

BESIII Spectroscopy

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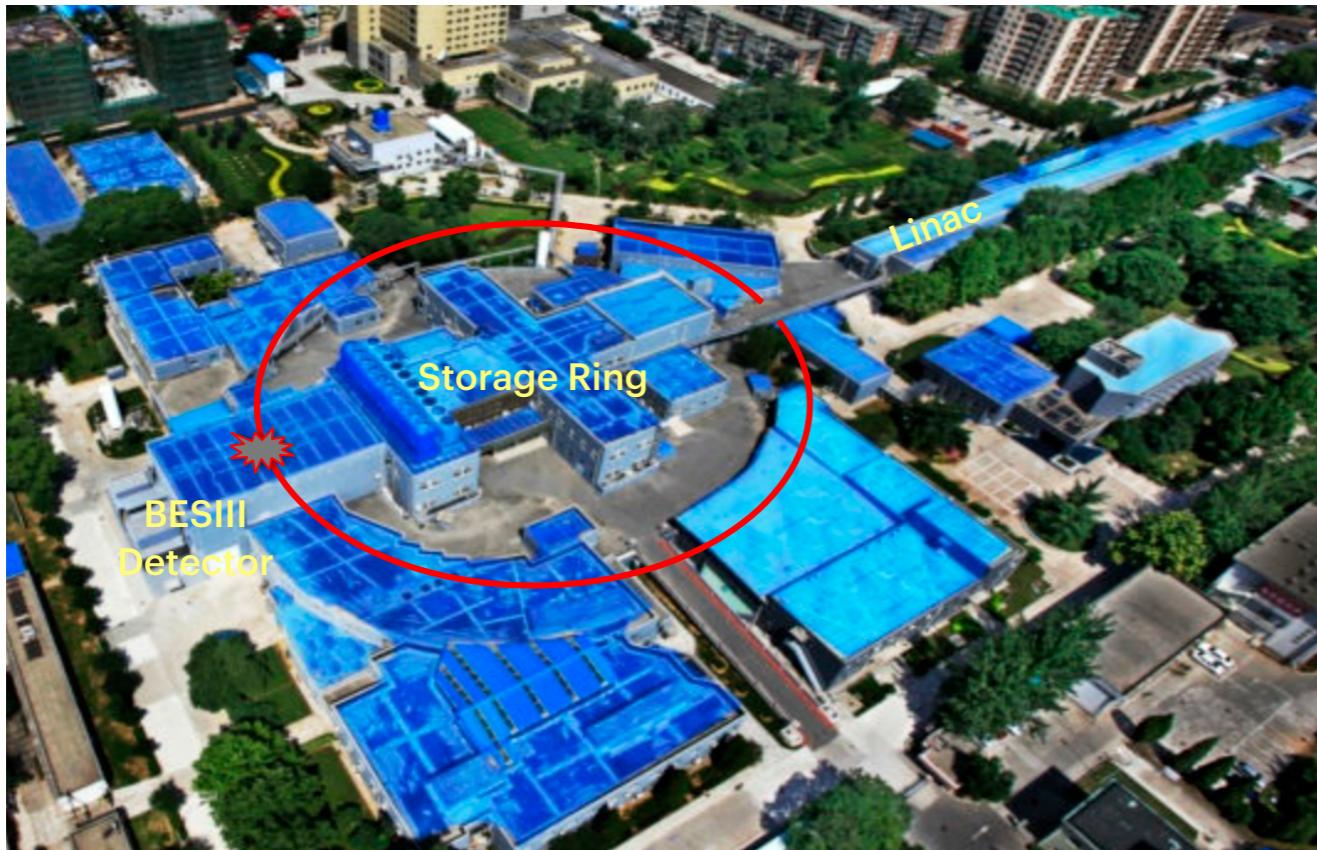


Second Strong2020 online Workshop
14-15 September 2021 · University of York

Outline

- Introduction to BESIII experiment
- Selected highlights of BESIII results related to spectroscopy
 - Charmonium spectroscopy
 - Charmonium states
 - Charmonium-like states
 - Light meson spectroscopy
- Prospects and summary

BEPCII and BESIII



BEPCII: τ -charm factory
 Beam Energy: 1-2.3 (2.45) GeV
 Lumi: $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (achieved 2016)
 BEPCII upgrade &
 BESIII construction: 2004-2008
 BESIII physics run: 2009-now

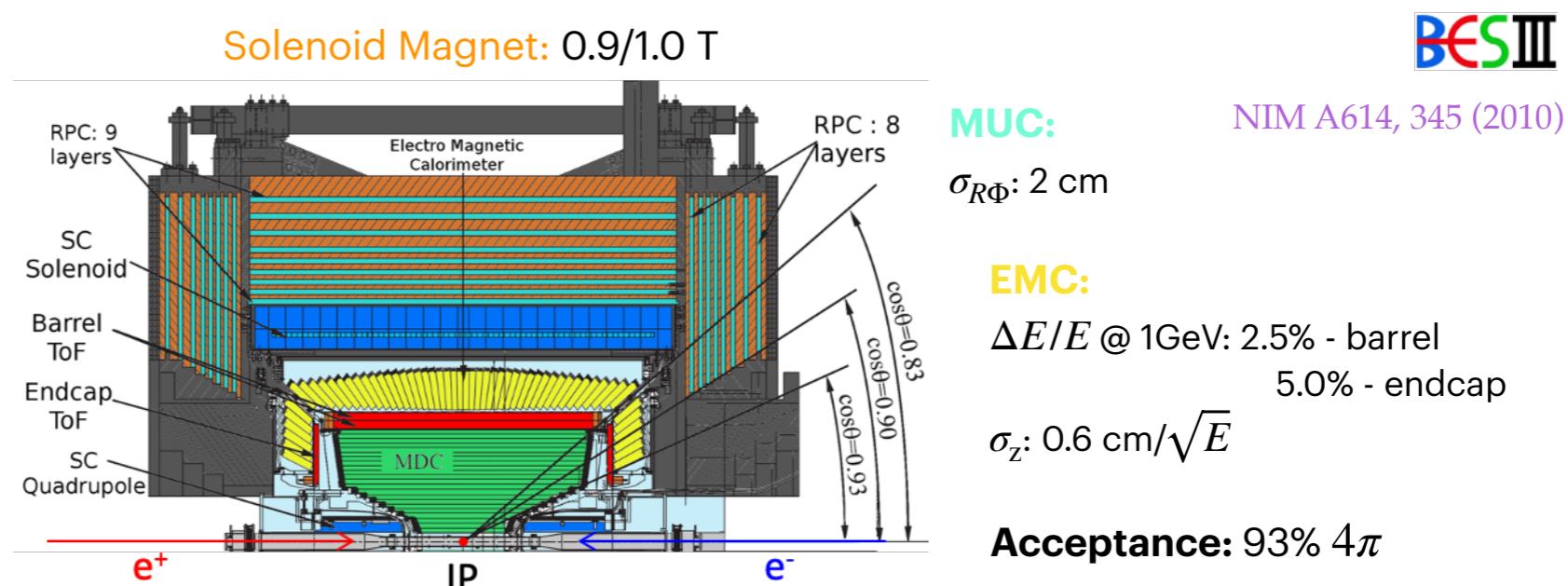
BESIII Detector

TOF:

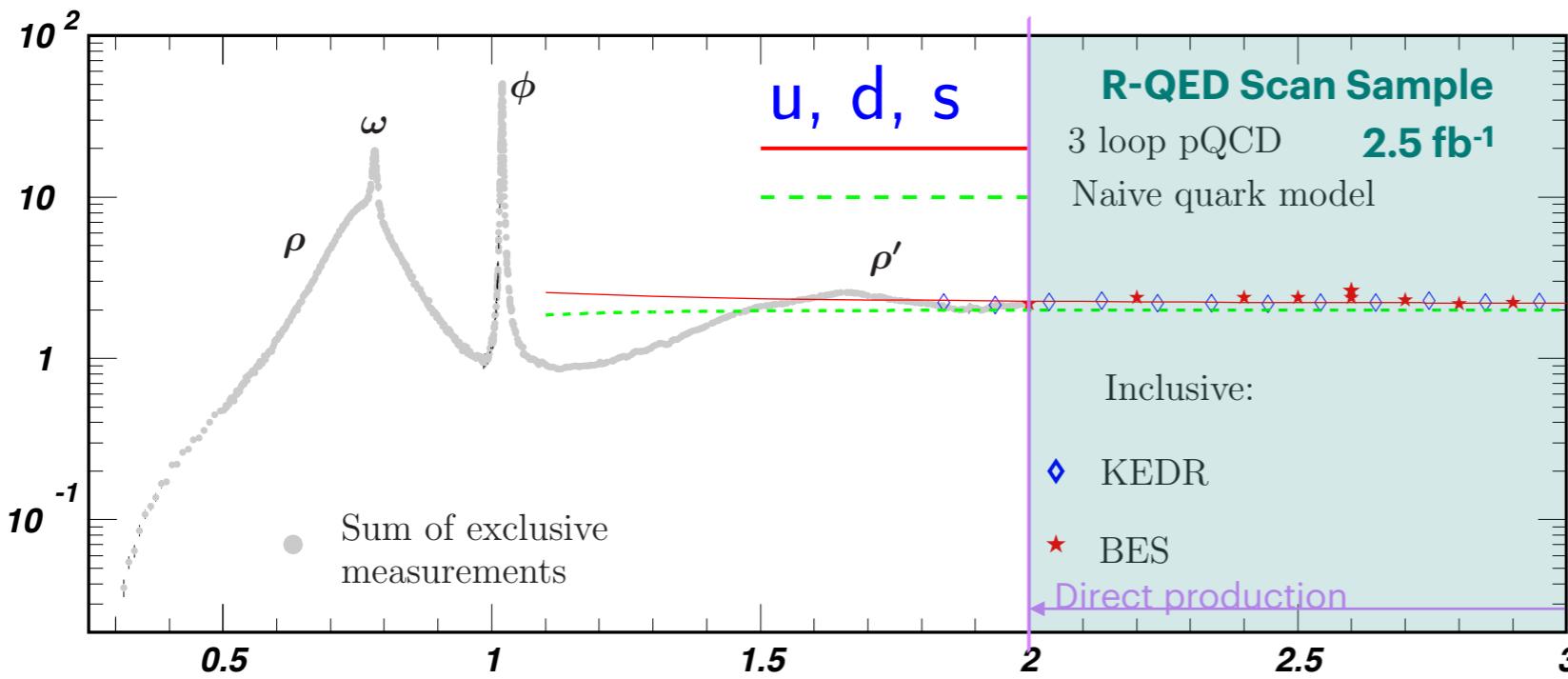
σ_T : 80 ps - barrel
 110 ps (60 ps) - endcap

MDC:

σ_{xy} : $130 \mu\text{m}$
 σ_p/p : 0.5% @ 1 GeV
 dE/dx : 6%



Data Samples



R-QED Scan Sample

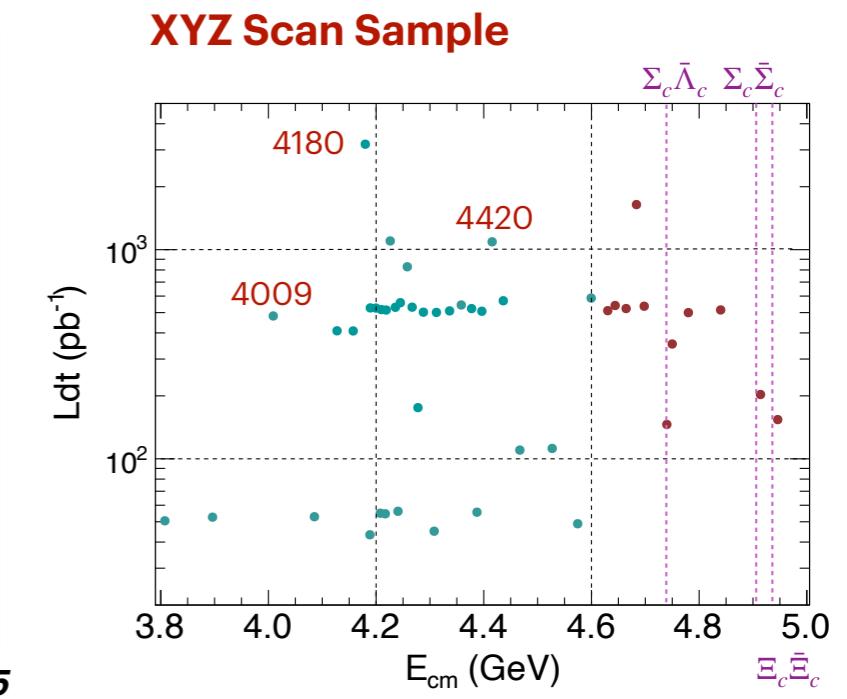
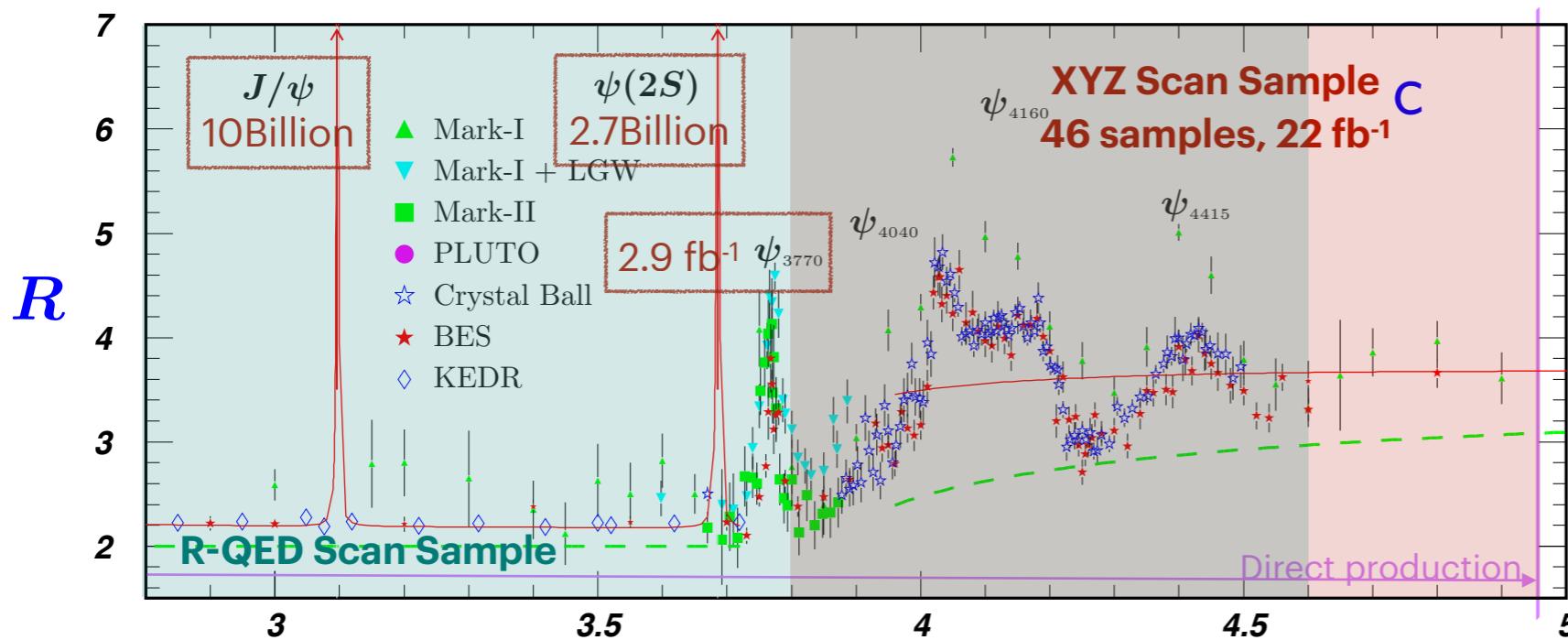
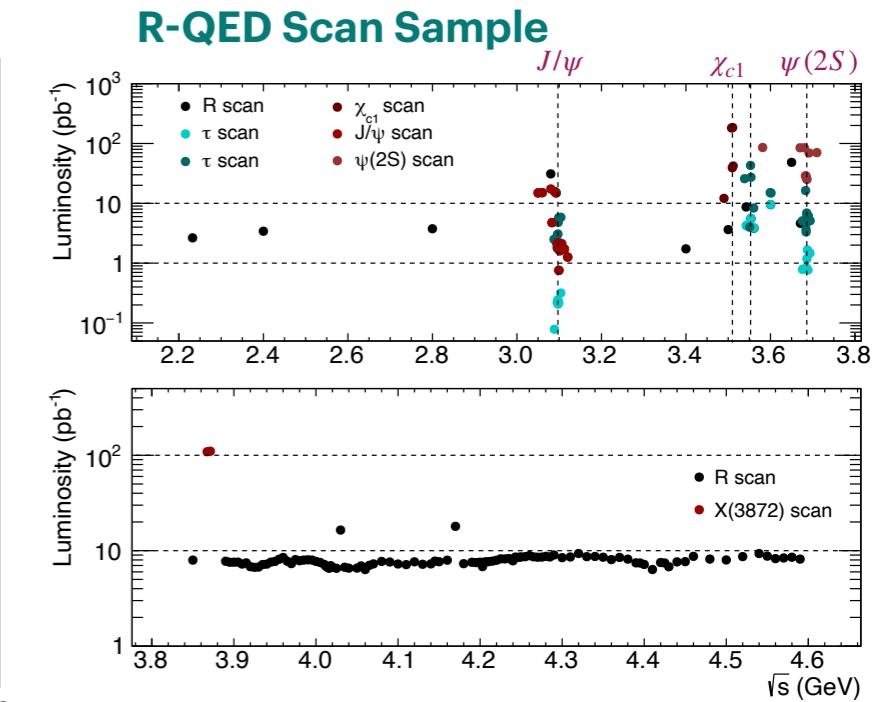
3 loop pQCD **2.5 fb $^{-1}$**
Naive quark model

Inclusive:

KEDR

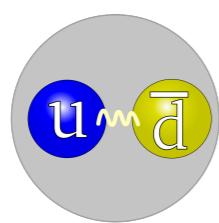
BES

Direct production

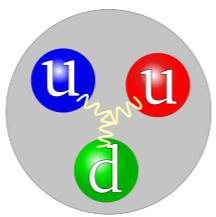


Hadrons and Exotic Hadrons

Conventional Hadrons

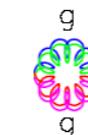


Meson

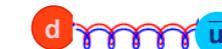


Baryon

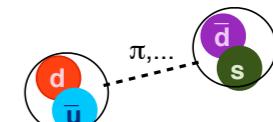
Exotic Hadrons



Glueball



Hybrid



Molecule



Tetraquark



Pentaquark



H-dibaryon

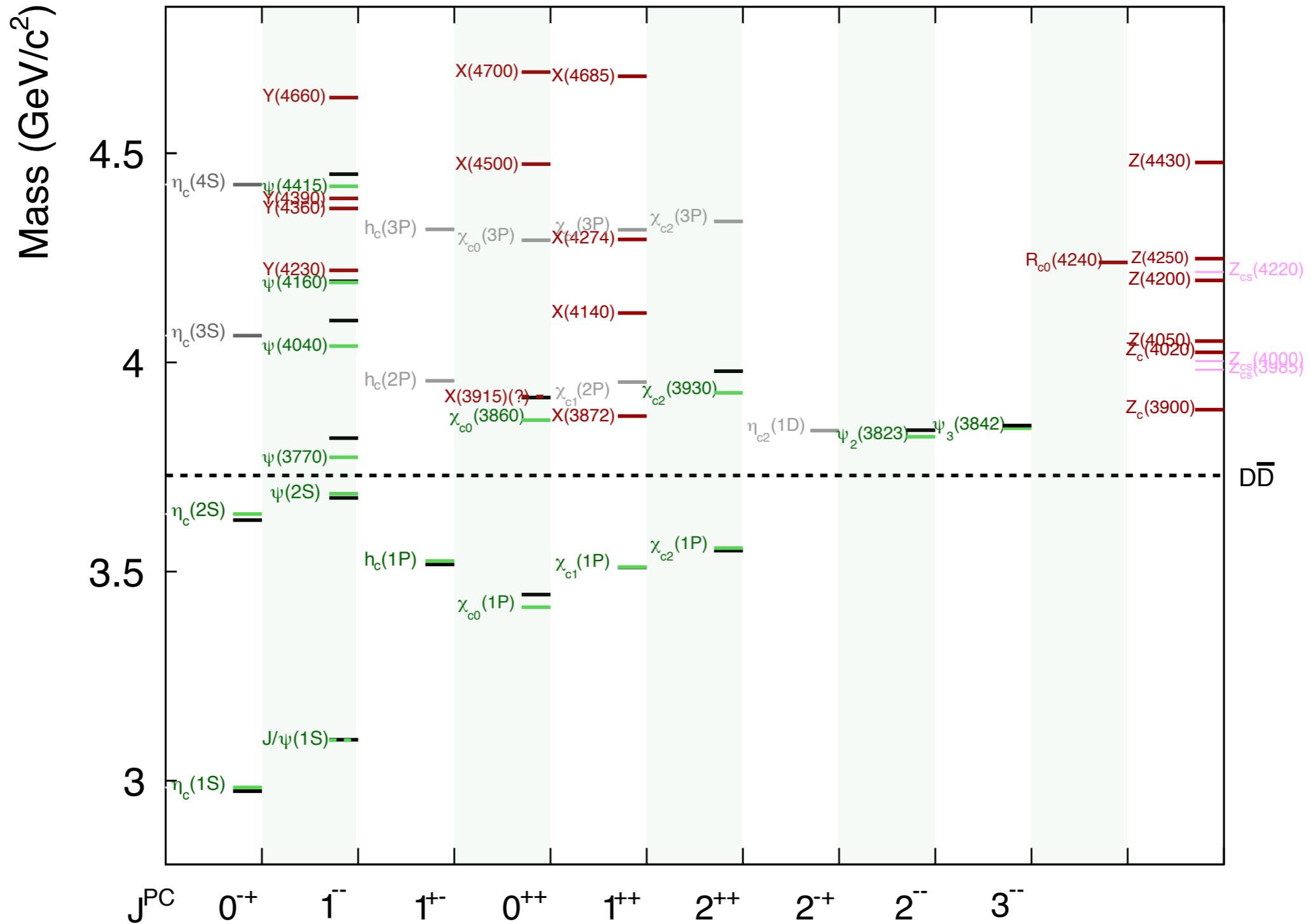
+ ...

Exotic Signature:

Exotic quantum numbers: $J^{PC}=0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \dots$

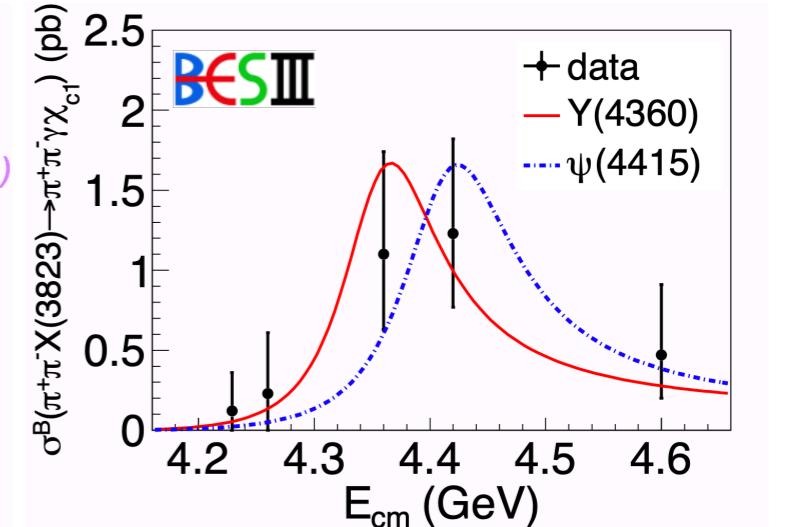
OR clear non-conventional-hadron signature

Charmonium Spectroscopy



1^3D_2 States - $\psi_2(3823)$

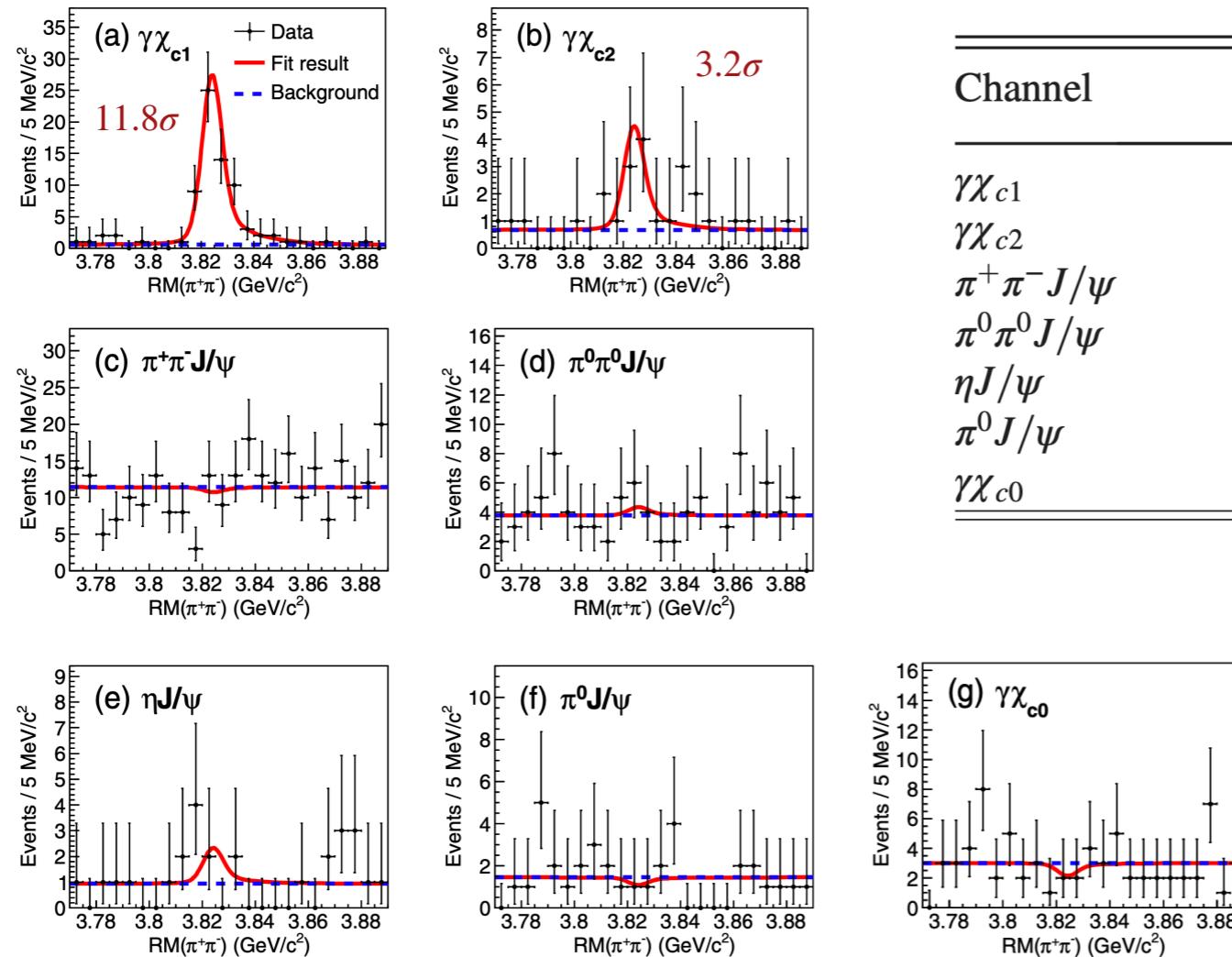
- Evidence of $\psi_2(3823)$ from Belle experiment in $B \rightarrow (\psi_2(3823) \rightarrow \gamma\chi_{c1})K$
 - $772 \times 10^6 B\bar{B}$ events, 3.8σ
 - $M = (3823.1 \pm 1.8 \pm 0.7) \text{ MeV}, \Gamma_{\text{tot}} < 24 \text{ MeV}$ *Phys.Rev.Lett. 111, 032001(2013)*
- Observed by BESIII experiment in $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823), \psi_2(3823) \rightarrow \gamma\chi_{c1}$
 - Scan data sample at $\sqrt{s} = 4.23, 4.26, 4.36, 4.42, 4.60 \text{ GeV}$, 6.2σ
 - $M = (3821.7 \pm 1.3 \pm 0.7) \text{ MeV}, \Gamma_{\text{tot}} < 16 \text{ MeV}$ *Phys.Rev.Lett. 115, 011803(2015)*
- Decays of $\psi_2(3823)$ to $\gamma\chi_{c2}, \pi^+\pi^-J/\psi, ggg, \gamma gg$ have been predicted by various theoretical work
 - $\Gamma_{\psi_2(3823) \rightarrow \gamma\chi_{c1}} \sim 200 - 350 \text{ keV}, \Gamma_{\psi_2(3823) \rightarrow \gamma\chi_{c2}} \sim 40 - 90 \text{ keV}$
 - $\Gamma_{\psi_2(3823) \rightarrow \gamma\chi_{c2}} / \Gamma_{\psi_2(3823) \rightarrow \gamma\chi_{c1}} \sim 0.19 - 0.32$ *Phys.Rev.D 55, 4001(1997)* *Phys.Rev.Lett. 89, 162002(2002)*
Phys.Rev.D 67, 014027(2003) *Phys.Rev.D 69, 054008(2004)*
Phys.Rev.D 72, 054026(2005) *Phys.Rev.D 79, 094004(2009)*
Phys.Rev.D 94, 034005(2016) *Front.Phys. 11, 111402 (2016)*
arXiv:1510.08269
 - $\Gamma_{\psi_2(3823) \rightarrow \pi^+\pi^-J/\psi} \sim 45 - 200 \text{ keV}$
 - $\Gamma_{\psi_2(3823) \rightarrow \pi^+\pi^-J/\psi} / \Gamma_{\psi_2(3823) \rightarrow \gamma\chi_{c1}} \sim 0.12 - 0.39$



New Decay Modes of $\psi_2(3823)$

- 9 fb^{-1} scan data sample between $\sqrt{s}=4.3$ and 4.7 GeV
- $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$, study of the decays of $\psi_2(3823) \rightarrow \gamma\chi_{c0,1,2}, \pi\pi J/\psi, \eta J/\psi, \pi^0 J/\psi$

Phys.Rev.D 103, L091102(2021)



Channel	$N\psi_2(3823)$	$\frac{\mathcal{B}(\psi_2(3823) \rightarrow \dots)}{\mathcal{B}(\psi_2(3823) \rightarrow \gamma\chi_{c1})}$
$\gamma\chi_{c1}$	63.1 ± 8.5	...
$\gamma\chi_{c2}$	$8.8^{+4.3}_{-3.4}$	$0.28^{+0.14}_{-0.11} \pm 0.02$
$\pi^+\pi^-J/\psi$	< 21.0	< 0.06
$\pi^0\pi^0J/\psi$	< 10.0	< 0.11
$\eta J/\psi$	< 9.8	< 0.14
π^0J/ψ	< 5.6	< 0.03
$\gamma\chi_{c0}$	< 6.3	< 0.24

consistent with theoretical prediction

New Decay Modes of $\psi_2(3823)$

- 9 fb⁻¹ scan data sample between $\sqrt{s}=4.3$ and 4.7 GeV

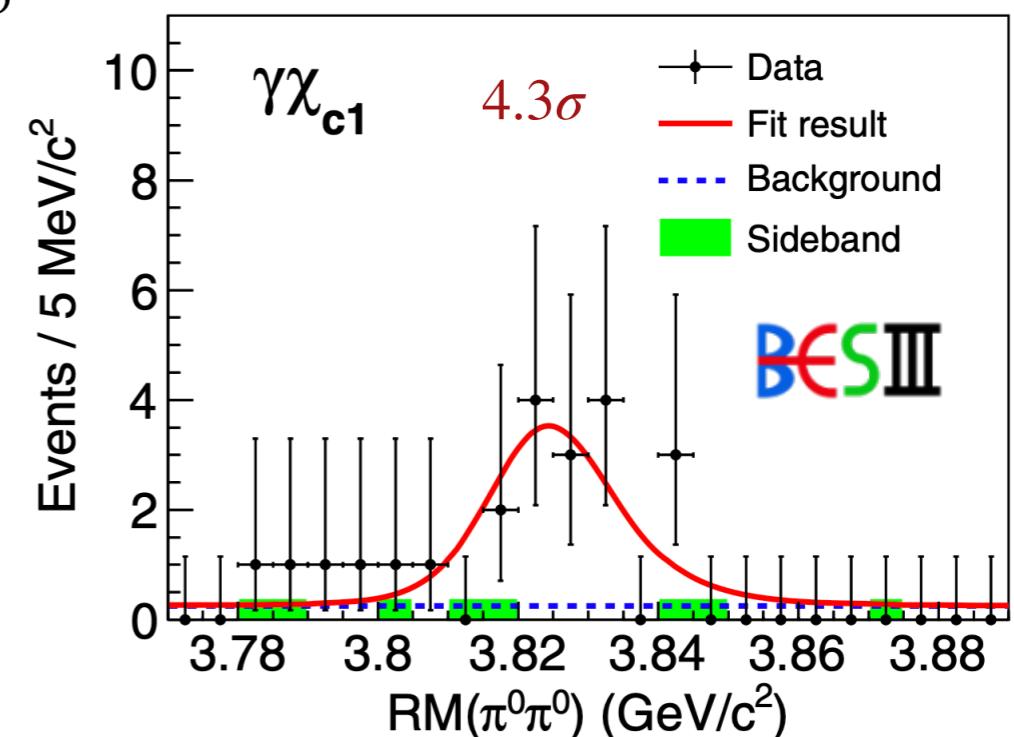
- Search for $e^+e^- \rightarrow \pi^0\pi^0\psi_2(3823)$ with $\psi_2(3823) \rightarrow \gamma\chi_{c1}$

$$\frac{\sigma[e^+e^- \rightarrow \pi^0\pi^0\psi_2(3823)]}{\sigma[e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)]} = 0.64^{+0.22}_{-0.20} \pm 0.05$$

$\psi_3(1^3D_3)$ candidate
Found by LHCb in 2019

- Search for $e^+e^- \rightarrow \pi^+\pi^-\psi_3(3842)$
- Not found in any decay modes

Phys.Rev.D 103, L091102(2021)

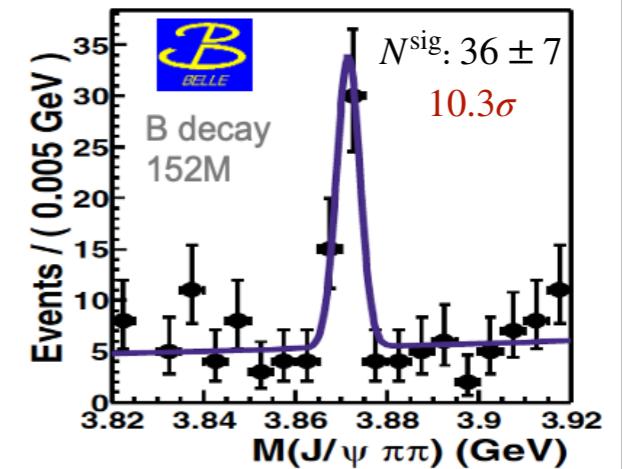


$$N_{\text{sig}} = 15.9^{+5.1}_{-4.4}$$

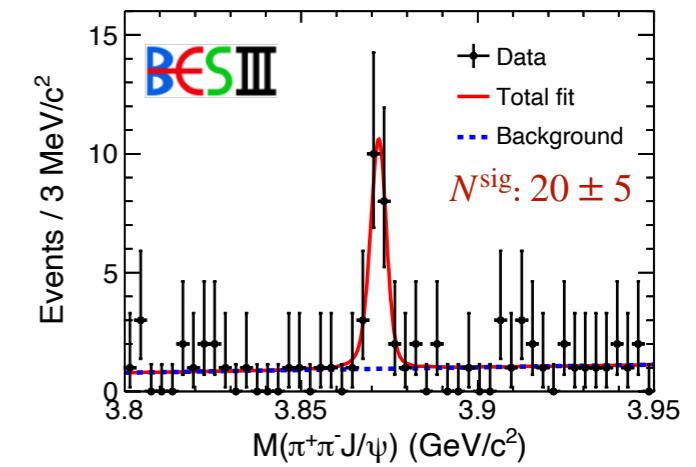
X(3872)

- First observation in $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ process
- Mass: (3871.65 ± 0.06) MeV
 $\text{PDG2020, Dominant by LHCb result: JHEP 2008 123}$
very close to $D\bar{D}^*$ mass threshold
 $[(3871.69 \pm 0.01)$ MeV]
- Width: (1.19 ± 0.21) MeV [BW Width]
 $\text{Phys.Rev.D 102, 092005 (2020)}$
- $J^{PC} = 1^{++}$ $\text{Phys.Rev.Lett. 110, 222001 (2013)}$
- Production: B decays, B_s decays, Λ_b decays,
 $p\bar{p}$ collision, pp collision, $PbPb$ collision,
 e^+e^- radiative transition, $\gamma\gamma^*$ process
- Decay: $D^0\bar{D}^{*0}$, $\pi^+\pi^-J/\psi$, $\pi^+\pi^-\pi^0J/\psi$, $\pi^0\chi_{cJ}$,
 $\gamma J/\psi$, $\gamma\psi(2S)[?]$

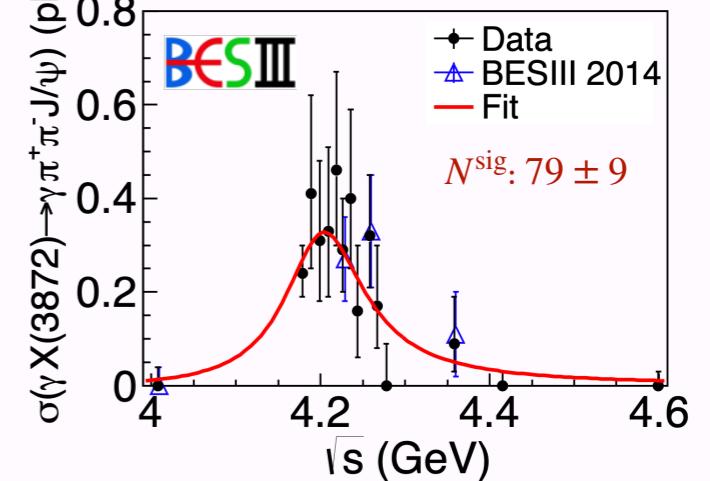
Phys.Rev.Lett. 91, 262001 (2003)



Phys.Rev.Lett. 112, 092001 (2014)

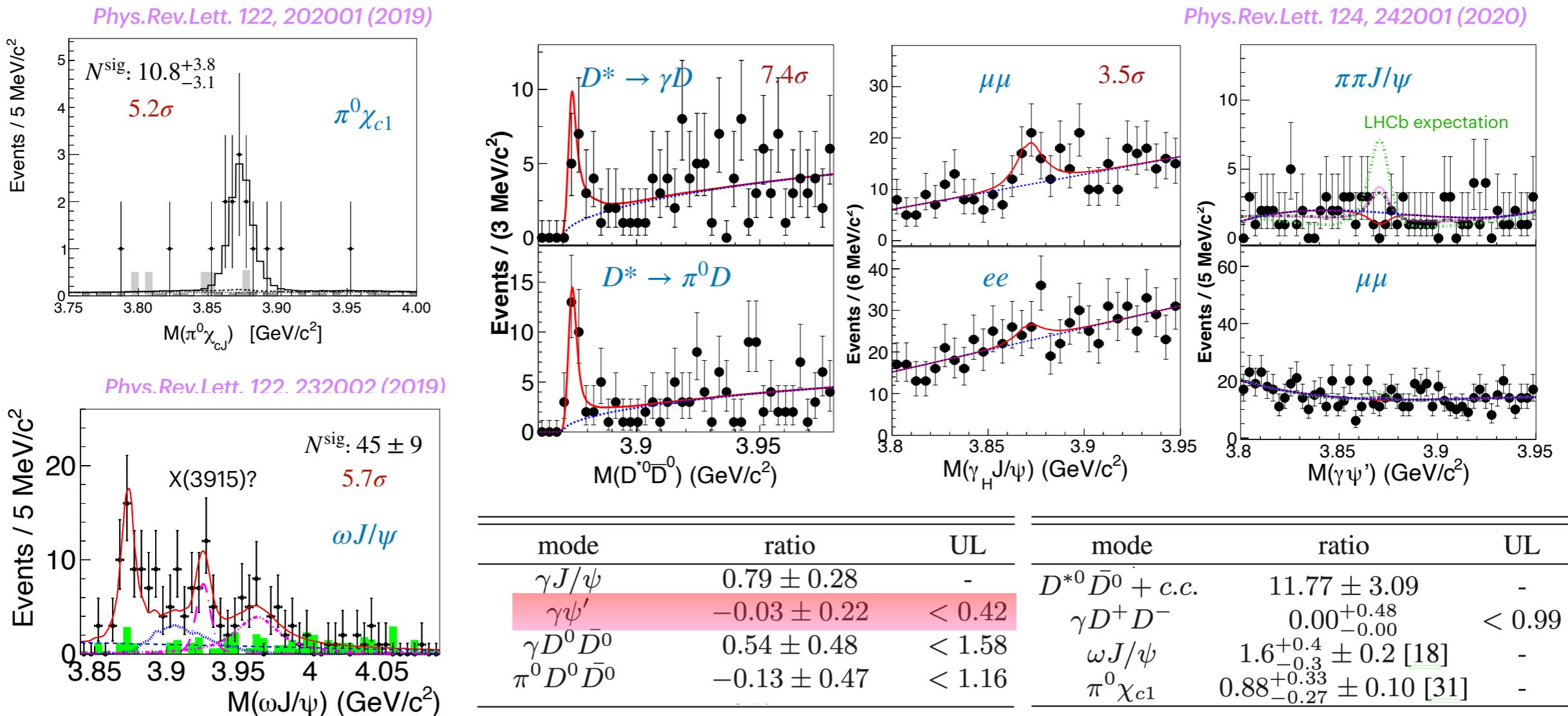


Phys.Rev.Lett. 122, 232002 (2019)



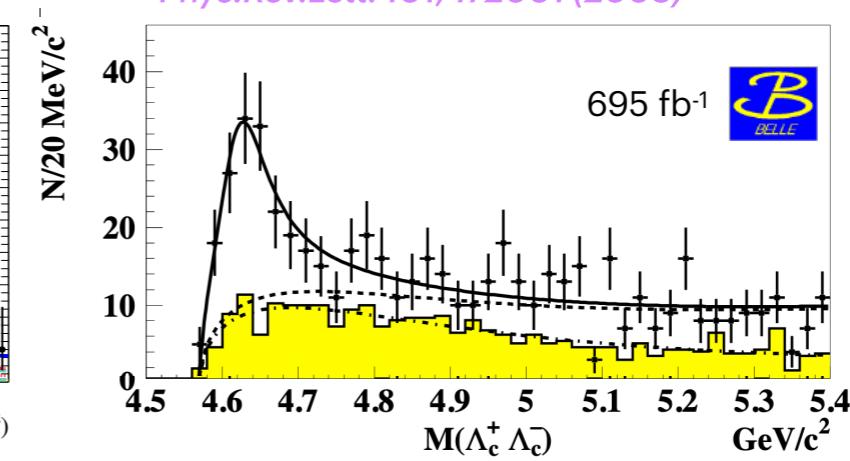
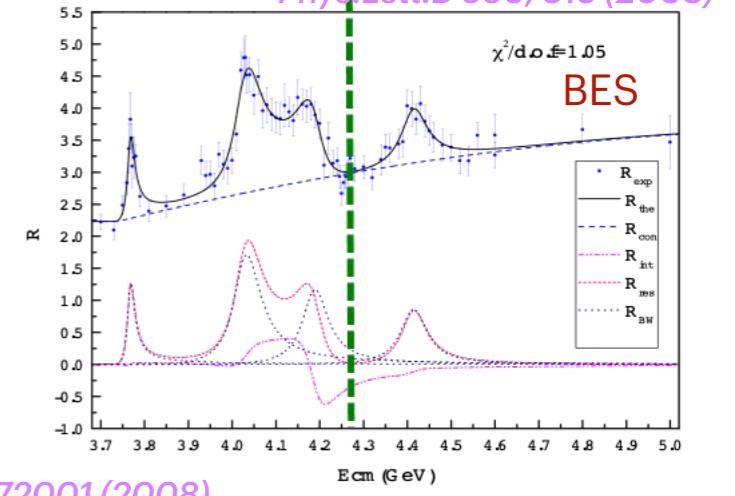
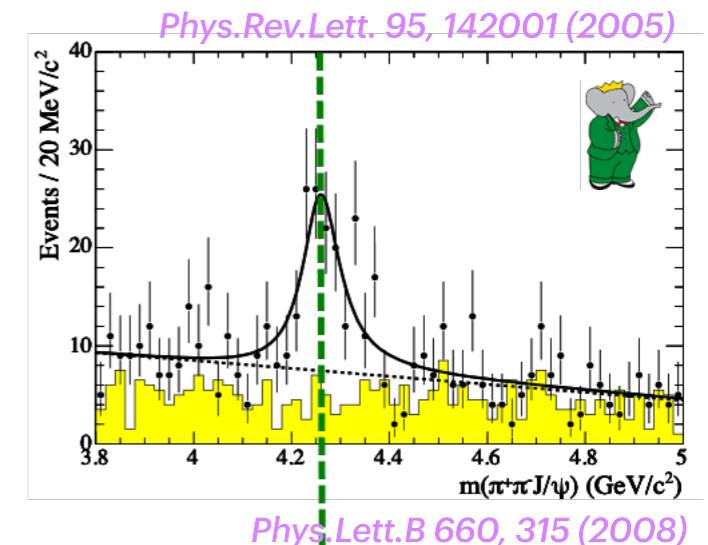
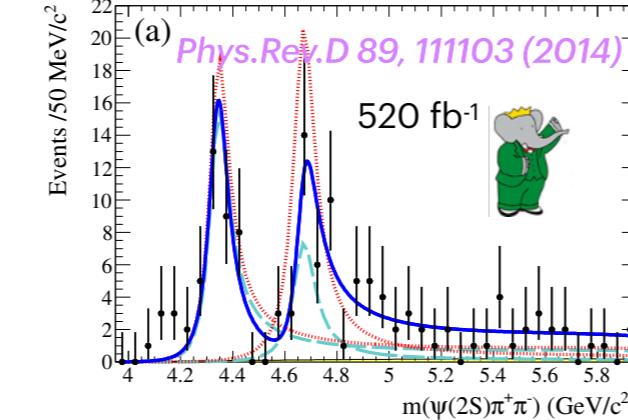
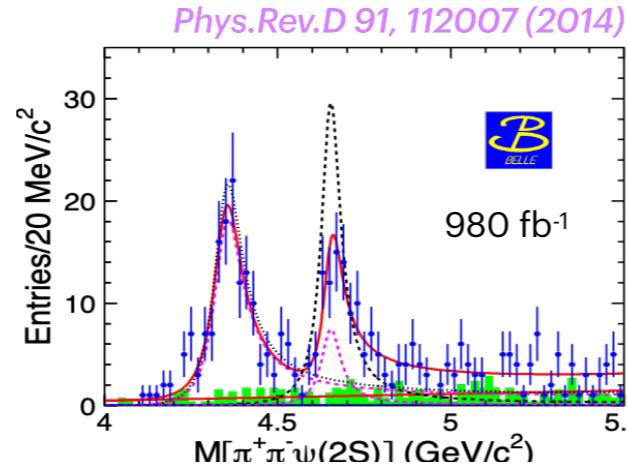
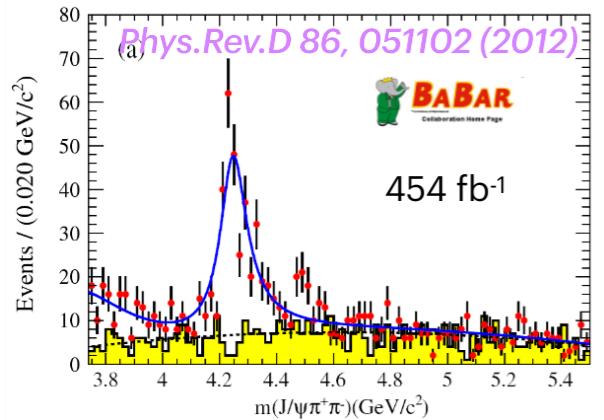
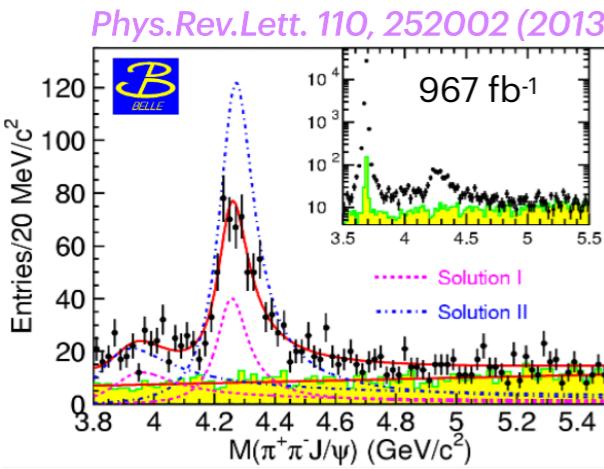
X(3872) Decays

- $e^+e^- \rightarrow \gamma X(3872)$ cross section peaks around 4.2 GeV, studied from 11.6 fb^{-1} data between $\sqrt{s}=4.0$ and 4.6 GeV

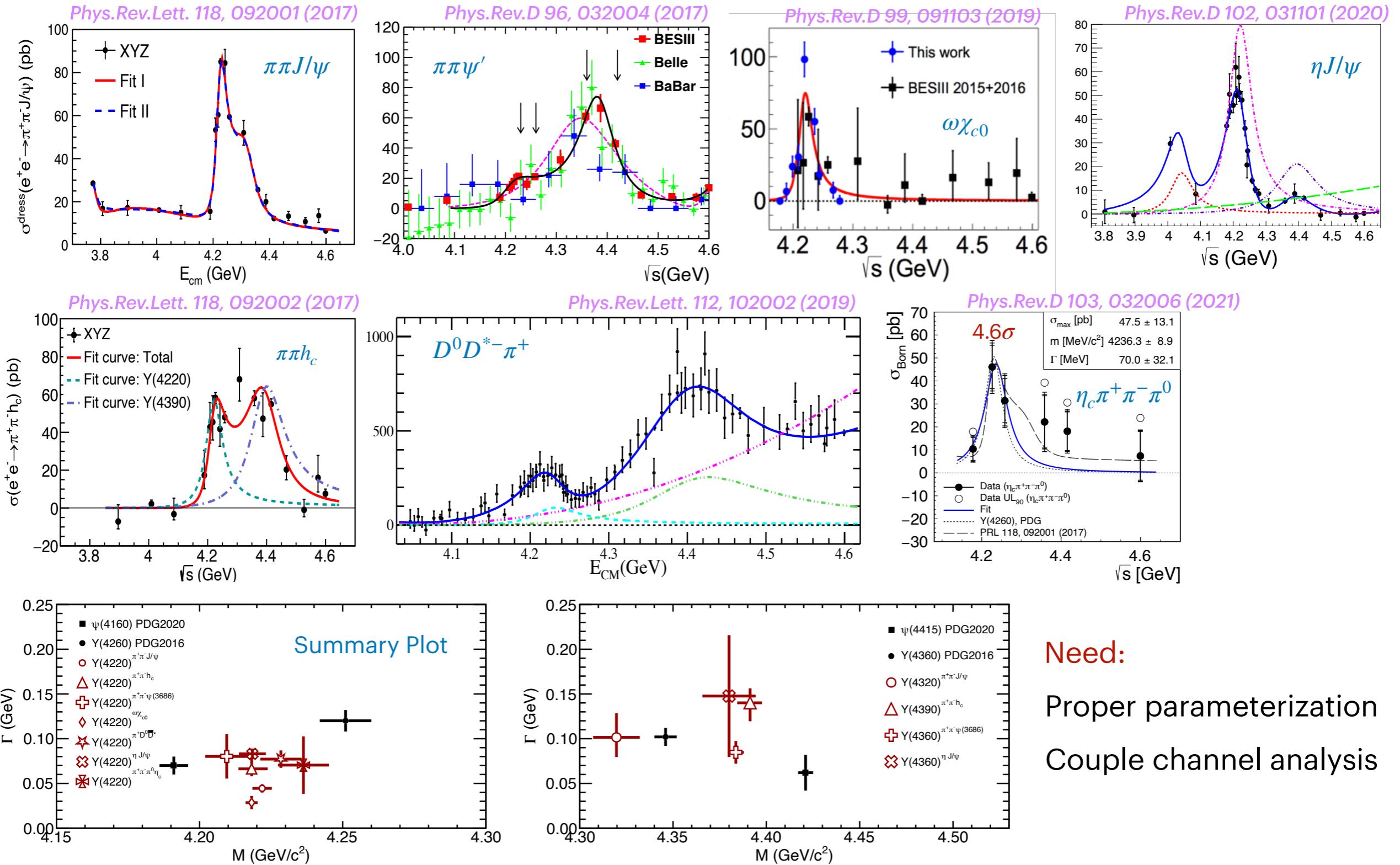


Y States

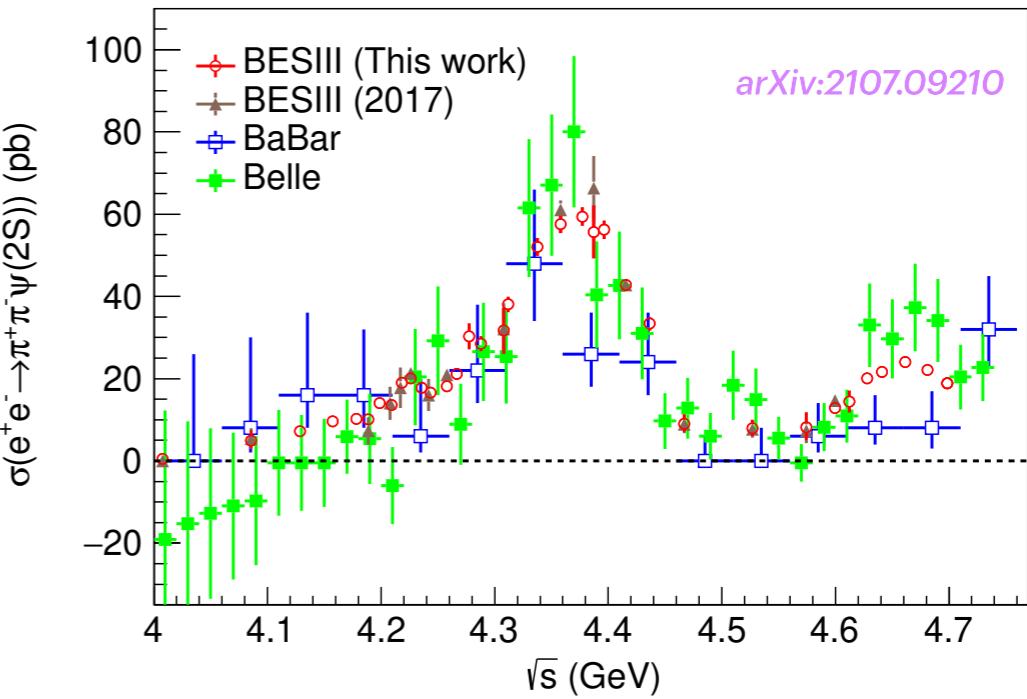
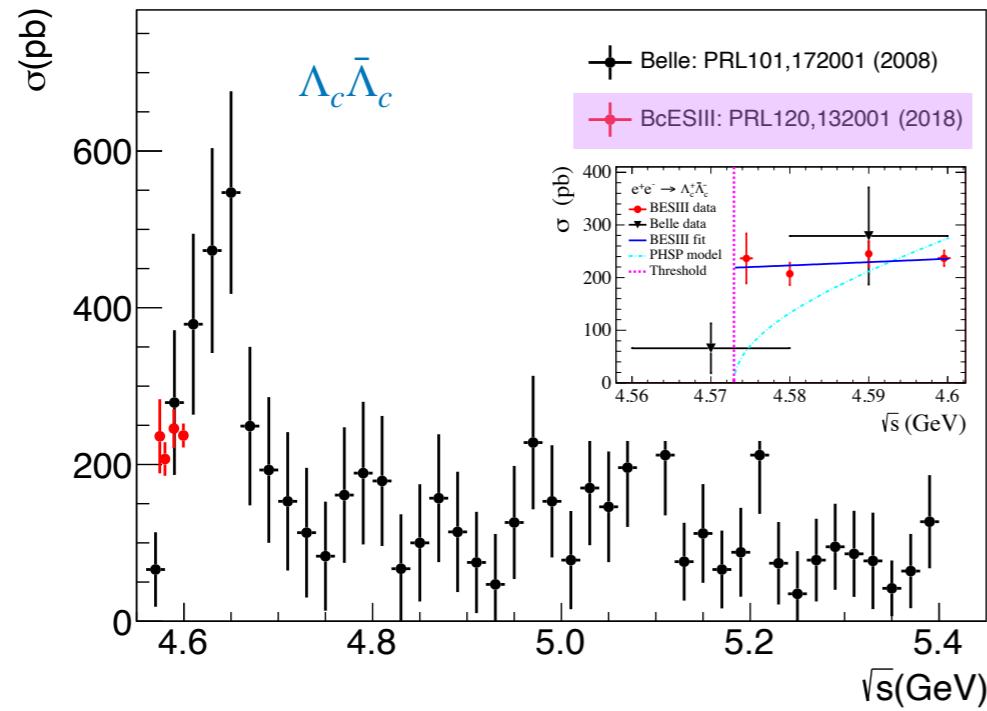
- First states $\Upsilon(4260)$, discovered in ISR process at BaBar
 - Not observed in inclusive hadron cross section
 - Not observed in open charm pair cross section
 - Confirmed by CLEO and Belle experiment
- $\Upsilon(4360)$ and $\Upsilon(4660)$ discovered in similar process



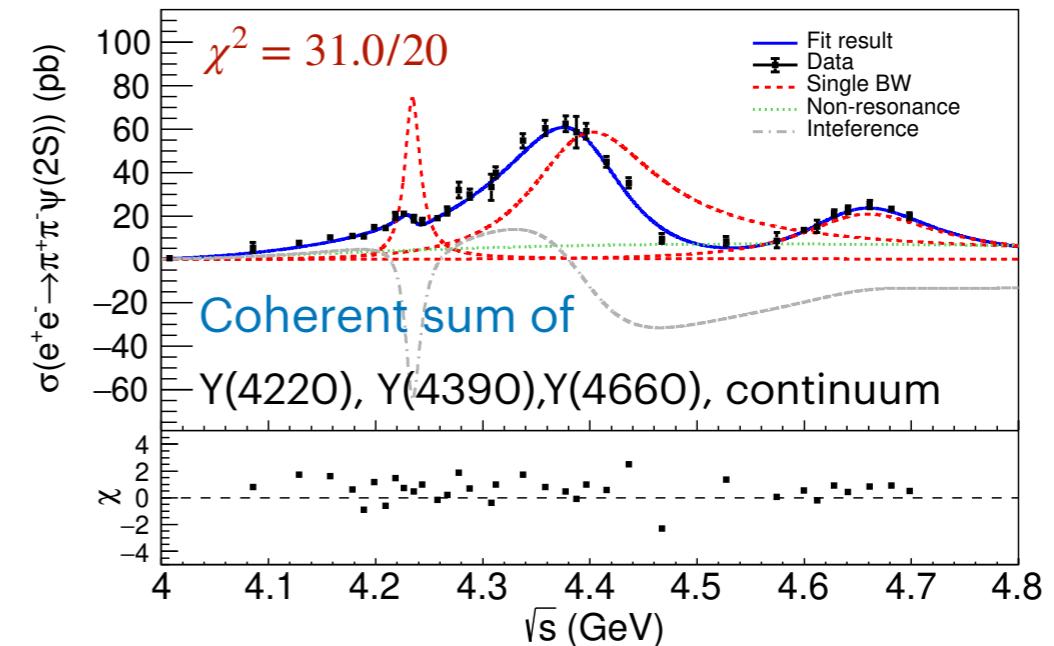
$\Upsilon(4260) \rightarrow \Upsilon(4230)$



New Information about Y(4660)

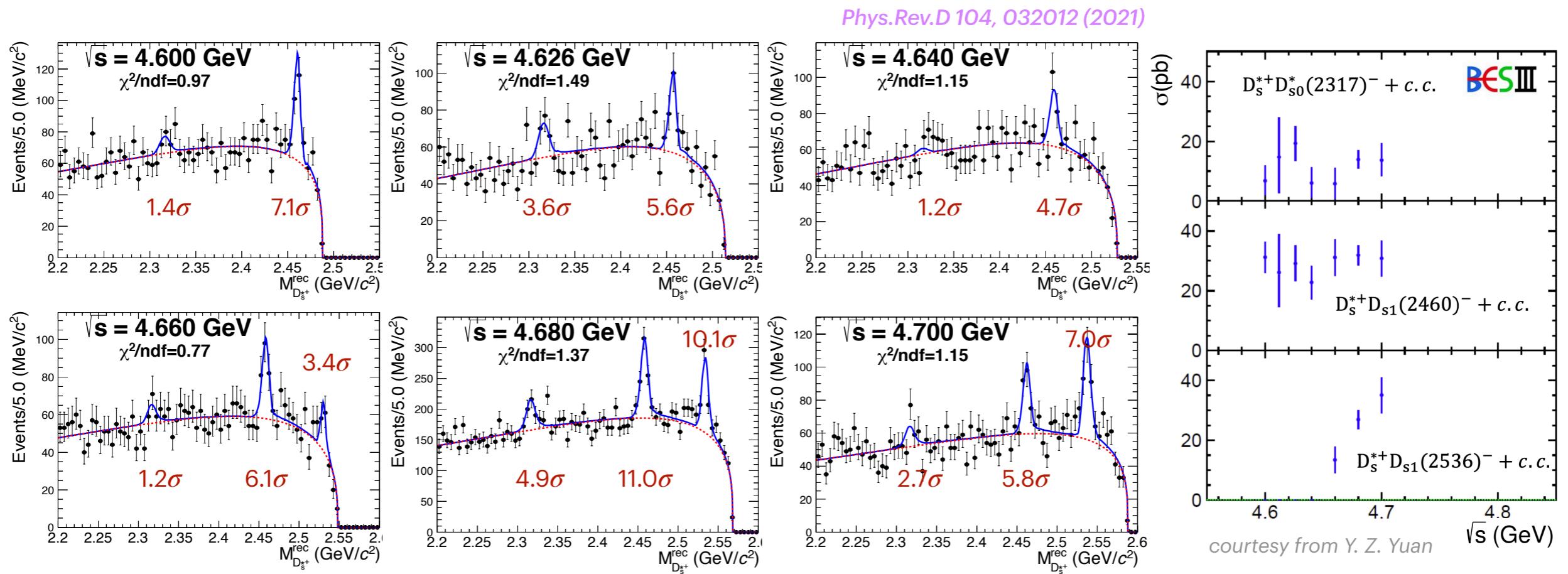


- Precision of BESIII measurement much higher than B-factories
- Parameterization of the cross section line-shape is a challenge task
- Data sample from $\sqrt{s} = 4.7 \text{ GeV}$ to 4.95 GeV taken in 20-21-run-period



$D_s^* D_{sJ}$ Cross Section Around 4.6

- Enhancement just above 4.6 GeV observed at Belle experiment in $e^+e^- \rightarrow D_s^\pm D_{s1}(2536)^\mp$ process, evidence seen in $e^+e^- \rightarrow D_s^\pm D_{s2}^*(2573)^\mp$ process
 $\text{Phys.Rev.D 100, 111103 (2019)}$ $\text{Phys.Rev.D 101, 091101 (2020)}$
- $e^+e^- \rightarrow D_s^{*\pm} D_{s0}^{*\mp}(2317), D_s^{*\pm} D_{s1}(2460)^\mp, D_s^{*\pm} D_{s1}(2536)^\mp$ studied at BESIII
 - Clear $D_s^* D_{sJ}$ signal in data, no significant resonance structures in cross section line-shape



Z_C States

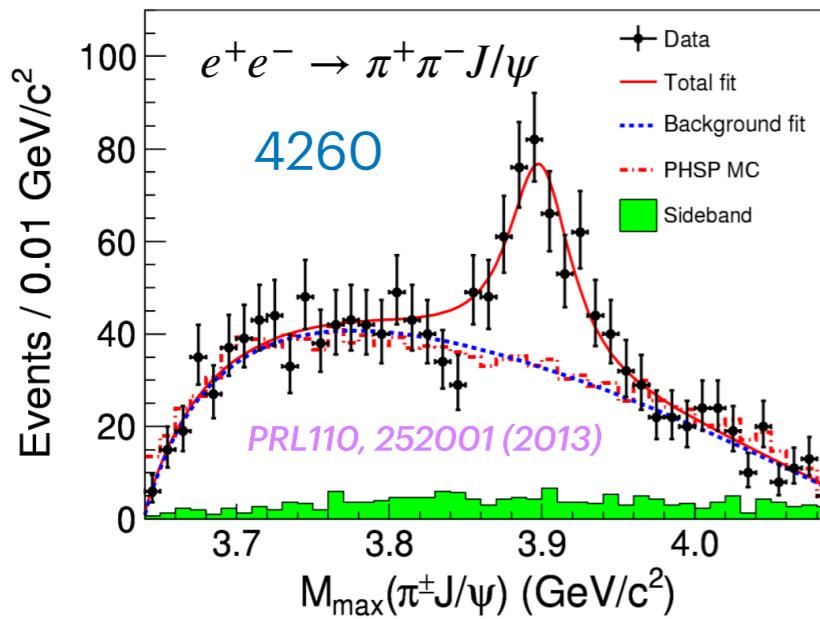
State	M (MeV/ c^2)	Γ (MeV)	J^{PC}	Process	Experiment
$Z_c(3900)^{(\pm,0)}$	3888.4 ± 2.5	28.3 ± 2.5	1^{+-}	$e^+e^- \rightarrow \pi^{(+,0)}(\pi^{(-,0)}J/\psi)$ $e^+e^- \rightarrow \pi^{(+,0)}(D\bar{D}^*)^{(-,0)}$ $H_b \rightarrow X\pi^+(\pi^-J/\psi)$ $e^+e^- \rightarrow \pi^+(\eta_c\rho^-)$	BESIII, Belle
$Z_c(4020)^{(\pm,0)}$	4024.1 ± 1.9	13 ± 5	$1^{+-}(?)$	$e^+e^- \rightarrow \pi^{(+,0)}(\pi^-h_c)$ $e^+e^- \rightarrow \pi^{(+,0)}(D^*\bar{D}^*)^{(-,0)}$	BESIII, Belle
$Z(4050)^\pm$	4051_{-40}^{+24}	82_{-28}^{+50}	? ⁺	$\bar{B}^0 \rightarrow K^-(\pi^+\chi_{c1})$	Belle
$Z(4055)^\pm$	3.5σ 4054 ± 3.2	45 ± 13	? ⁻	$e^+e^- \rightarrow \pi^+(\pi^-\psi(2S))$	Belle
$Z(4100)^\pm$	3.4σ 4096 ± 28	152_{-70}^{+80}	? ^{??}	$B^0 \rightarrow K^+(\pi^-\eta_c)$	LHCb
$Z(4200)^\pm$	4196_{-32}^{+35}	370_{-150}^{+100}	1^{+-}	$\bar{B}^0 \rightarrow K^-(\pi^+J/\psi)$	Belle, LHCb
$Z(4250)^\pm$	4248_{-50}^{+190}	177_{-70}^{+320}	? ⁺	$\bar{B}^0 \rightarrow K^-(\pi^+\chi_{c1})$	Belle
$Z(4430)^\pm$ <i>first/2008</i>	4478_{-18}^{+15}	181 ± 31	1^{+-}	$B^0 \rightarrow K^+(\pi^-\psi(2S))$ $\bar{B}^0 \rightarrow K^-(\pi^+J/\psi)$	Belle, LHCb
$R_{c0}(4240)$	4239_{-21}^{+50}	220_{-90}^{+120}	0^{--}	$B^0 \rightarrow K^+\pi^-\psi(2S)$	LHCb
$Z_{cs}(3985)^\pm$	$3982.5_{-3.4}^{+2.8}$	$12.8_{-5.3}^{+6.1}$?	$e^+e^- \rightarrow K^+(D_s^-D^{*0} + D_s^{*-}D^0)$	BESIII
$Z_{cs}(4000)^\pm$	4003_{-15}^{+7}	131 ± 30	1^+	$B^+ \rightarrow \phi(J/\psi K^+)$	LHCb
$Z_{cs}(4220)^\pm$	4216_{-38}^{+49}	233_{-90}^{+110}	1^+	$B^+ \rightarrow \phi(J/\psi K^+)$	LHCb

- Produced in e^+e^- annihilation or b -flavor hadron decays
- Typically in h+charmonium final states
- Intrinsic nature unclear, exotic states? kinematic effects?

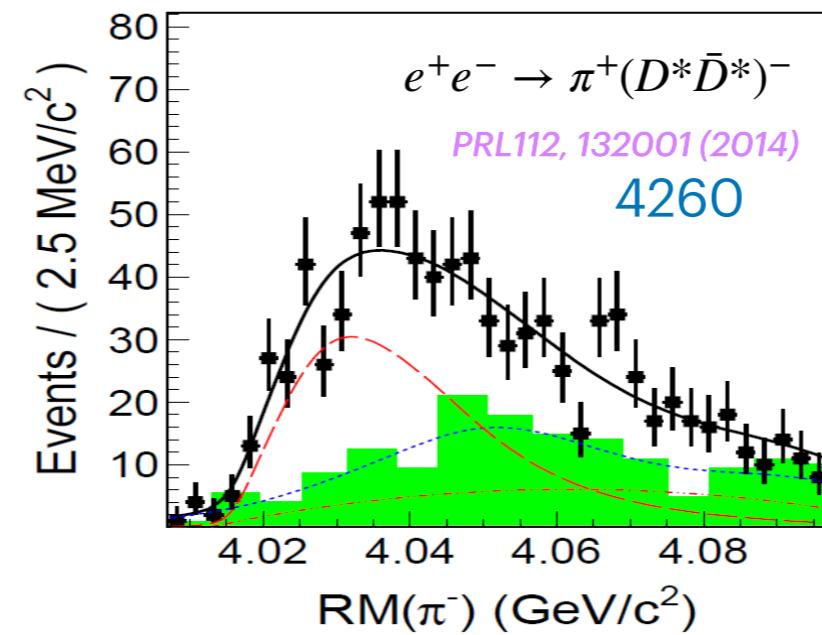
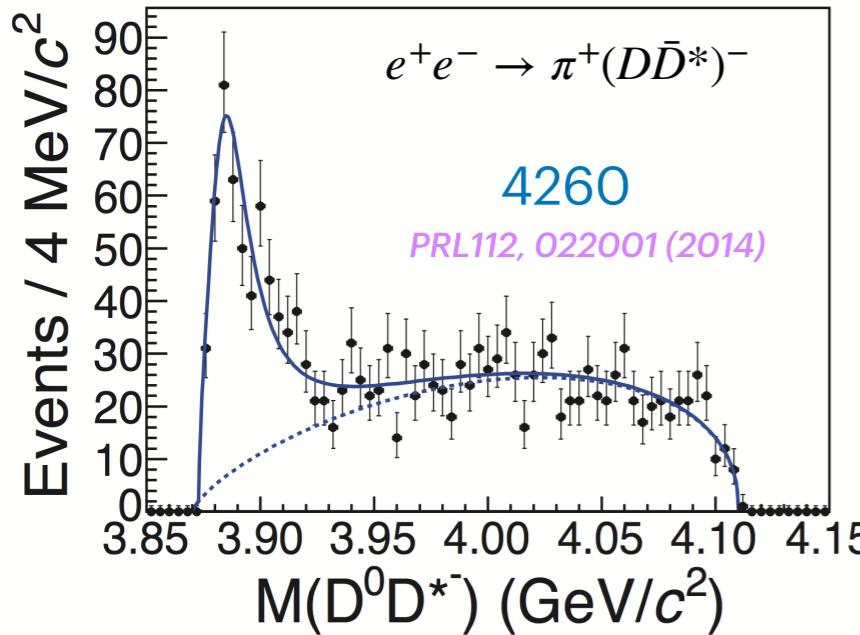
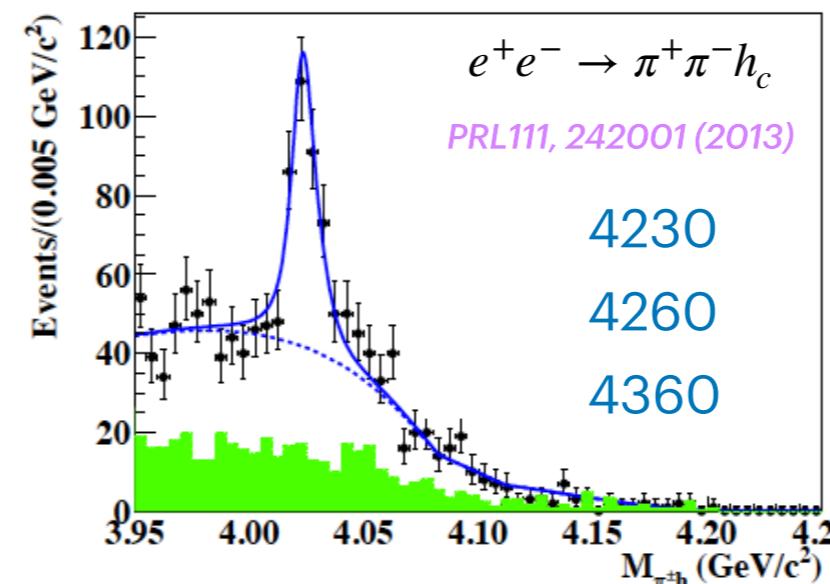
Spin-parity and Argand plot;
Production mechanism;
More decay modes; Partner states;...

Z_c States

$Z_c(3900)/Z_c(3885)$



$Z_c(4020)/Z_c(4025)$



Seen in both charged and neutral modes

New decay modes

searched with

$Z_c(4020) \rightarrow \gamma X(3872)$,

$Z_c \rightarrow \pi\eta_c$, $Z_c \rightarrow \eta\eta_c'$,

and $Z_c \rightarrow \pi\chi_{cJ}$ processes, no signal observed in all cases

PRD104, 012001 (2021)

PRD103, 032004 (2021)

PRD103, 032006 (2021)

PRD103, 052010 (2021)

PRL115, 112003 (2015)

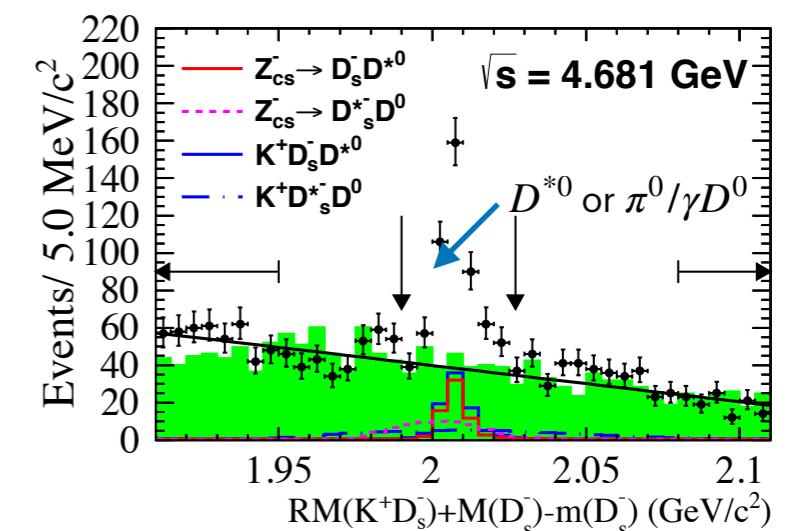
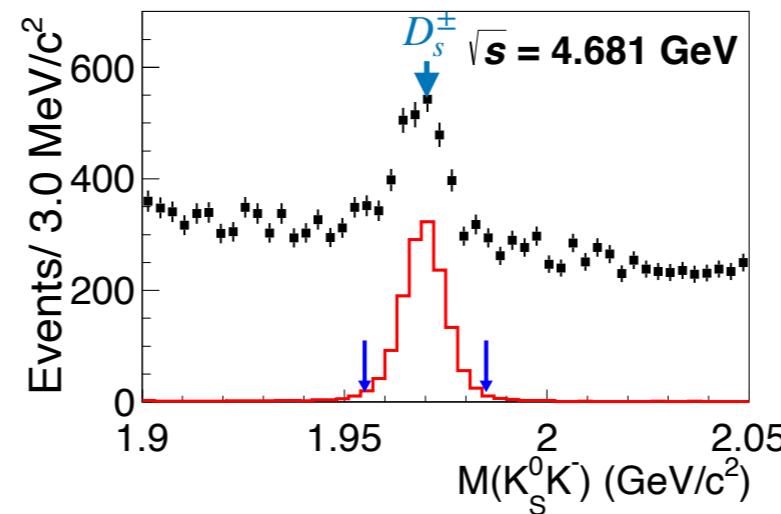
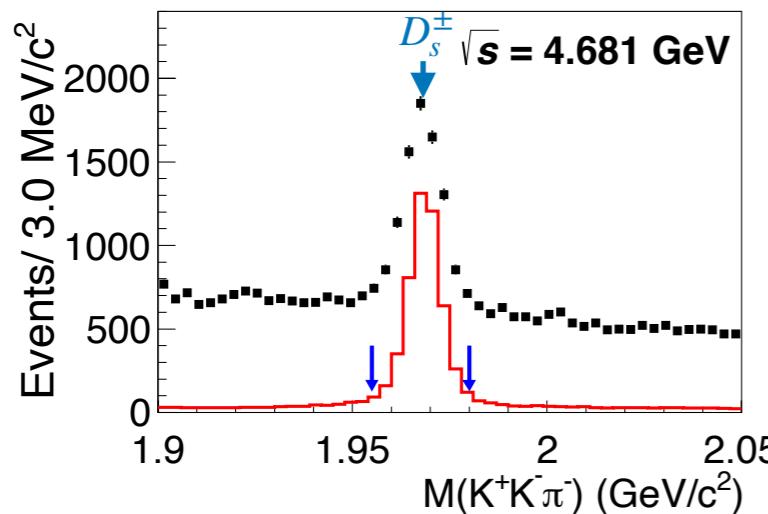
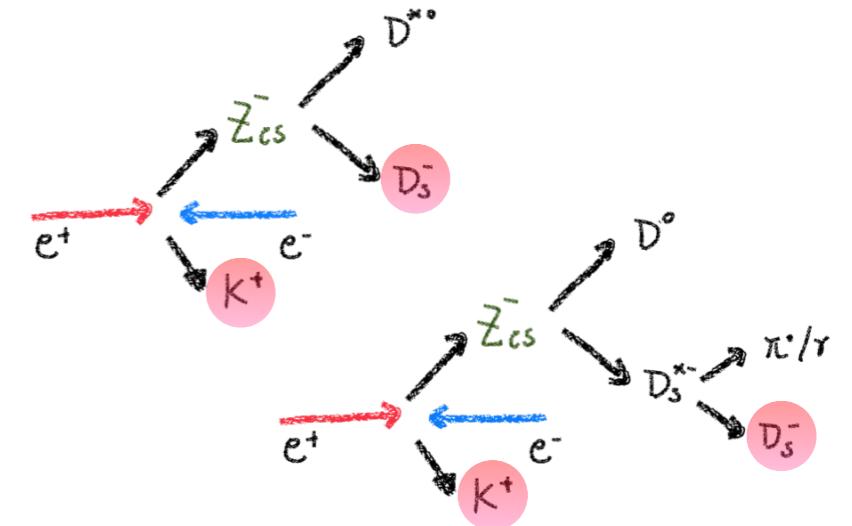
PRL115, 222002 (2015)

PRL113, 212002 (2014)

PRL115, 182002 (2015)

Observation of $Z_{CS}(3985)$

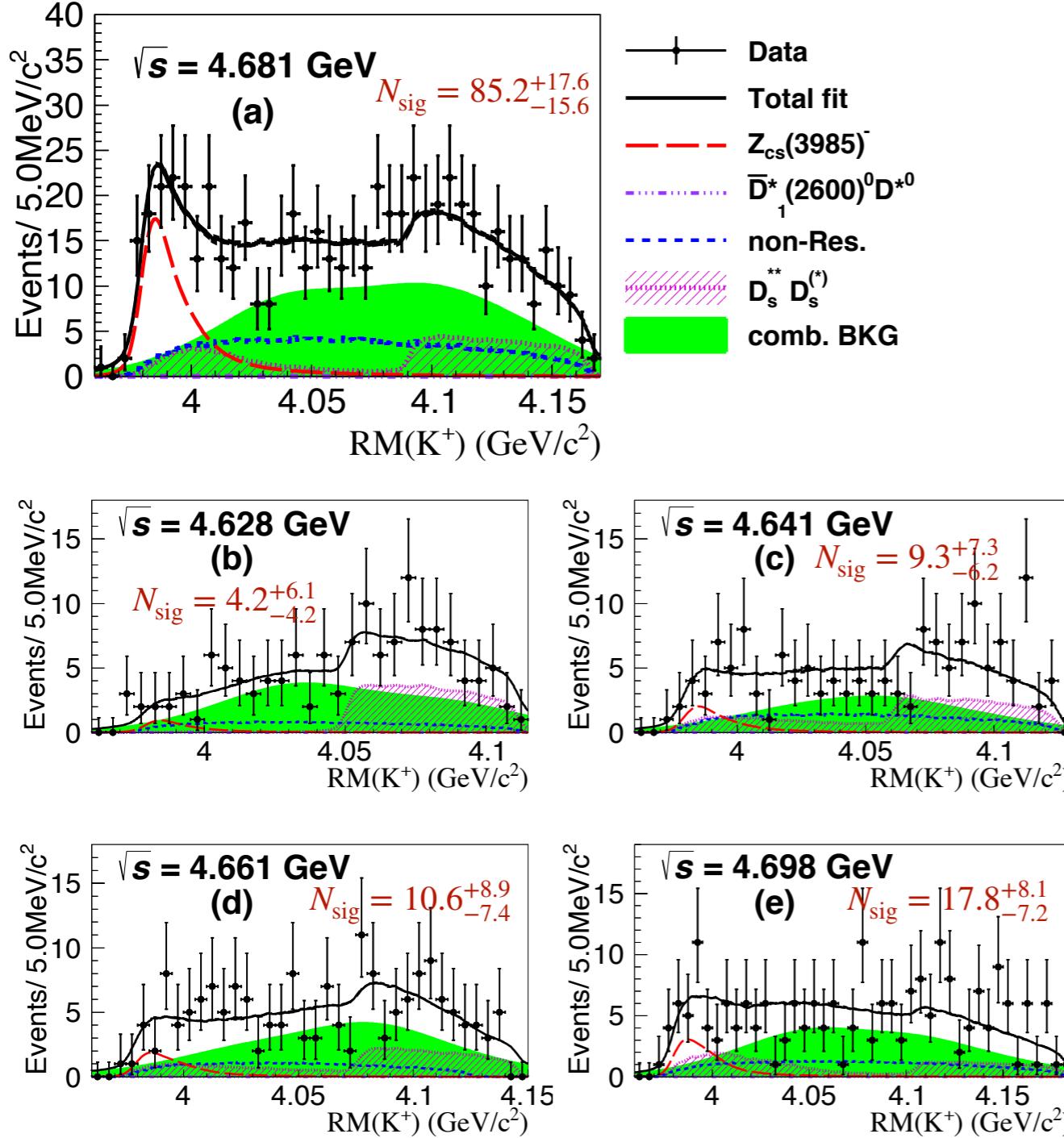
- $e^+e^- \rightarrow K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ *Phys.Rev.Lett. 126, 102001 (2021)*
- 3.7 fb⁻¹ data at 4628, 4640, 4660, 4680, and 4700
- Partial reconstruction of the process, tag K and D_s^-
- D_s^- reconstructed with $K^+K^-\pi^-$ [$\phi\pi$ or K^*K] and $K_S^0K^-$



- Both decay modes can survive the selection
- Combinatorial background described by wrong sign (WS) events
- Absolute contribution in signal region determined from a fit to $RM(K^+D_s^-)$

Observation of $Z_{CS}(3985)$

Phys.Rev.Lett. 126, 102001 (2021)



- An enhancement around 3.98 GeV
- Cannot be described by $D_s^{(*)-}D_s^{**+}$ and $D^{(*)0}\bar{D}^{**0}$ or interference between two of them
- Assume $J^P=1^+$
- Simultaneous fit to five data samples
- Signal component:

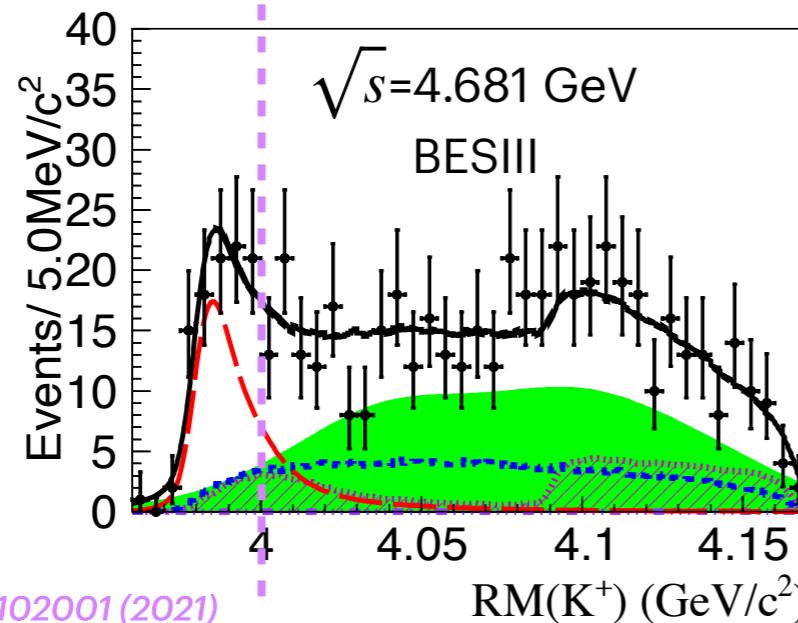
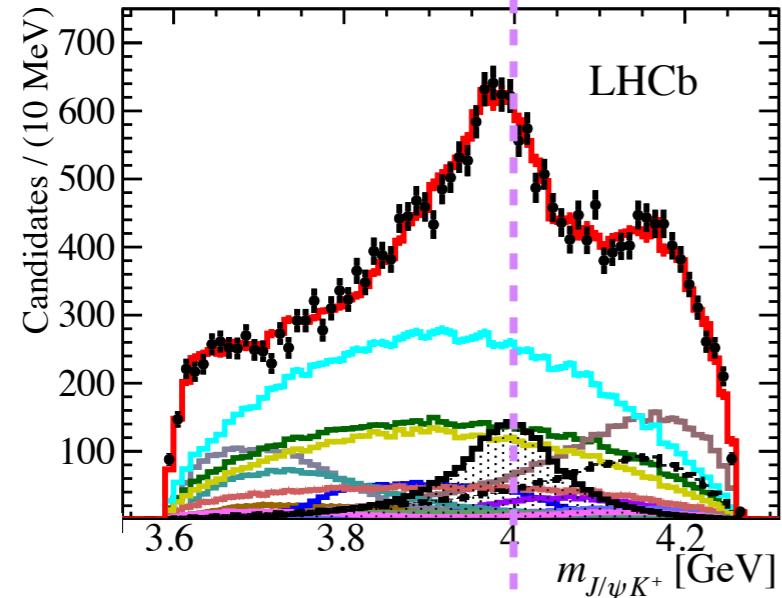
$$\left| \frac{\sqrt{q \cdot p_j}}{M^2 - m_0^2 + i m_0 (f \Gamma_1(M) + (1-f) \Gamma_2(M))} \right|^2$$

$f = 0.5$ represents the fraction of the two decay modes

- Pole position: $m = 3982.5^{+1.8}_{-2.6} \pm 2.1 \text{ MeV}/c^2$
 $\Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0 \text{ MeV}$
- Significance: 5.3σ
- At least four quarks ($c\bar{c}s\bar{u}$)

$Z_{cs}(3985)$ and $Z_{cs}(4000)$

Phys. Rev. Lett. 127, 082001 (2021)



Phys. Rev. Lett. 126, 102001 (2021)

$Z_{cs}(4000)$:

- $J^P=1^+$
- $m = 4003 \pm 6^{+4}_{-24} \text{ MeV}/c^2$
- $\Gamma=131 \pm 15 \pm 26 \text{ MeV}$

Mass consistent within 1σ

Width differs significantly

$Z_{cs}(3985)$:

- $m = 3985^{+2.1}_{-2.0} \pm 1.7 \text{ MeV}/c^2$
- $\Gamma=13.8^{+8.1}_{-5.2} \pm 4.9 \text{ MeV}$

Studies in $D_s D^* + D_s^* D$ system from B decay and $K^+ K^- J/\psi$ system from $e^+ e^-$ annihilation are needed!

No clear structure from Belle study in $e^+ e^- \rightarrow K \bar{K} J/\psi$

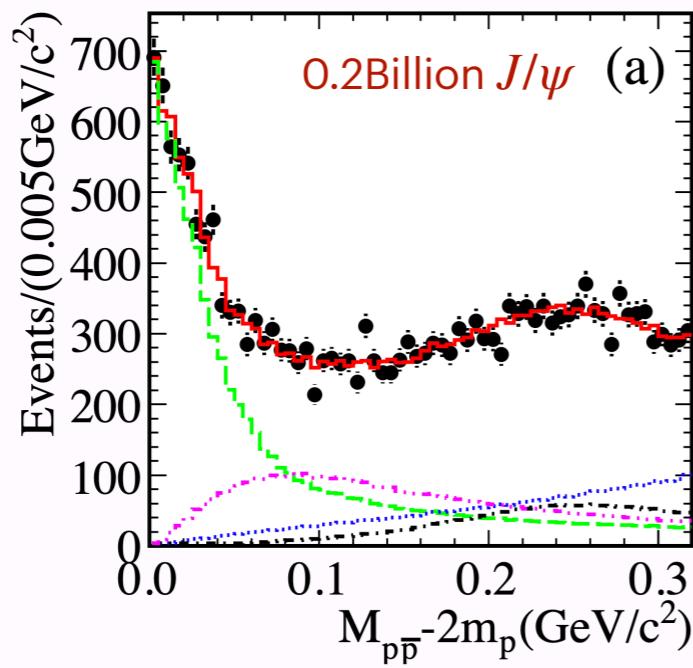
PRD89, 072015 (2014)

Structures Around $M(p\bar{p})$

$X(p\bar{p})$ in $J/\psi \rightarrow \gamma p\bar{p}$

- First observed at BESII, confirmed at BESIII with higher significance using PWA (FSI considered)
 - Mass: $(1832^{+19+18}_{-5-17} \pm 19)$ MeV
 - Width: < 76 MeV
 - J^{PC} : 0^{-+}

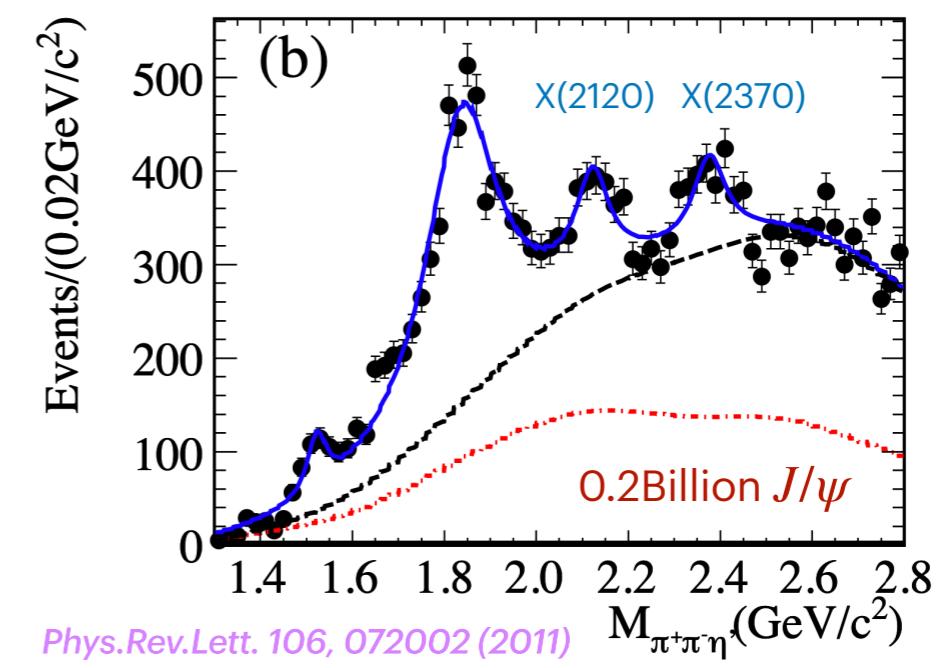
Phys.Rev.Lett. 108, 112003 (2012)



$X(1835)$ in $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$

- First observed at BESII, confirmed at BESIII experiment with higher significance
 - Mass: $(1836.5 \pm 3.0^{+5.6}_{-2.1})$ MeV
 - Width: $(190 \pm 9^{+38}_{-36})$ MeV
 - J^{PC} : $|\cos\theta_\gamma|$ agrees with expectation of 0^{-+}
- Also observed in $J/\psi \rightarrow \gamma K_S K_S \eta$, $J^P=0^-$

Phys.Rev.Lett. 115, 091803 (2015)

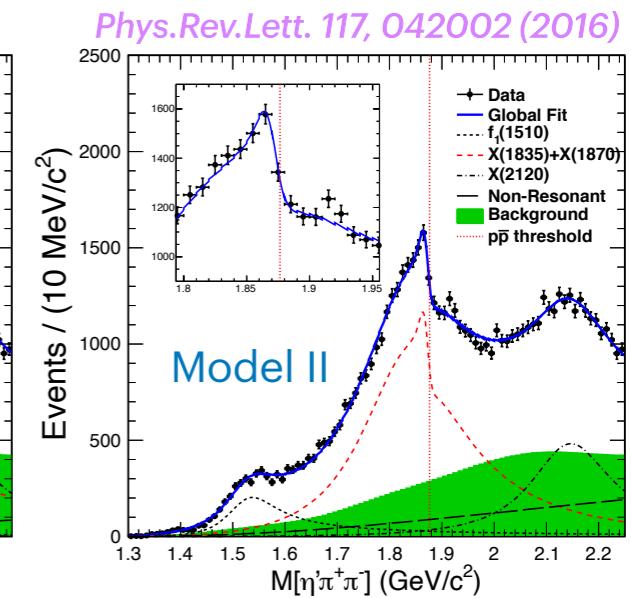
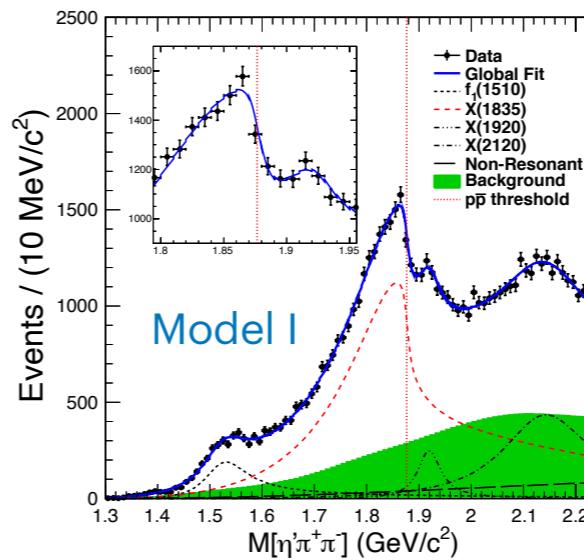


Structures Around $M(p\bar{p})$

1.3 B J/ψ events

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

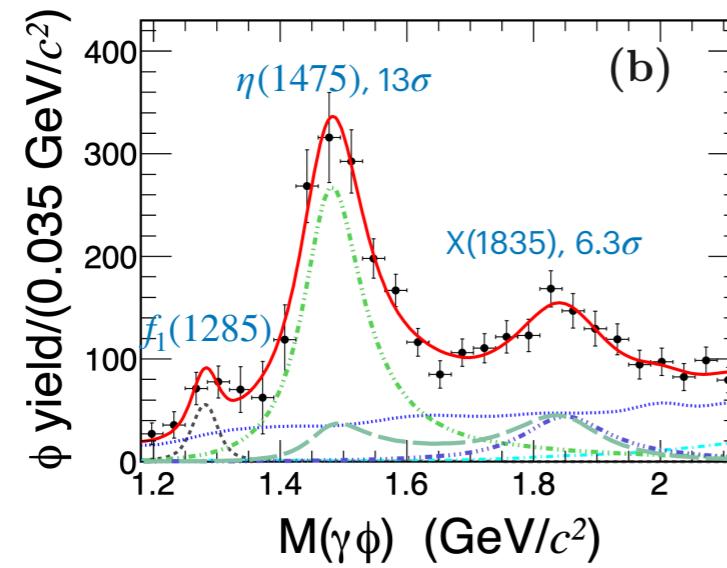
- Model I:** Flatte line-shape with strong coupling to $p\bar{p}$ and narrow BW at 1920 MeV
- Model II:** Two-coherent BWs, $X(1835)+X(1870)$ (7σ)



- $J/\psi \rightarrow \gamma\gamma\phi$

Phys.Rev.D 97, 051101(R) (2018)

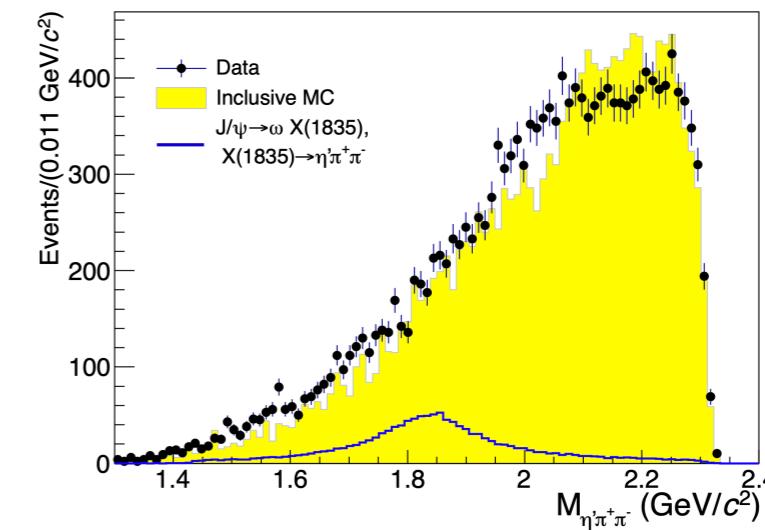
- $\eta(1475)$ and $X(1835)$ consider coherently
- $X(1835)$: $J^{PC}=0^{-+}$, sizeable $s\bar{s}$ component



- $J/\psi \rightarrow \omega\pi^+\pi^-\eta'$

Phys.Rev.D 99, 071101 (2019)

- No obvious $X(1835)$ signal
- $B[J/\psi \rightarrow \omega X(1835) \rightarrow \omega\pi^+\pi^-\eta'] < 6.2 \times 10^{-5}$



Summary and Outlook

- Unique data samples at BESIII provide good opportunity for spectroscopy study
 - 10B J/ψ events, 2.7B $\psi(2S)$ events for light hadron spectroscopy study through radiative and hadronic transition processes
 - $X(18xx)$ around $p\bar{p}$ threshold
 - Glueballs: 0^{++} in 1.5-1.7 GeV; 2^{++} in 2.3-2.4 GeV; 0^{-+} in 2.3-2.6 GeV
 - $\phi(2170)/Y(2175)$
 - Scan data sample between 4.0 to 4.95 GeV
 - Study of excited charmonium states: decay modes of $\psi_2(3823)$
 - Charmonium-like states: decay modes of $X(3872)$; high precision measurement of cross section for study of Y states; decay modes of Z_c states and observation of new Z_{cs} states
- More results will full data set are ongoing, more exciting results are expected

BESIII Collaboration

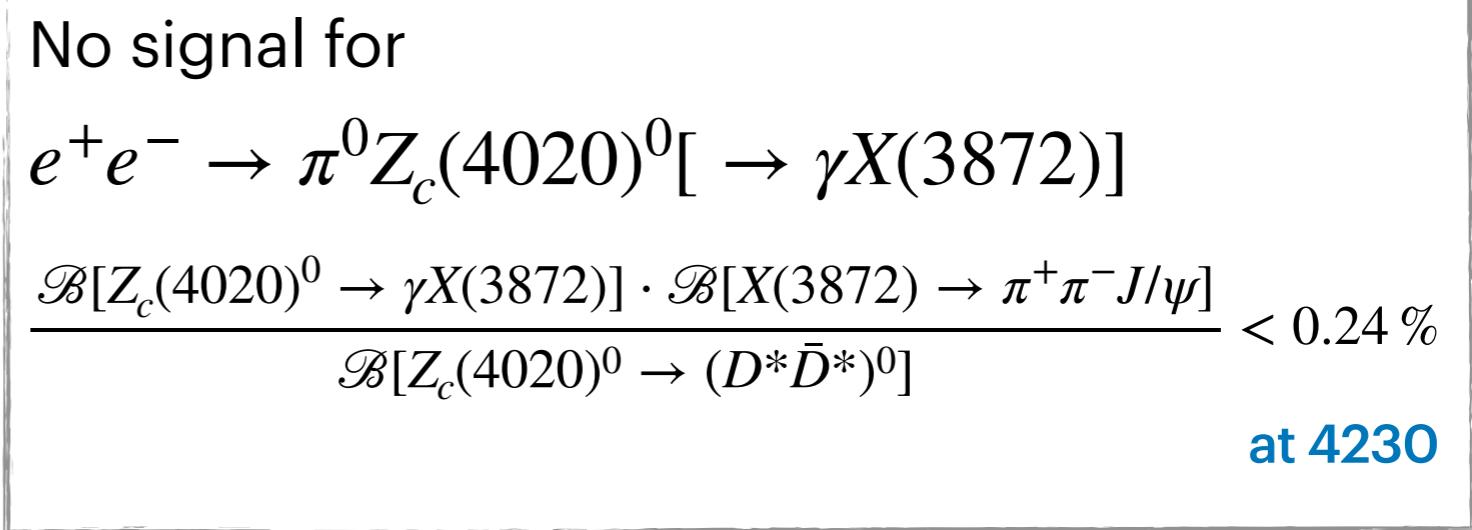
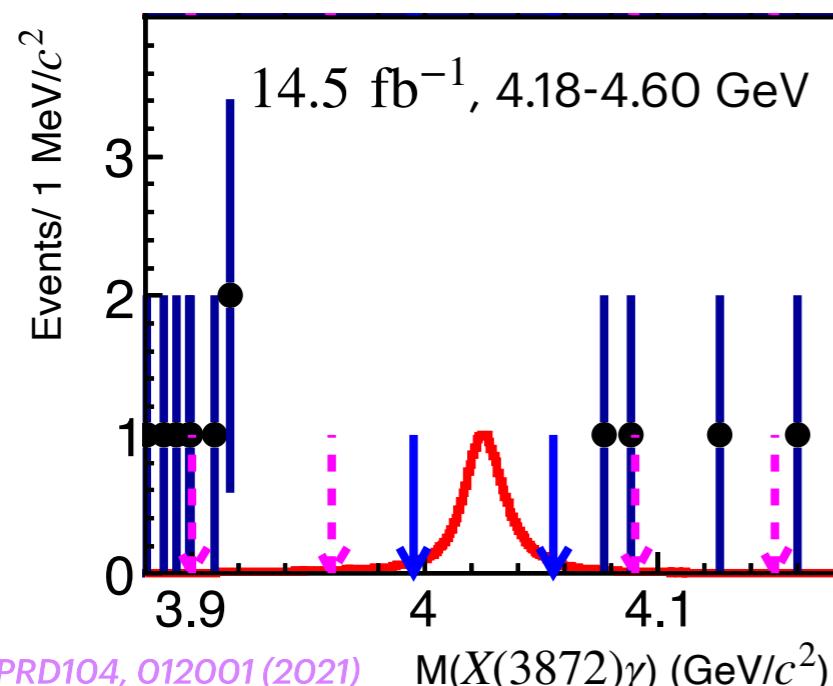
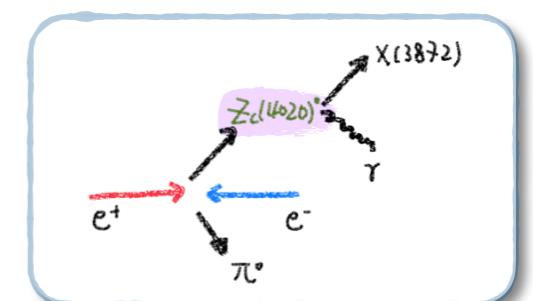
Political Map of the World, November 2011



$Z_c(4020) \rightarrow \gamma X(3872)$

- Connection between Z_c states and X states in molecule picture
- Branching fraction of $Z_c(4020)^0 \rightarrow \gamma X(3872)$ and $Z_c(4020)^\pm \rightarrow \pi^\pm X(3872)$ of several per mille level

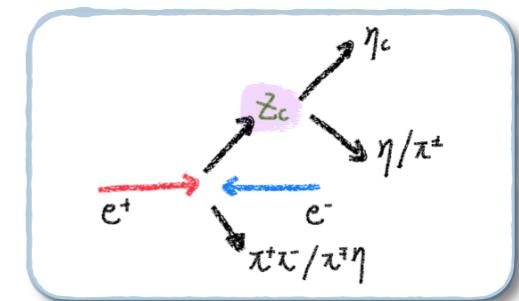
PRD99, 054028 (2019)



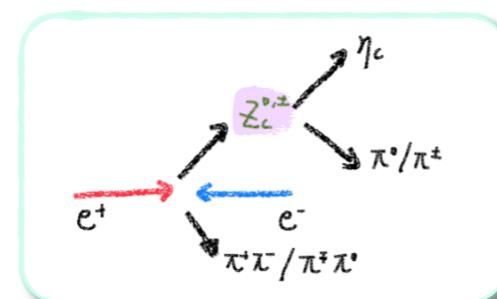
Do not contradict with theoretical prediction!

$Z_c \rightarrow \pi\eta_c$ and $\eta\eta_c$

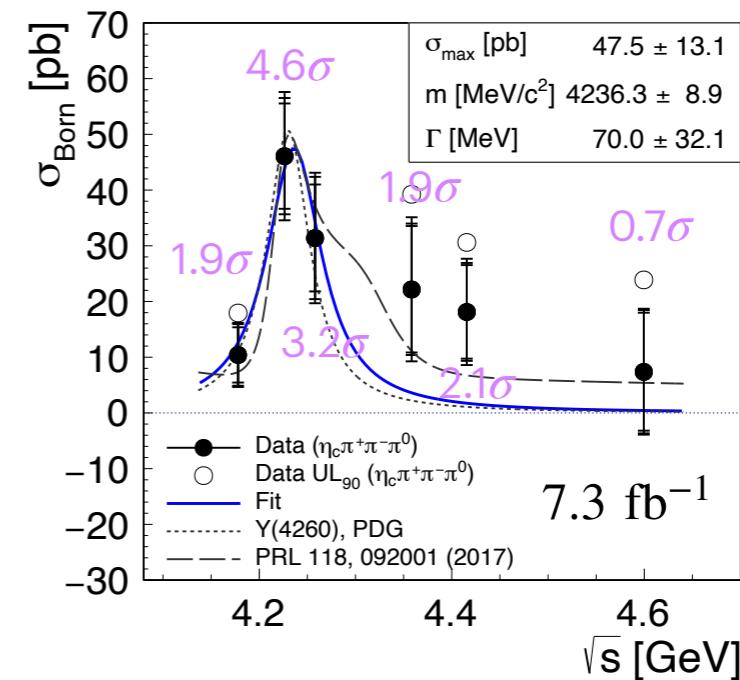
- $e^+e^- \rightarrow \eta_c\eta\pi^+\pi^-$ PRD103, 032004 (2021)
 - 4.1 fb^{-1} data between 4.23 and 4.60 GeV
 - No signal for $\eta_c\eta\pi^+\pi^-$ [also apply for Z_c search]
 - $\sigma^{\text{up}} < 6.2, 10.8, 27.6, 22.6, 23.7 \text{ pb}$ at 90 % C.L.



- $e^+e^- \rightarrow \eta_c\pi^+\pi^-\pi^0, \eta_c\pi^+\pi^-, \eta_c\pi^0\gamma$ in search of Z_c close to $m(D\bar{D})$
 - $e^+e^- \rightarrow \eta_c\pi^+\pi^-\pi^0$ observed at 4230, used to study $Z_c \rightarrow \eta_c\pi^{\pm,0}$

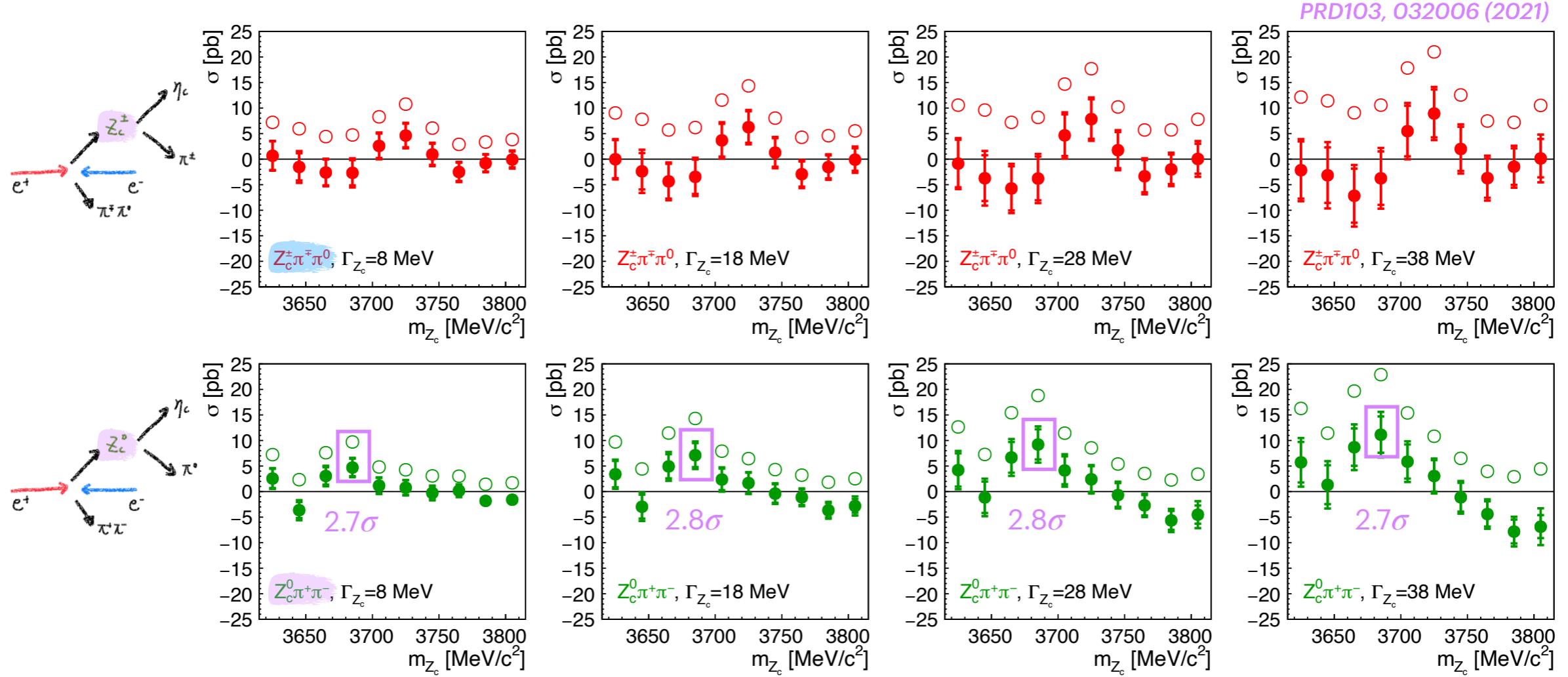


PRD103, 032006 (2021)



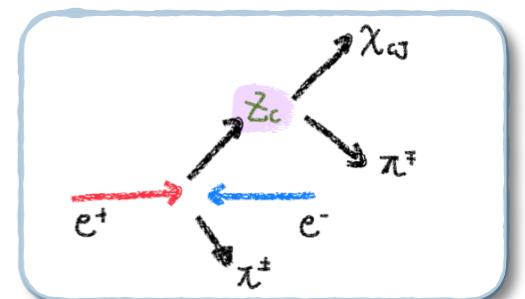
$Z_c \rightarrow \pi\eta_c$ and $\eta\eta_c$

- $e^+e^- \rightarrow Z_c [\rightarrow \eta_c \pi^{\pm,0}] \pi\pi$ in search of Z_c close to $m(D\bar{D})$

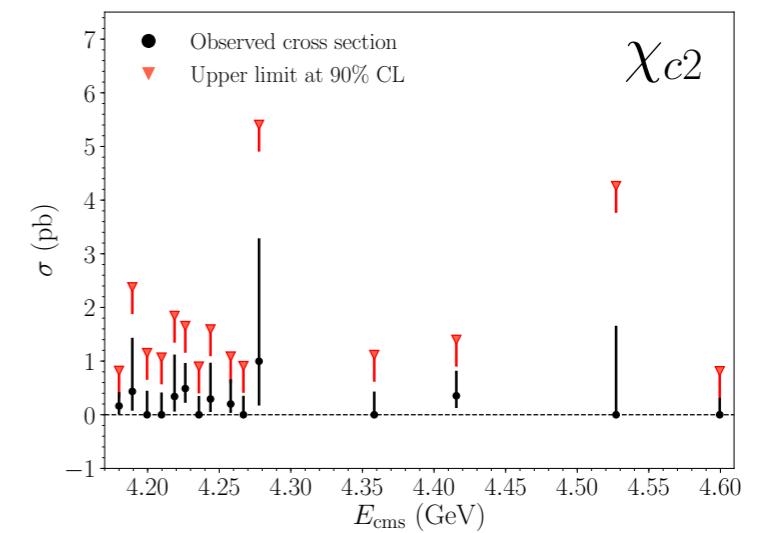
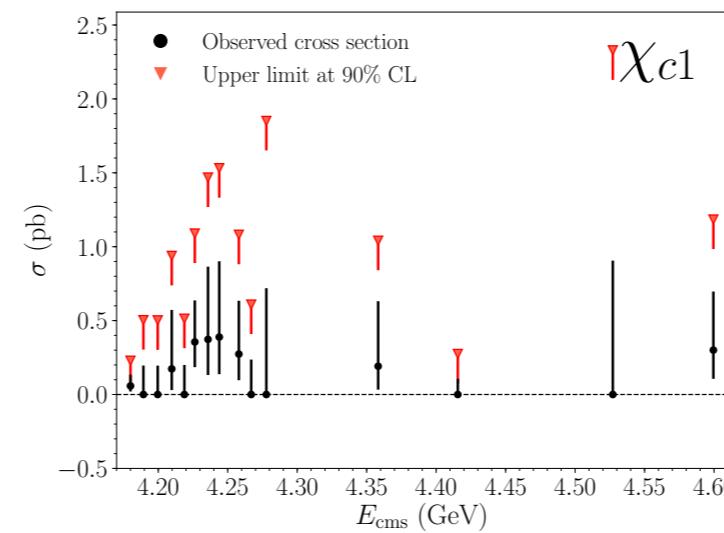
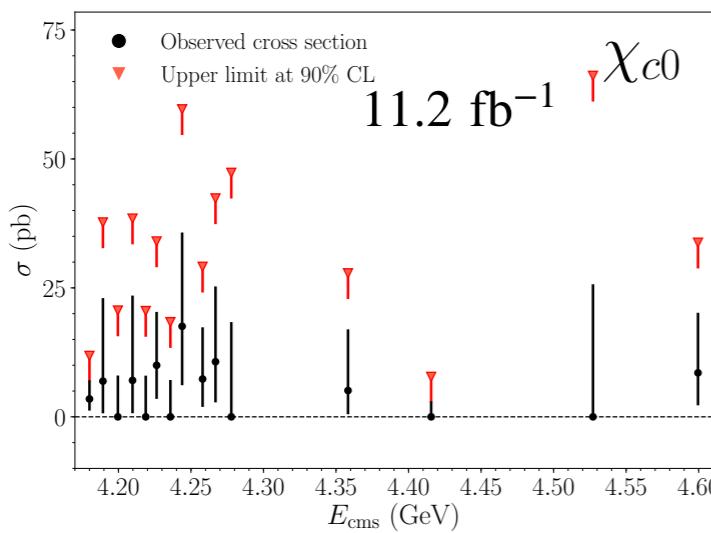


$$Z_c \rightarrow \pi^\pm \chi_{cJ}$$

- $Z_c(4050)$ and $Z_c(4250)$ in $\pi^\pm \chi_{c1}$ from B decays
- $Z_c(3900)$ and $Z_c(4020)$ from e^+e^- annihilation at BESIII



Cross section of $e^+e^- \rightarrow \pi^+\pi^-\chi_{cJ}$



- No obvious signal of $e^+e^- \rightarrow \pi^+\pi^-\chi_{cJ}$
- Upper limit of cross section also apply for $Z_c \rightarrow \pi^\pm \chi_{cJ}$

PRD103, 052010 (2021)