The BESIII Experiment: Results and Prospects

Ryan Mitchell
Indiana University
Workshop on Double-Charm Tetraquarks
November 22, 2021

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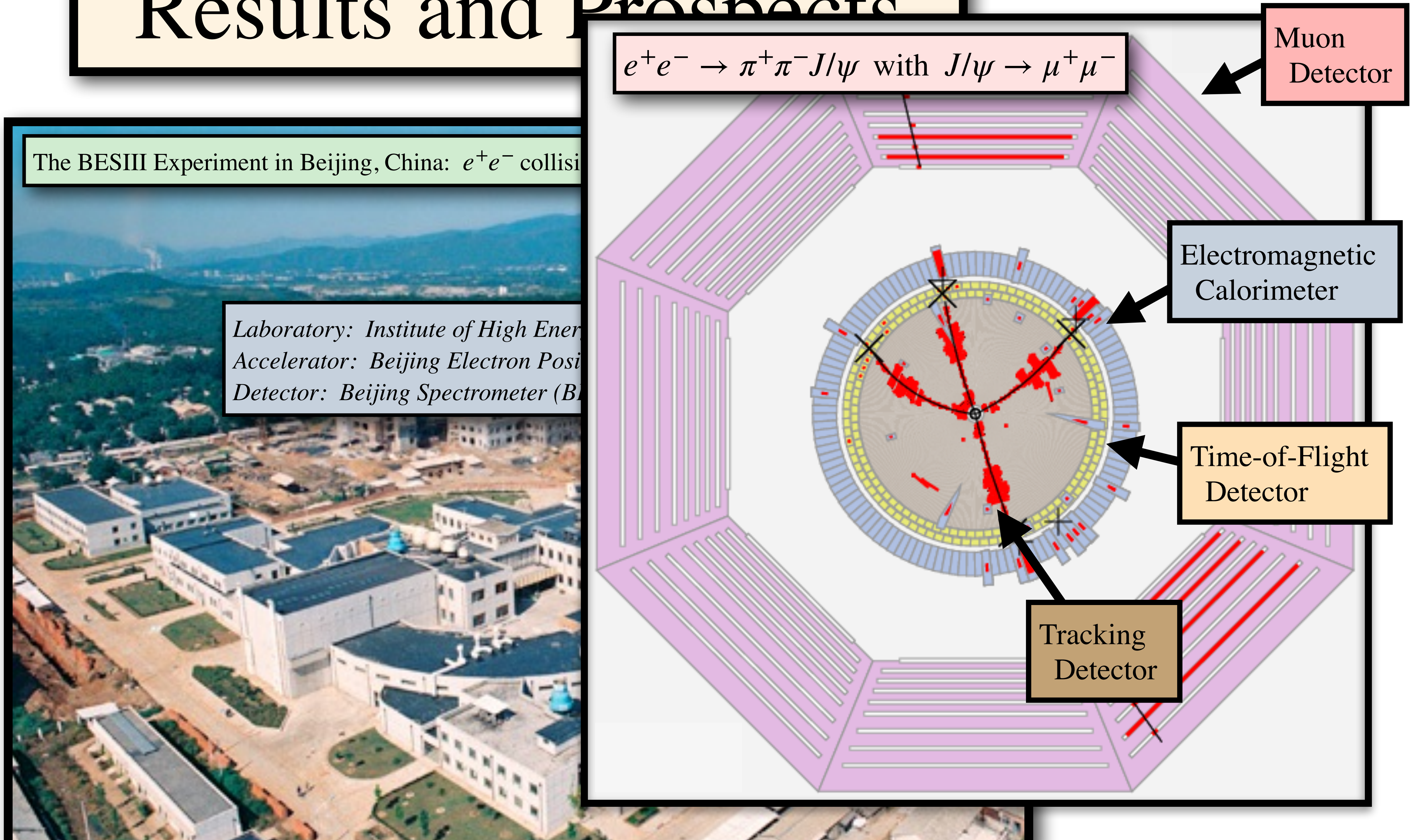

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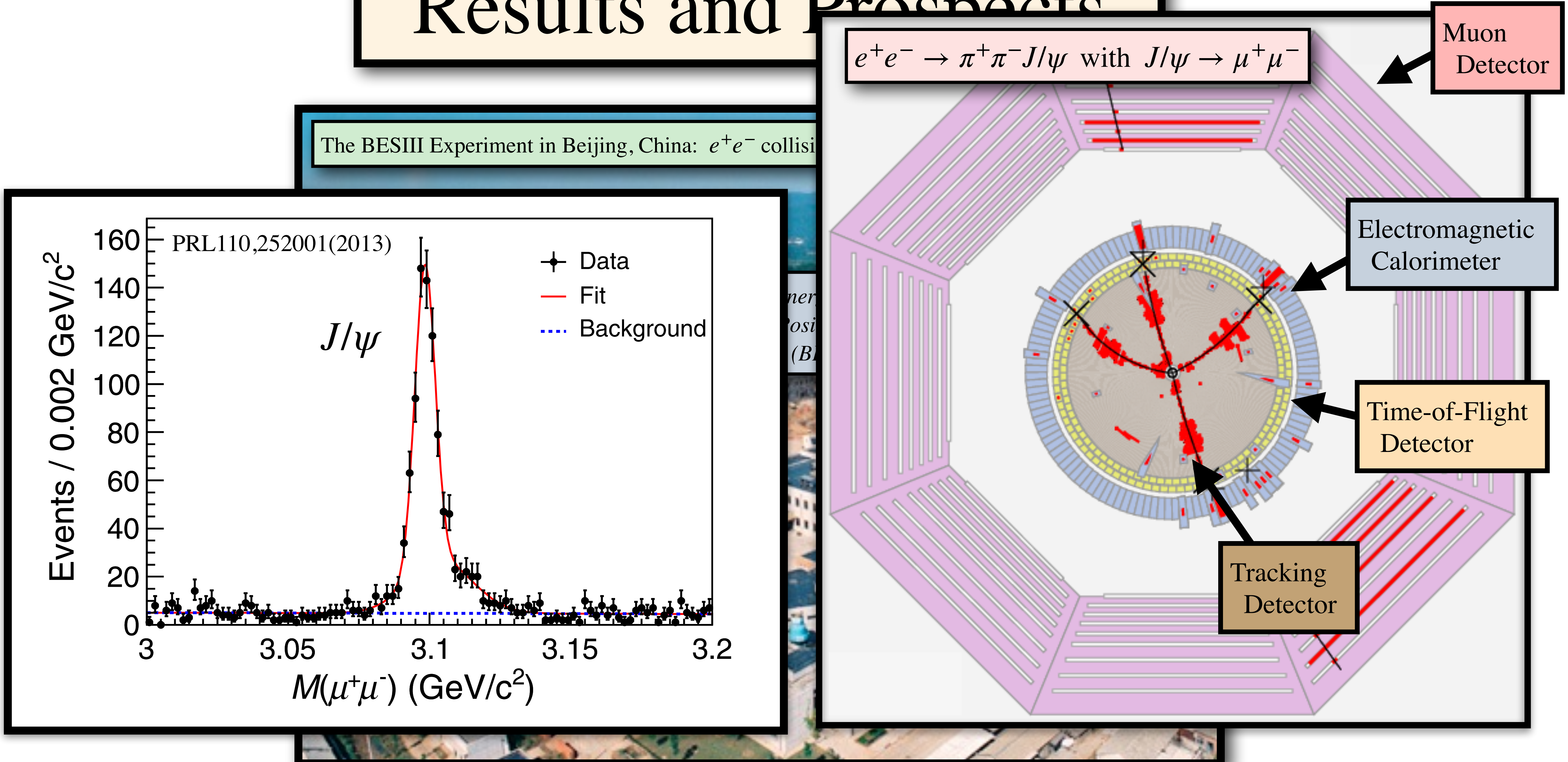

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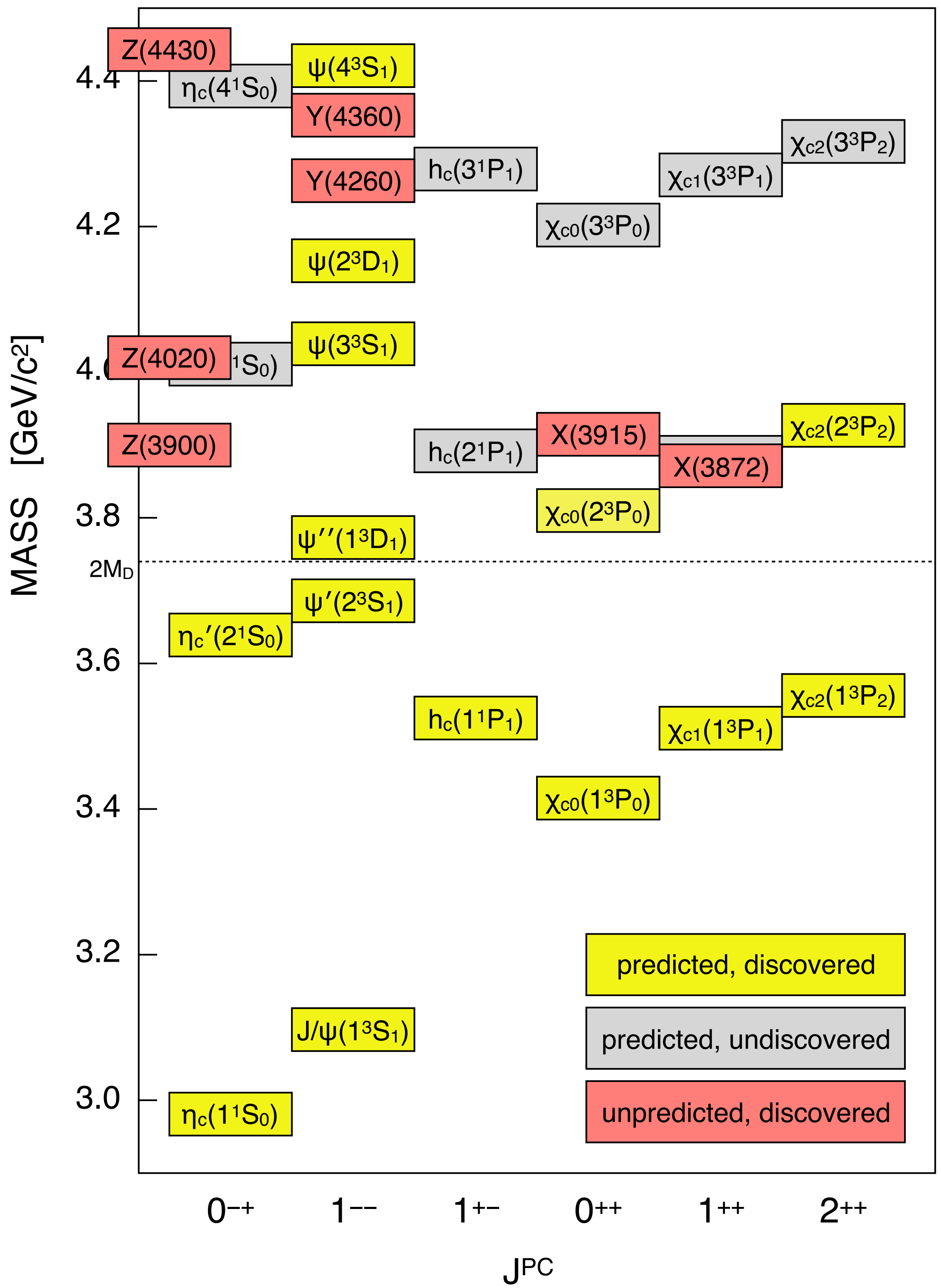
Physics at BESIII

Charmonium Spectrum

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



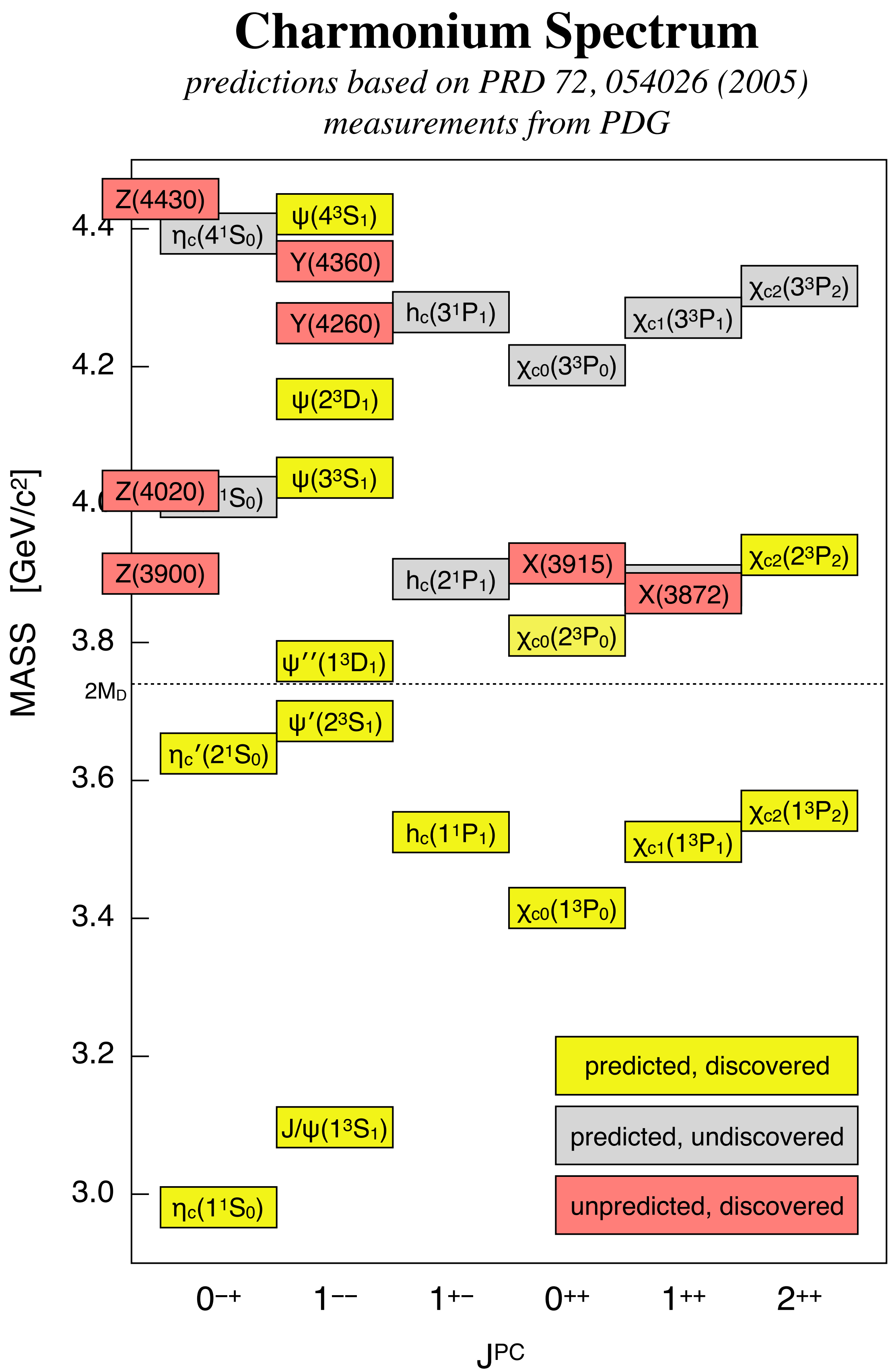
BESIII Data Sets (primary):

(e^+e^- collisions at E_{CM} between 2.0 and 4.95 GeV)

2009: 106M $\psi(2S)$
225M J/ψ
2010: 975 pb^{-1} at $\psi(3770)$
2011: 2.9 fb^{-1} *(total)* at $\psi(3770)$
482 pb^{-1} at 4.01 GeV
2012: 0.45B *(total)* $\psi(2S)$
1.3B *(total)* J/ψ
2013: 1092 pb^{-1} at 4.23 GeV
826 pb^{-1} at 4.26 GeV
540 pb^{-1} at 4.36 GeV
10×50 pb^{-1} scan 3.81 — 4.42 GeV
2014: 1029 pb^{-1} at 4.42 GeV
110 pb^{-1} at 4.47 GeV, 4.53 GeV
567 pb^{-1} at 4.6 GeV
0.8 fb^{-1} R-scan 3.85 — 4.59 GeV
2015: R-scan 2 — 3 GeV + 2.175 GeV
2016: ~3fb^{-1} at 4.18 GeV (for D_s)
2017: 7×500 pb^{-1} scan 4.19 — 4.27 GeV
2018: more J/ψ *(and tuning new RF cavity)*
2019: 10B *(total)* J/ψ
8×500 pb^{-1} scan 4.13, 4.16, 4.29 — 4.44 GeV
2020: 3.8 fb^{-1} scan 4.61 — 4.70 GeV
2021: 3B (total) $\psi(2S)$
2 fb^{-1} scan 4.74 — 4.95 GeV

Many topics!
spectroscopy
(light and heavy),
flavor physics,
new physics,
R scans,
τ physics, etc.

Physics at BESIII



Primary Data for Spectroscopy:

Light Quark Spectroscopy

10 billion J/ψ

Precision Charmonium Physics

3 billion $\psi(2S)$

Charmonium (XYZ) Spectroscopy

$\geq$ 500 pb^{-1} at ~30 points
between 4.0 and 4.95 GeV

This talk:

(prelim) An example J/ψ decay.

(1) The "Y" states in $e^+e^- \to Y$.

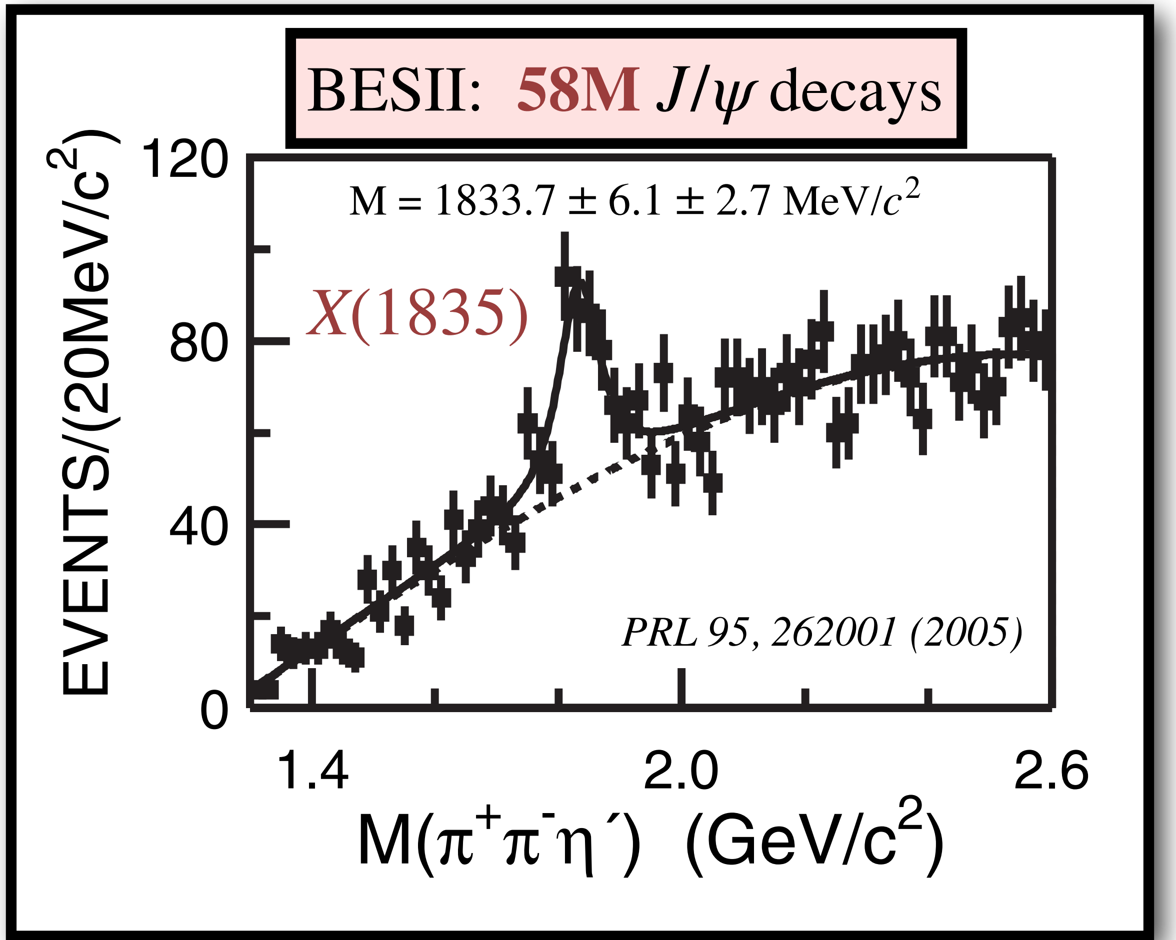
(2) The $X(3872)$ in $e^+e^- \to \gamma X(3872)$.

(3) The Z_c states in $e^+e^- \to \pi Z_c$.

(4) The Z_{cs} state in $e^+e^- \to K Z_{cs}$.

(final) Upgrade of BEPCII to BEPCII-U.

An Example from J/ψ Decays: $J/\psi \to \gamma(\eta'\pi^+\pi^-)$



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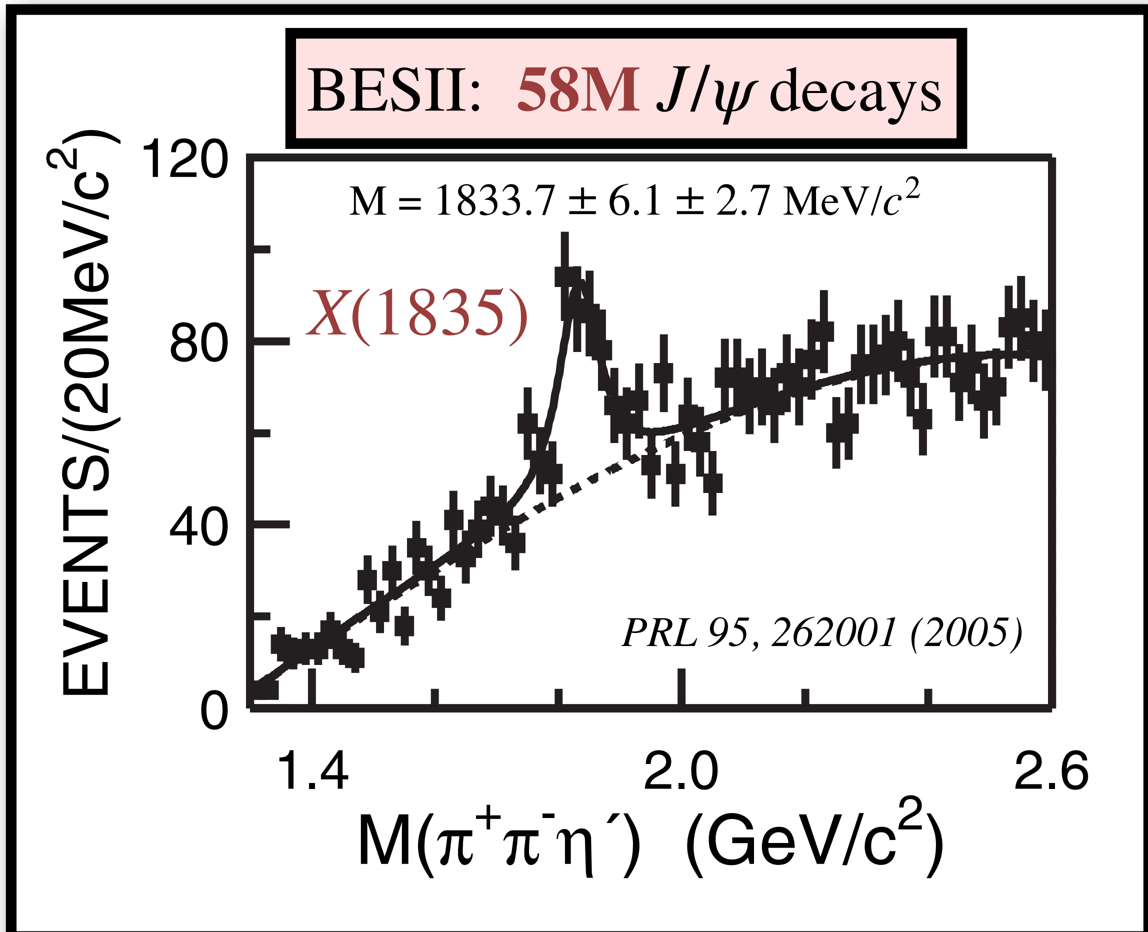

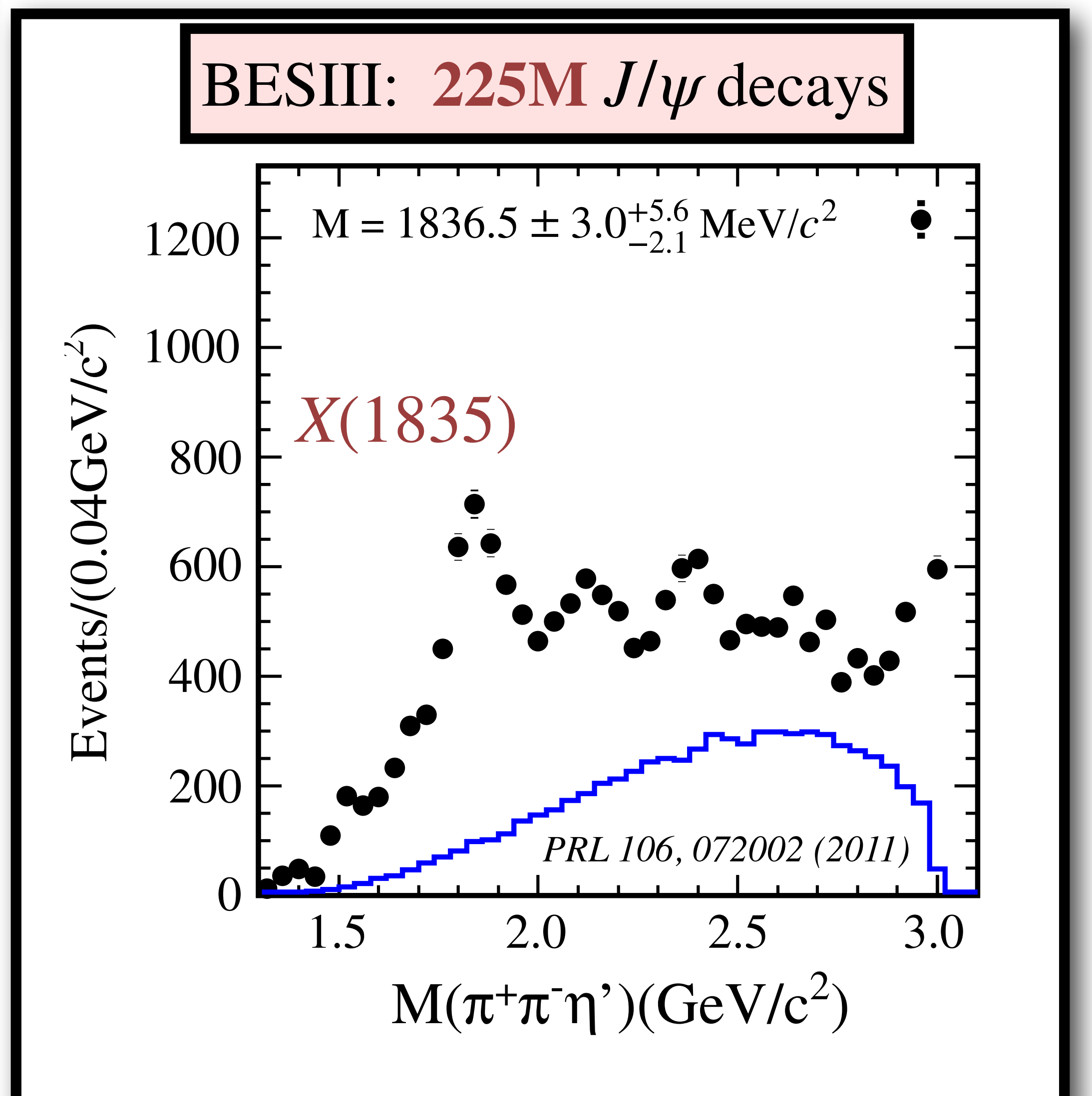

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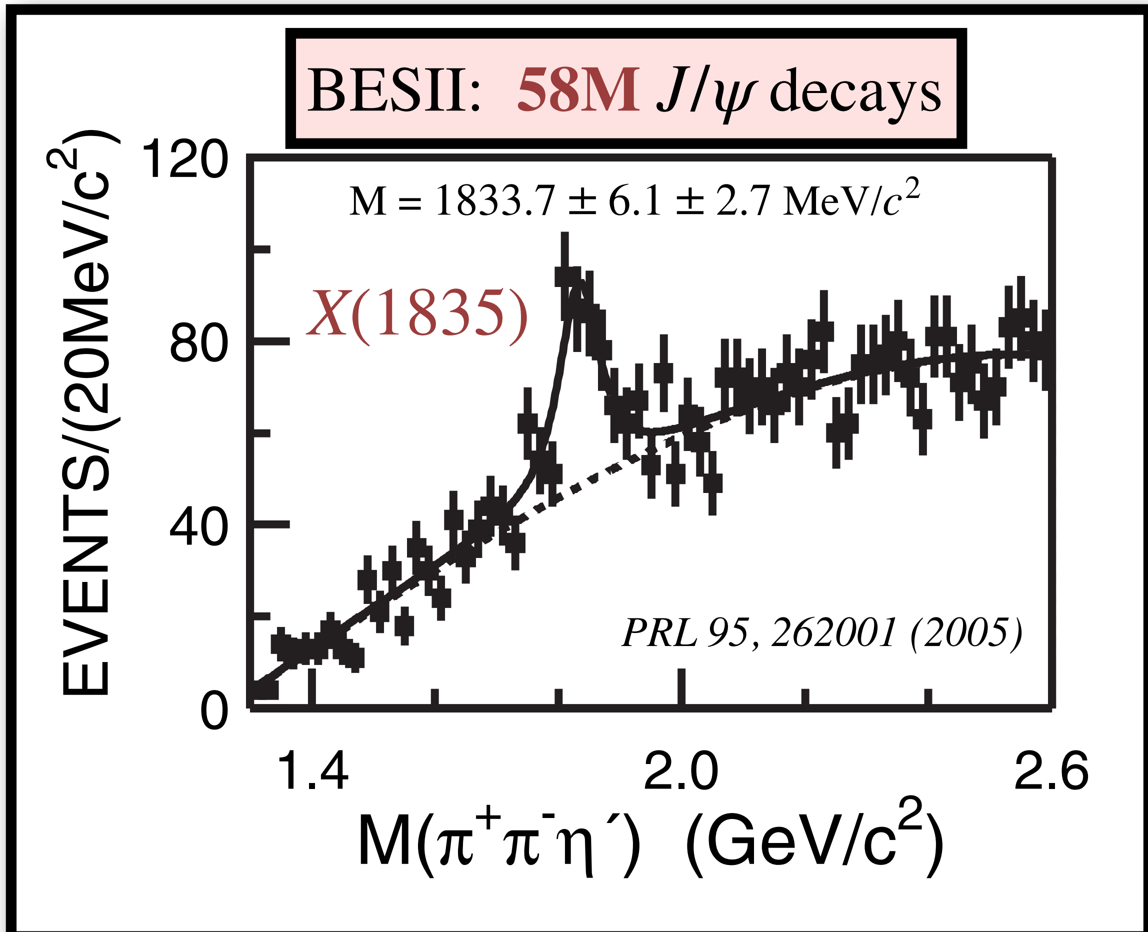

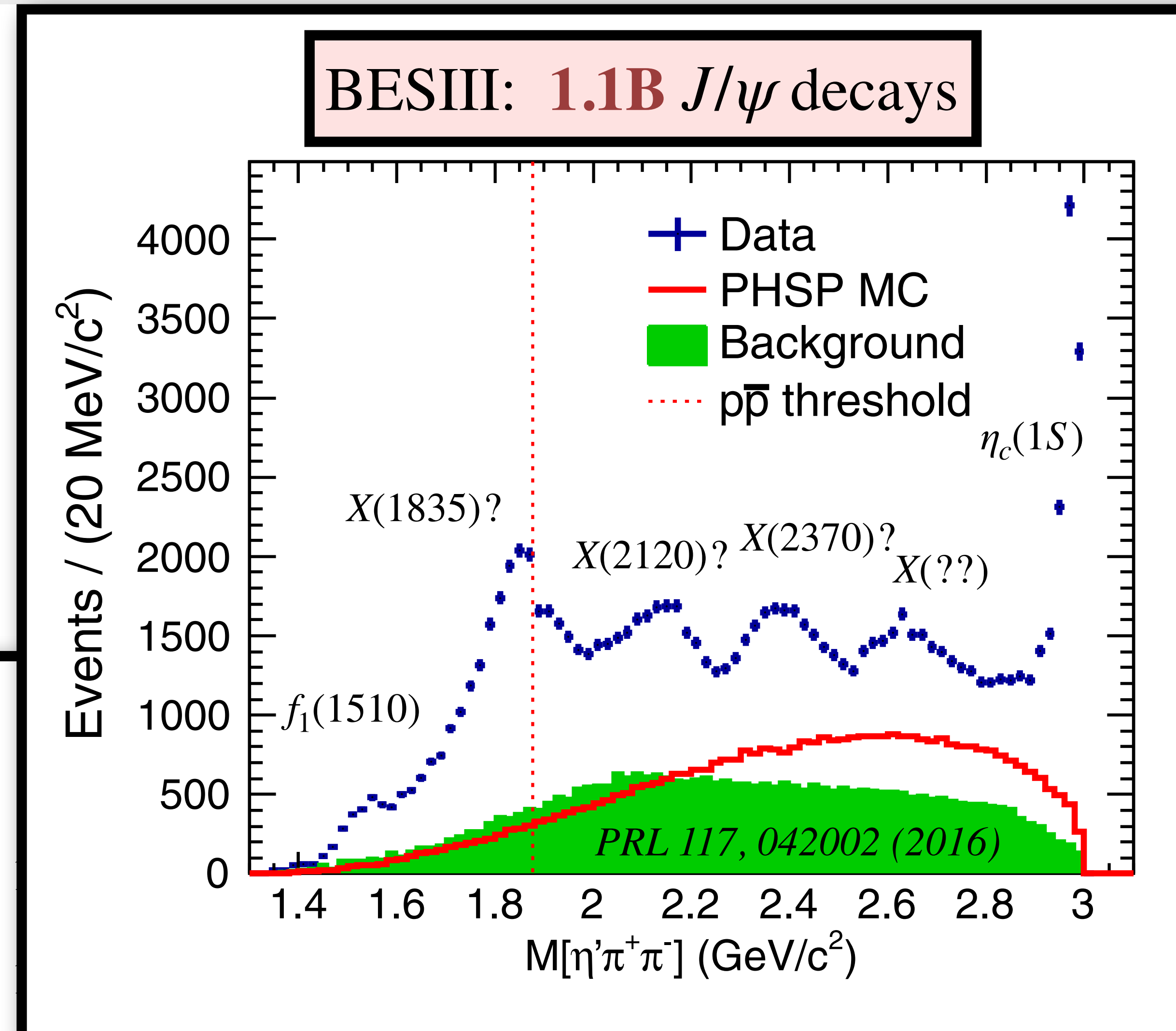

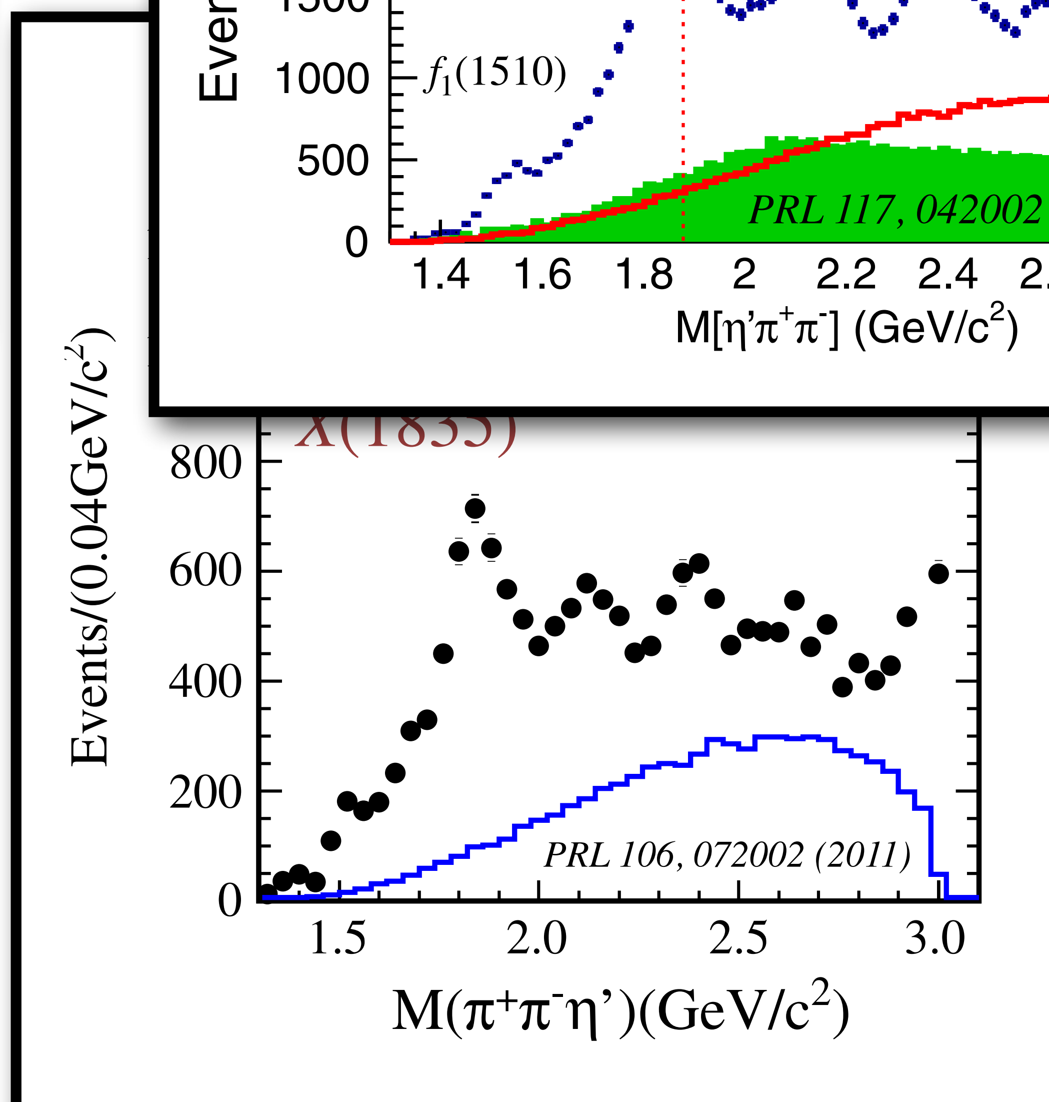

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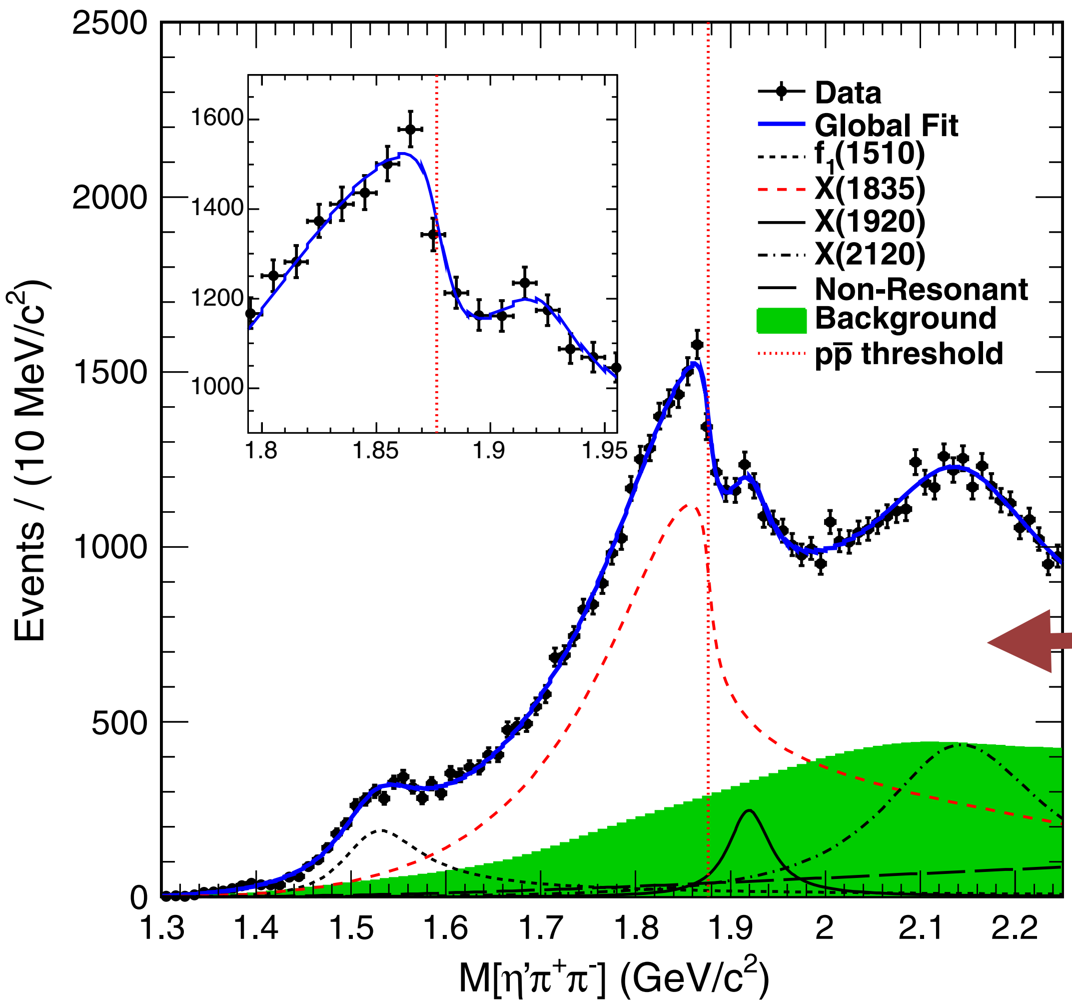
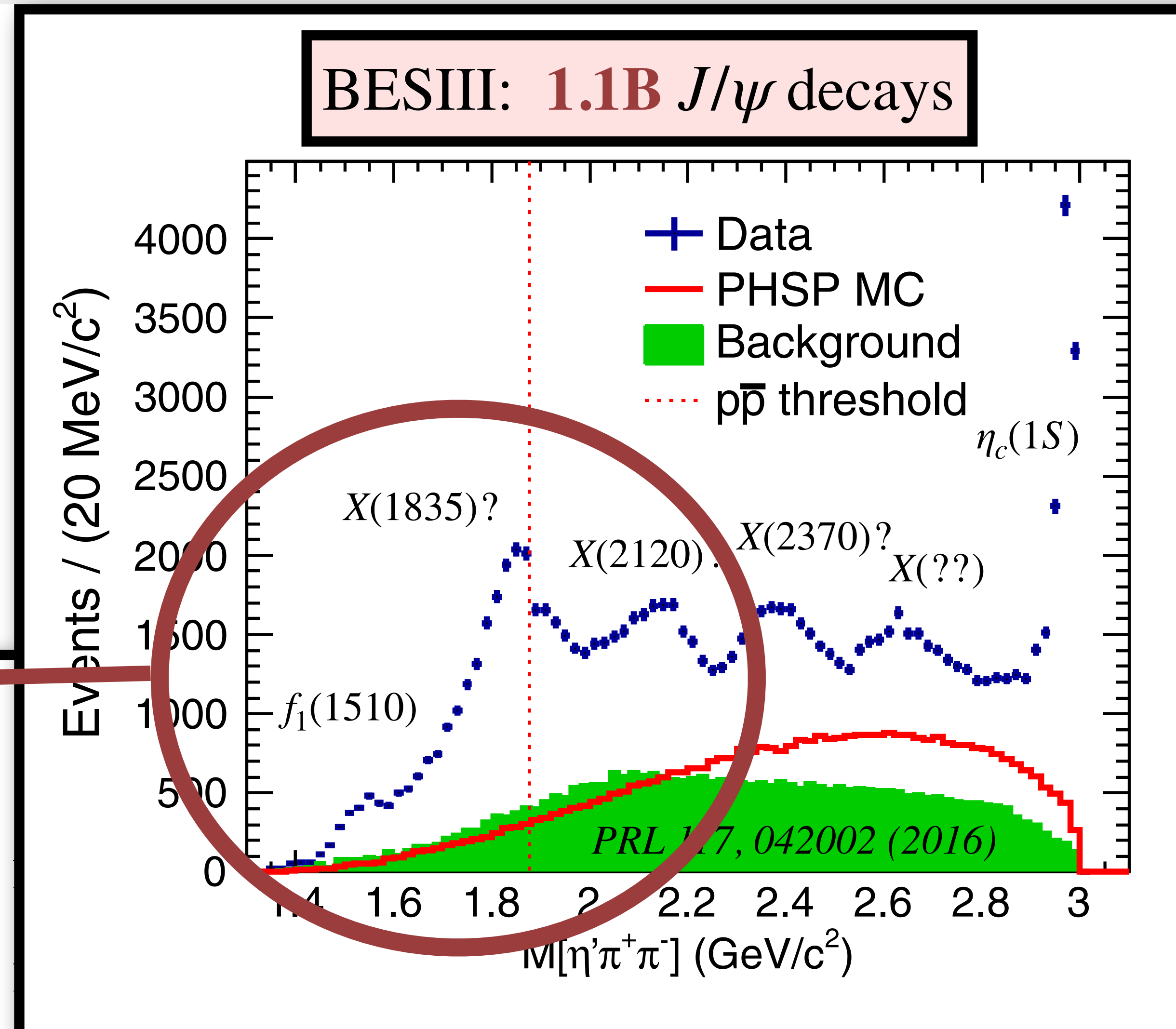
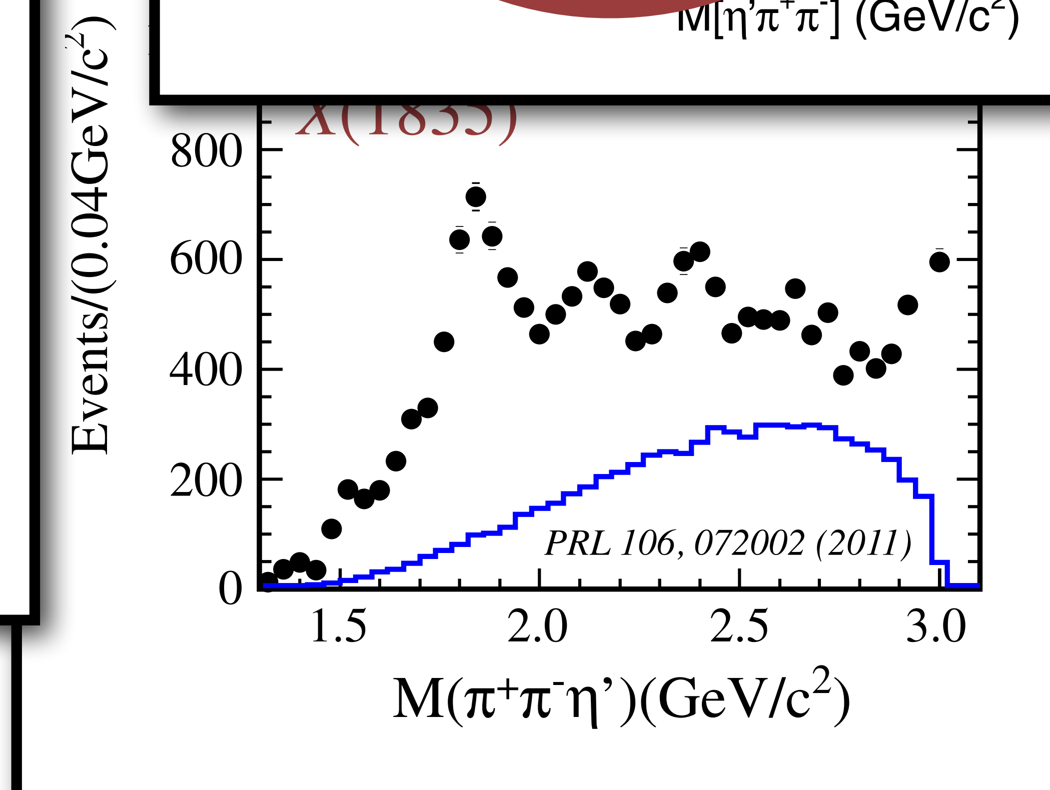
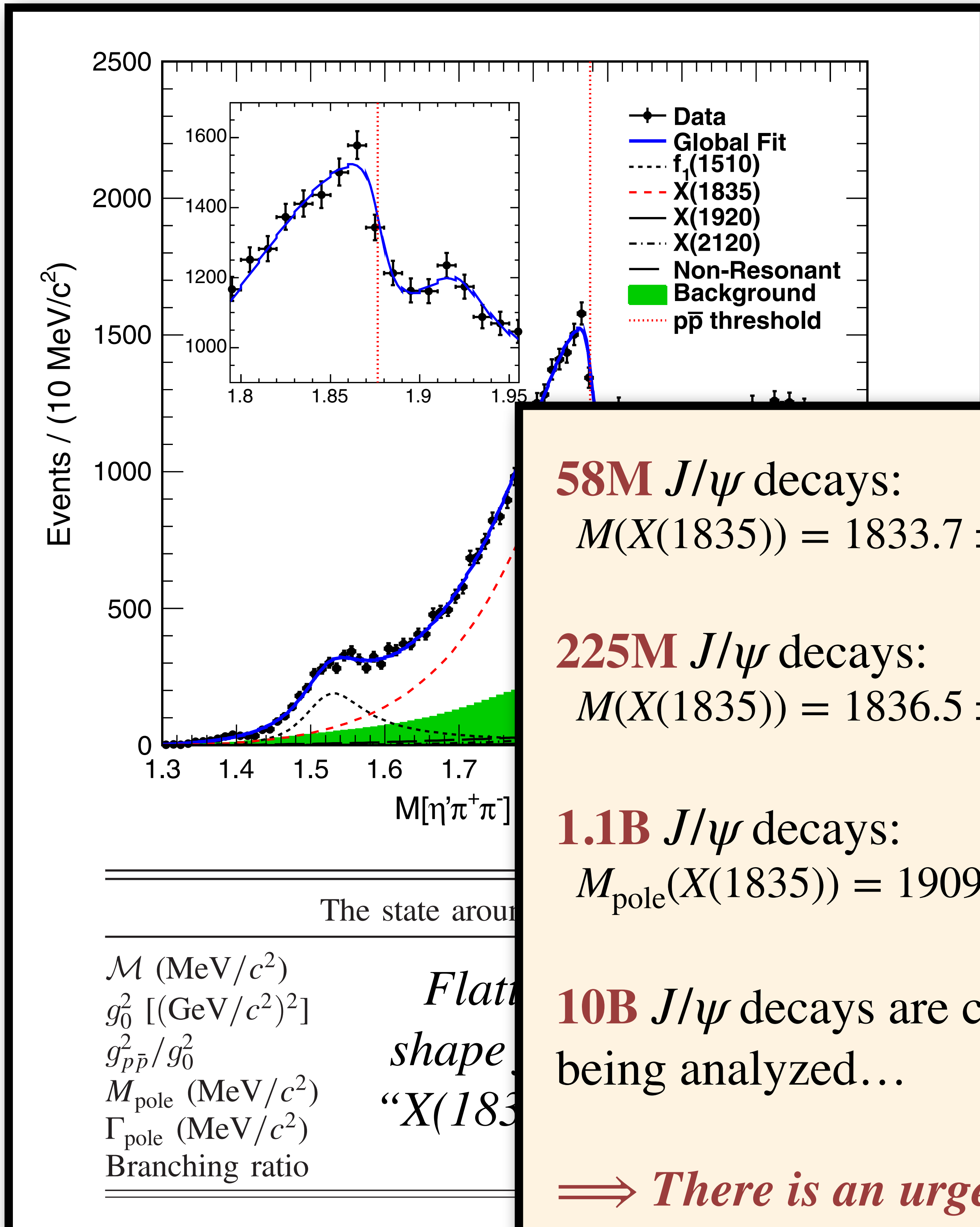


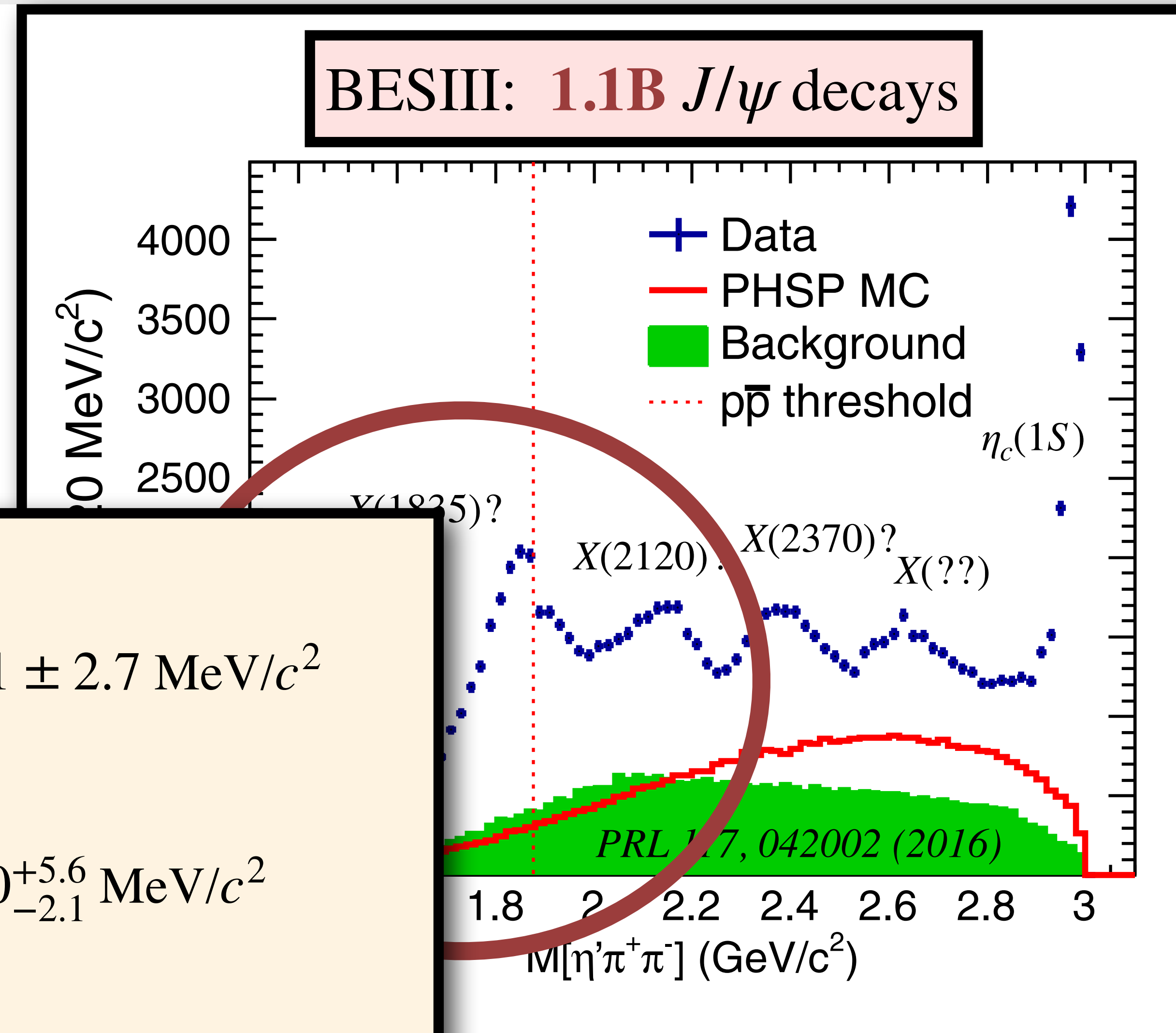
The state around 1.85 GeV/c^2		
$\mathcal{M}$ (MeV/c^2)	*Flatté*	$1638.0 \pm 121.9^{+127.8}_{-254.3}$
g_0^2 [(GeV/c^2)^2]	*shape for*	$93.7 \pm 35.4^{+47.6}_{-43.9}$
$g^2_{p\bar{p}}/g^2_0$	*"X(1835)"*	$2.31 \pm 0.37^{+0.83}_{-0.60}$
$M_{\rm pole}$ (MeV/c^2)		$1909.5 \pm 15.9^{+9.4}_{-27.5}$
$\Gamma_{\rm pole}$ (MeV/c^2)		$273.5 \pm 21.4^{+6.1}_{-64.0}$
Branching ratio		$(3.93 \pm 0.38^{+0.31}_{-0.84}) \times 10^{-4}$

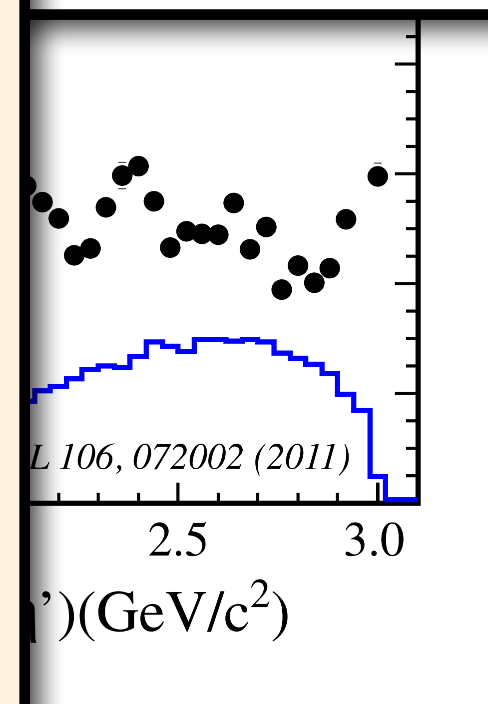




An Example from J/ψ Decays: $J/\psi \to \gamma(\eta'\pi^+\pi^-)$







58M J/ψ decays:
$M(X(1835)) = 1833.7 \pm 6.1 \pm 2.7$ MeV/c^2

225M J/ψ decays:
$M(X(1835)) = 1836.5 \pm 3.0^{+5.6}_{-2.1}$ MeV/c^2

1.1B J/ψ decays:
$M_{\rm pole}(X(1835)) = 1909.5 \pm 15.9^{+9.4}_{-27.5}$ MeV/c^2

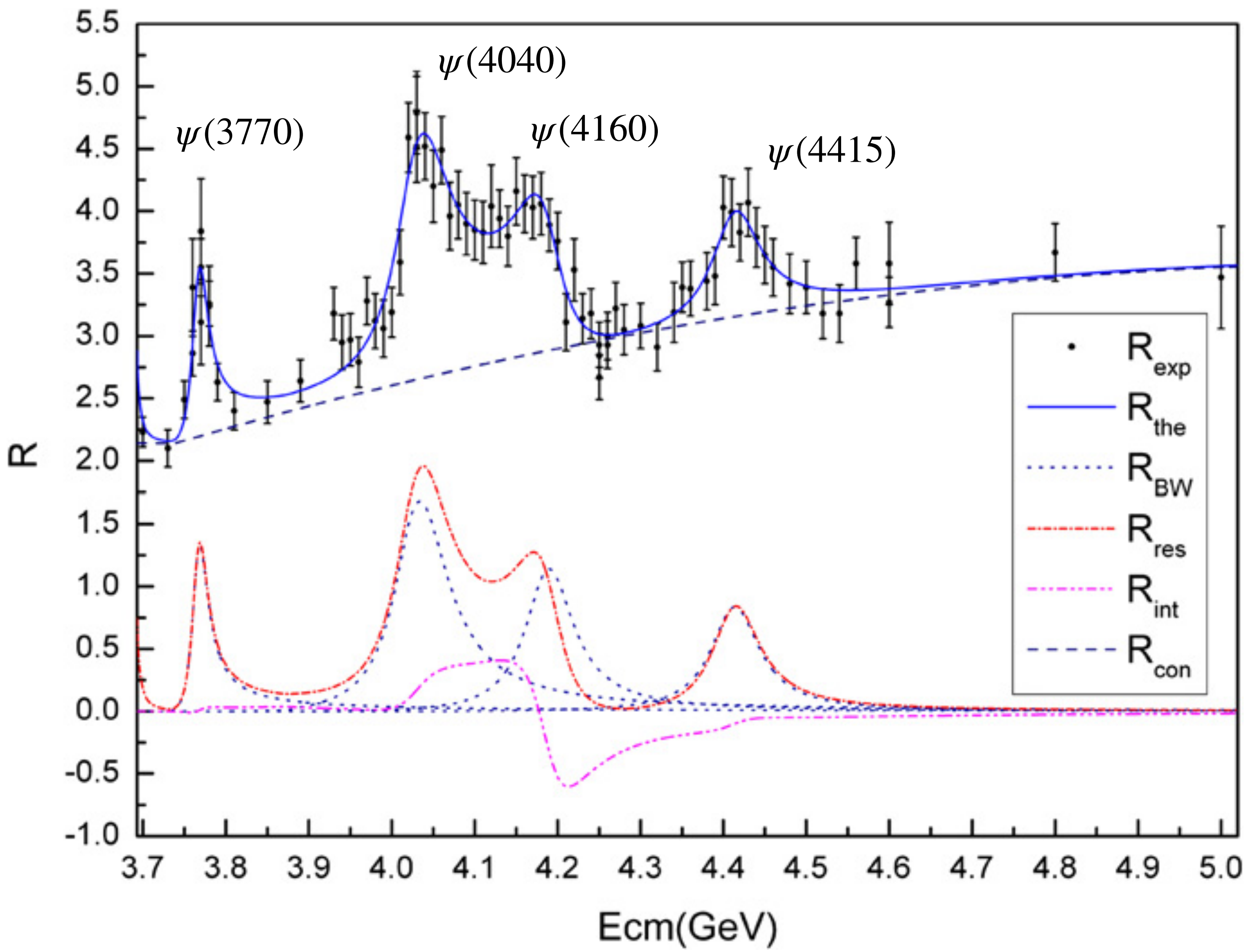
10B J/ψ decays are currently being analyzed…

$\Longrightarrow$ There is an urgent need for more rigorous methods to extract resonance properties from data.

XYZ at BESIII: (1) Start with $e^+e^- \to Y$

(really ψ, since $I^G J^{PC} = 0^- 1^{--}$)

$e^+e^- \to$ hadrons
[BESII, PLB 660, 315 (2008)]



$\psi(3770) = 1^3D_1$ $\qquad$ $\psi(4160) = 2^3D_1$

$\psi(4040) = 3^3S_1$ $\qquad$ $\psi(4415) = 4^3S_1$

XYZ at BESIII: (1) Start with $e^+e^- \to Y$

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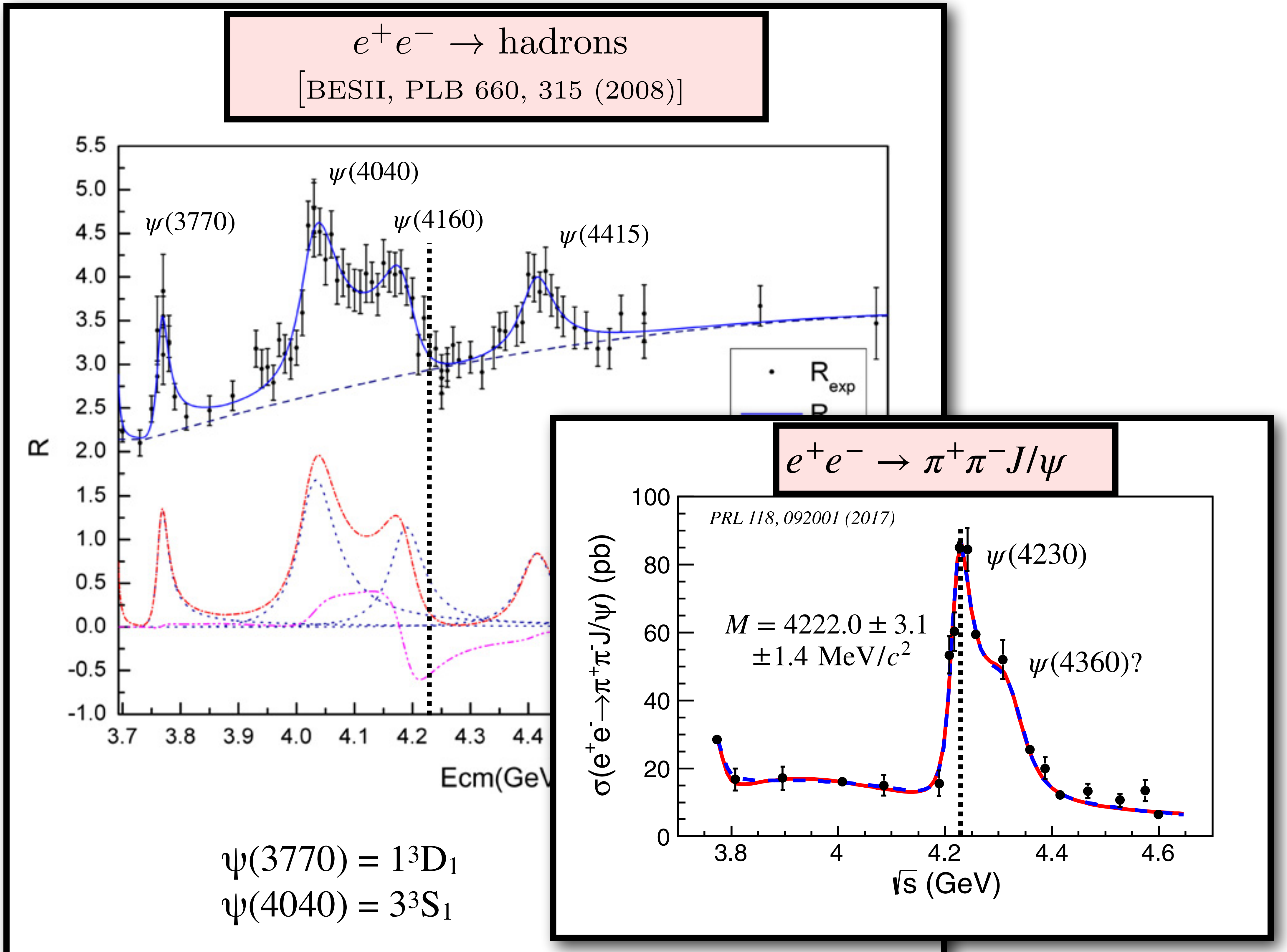
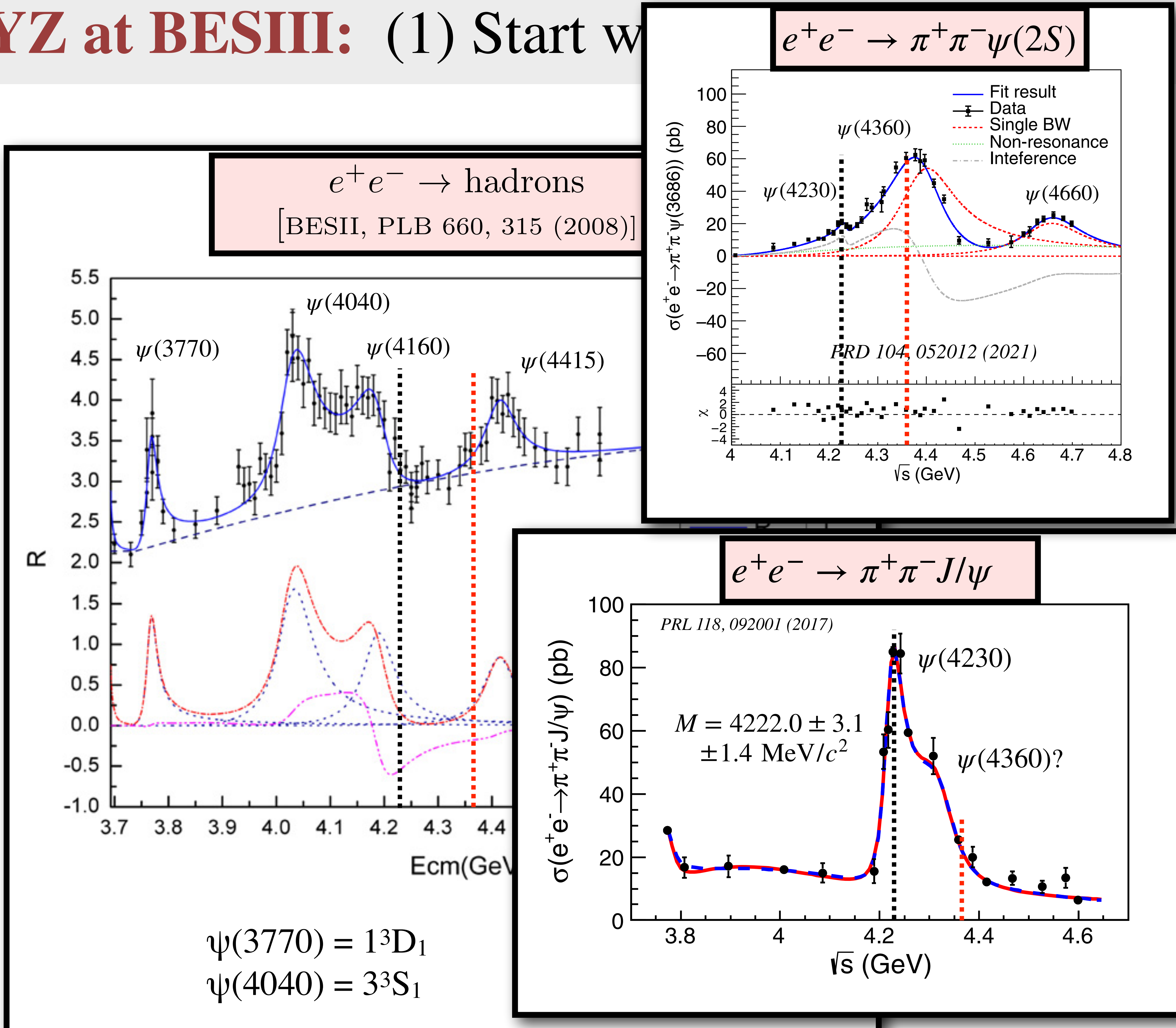


XYZ at BESIII: (1) Start w



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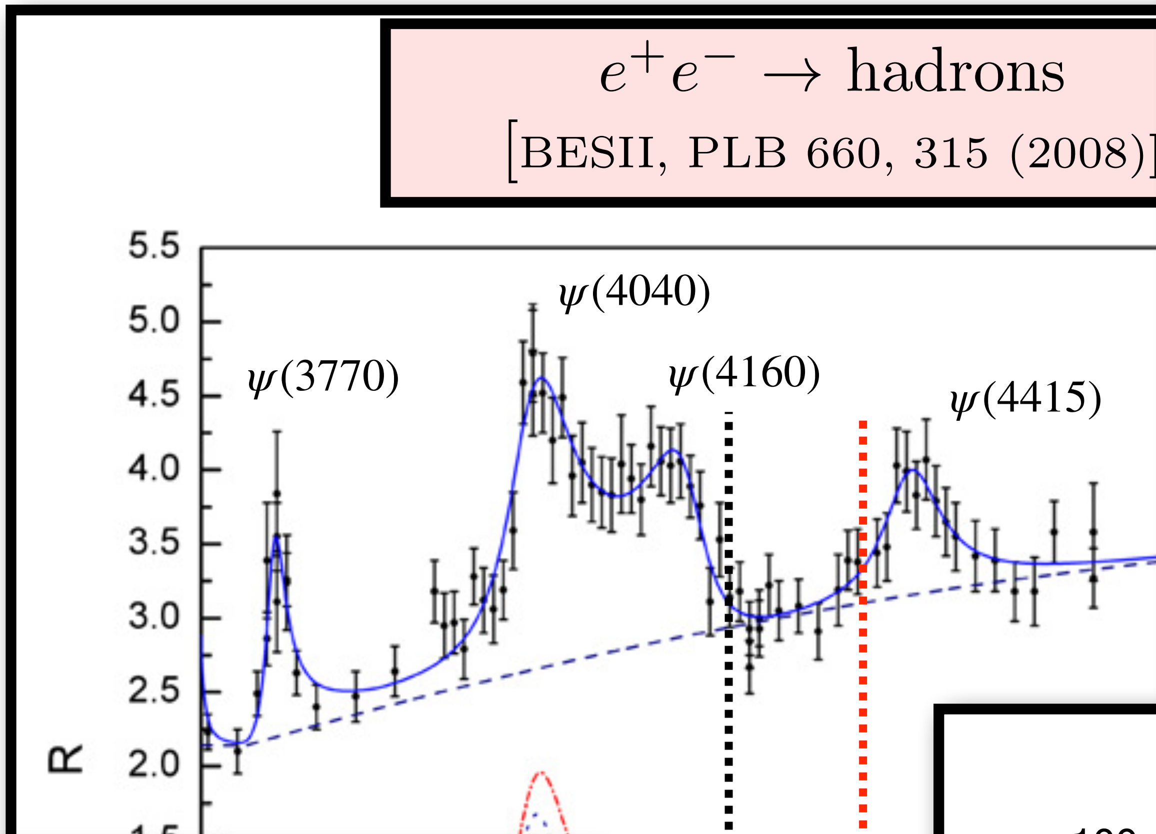

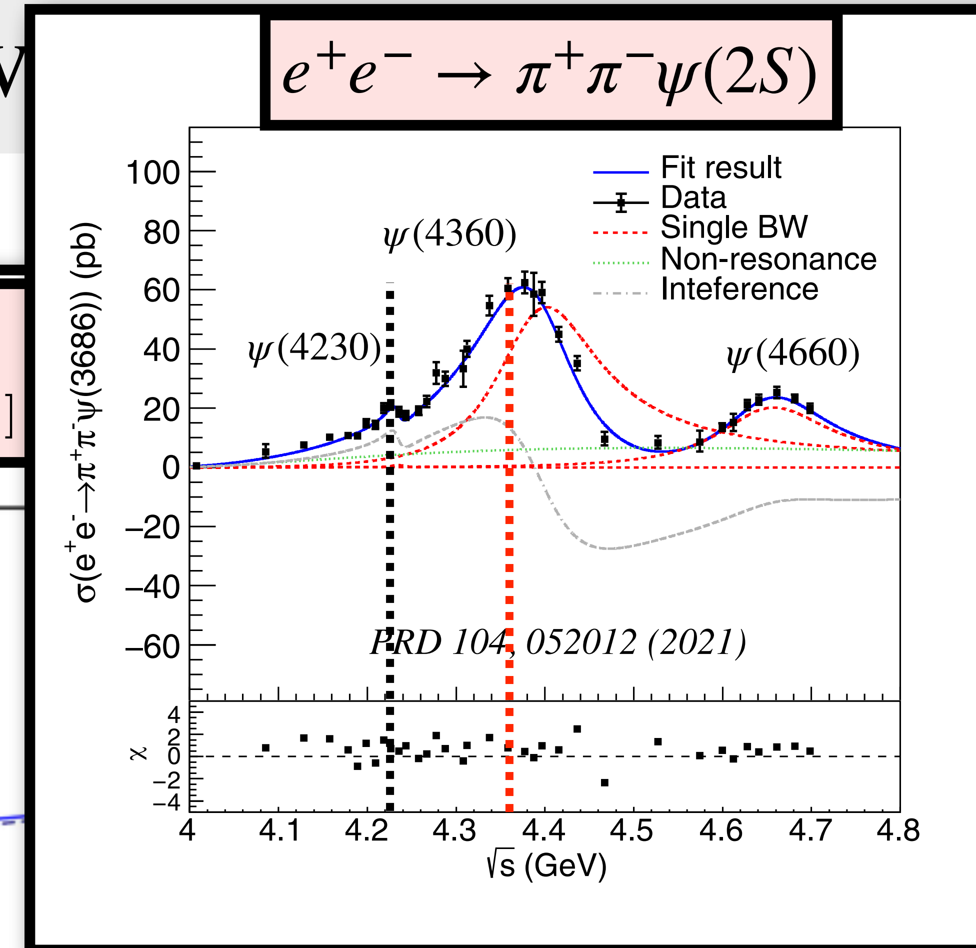

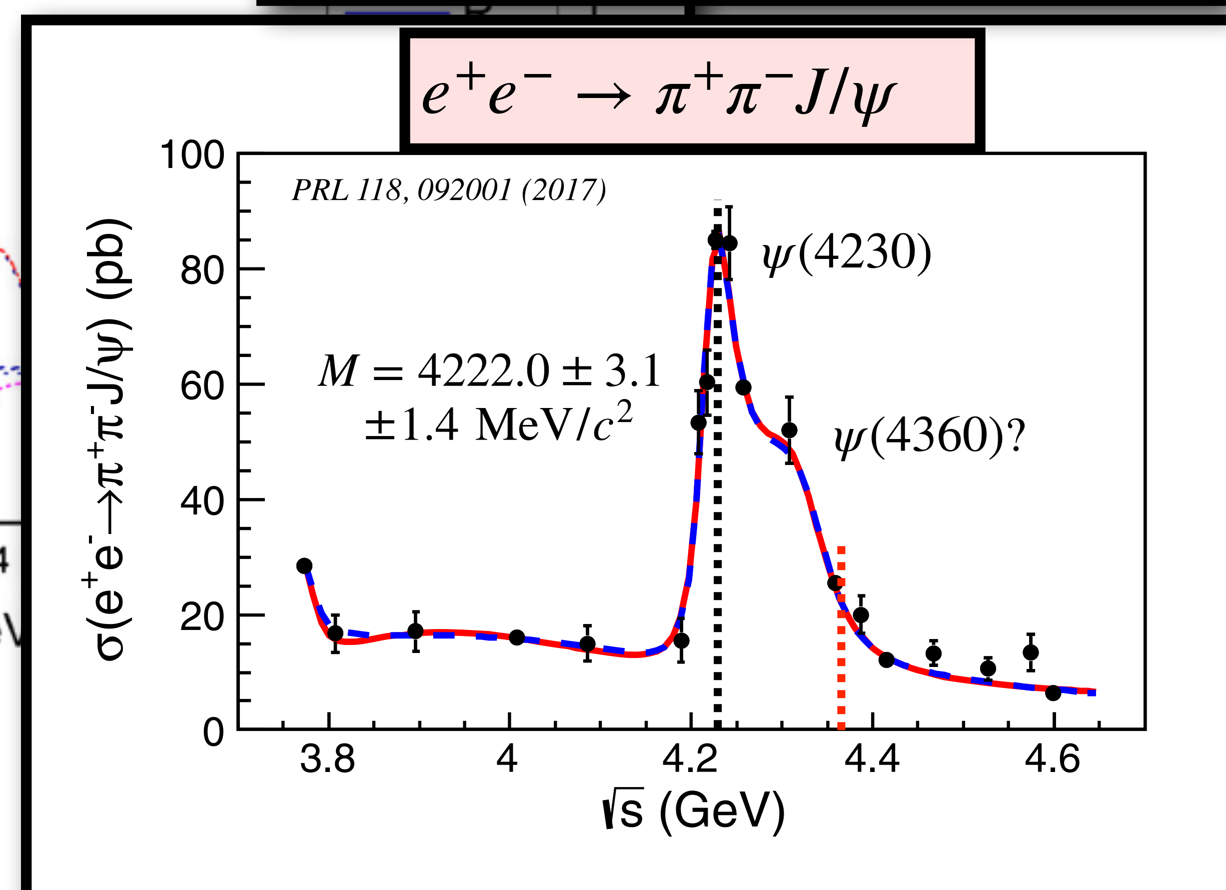

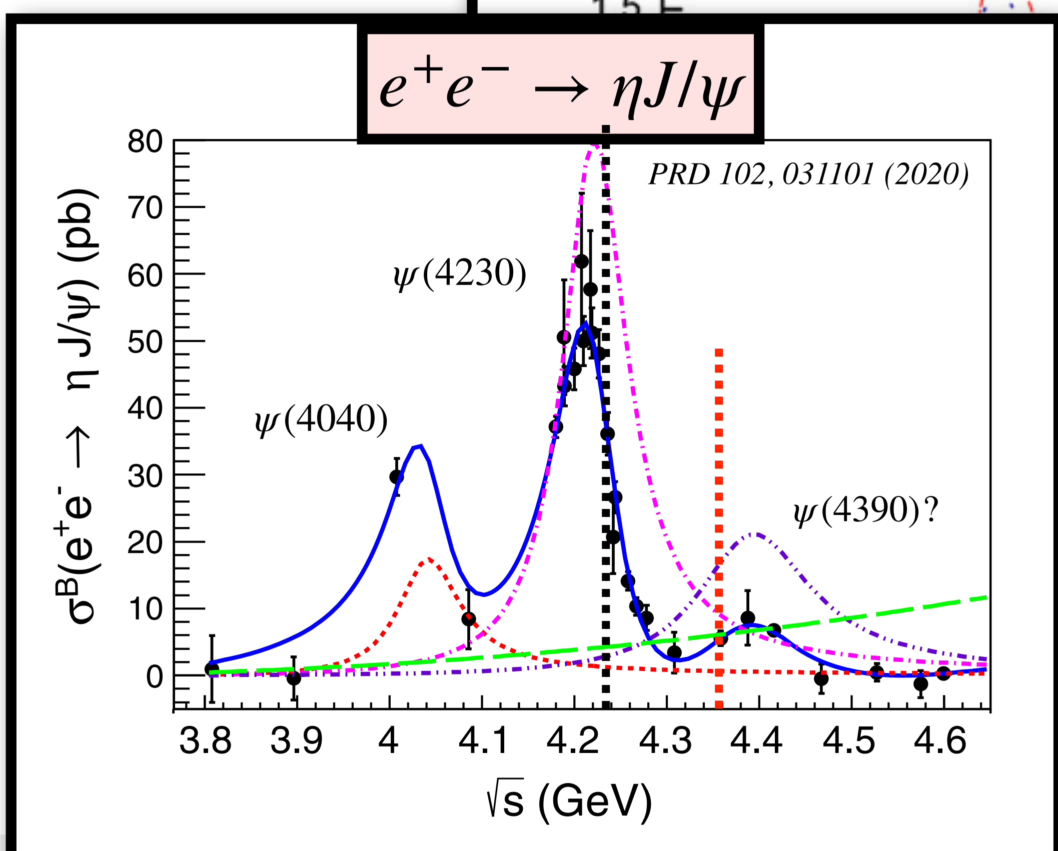

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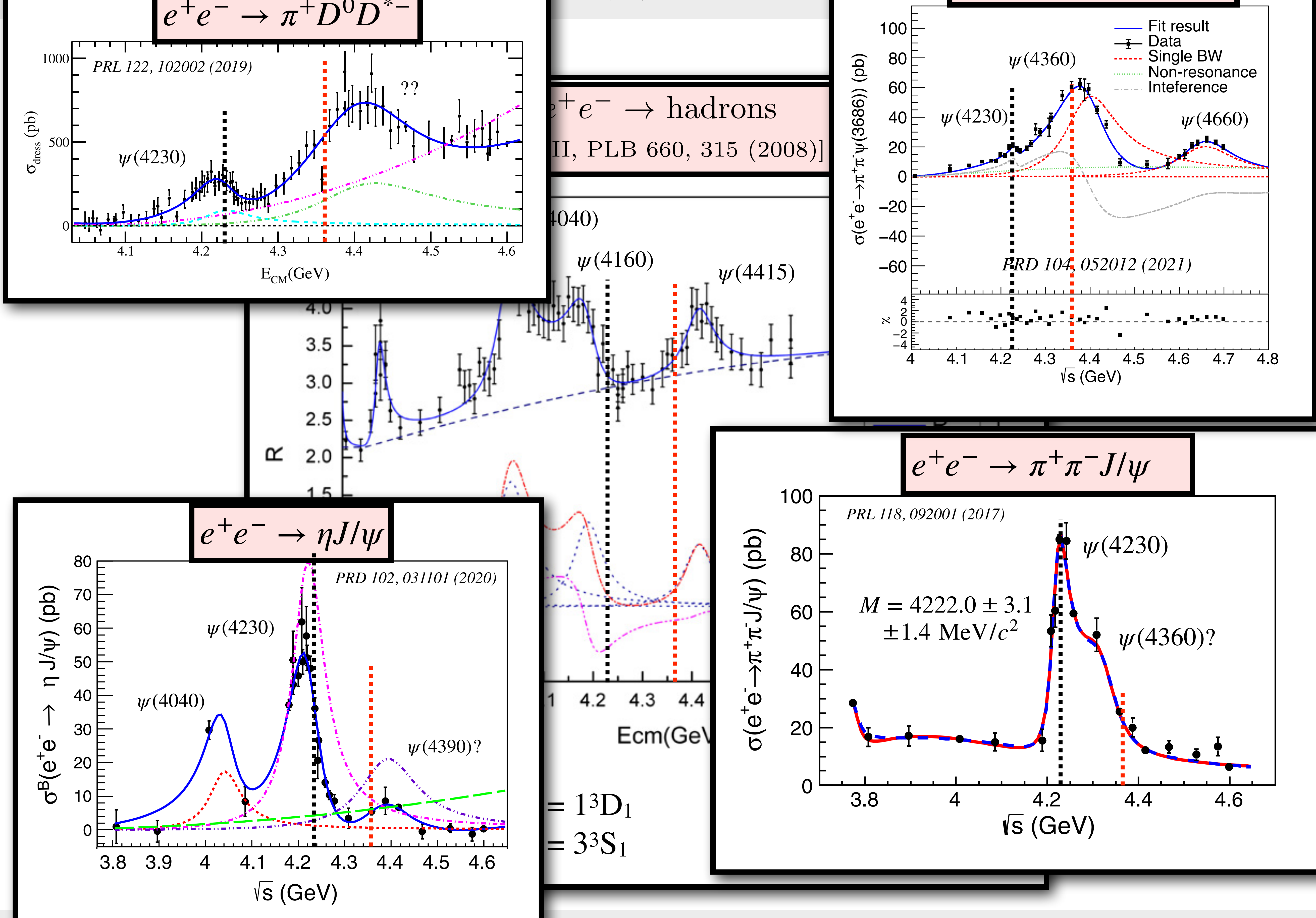

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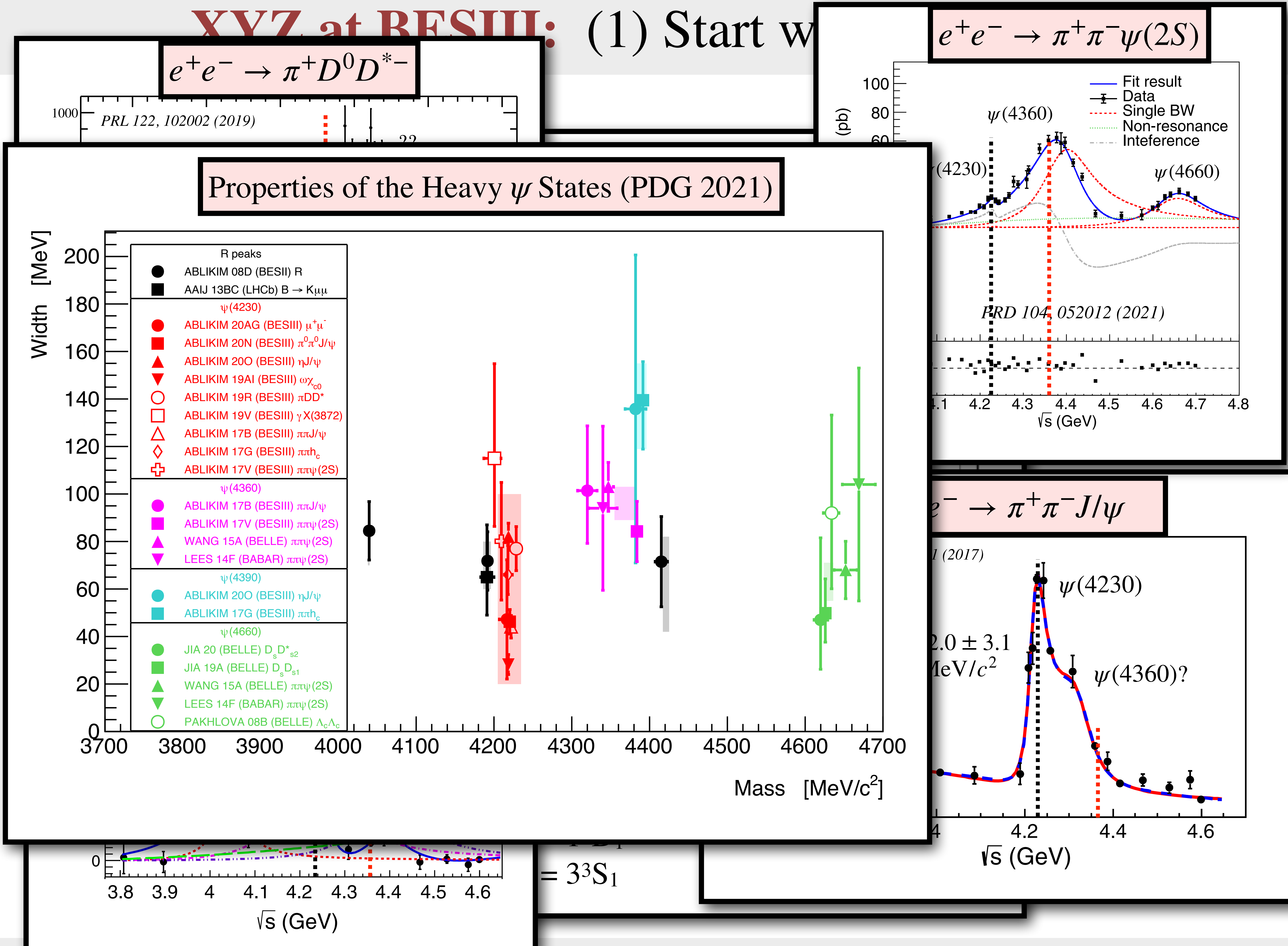
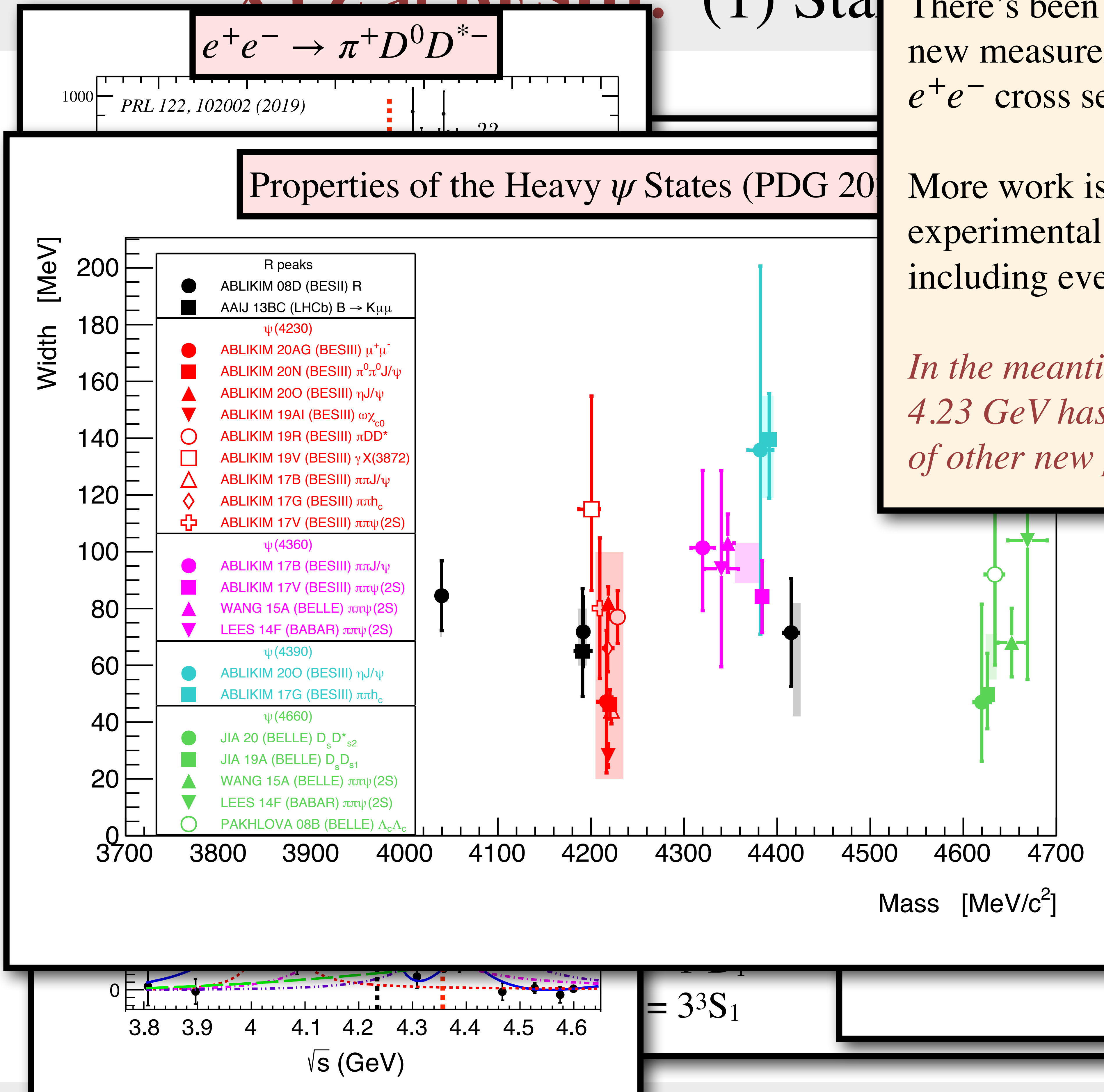


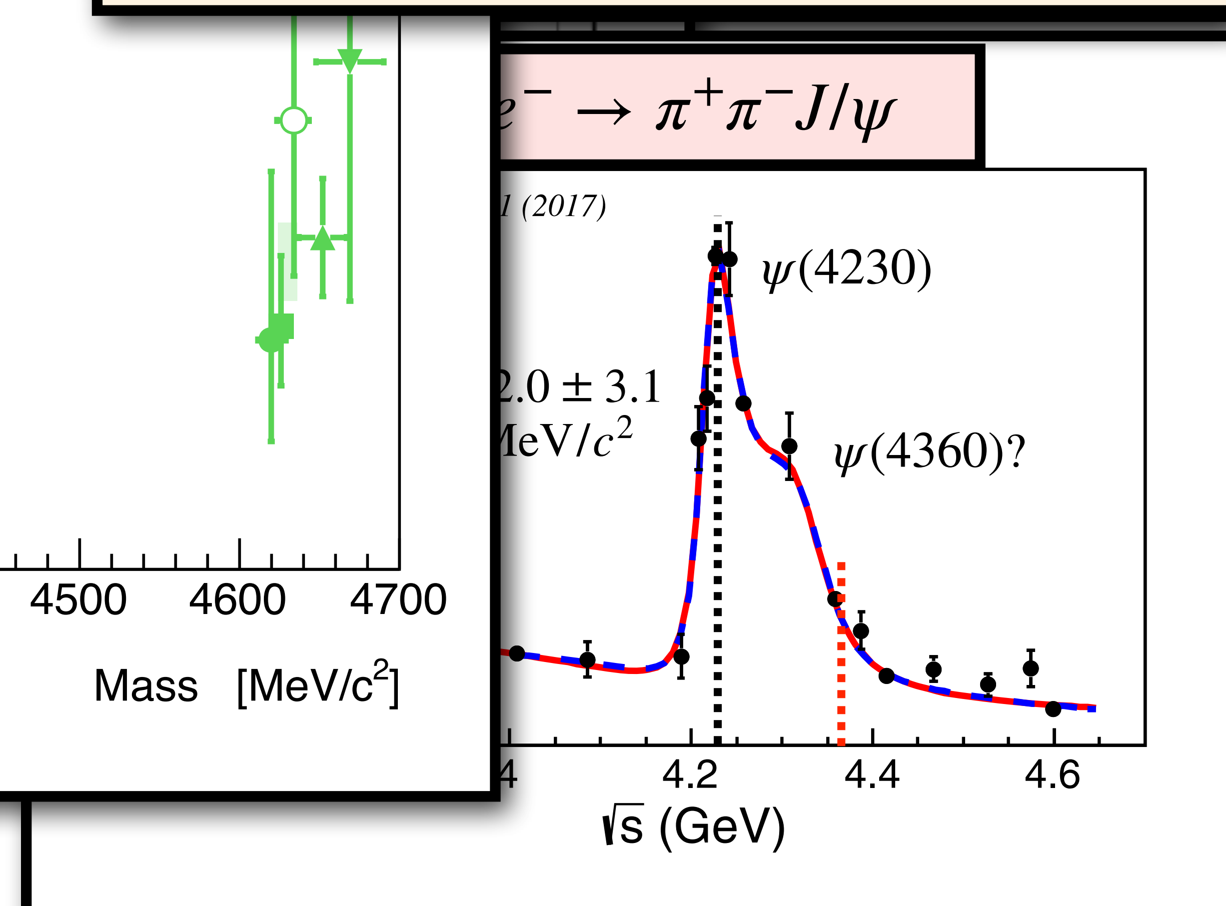
XYZ at BESIII: (1) Sta

There's been great progress in providing new measurements of exclusive e^+e^- cross sections!

More work is required to sort out the experimental properties of the ψ states, including even how many there are.

In the meantime, the region around 4.23 GeV has proven to be a rich source of other new phenomena…

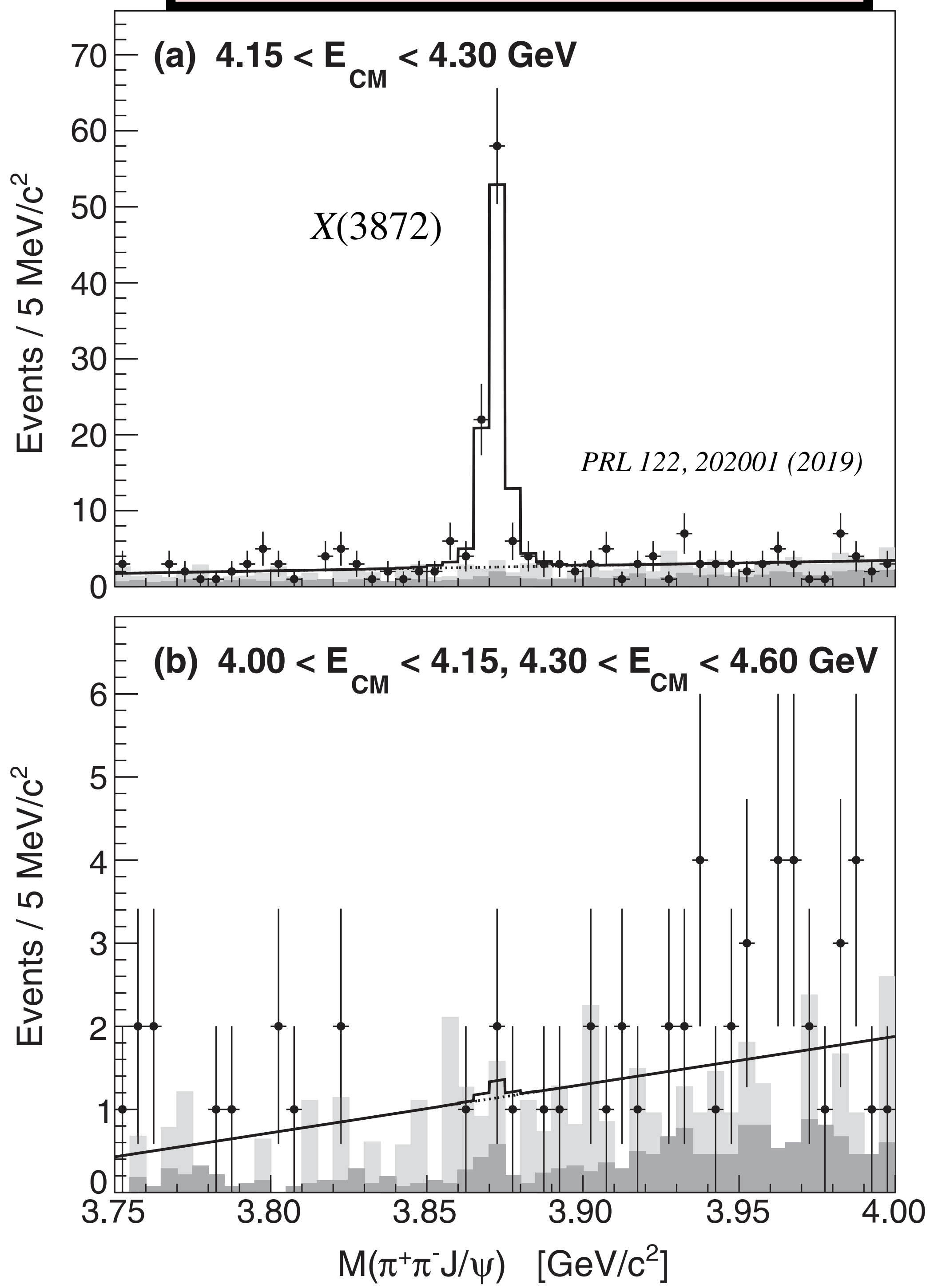




XYZ at BESIII: (2) Access the X with $e^+e^- \to Y \to \gamma X(3872)$

(really $\chi_{c1}(3872)$, since $I^G J^{PC} = 0^+1^{++}$)

$e^+e^- \to \gamma X(3872) \to \gamma(\pi^+\pi^- J/\psi)$



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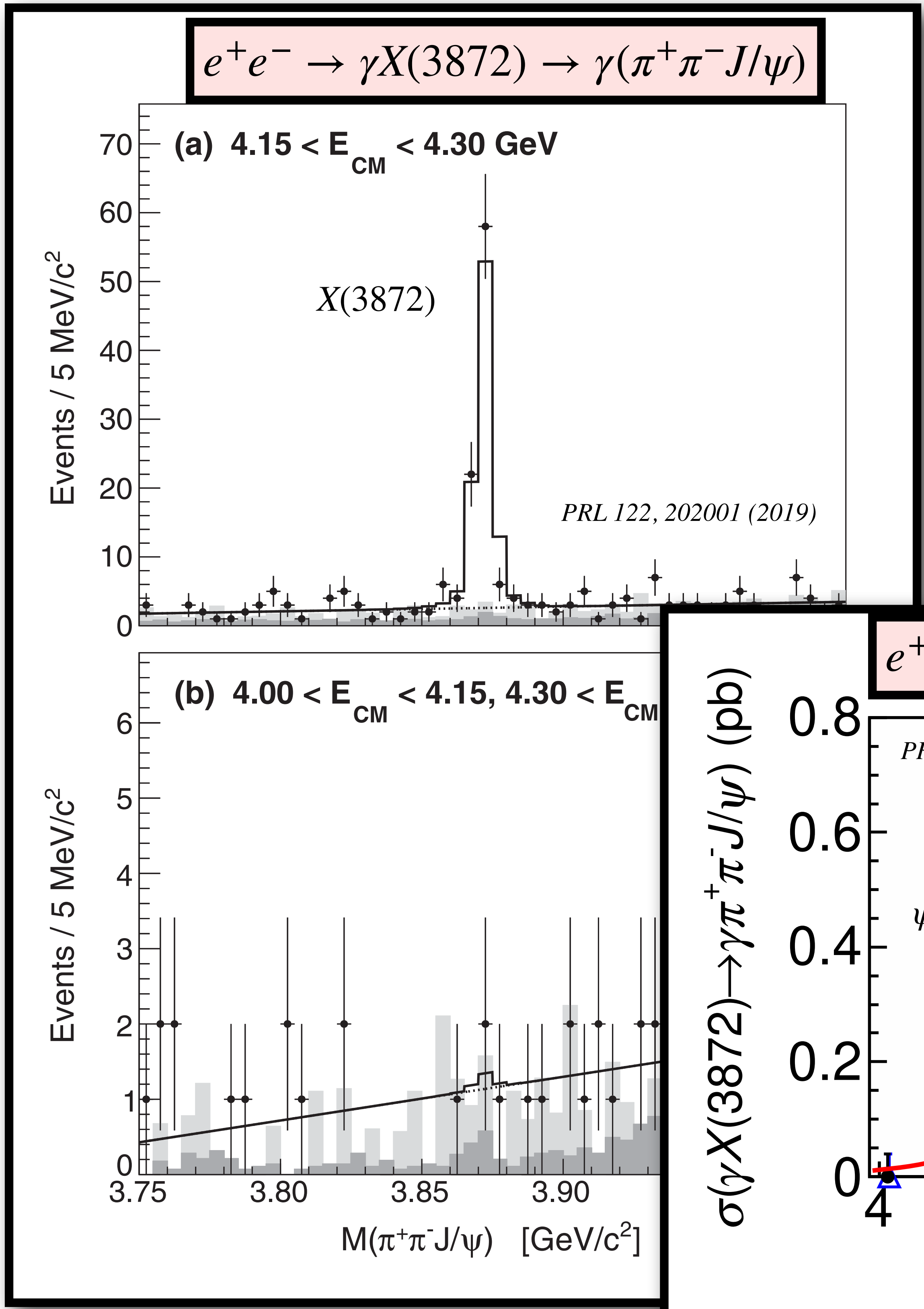

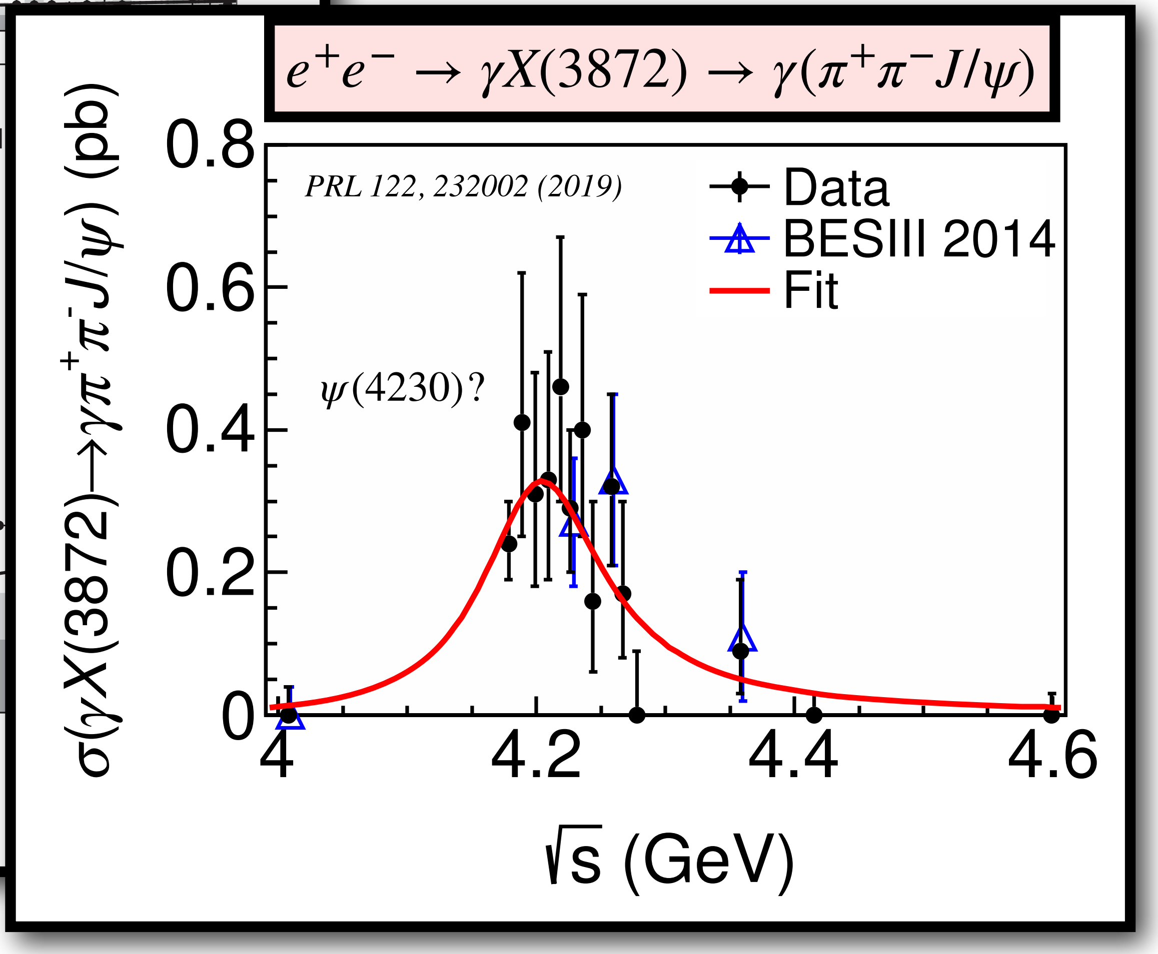

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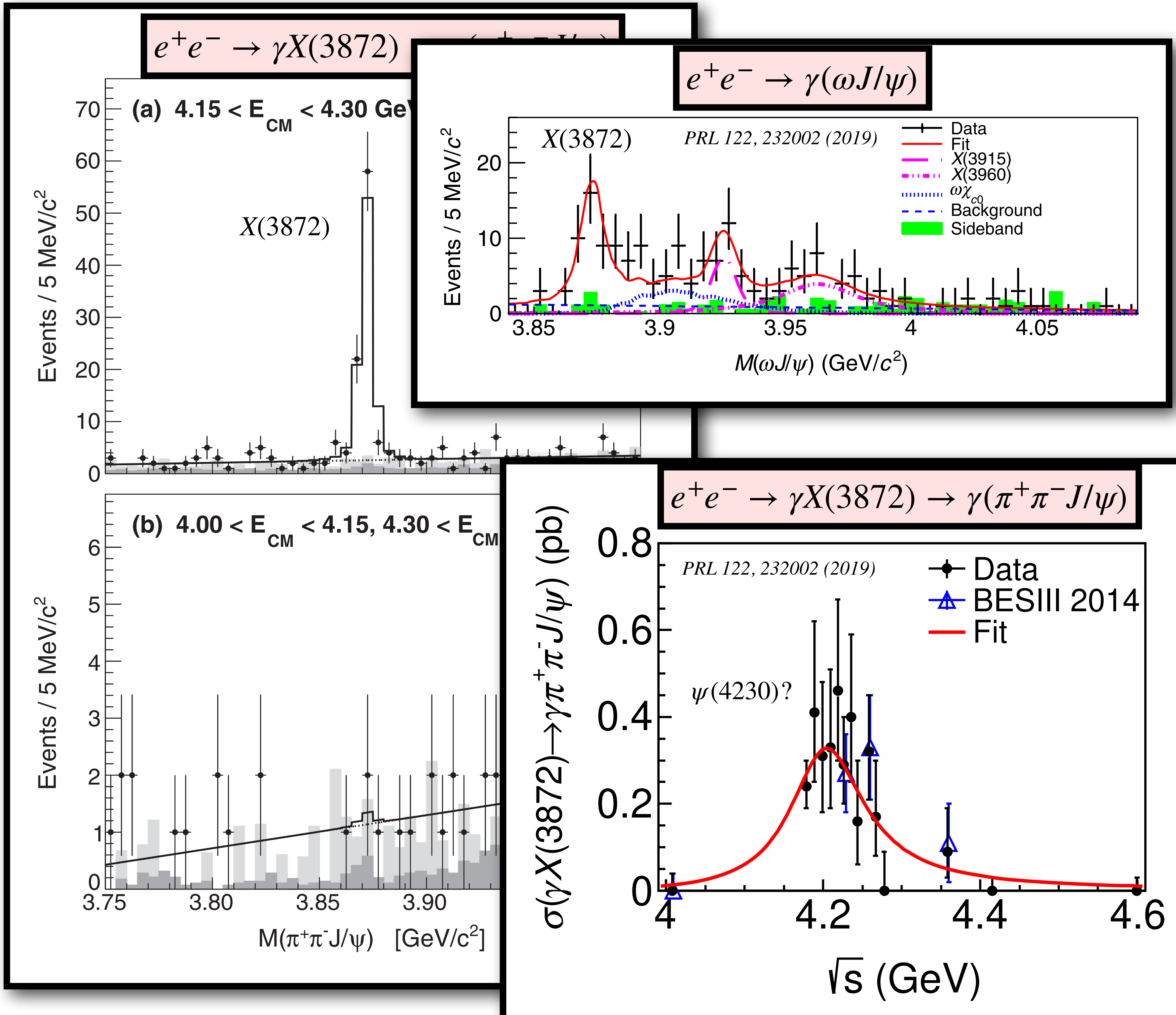

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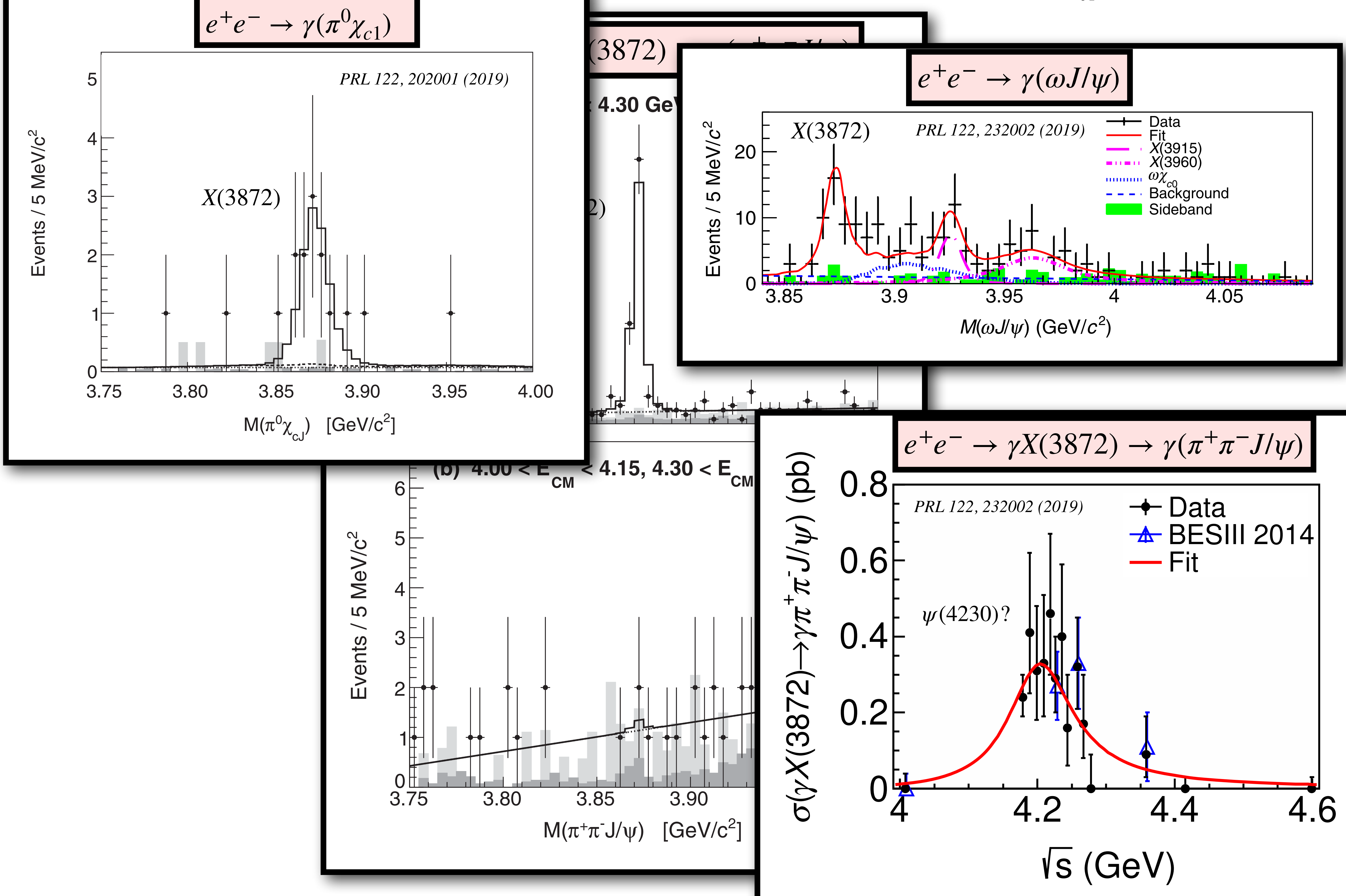

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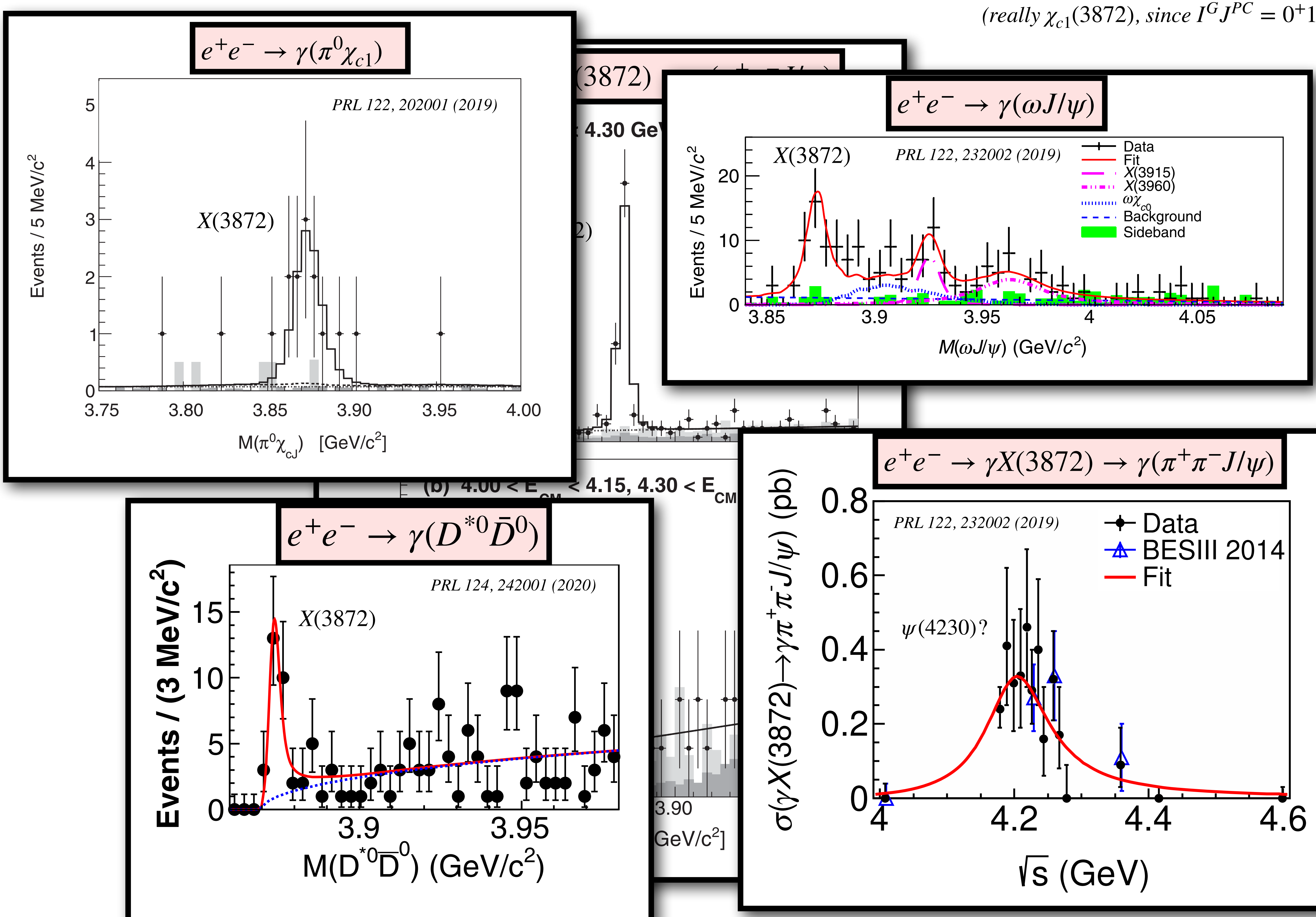

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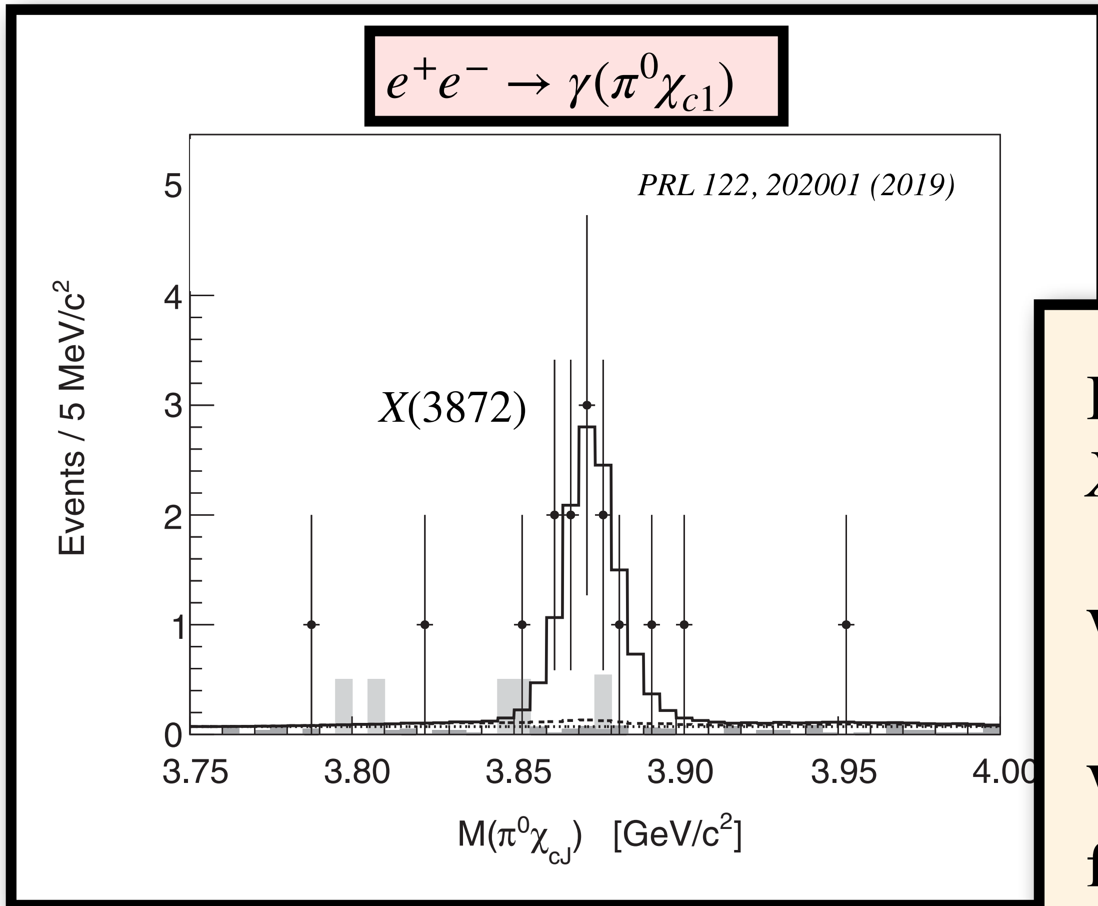
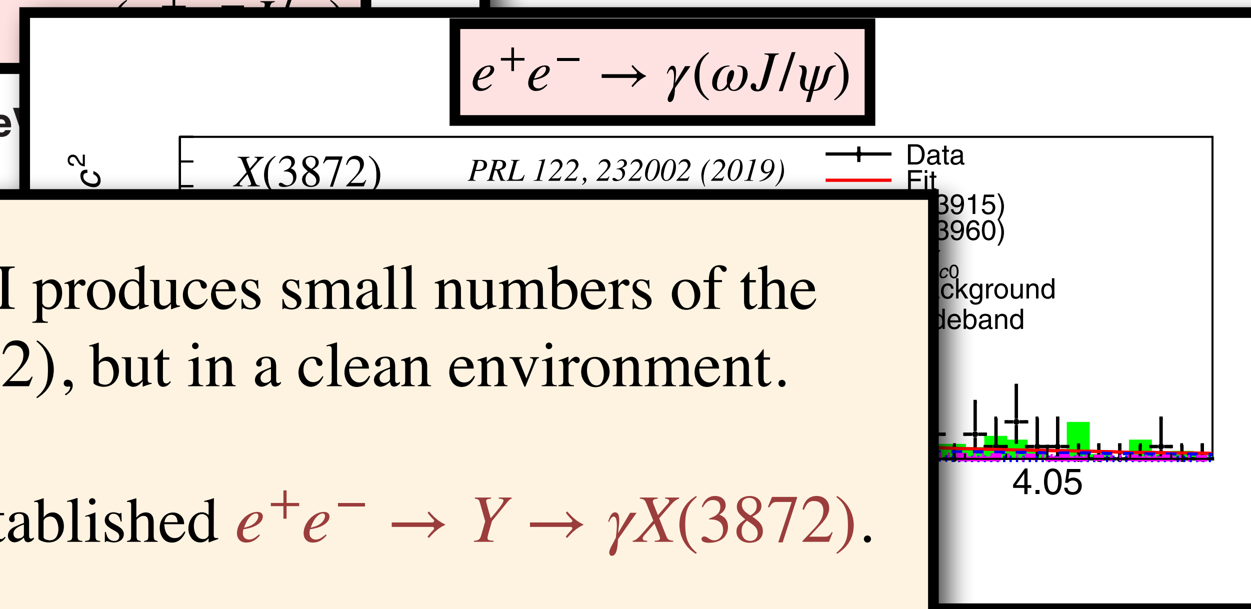
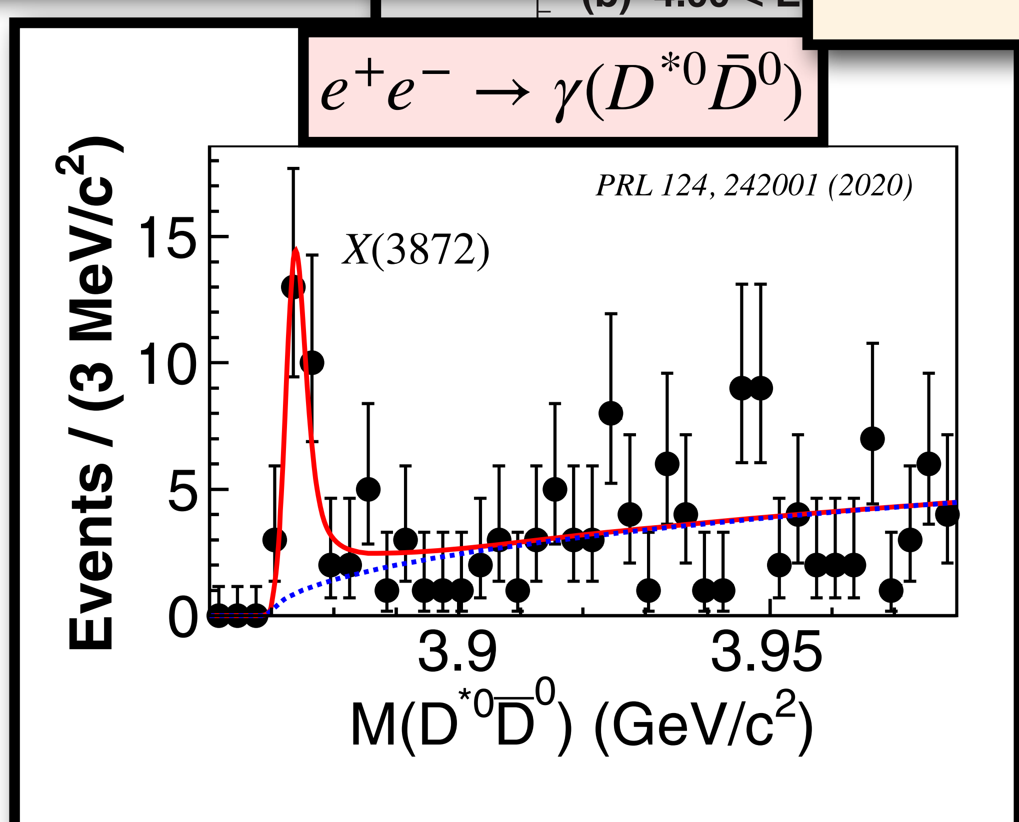


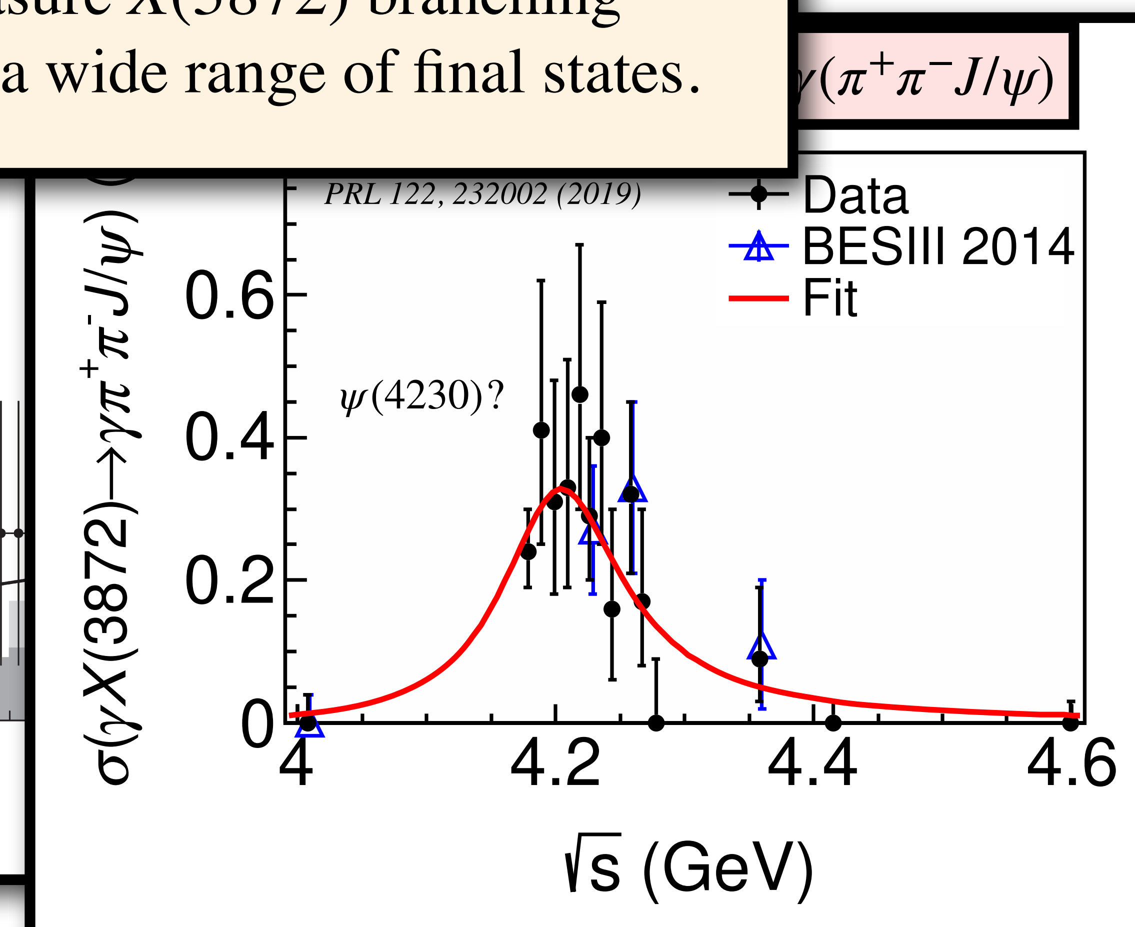


BESIII produces small numbers of the $X(3872)$, but in a clean environment.

We established $e^+e^- \to Y \to \gamma X(3872)$.

We can measure $X(3872)$ branching fractions to a wide range of final states.



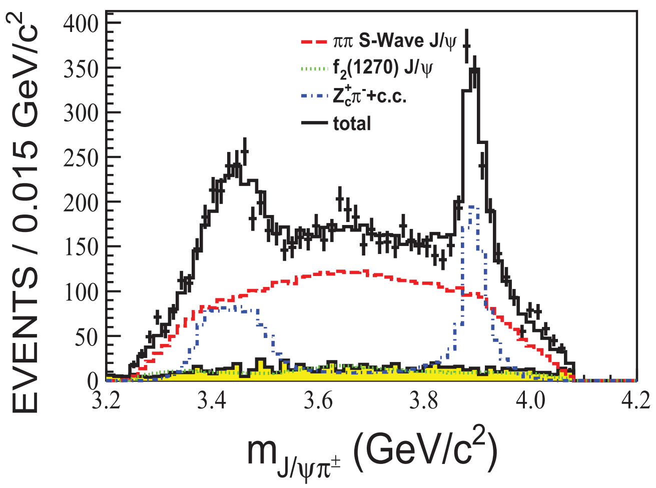


XYZ at BESIII: (3) Access the Z_c with $e^+e^- \to Y \to \pi Z_c$

(Z_c means $I^G J^{PC} = 1^+1^{+-}$)

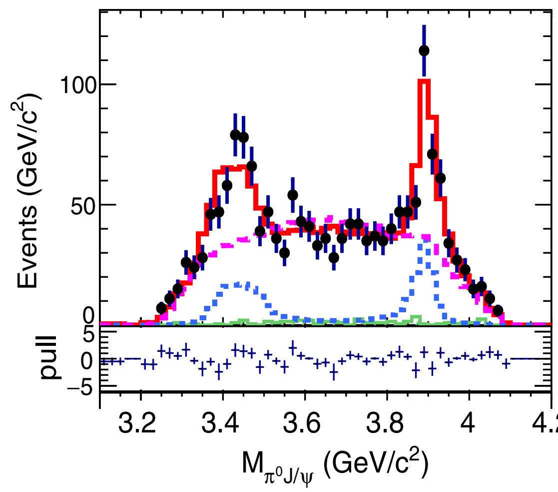
$e^+e^- \to \pi Z_c(3900)$

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



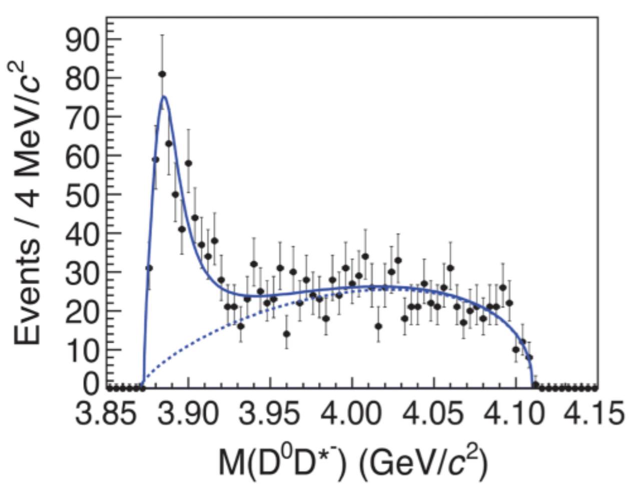
PRL 119, 072001 (2017)

$e^+e^- \to \pi^0(\pi^0 J/\psi)$



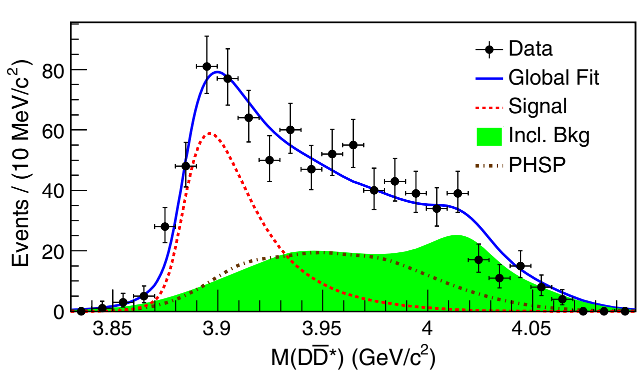
PRD 102, 012009 (2020)

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



PRL 112, 022001 (2014)

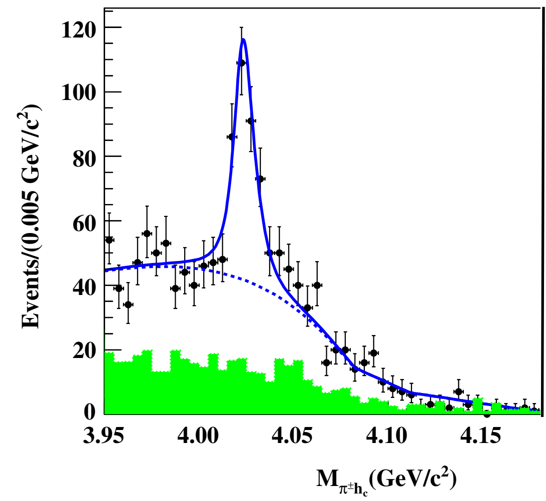
$e^+e^- \to \pi^0(D\bar{D}^*)^0$



PRL 115, 222002 (2015)

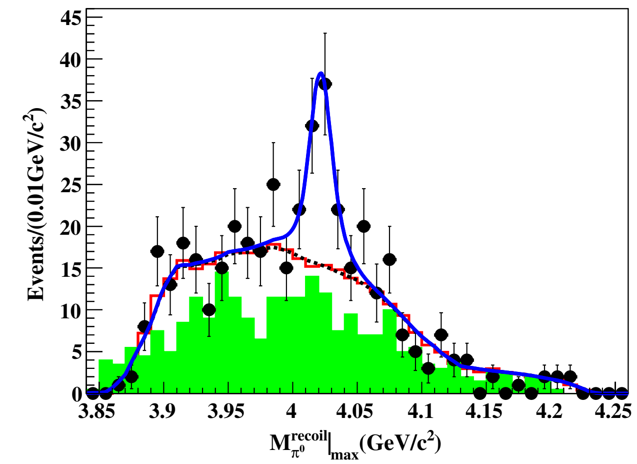
$e^+e^- \to \pi Z_c(4020)$

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



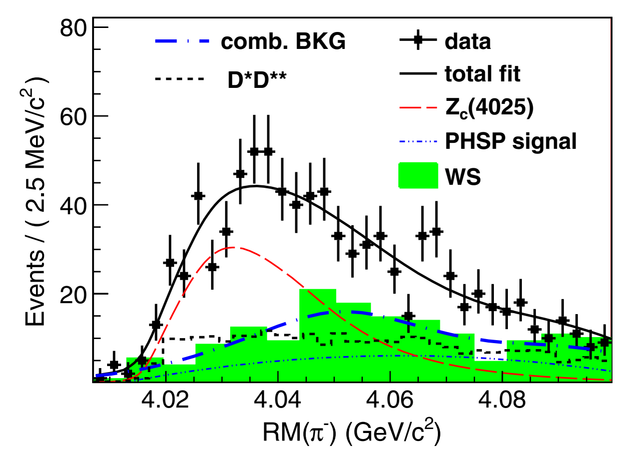
PRL 111, 242001 (2013)

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



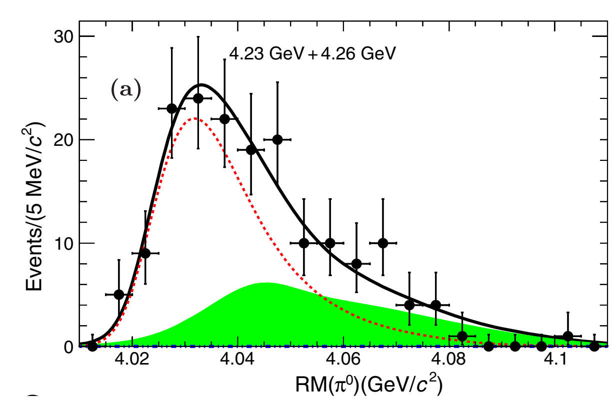
PRL 113, 212002 (2014)

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



PRL 112, 132001 (2014)

$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$



PRL 115, 182002 (2015)

XYZ at BESIII: (3) Access the Z_c with $e^+e^- \to Y \to \pi Z_c$

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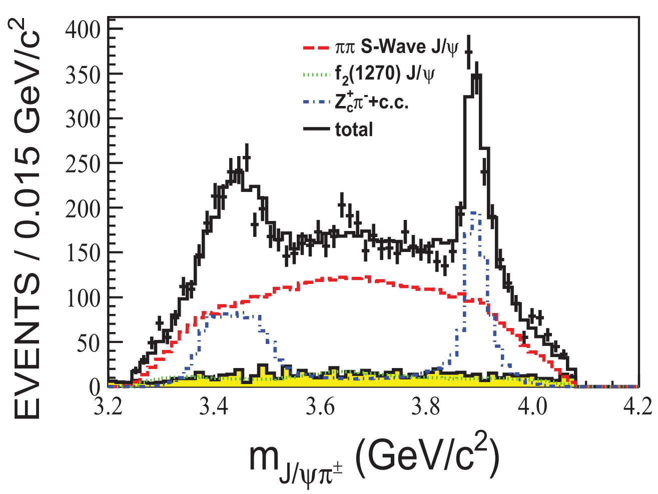

PRL 119, 072001 (2017)

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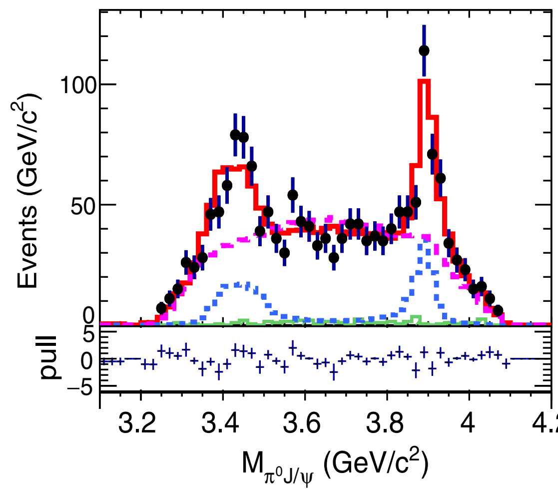
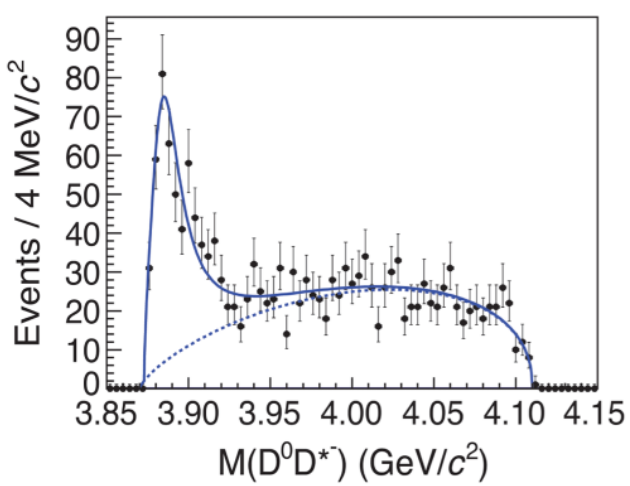


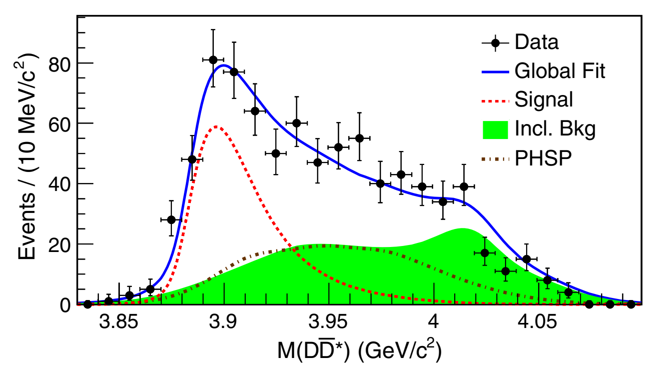
PRD 102, 012009 (2020)

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



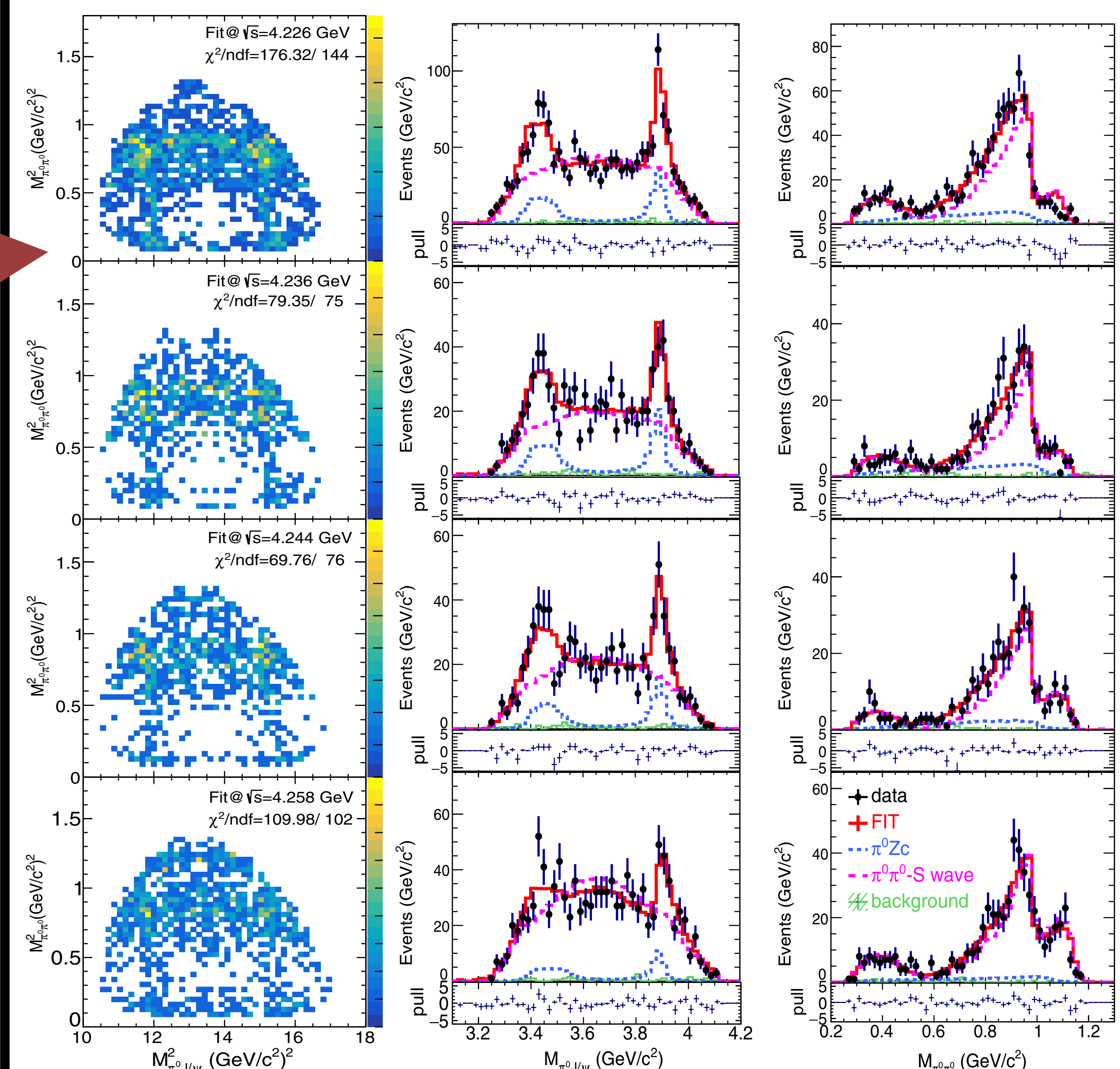
PRL 112, 022001 (2014)

$e^+e^- \to \pi^0(D\bar{D}^*)^0$



PRL 115, 222002 (2015)

Amplitude Analysis of $e^+e^- \to \pi^0\pi^0 J/\psi$



RM(π) (GeV/c²)

PRL 115, 182002 (2015)

PRL 112, 132001 (2014)

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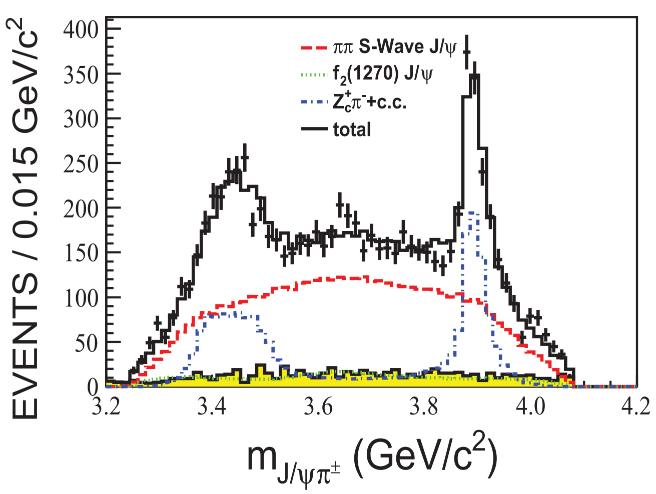
(Z_c means $I^G J^{PC} = 1^+1^{+-}$)

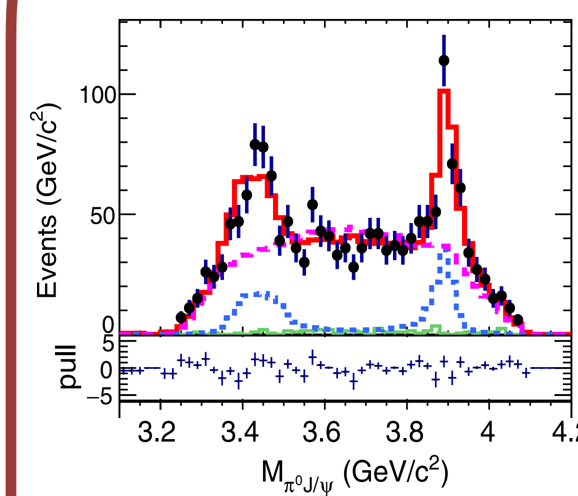
$e^+e^- \to \pi Z_c(3900)$

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



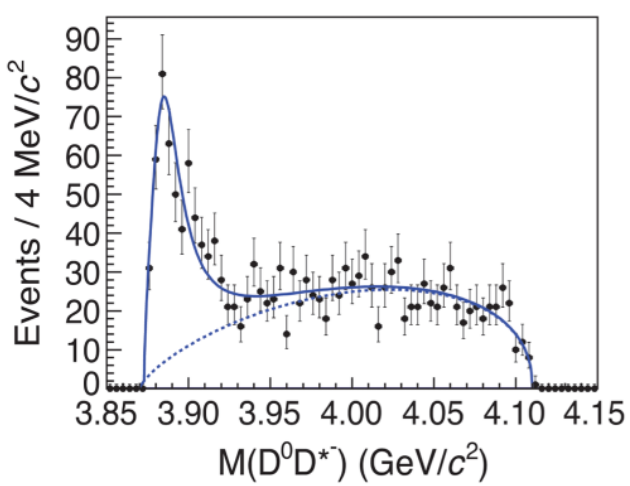
PRL 119, 072001 (2017)

$e^+e^- \to \pi^0(\pi^0 J/\psi)$



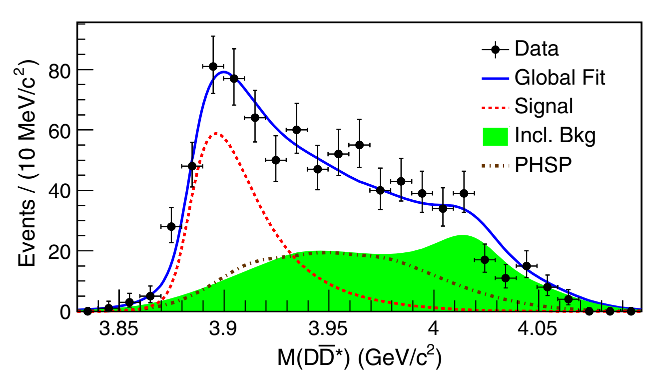
PRD 102, 012009 (2020)

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



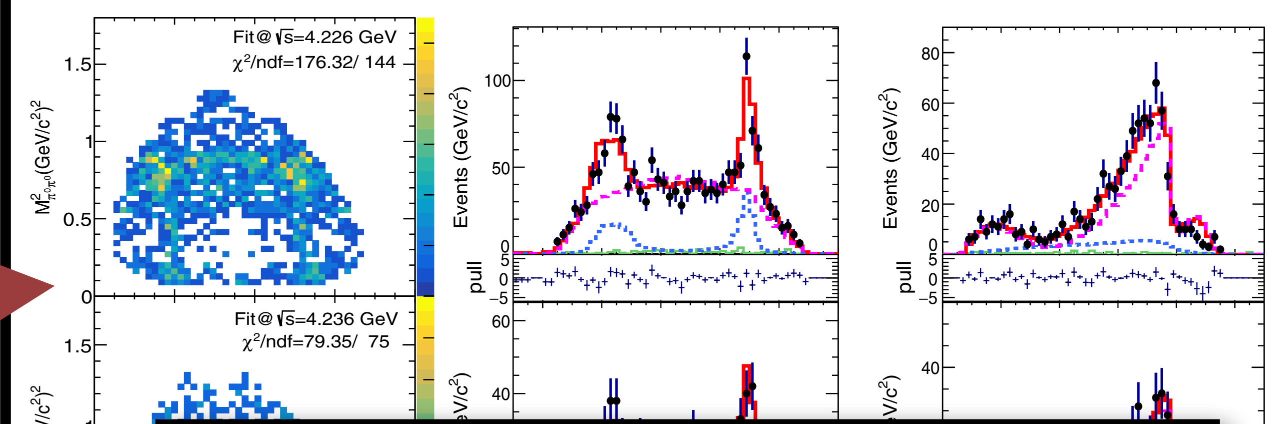
PRL 112, 022001 (2014)

$e^+e^- \to \pi^0(D\bar{D}^*)^0$

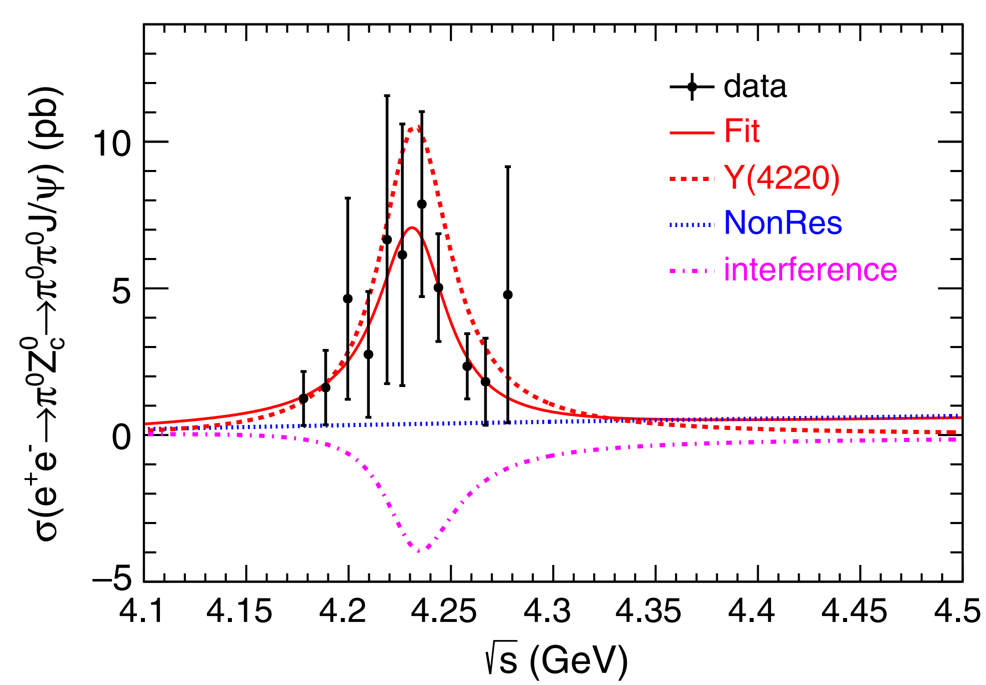


PRL 115, 222002 (2015)

Amplitude Analysis of $e^+e^- \to \pi^0\pi^0 J/\psi$



Cross Section of $e^+e^- \to \pi^0 Z_c(3900)^0$

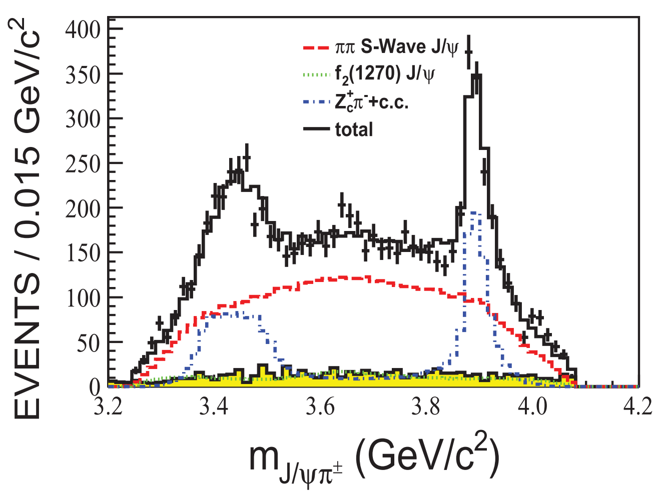


XYZ at BESIII: (3) Access the Z_c with $e^+e^- \to Y \to \pi Z_c$

(Z_c *means* $I^G J^{PC} = 1^+1^{+-}$)

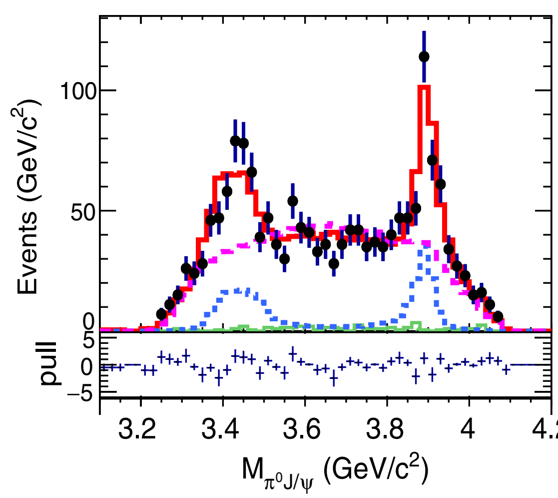
$e^+e^- \to \pi Z_c(3900)$

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



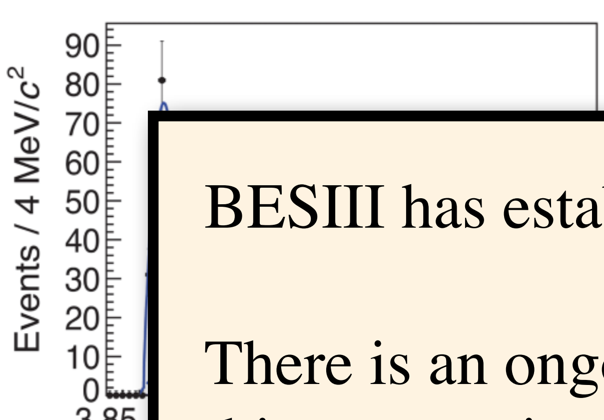
PRL 119, 072001 (2017)

$e^+e^- \to \pi^0(\pi^0 J/\psi)$



PRD 102, 012009 (2020)

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

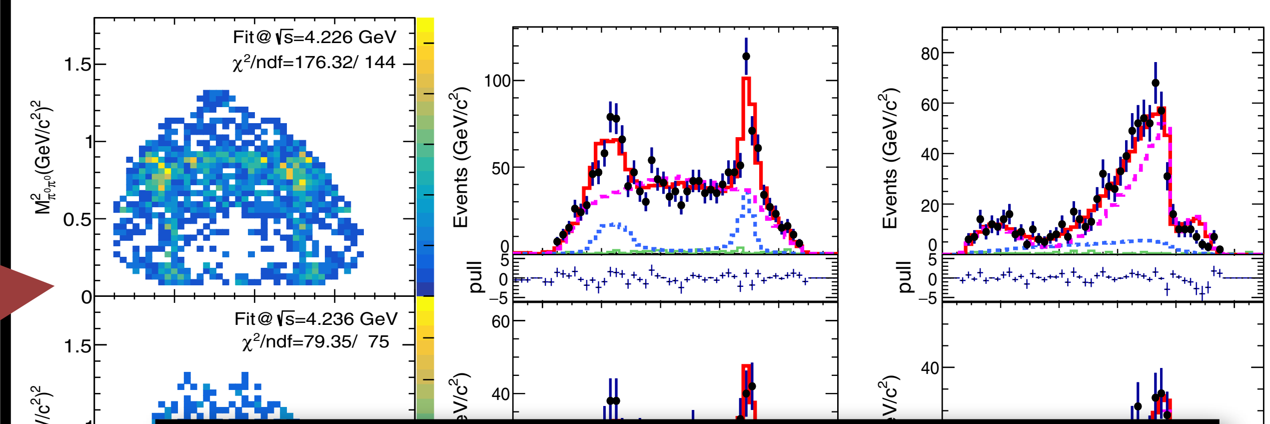


$e^+e^- \to \pi^0(D\bar{D}^*)^0$

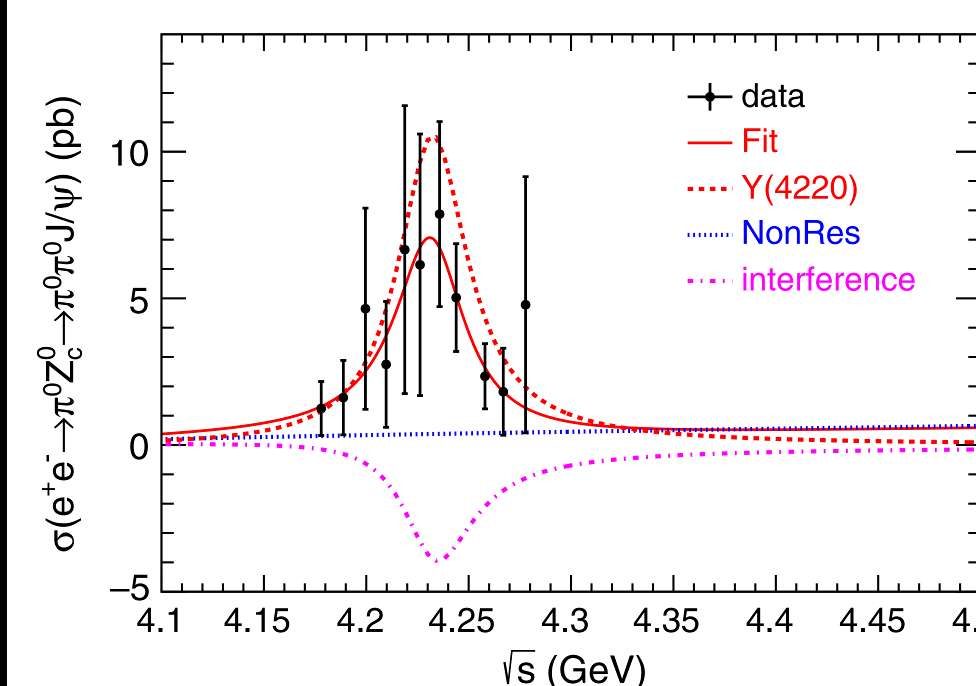
BESIII has established $e^+e^- \to Y \to \pi Z_c$.

There is an ongoing effort to understand this process in the region above the $\psi(4230)$.

Amplitude Analysis of $e^+e^- \to \pi^0\pi^0 J/\psi$



Cross Section of $e^+e^- \to \pi^0 Z_c(3900)^0$



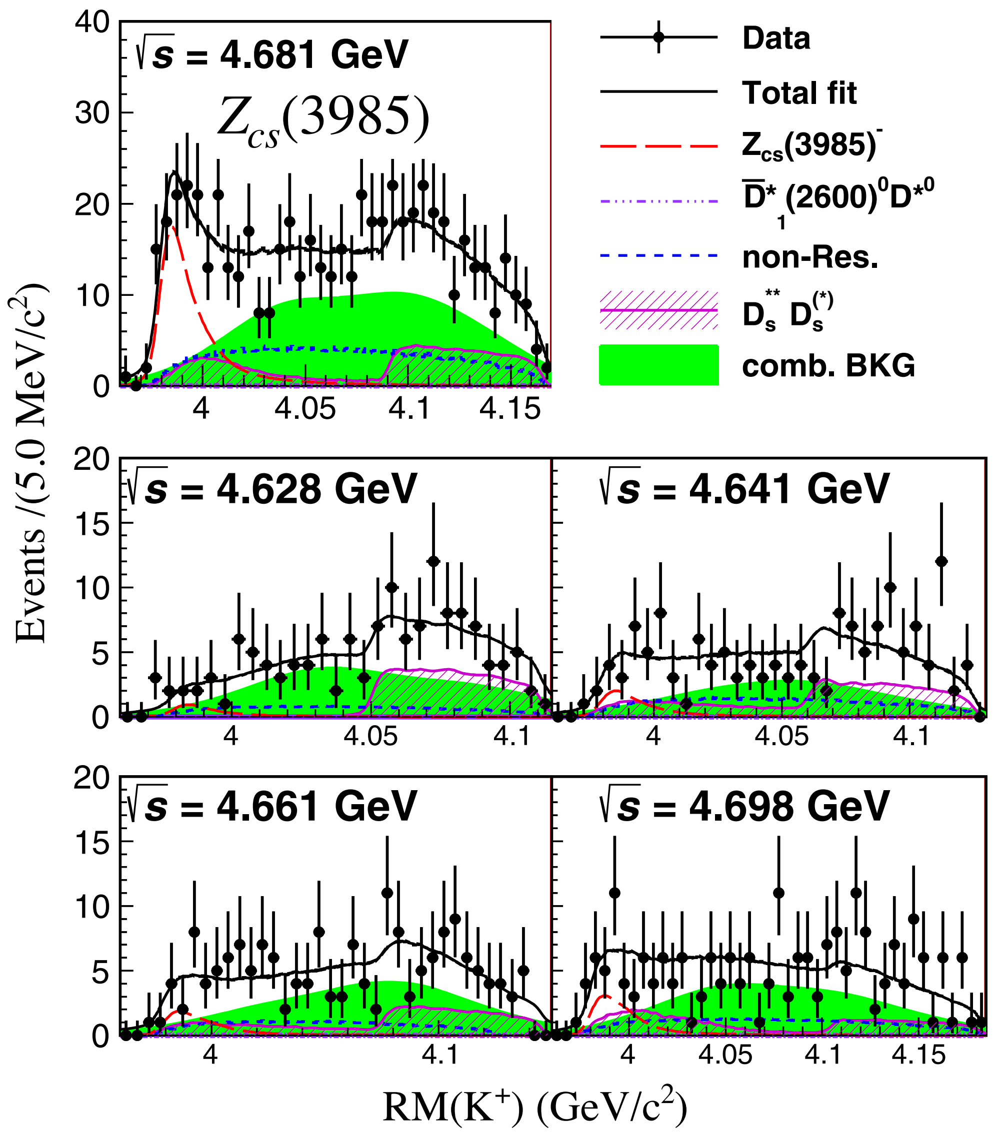
XYZ at BESIII: (4) Access the Z_{cs} with $e^+e^- \to KZ_{cs}$

(Z_{cs} means $IJ^P = \frac{1}{2}1^+$ and $S = 1$)

In 2020, we shifted our attention to higher energies, scanning the region between 4.6 and 4.7 GeV.

$e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

PRL 126, 102001 (2021)



$$m_{\rm pole}[Z_{cs}(3985)^-] = (3982.5^{+1.8}_{-2.6} \pm 2.1)\ {\rm MeV}/c^2,$$

$$\Gamma_{\rm pole}[Z_{cs}(3985)^-] = (12.8^{+5.3}_{-4.4} \pm 3.0)\ {\rm MeV}.$$

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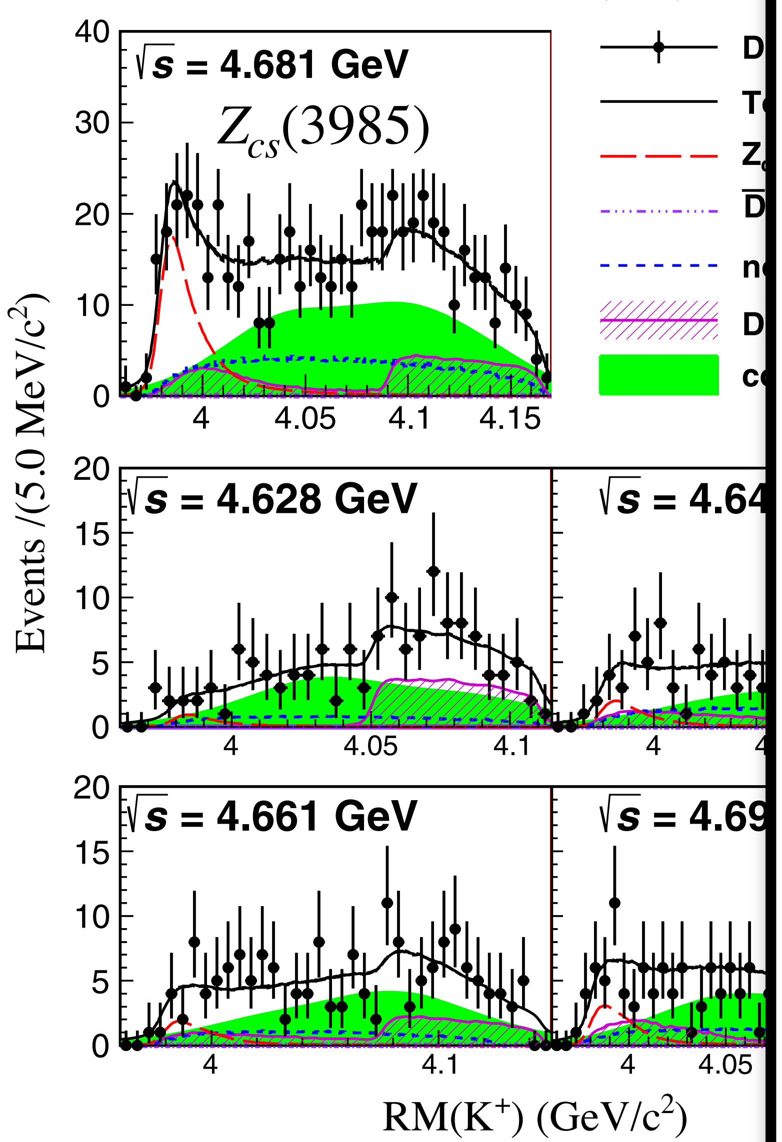

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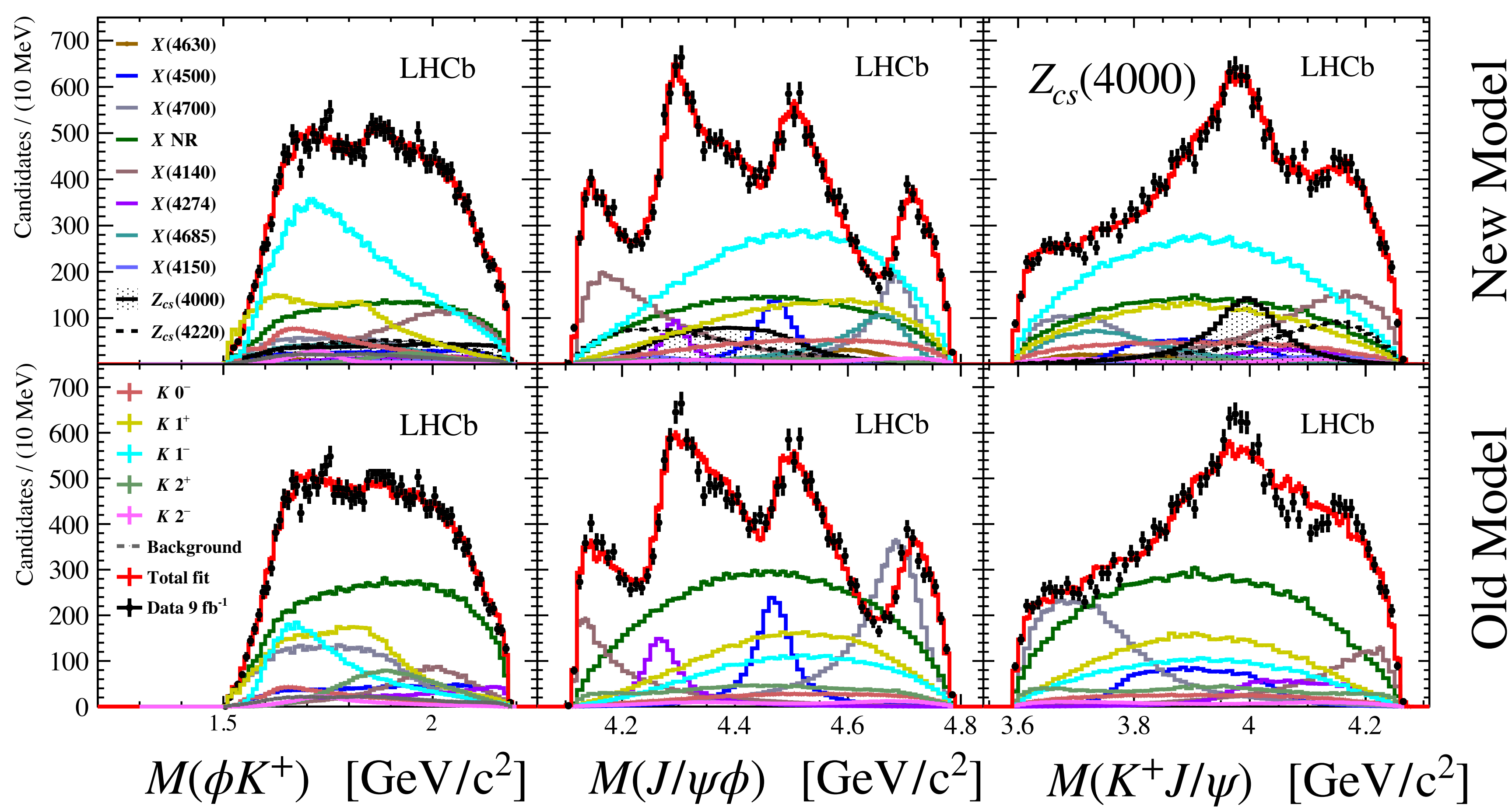
$B \to \phi(K^+ J/\psi)$ at LHCb

PRL 127, 082001 (2021)



$M(Z_{cs}(4000)) = 4003 \pm 6^{+4}_{-14}\ \text{MeV}/c^2$

$\Gamma(Z_{cs}(4000)) = 131 \pm 15 \pm 26\ \text{MeV}$

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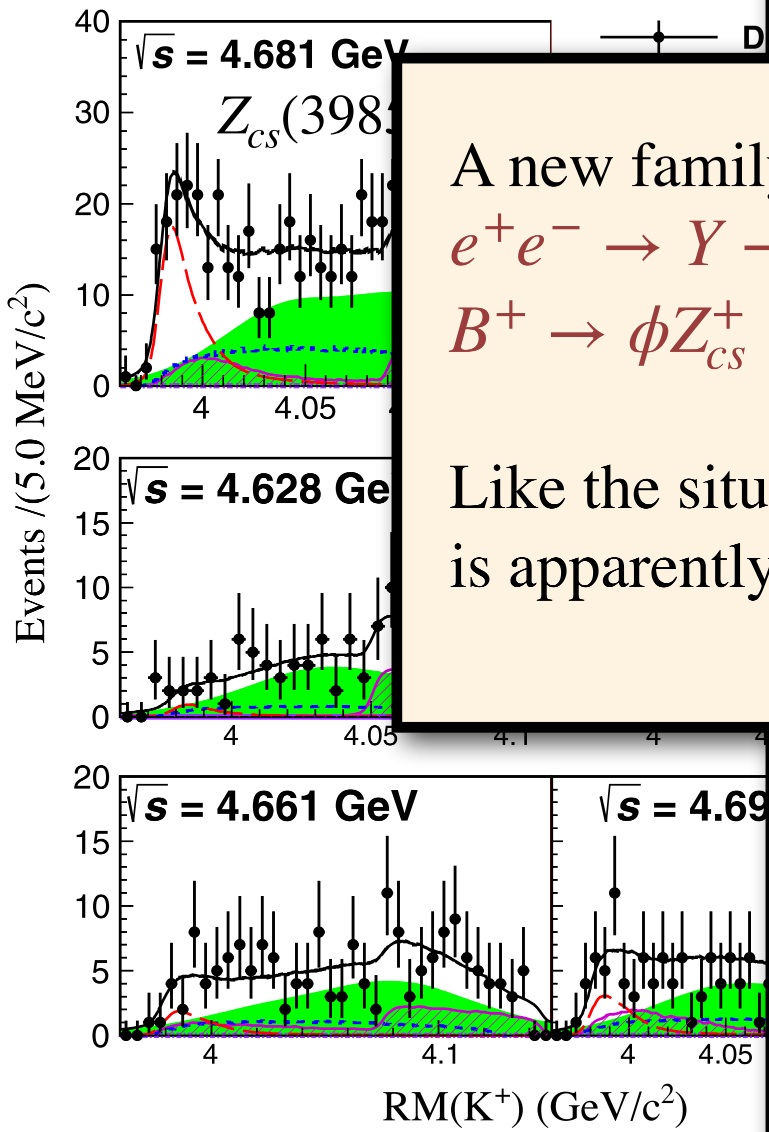
(Z_{cs} means $IJ^P = \frac{1}{2}1^+$ and $S = 1$)

In 2020, we shifted our attention to higher energies, scanning the region between 4.6 and 4.7 GeV.

$e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} \ldots$

PRL 126, 102001 (2021)



$$m_{\text{pole}}[Z_{cs}(3985)^-] = (3982.5^{+1.8}_{-2.6} \pm 2.1)\ \text{MeV}/c^2,$$

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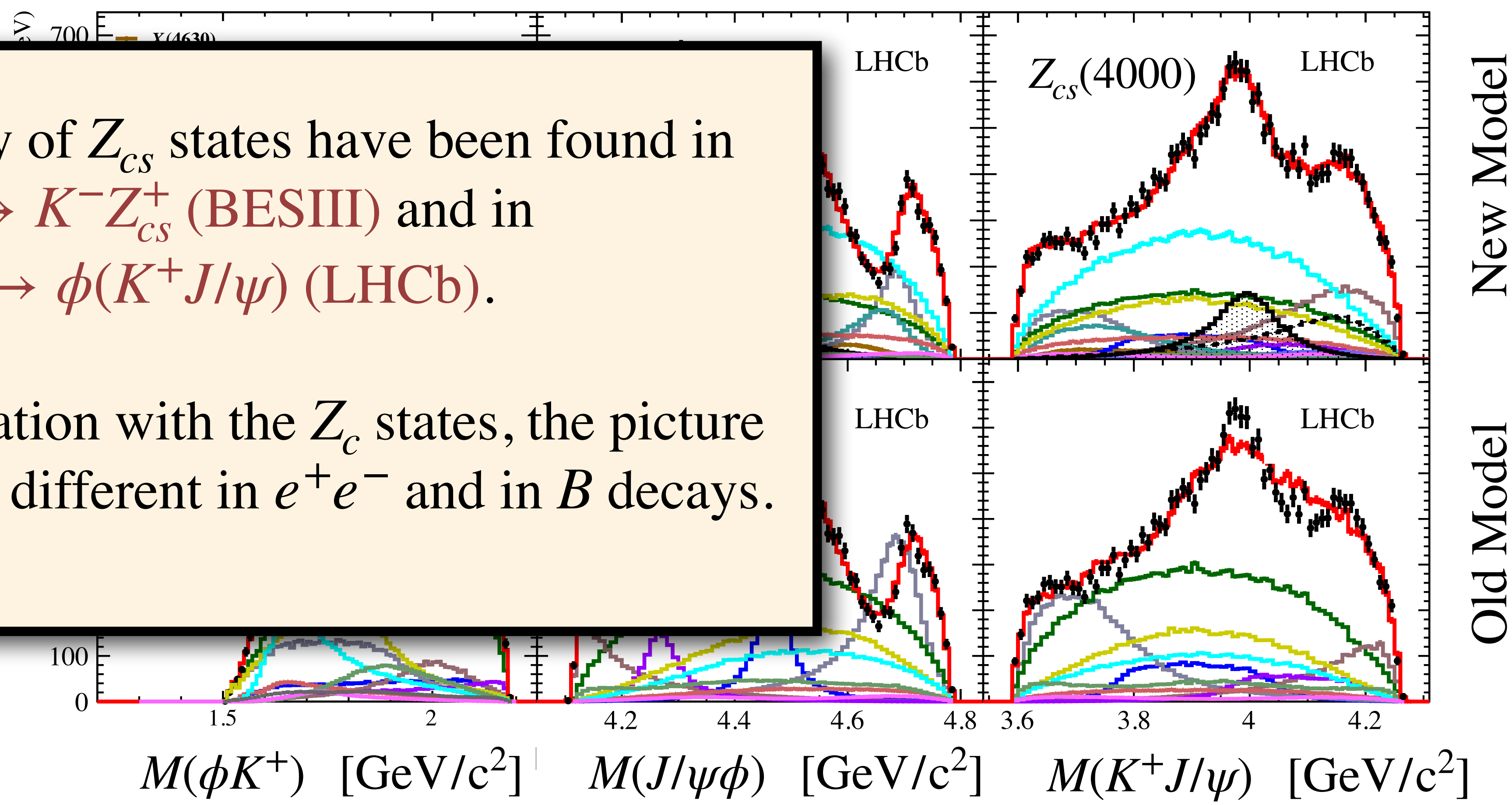
PRL 127, 082001 (2021)



$$M(Z_{cs}(4000)) = 4003 \pm 6^{+4}_{-14}\ \text{MeV}/c^2$$

$$\Gamma(Z_{cs}(4000)) = 131 \pm 15 \pm 26\ \text{MeV}$$

A new family of Z_{cs} states have been found in $e^+e^- \to Y \to K^-Z_{cs}^+$ (BESIII) and in $B^+ \to \phi Z_{cs}^+ \to \phi(K^+J/\psi)$ (LHCb).

Like the situation with the Z_c states, the picture is apparently different in e^+e^- and in B decays.

Prospects for BESIII: Upgrade BEPCII to BEPCII-U

Accelerator upgrade (BEPCII → BEPCII-U):

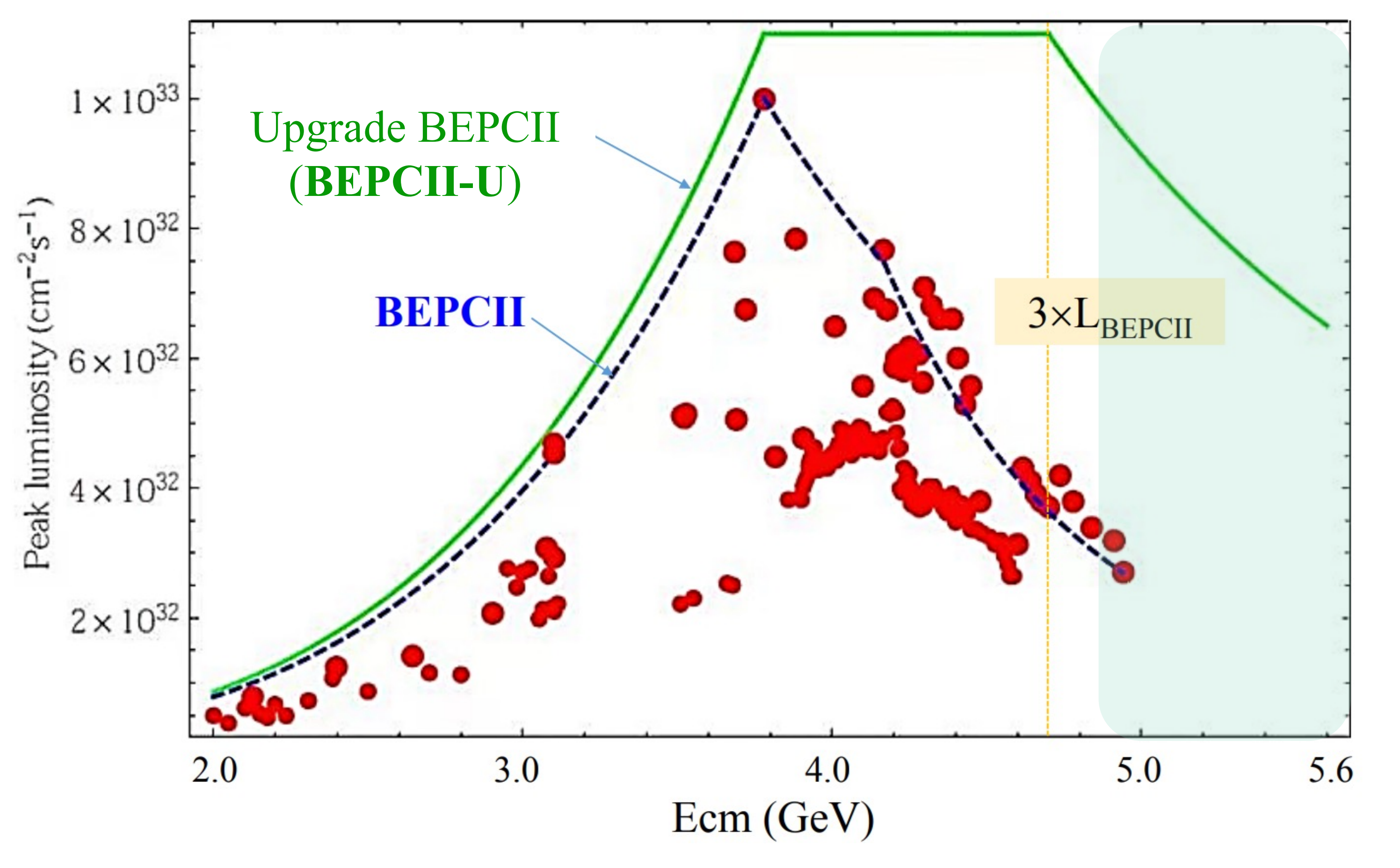
* increase the luminosity by 3× at high energies; and
* extend the energy reach (E_{cm}) to 5.6 GeV.

Method:

* add one additional RF cavity per beam; and
* optimize optics in the interaction region.

Timeline:

* the project was approved in July 2021;
* it requires 2.5 years of construction (with no shutdown);
* installation will start in July 2024; and
* running begins January 2025.



Physics Goals:

(1) Explore an unknown energy region.

(2) Access charm baryons at threshold.

$$2 \times M(\Lambda_c^+) = 4572.9 \text{ MeV}$$
$$2 \times M(\Sigma_c^{++,+,0}) = 4905.8 - 4907.9 \text{ MeV}$$
$$2 \times M(\Xi_c^{+,0}) = 4935.4 - 4940.9 \text{ MeV}$$
$$2 \times M(\Omega_c^0) = 5390.4 \text{ MeV}$$

Summary

BESIII continues to use e^+e^- collisions to explore the τ-charm region in detail.

* **10 billion J/ψ decays** allow unprecedented access to light quark hadrons
(and increases the urgency for methods to rigorously extract resonance parameters).

* **3 billion $\psi(2S)$ decays** allow new precision studies of charmonium and offer complementary initial states ($\eta_c(1S,2S)$, $\chi_{cJ}(1P)$, $h_c(1P)$, $\psi(2S)$) from which to study light quark hadrons.

* **XYZ physics** remains a key component of the BESIII physics program:
(1) we continue to map out complex structure in exclusive e^+e^- cross sections ("Y" states);
(2) with $E_{\rm cm}$ near 4.23 GeV, we produce the $X(3872)$ through $e^+e^- \to \gamma X(3872)$;
(3) also near 4.23 GeV, we see the $Z_c(3900)$ and $Z_c(4020)$ through $e^+e^- \to \pi Z_c$; and
(4) at higher $E_{\rm cm}$, above 4.6 GeV, we see the $Z_{cs}(3985)$ in $e^+e^- \to KZ_{cs}$.

* BEPCII will soon be upgraded to **BEPCII-U**, opening a path to unexplored territory.