



Modern aspects of light-quark and charmonium spectroscopy at BESIII

Nils Hüsken
on behalf of the BESIII collaboration

Workshop: Recent results and perspectives in hadron physics
Orsay, October 17th, 2022

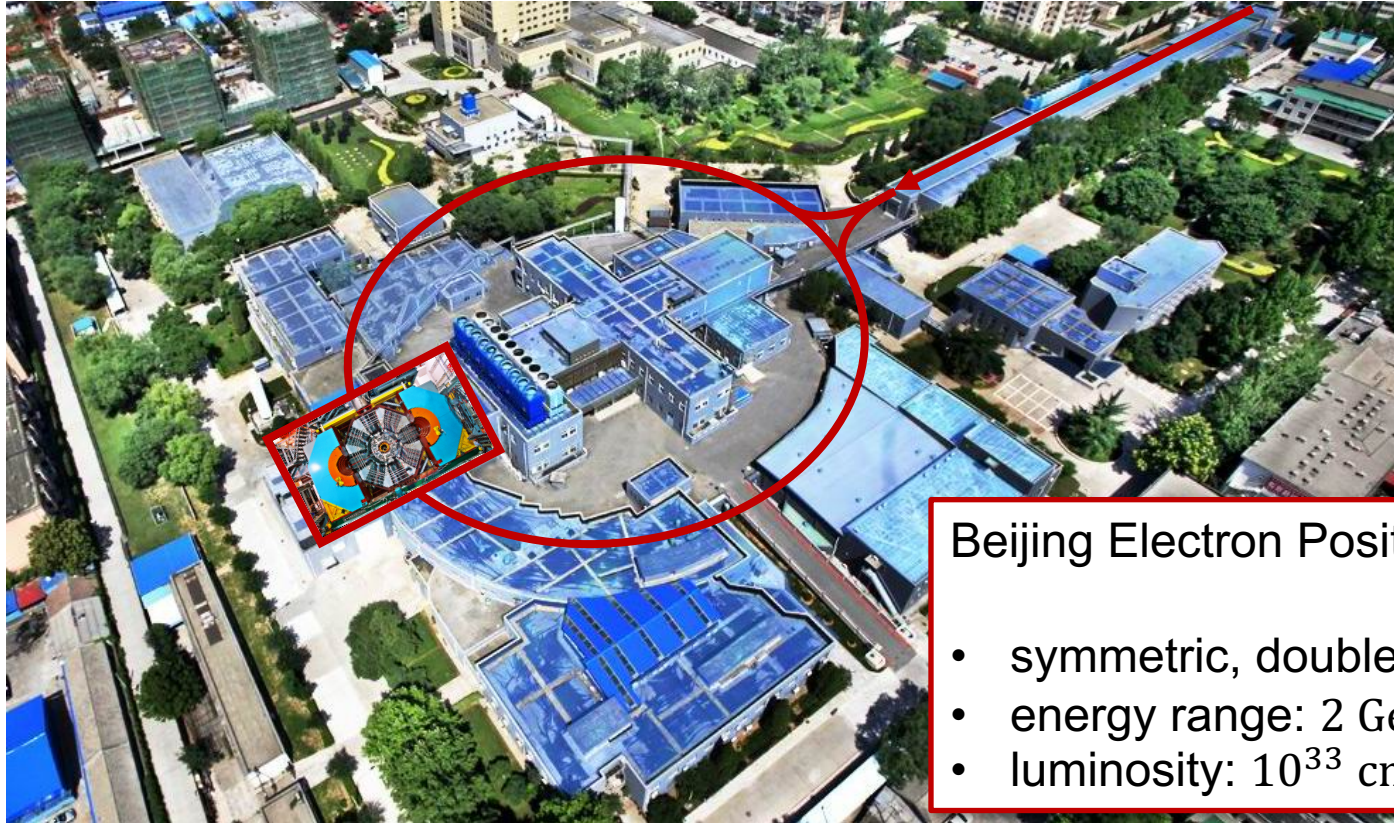
INDIANA UNIVERSITY BLOOMINGTON



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 $\psi(3770)$)

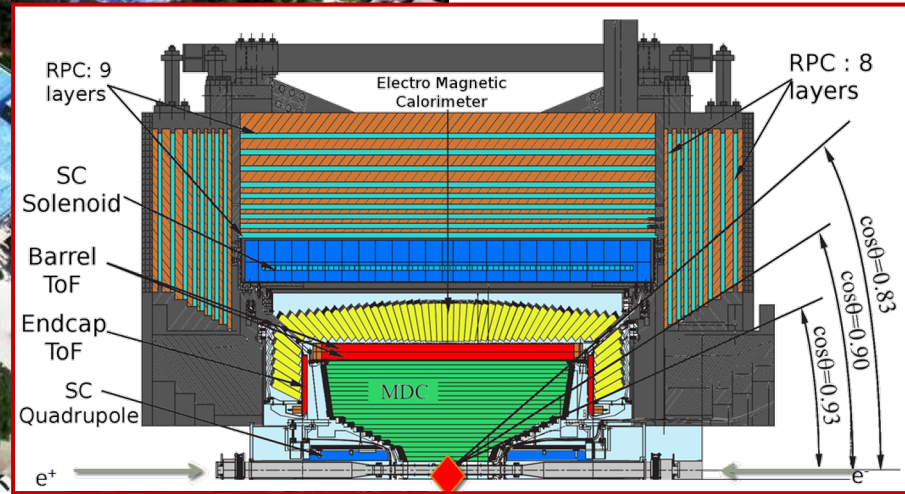
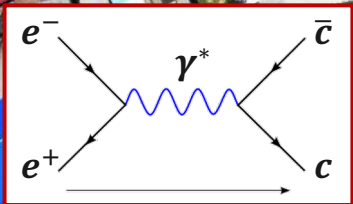


BESIII

~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

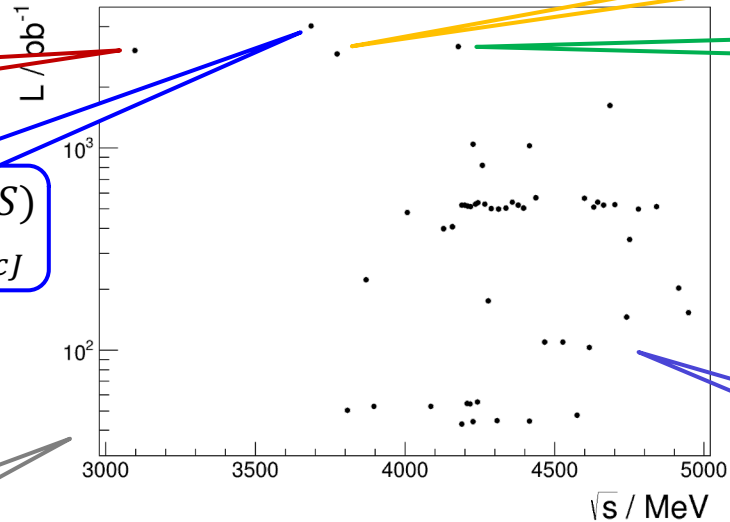
- light hadron spectroscopy
- η & η' decays
- charmonium transitions
- hyperon physics
- ...

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

- excited ρ , ω , ϕ
- ...

$10^{10} J/\psi$

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



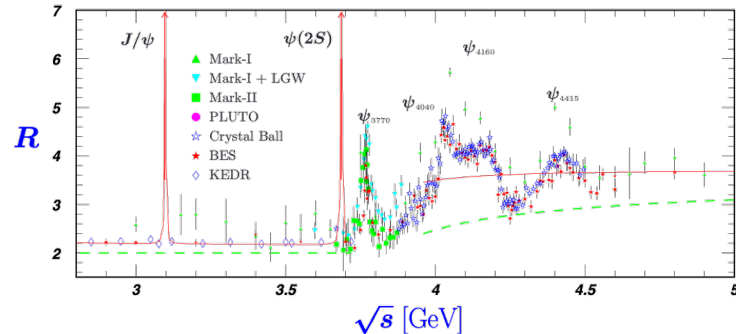
$\sim 2.9 \text{ fb}^{-1}$ at $\psi(3770)$

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

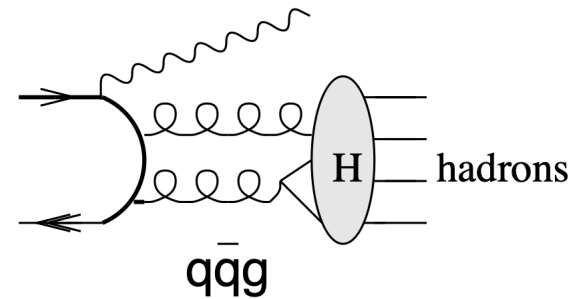
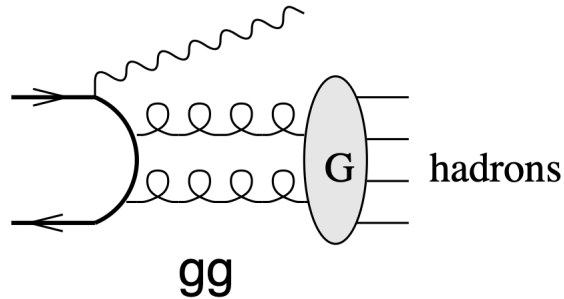


Light hadron spectroscopy



Radiative J/ψ decays

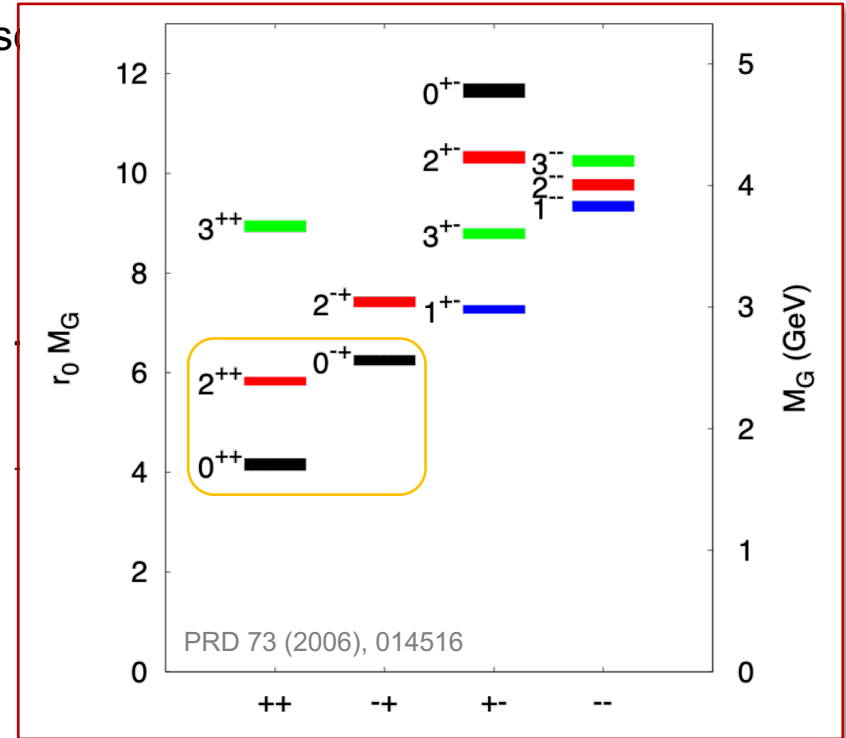
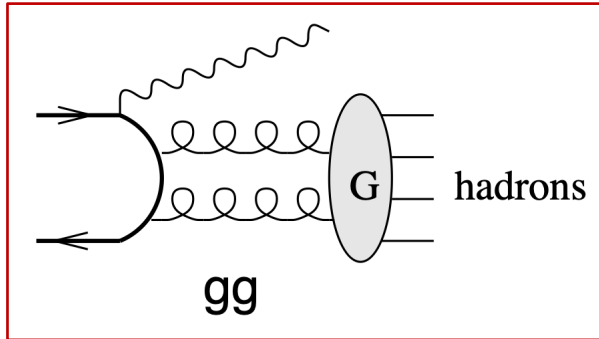
- a unique laboratory for light hadron spectroscopy
 - clean, high statistics sample
 - well-defined initial state $J^{PC} = 1^{--}$
 - gluon-rich environment



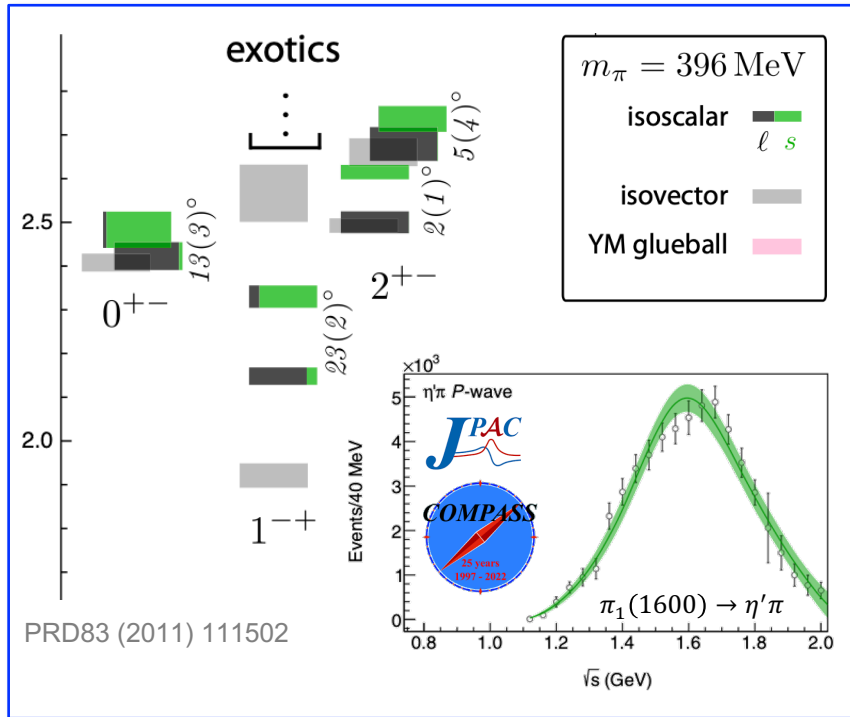
eConf C020620 (2002) THAT07

Radiative J/ψ decays

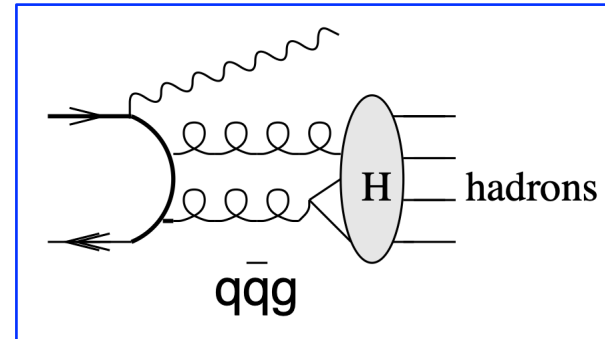
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Radiative J/ψ decays



ctroscopy

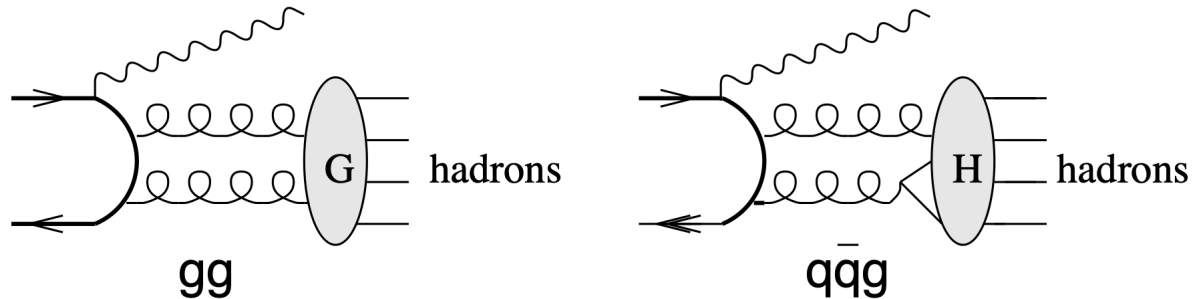


eConf C020620 (2002) THAT07



Radiative J/ψ decays

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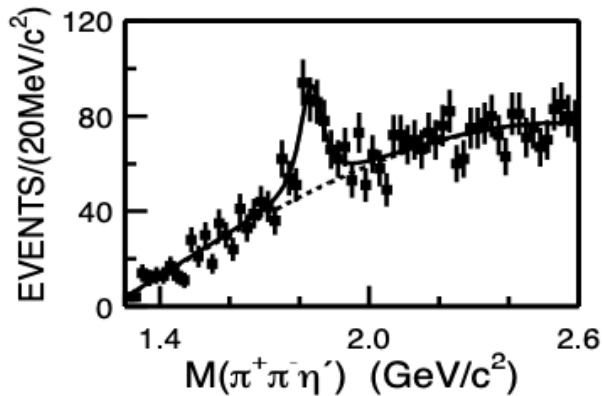
eConf C020620 (2002) THAT07

- searches for scalar, pseudo-scalar and tensor glueball candidates, iso-scalar partners of the spin-exotic $J^{PC} = 1^{-+}$ hybrid candidate $\pi_1(1600)$

Radiative J/ψ decays

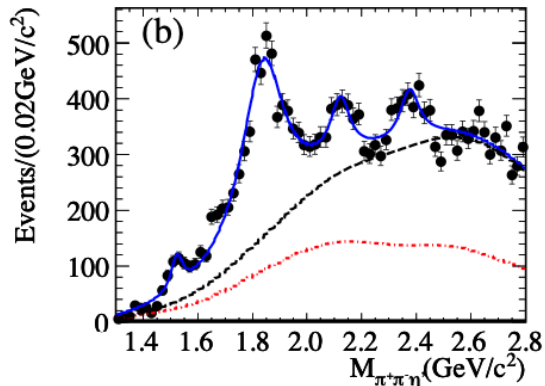
- structures in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

PRL 95 (2005) 262001



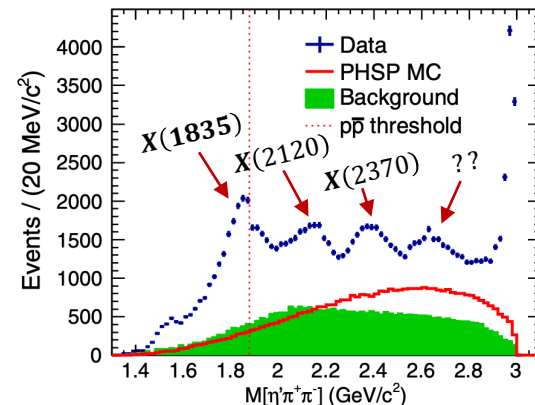
$58 \cdot 10^6 J/\psi$

PRL 106 (2011) 072002



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

PRL 117 (2016) 4, 042002



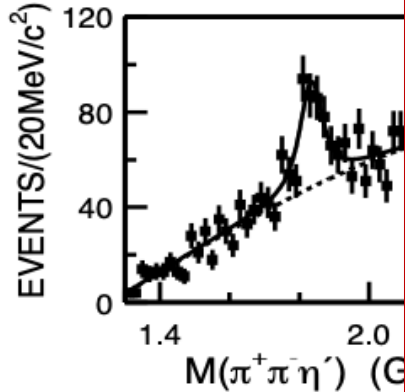
$1.3 \cdot 10^9 J/\psi$



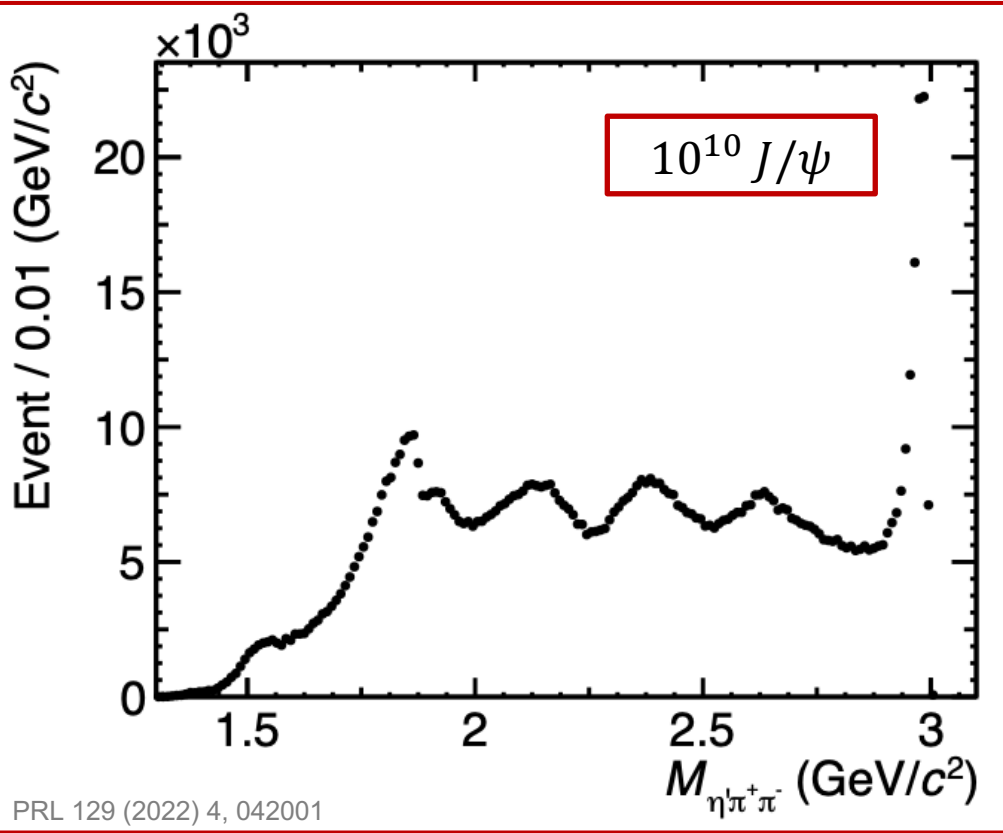
Radiative J/ψ decays

- structures in J/ψ

PRL 95 (2005) 262001

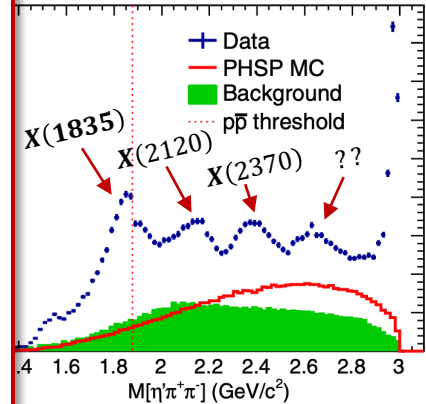


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PRL 129 (2022) 4, 042001

2016) 4, 042002

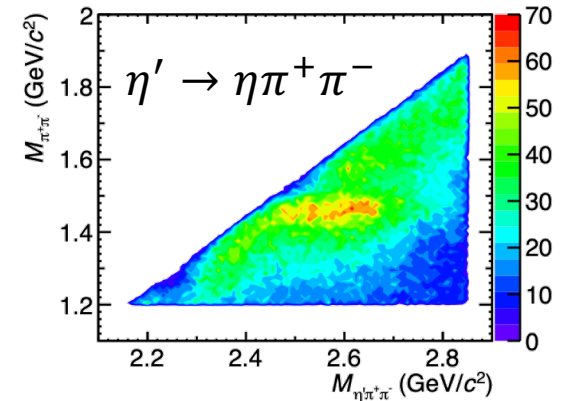
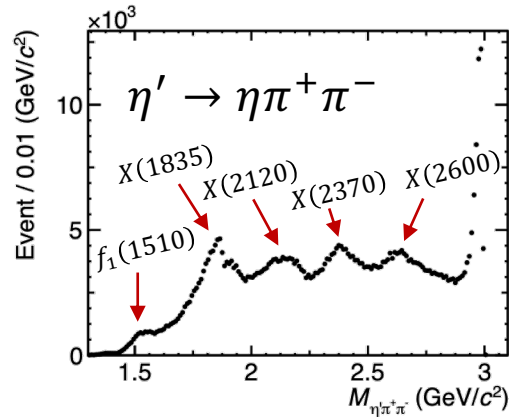
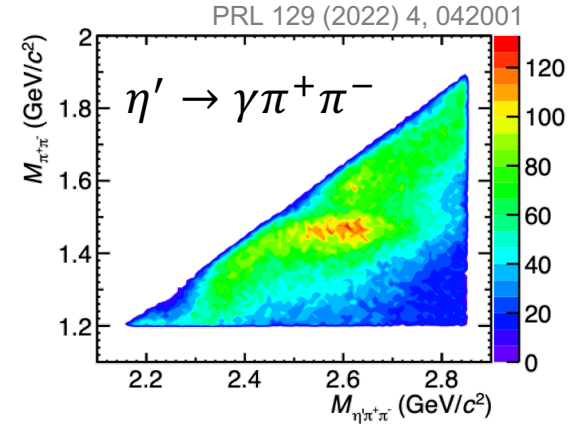
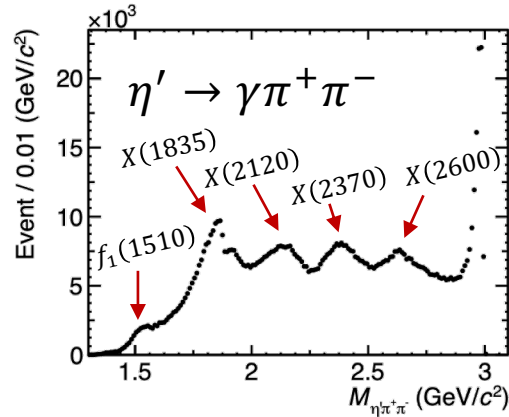


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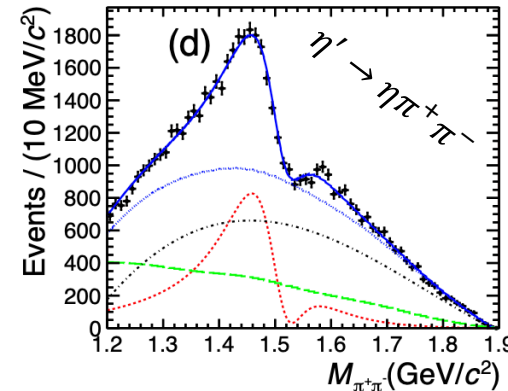
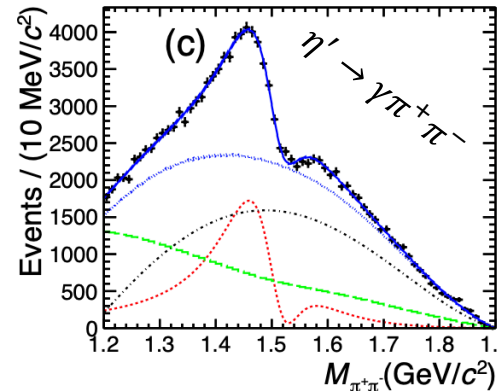
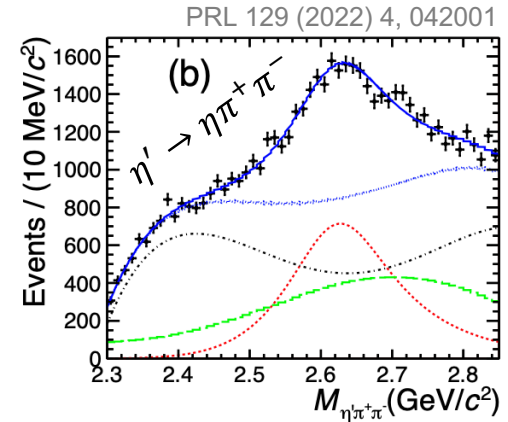
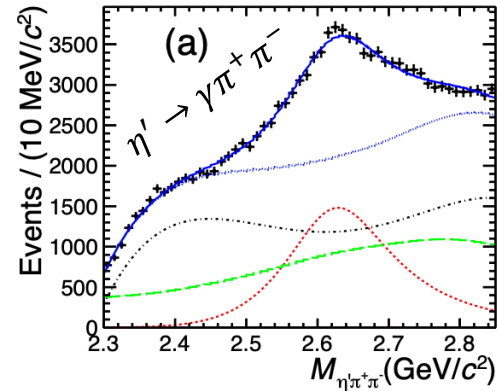
Radiative J/ψ decays

- 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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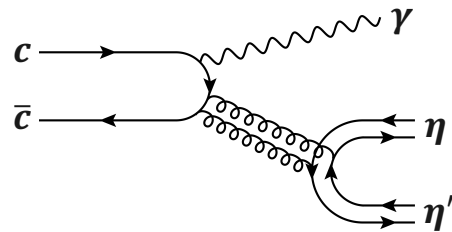


PRL 129 (2022) 4, 042001



Radiative J/ψ decays

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

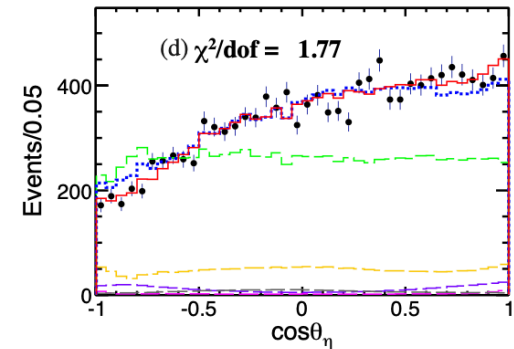
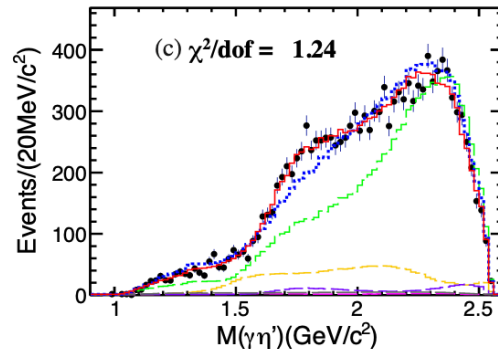
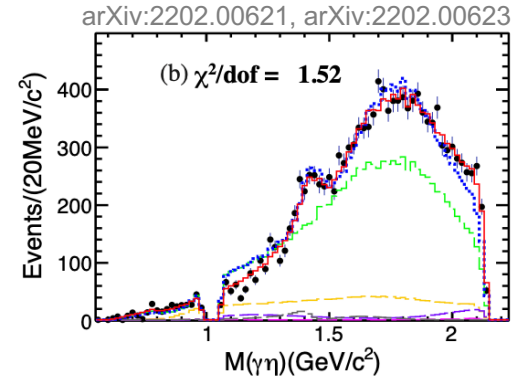
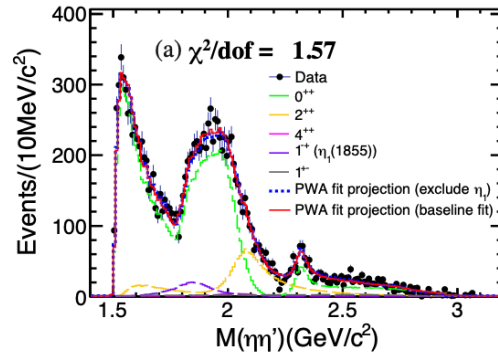


- iso-scalar spin-exotic $\eta_1(1855)$

$$m = 1855 \pm 9_{-1}^{+6} \text{ MeV}$$

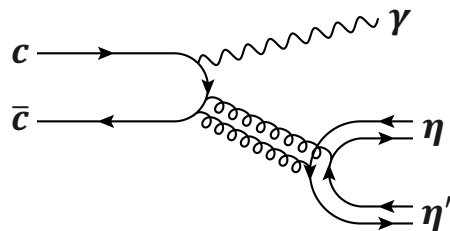
$$\Gamma = 188 \pm 18_{-8}^{+3} \text{ MeV}$$

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



Radiative J/ψ decays

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

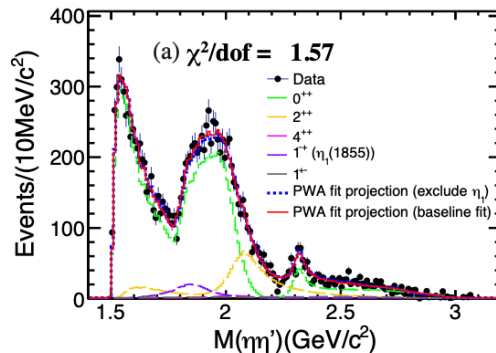


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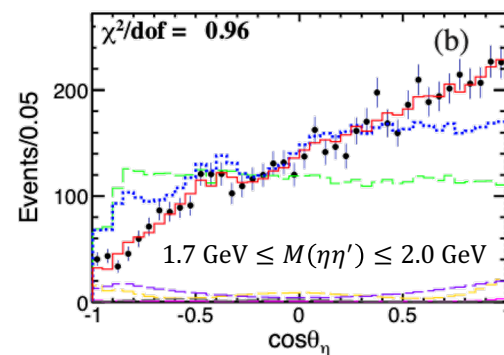
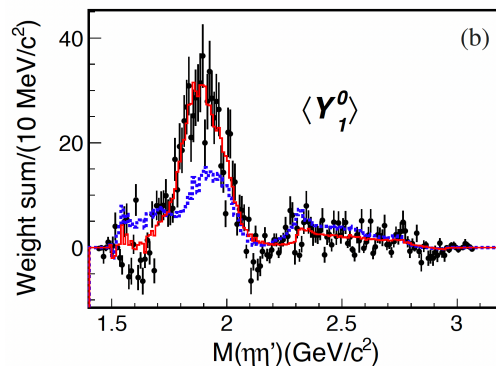
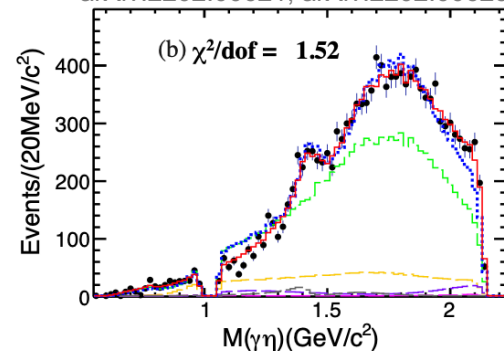
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arXiv:2202.00621, arXiv:2202.00623



Radiative J/ψ decays

- scalar glueball decays to $\eta\eta'$ expected to be suppressed $\frac{B(G \rightarrow \eta\eta')}{B(G \rightarrow \pi\pi)} < 0.04$

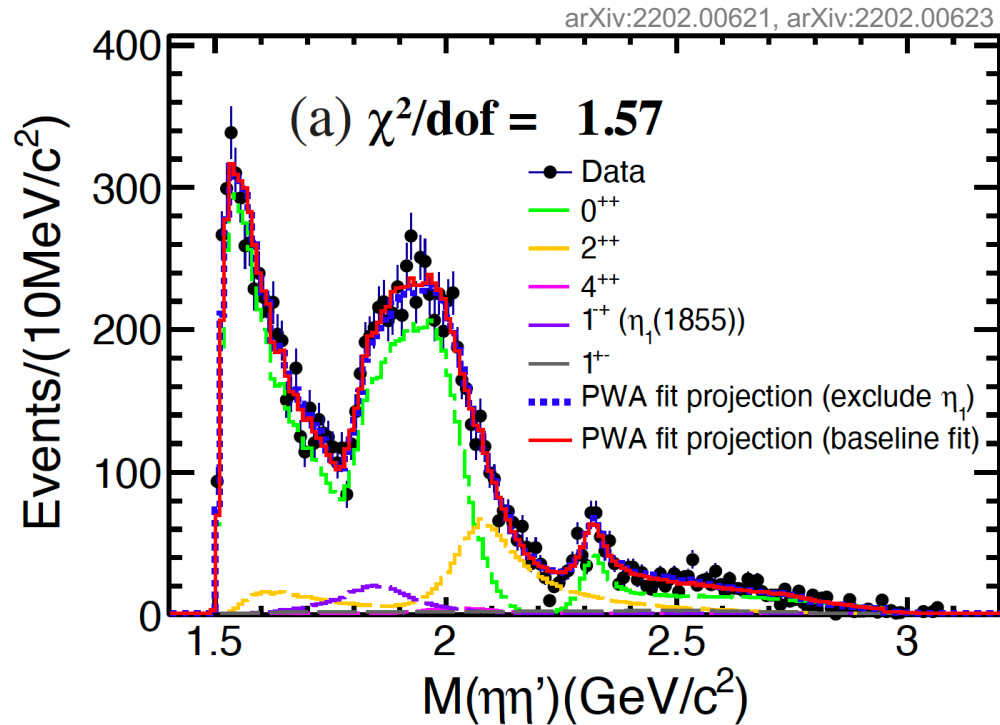
PRD 92, 121902 (2015)

- significant $f_0(1500)$ contribution, but no $f_0(1710)$ (there is a small $f_0(1810)$ in the fit)

- $\frac{B(f_0(1500) \rightarrow \eta\eta')}{B(f_0(1500) \rightarrow \pi\pi)} = (8.96_{-2.87}^{+2.95}) \times 10^{-2}$,

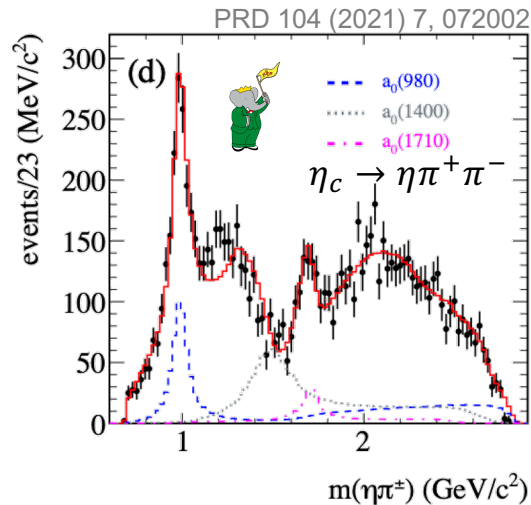
- $\frac{B(f_0(1710) \rightarrow \eta\eta')}{B(f_0(1710) \rightarrow \pi\pi)} < 1.61 \times 10^{-3}$ (90% CL)

- $\frac{B(f_0(1810) \rightarrow \eta\eta')}{B(f_0(1710) \rightarrow \pi\pi)} = (1.39_{-0.52}^{+0.62}) \times 10^{-2}$

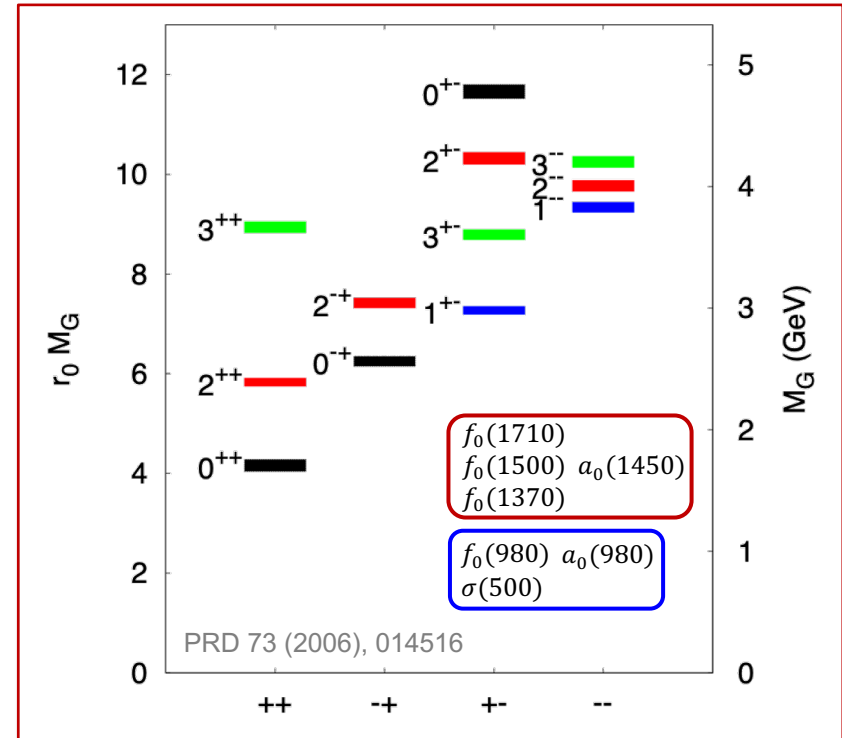


Light hadrons in open-charm decays

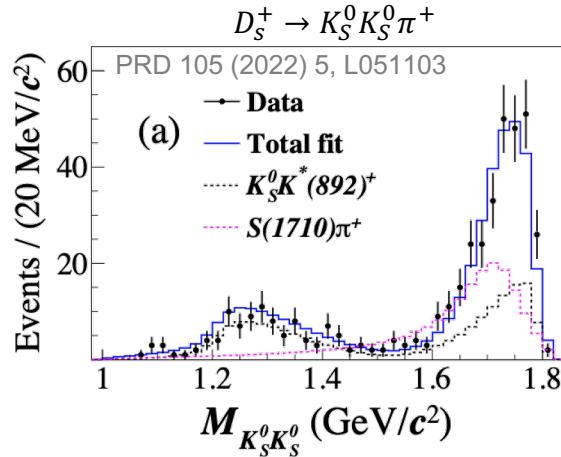
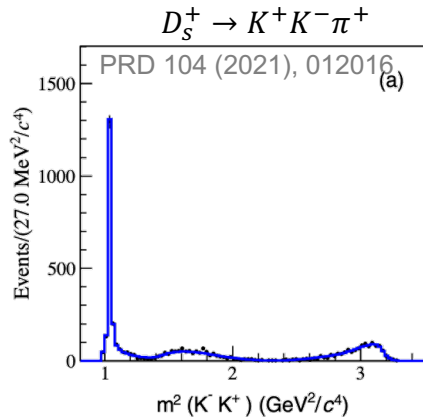
- BaBar recently observed an $a_0(1710)$



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



Light hadrons in open-charm decays



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

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

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

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

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

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

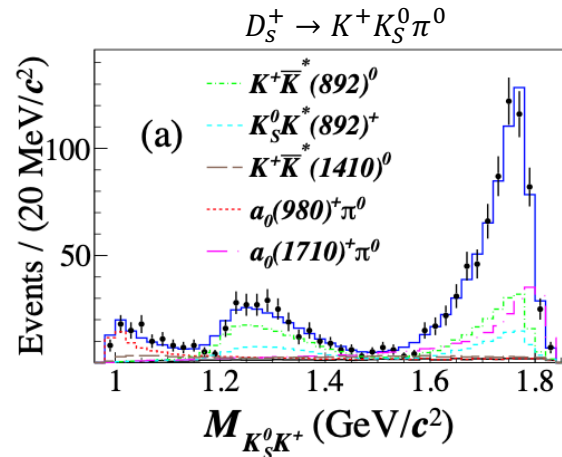
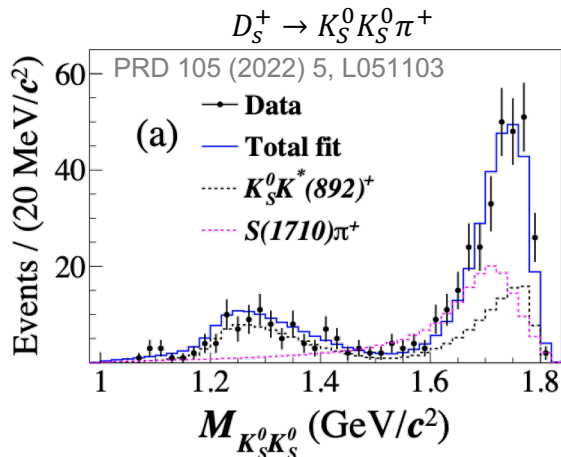
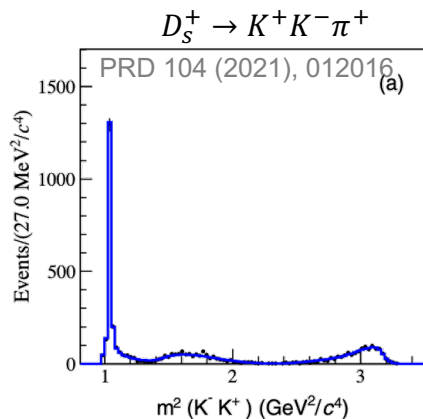
S. U. Chung, BNL-QGS-13-0901

→ $a_0(980)$ - $f_0(980)$ interference

→ $a_0(1710)$ - $f_0(1710)$ interference → $a_0(1710)$ needed!



Light hadrons in open-charm decays



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→ $a_0(980)$ - $f_0(980)$ interference

→ $a_0(1710)$ - $f_0(1710)$ interference → $a_0(1710)$ 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)

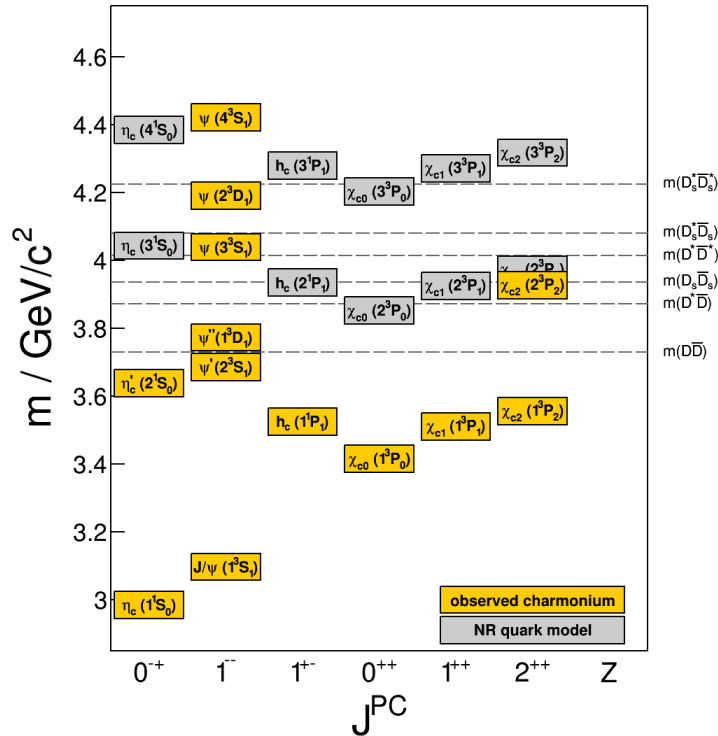
arXiv:2204.09614 [hep-ex]



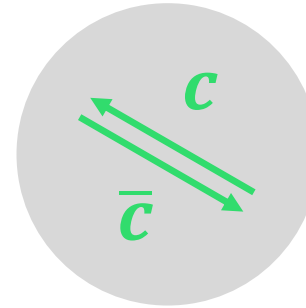
Charmonium(-like) states



Charmonium



- QCD-analogue to hydrogen atom / positronium



- spectrum from potential models:

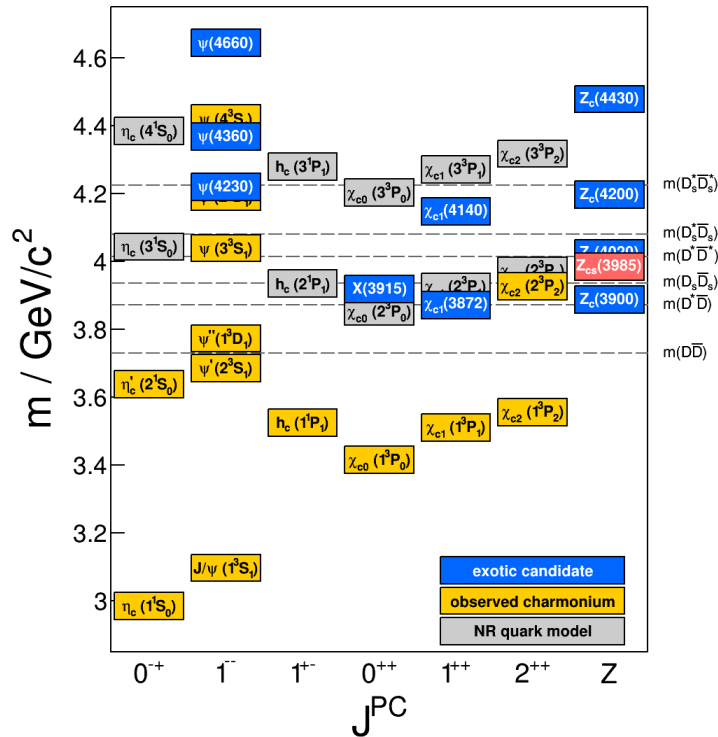
$$V_{q\bar{q}} = -\frac{4}{3} \cdot \frac{\alpha_s(r)}{r} + k \cdot r \quad + \text{spin-dependent terms}$$

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

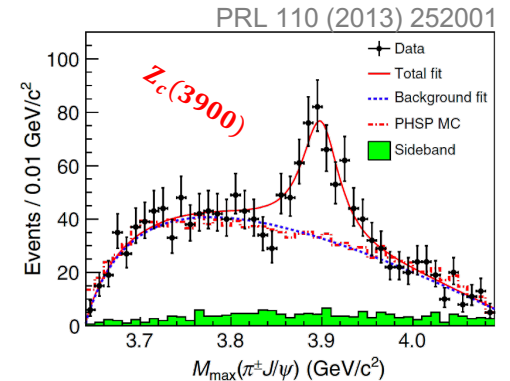
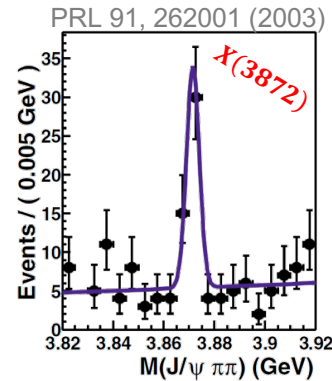
- good agreement with experiments



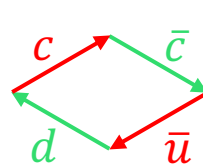
Charmonium-like states



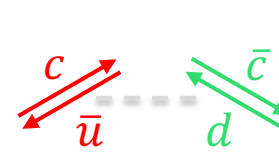
- several unexpected states observed



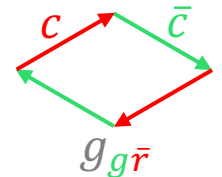
- their nature is still unclear



tetraquark



molecular state

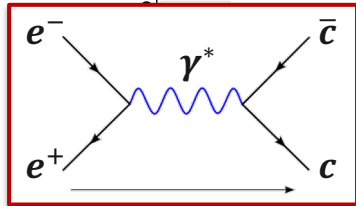
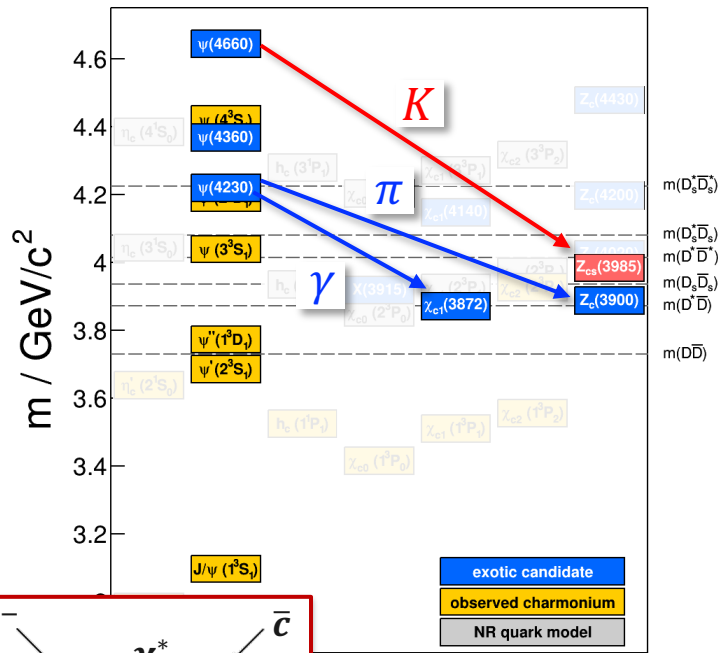


hybrid meson

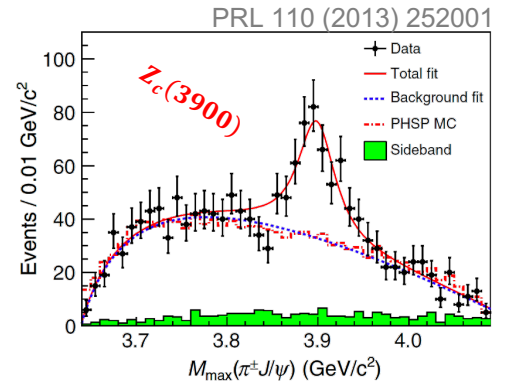
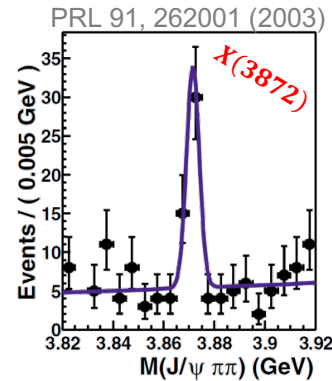
model values from
PRD 72 (2005) 054026



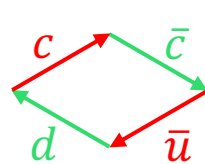
Charmonium-like states



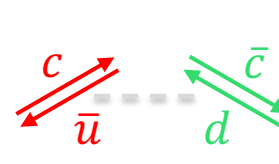
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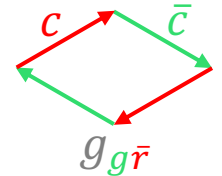
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tetraquark

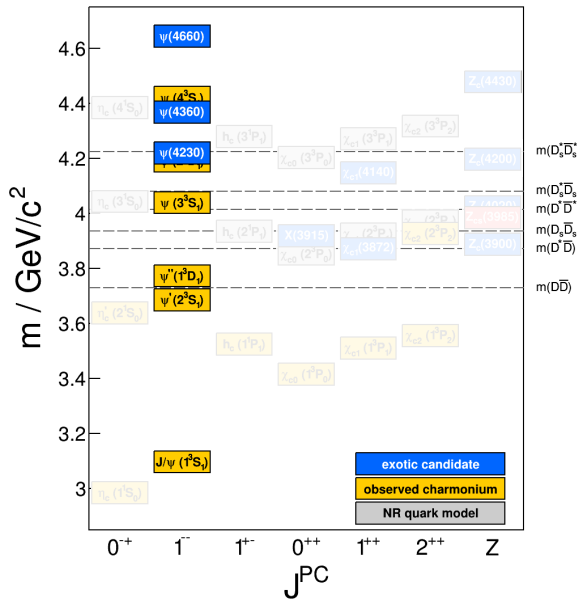


molecular state

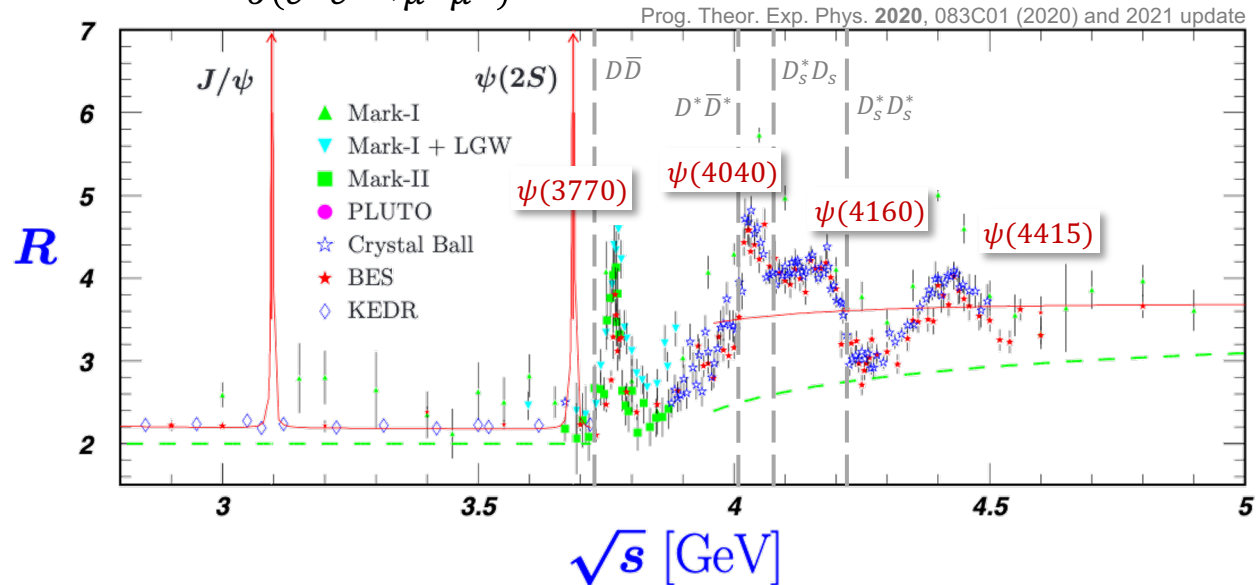


hybrid meson

Vector states



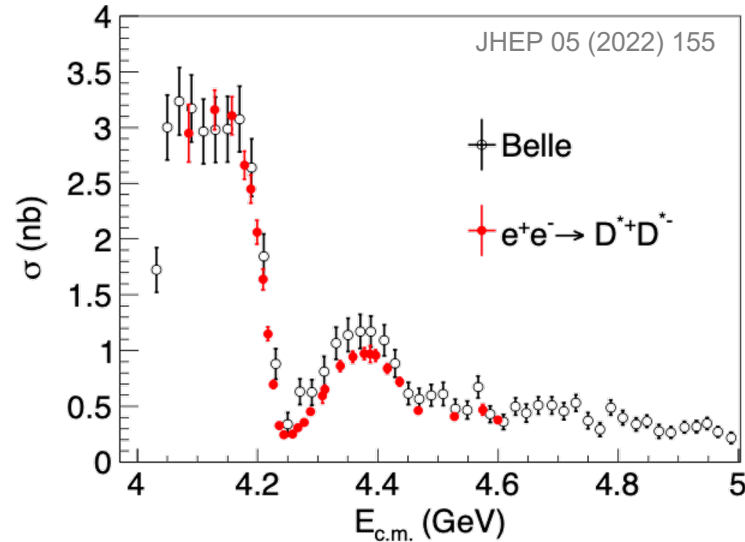
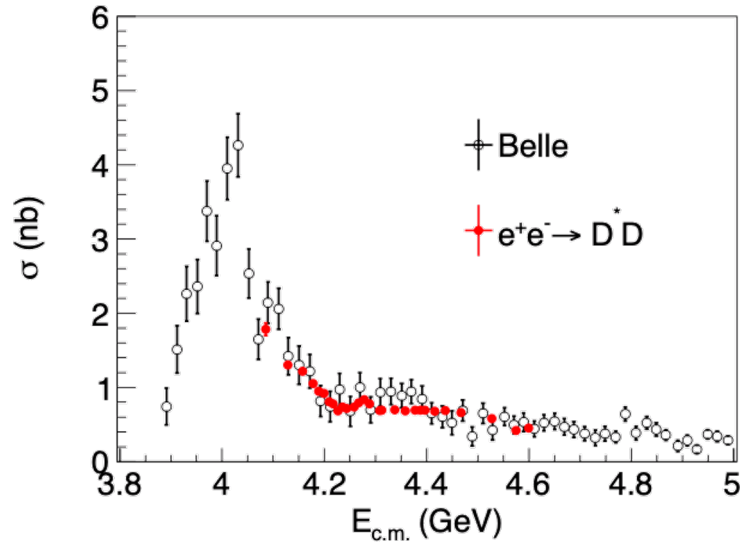
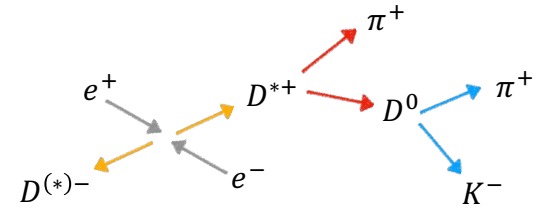
$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$



- 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 $e^+e^- \rightarrow \text{hadrons}$

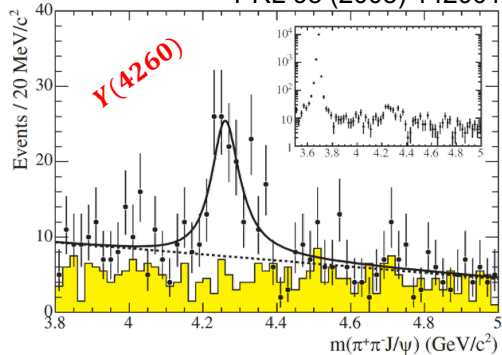
Vector states: Open-charm production

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



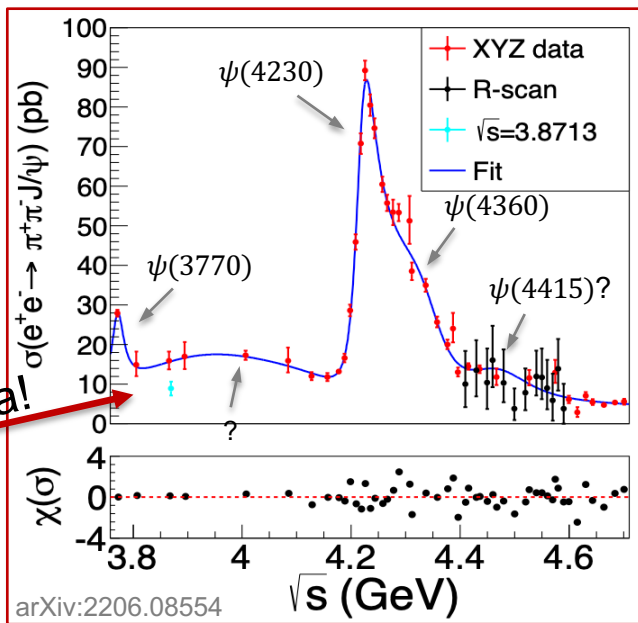
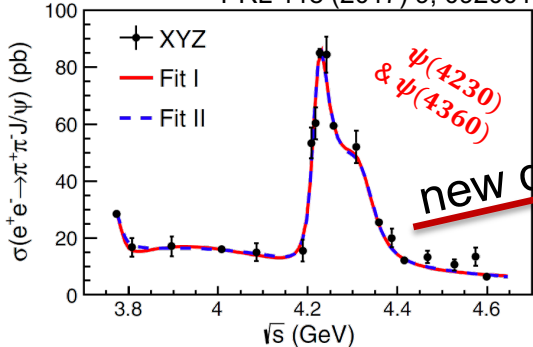
Vector states: Hidden-charm production

PRL 95 (2005) 142001



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

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

$$m_1 = 4221.4 \pm 1.5 \pm 2.0 \text{ MeV}$$

$$\Gamma_1 = 41.8 \pm 2.9 \pm 2.7 \text{ MeV}$$

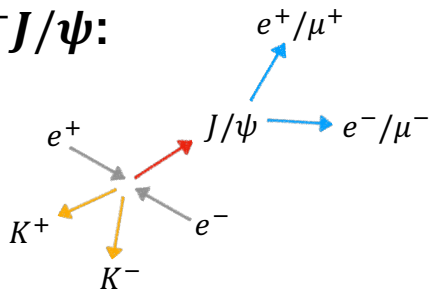
$$m_2 = 4298 \pm 12 \pm 26 \text{ MeV} \quad \blacktriangleleft$$

$$\Gamma_2 = 127 \pm 17 \pm 10 \text{ MeV} \quad \blacktriangleright$$

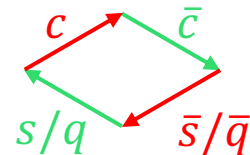
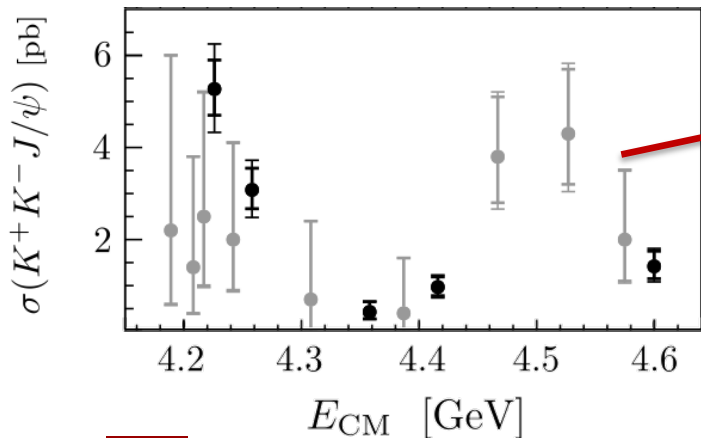


Vector states: Hidden-charm production

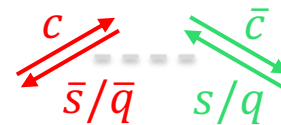
- $e^+e^- \rightarrow K^+K^-J/\psi$:



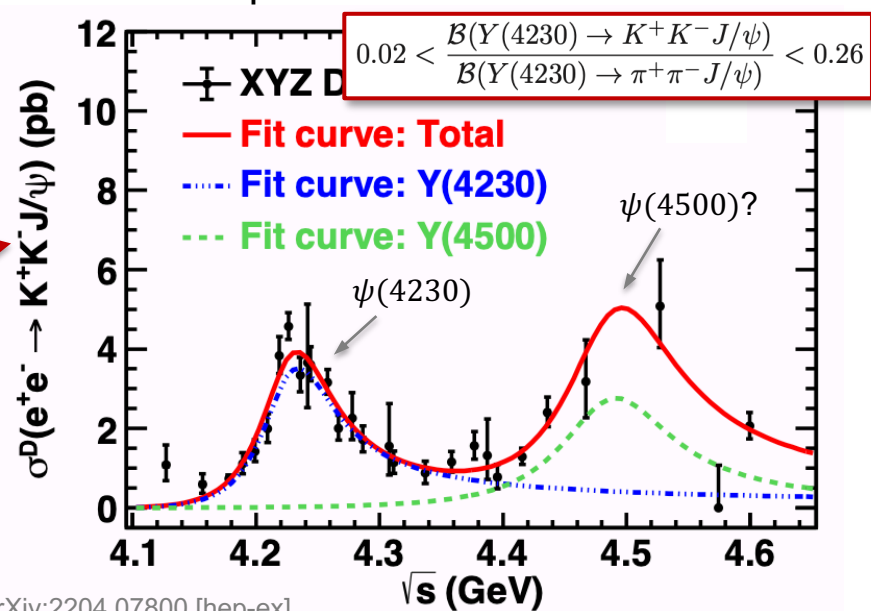
reconstruct $J/\psi \rightarrow l^+l^-$ and at least one kaon



tetraquark



molecular state

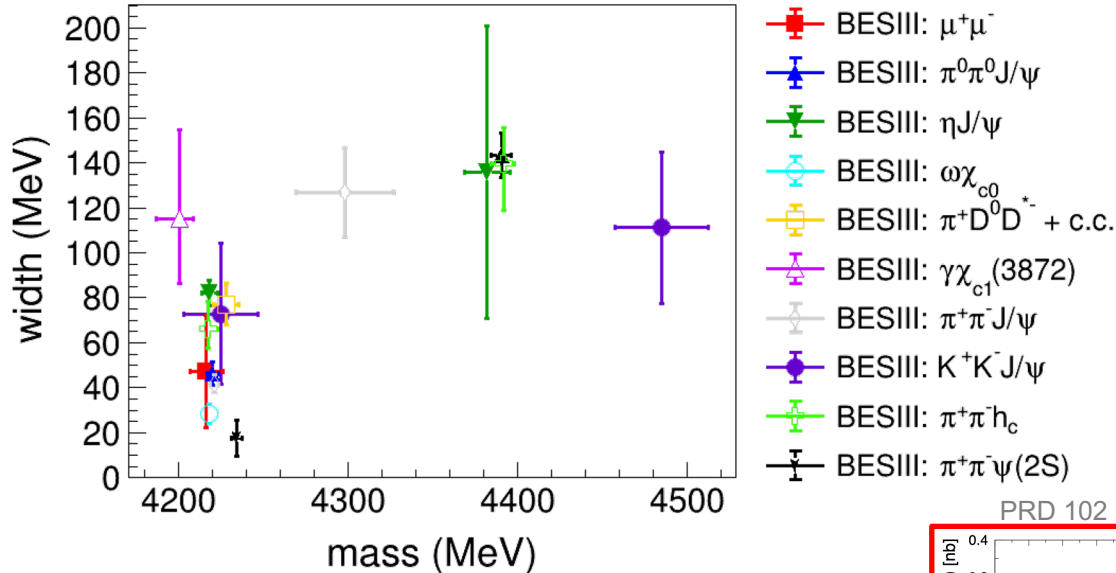


arXiv:2204.07800 [hep-ex]



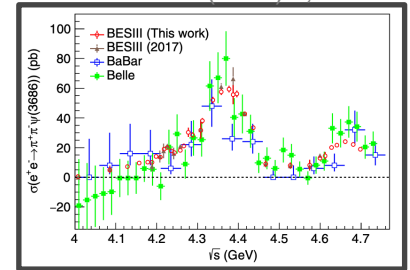
Vector states: Hidden-charm production

- different channels show (slightly) different masses and widths

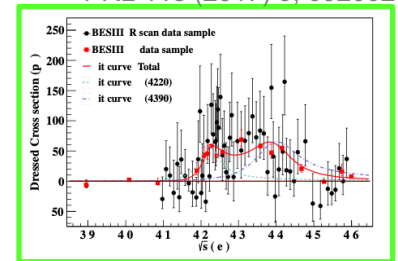


- coupled channel studies are needed!

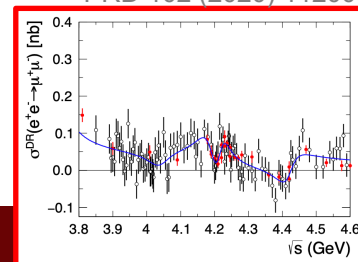
PRD 104 (2021) 5, 052012



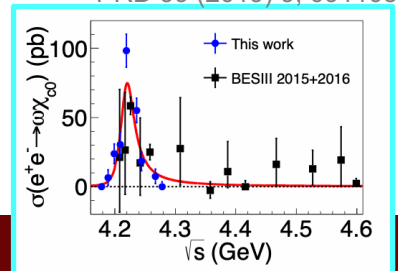
PRL 118 (2017) 9, 092002



PRD 102 (2020) 112009

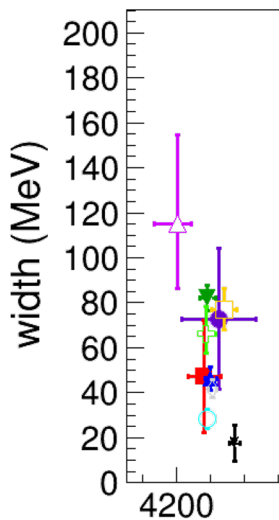


PRD 99 (2019) 9, 091103

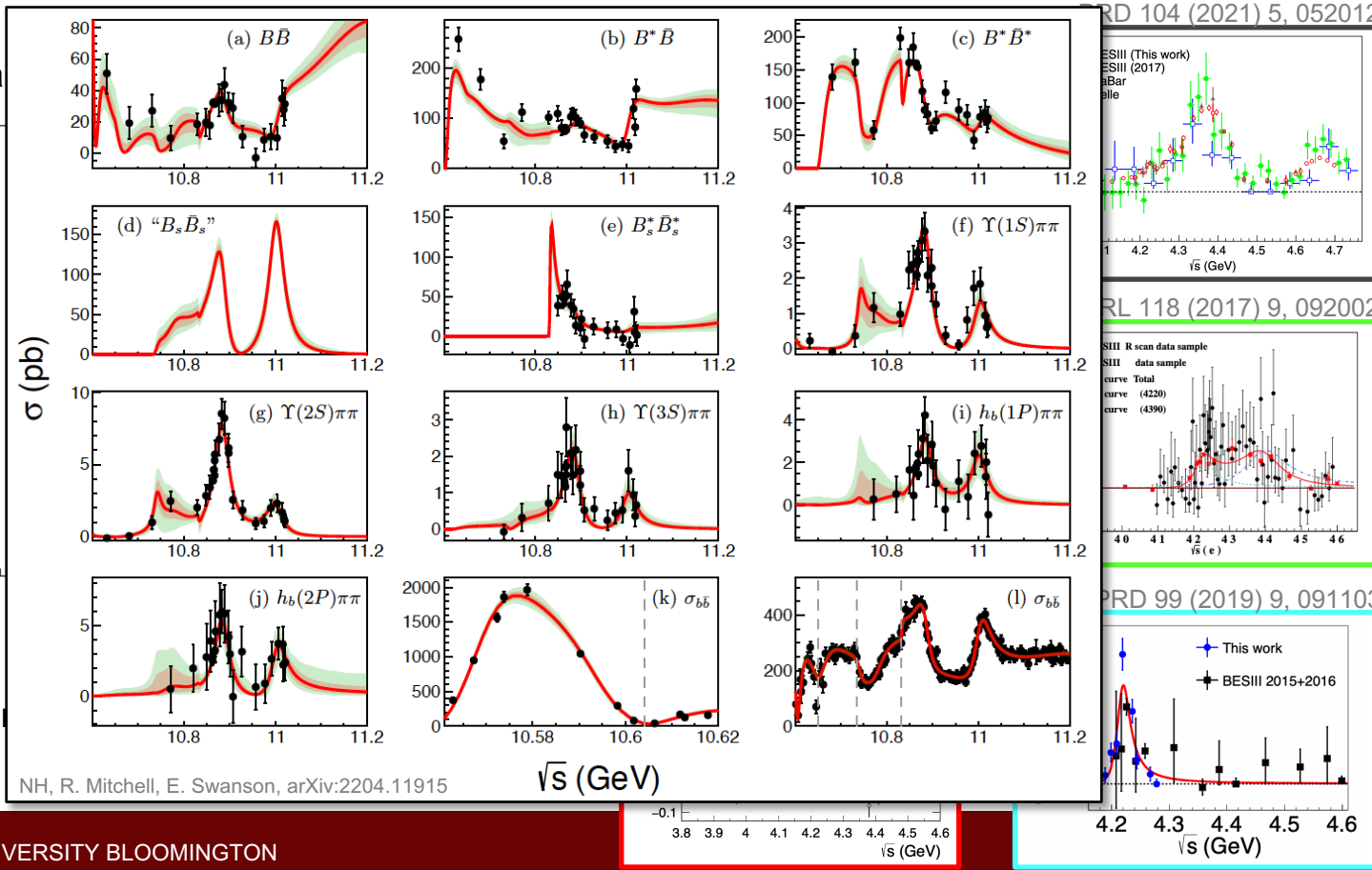


Vector states: Hidden-charm production

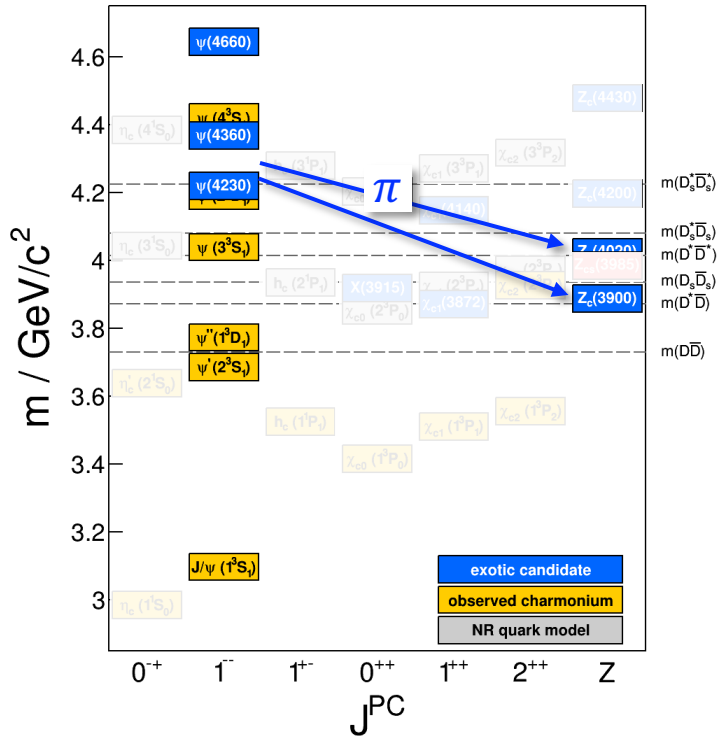
- different channels



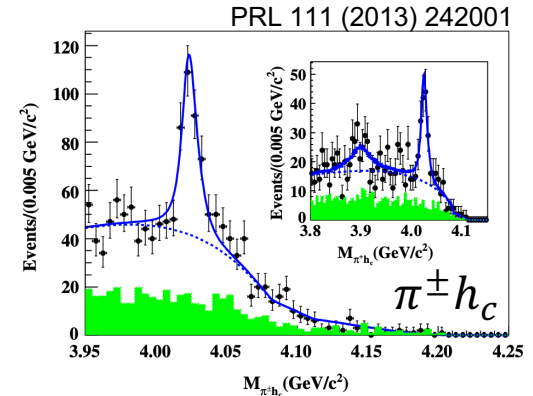
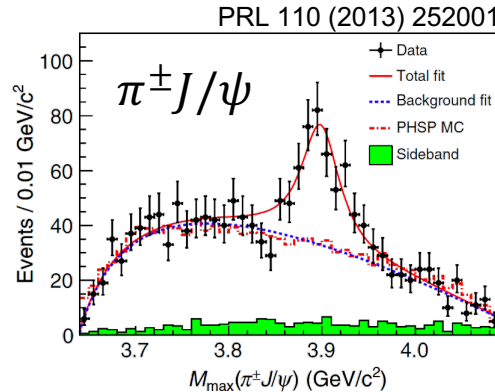
- coupled channels



Charged charmonium-like states

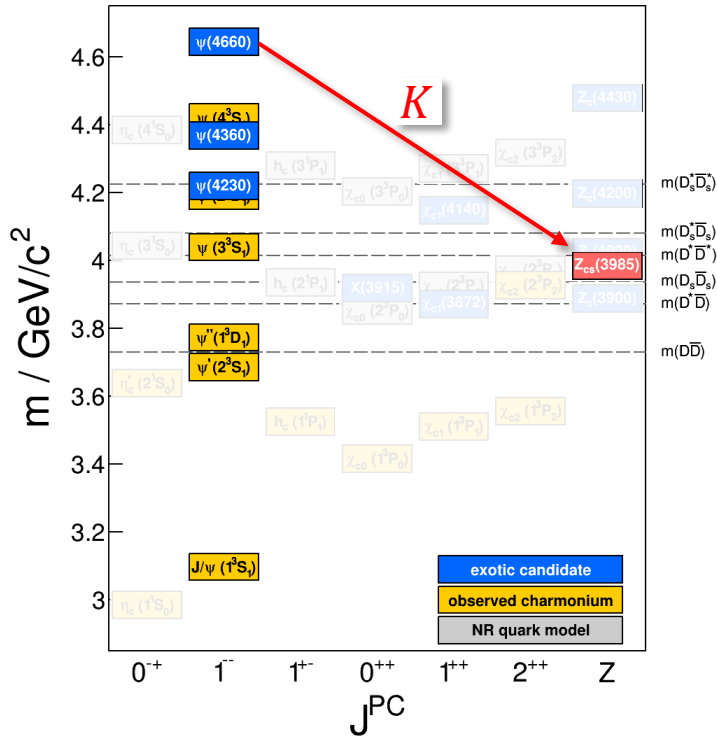


- openly exotic with $I \neq 0$ ($q \neq 0$)
- nature still unclear (tetraquark, molecule, ...)

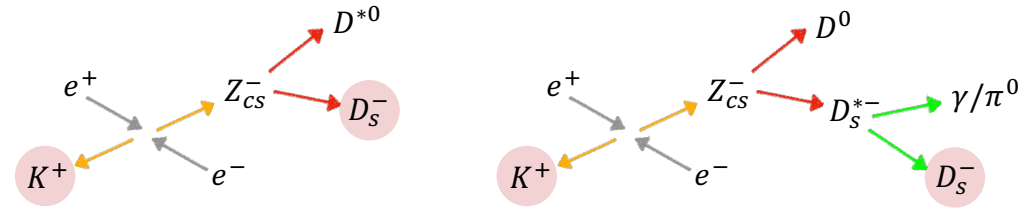


- if genuine resonance, minimal quark content of $c\bar{c}q\bar{q}$
- intriguing connection to $\psi(4230)$

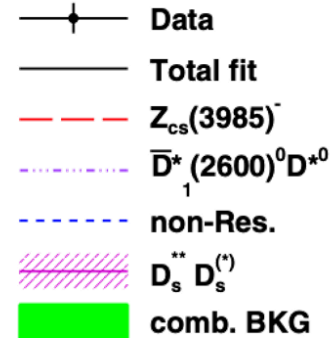
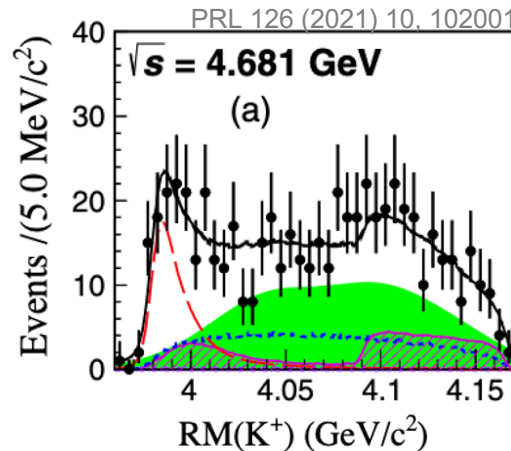
Charged charmonium-like states



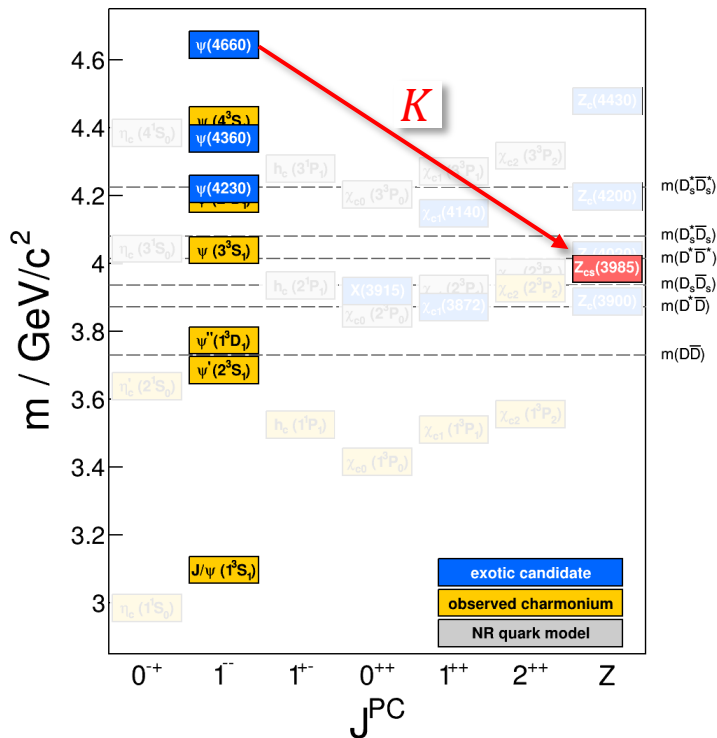
- search for an open-strange $c\bar{c}s\bar{q}$ partner Z_{cs}



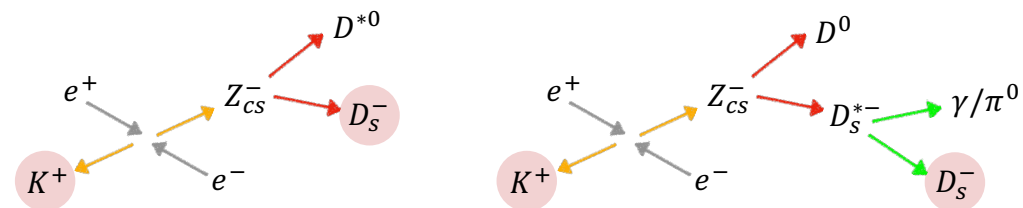
partial reconstruction method: K^+, D_s^-



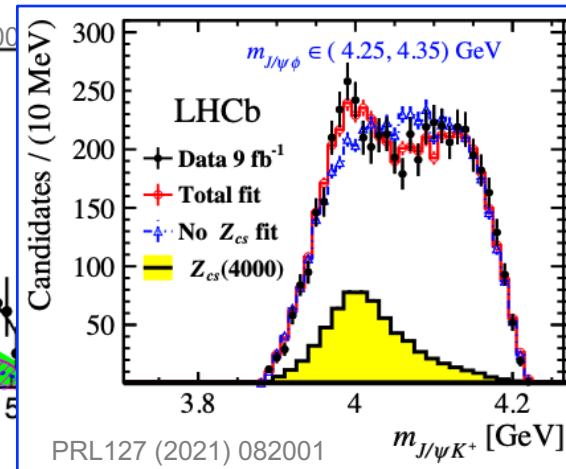
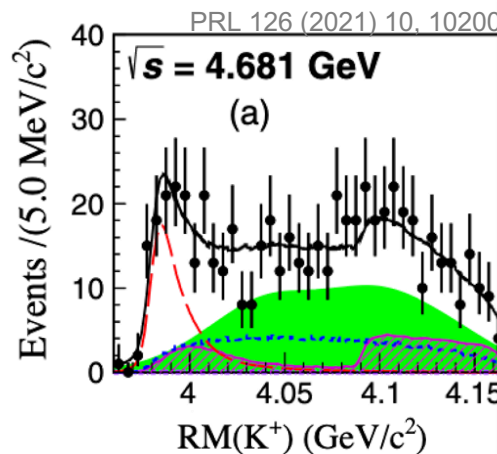
Charged charmonium-like states



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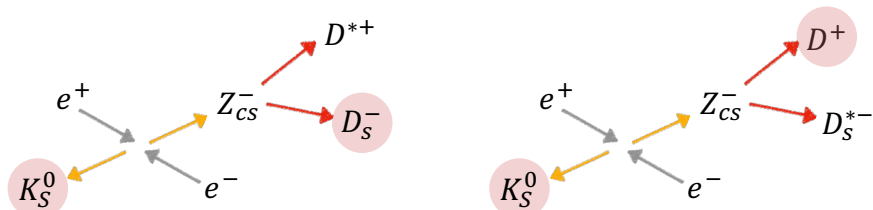


partial reconstruction method: K^+ , D_s^-



Charged charmonium-like states

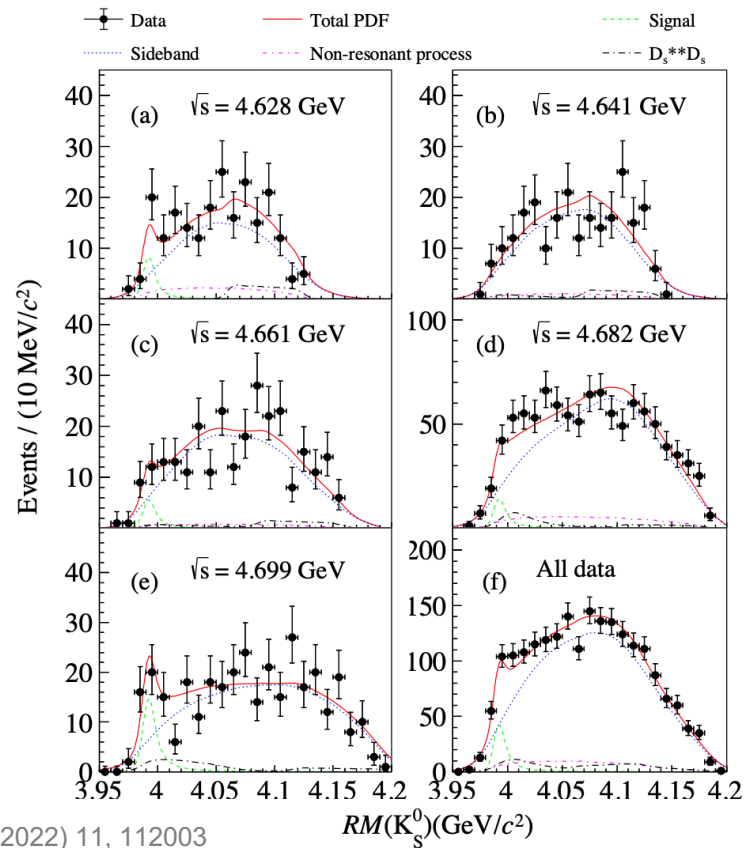
- search for Z_{cs}^0 in $e^+e^- \rightarrow K_S^0(D_S^+D^{*-} + D_S^{*+}D^-)$



partial reconstruction method: K_S^0 , ground state D_S^-/D^+

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

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

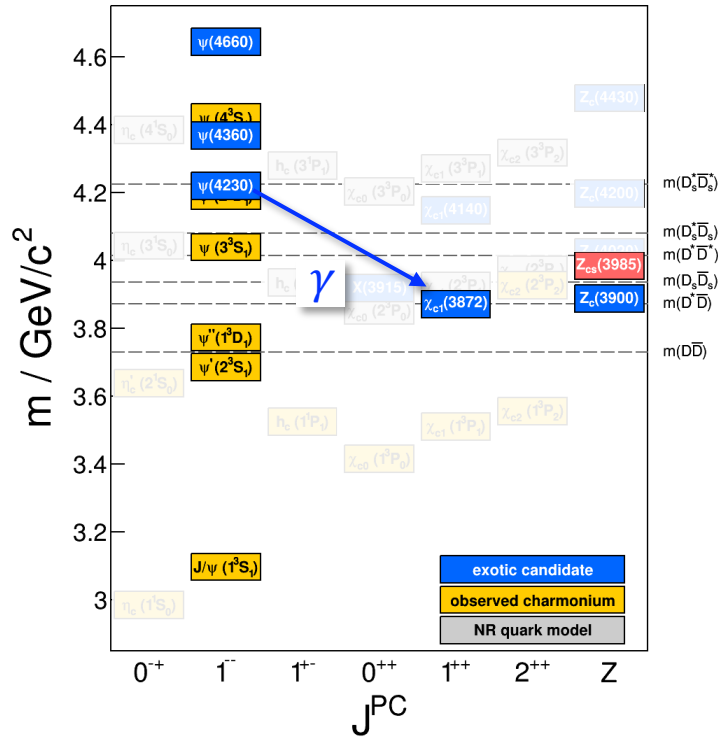


PRL 129 (2022) 11, 112003

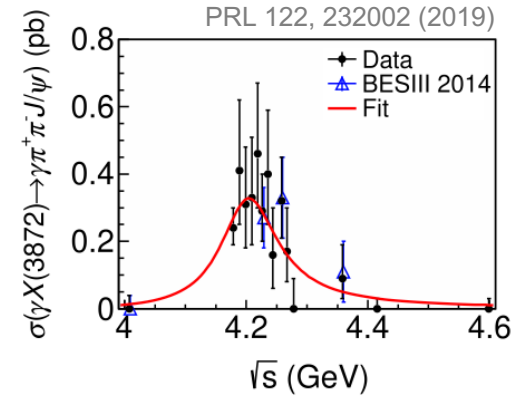
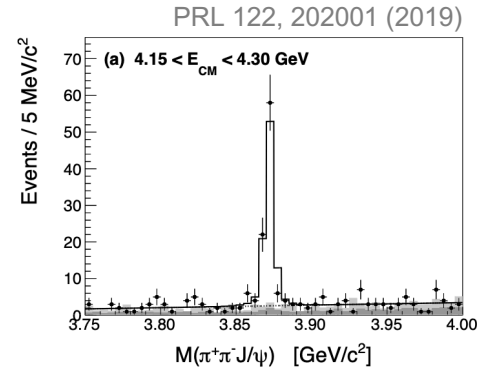
$RM(K_S^0)(\text{GeV}/c^2)$



On $\chi_{c1}(3872)$

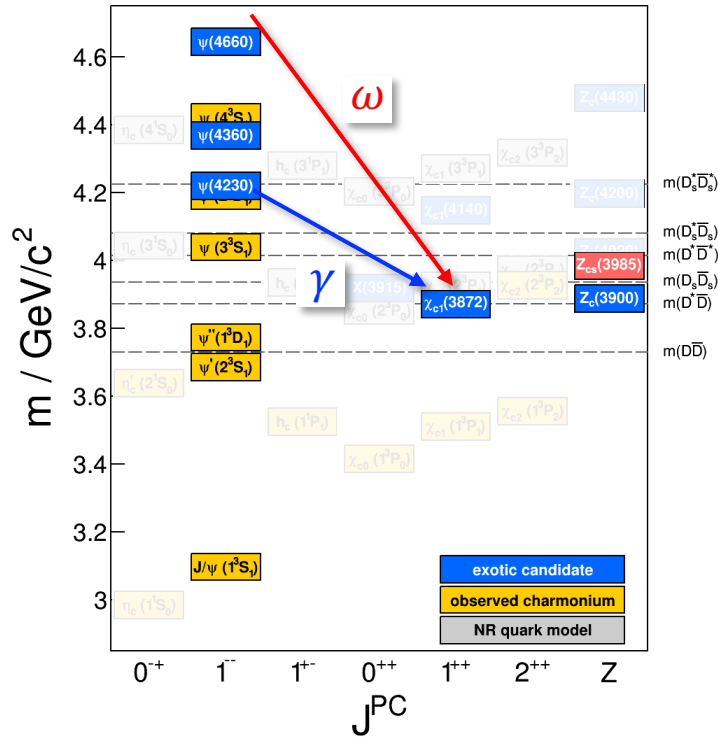


- established production process $e^+e^- \rightarrow \gamma\chi_{c1}(3872)$

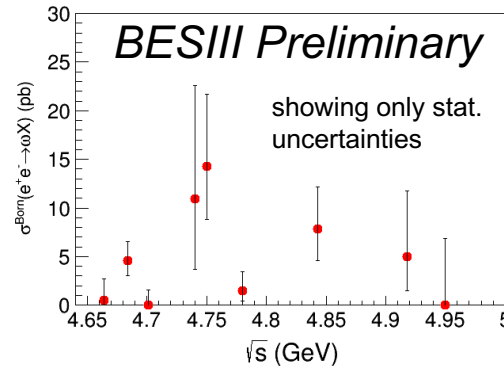
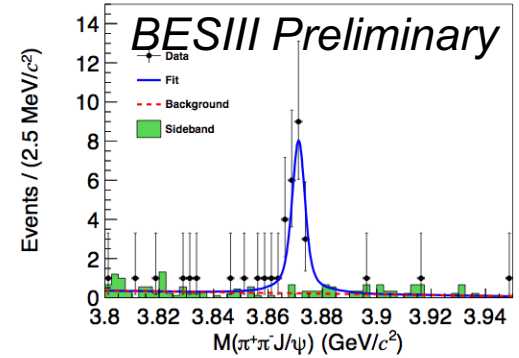
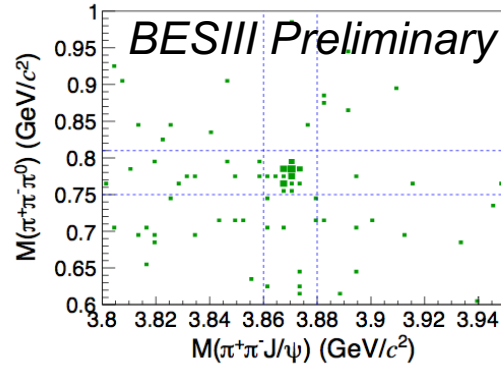


- used in multiple studies of $\chi_{c1}(3872)$ decay modes
- indication for resonant production through $\psi(4230)$

On $\chi_{c1}(3872)$



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



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



Summary and Outlook

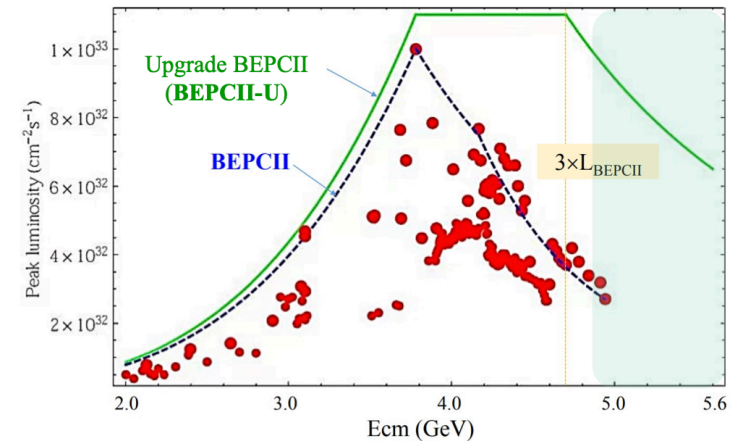
- BESIII is taking data since 2008
- broad physics reach
 - light hadron spectroscopy & decays
 - open charm physics
 - (exotic) charmonia
 - precision measurements (R , TFF, ...)
 - ...
- several new data sets currently being analyzed
 - first exciting results from new J/ψ and XYZ data
 - many analyses in progress, plenty of results to come
- data taking is ongoing
 - new: $2.7 \cdot 10^9 \psi(2S)$, soon: 20 fb^{-1} at the $\psi(3770)$



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- 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 (BEPCII-U) coming





*Thank you for
your attention!*



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