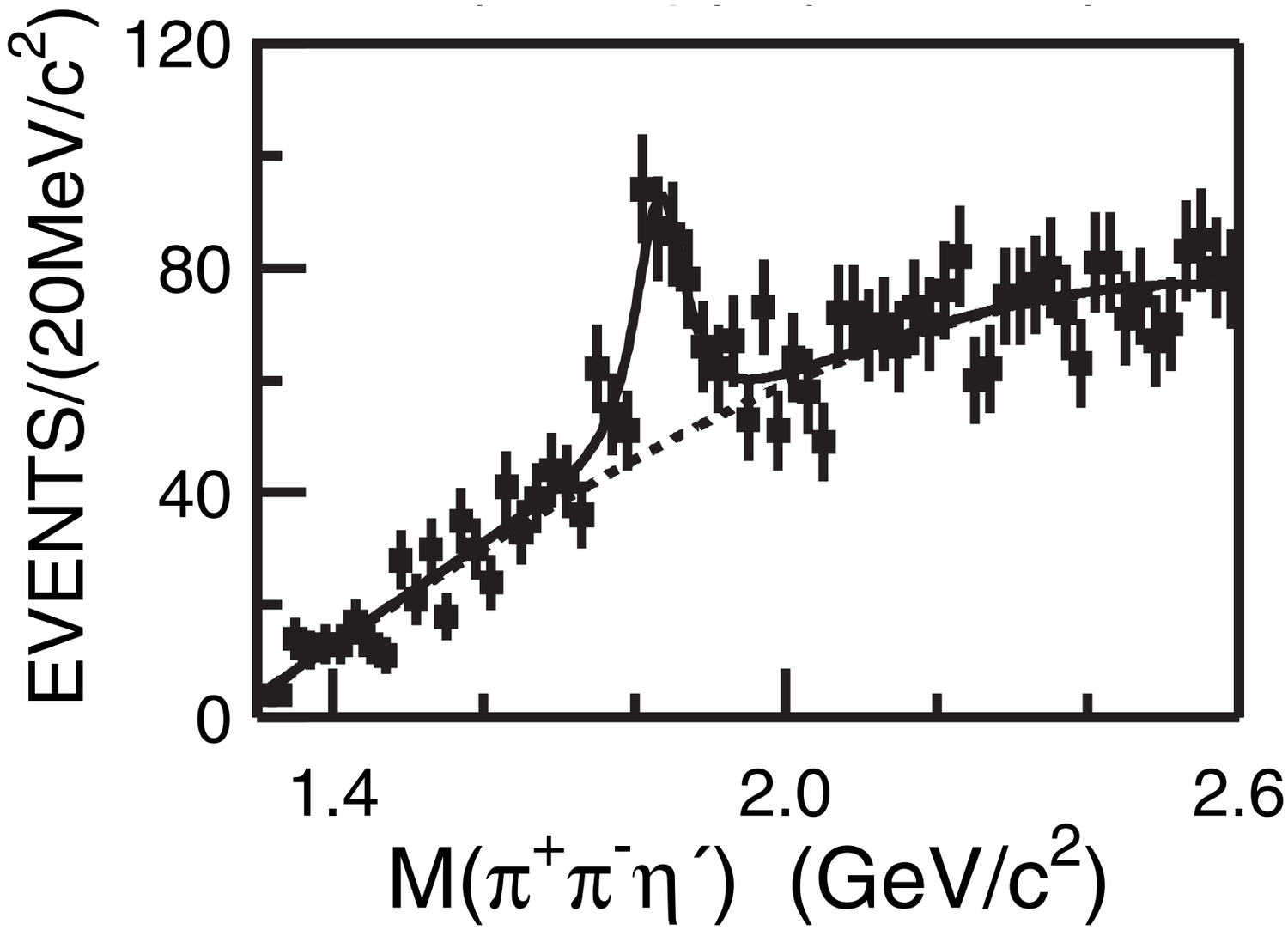
Fit Components: X(1835), 0^{++} phase space, $f_0(2100)$, $f_2(1910)$

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

(1) The **proton antiproton** Question

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

[BESII, PRL 95, 262001 (2005)]



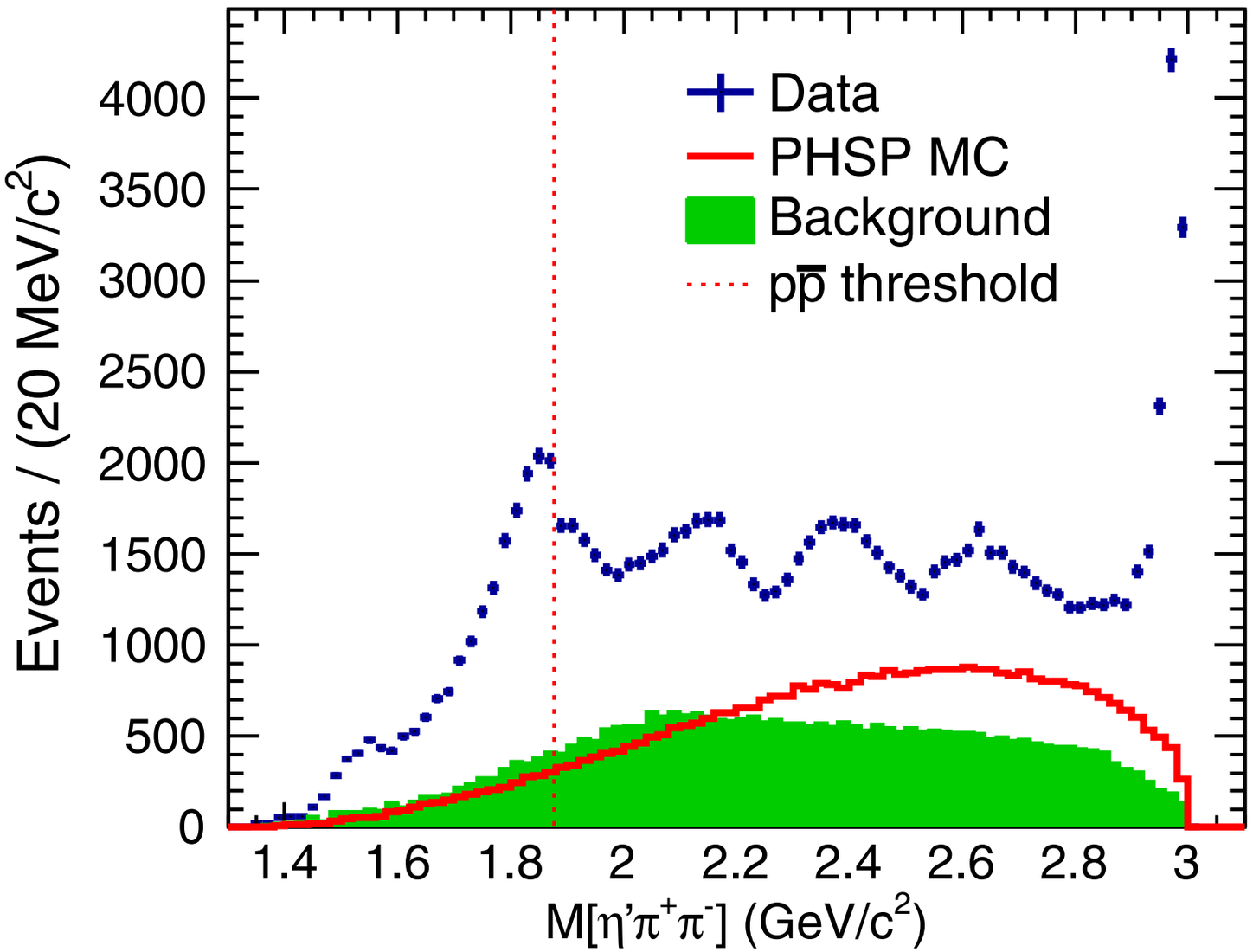
(using 58M J/ψ decays)

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

(1) The **proton antiproton** Question

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

[PRL 117, 042002 (2016)]



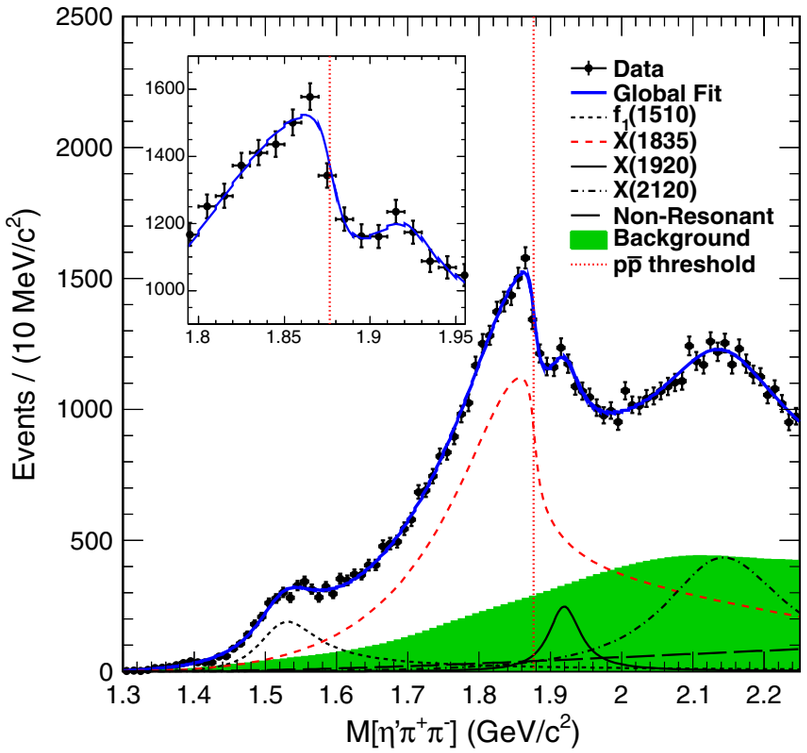
$f_1(1510)$
X(1835)??
X(2120)
X(2370)
??(2600)

(using 1.1B J/ψ decays)

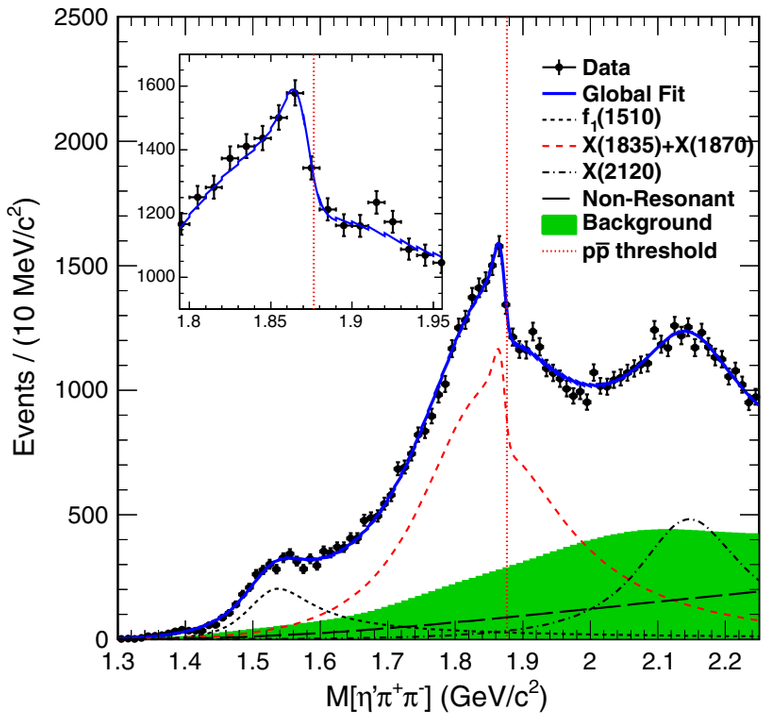
(1) The **proton antiproton** Question

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

[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)	$(1.57 \pm 0.09^{+0.49}_{-0.86}) \times 10^{-5}$

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e.g. Y(4230), Y(4260), Y(4360), Y(4660), etc.

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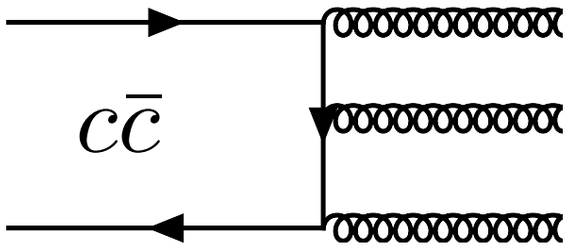


implies:

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

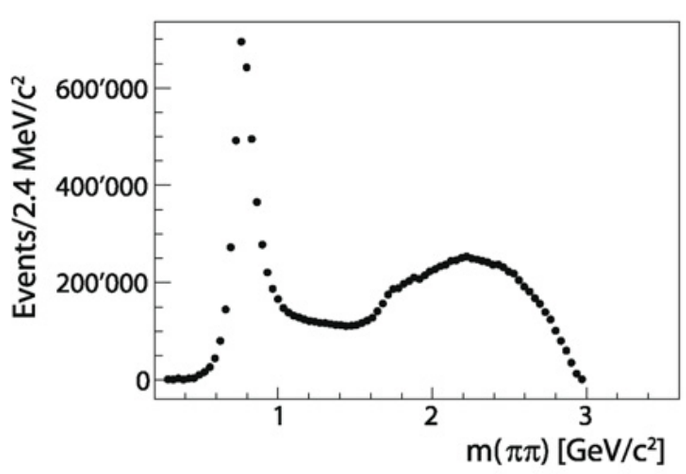
but:

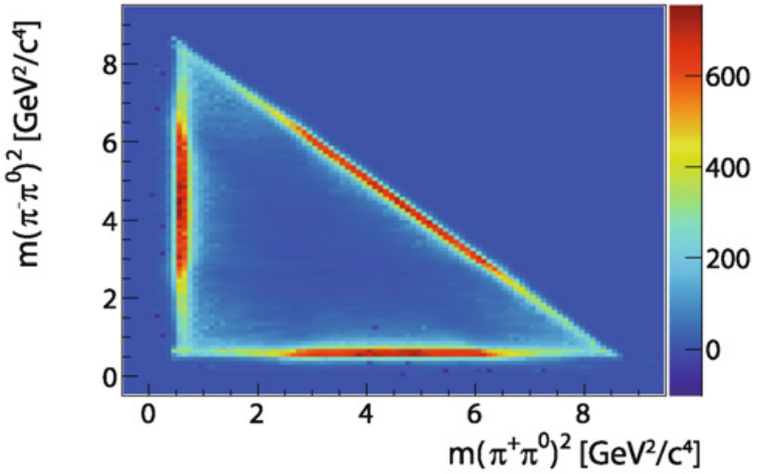
$$\frac{\mathcal{B}(\psi(2S) \to \pi^+\pi^-\pi^0)}{\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^0)}$$

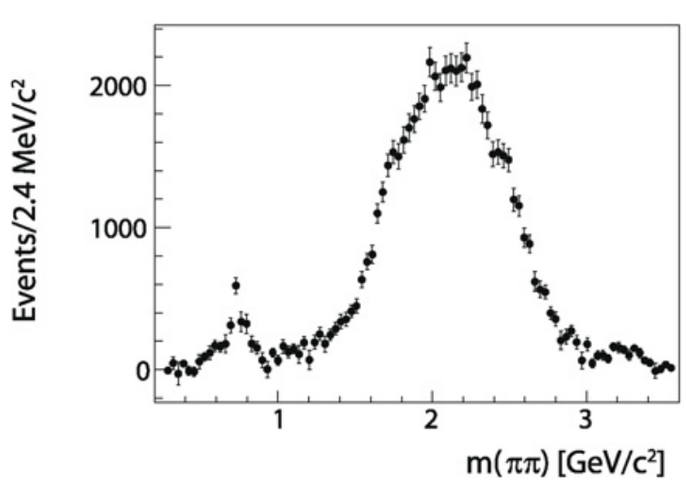
$$= \left(1.00 \pm 0.01\ (\text{stat.})^{+0.06}_{-0.05}\ (\text{syst.})\right)\%$$

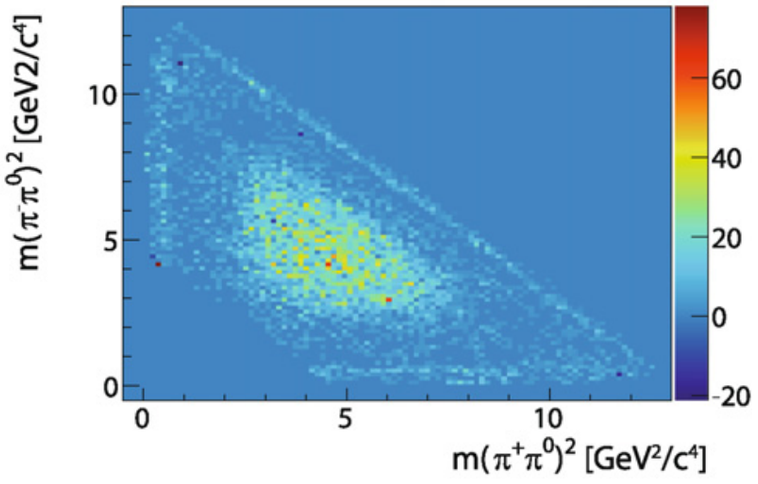
J/ψ and $\psi(2S) \to \pi^+\pi^-\pi^0$

[PLB 710, 594 (2012)]



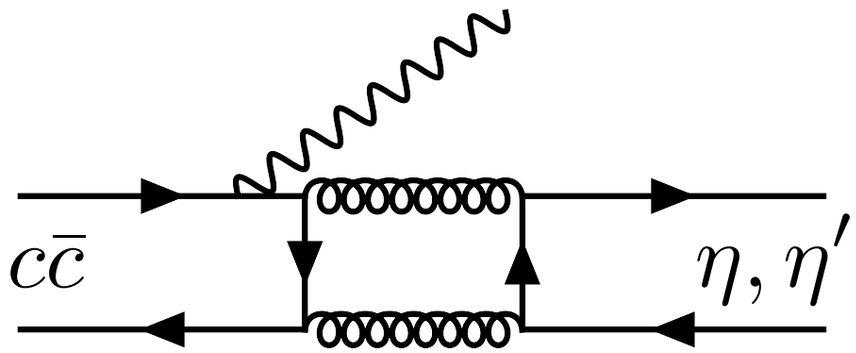






(using 225M J/ψ decays and 106M ψ(2S) decays)

(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:

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

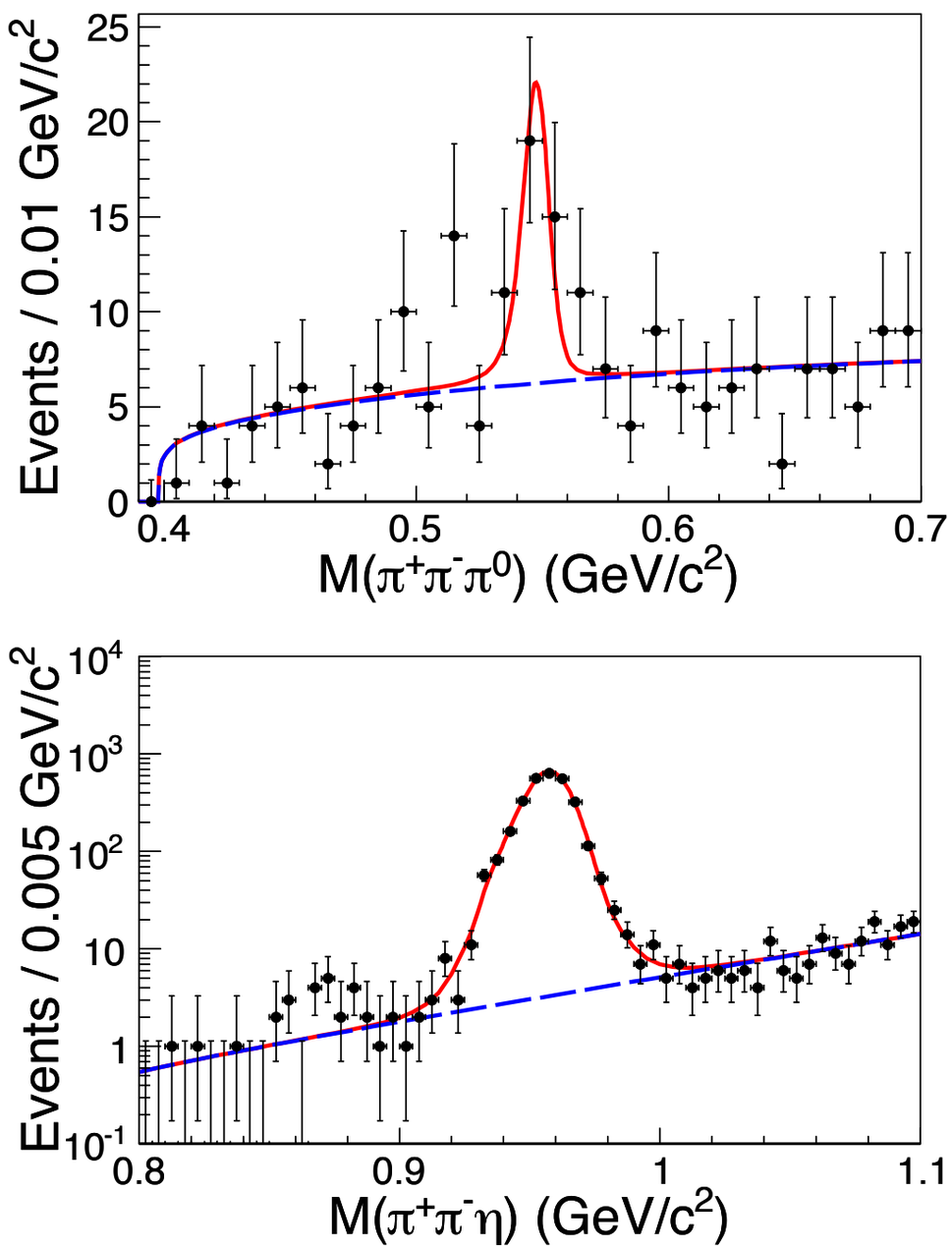
and:

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

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

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

[PRD 96, 052003 (2017)]



(using 448M ψ(2S) decays)

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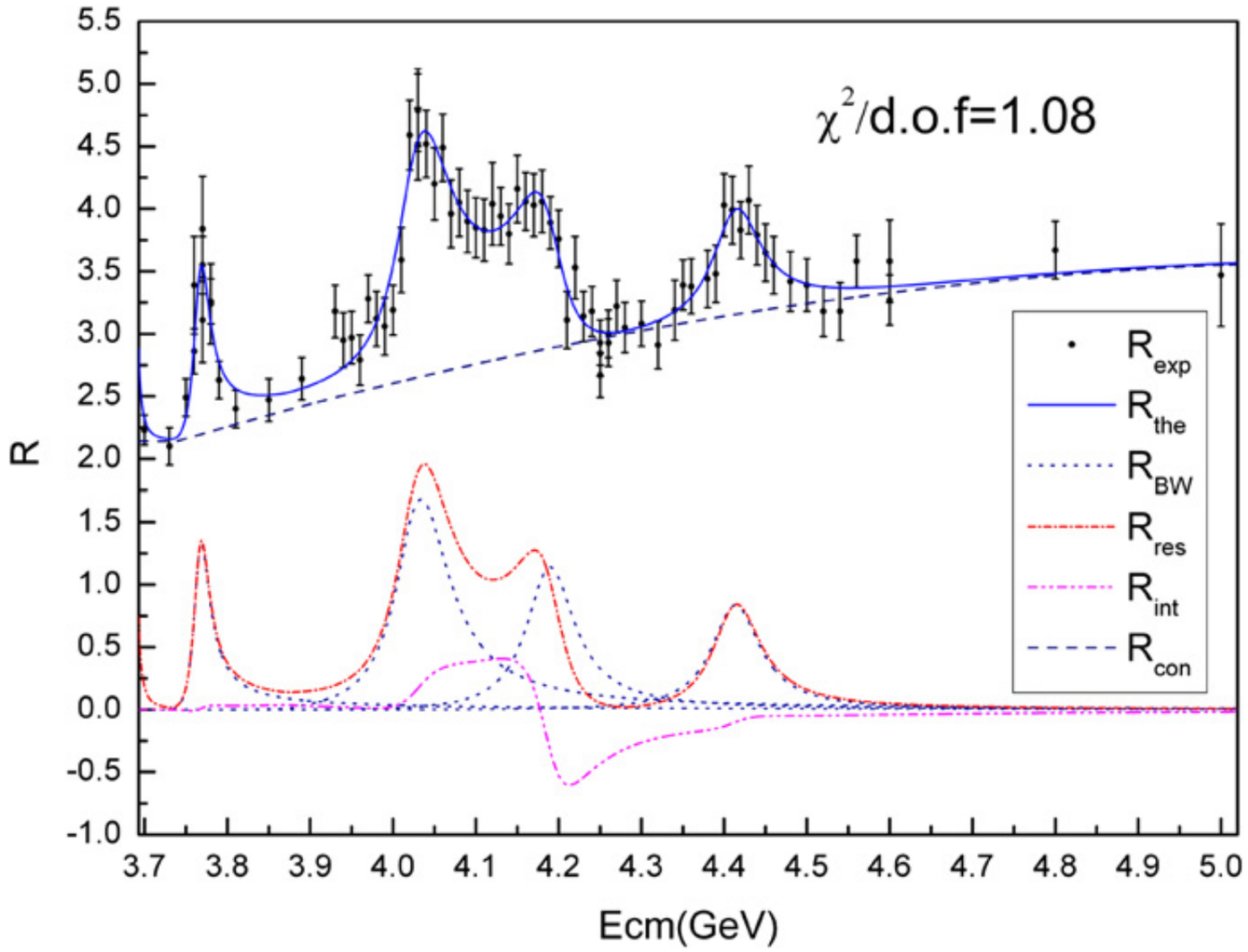
$e^+e^- \to$ hadrons

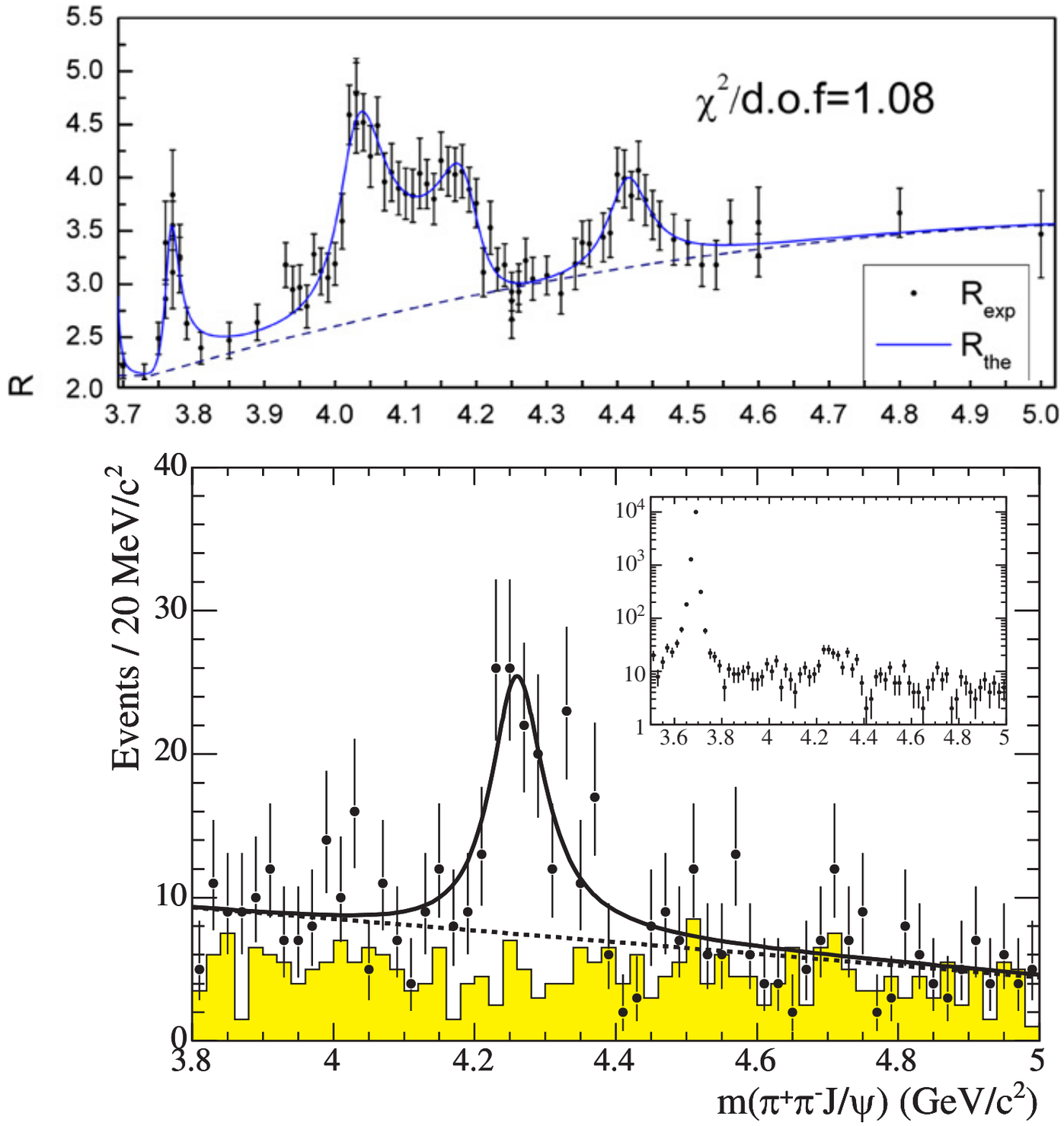
[BESII, PLB 660, 315 (2008)]



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)]



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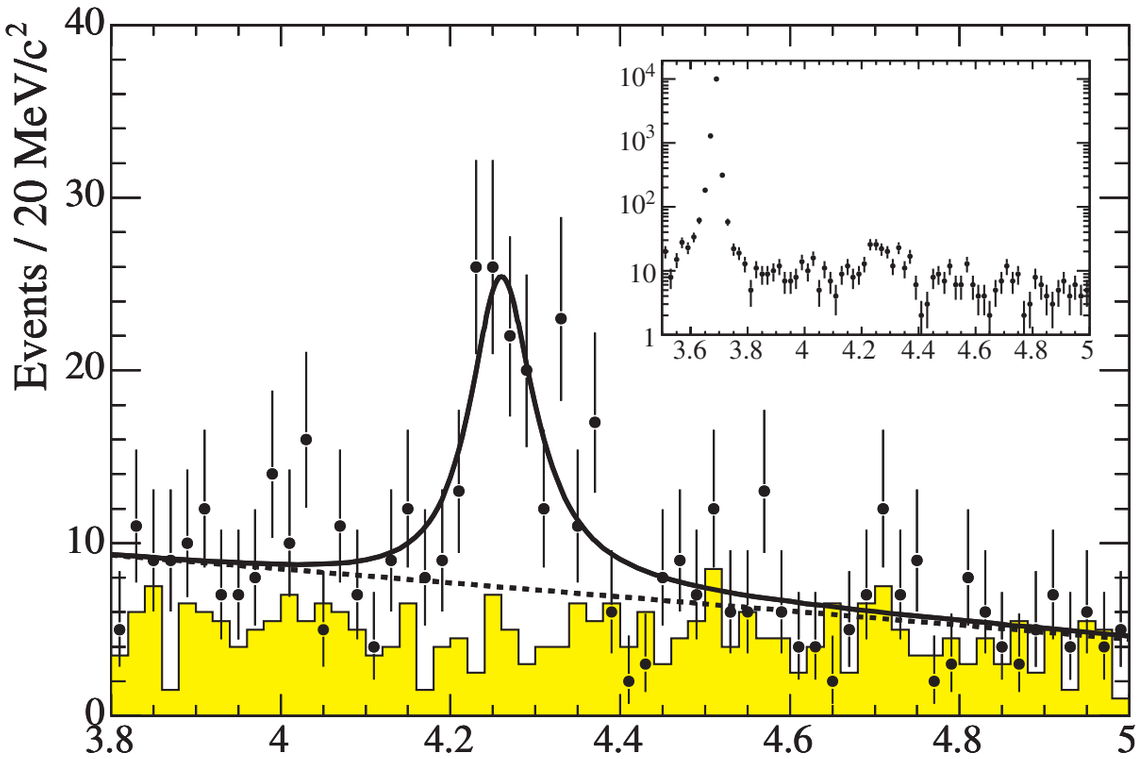
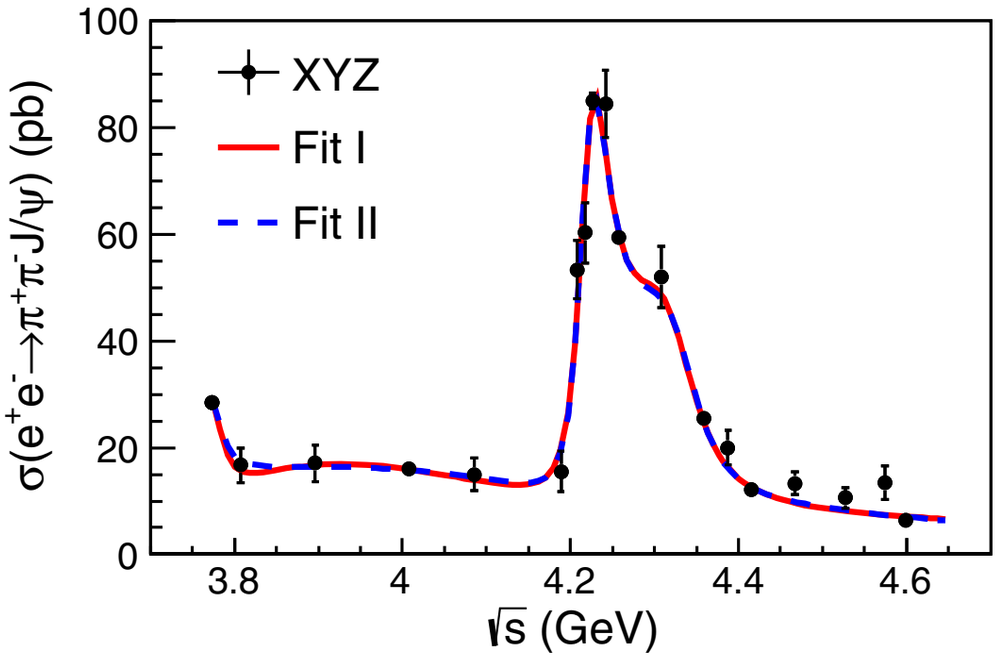
$e^+e^- \to \pi^+\pi^- J/\psi$
[BaBar, PRL 95, 142001 (2005)]

vs.

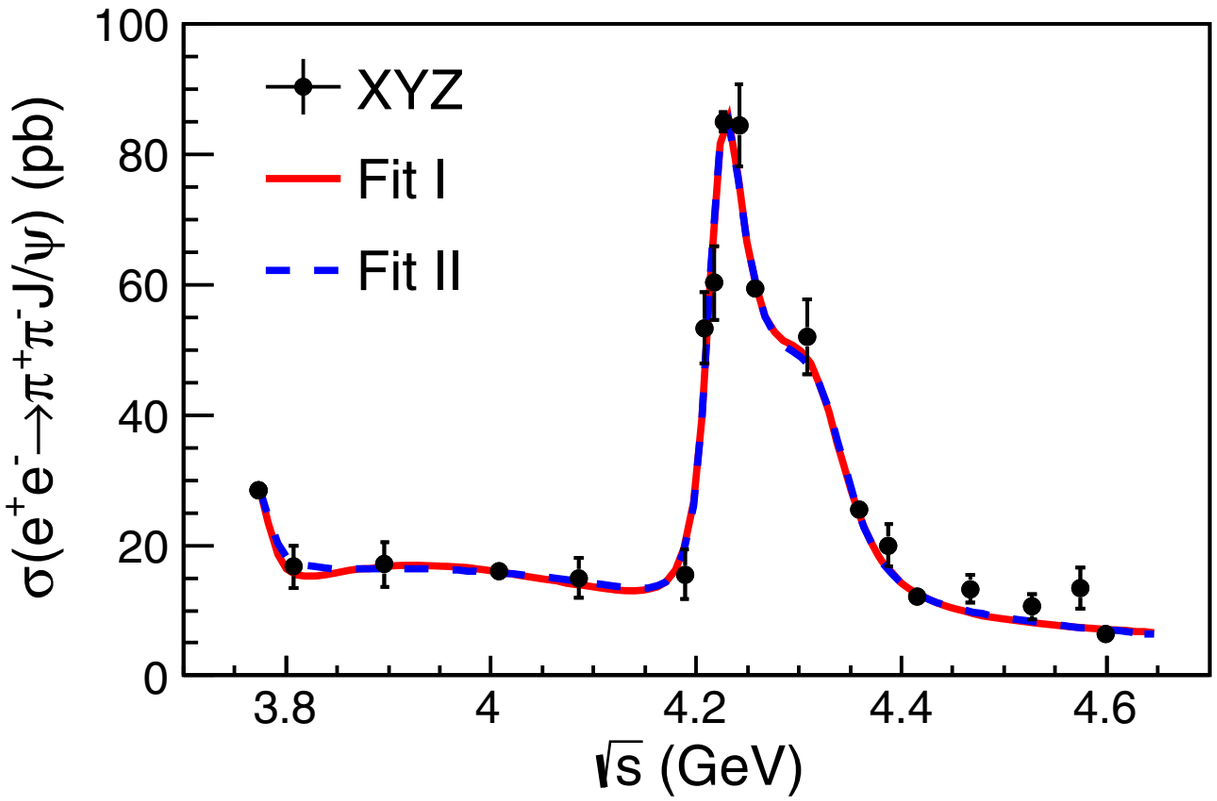
$e^+e^- \to \pi^+\pi^- J/\psi$
[PRL 118, 092001 (2017)]

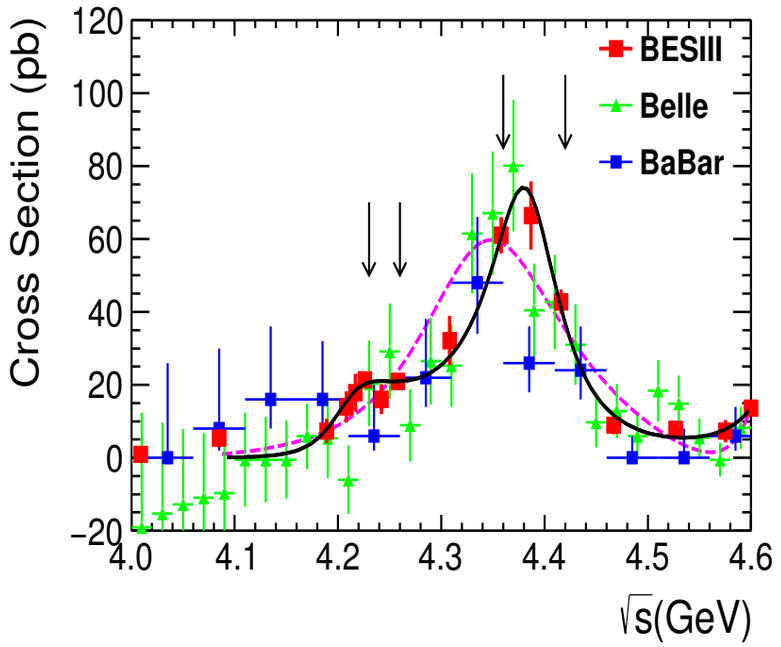




(3) The **Y** Question

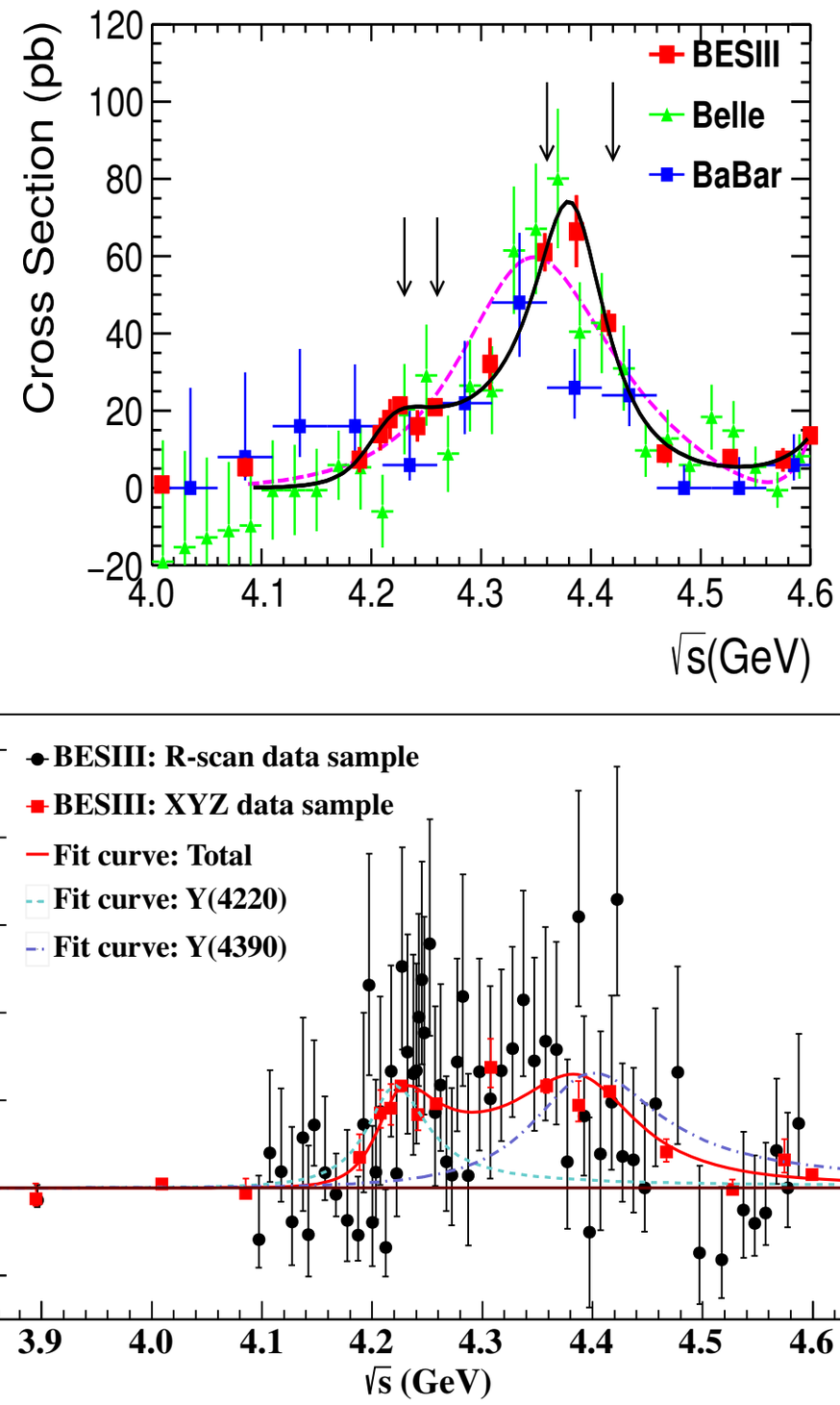
$e^+e^- \to \pi^+\pi^- J/\psi$ [PRL 118, 092001 (2017)] vs. $e^+e^- \to \pi^+\pi^-\psi(2S)$ [PRD 96, 032004 (2017)]





(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)]

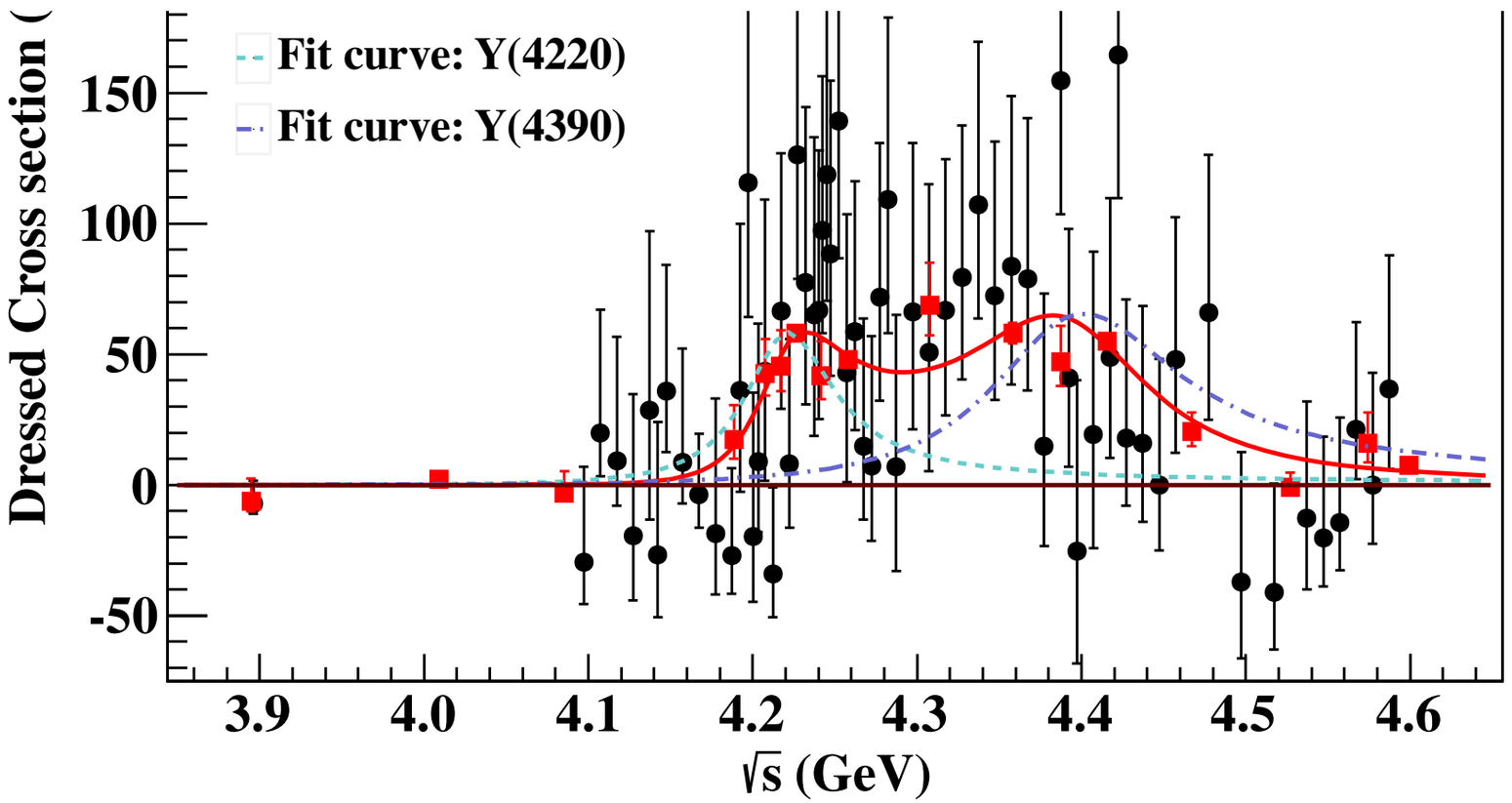


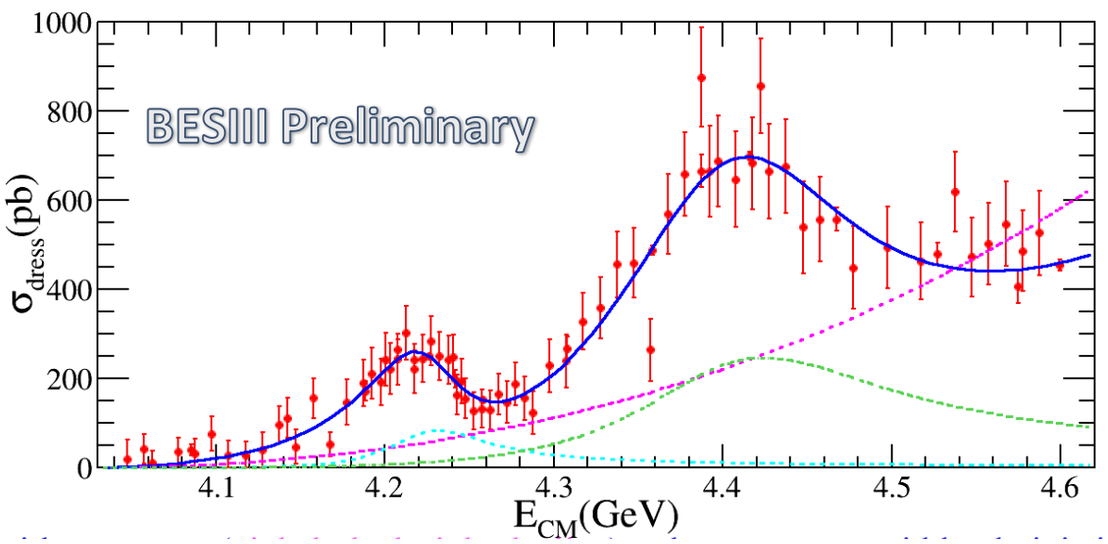
(3) The **Y** Question

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

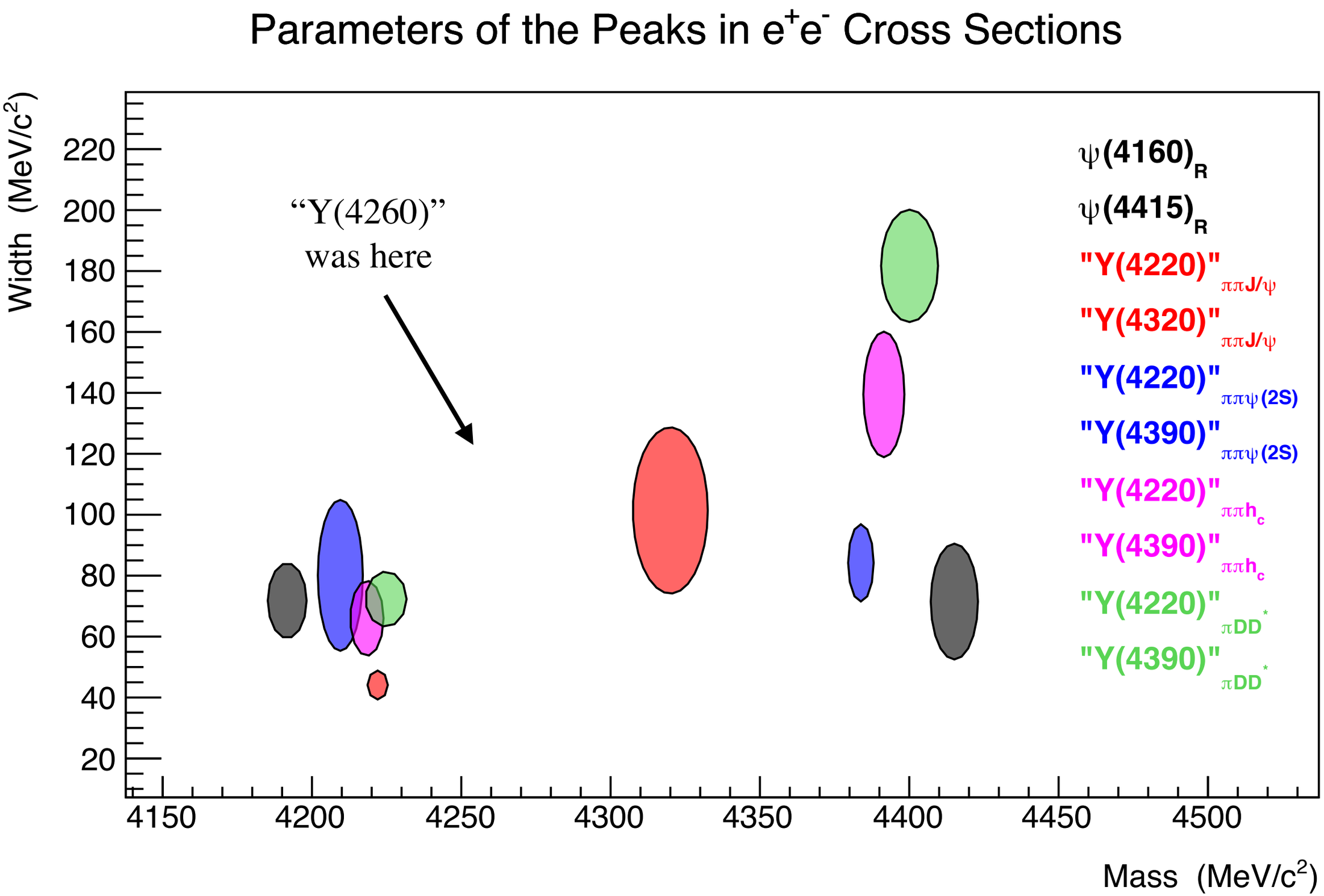
vs.

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





(3) The **Y** Question



Examples of Open Questions in Spectroscopy at BESIII

(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.

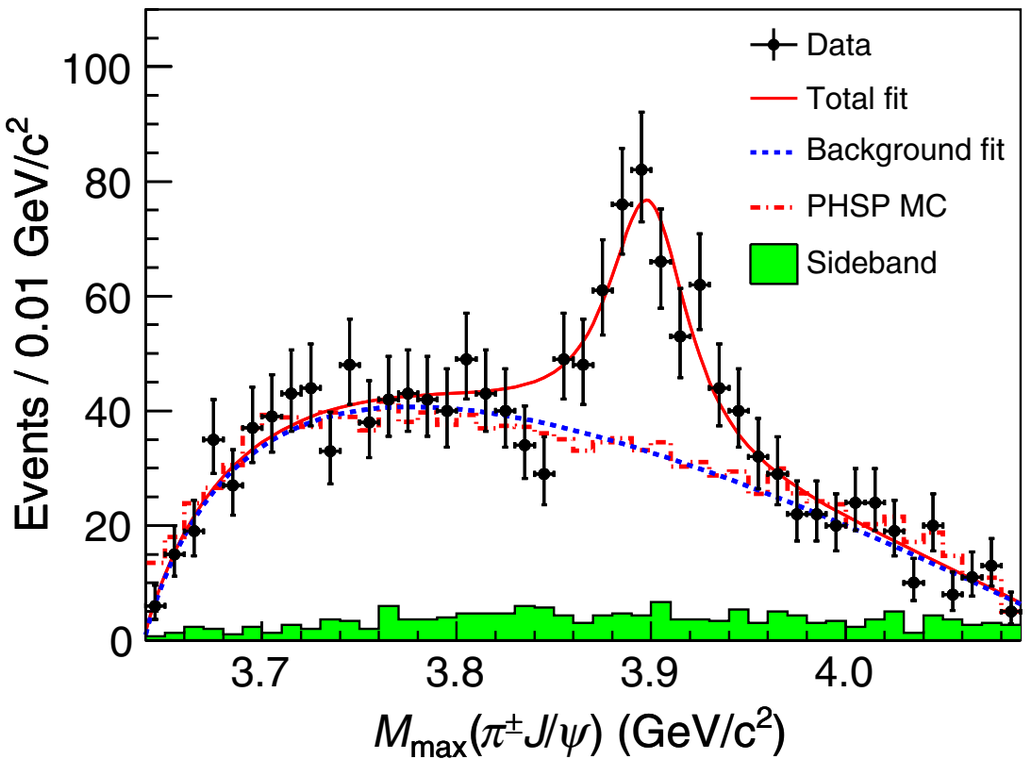
(4) The **Z** Question

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)]

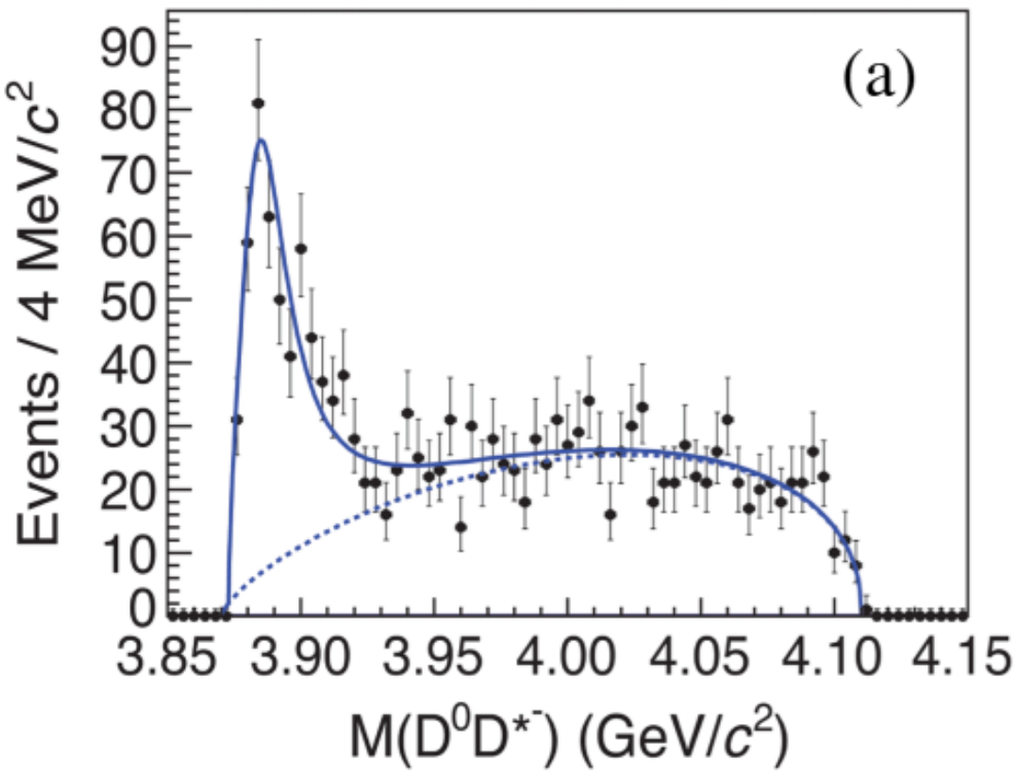


(using 525 pb^{-1} at 4.26 GeV)

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

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

[PRL 112, 022001 (2014)]



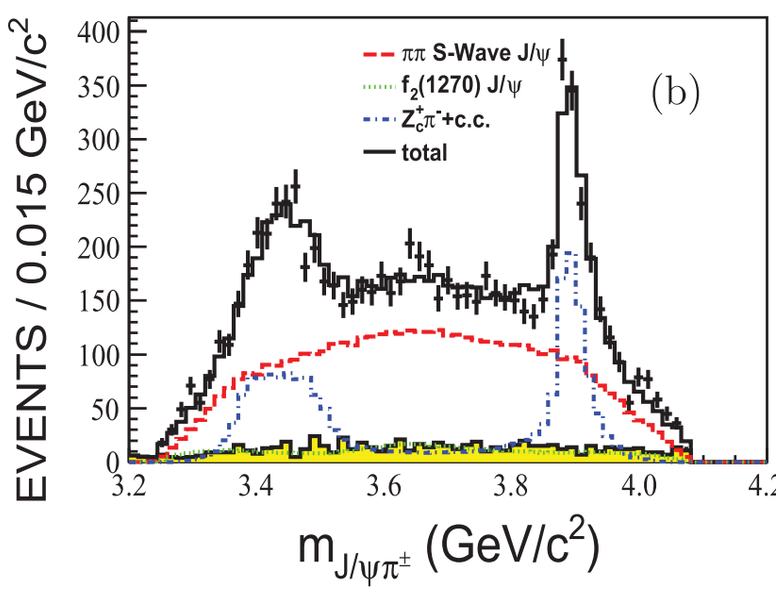
(using 525 pb^{-1} at 4.26 GeV)

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

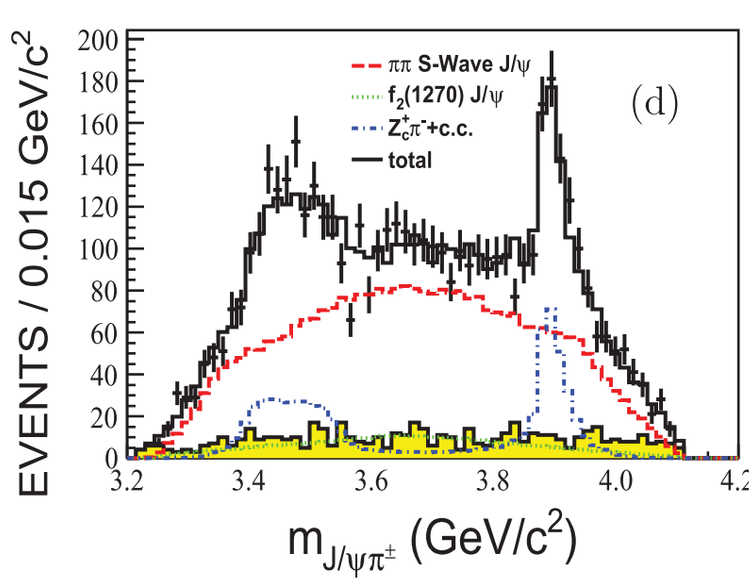
(4) The **Z** Question

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

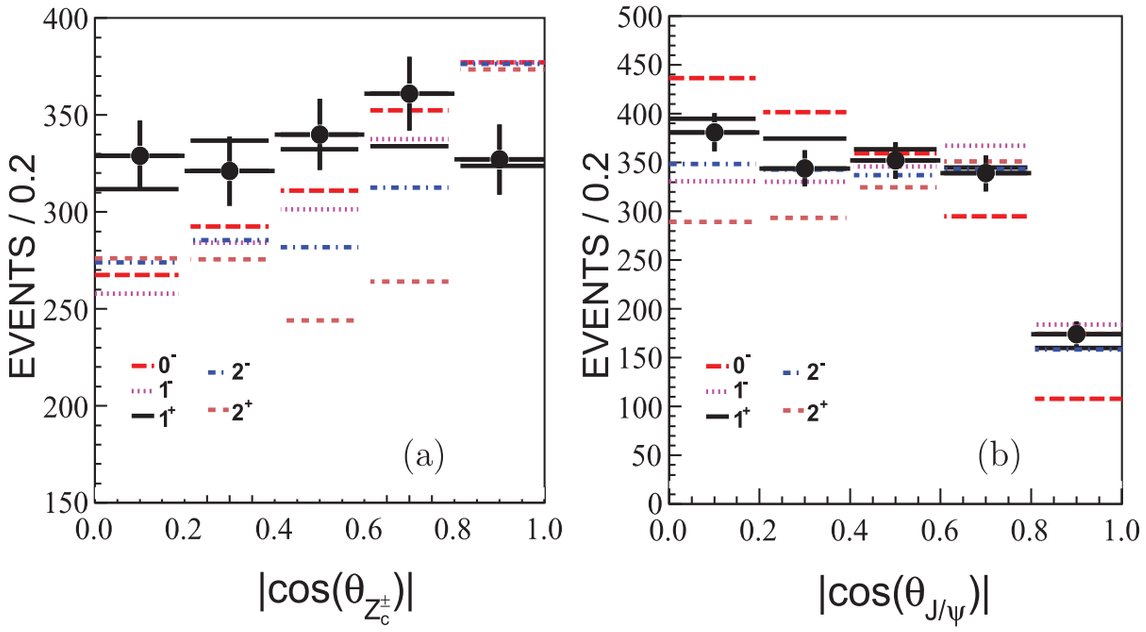
[PRL 119, 072001 (2017) (Aug. 16)]



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



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

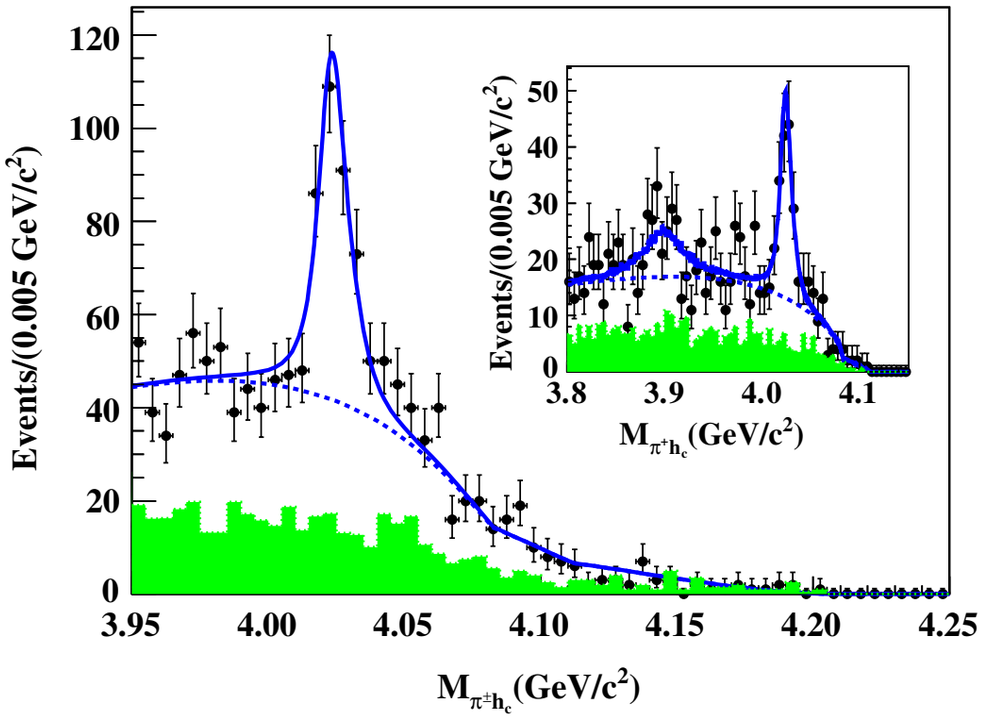


$$M = (3881.2 \pm 4.2 \pm 52.7)\ \mathrm{MeV}/c^2;$$
$$\Gamma = (51.8 \pm 4.6 \pm 36.0)\ \mathrm{MeV}/c^2;$$
$$J^P = 1^+$$

(4) The **Z** Question

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

[PRL 111, 242001 (2013)]

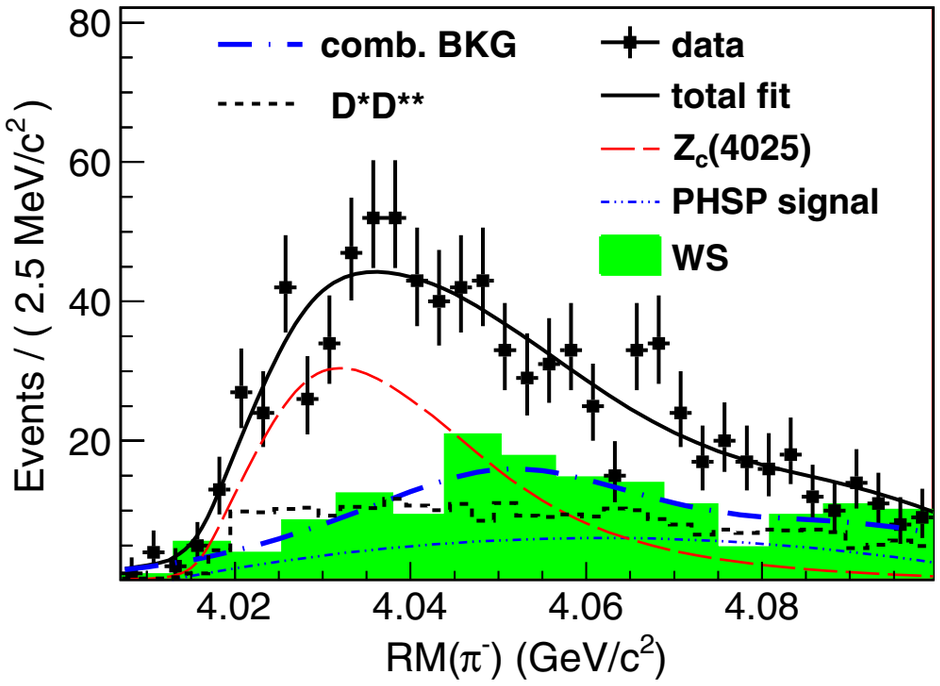


(using 1090 pb^{-1} at 4.23 GeV,
827 pb^{-1} at 4.26 GeV,
545 pb^{-1} at 4.36 GeV)

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

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

[PRL 112, 132001 (2014)]



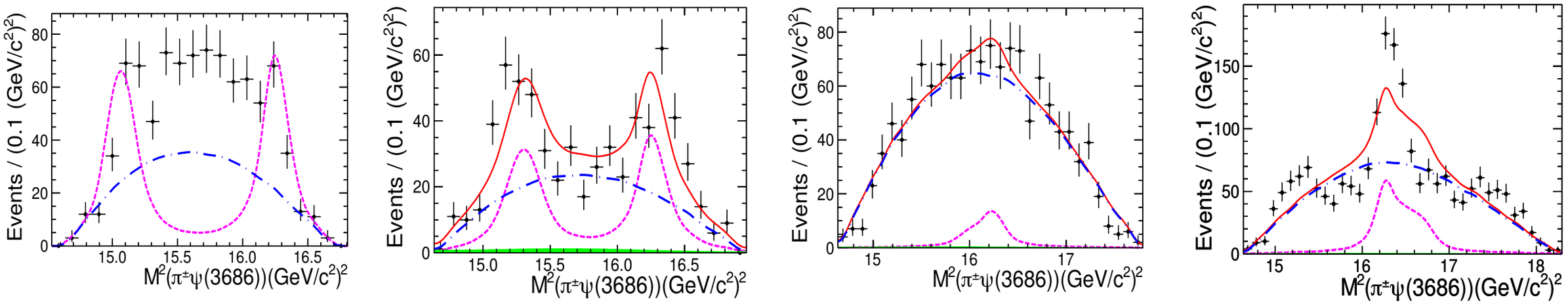
(using 827 pb^{-1} at 4.26 GeV)

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

(4) The **Z** Question

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

[PRD 96, 032004 (2017)]



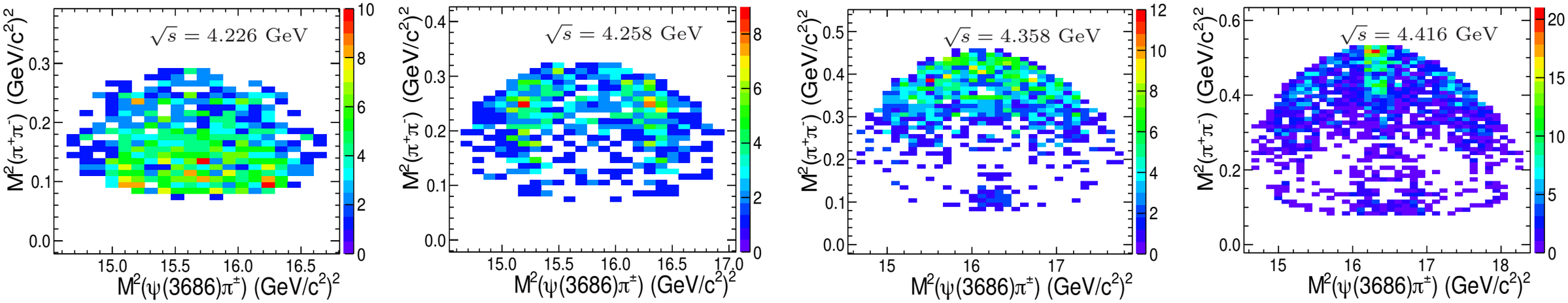
(1092 pb⁻¹ at 4.23 GeV; 826 pb⁻¹ at 4.26 GeV; 540 pb⁻¹ at 4.36 GeV; 1074 pb⁻¹ at 4.42 GeV)

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

(4) The **Z** Question

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

[PRD 96, 032004 (2017)]



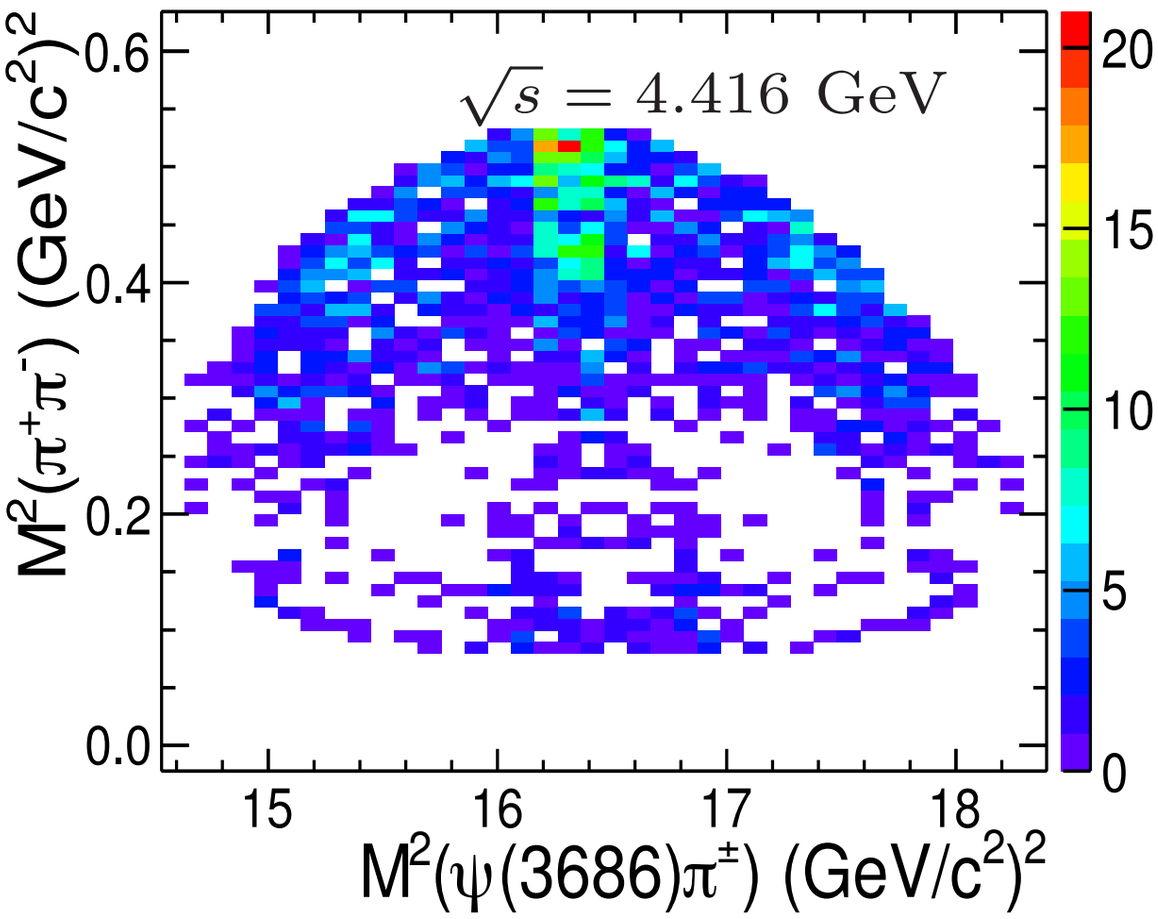
(1092 pb^{-1} at 4.23 GeV; 826 pb^{-1} at 4.26 GeV; 540 pb^{-1} at 4.36 GeV; 1074 pb^{-1} at 4.42 GeV)

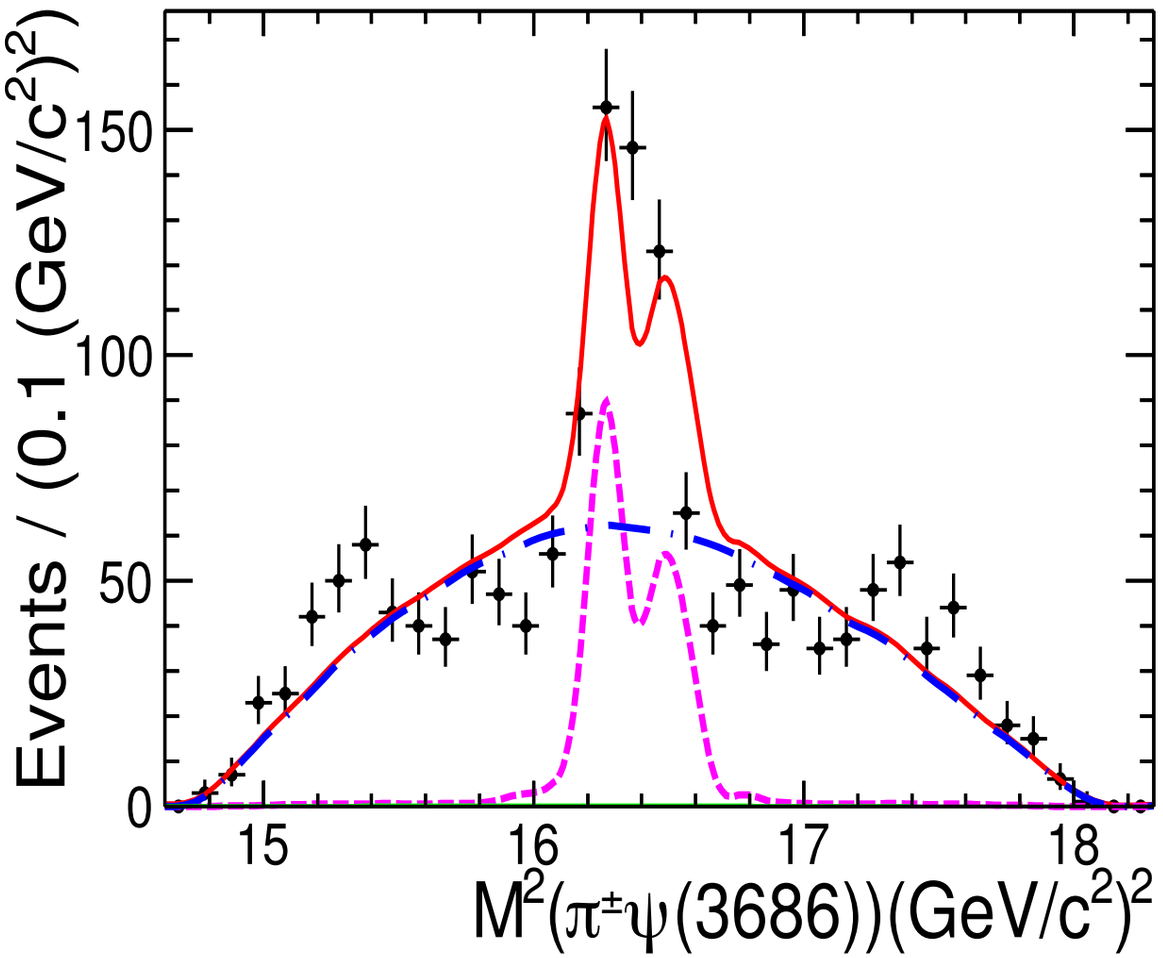
$$M = (4032.1 \pm 2.4)\ \mathrm{MeV}/c^2;$$
$$\Gamma = (26.1 \pm 5.3)\ \mathrm{MeV}/c^2$$

(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$/c^2$

Spectroscopy at BESIII:

BESIII Data Sets and Physics Reach

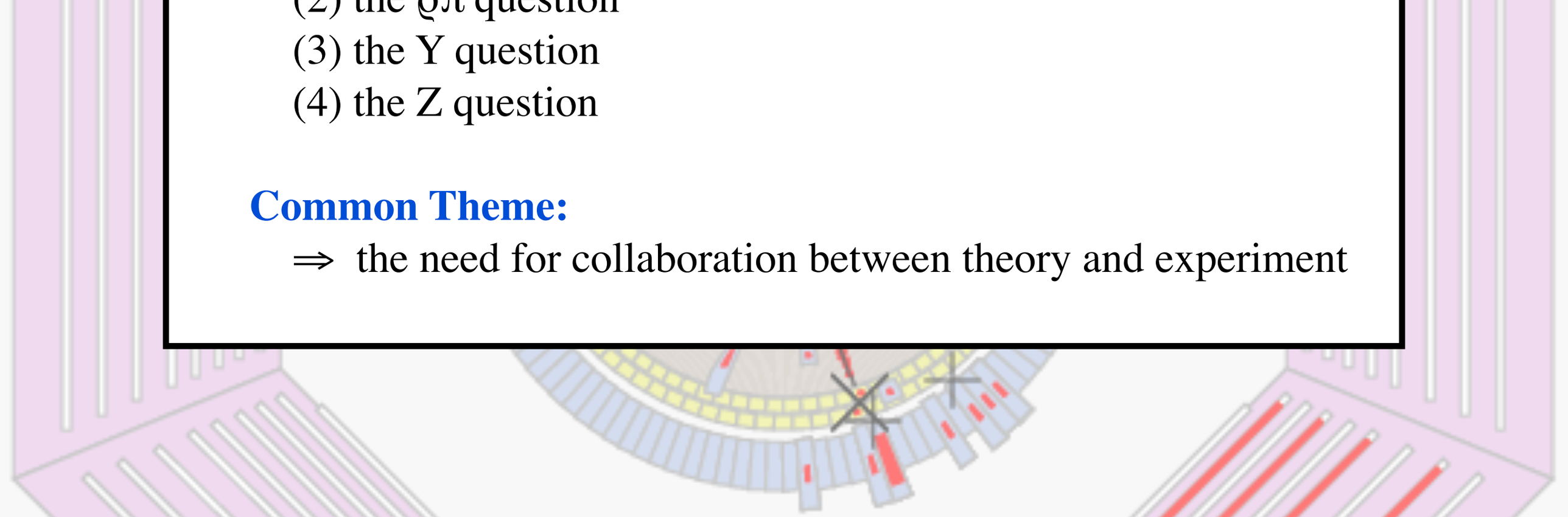
Examples of Precision Spectroscopy

Examples of Open Questions in Spectroscopy:

(1) the proton antiproton question
(2) the $\varrho\pi$ question
(3) the Y question
(4) the Z question

Common Theme:

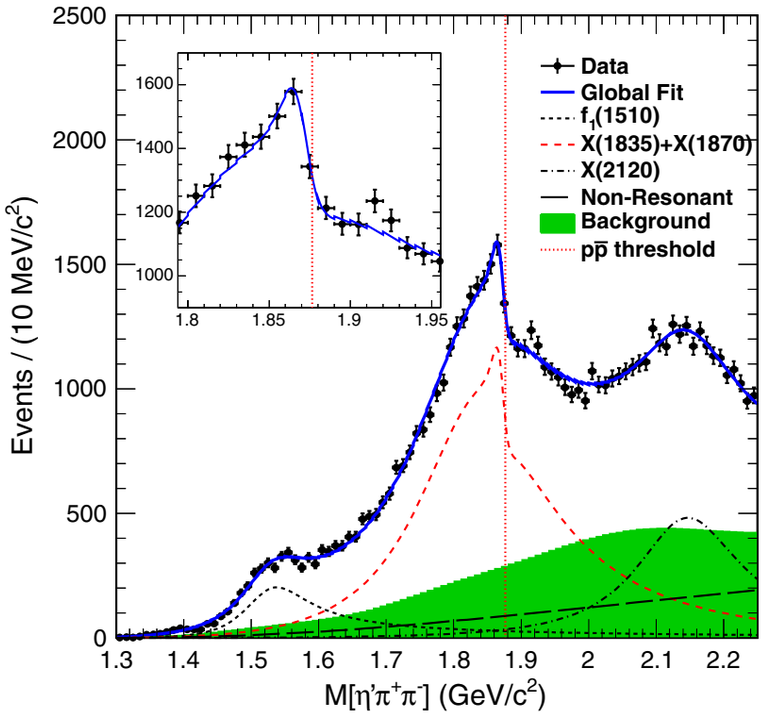
$\Rightarrow$ the need for collaboration between theory and experiment



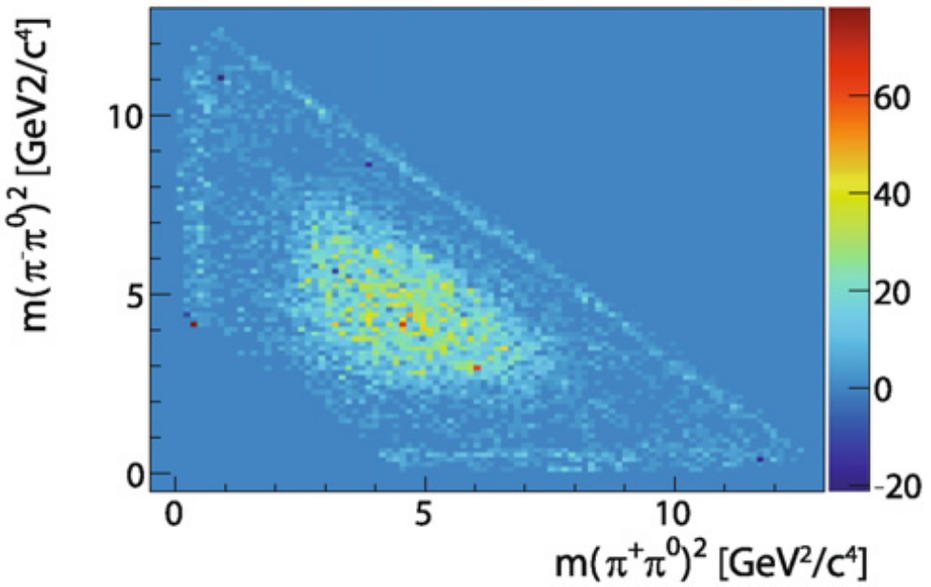
$e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$

Progress is Limited (in many cases) by Theory and Methodology

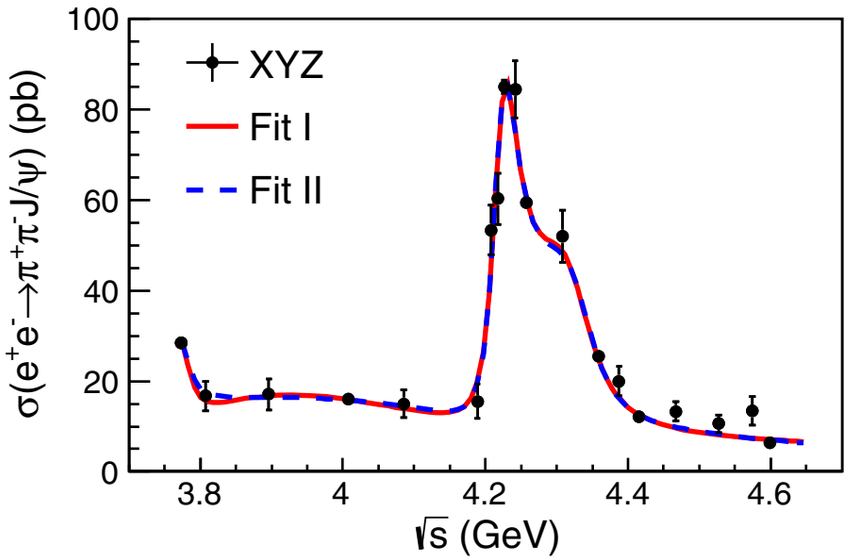
(1) The proton antiproton Question



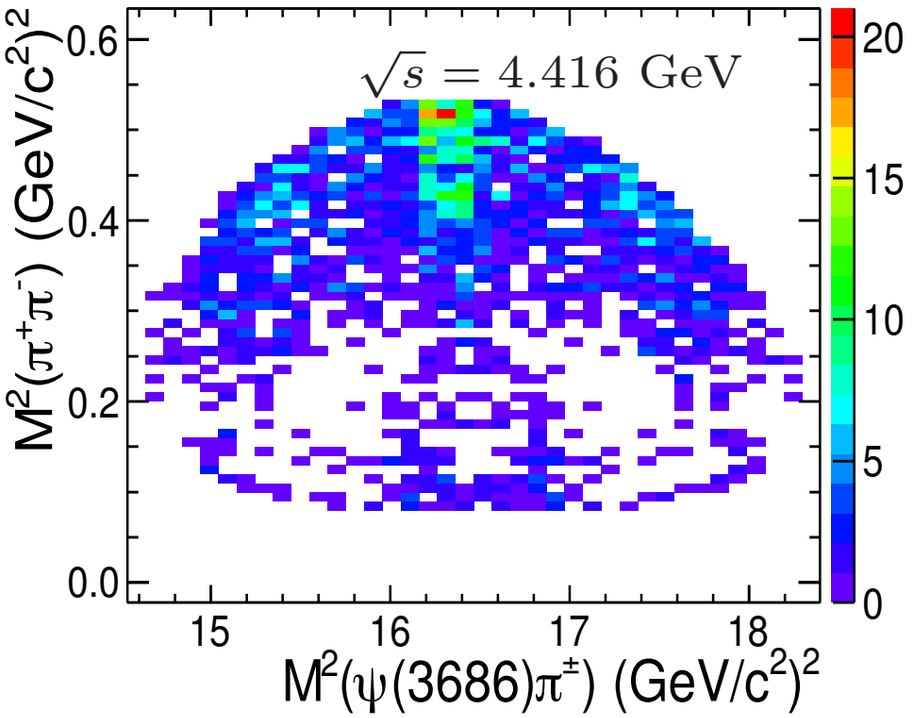
(2) The ϱπ Question



(3) The Y Question



(4) The Z Question



Spectroscopy at BESIII:

BESIII Data Sets and Physics Reach

Examples of Precision Spectroscopy

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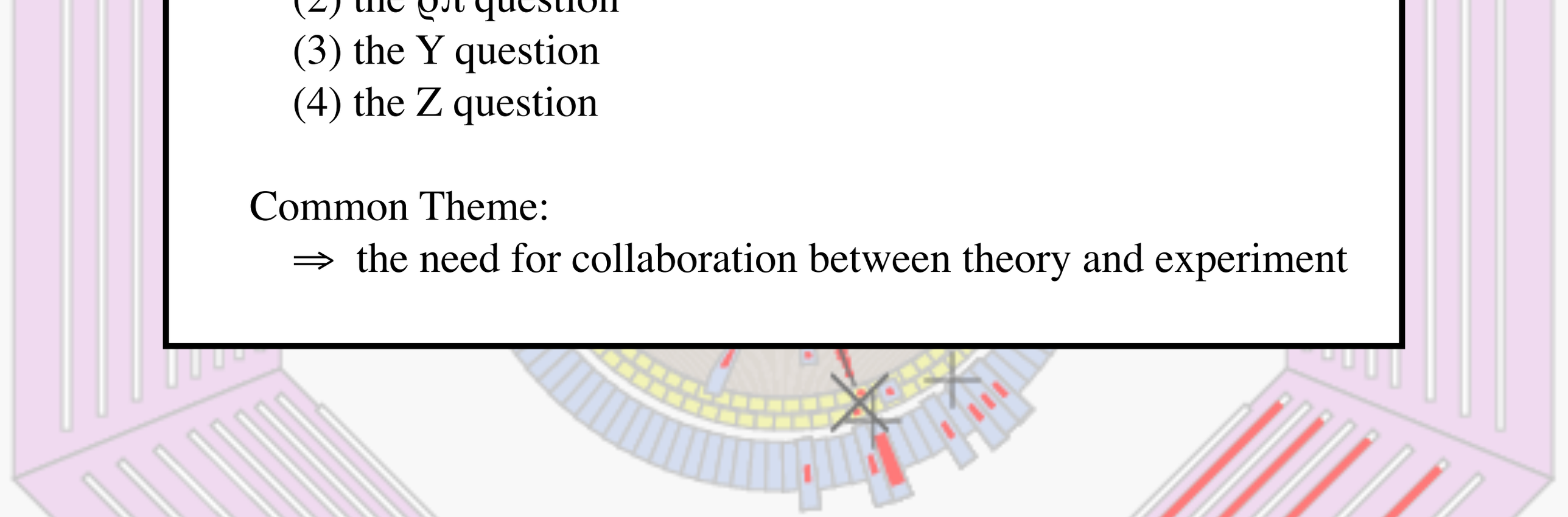

$e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$

Spectroscopy at BESIII:

BESIII Data Sets and Physics Reach

Examples of Precision Spectroscopy

Examples of Open Questions in Spectroscopy:

(1) the proton antiproton question
(2) the $\varrho\pi$ question
(3) the Y question
(4) the Z question

Conclusions:

$\Rightarrow$ There is much still to learn about spectroscopy at BESIII.

$\Rightarrow$ Spectroscopy is in an era where experiment-theory collaboration is crucial.

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