Experimental Status of Exotic Charmonium

(and how it might relate to the 22 GeV upgrade)

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Indiana University

January 23, 2023
SCIENCE AT THE LUMINOSITY FRONTIER:
JEFFERSON LAB AT 22 GEV

What is Exotic Charmonium?

Exotic charmonium:

- states that include $c\bar{c}$ quarks but have properties inconsistent with those expected for $c\bar{c}$ mesons
- informally known as the X, Y, and Z states
- dozens of candidates found by Belle, BESIII, and LHCb, among others, in a variety of production mechanisms *(e^+e^- annihilation, B decay, pp collisions, etc.)*
- novel configurations of quarks and gluons that can be used to study the strong force

Three prominent examples of exotic charmonium candidates:

- the $X(3872)$ *[or more formally, the $\chi_{c1}(3872)$]*
- the $Y(4230)$ *[or more formally, the $\psi(4230)$] [formerly known as the $Y(4260)$]*
- the $Z_c(3900)$

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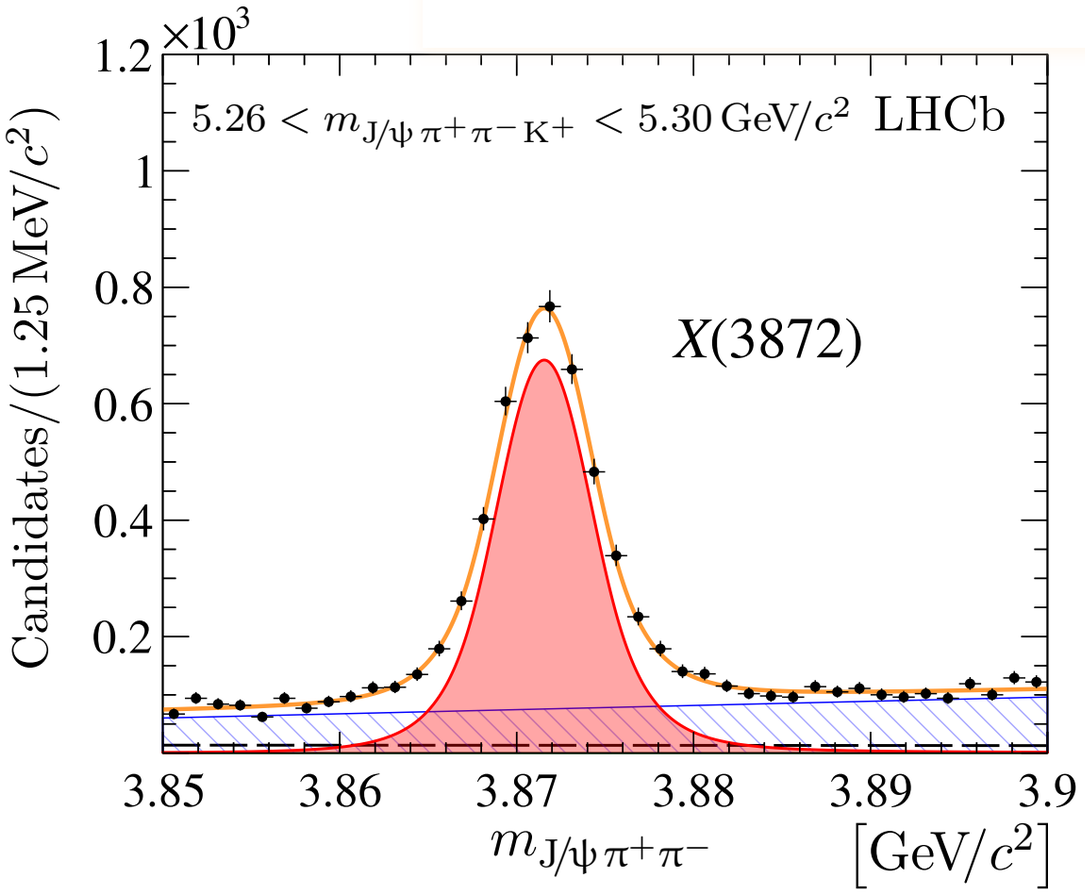
LHCB, JHEP 08, 123 (2020)

Study of the $\psi_2(3823)$ and $\chi_{c1}(3872)$ states in $B^+ \to (J/\psi\pi^+\pi^-)\, K^+$ decays



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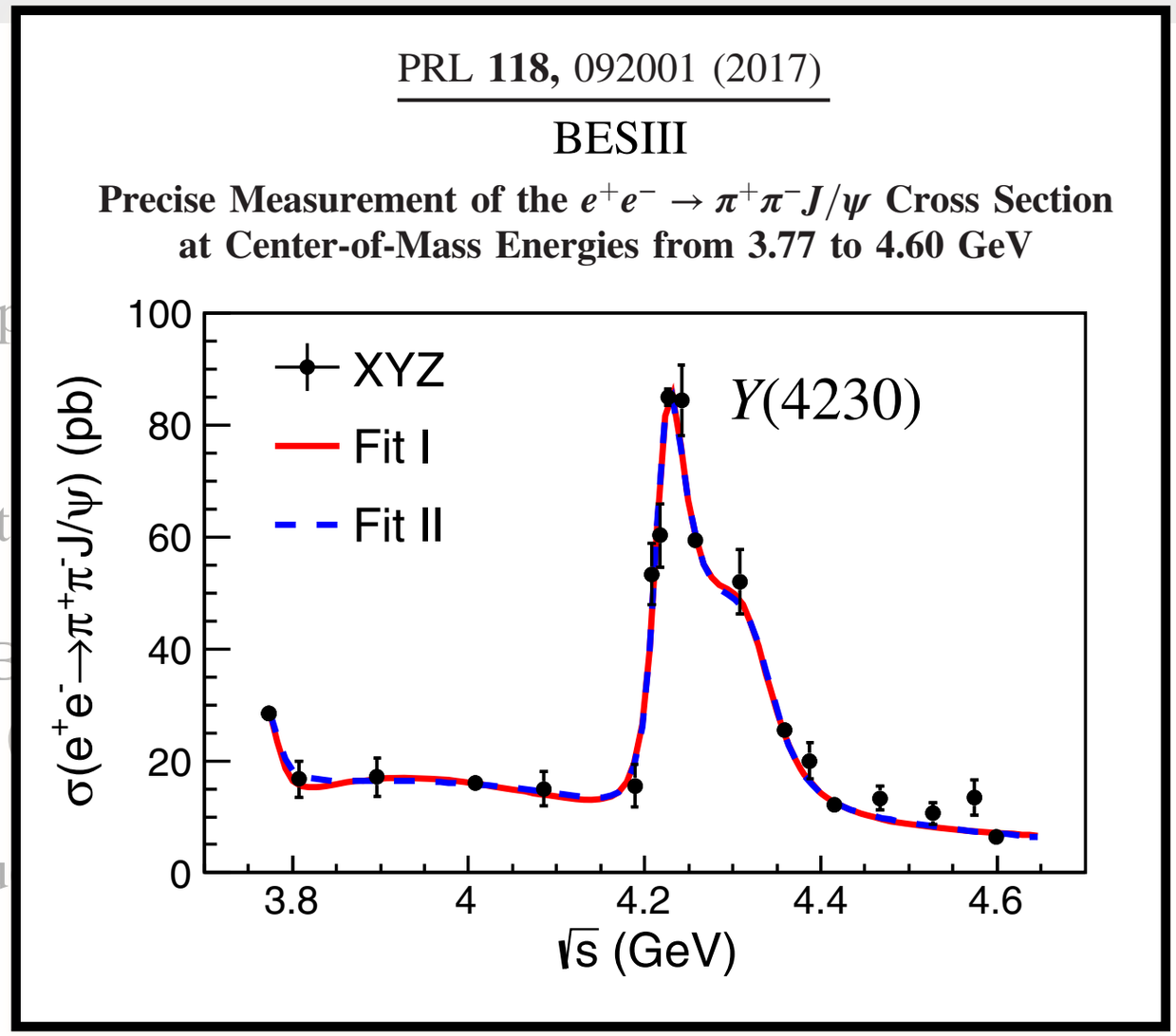

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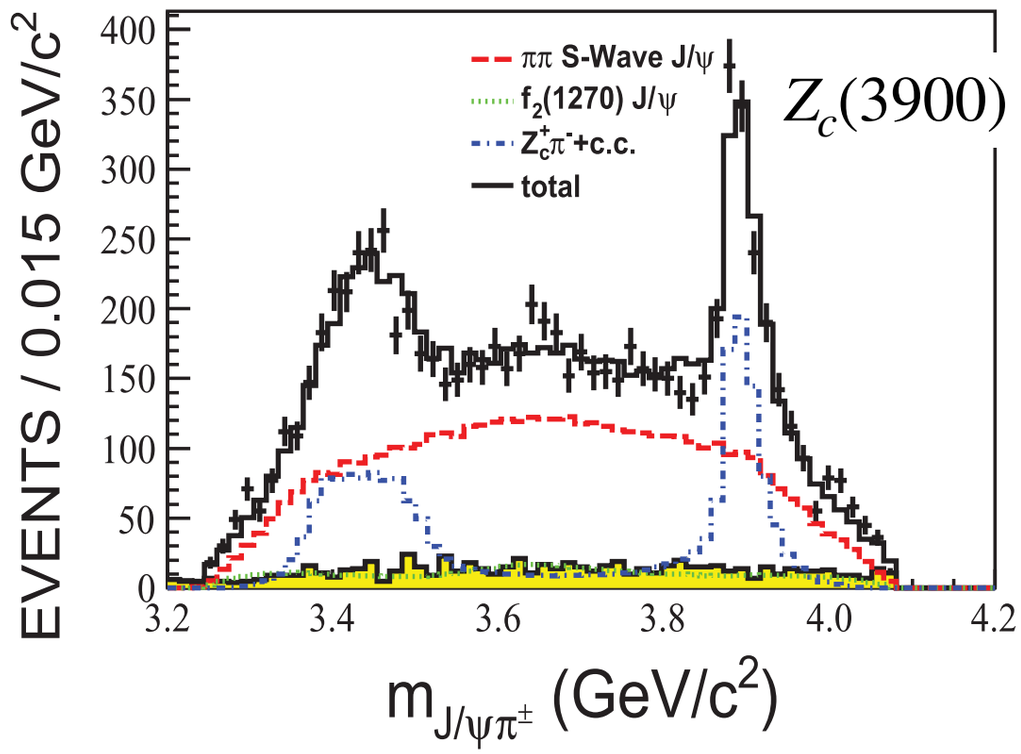
PRL **119,** 072001 (2017)

BESIII

Determination of the Spin and Parity of the $Z_c(3900)$

$e^+e^- \to \pi^+\pi^- J/\psi$ at 4.23 GeV



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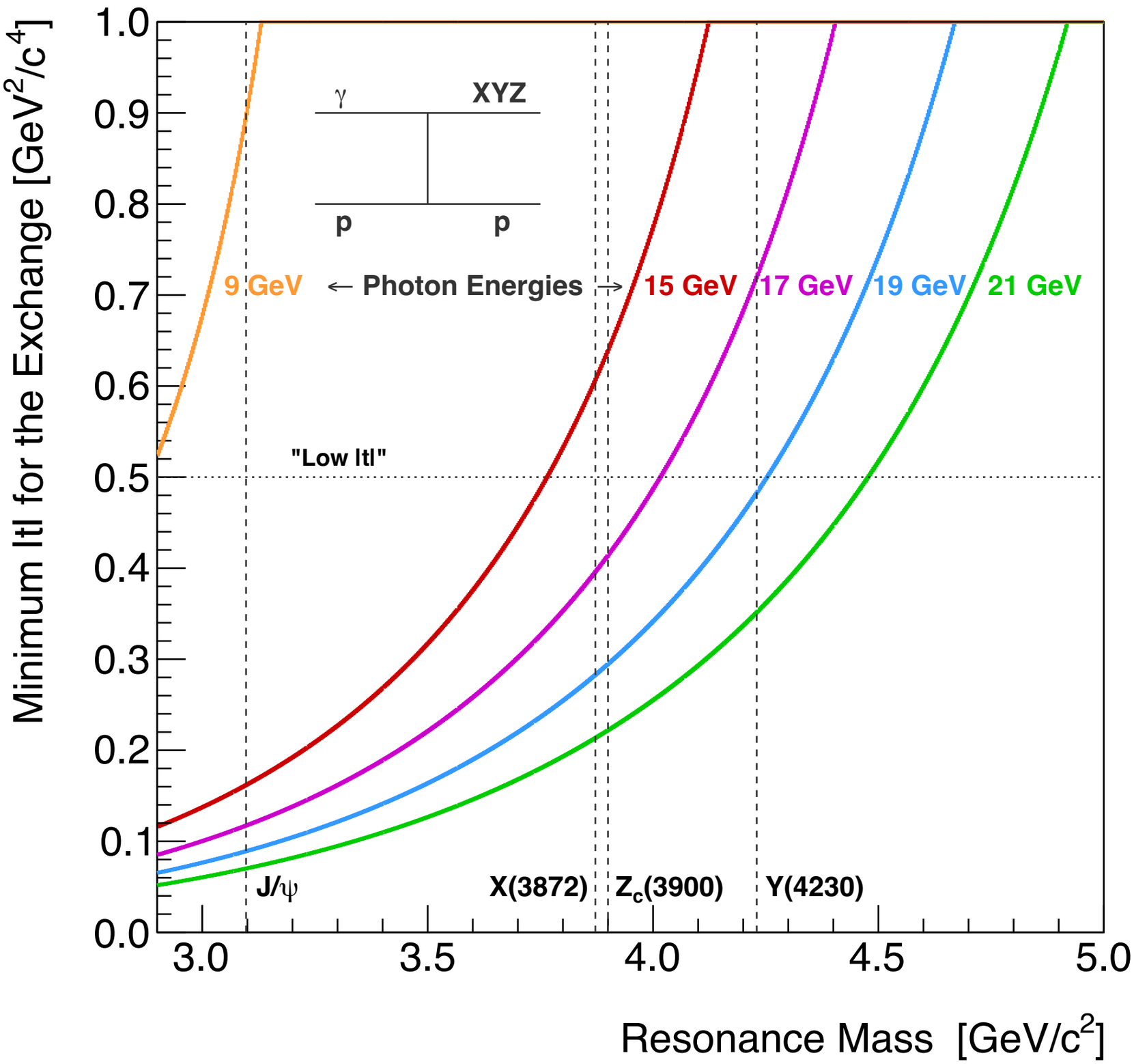
Photoproduction of Exotic Charmonium at JLab



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This Talk:

(I) Understanding the $X(3872)$

- known facts
- the global program
- the role of JLab 22 GeV

(II) Understanding the $Y(4230)$

- known facts
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(III) Understanding the $Z_c(3900)$

- known facts
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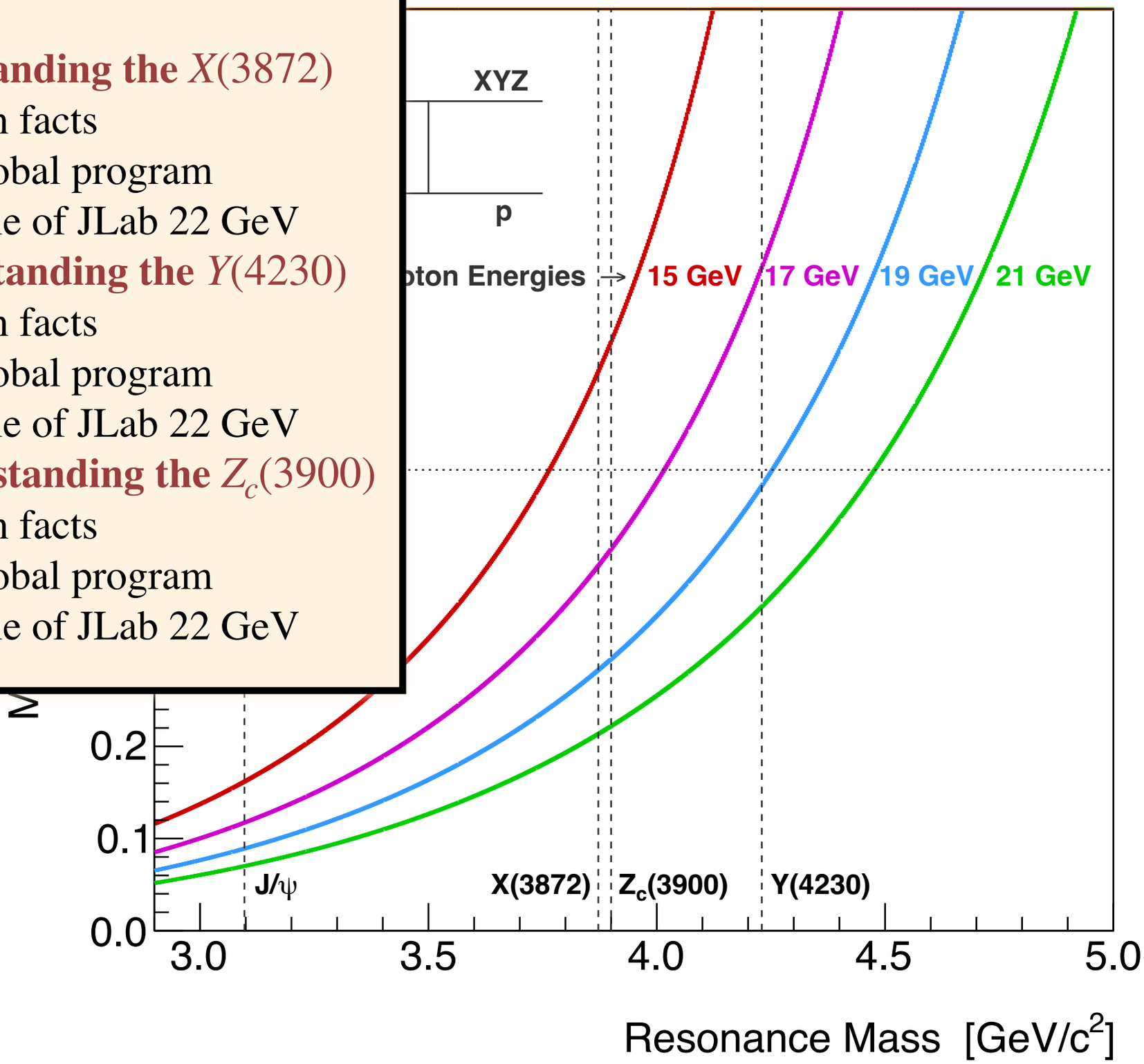

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(1) Its mass is *very* close to D^0D^{*0} threshold:

- $M(3872) - M(D^0D^{*0})$
  $= M(3872) - 2M(D^0) - [M(D^{*0}) - M(D^0)]$
  $= (3871.65 \pm 0.06) - 2(1864.84 \pm 0.05) - (142.02 \pm 0.03)$
  $= -0.05 \pm 0.12\ \mathrm{MeV}/c^2$

(2) It's produced in many different processes:

- $B \to KX(3872)$
- $pp \to X(3872)$ inclusive
- PbPb $\to X(3872)$ inclusive
- $e^+e^- \to \gamma X(3872)$
- $e^+e^- \to \omega X(3872)$
- among others

(3) Absolute branching fractions to many channels are known:
[*thanks to an absolute measurement of* $B(B^+ \to K^+X(3872))$]:

- $\rho J/\psi, \omega J/\psi, D^0D^{*0}, \pi^0\chi_{c1}$, etc.

(4) Its total width has been measured several ways.

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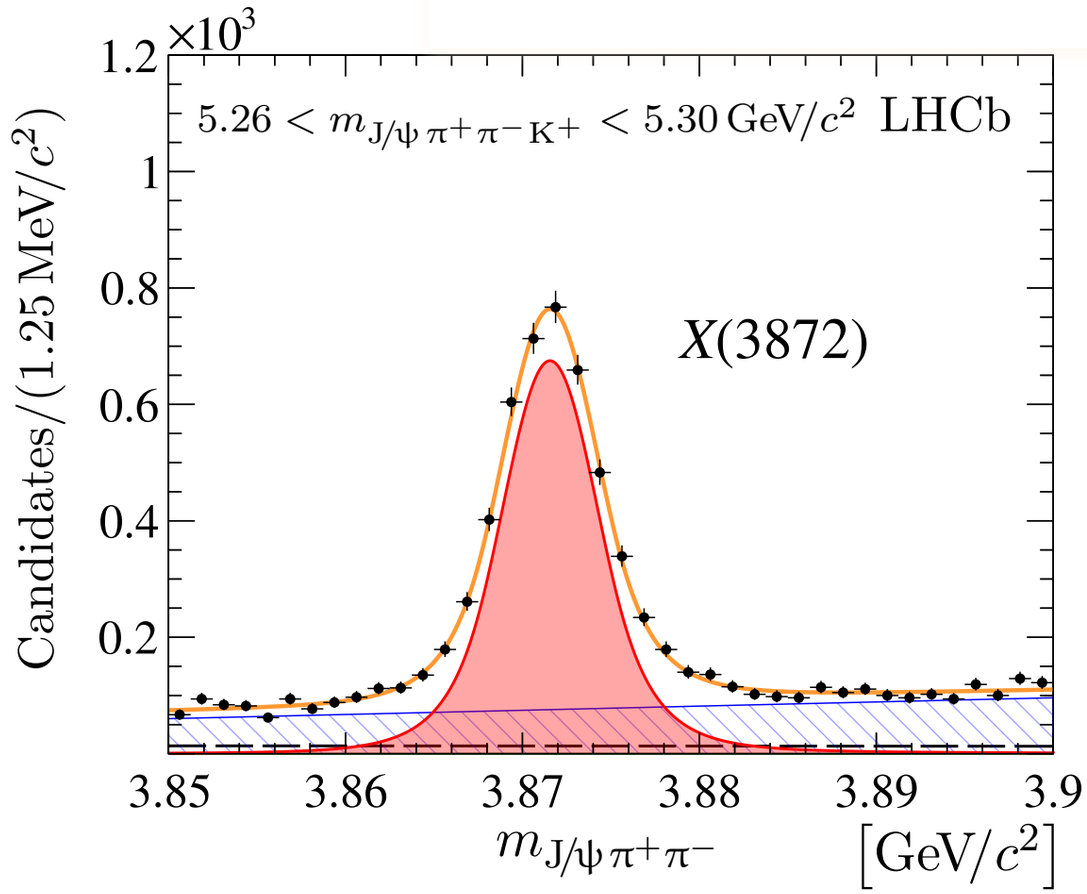

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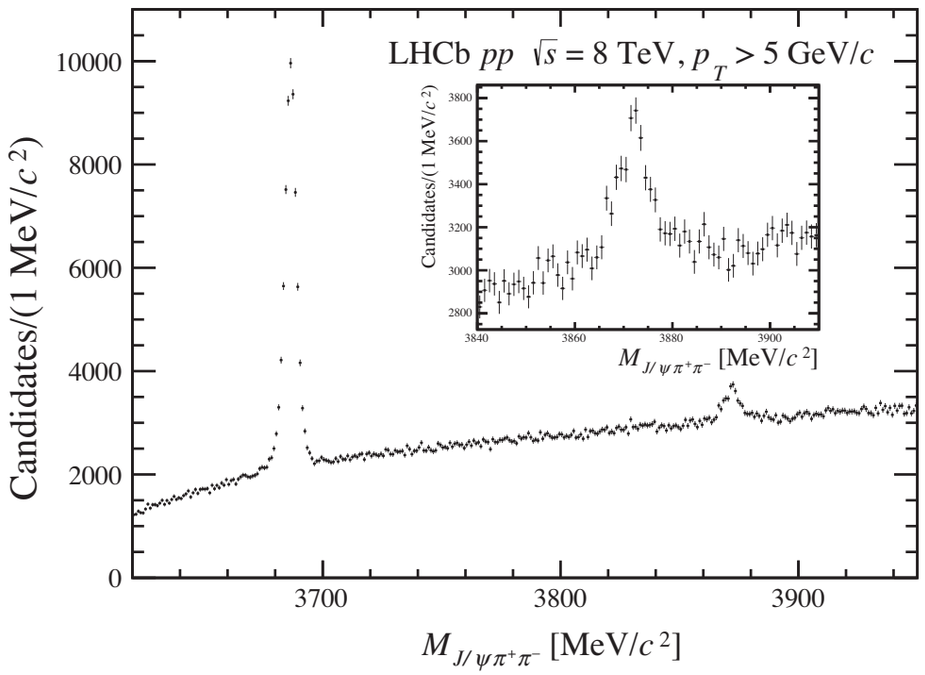
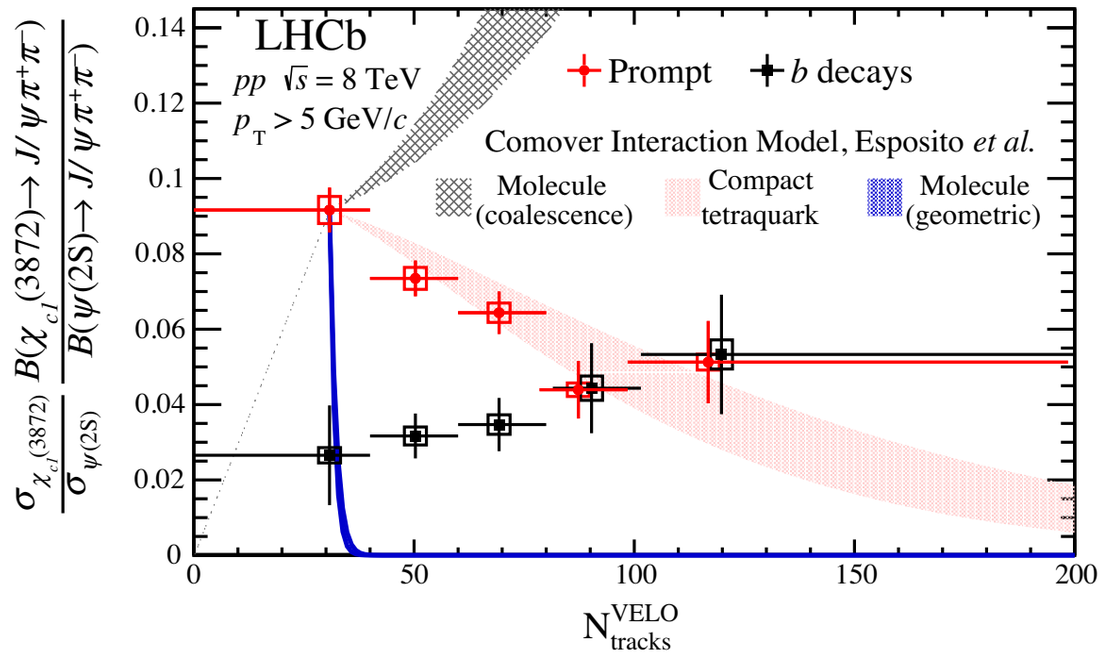
PHYSICAL REVIEW LETTERS **126,** 092001 (2021)

LHCb

Observation of Multiplicity Dependent Prompt $\chi_{c1}(3872)$ and $\psi(2S)$ Production in pp Collisions





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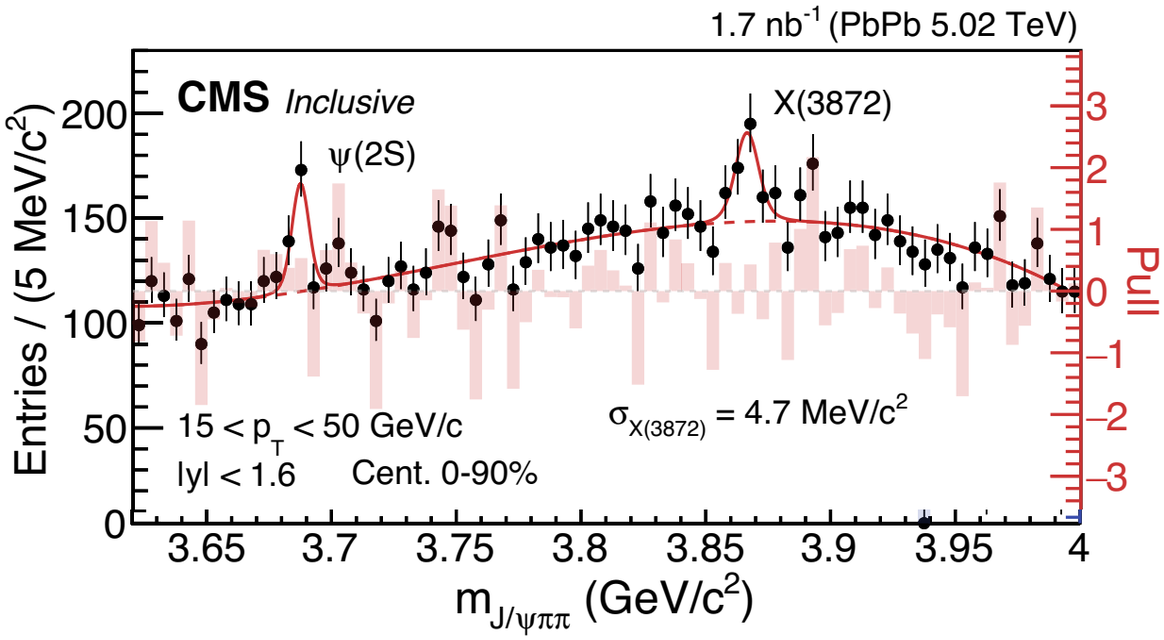
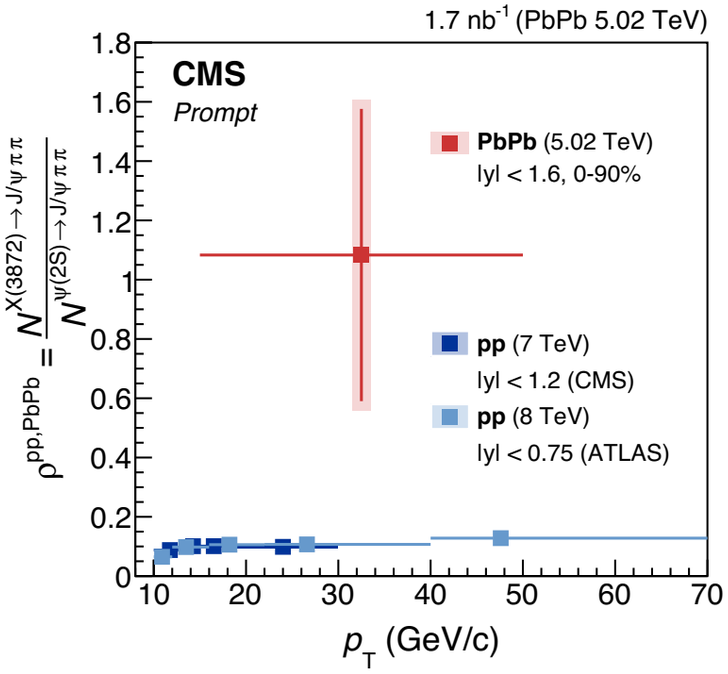
PHYSICAL REVIEW LETTERS **128,** 032001 (2022)

CMS

Evidence for X(3872) in Pb-Pb Collisions and Studies of its Prompt Production at $\sqrt{s_{NN}} = 5.02$ TeV





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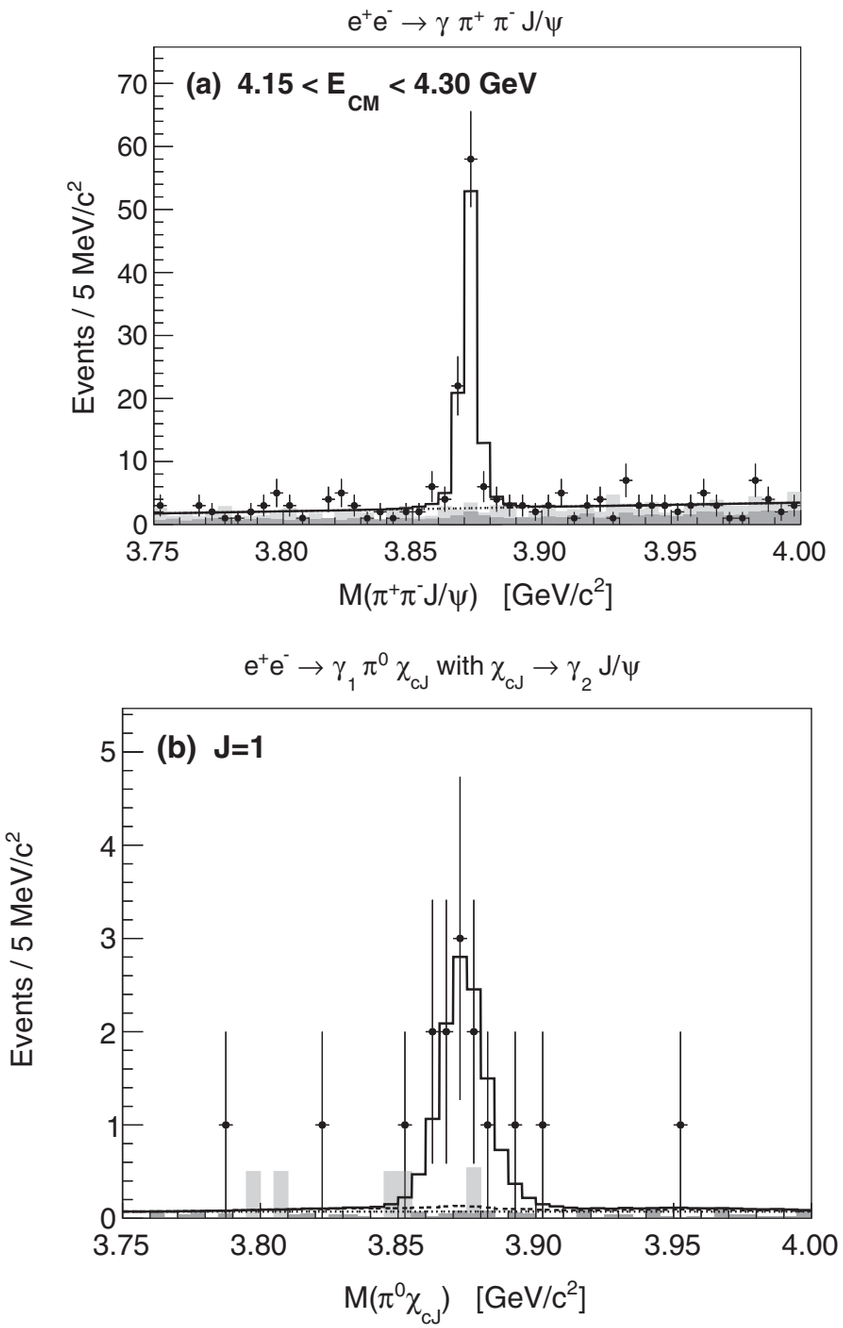
PHYSICAL REVIEW LETTERS **122,** 202001 (2019)

BESIII

Observation of the Decay $X(3872) \to \pi^0\chi_{c1}(1P)$



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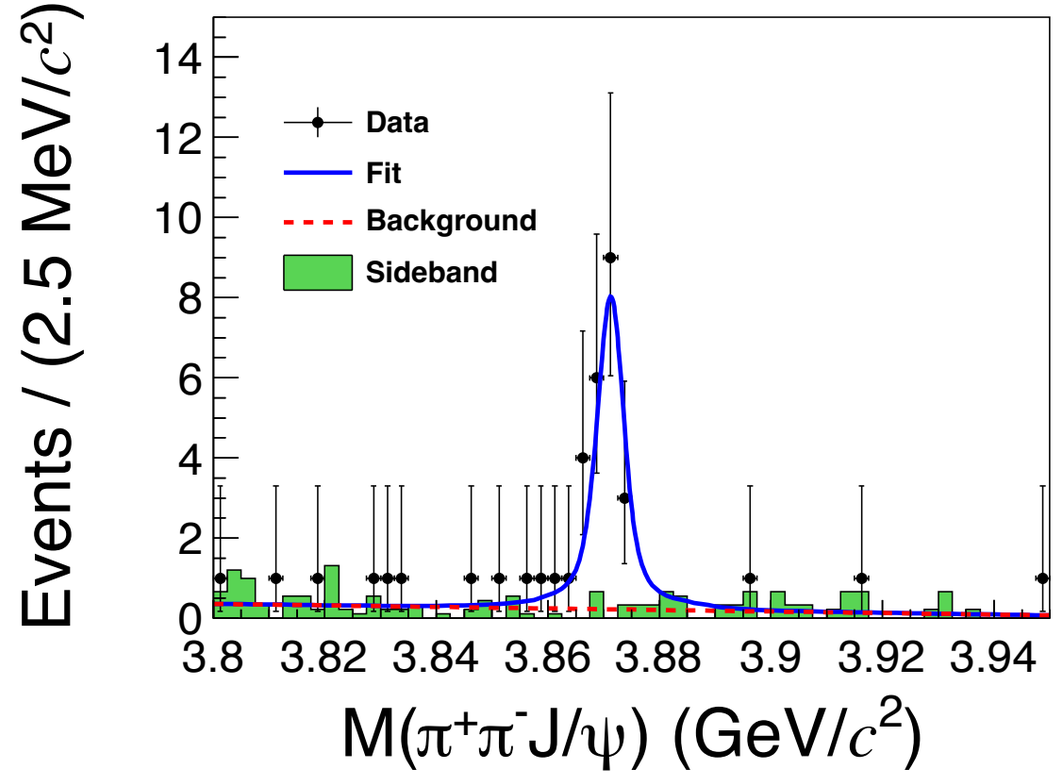
BESIII, arXiv:2212.07291

Observation of a new $X(3872)$ production process $e^+e^- \to \omega X(3872)$



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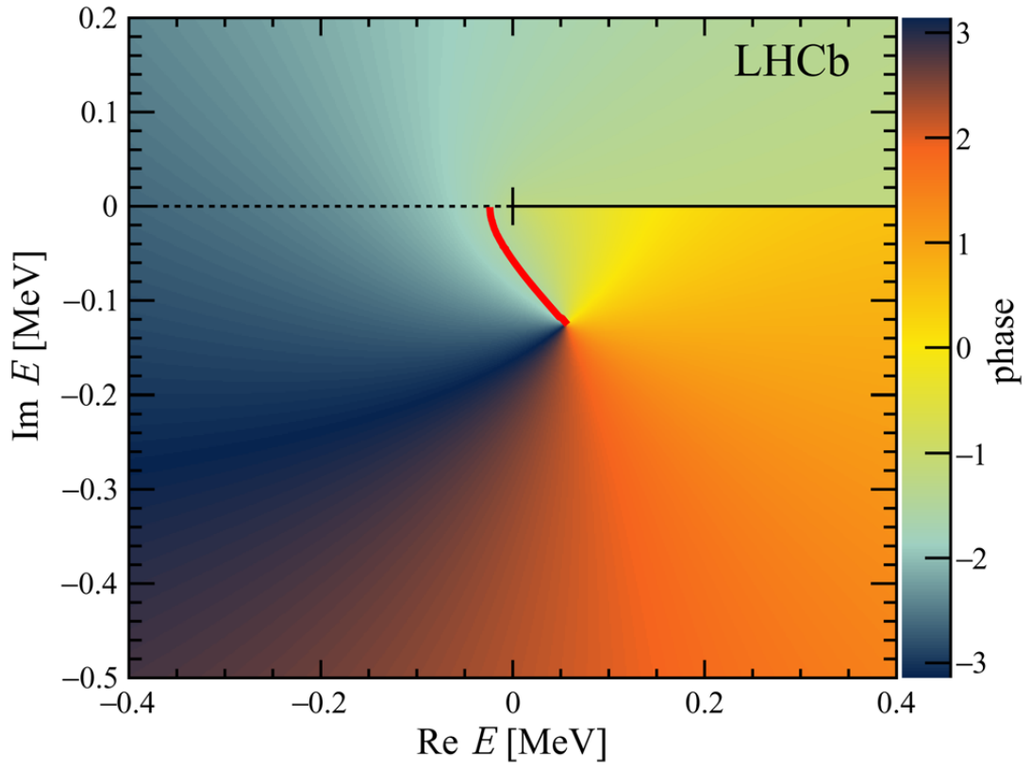
PHYSICAL REVIEW D **102,** 092005 (2020)

LHCb

Study of the lineshape of the $\chi_{c1}(3872)$ state



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(1) Study the lineshape in more detail *(to distinguish between tetraquark and molecular interpretations, etc.)*:

- increased statistics at the LHC
- multi-channel analyses at BESIII (and later STCF in China?)
- $p\bar{p}$ production at PANDA?

(2) Find (presumably) related states:

- the $T_{cc}(3875)$ at LHCb
- the $T_{cs}(2900)$ at LHCb
- the $T_{c\bar{s}}(2900)$ (with $I = 1$) at LHCb (arXiv:2212:02716)

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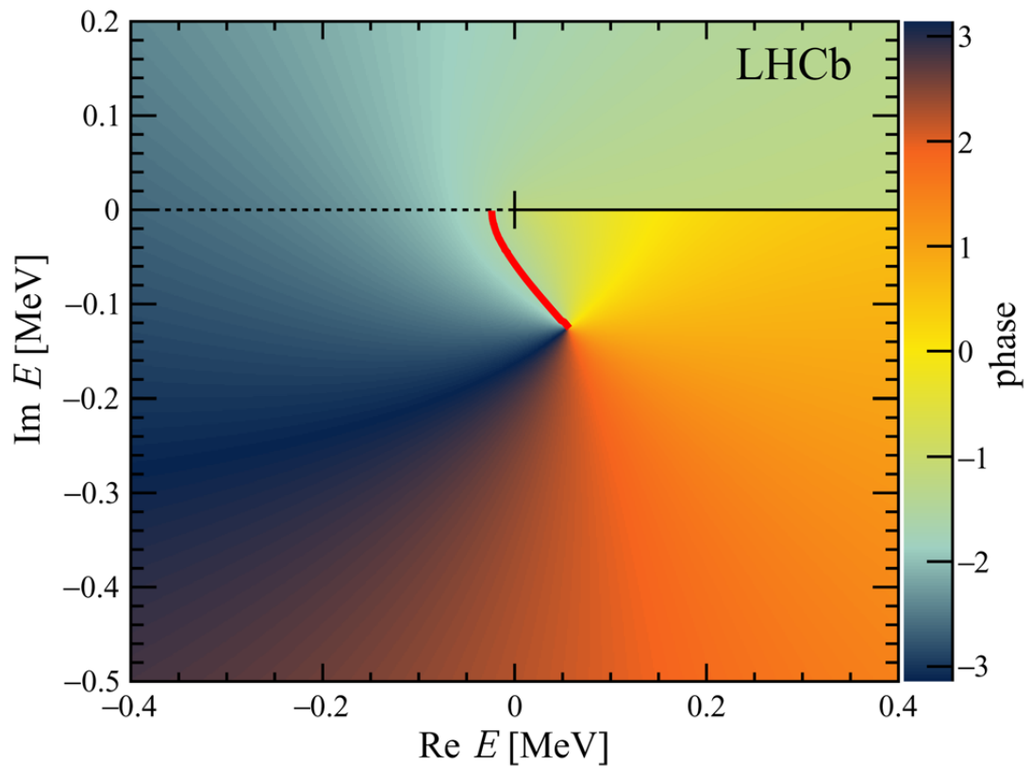

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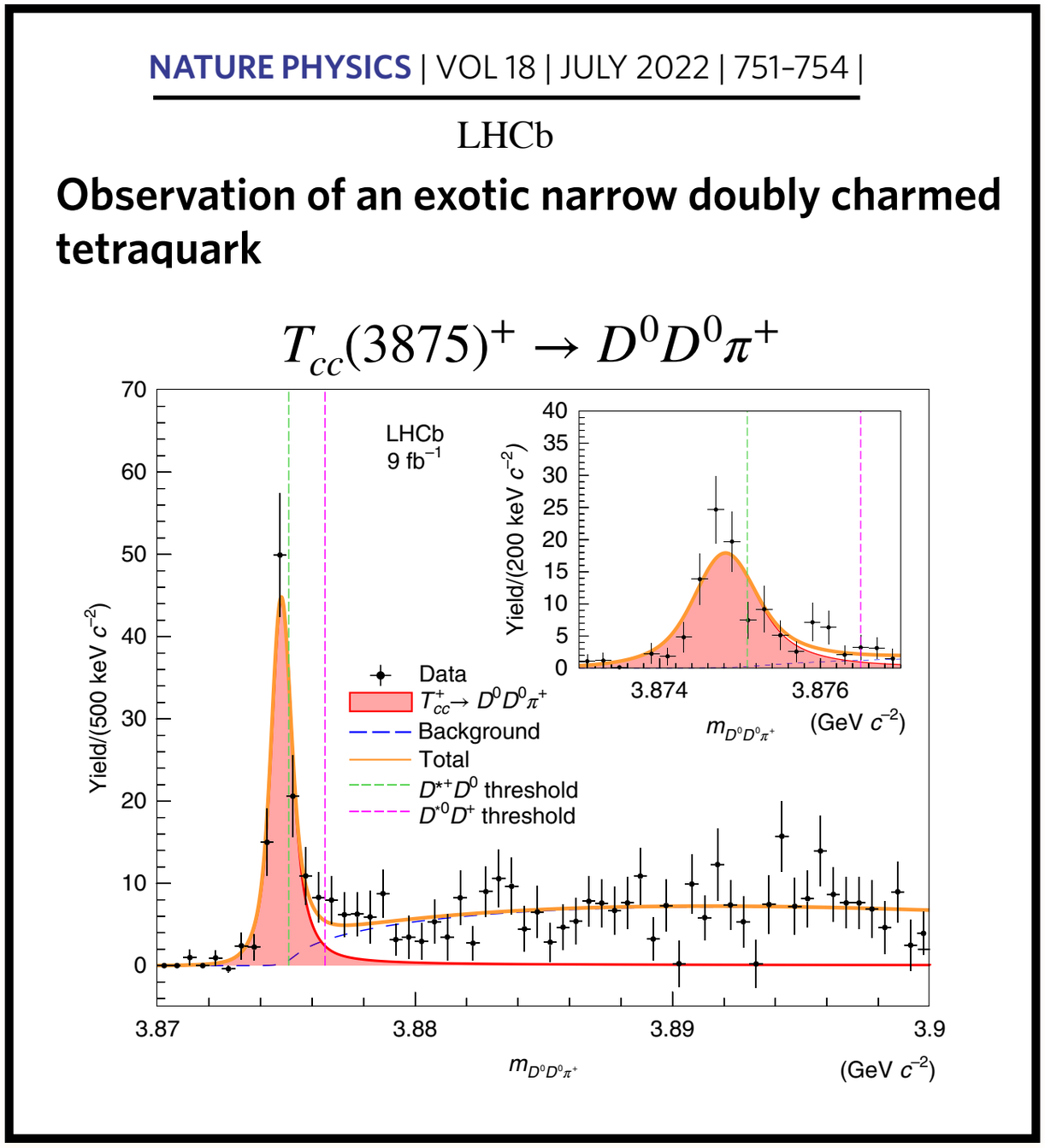

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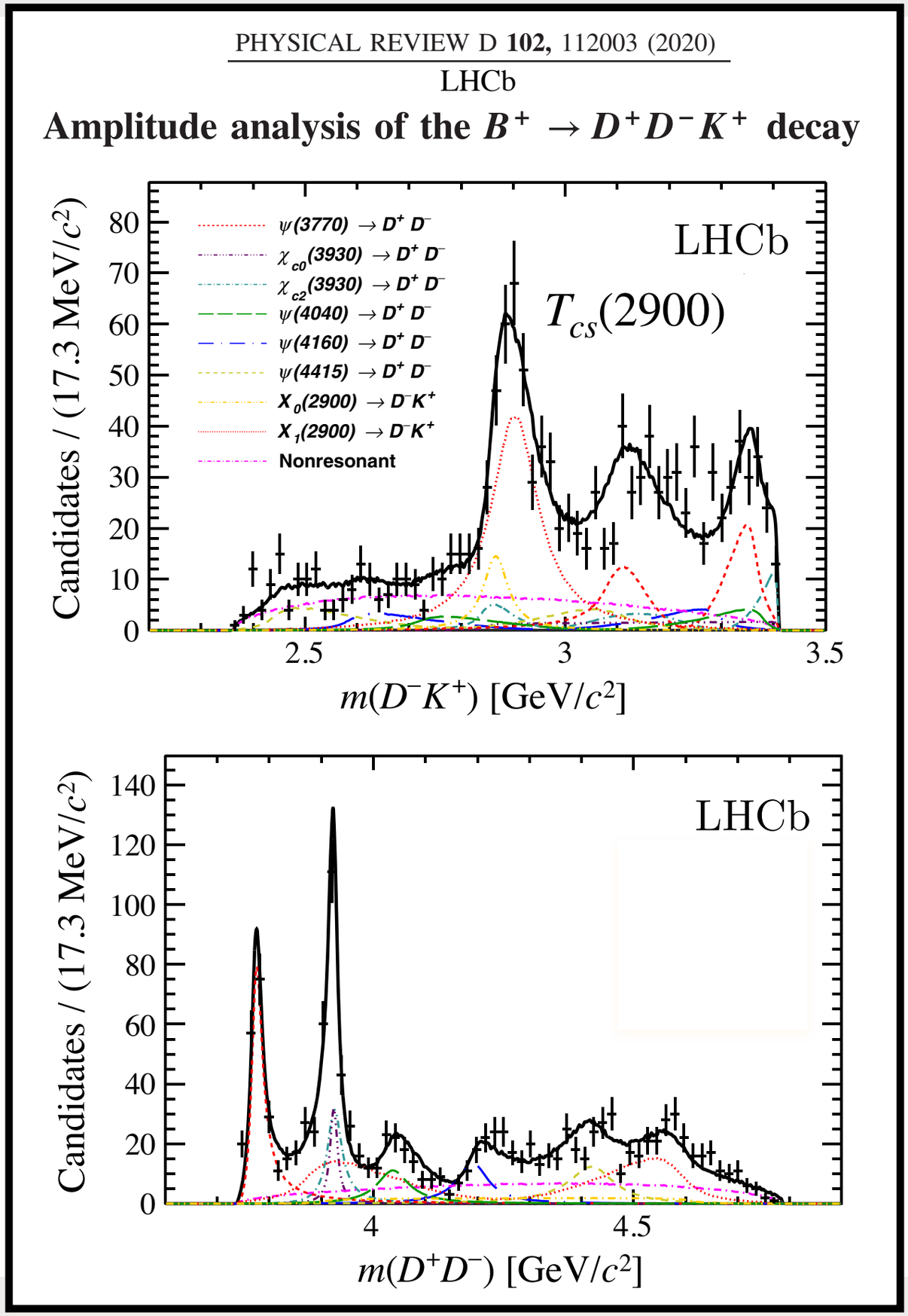

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(1) Use photoproduction of the $X(3872)$ as a way to fine-tune models of XYZ photoproduction:

- general features of the $X(3872)$ are known
- models of $X(3872)$ photoproduction have significant uncertainties

(2) Investigate the intriguing photoproduction (muoproduction) results from COMPASS:

- upper limits on $\gamma N \to X(3872)N'$, but observation of $\gamma N \to \tilde{X}(3872)\pi N'$ (?)

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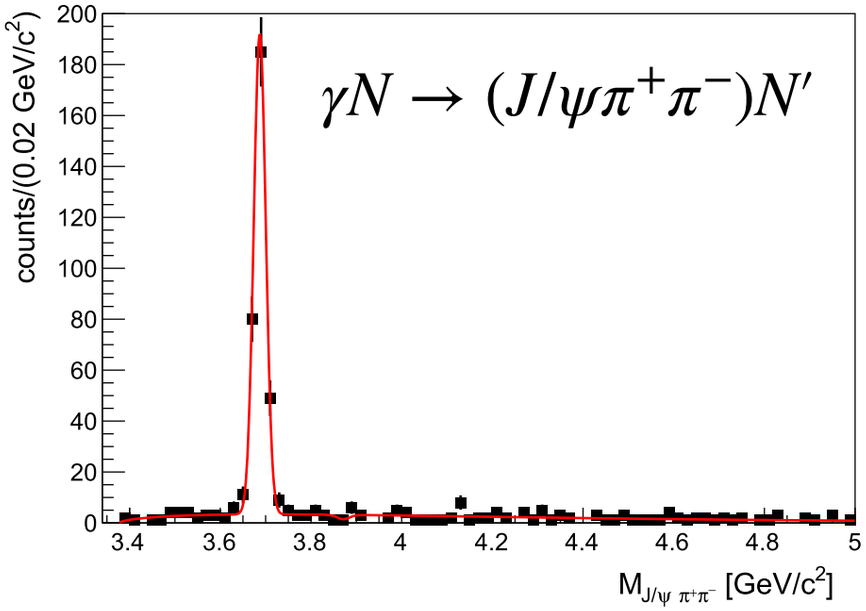
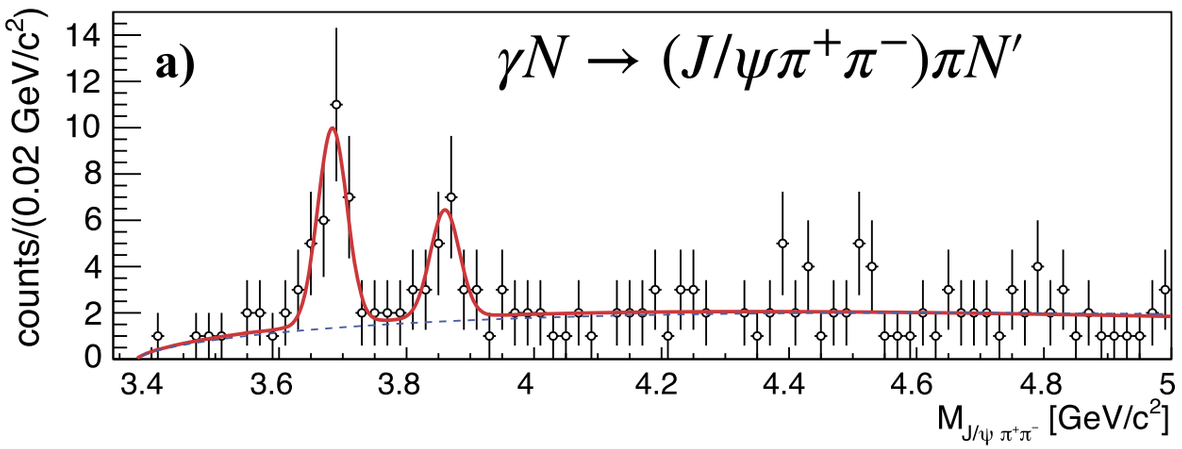
Physics Letters B 783 (2018) 334–340

COMPASS

Search for muoproduction of $X(3872)$ at COMPASS and indication of a new state $\widetilde{X}(3872)$





$\sigma_{\gamma N\to X(3872)N'} \times \mathcal{B}_{X(3872)\to J/\psi\pi\pi} < 2.9$ pb (CL = 90%).

$\sigma_{\gamma N\to \widetilde{X}(3872)\pi N'} \times \mathcal{B}_{\widetilde{X}(3872)\to J/\psi\pi\pi} = 71 \pm 28(\text{stat}) \pm 39(\text{syst})$ pb.

(II) Understanding the $Y(4230)$: *Known Facts*

(1) The $Y(4230)$ is one of a series of states seen in e^+e^- cross sections:

- the 2022 PDG includes:
  $\psi(4040), \psi(4160), \psi(4230),$
  $\psi(4360), \psi(4415), \psi(4630)$

(2) Exclusive e^+e^- cross sections vary dramatically from final state to final state:

- $\pi\pi J/\psi, \pi\pi\psi(2S), \omega\chi_{c0}, \eta J/\psi,$ etc. etc.

(3) Similar features are (apparently) absent in the inclusive e^+e^- cross section.

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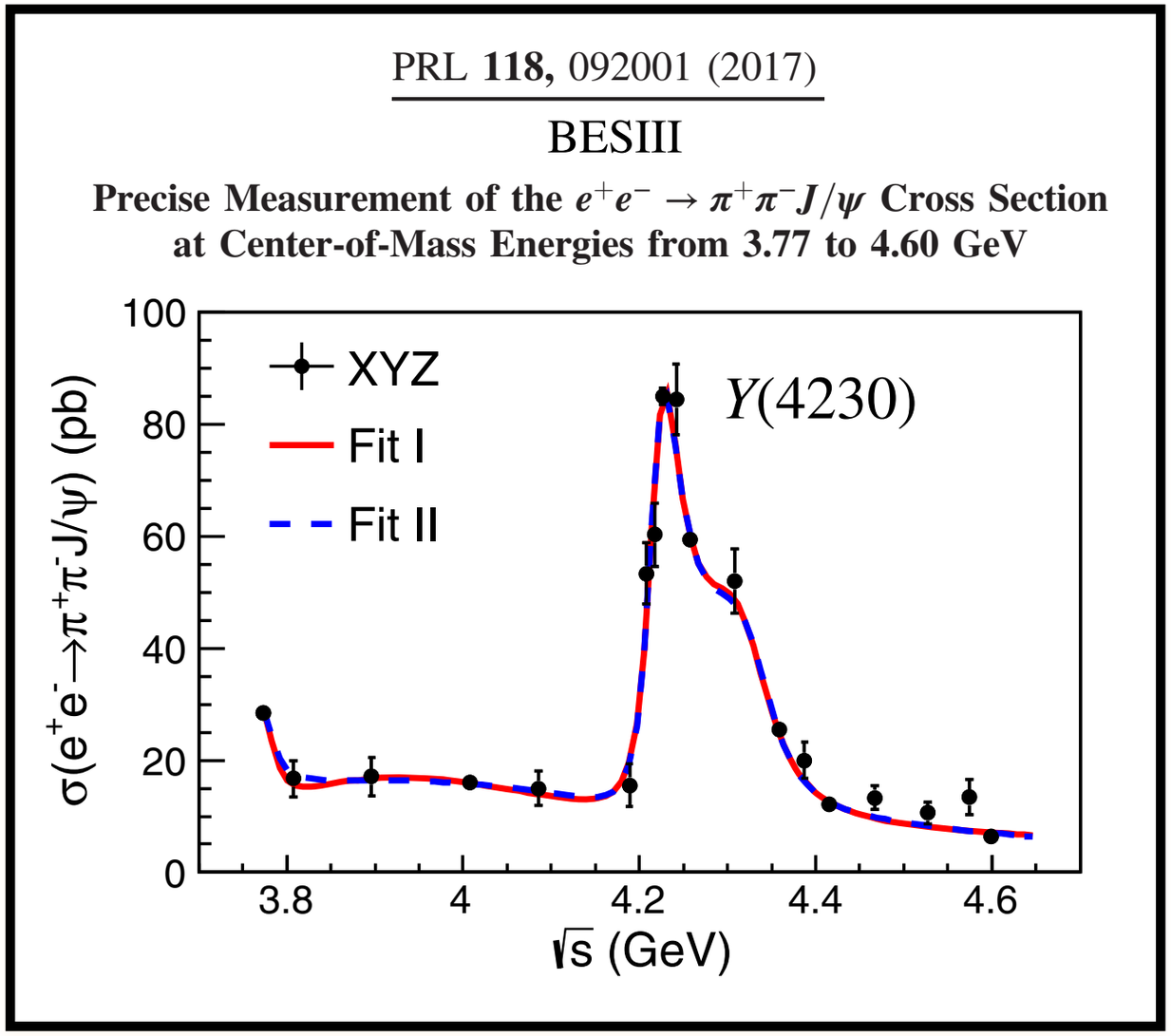

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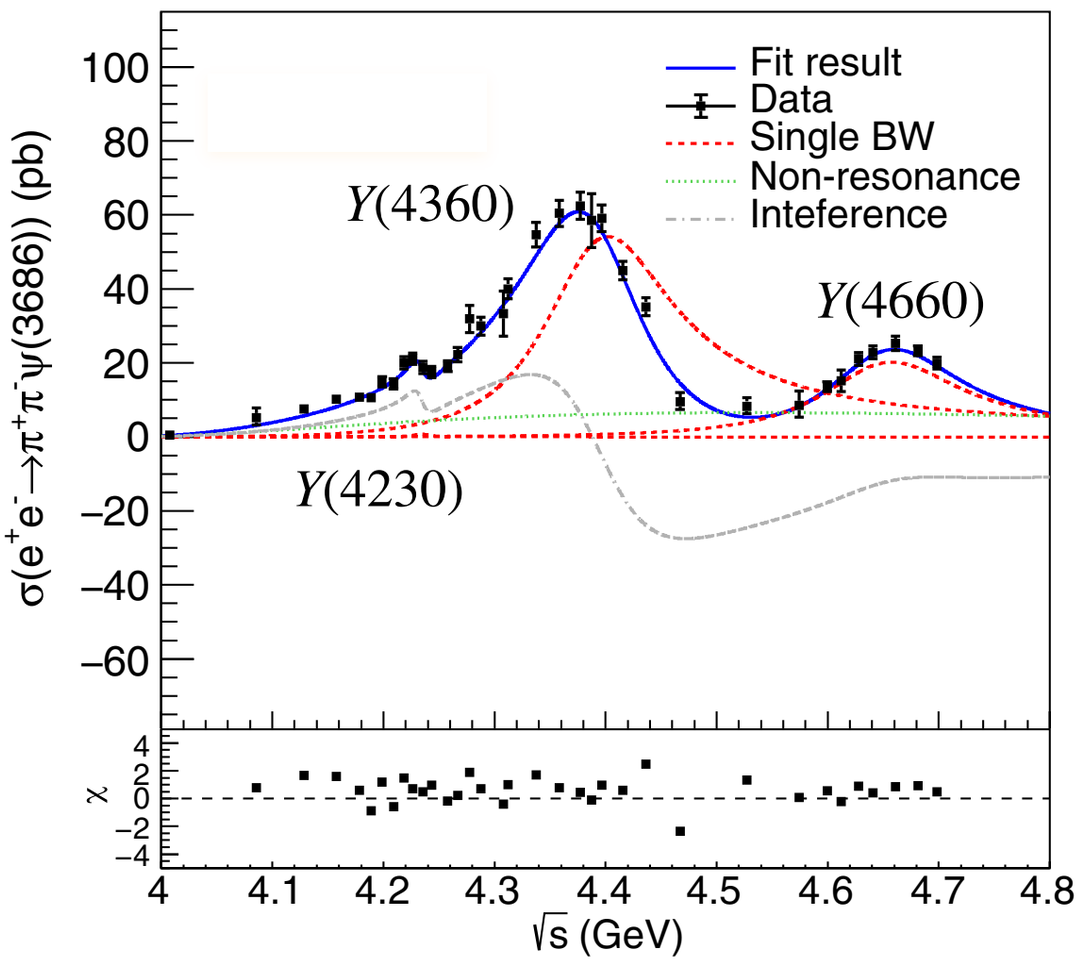
PHYSICAL REVIEW D **104,** 052012 (2021)

BESIII

Cross section measurement of $e^+e^- \to \pi^+\pi^-\psi(3686)$ from $\sqrt{s} = 4.0076$ GeV to 4.6984 GeV



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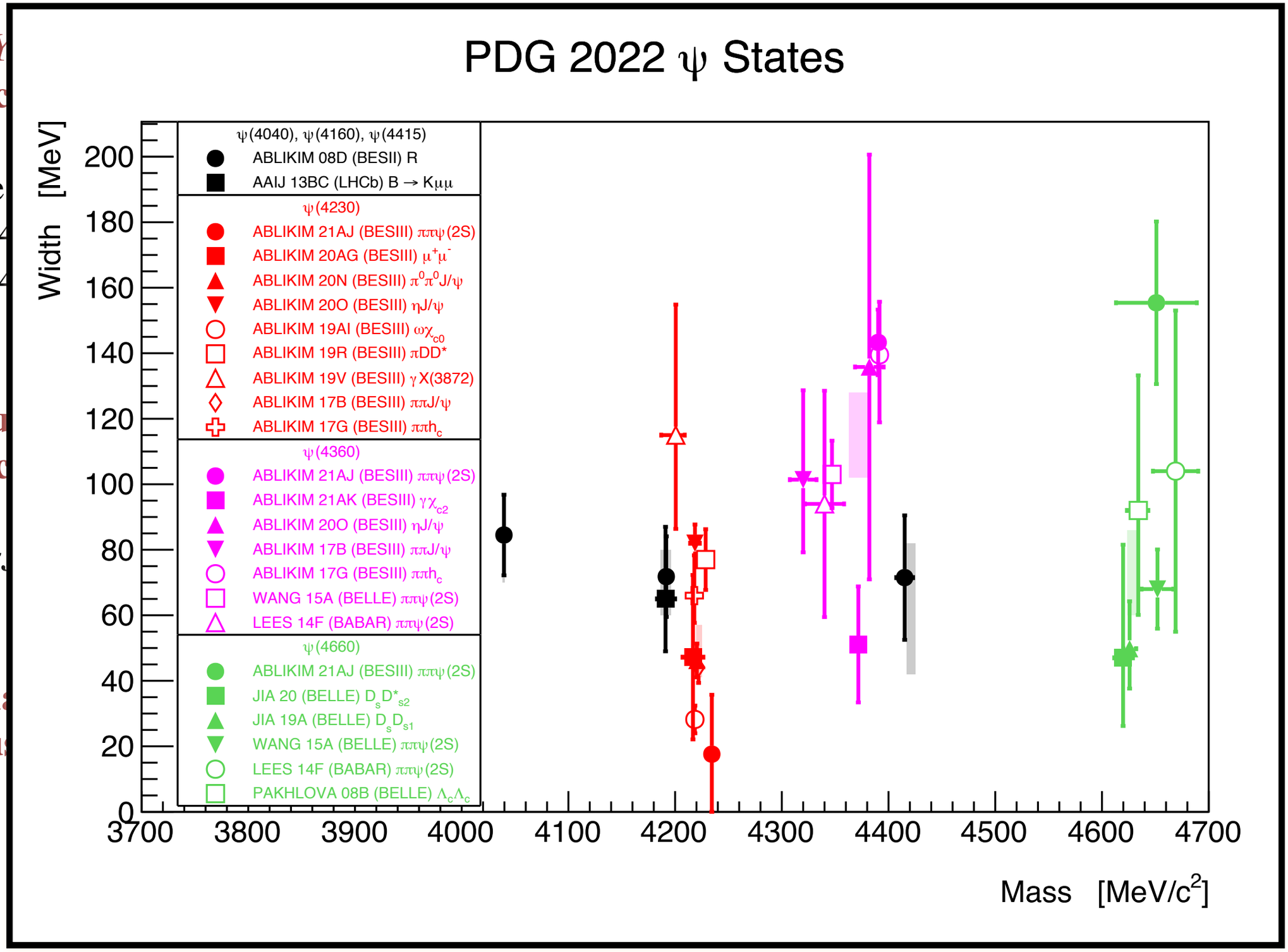

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(1) Investigate similar features in bottomonium to isolate states:

- global multi-channel K-matrix fits
- improve statistics with energy scans at Belle II?

(2) Apply lessons from bottomonium to charmonium to isolate states:

- global multi-channel K-matrix fits (ongoing, harder than bottomonium)
- measure more exclusive e^+e^- cross sections at BESIII (and STCF in China?)

(3) Find new production mechanisms:

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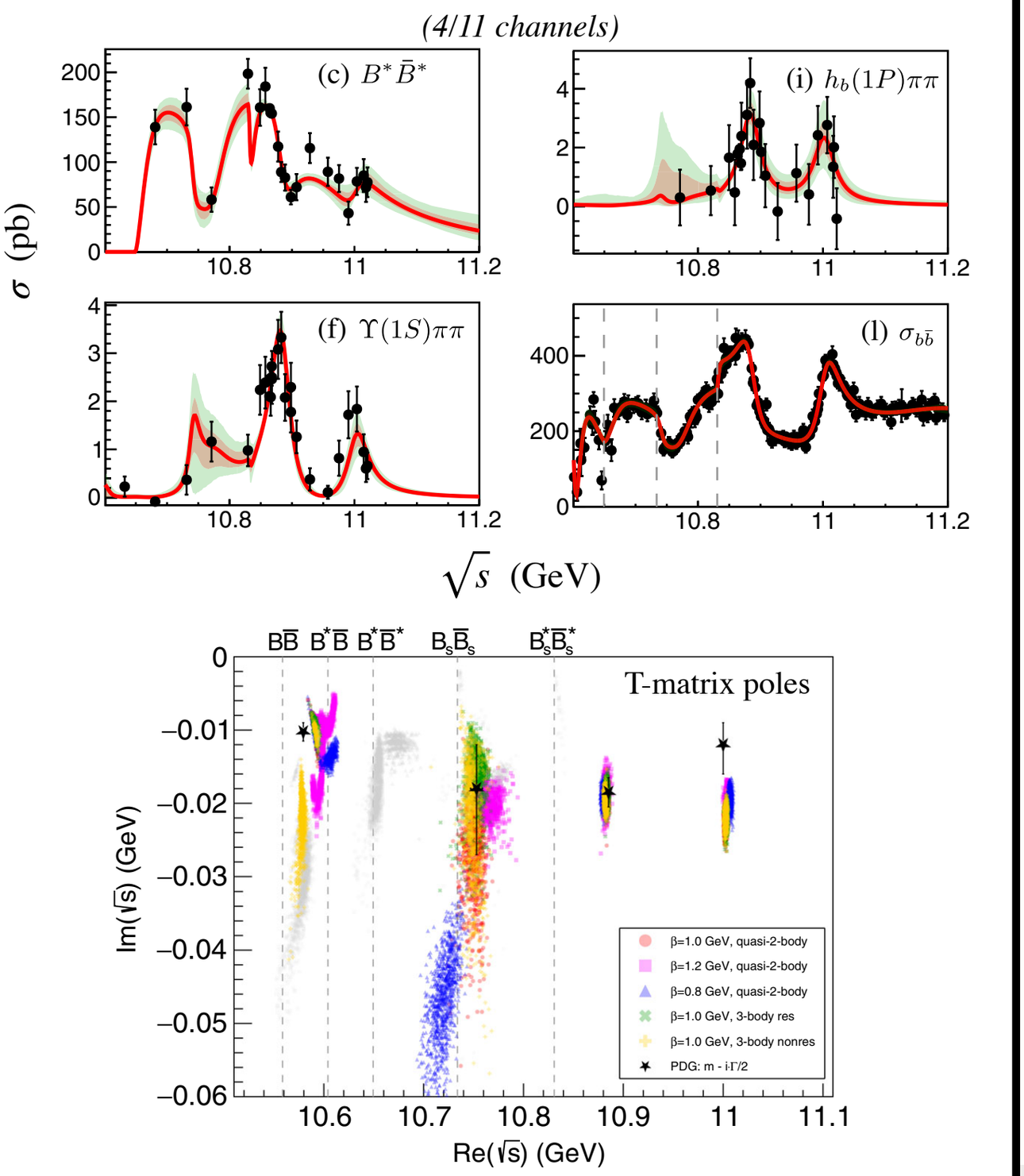
PHYSICAL REVIEW D **106,** 094013 (2022)

K-matrix analysis of e^+e^- annihilation in the bottomonium region

N. Hüsken,[1,2] R. E. Mitchell,[1] and E. S. Swanson[3]



(II) Understanding the $Y(4230)$: *The Role of JLab 22 GeV*

(1) Exploit the (presumably) close connection between e^+e^- and γp cross sections:

- measure exclusive cross sections for $\gamma p \to (\pi\pi J/\psi), (\eta J/\psi), (D\bar{D}), (etc.)p$ to create another handle for understanding the Y states

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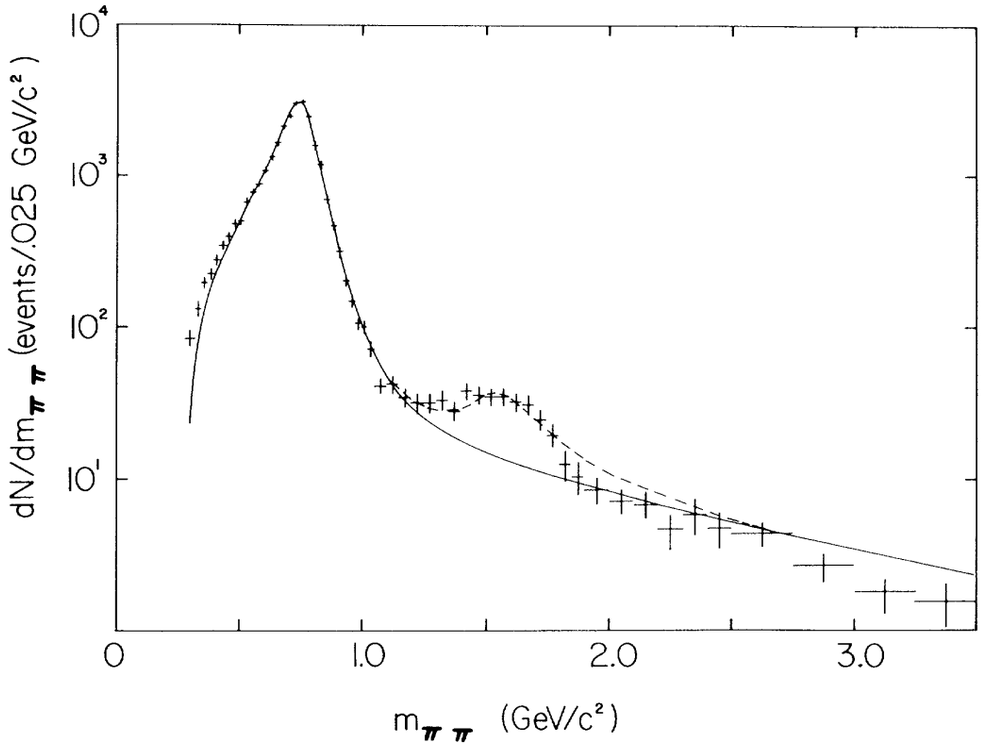
PRL 53, 751 (1984)

(SLAC Hybrid Facility Photon Collaboration)

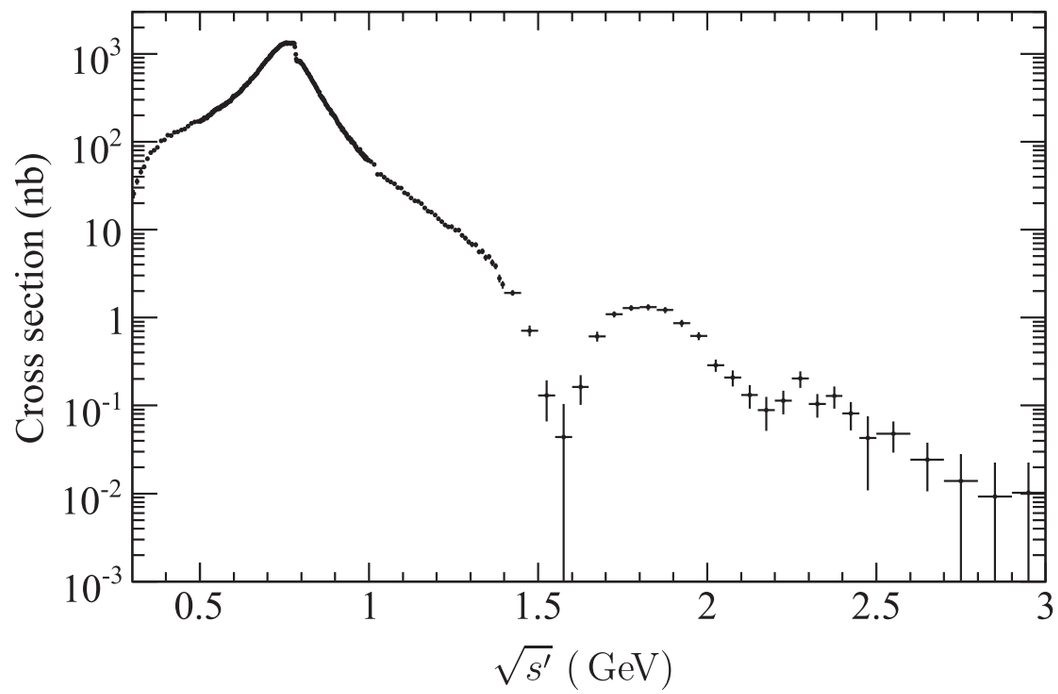
Study of the $\rho'(1600)$ Mass Region Using $\gamma p \to \pi^+\pi^- p$ at 20 GeV



PHYSICAL REVIEW D **86,** 032013 (2012)

BABAR

Precise measurement of the $e^+e^- \to \pi^+\pi^-(\gamma)$ cross section with the initial-state radiation method at *BABAR*



(III) Understanding the $Z_c(3900)$: *Known Facts*

(1) The $Z_c(3900)$ appears in the substructure of $Y(4230)$ decays:

- $e^+e^- \to Y(4230) \to \pi^\mp Z_c(3900)^\pm \to \pi^\mp(\pi^\pm J/\psi)$
- $e^+e^- \to Y(4230) \to \pi^\mp Z_c(3900)^\pm \to \pi^\mp(D\bar{D}^* + \bar{D}D^*)^\pm$
- $e^+e^- \to Y(4230) \to \pi^0 Z_c(3900)^0 \to \pi^0(\pi^0 J/\psi)$
- $e^+e^- \to Y(4230) \to \pi^0 Z_c(3900)^0 \to \pi^0(D\bar{D}^* + \bar{D}D^*)^0$

(2) The J^{PC} is conclusively 1^{+-}.

(3) Similar structures have been found in related $Y(4230)$ decays:

- $e^+e^- \to Y(4230) \to \pi^\mp Z_c(4020)^\pm \to \pi^\mp(\pi^\pm h_c)$
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(4) Presumably related to the $Z_c(3900)$, Z_{cs} states have also been found:

- $e^+e^- \to KZ_{cs} \to K(D_sD^* + D_s^*D)$ at BESIII
- $B \to \phi Z_{cs} \to \phi(KJ/\psi)$ at LHCb

(5) So far the $Z_c(3900)$ has only been seen in $Y(4230)$ decays.

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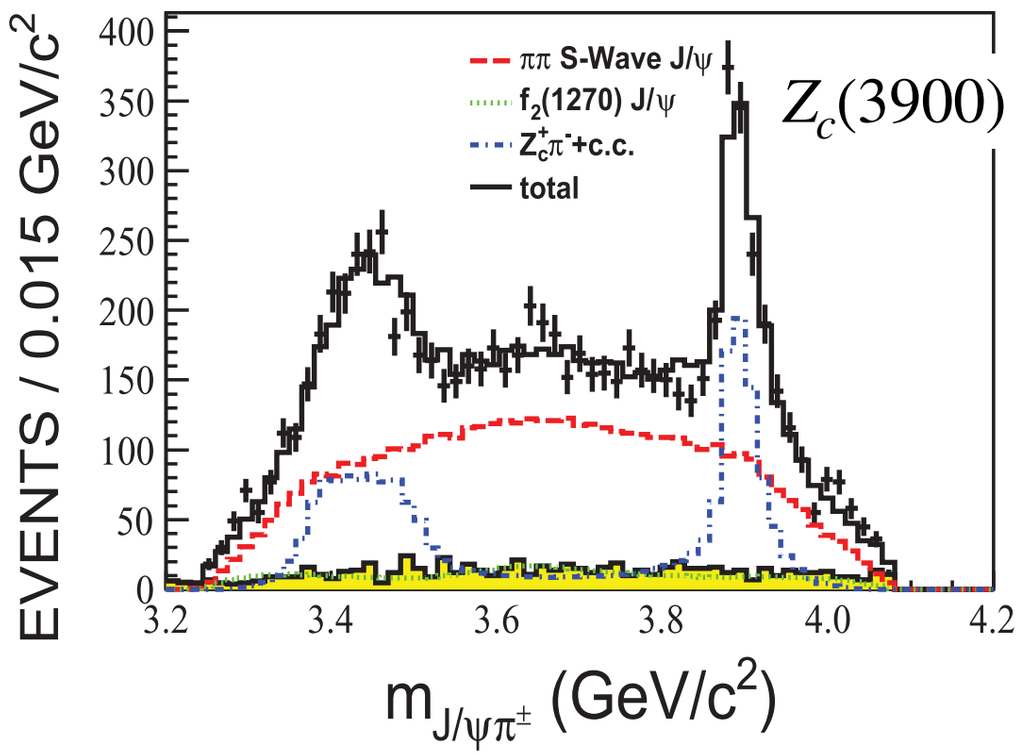
PRL **119,** 072001 (2017)

BESIII

Determination of the Spin and Parity of the $Z_c(3900)$

$e^+e^- \to \pi^+\pi^- J/\psi$ at 4.23 GeV



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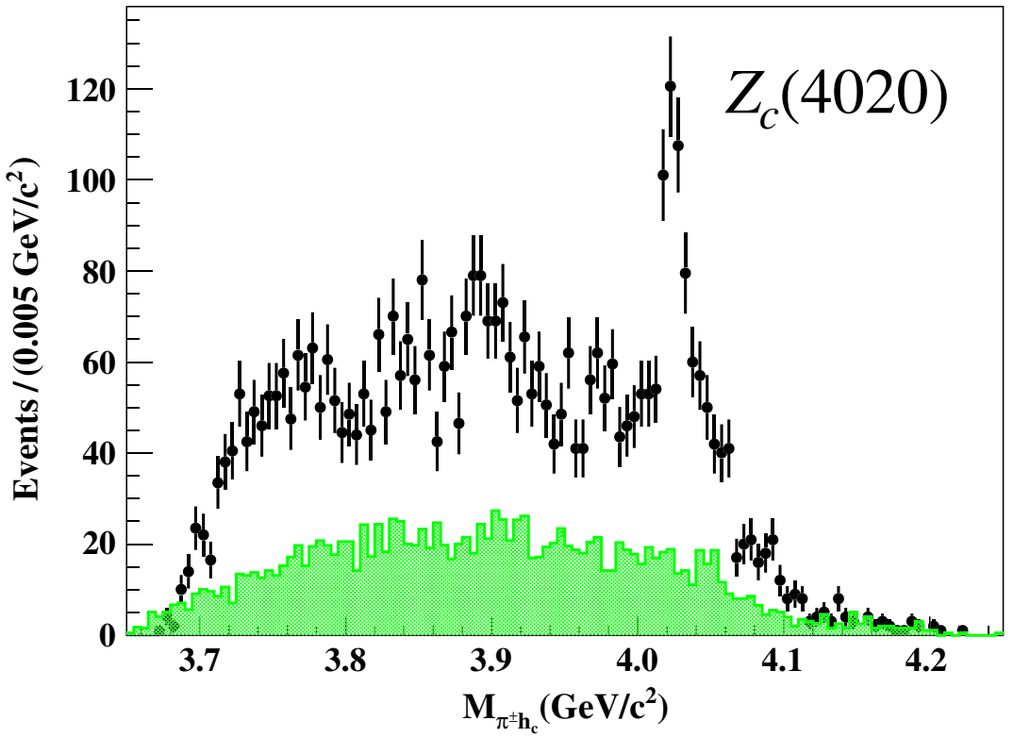
PRL **111,** 242001 (2013)

BESIII

Observation of a Charged Charmoniumlike Structure $Z_c(4020)$ and Search for the $Z_c(3900)$ in $e^+e^- \to \pi^+\pi^- h_c$



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(III) Understanding the $Z_c(3900)$: *The Global Program*

(1) Study the $Z_c(3900)$ lineshapes in more detail
***(to distinguish between interpretations of the Z_c)*:**

- perform multi-channel fits
- study the Z_c at multiple e^+e^- energies
- collect substantially more data at BESIII (and STCF in China?)

(2) Study similar features in bottomonium:

- $e^+e^- \to \pi^\mp Z_b(10610,10650)^\pm \to \pi^\mp(\pi^\pm\Upsilon(1S,2S,3S))$
- $e^+e^- \to \pi^\mp Z_b(10610,10650)^\pm \to \pi^\mp(\pi^\pm h_b(1P,2P))$
- $e^+e^- \to \pi^\mp Z_b(10610)^\pm \to \pi^\mp(B\bar{B}* + \bar{B}B*)^\pm$
- $e^+e^- \to \pi^\mp Z_b(10650)^\pm \to \pi^\mp(B*\bar{B}*)^\pm$

(3) Compare the $Z_c(3900)$ to the set of Z_c seen in B decays:

- collect BESIII data with higher e^+e^- energies
  (an upgrade in summer 2024 will raise the maximum energy to 5.6 GeV and increase the luminosity by a factor of 3)
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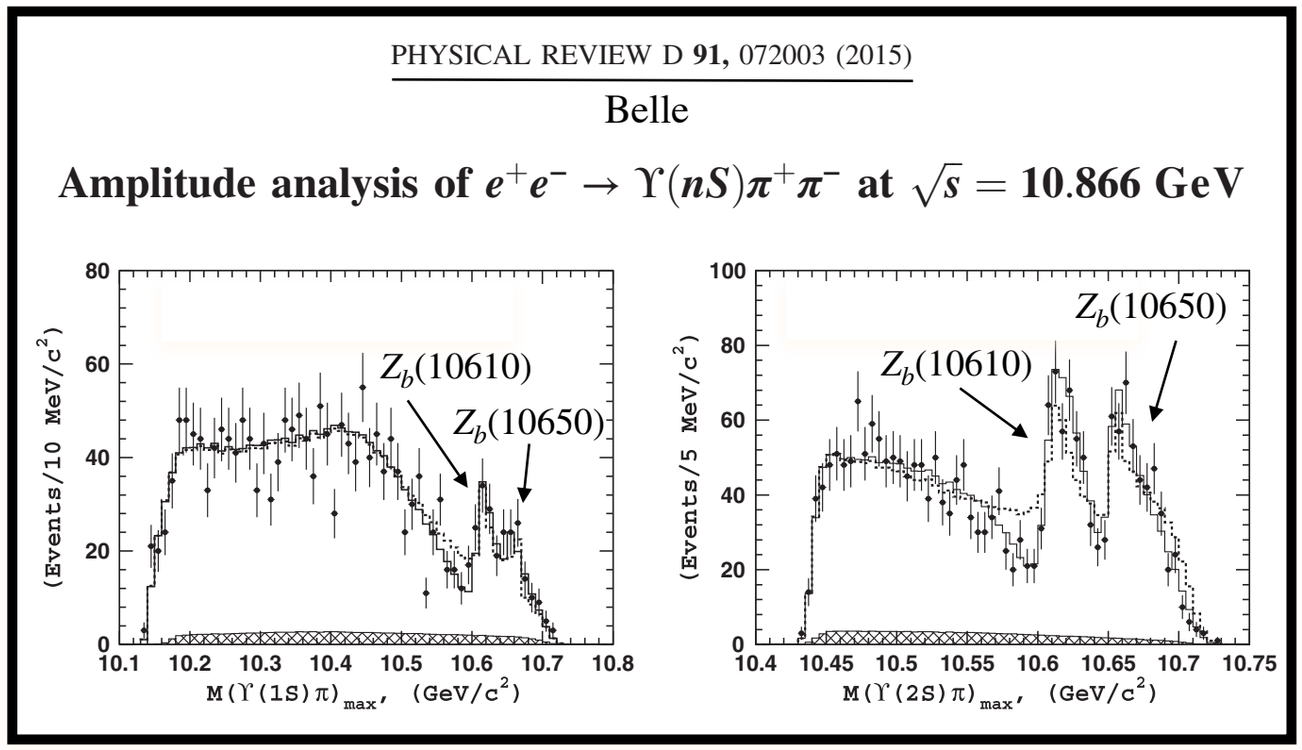

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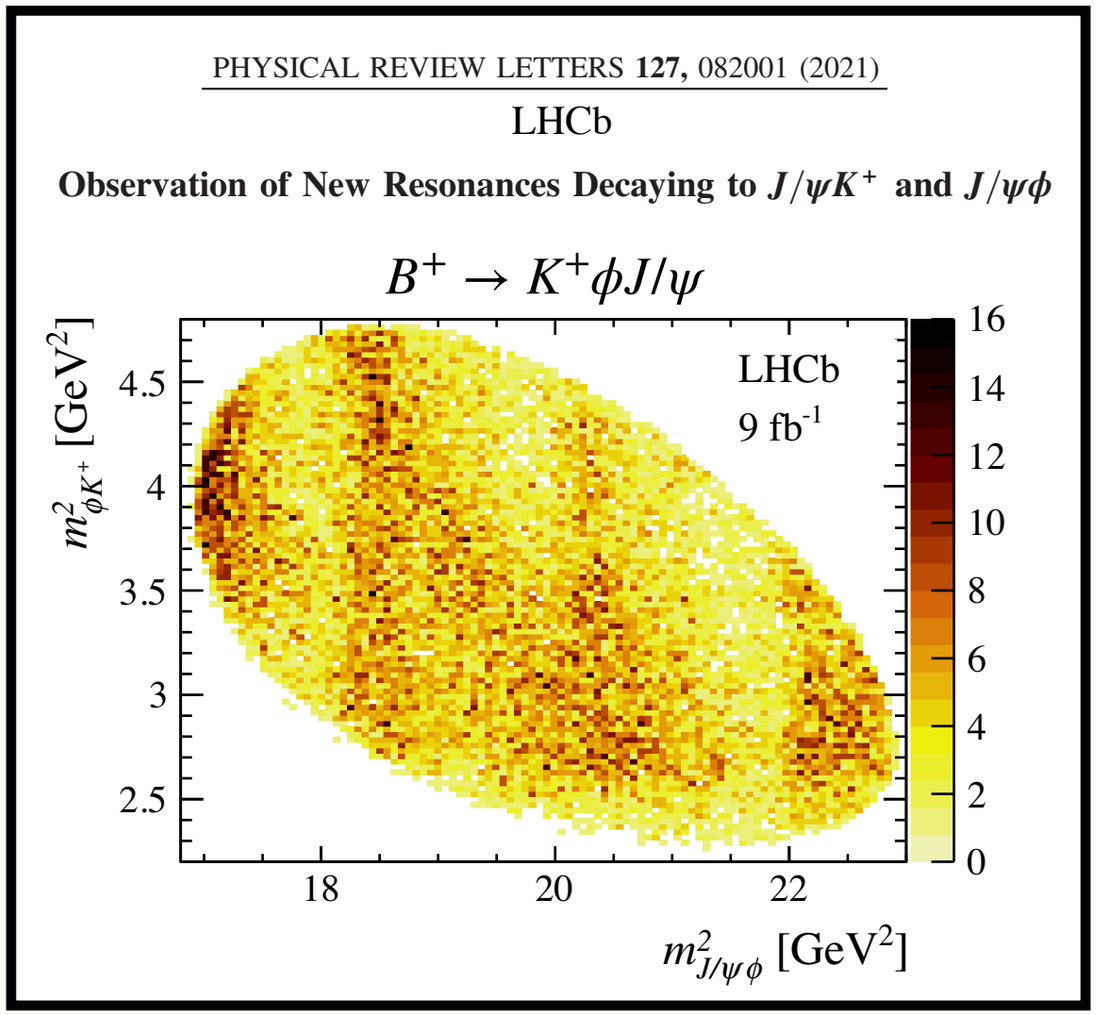

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(III) Understanding the $Z_c(3900)$: *The Role of JLab 22 GeV*

(1) The $Z_c(3900)$ could potentially be photoproduced through single pion exchange.

- the theoretical model for this process ought to be reliable (see Alessandro's talk)

- if the $Z_c(3900)$ is not found, this could (hopefully) provide important information about the nature of the $Z_c(3900)$

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XYZ spectroscopy at electron-hadron facilities: Exclusive processes

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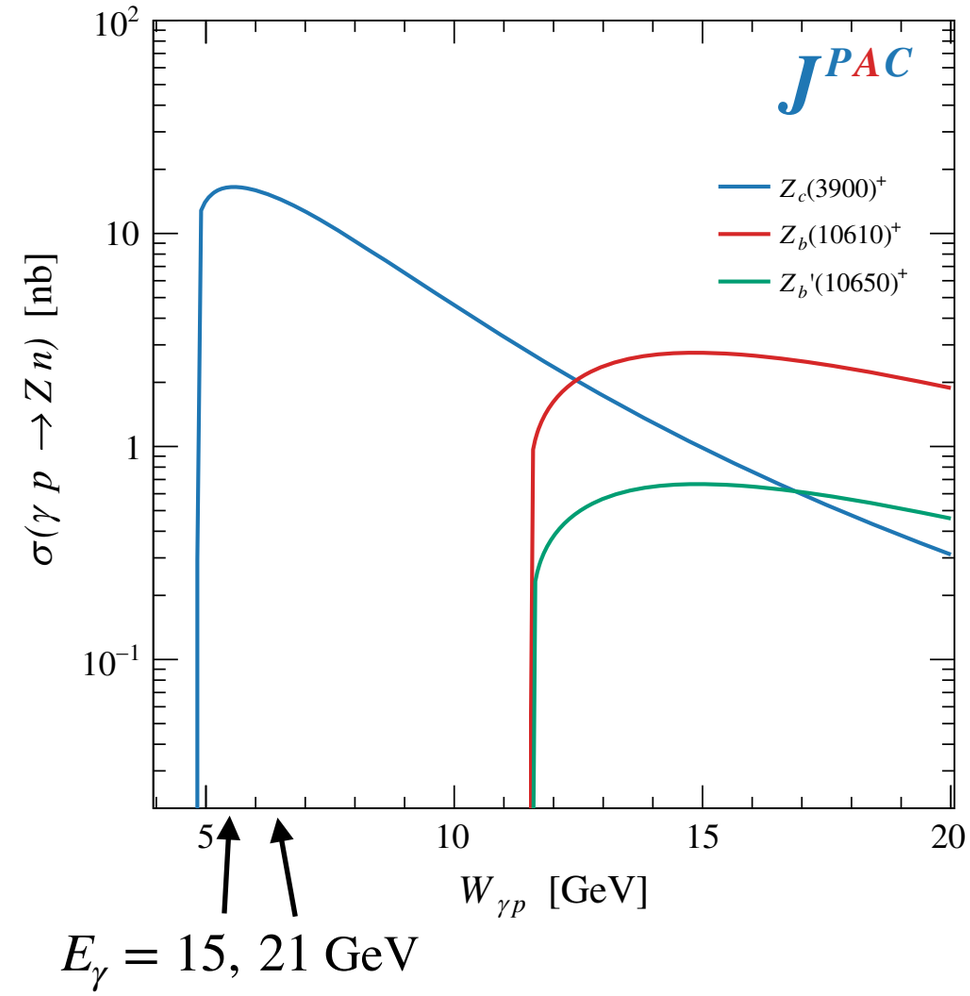
C. Fernández-Ramírez,[7] V. Mathieu,[8] and A. Szczepaniak[1,5,6]

(Joint Physics Analysis Center)



Conclusions and Outlook

Heavy quark meson spectroscopy has expanded tremendously over the last decade.

Discoveries are being made almost monthly by LHCb, BESIII, Belle/Belle II, CMS, ATLAS, etc.

LHC will soon increase statistics; BESIII will soon have an upgrade; Belle II is just starting; a super tau-charm factory (STCF) is potentially on the horizon, etc.

This Talk:

(I) Understanding the $X(3872)$
- known facts
- the global program
- the role of JLab 22 GeV

(II) Understanding the $Y(4230)$
- known facts
- the global program
- the role of JLab 22 GeV

(III) Understanding the $Z_c(3900)$
- known facts
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- the role of JLab 22 GeV

The JLab 22 GeV program could contribute:

- use the $X(3872)$ as a benchmark
- explore the intriguing results from COMPASS
- establish a connection between e^+e^- and γp cross sections
- look for the $Z_c(3900)$ in photoproduction with "simple" pion exchange