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# Recent results on hadron spectroscopy at BESIII

Nils Hüsken  
on behalf of the BESIII collaboration

NSTAR2022  
October 19th, 2022

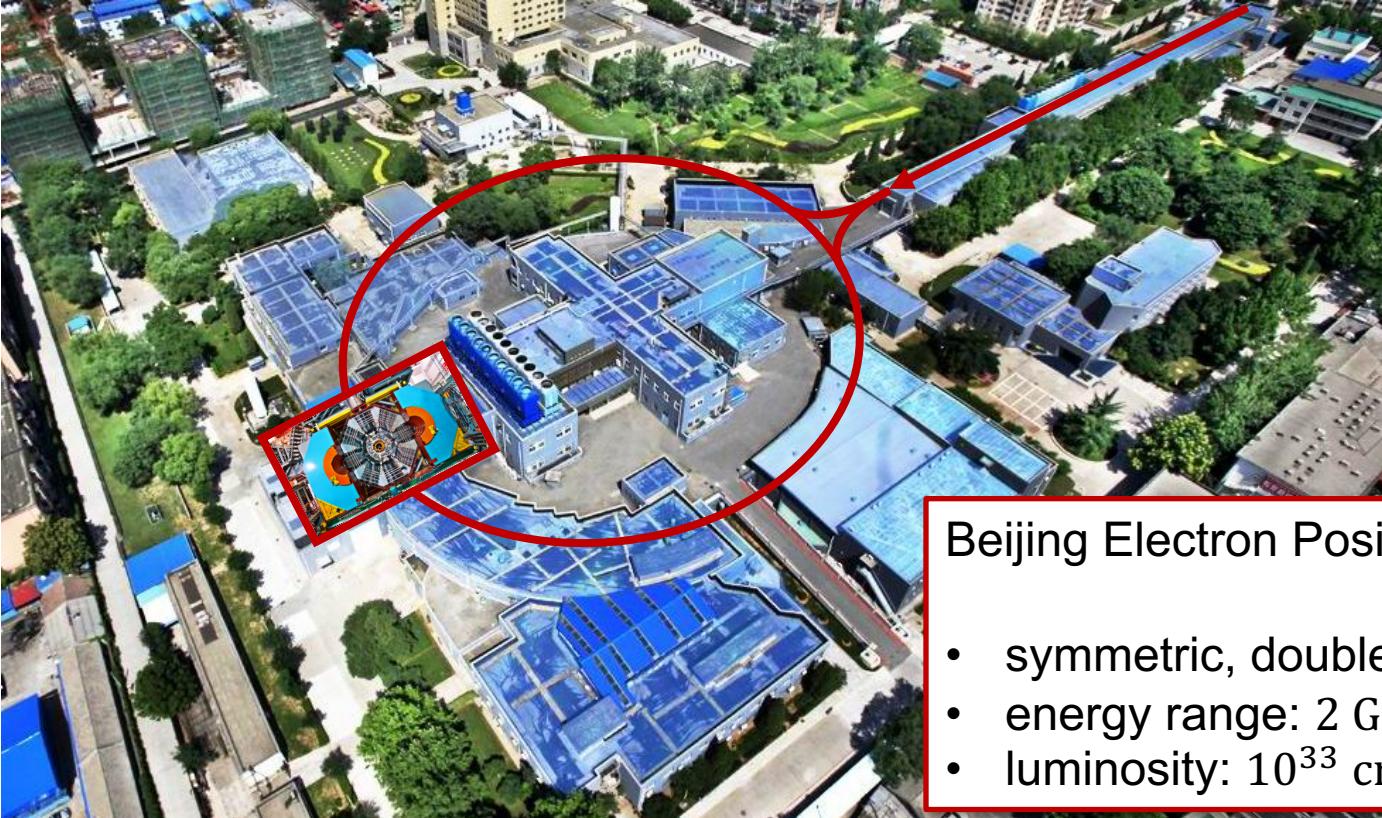
INDIANA UNIVERSITY BLOOMINGTON



# The BESIII Experiment



# BESIII

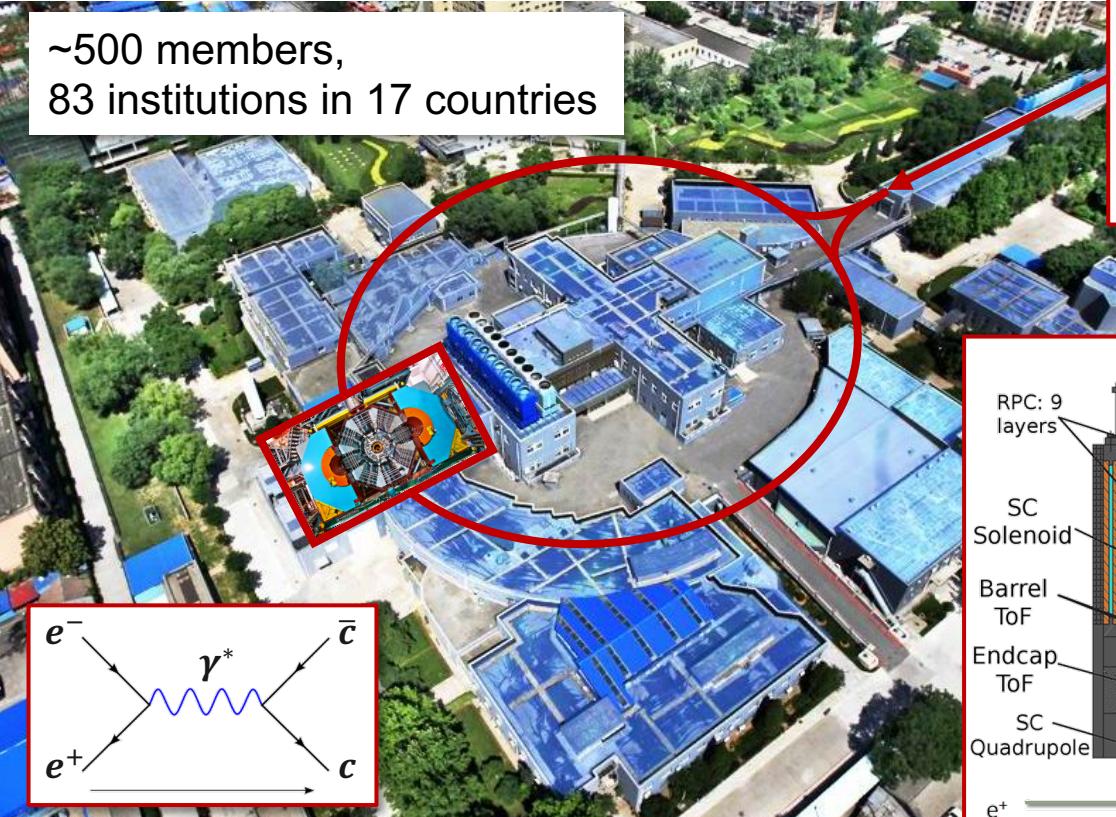


Beijing Electron Positron Collider:

- symmetric, double-ring  $e^+e^-$  collider
- energy range:  $2 \text{ GeV} < \sqrt{s} < 4.94 \text{ GeV}$
- luminosity:  $10^{33} \text{ cm}^{-2}\text{s}^{-1}$  (at  $\psi(3770)$ )

# BESIII

~500 members,  
83 institutions in 17 countries



Beijing Spectrometer BESIII:

- drift chamber in 1 T magnetic field
- time-of-flight detector
- electromagnetic calorimeter
- muon counter



# BESIII

- light hadron spectroscopy
- $\eta$  &  $\eta'$  decays
- charmonium transitions
- hyperon physics
- ...

+ another  $\sim 715 \text{ pb}^{-1}$  for  $2.0 \text{ GeV} \leq \sqrt{s} \leq 3.08 \text{ GeV}$

- excited  $\rho, \omega, \phi$
- ...

$10^{10} J/\psi$

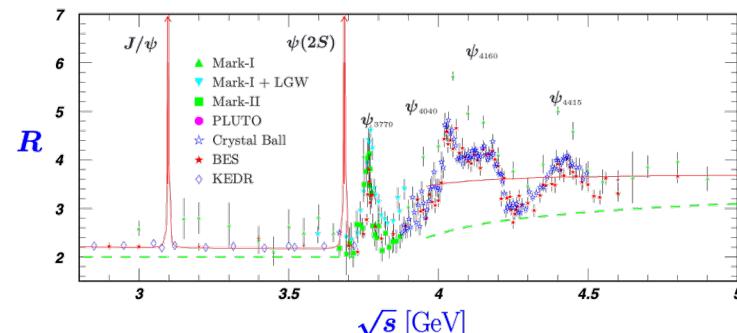
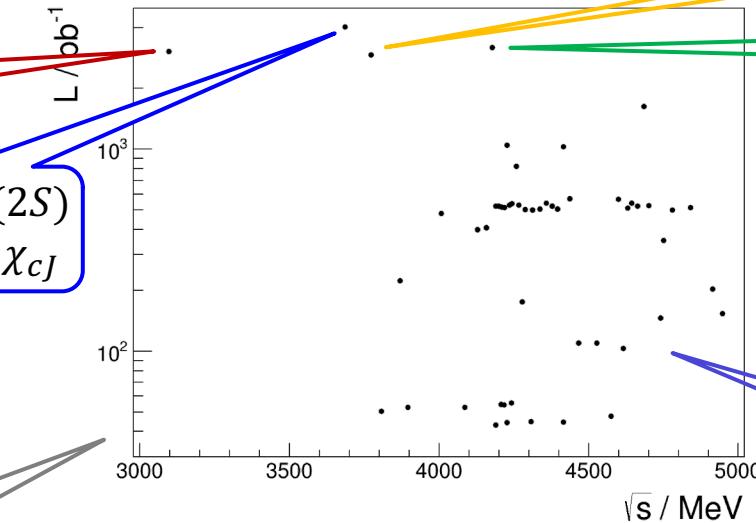
$2.7 \times 10^9 \psi(2S)$   
 $\sim 260 \times 10^6 \chi_{cJ}$

$\sim 2.9 \text{ fb}^{-1}$  at  $\psi(3770)$

$\sim 3.2 \text{ fb}^{-1}$  at  $4.178 \text{ GeV}$

- $D_{(s)}$  meson decays
- $D^0 \bar{D}^0$  pairs
- ISR processes
- $\gamma\gamma$  physics
- ...

$\sim 22 \text{ fb}^{-1}$  in  $XYZ$  region



- $XYZ$  spectroscopy
- $XYZ$  decays
- open-charm production
- charmed baryons
- ...

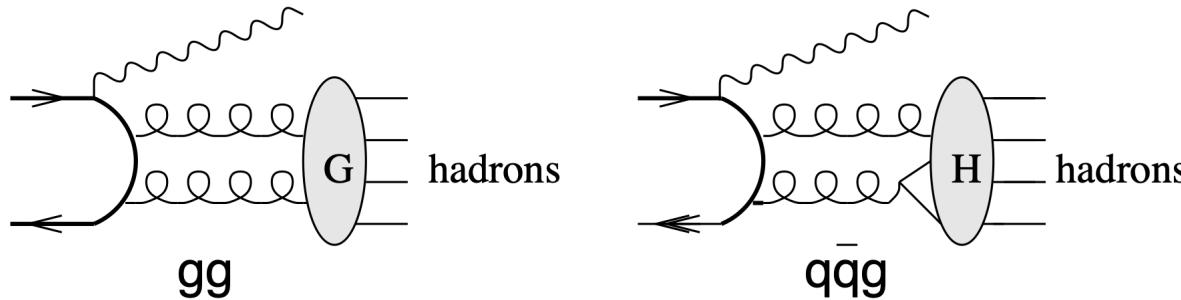


# Light hadron spectroscopy



# Radiative $J/\psi$ decays

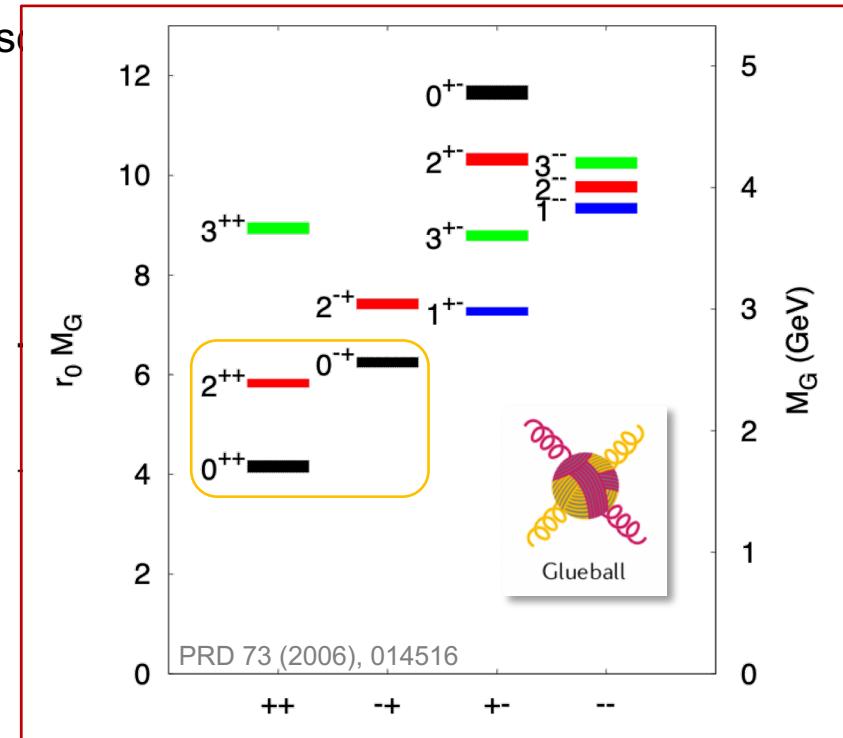
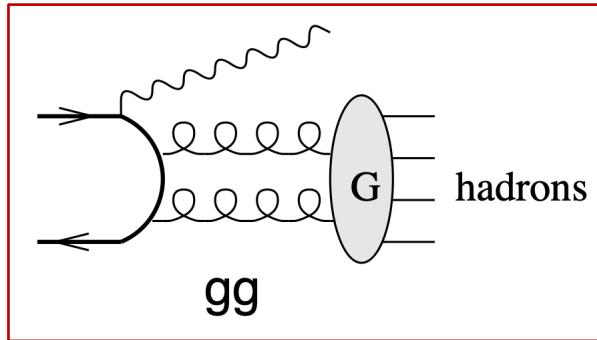
- a unique laboratory for light hadron spectroscopy
  - clean, high statistics sample
  - well-defined initial state  $J^{PC} = 1^{--}$
  - gluon-rich environment



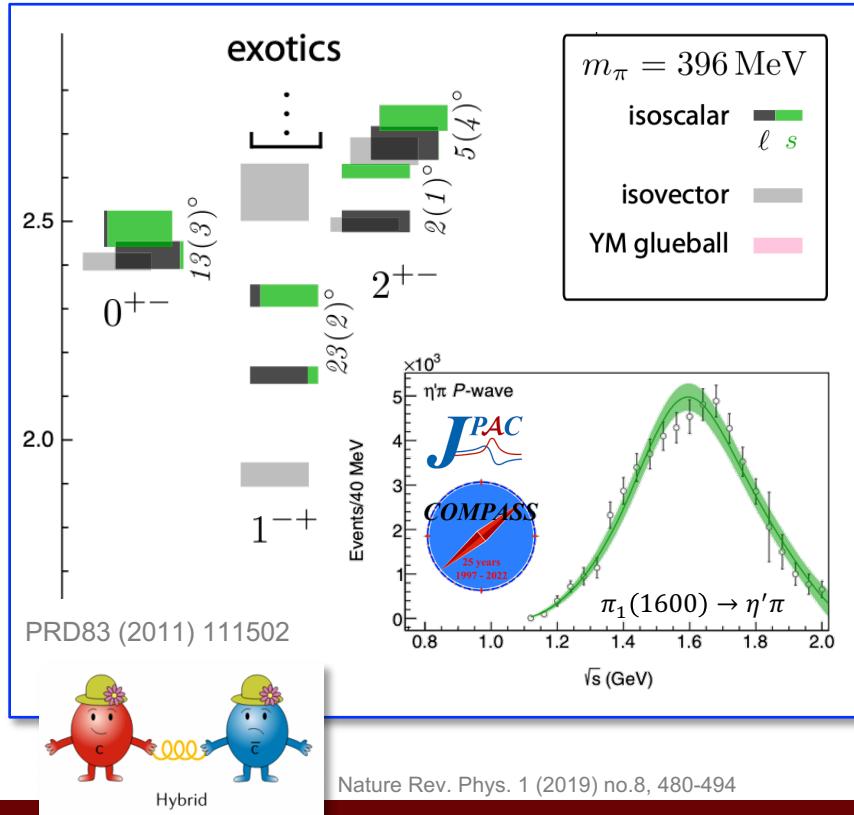
eConf C020620 (2002) THAT07

# Radiative $J/\psi$ decays

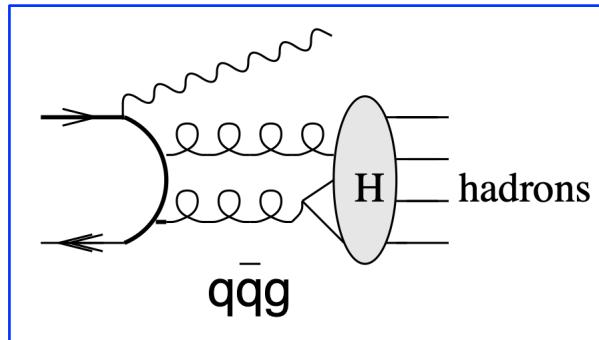
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# Radiative $J/\psi$ decays



ctroscopy



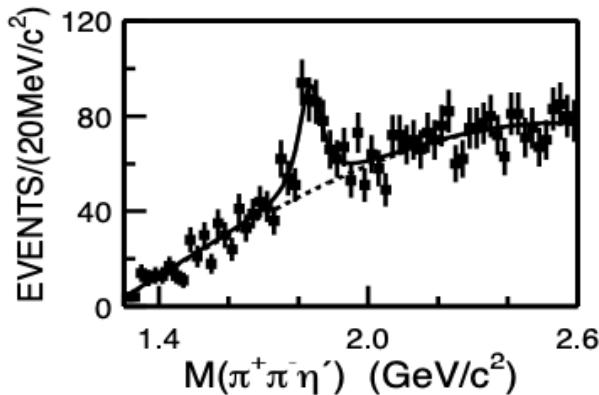
eConf C020620 (2002) THAT07



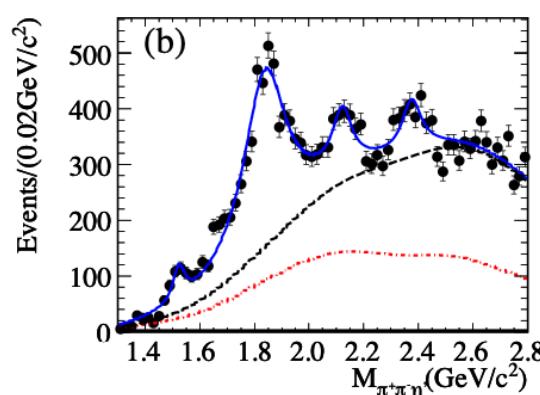
# Radiative $J/\psi$ decays

- structures in  $J/\psi \rightarrow \gamma\eta'\pi^+\pi^-$

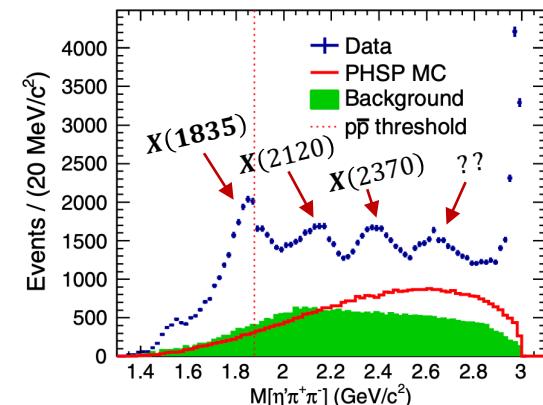
PRL 95 (2005) 262001



PRL 106 (2011) 072002



PRL 117 (2016) 4, 042002



$$58 \cdot 10^6 J/\psi$$

$$225 \cdot 10^6 J/\psi$$

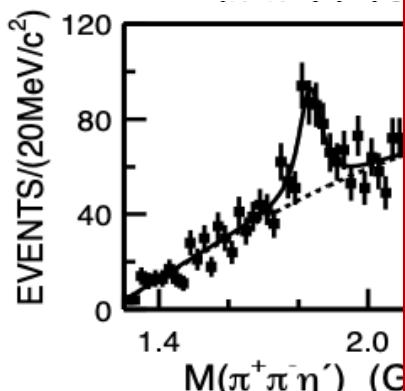
$$1.3 \cdot 10^9 J/\psi$$



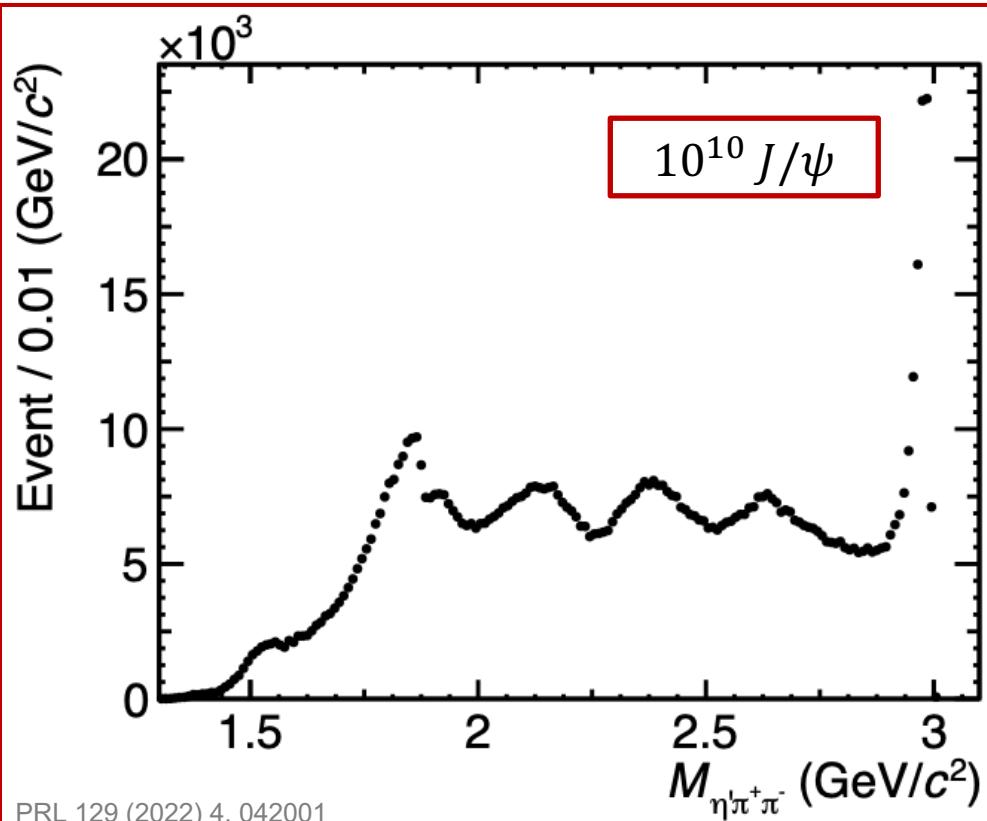
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PRL 95 (2005) 262001

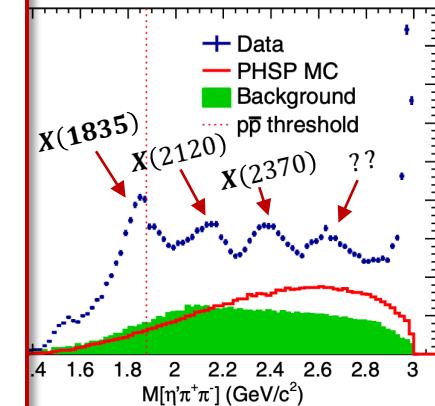


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PRL 129 (2022) 4, 042001

2016) 4, 042002

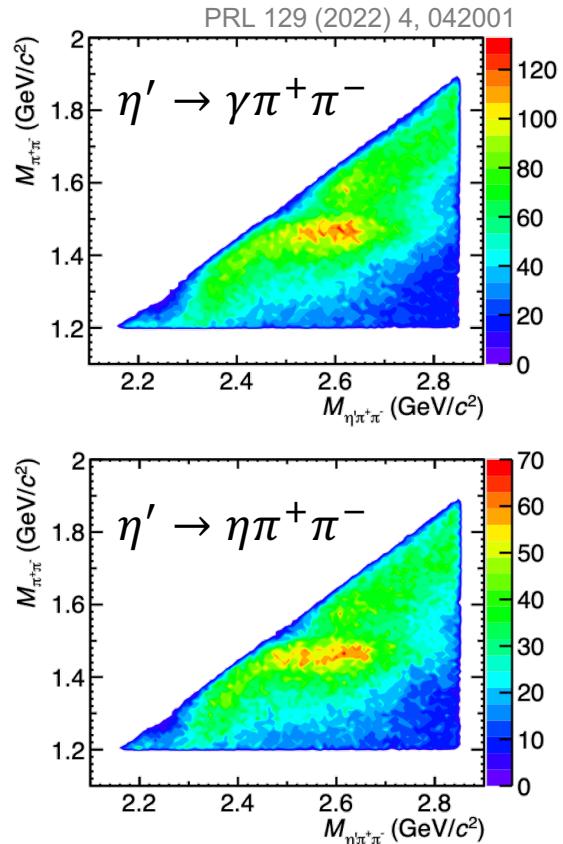
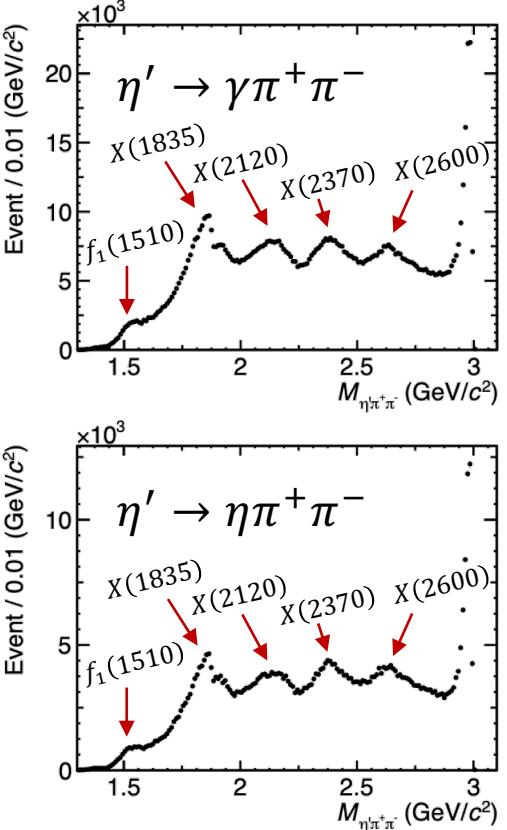


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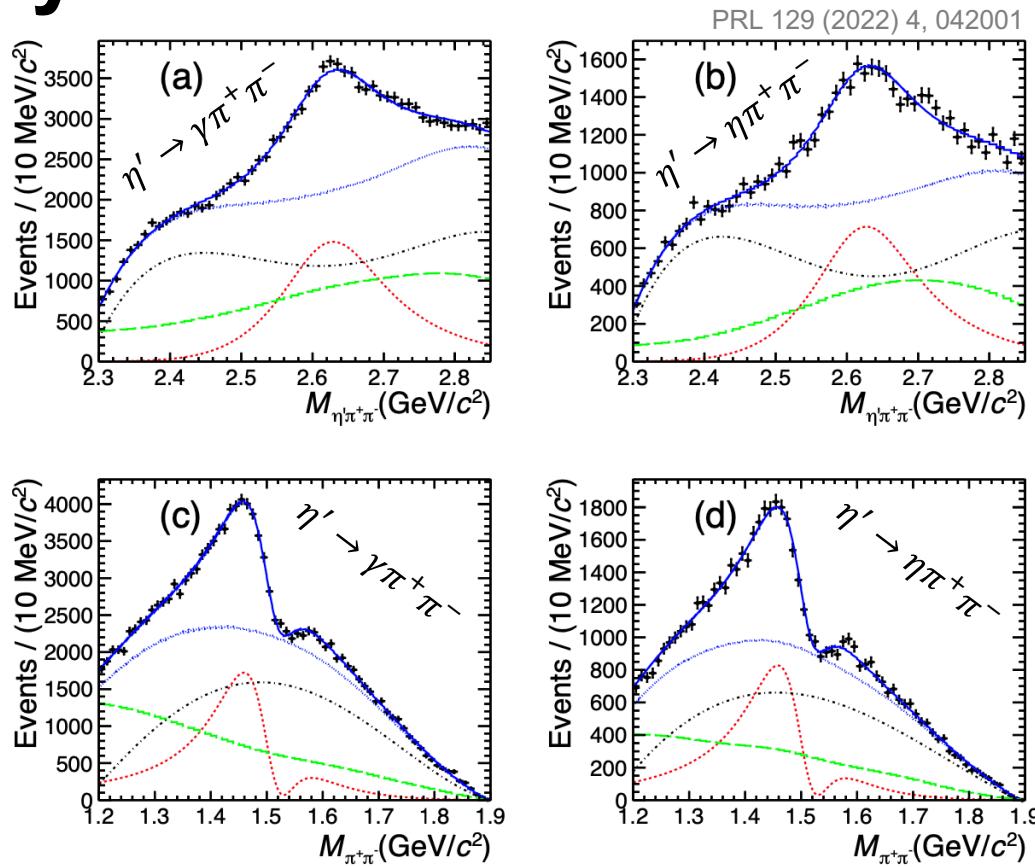
# Radiative $J/\psi$ decays

- structures in  $J/\psi \rightarrow \gamma\eta'\pi^+\pi^-$
- confirmation of  $X(1835)$ ,  $X(2120)$  and  $X(2370)$
- new structure  $X(2600)$
- correlation with  $M_{\pi^+\pi^-} \approx 1.5$  GeV
- complicated pattern in  $M_{\pi^+\pi^-}$
- more studies (including  $J^{PC}$  determination!) necessary



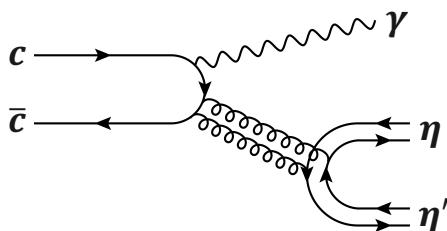
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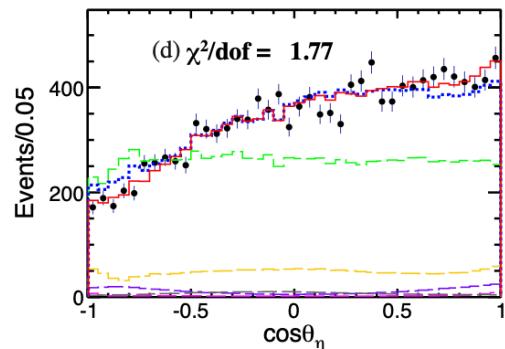
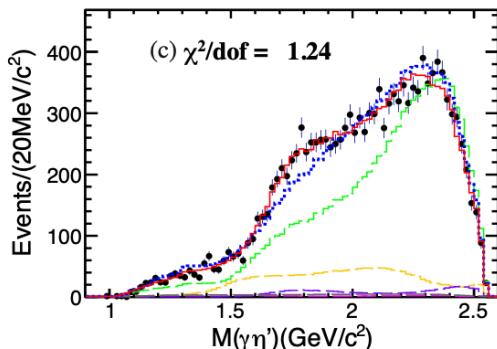
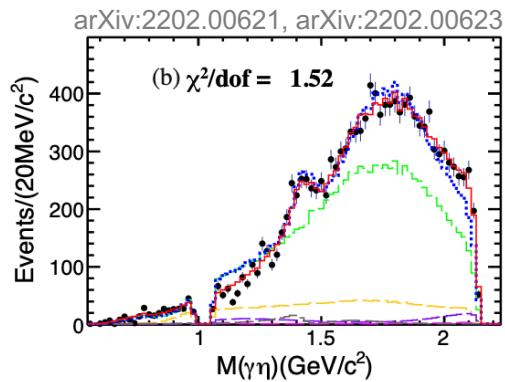
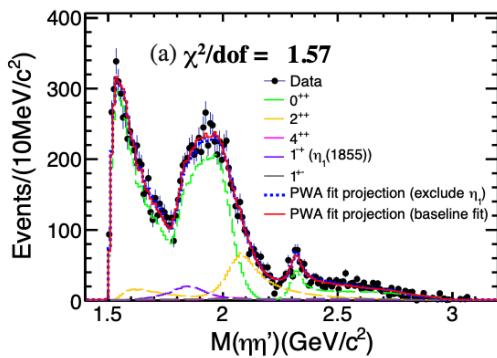
- PWA of  $J/\psi \rightarrow \gamma \eta \eta'$



- iso-scalar spin-exotic  $\eta_1(1855)$

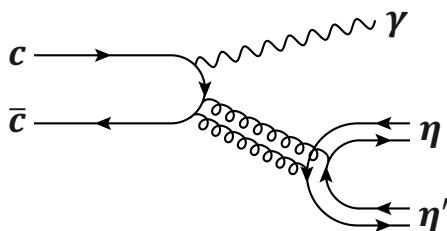
$$m = 1855 \pm 9^{+6}_{-1} \text{ MeV}$$
$$\Gamma = 188 \pm 18^{+3}_{-8} \text{ MeV}$$

- study of other production & decays necessary to understand nature of this state



# Radiative $J/\psi$ decays

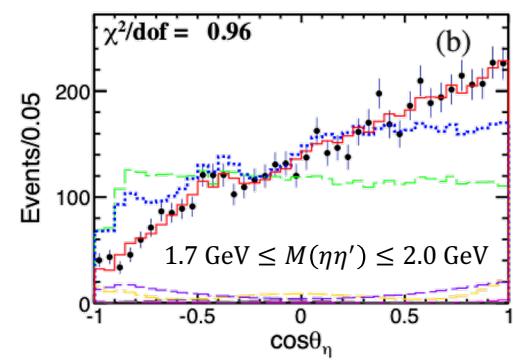
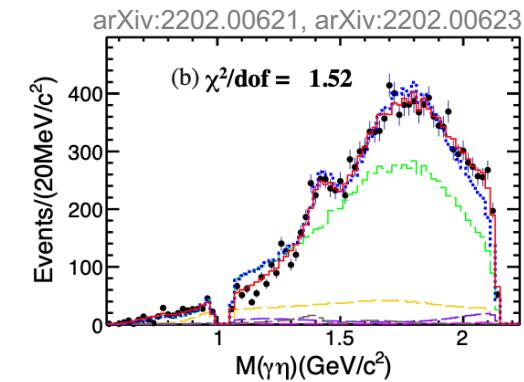
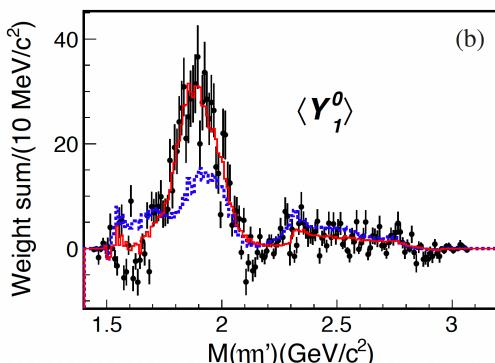
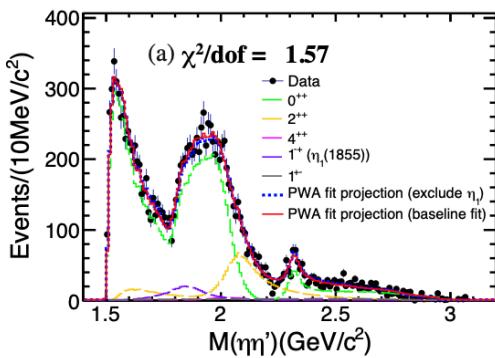
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- iso-scalar spin-exotic  $\eta_1(1855)$

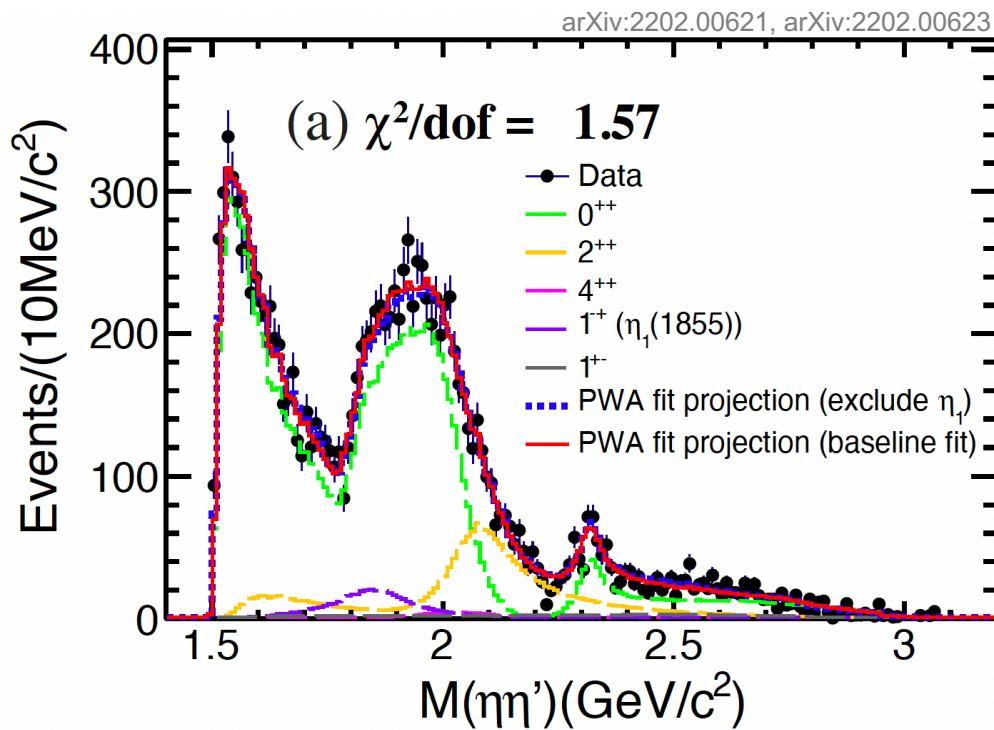
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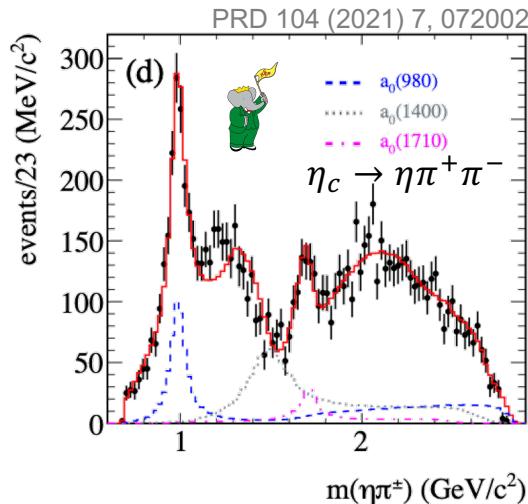
# Radiative $J/\psi$ decays

- scalar glueball decays to  $\eta\eta'$  expected to be suppressed  $\frac{B(G \rightarrow \eta\eta')}{B(G \rightarrow \pi\pi)} < 0.04$   
PRD 92, 121902 (2015)
- significant  $f_0(1500)$  contribution, but no  $f_0(1710)$  (there is a small  $f_0(1810)$  in the fit)
- $\frac{B(f_0(1500) \rightarrow \eta\eta')}{B(f_0(1500) \rightarrow \pi\pi)} = (8.96^{+2.95}_{-2.87}) \times 10^{-2}$ ,
- $\frac{B(f_0(1710) \rightarrow \eta\eta')}{B(f_0(1710) \rightarrow \pi\pi)} < 1.61 \times 10^{-3}$  (90% CL)
- $\frac{B(f_0(1810) \rightarrow \eta\eta')}{B(f_0(1710) \rightarrow \pi\pi)} = (1.39^{+0.62}_{-0.52}) \times 10^{-2}$

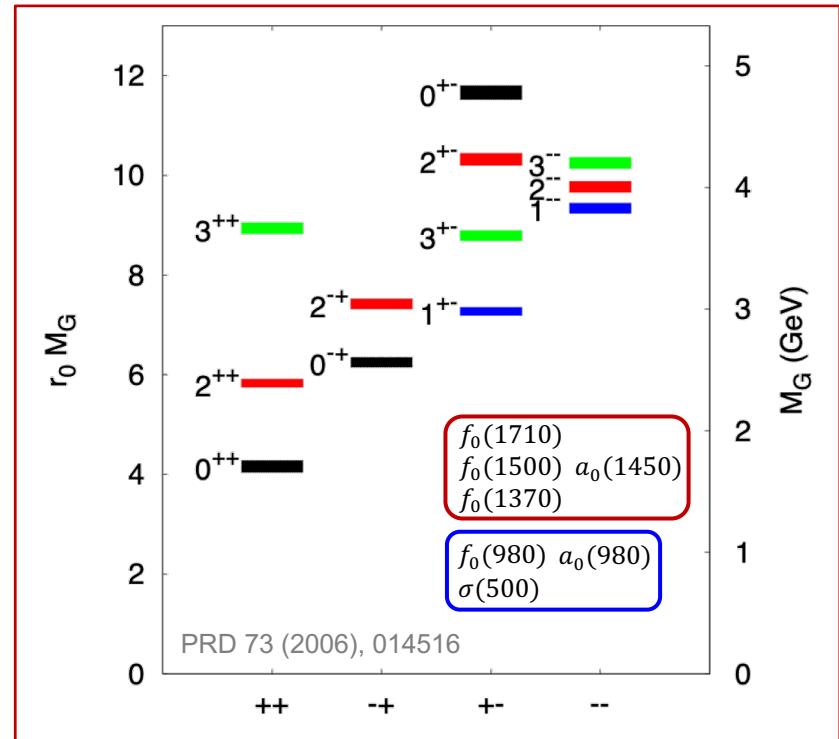


# Light hadrons in open-charm decays

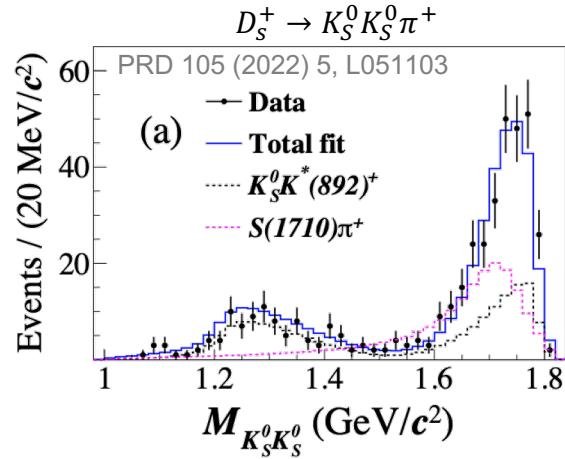
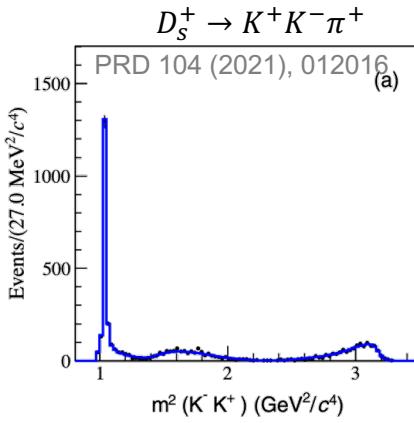
- BaBar recently observed an  $a_0(1710)$



- we study iso-scalars and iso-vectors in  $D_s^+ \rightarrow K^+K^-\pi^+$ ,  $K_S^0K_S^0\pi^+$  and  $K^+K_S^0\pi^0$



# Light hadrons in open-charm decays



$$BF(D_s^+ \rightarrow S(980)\pi^+) = 1.05 \pm 0.04 \pm 0.06 \%$$

$$BF(D_s^+ \rightarrow S(1710)\pi^+) = 0.10 \pm 0.02 \pm 0.03 \%$$

$$BF(D_s^+ \rightarrow S(980)\pi^+) \rightarrow \text{decay not found}$$

$$BF(D_s^+ \rightarrow S(1710)\pi^+) = 0.31 \pm 0.03 \pm 0.01 \%$$

$$|I = 1\rangle \sim |K^+ K^-\rangle + |K^- K^+\rangle + |K^0 \bar{K}^0\rangle + |\bar{K}^0 K^0\rangle$$

$$|I = 0\rangle \sim |K^+ K^-\rangle + |K^- K^+\rangle - |K^0 \bar{K}^0\rangle - |\bar{K}^0 K^0\rangle$$

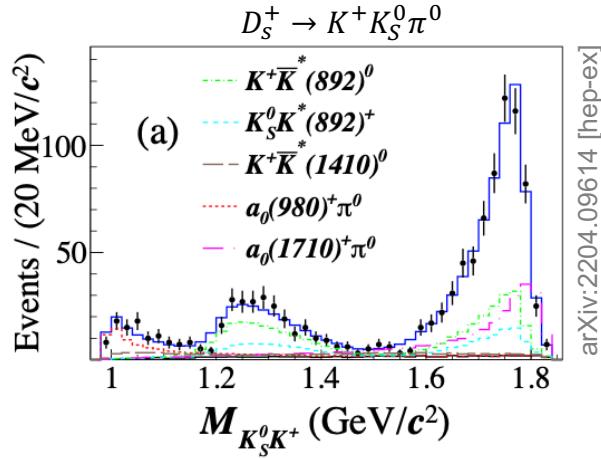
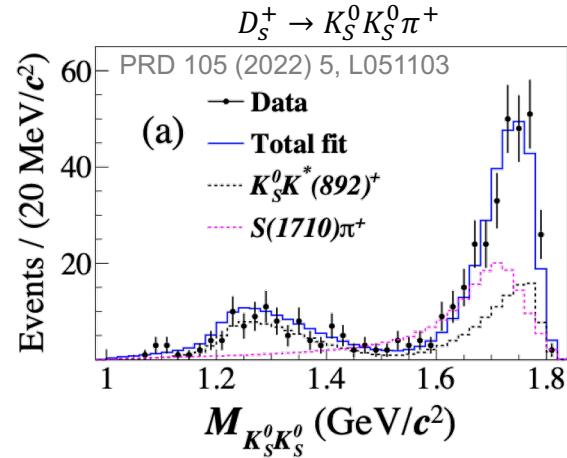
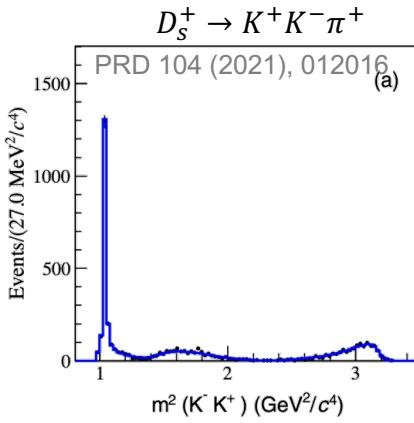
S. U. Chung, BNL-QGS-13-0901

$\rightarrow a_0(980)$ - $f_0(980)$  interference

$\rightarrow a_0(1710)$ - $f_0(1710)$  interference  $\rightarrow a_0(1710)$  needed!



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$\rightarrow a_0(980)$ - $f_0(980)$  interference

$\rightarrow a_0(1710)$ - $f_0(1710)$  interference  $\rightarrow a_0(1710)$  needed!

➤ confirmation of an  $I = 1$  state  $a_0(1710)$  in the charged channel

➤ existence suggested in

Geng, Oset, PRD 79, 074009 (2009)

Dai, Oset, Geng, EPJC 82, 225 (2022)

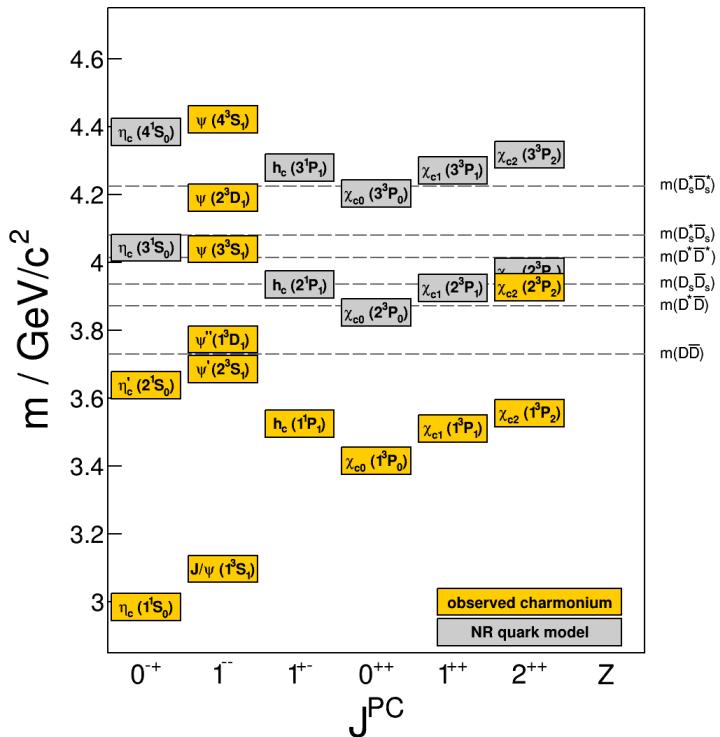
Klempt, PLB 820, 136512 (2021)



# Charmonium(-like) states



# Charmonium



model values from  
PRD 72 (2005) 054026

- spectrum from potential models:

$$V_{q\bar{q}} = -\frac{4}{3} \cdot \frac{\alpha_s(r)}{r} + k \cdot r$$

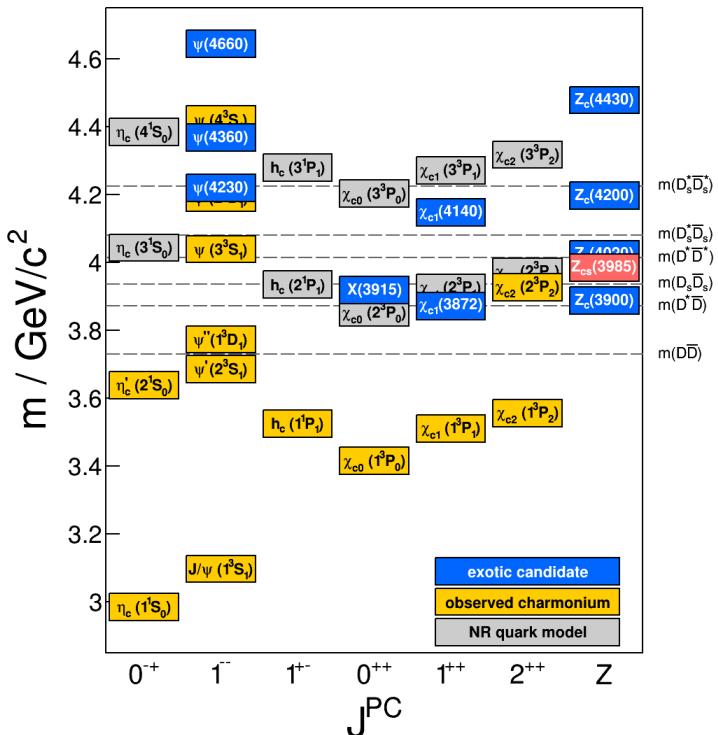
+ spin-dependent terms

see e.g.: Godfrey & Isgur, PRD 32 (1985) 189-231  
 Barnes, Godfrey, Swanson, PRD 72 (2005) 054026  
 Godfrey & Moates, PRD 92 (2015) 054034

- good agreement with experiments



# Charmonium



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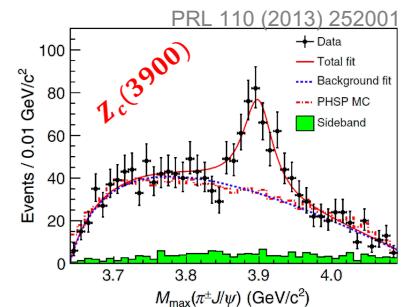
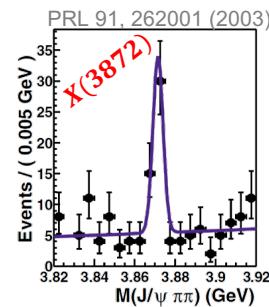
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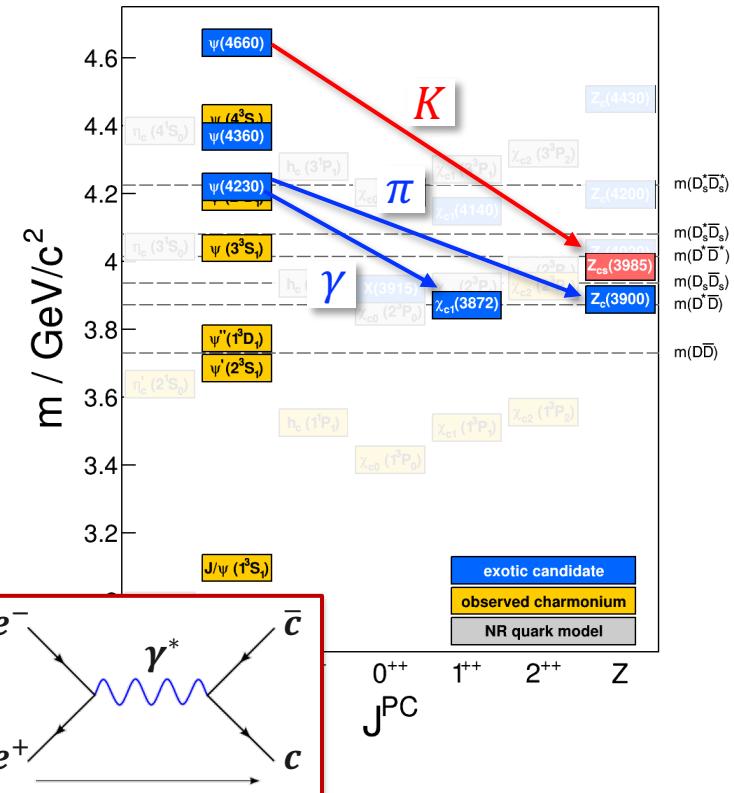
- good agreement with experiments
- several unexpected states observed



- their nature is still unclear



# Charmonium



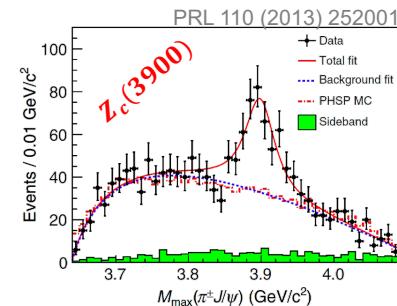
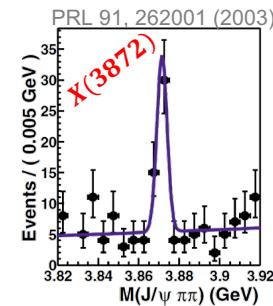
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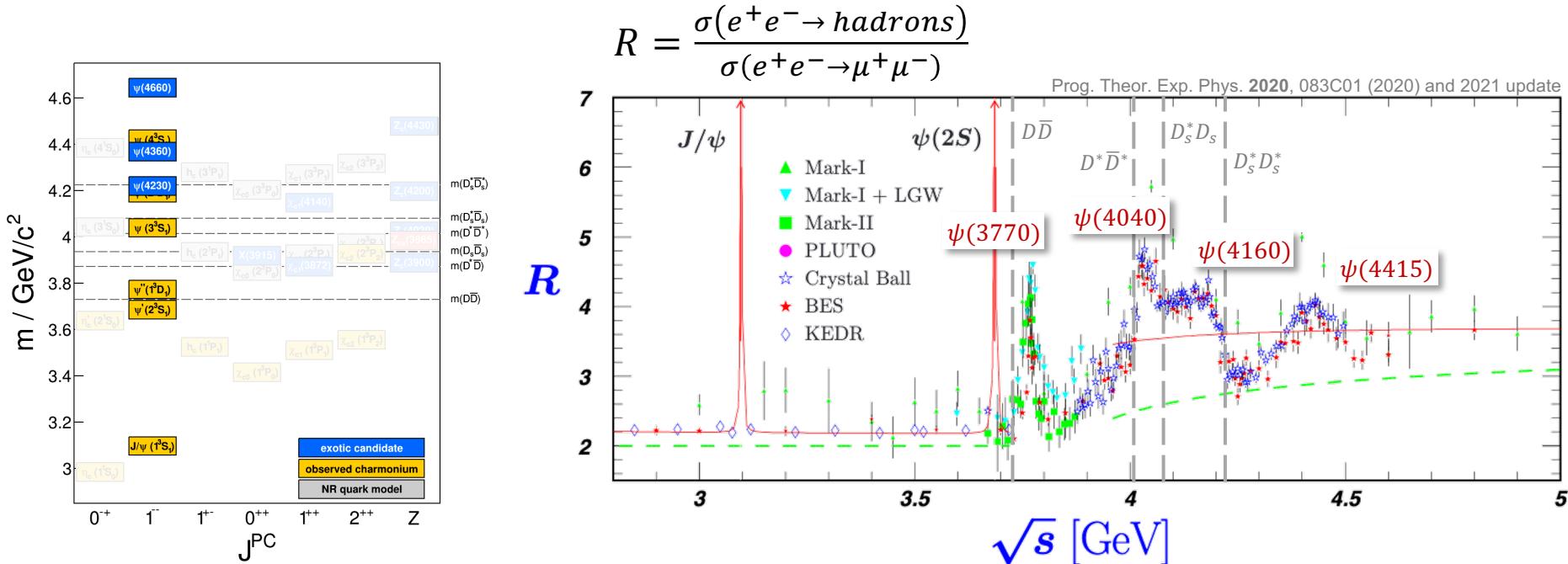
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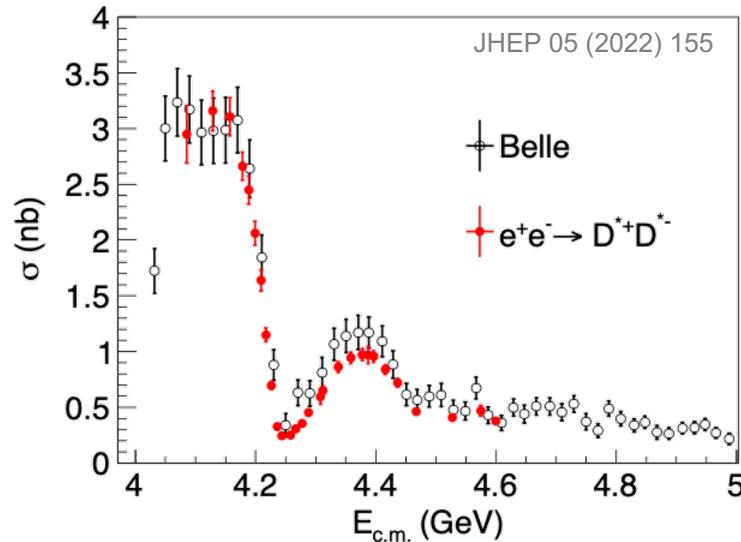
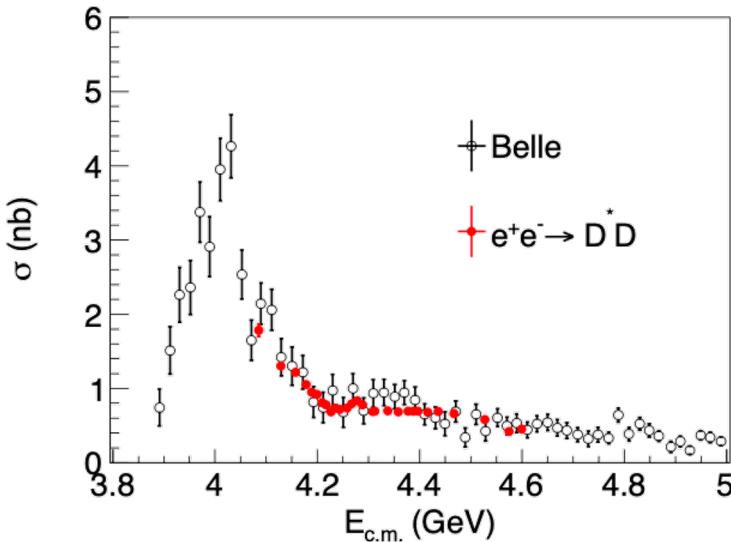
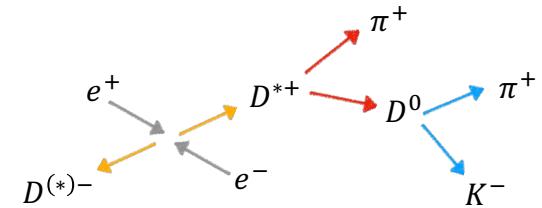
# Vector states



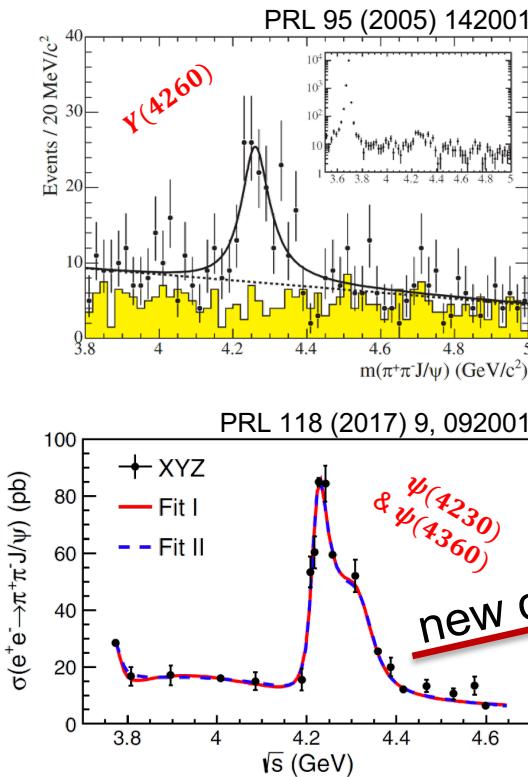
- 4 conventional  $c\bar{c}$ -states above  $D\bar{D}$  threshold:  $\psi(3770)$ ,  $\psi(4040)$ ,  $\psi(4160)$  and  $\psi(4415)$
- almost all information on them is from inclusive  $e^+e^- \rightarrow \text{hadrons}$

# Vector states: Open-charm production

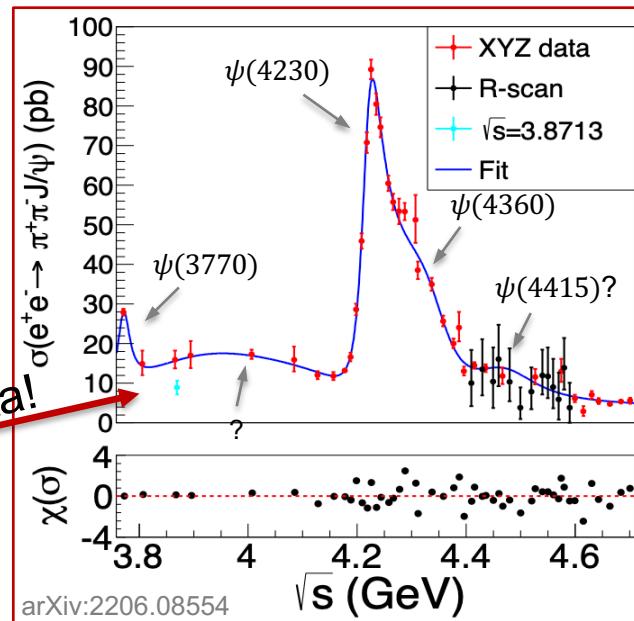
- measurement of  $e^+e^- \rightarrow D^{*+}D^-$  and  $D^{*+}D^{*-}$
- reconstruct  $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$ , identify missing  $D^{(*)-}$



# Vector states: Hidden-charm production



- $Y(4260)$  first observed by BaBar in  $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-J/\psi$
- we find two structures  $\psi(4230)$  &  $\psi(4360)$



→ new features have significant impact on  $\psi(4360)$  parameters

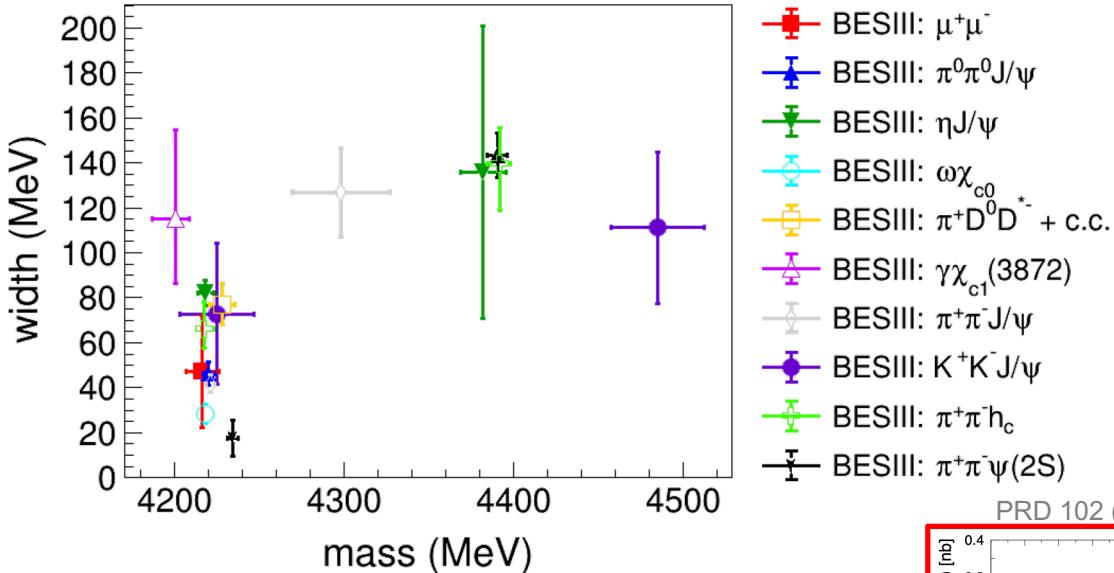
$$m_1 = 4221.4 \pm 1.5 \pm 2.0 \text{ MeV}$$
$$\Gamma_1 = 41.8 \pm 2.9 \pm 2.7 \text{ MeV}$$

$$m_2 = 4298 \pm 12 \pm 26 \text{ MeV}$$
$$\Gamma_2 = 127 \pm 17 \pm 10 \text{ MeV}$$

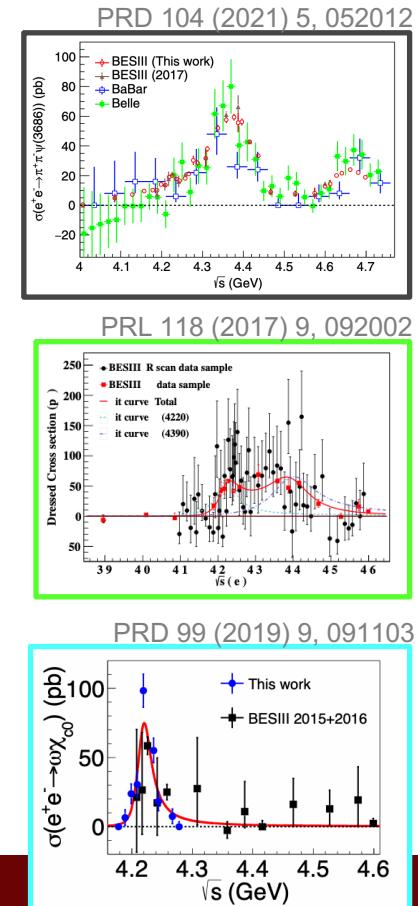


# Vector states: Hidden-charm production

- different channels show (slightly) different masses and widths

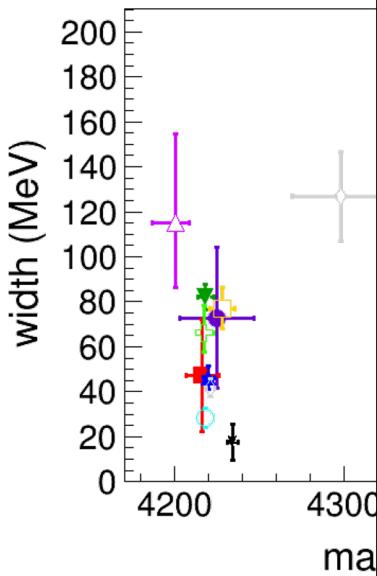


- coupled channel studies are needed!

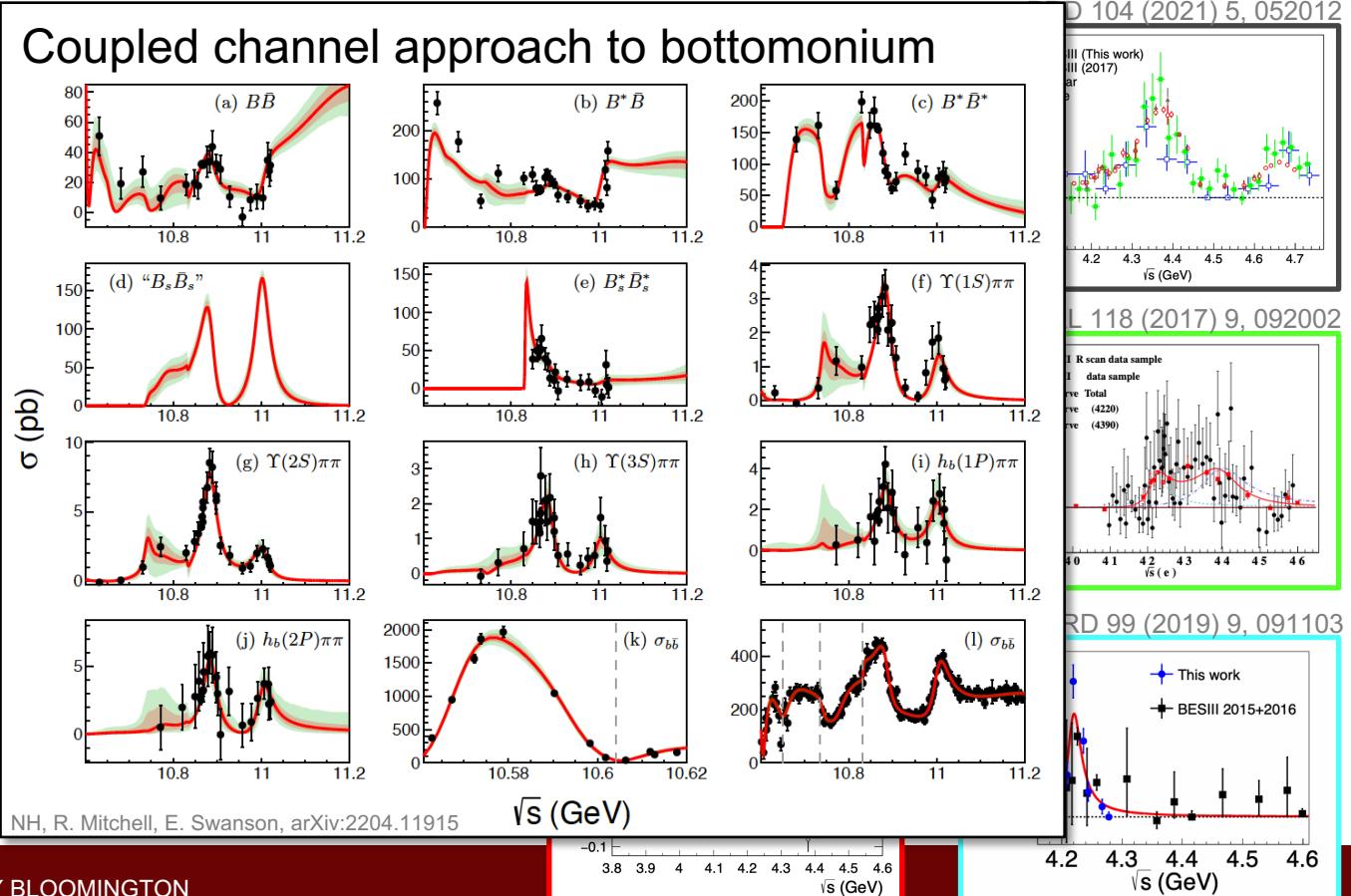


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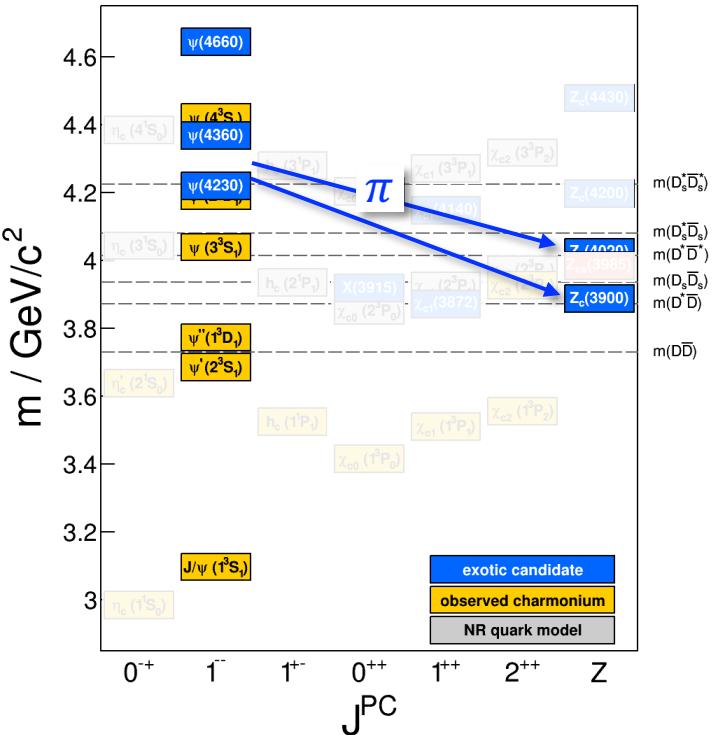
- different channels



- coupled channel s



# Charged charmonium-like states

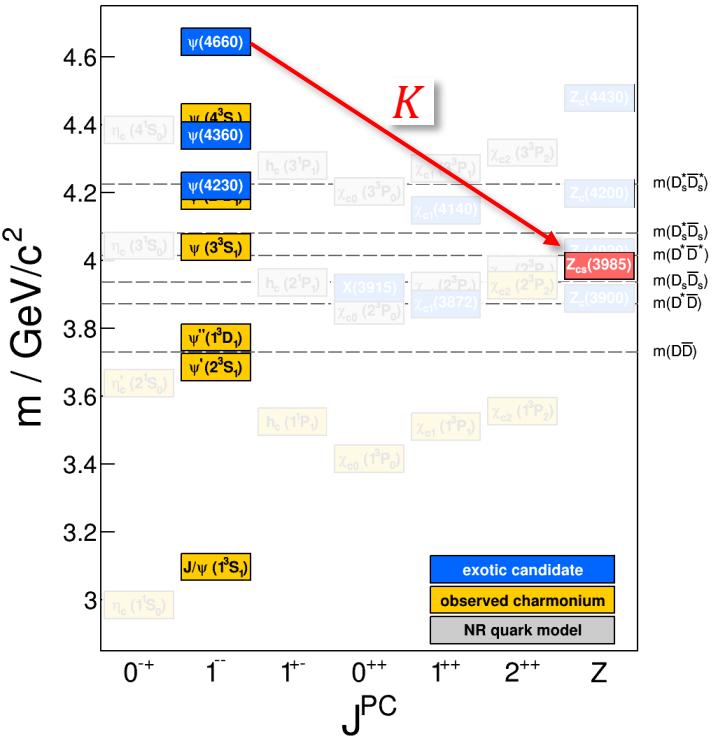


- openly exotic with  $I \neq 0$  ( $q \neq 0$ )
- nature still unclear (tetraquark, molecule, ...)
- PRL 110 (2013) 252001

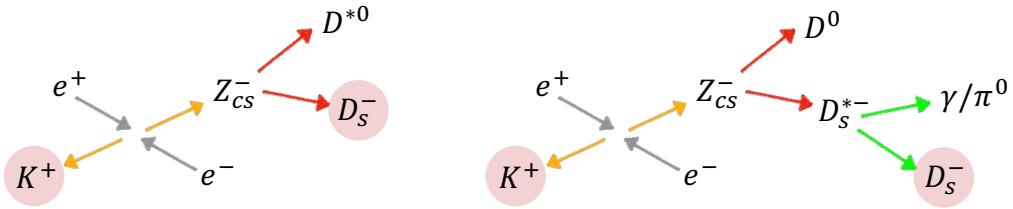
Plot of Events / 0.01 GeV/c<sup>2</sup> versus  $M_{\max}(\pi^\pm J/\psi)$  (GeV/c<sup>2</sup>). The data (black points with error bars) shows a peak around 3.9 GeV/c<sup>2</sup>. The total fit (red solid line) includes a background fit (blue dashed line), PHSP MC (dotted red line), and a sideband (green histogram). The x-axis ranges from 3.7 to 4.0 GeV/c<sup>2</sup>.
- PRL 111 (2013) 242001

Plot of Events / 0.005 GeV/c<sup>2</sup> versus  $M_{\pi^+ h_c}$  (GeV/c<sup>2</sup>). The data (black points with error bars) shows two peaks at approximately 3.95 GeV/c<sup>2</sup> and 4.15 GeV/c<sup>2</sup>. The total fit (red solid line) includes a background fit (blue dashed line) and PHSP MC (dotted red line). The sideband distribution (green histogram) is shown for the 3.8-4.0 GeV/c<sup>2</sup> range. The x-axis ranges from 3.95 to 4.25 GeV/c<sup>2</sup>.
- if genuine resonance, minimal quark content of  $c\bar{c}q\bar{q}$
- intriguing connection to  $\psi(4230)$

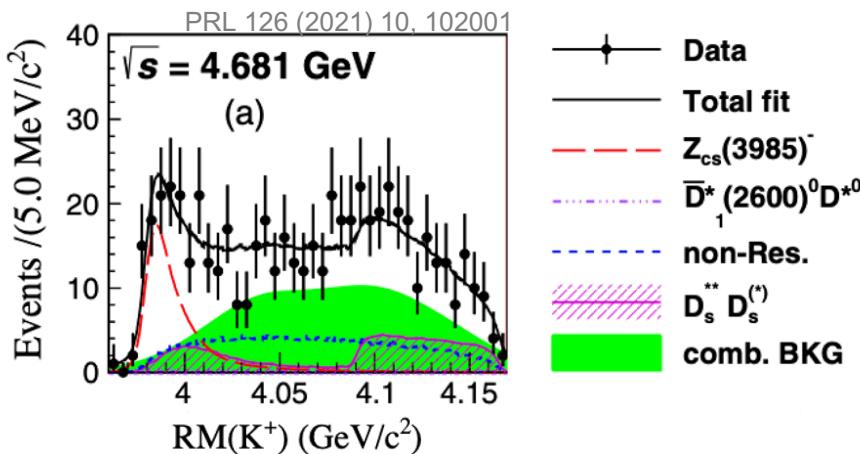
# Charged charmonium-like states



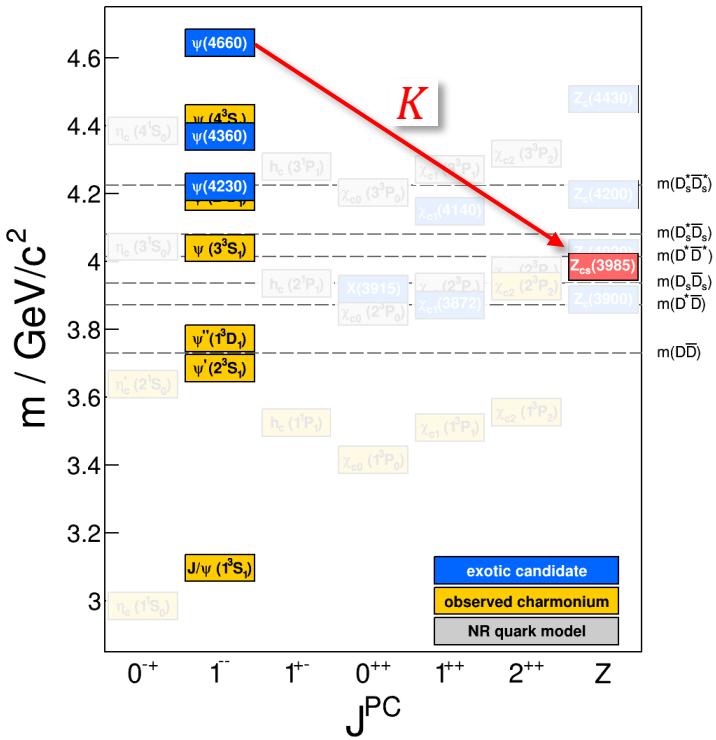
- search for an open-strange  $c\bar{c}s\bar{q}$  partner  $Z_{cs}$



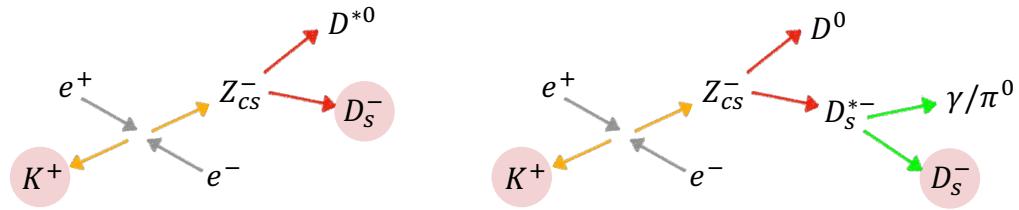
partial reconstruction method:  $K^+, D_s^-$



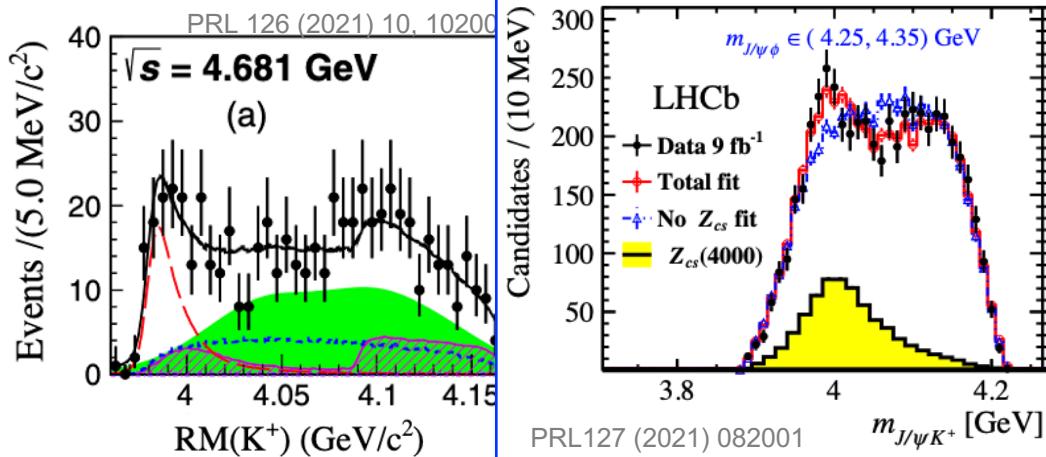
# Charged charmonium-like states



- search for an open-strange  $c\bar{c}s\bar{q}$  partner  $Z_{cs}$

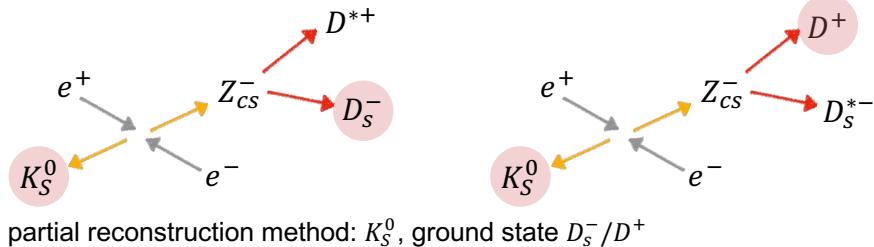


partial reconstruction method:  $K^+, D_s^-$



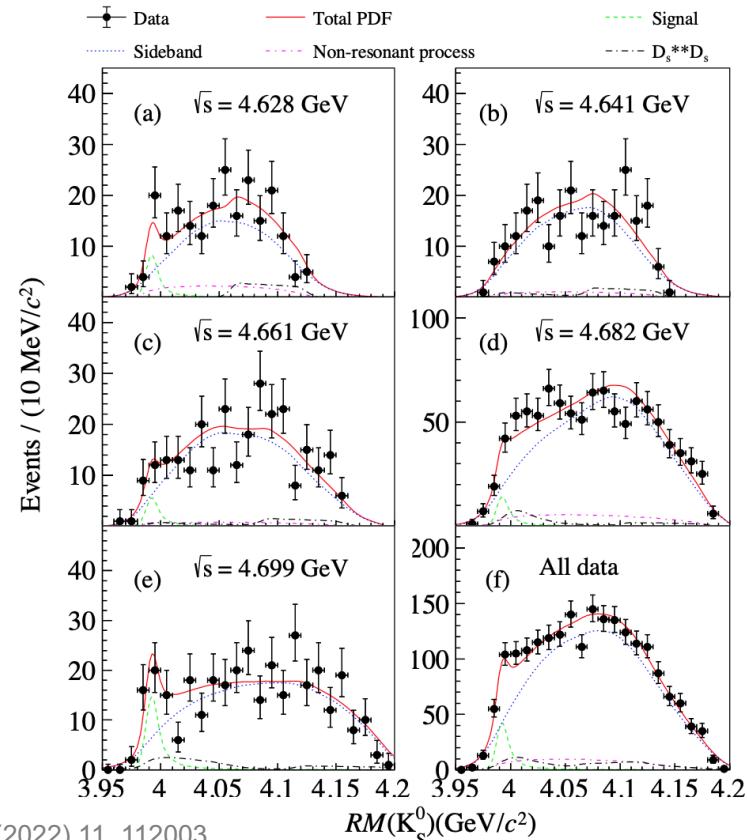
# Charged charmonium-like states

- search for  $Z_{cs}^0$  in  $e^+e^- \rightarrow K_S^0(D_s^+D^{*-} + D_s^{*+}D^-)$



- signal significance of  $4.6\sigma$
- mass and width consistent with charged  $Z_{cs}^\pm$ , potential isospin-partner

	Mass ( $\text{MeV}/c^2$ )	Width (MeV)
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$

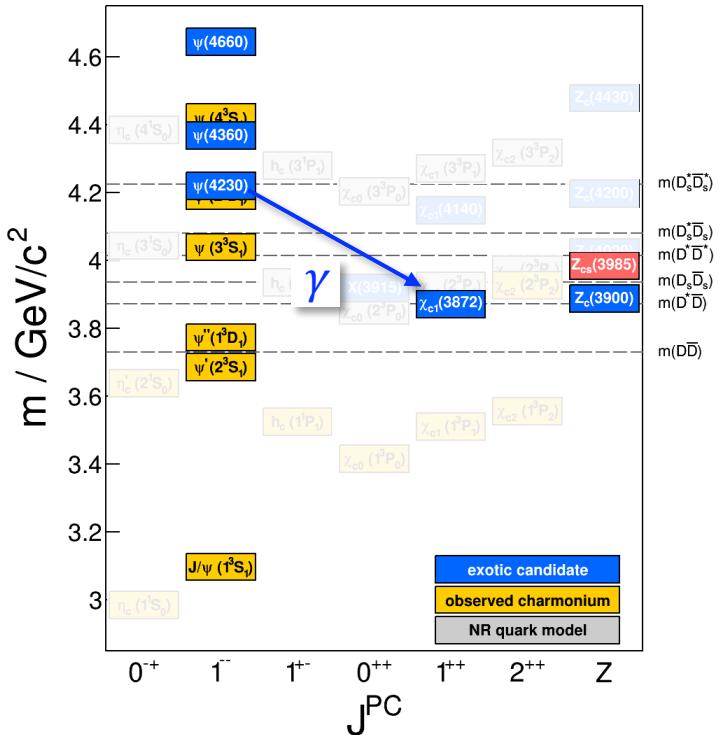


PRL 129 (2022) 11, 112003

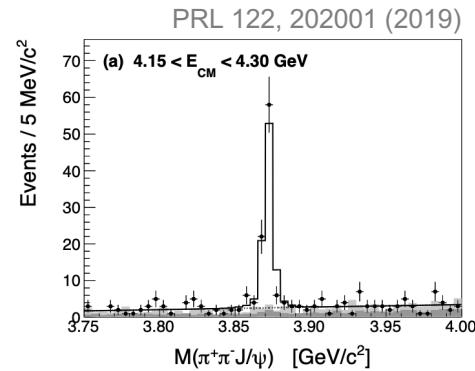


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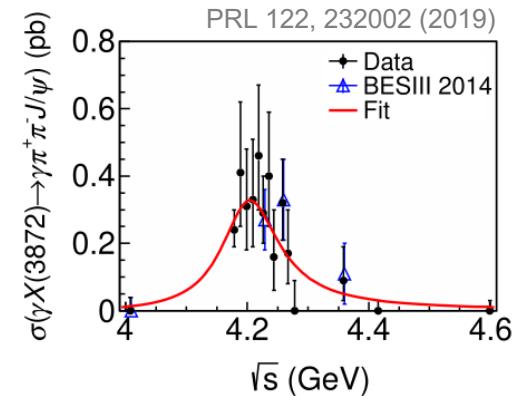
# On $\chi_{c1}(3872)$



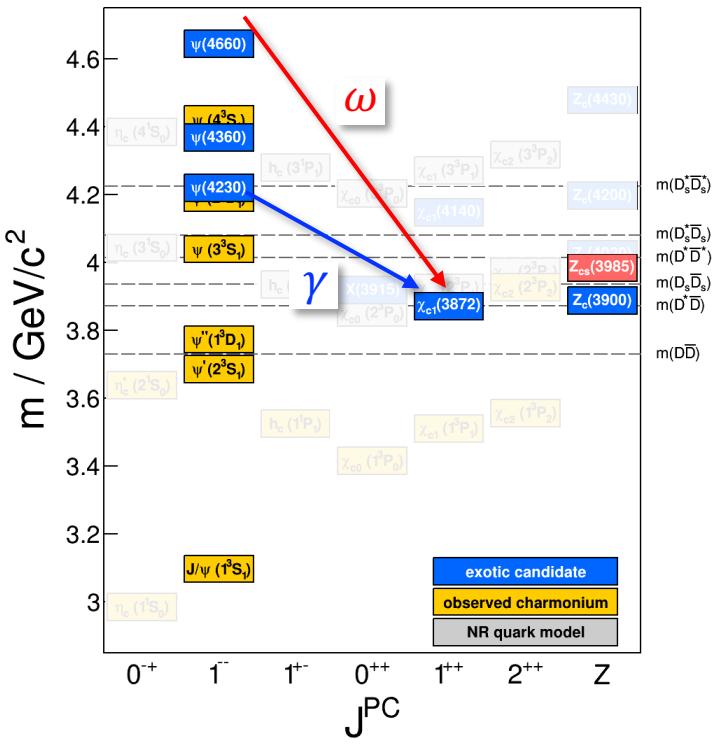
- established production process  $e^+e^- \rightarrow \gamma\chi_{c1}(3872)$



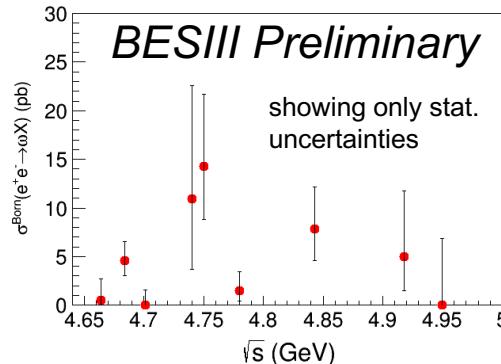
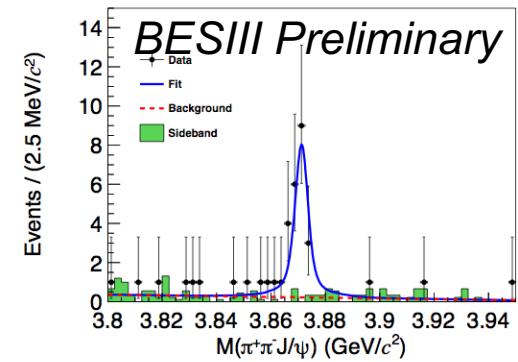
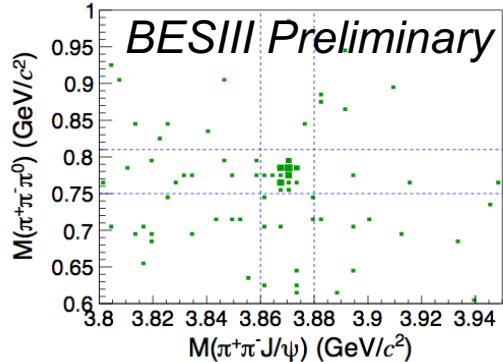
- used in multiple studies of  $\chi_{c1}(3872)$  decay modes
- indication for resonant production through  $\psi(4230)$



# On $\chi_{c1}(3872)$



- new production process  $e^+e^- \rightarrow \omega\chi_{c1}(3872)!$



$N_{sig} = 24.0 \pm 5.3$   
significance:  $7.5\sigma$

→ similar cross section as  
for  $e^+e^- \rightarrow \omega\chi_{cJ}(1P)$



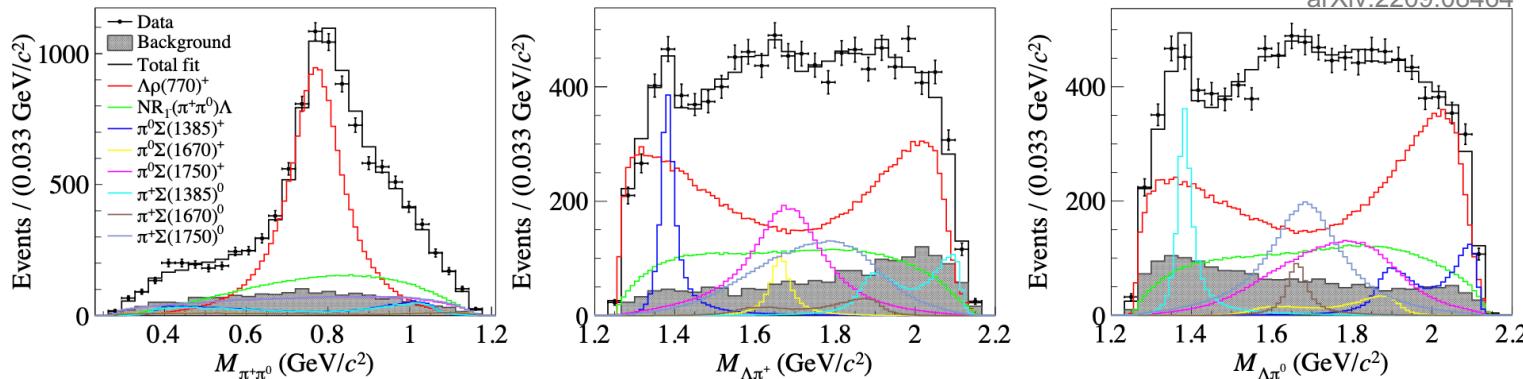
# Baryon spectroscopy



# Baryon spectroscopy

- $\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^0$ :
  - branching fraction measured in the past
  - no experimental information on intermediate states
  - theoretical predictions for  $\Lambda_c^+ \rightarrow \Lambda\rho^+$  and  $\Sigma^*\pi$  exist
- PWA using  $\Lambda_c^+\bar{\Lambda}_c^-$  pair production for  $4.6 \text{ GeV} \leq \sqrt{s} \leq 4.7 \text{ GeV}$

PRD 101 (2020) 053002  
PRD 46 (1992) 1042; PRD 55 (1997) 1697  
EPJ C 80 (2020) 1067  
PRD 99 (2019) 114022

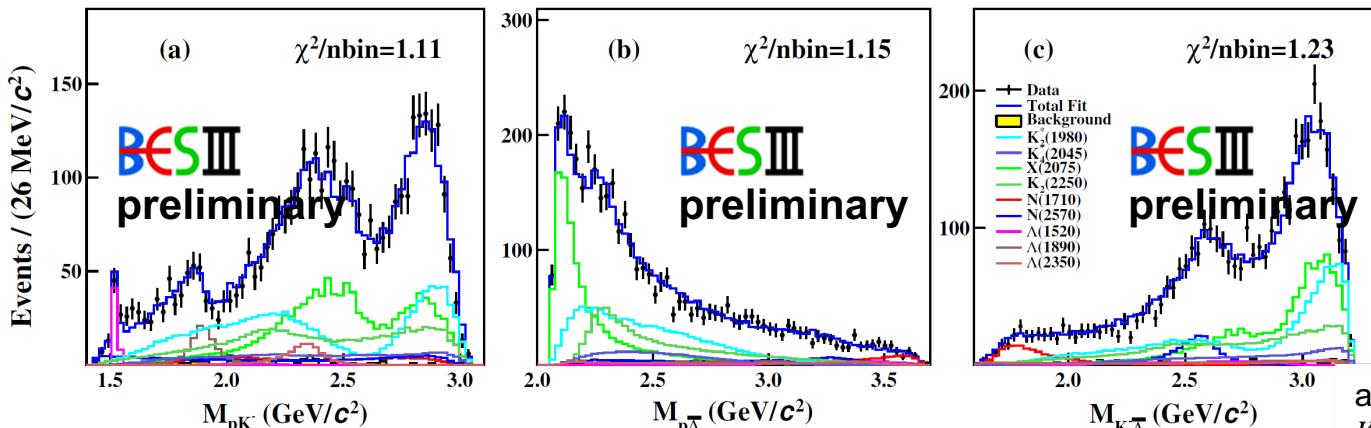


- finds contributions from  $\Lambda\rho$ ,  $\Sigma(1385)\pi$ ,  $\Sigma(1670)\pi$  and  $\Sigma(1750)\pi$

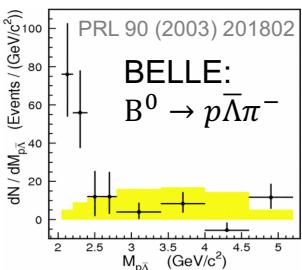
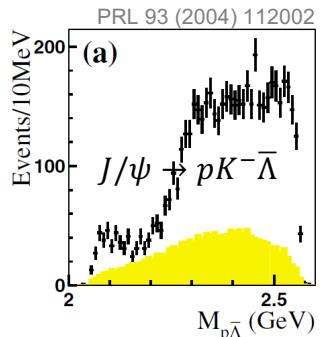


# Baryon spectroscopy

- $e^+e^- \rightarrow pK^-\bar{\Lambda}$ :
  - $p\bar{\Lambda}$  threshold enhancement  $X(2075)$  in  $J/\psi, \chi_{c0}, B^0$  and  $B^+$  decays
  - using XYZ datasets between 4 and 5 GeV ( $L_{int} = 21.7 \text{ fb}^{-1}$ )



- $J^P$  of threshold structure  $X(2075)$  found as  $1^+$  ( $> 5\sigma$ )

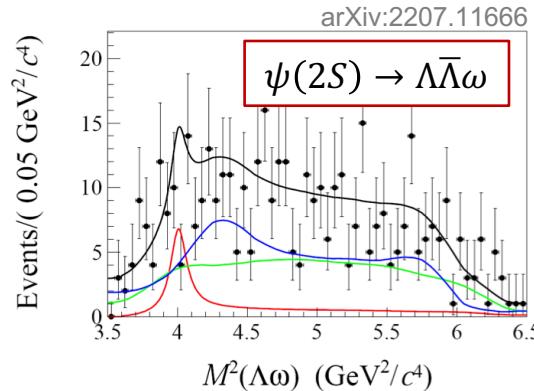
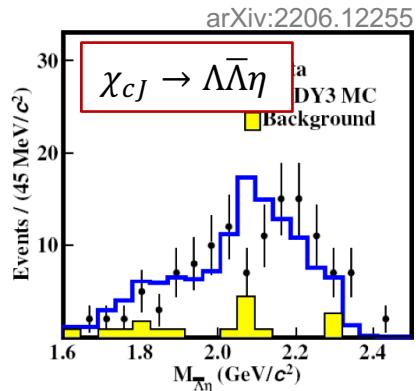


additional contributions from  
 $K_2^*(1980), K_4^*(2045), K_2(2250)$   
 $N(1720), N(2570)$   
 $\Lambda(1520), \Lambda(1890), \Lambda(2350)$

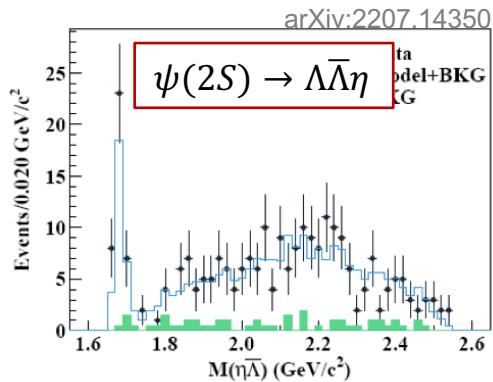


# Baryon spectroscopy

- $c\bar{c} \rightarrow B\bar{B}M$  decays for baryon spectroscopy



using  $448 \times 10^6 \psi(2S)$



- we now have  $10^{10} J/\psi$  and  $2.7 \times 10^9 \psi(2S)$ !
- expect many interesting, detailed studies on  $c\bar{c} \rightarrow B\bar{B}M$  decays in the (near) future
- other topics in baryon physics: form factors, hyperon decays, ...

# Summary and Outlook

- BESIII very active in hadron spectroscopy
  - light hadrons: important contributions to glueball and hybrid searches
  - charmonium-like: direct production of vector states  $Y$ , radiative and hadronic transitions to  $X, Z$  - states
- broad physics reach
  - light hadron spectroscopy & decays
  - open charm physics
  - (exotic) charmonia
  - precision measurements ( $R$ , TFF, ...)
  - ...
- data taking is ongoing
  - new:  $2.7 \cdot 10^9 \psi(2S)$ , soon:  $20 \text{ fb}^{-1}$  at the  $\psi(3770)$



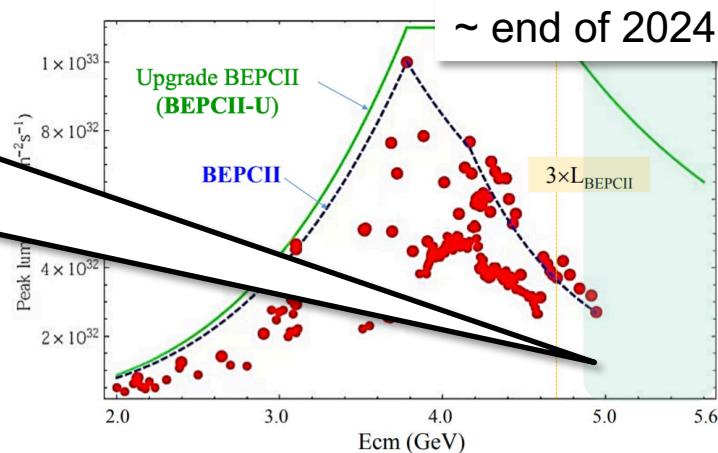
# Summary and Outlook

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  - light hadrons: important contributions to glueball and hybrid searches
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- broad phase
  - light
  - open
  - (exot)
  - preci
  - ...
- data taking is ongoing
  - new:  $2.7 \cdot 10^9 \psi(2S)$ , soon:  $20 \text{ fb}^{-1}$  at the  $\psi(3770)$

increased center-of-mass energy:

- up to 5.6 GeV, enabling studies of charmed baryons:  $\Sigma_c \bar{\Sigma}_c, \Xi_c \bar{\Xi}_c, \Omega_c \bar{\Omega}_c$
- above  $J/\psi p\bar{p}$  threshold,  $P_c$  states?
- largely unexplored energy region, new surprises?

- first data at higher c.m. energies  $4.7 \text{ GeV} < \sqrt{s} < 4.94 \text{ GeV}$  is available
- further upgrade in energy (5.6 GeV) and luminosity (BEPCCII-U) coming





Thank you for  
your attention!



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