Recent Progress on XYZ states from BESIII

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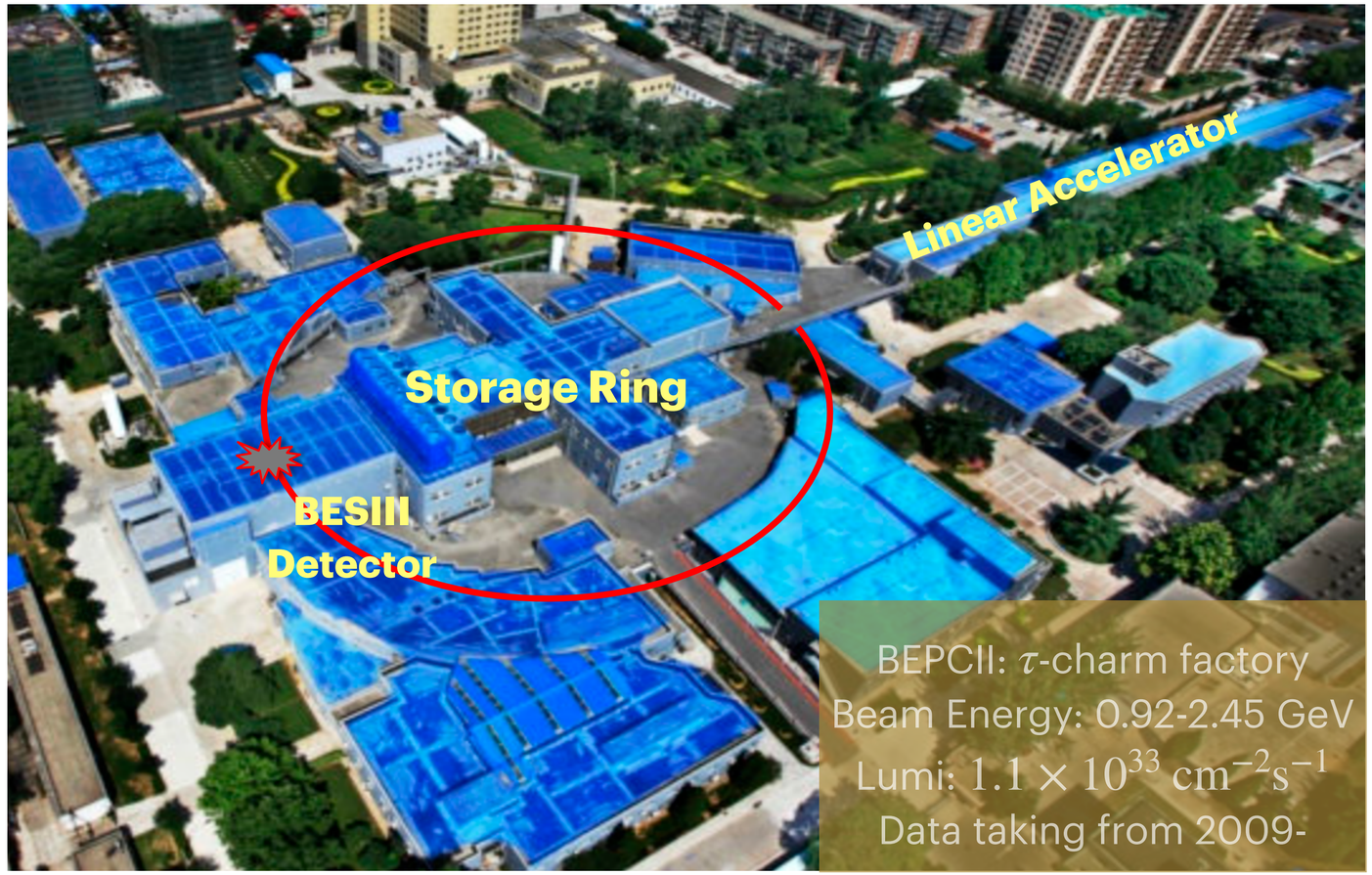
On Behalf of BESIII Collaboration

第十届XYZ研讨会

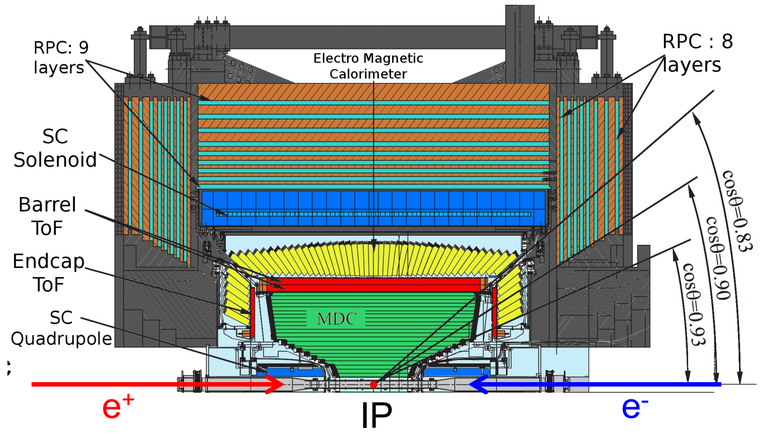
Changsha 2025.04.12

Beijing Electron Positron Collider II and BESIII



BEPCII: τ-charm factory
Beam Energy: 0.92-2.45 GeV
Lumi: 1.1×10^{33} cm^{-2}s^{-1}
Data taking from 2009-

Solenoid Magnet: 0.9/1.0 T



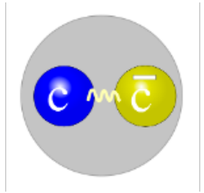
MUC $\sigma_{R\Phi}$: 2 cm

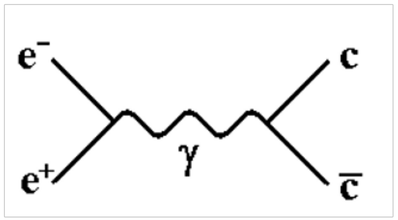
TOF
σ_T :80 ps
110 ps (60 ps)

MDC
dE/dx: 6%
σ_p/p: 0.5% at 1GeV/c

EMC
$\Delta E/E$: at 1GeV
2.5%
5.0%
σ_Z: 0.6 cm/$\sqrt{E}$

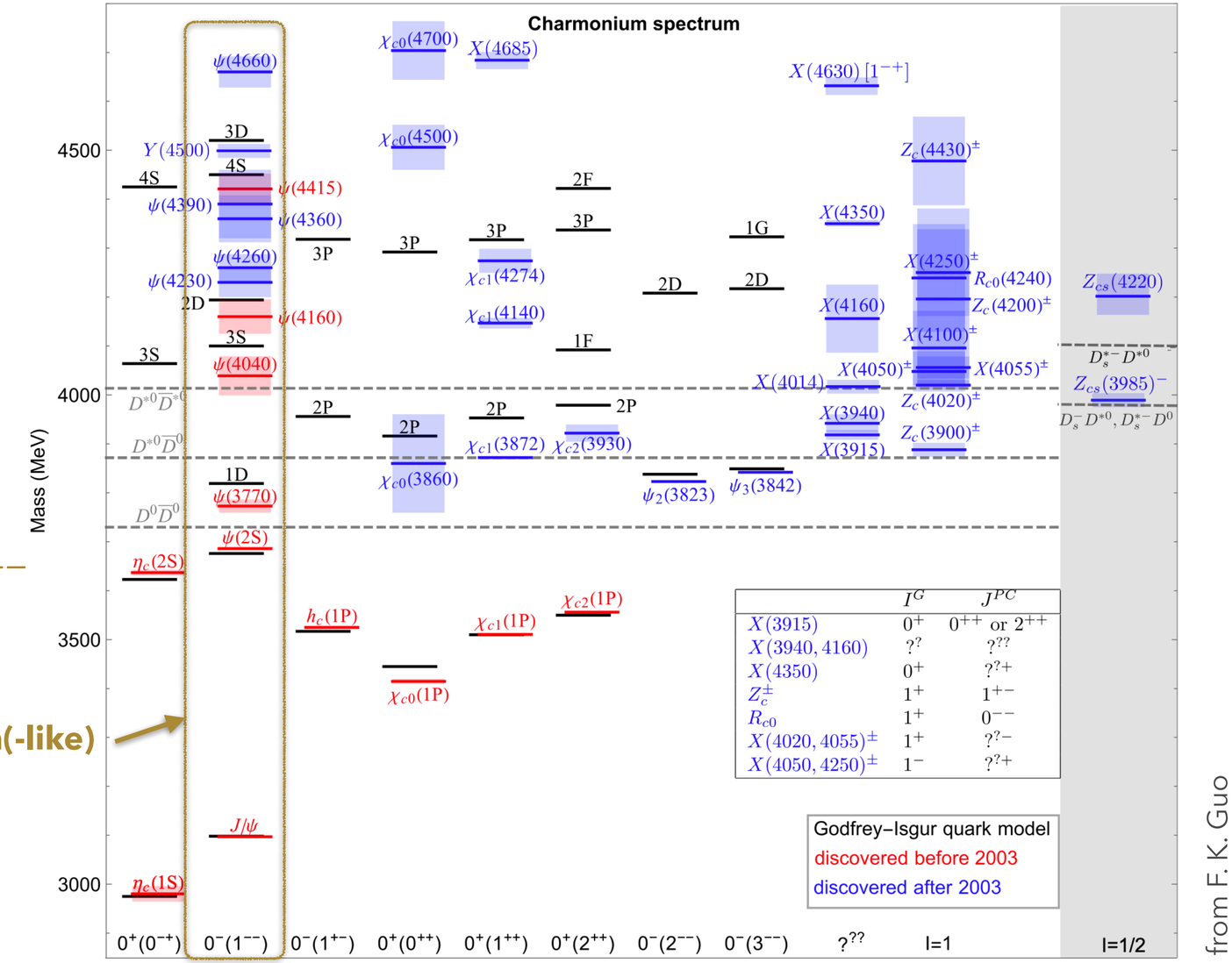
Charmonium Production at BESIII





$J^{PC} = 1^{--}$

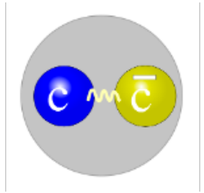
Vector Charmonium(-like)

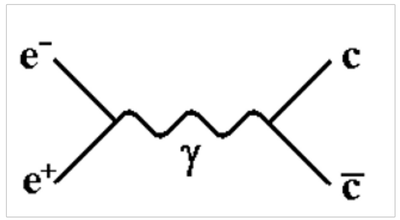


	I^G	J^{PC}
$X(3915)$	0^+	0^{++} or 2^{++}
$X(3940, 4160)$	$?^?$	$?^{??}$
$X(4350)$	0^+	$?^{?+}$
$Z_c^{\pm}$	1^+	1^{+-}
R_{c0}	1^+	0^{--}
$X(4020, 4055)^{\pm}$	1^+	$?^{?-}$
$X(4050, 4250)^{\pm}$	1^-	$?^{?+}$

from F. K. Guo

Charmonium Production at BESIII





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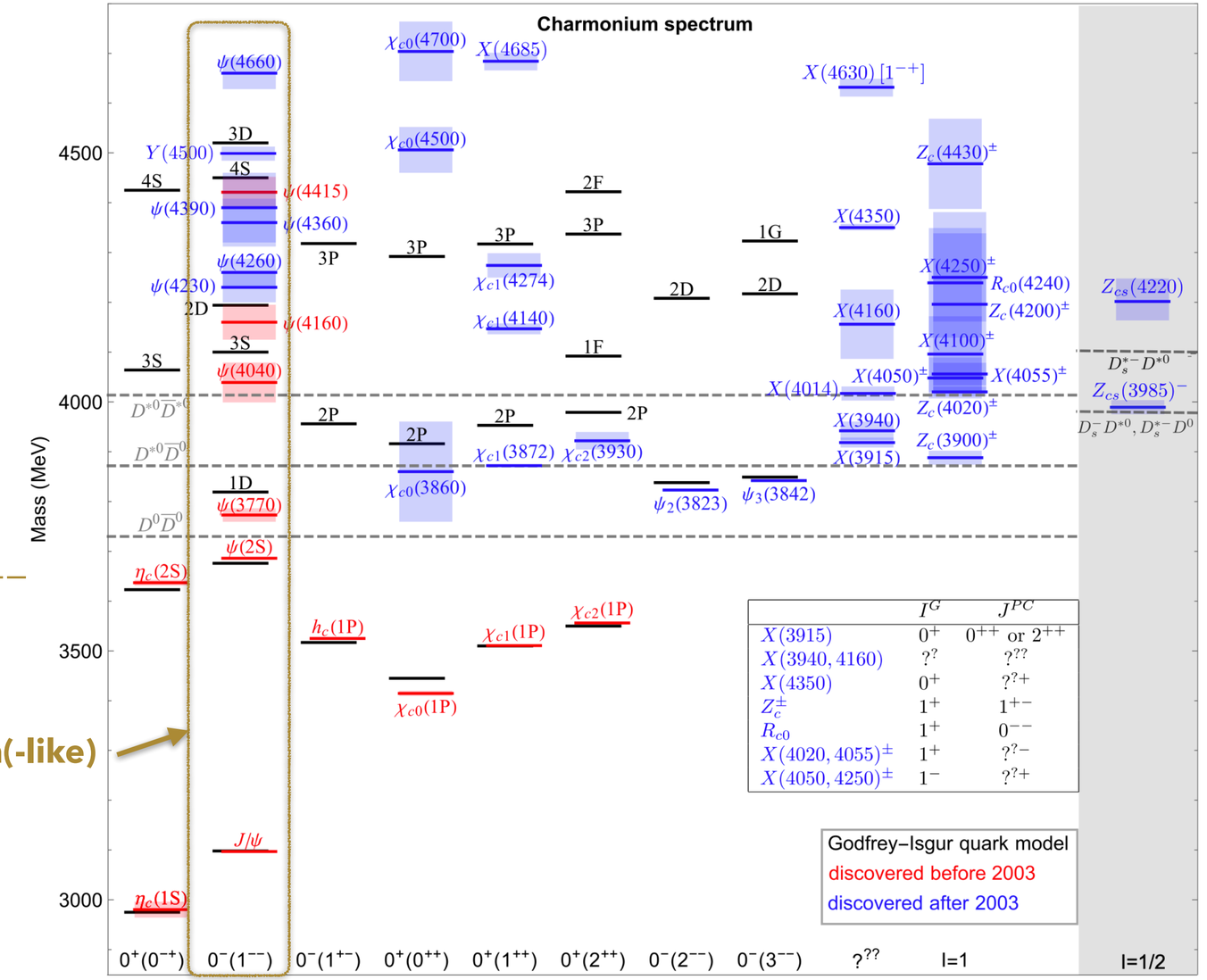
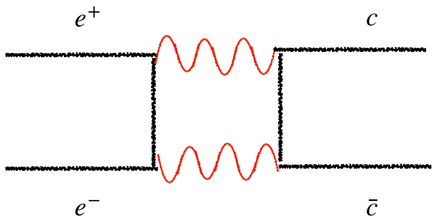


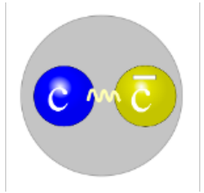
from F. K. Guo

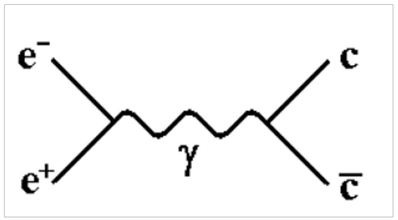
C-even states



PRL129, 122001 (2022)

Charmonium Production at BESIII





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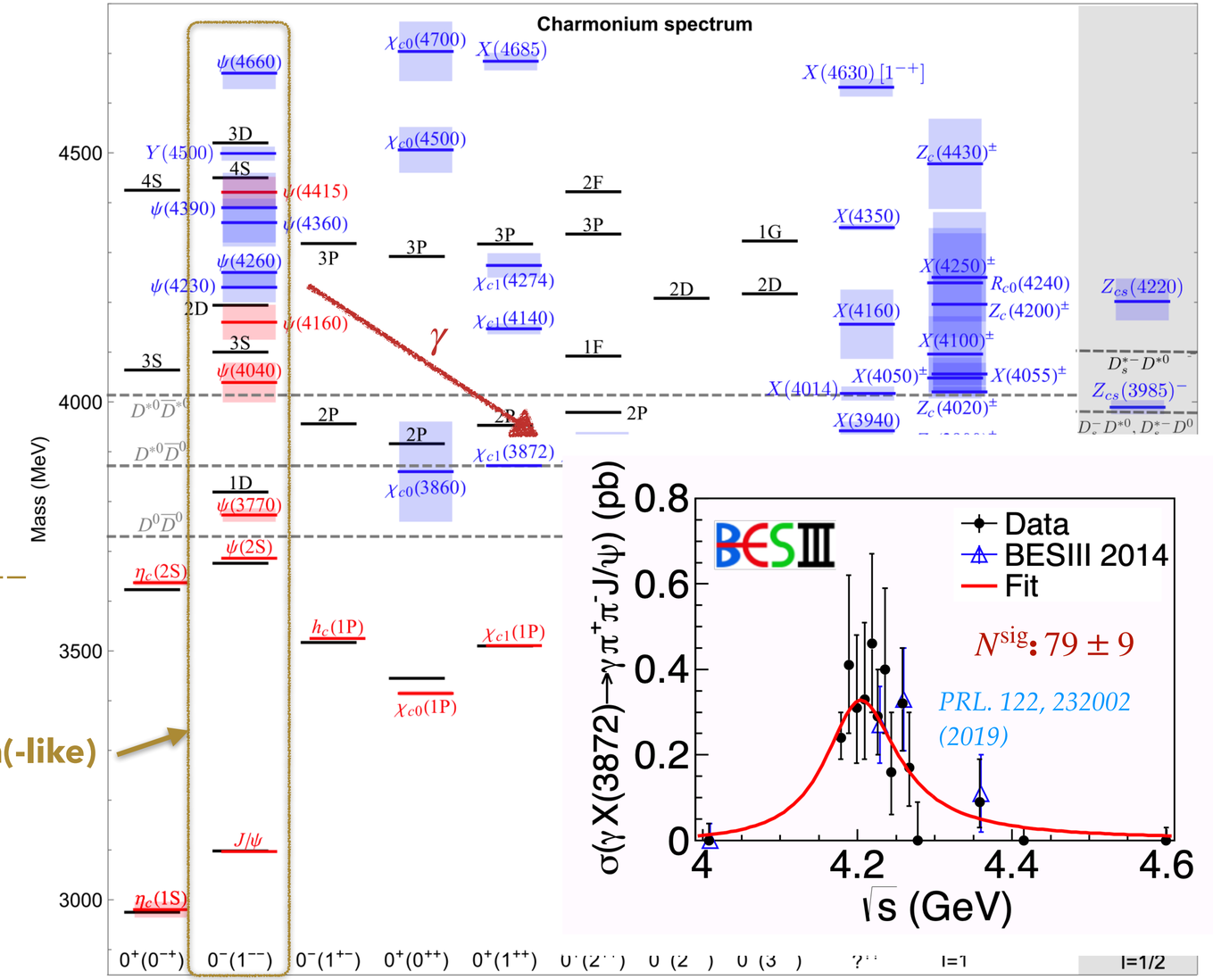

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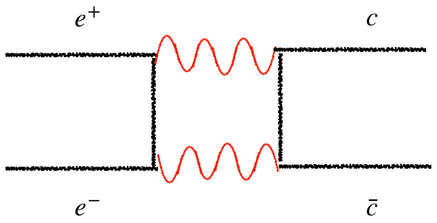

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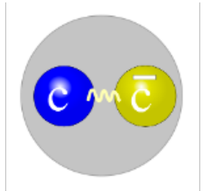

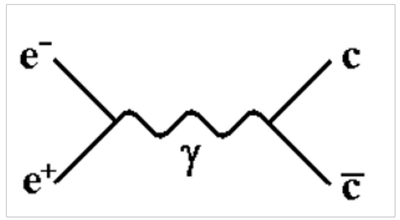

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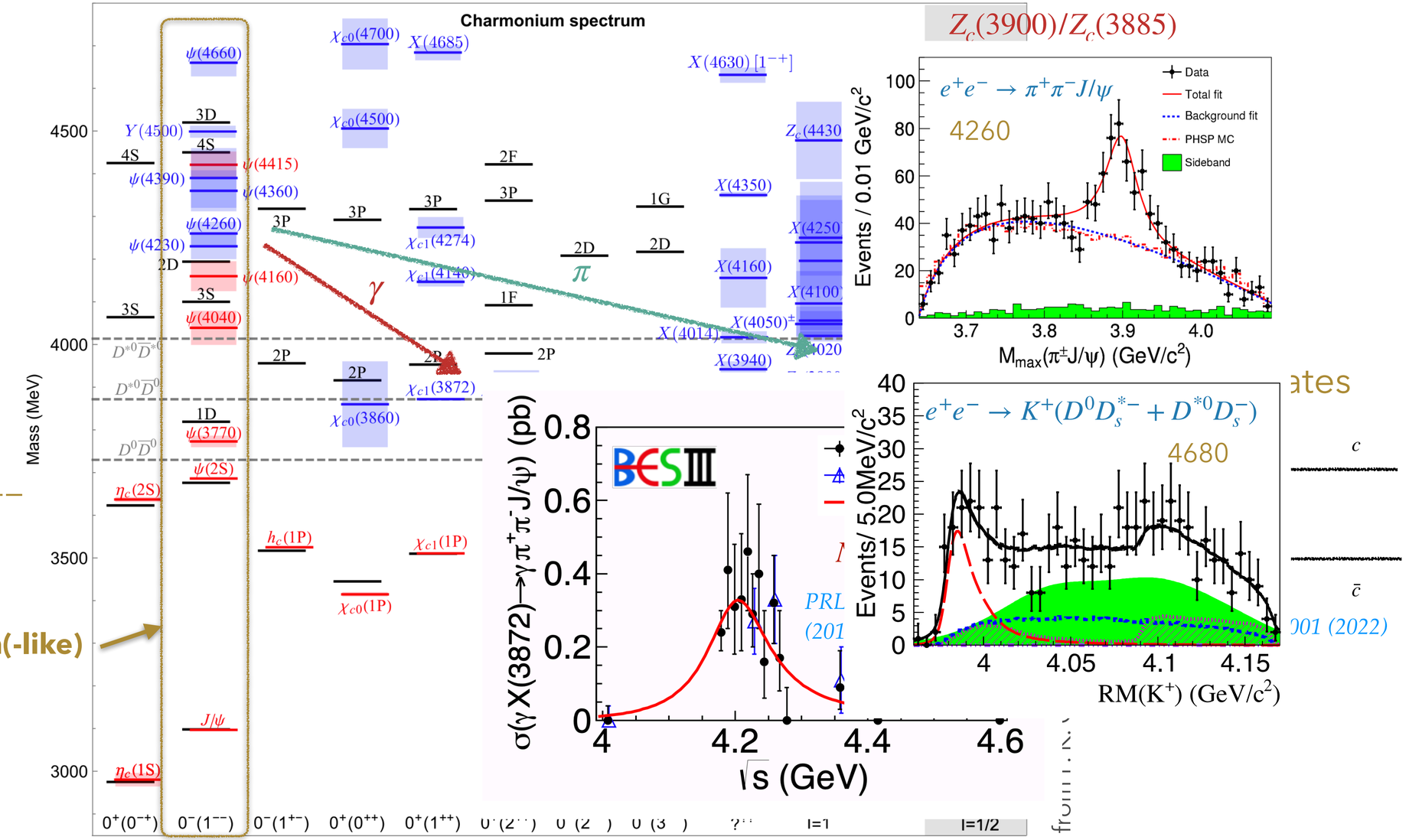


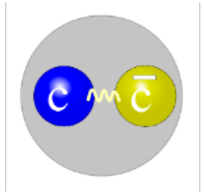
$Z_c(3900)/Z_c(3885)$

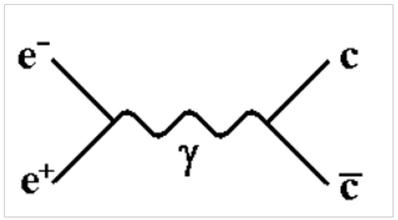
ates

PRL (201

001 (2022)

Charmonium Production at BESIII





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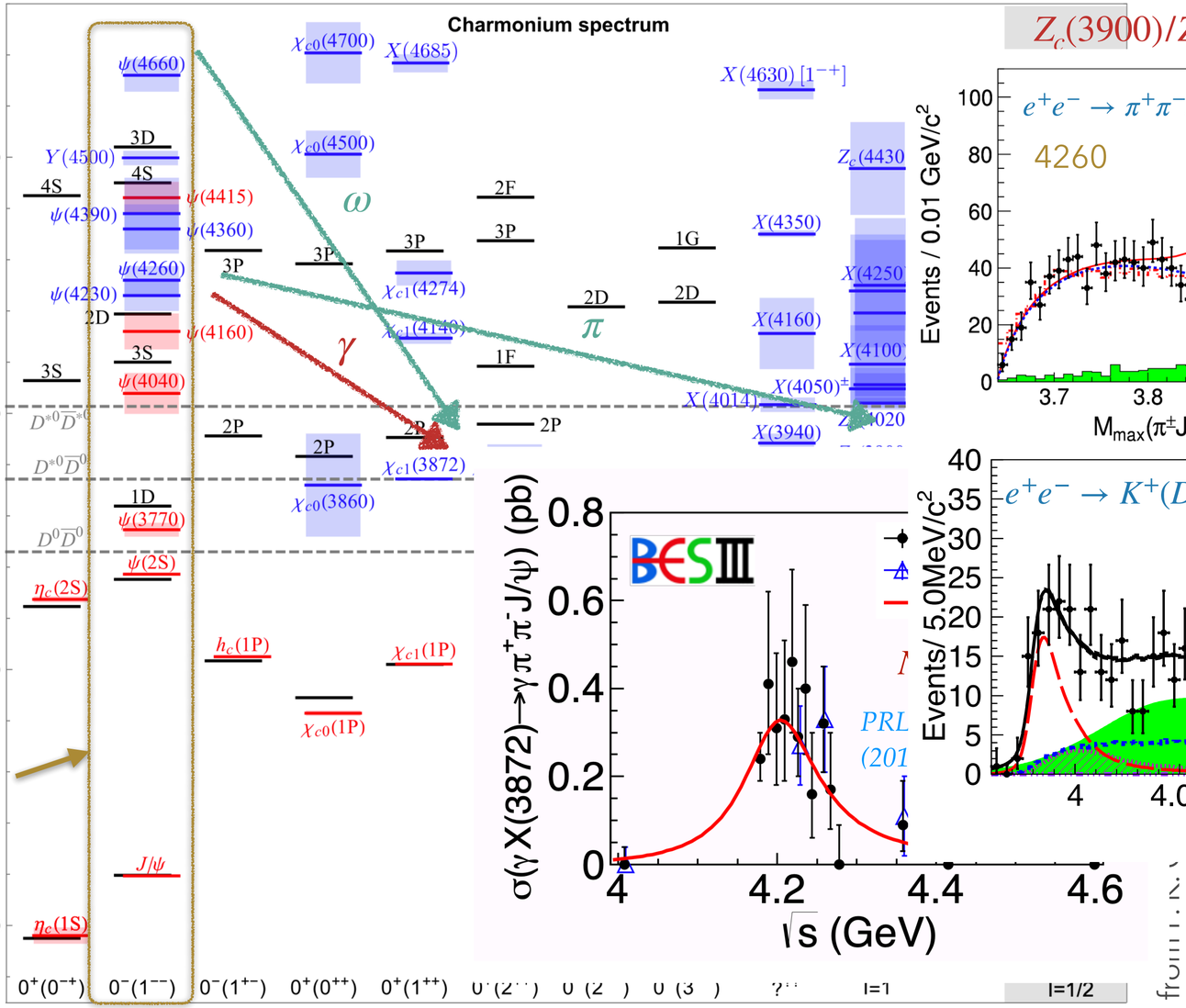

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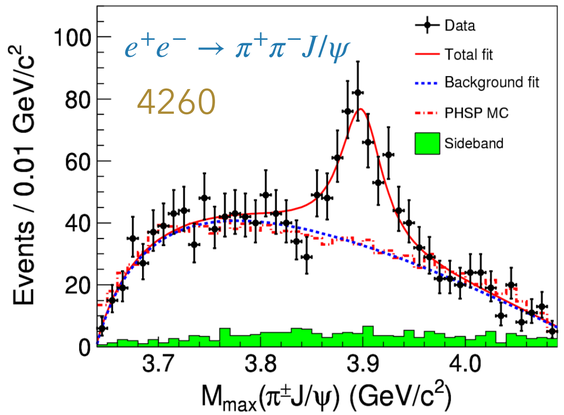
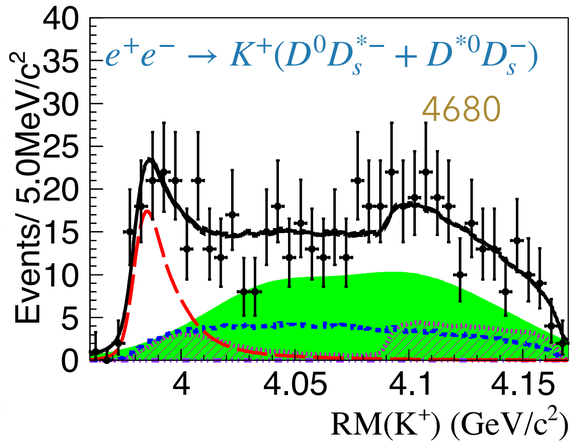
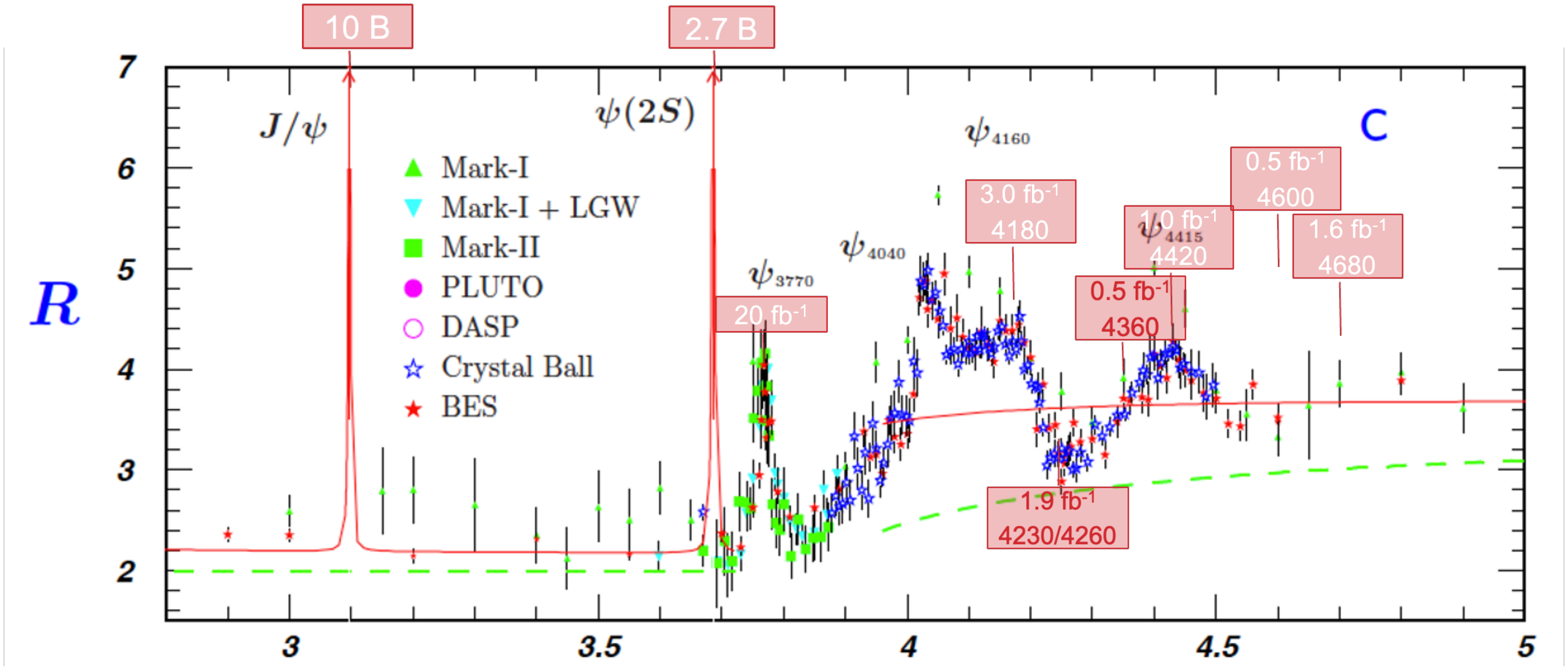




ates

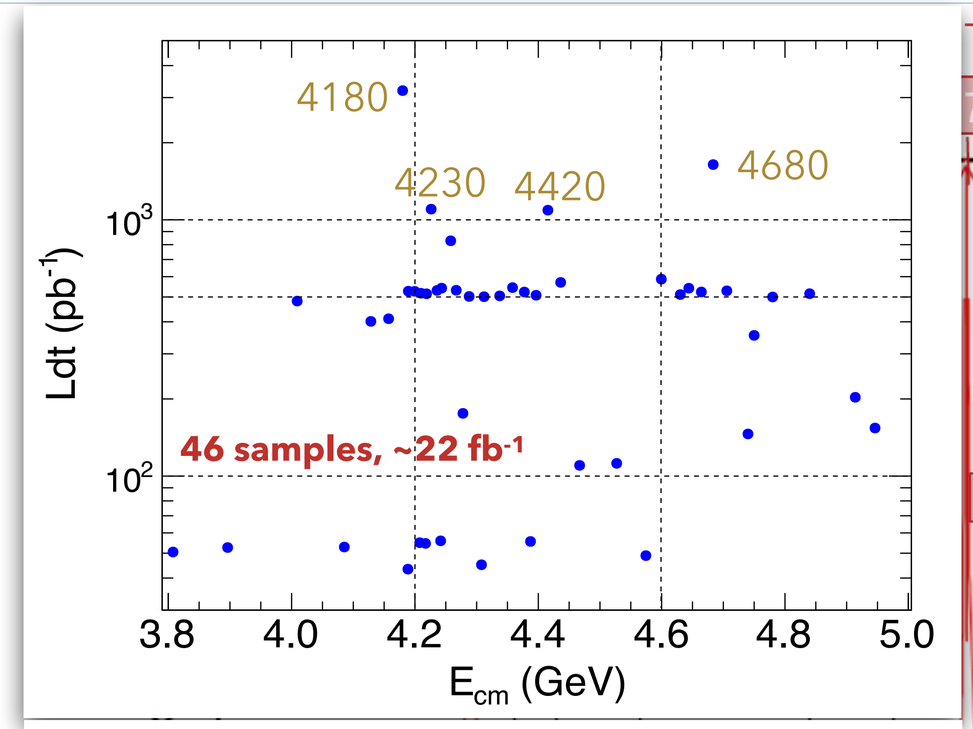
001 (2022)

BESIII Data Samples

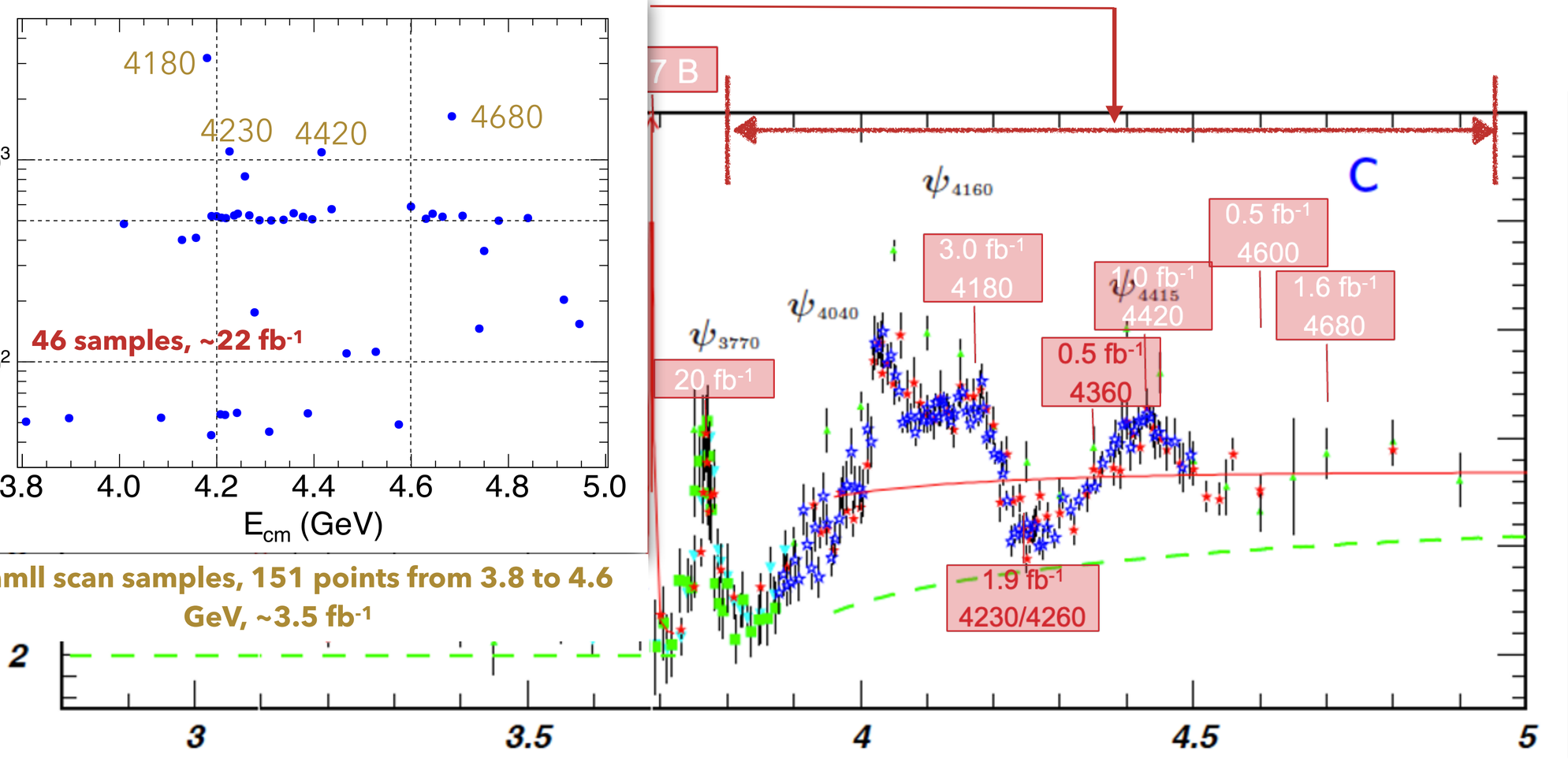


Can measure $\sigma[e^+e^- \to h_i]$ (CS) with high precision using direct e^+e^- annihilation data at BESIII ⇒ Y states

BESIII Data Samples



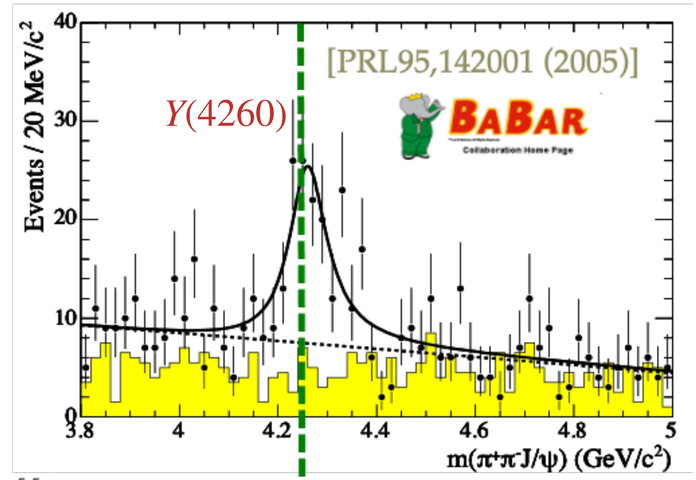
+ Samll scan samples, 151 points from 3.8 to 4.6 GeV, ~3.5 fb^{-1}

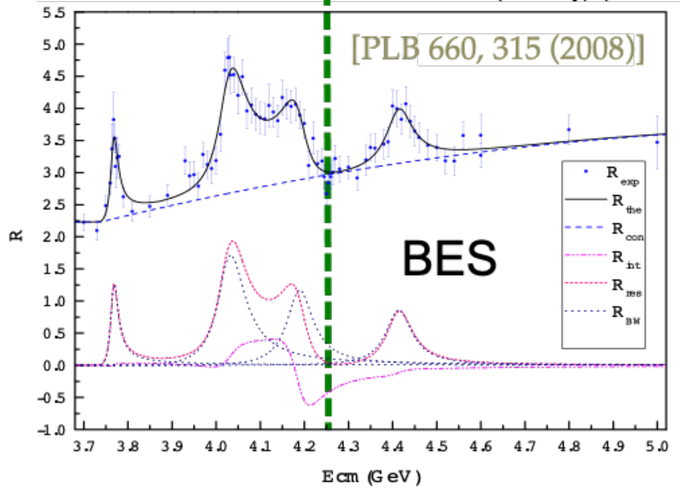


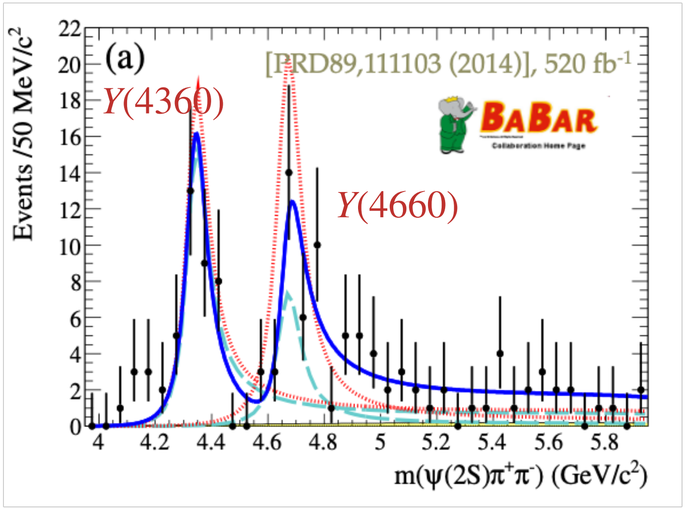
Can measure $\sigma[e^+e^- \to h_i]$ (CS) with high precision using direct e^+e^- annihilation data at BESIII ⇒ Y states

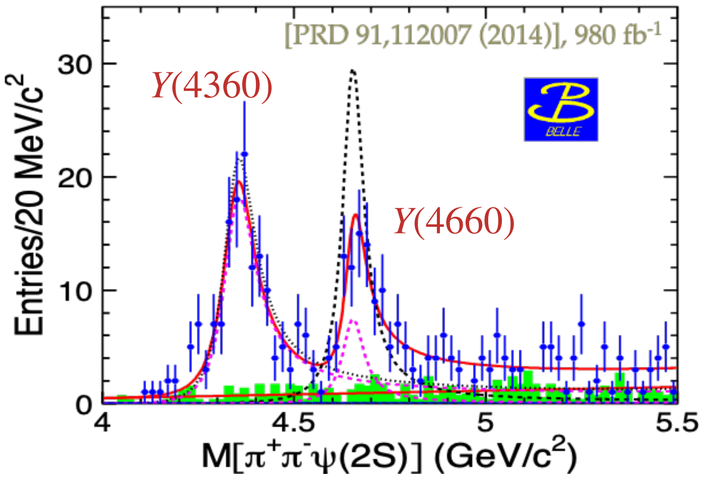
Discovery of Y States

- $Y(4260)$, discovered in ISR process at BaBar, $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$
  - Confirmed by CLEO and Belle
  - Mass > 4 GeV, above $D\bar{D}$ threshold
  - Not observed in inclusive hadron cross section
  - Not observed in open charm pair cross section
- Later, $Y(4360)$ was discovered at BaBar, $Y(4660)$ was discovered at Belle, both in $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$ process









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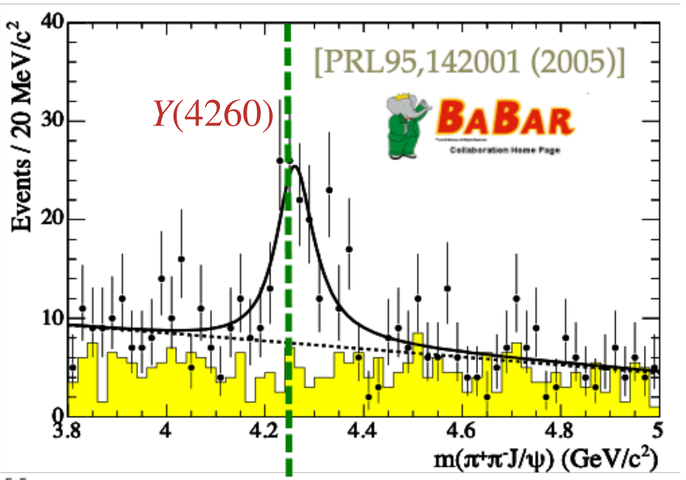
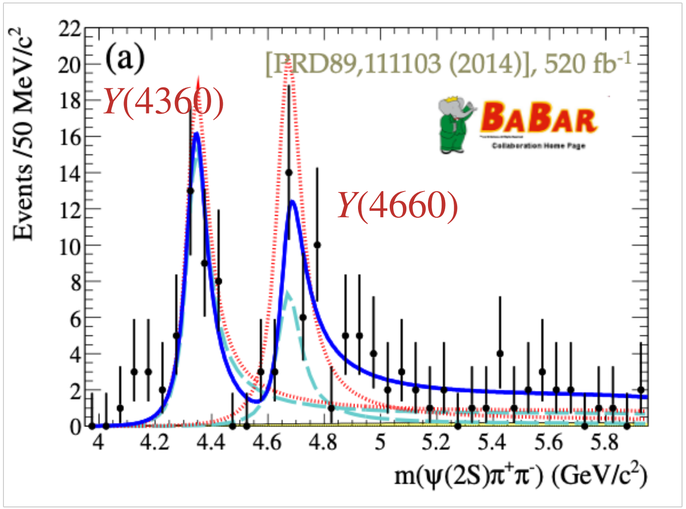
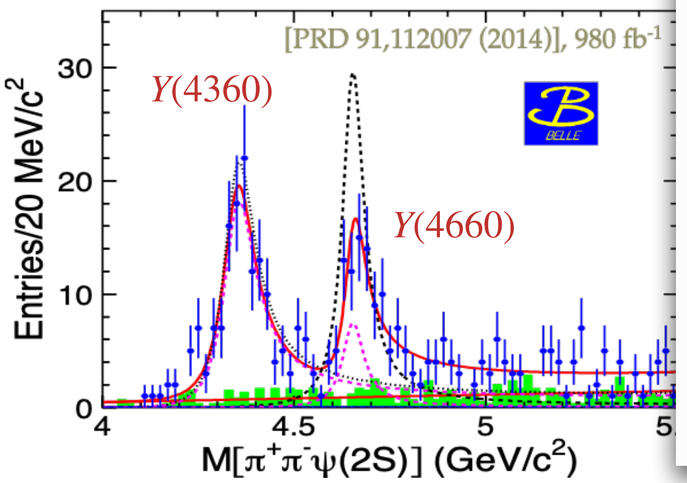
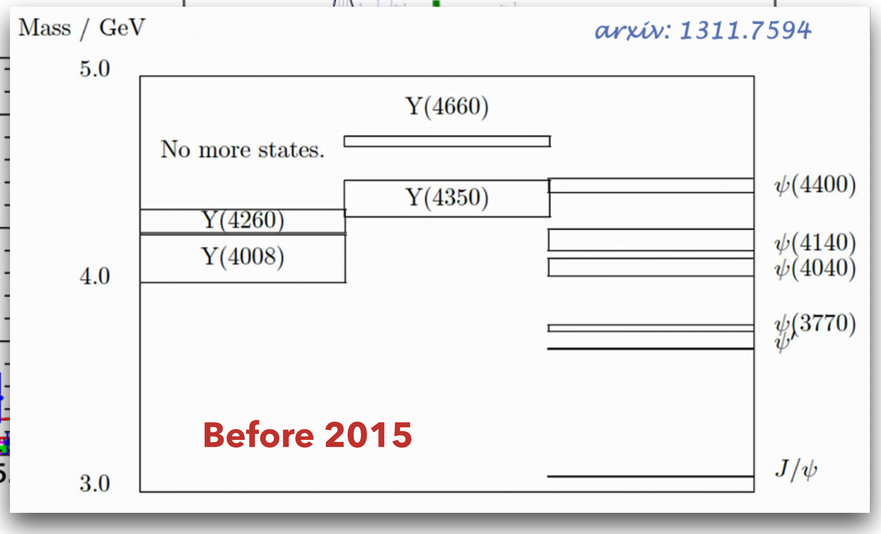


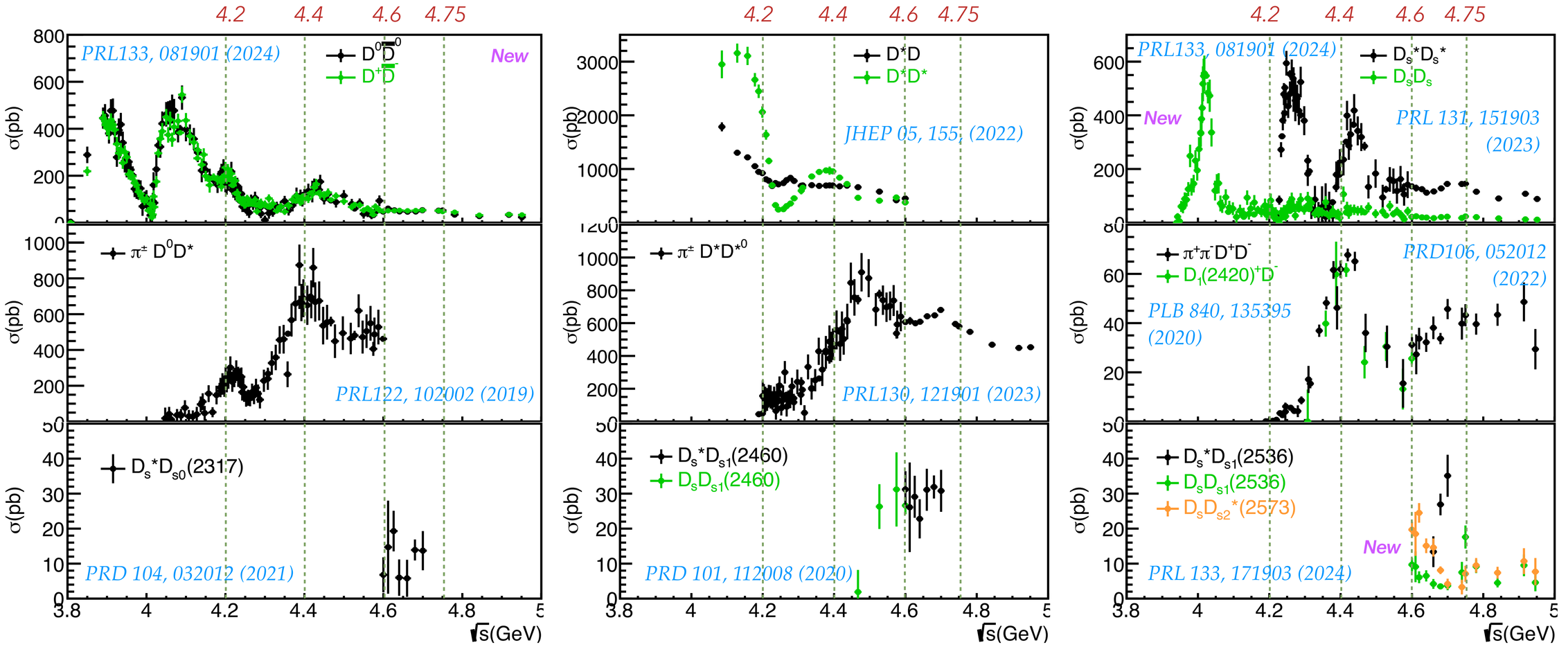






Overview of CS measurements at BESIII

- Precise cross section measurements of open charm, hidden charm, and light hadron processes



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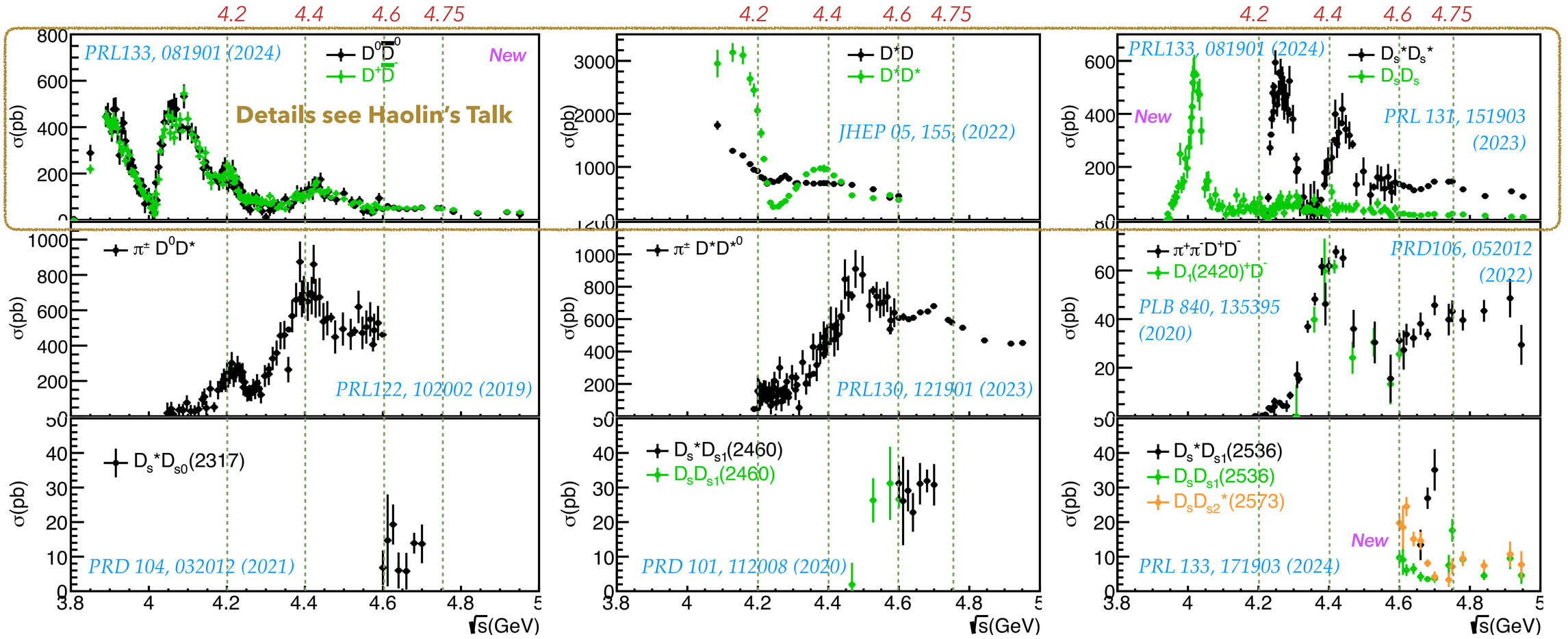

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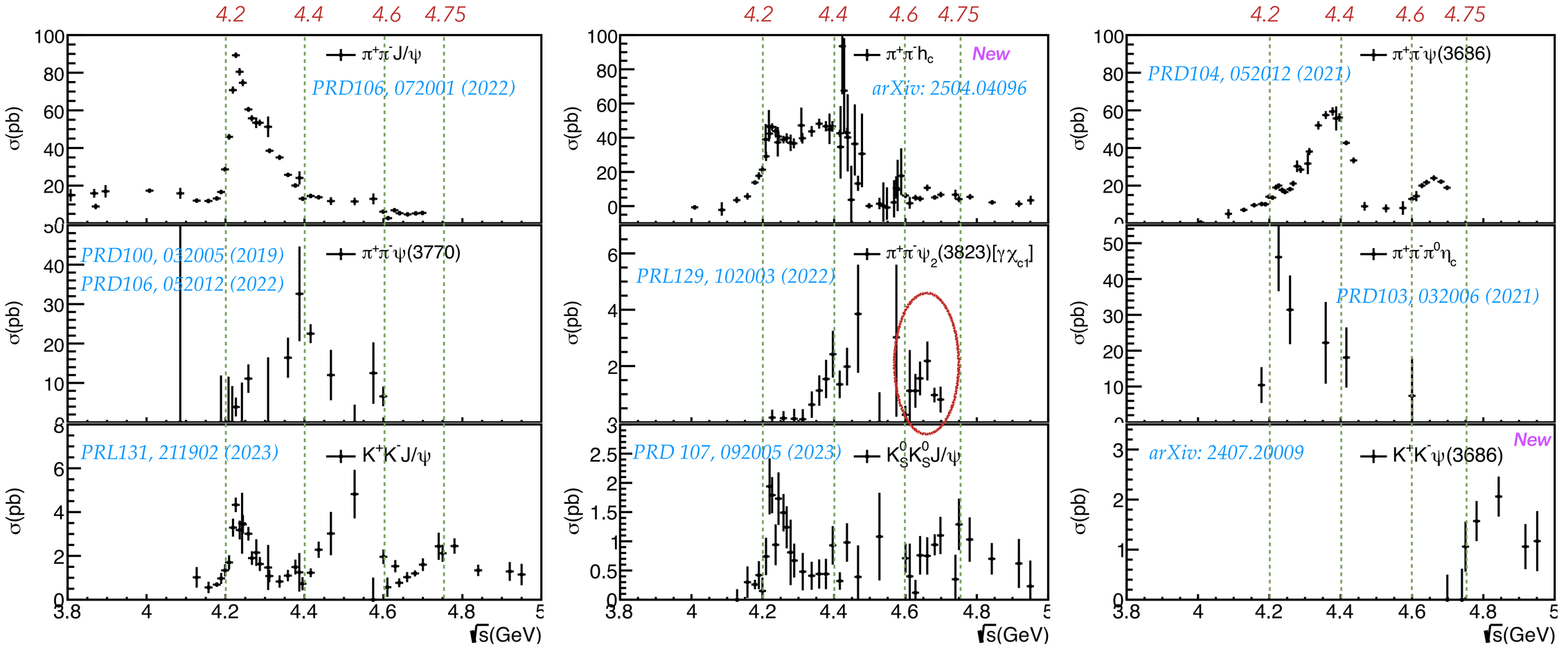

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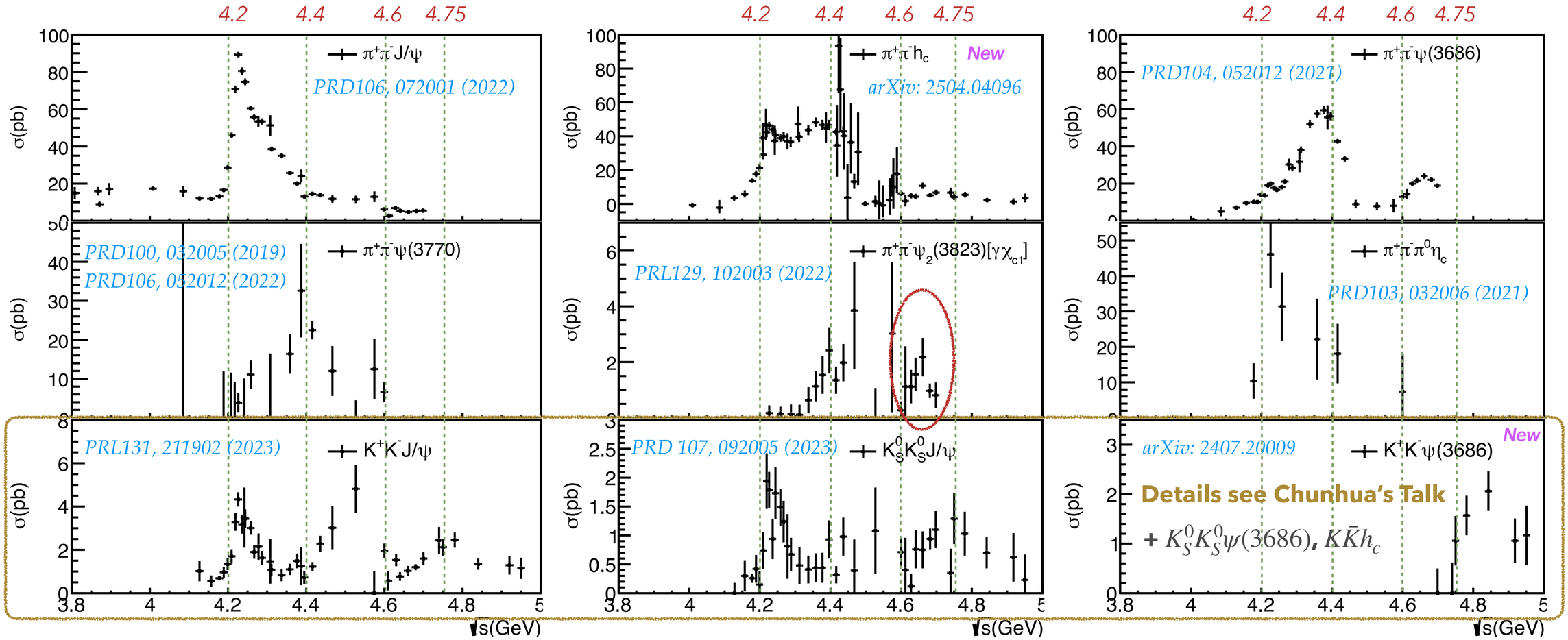

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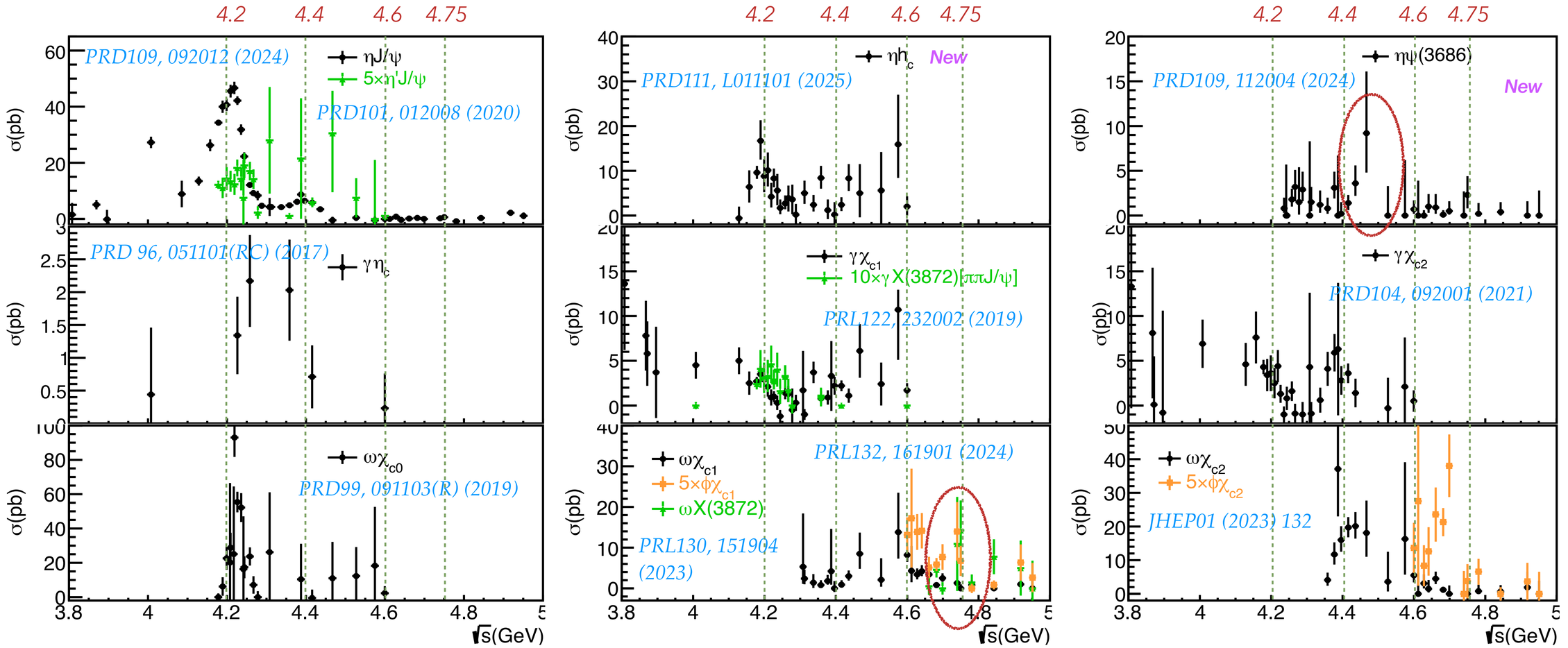
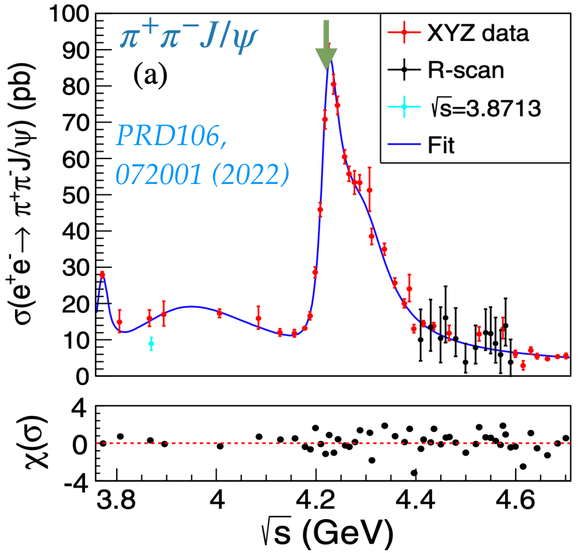
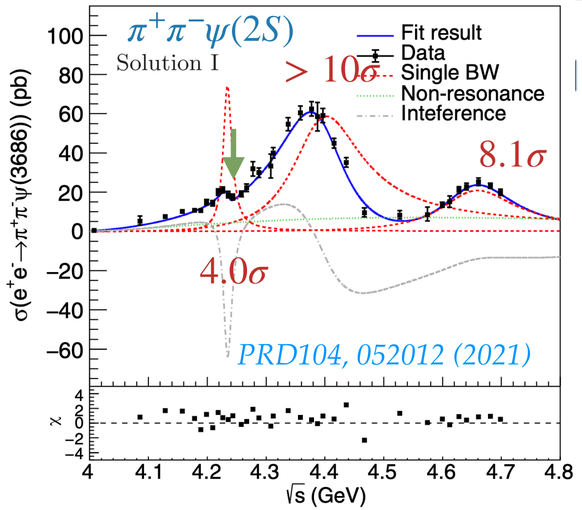
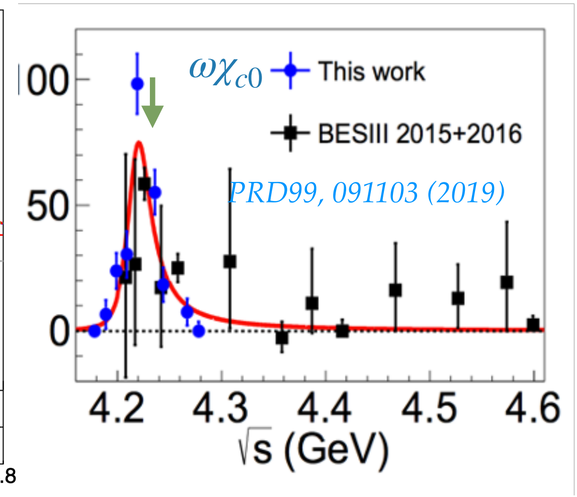


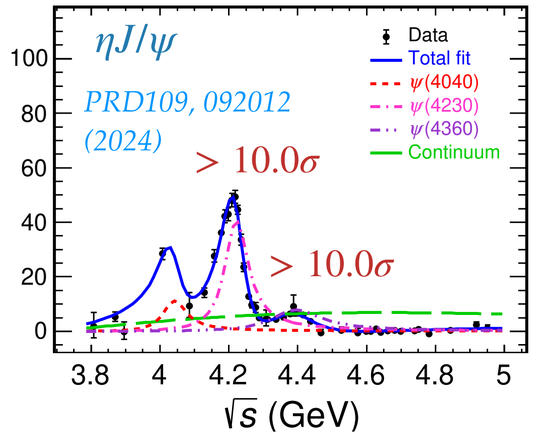
Y(4260)⇒Y(4230)

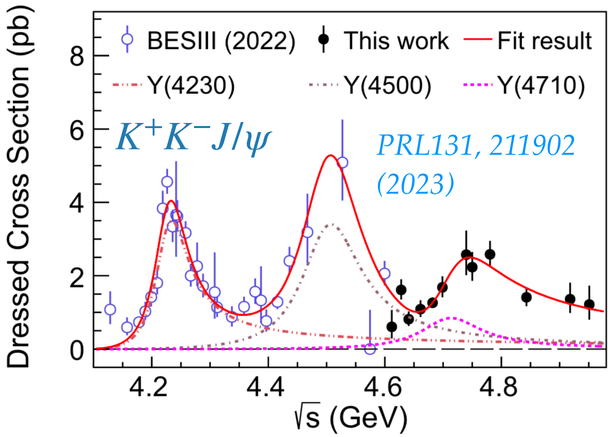
- Seen in more than 10 decay modes, including open charm final states

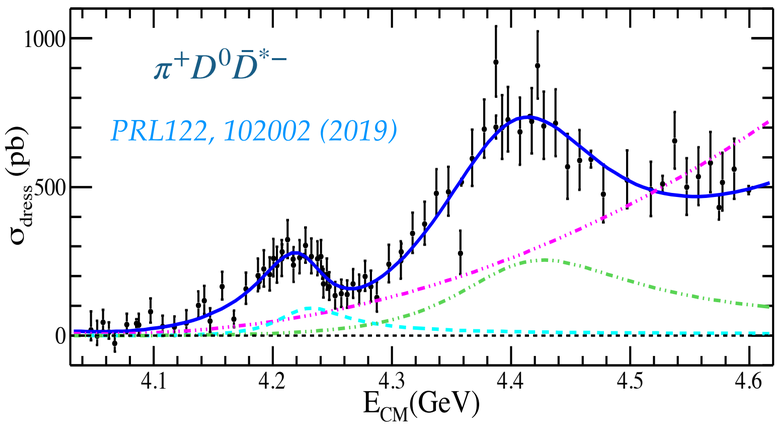


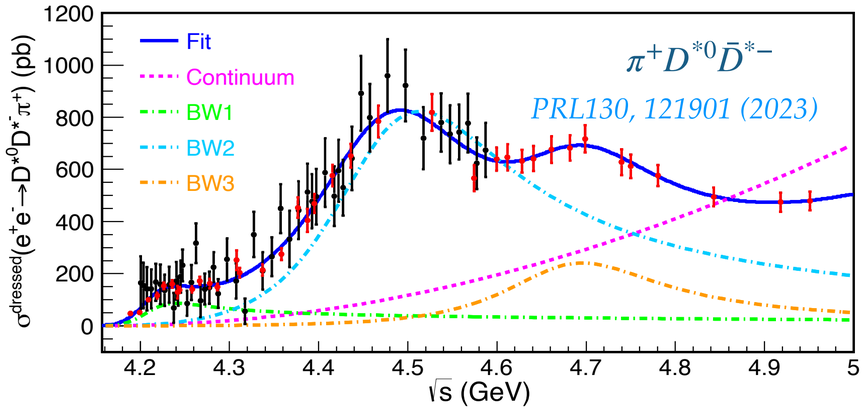












Y(4260)⇒Y(4230)

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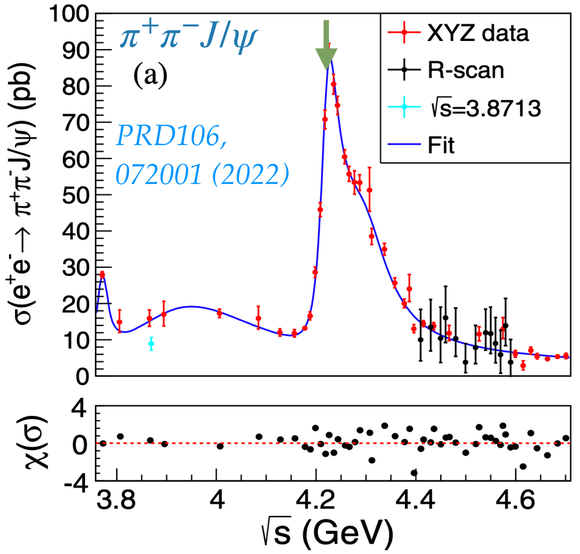
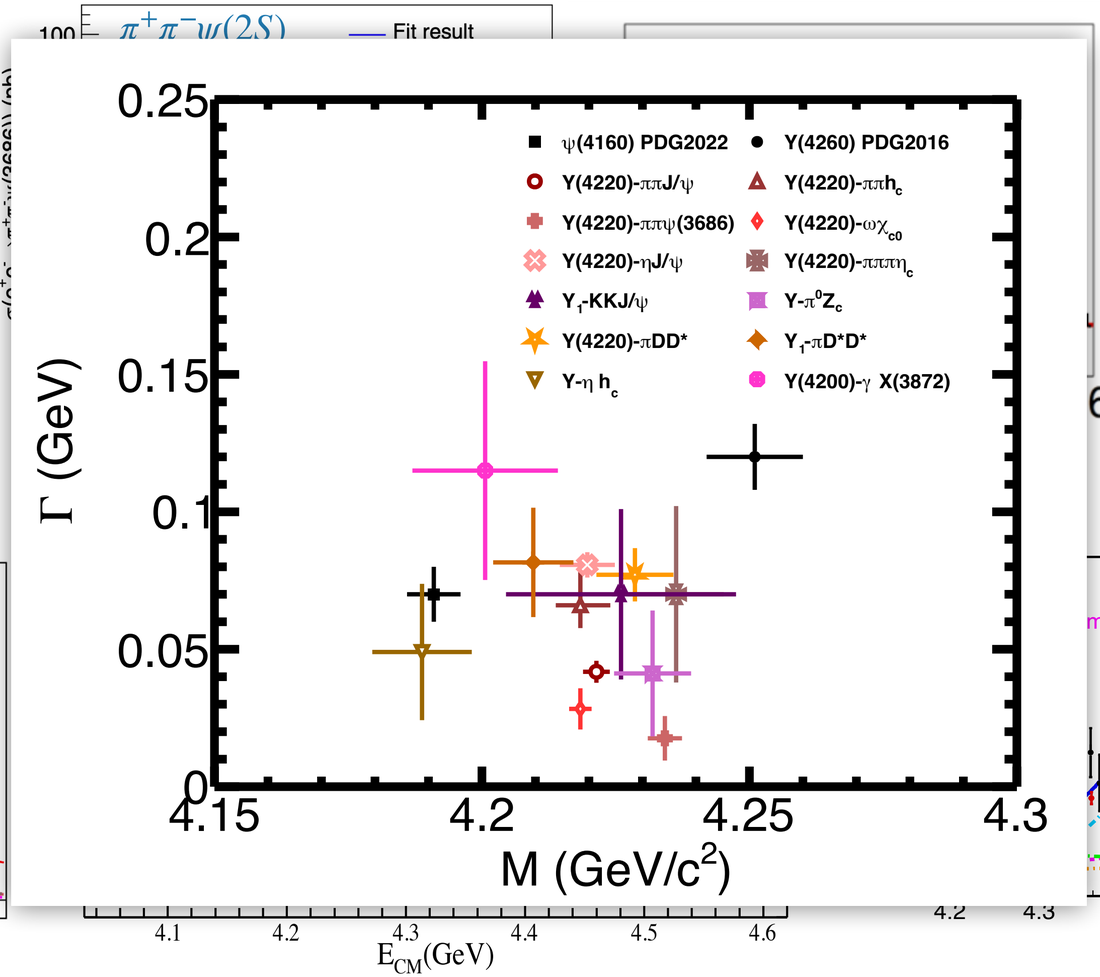
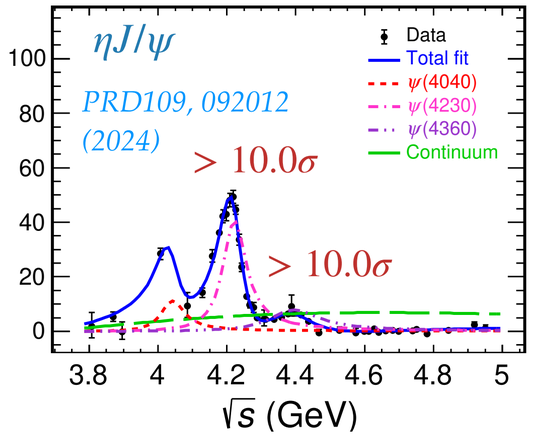
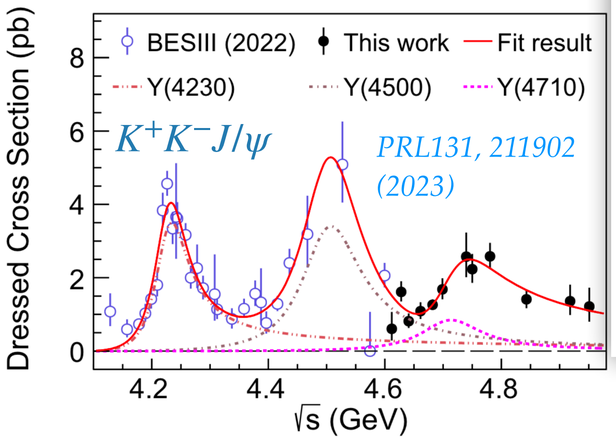
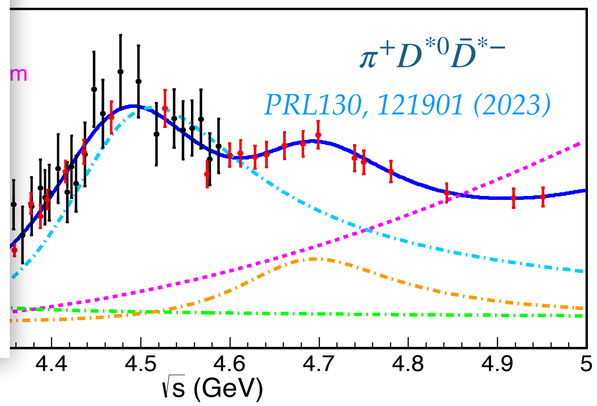




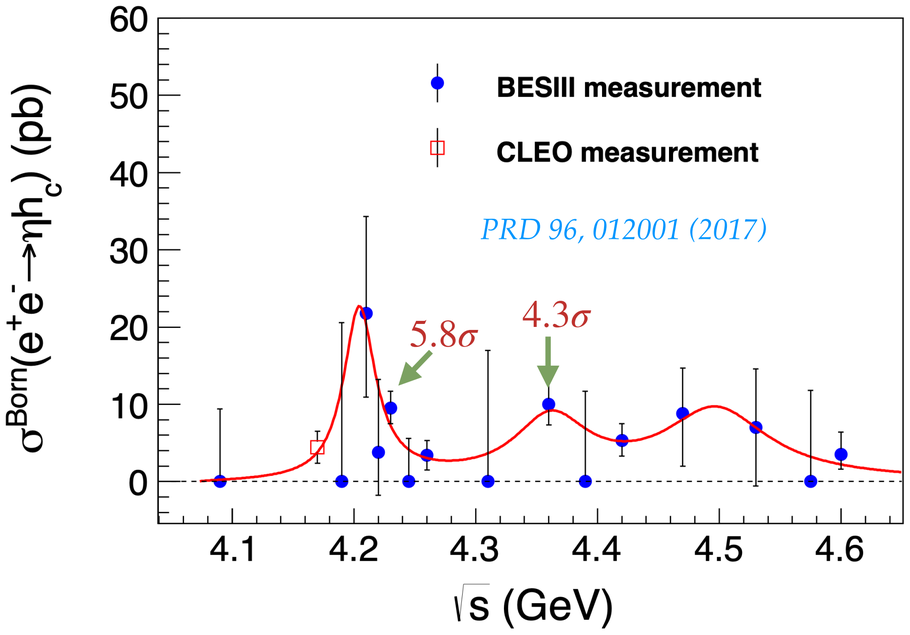




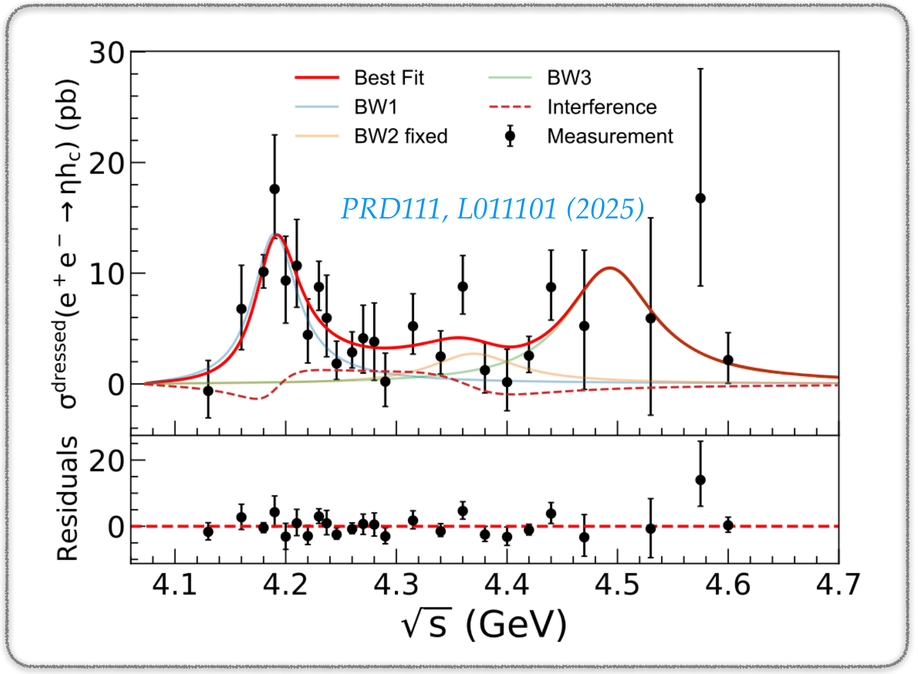


Update of $\sigma[e^+e^- \to \eta h_c]$

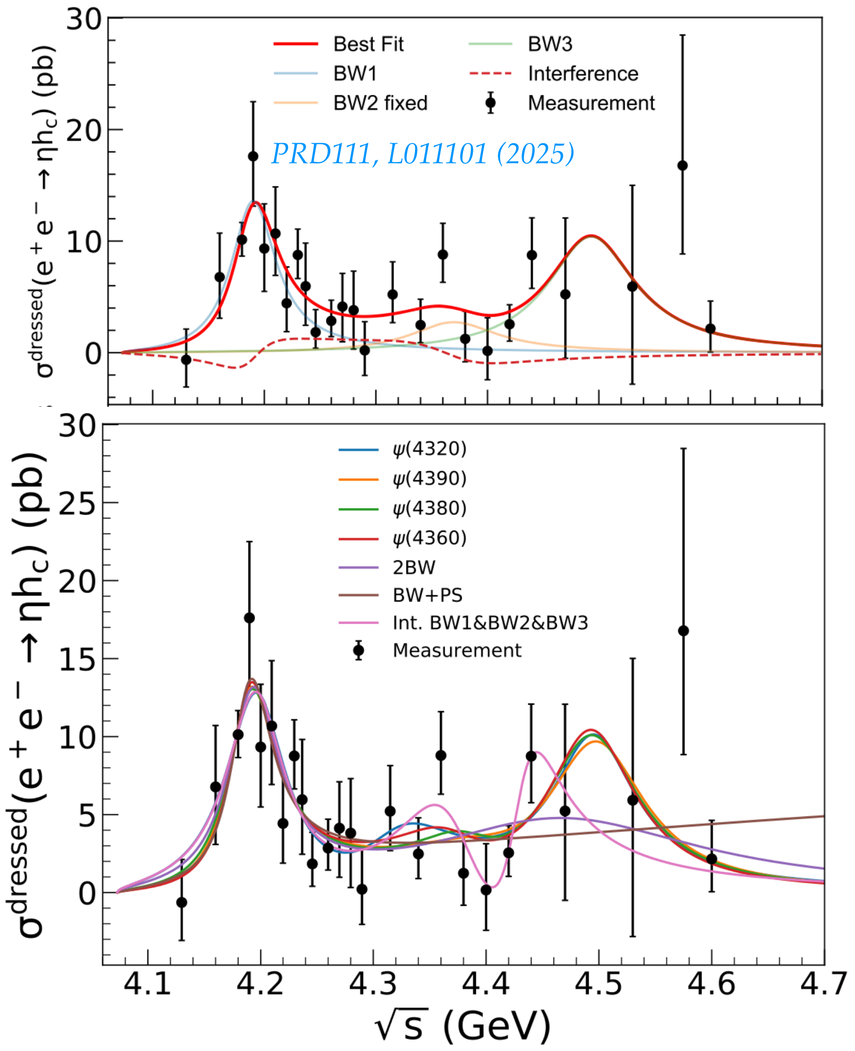
- The first evidence of $e^+e^- \to \eta h_c$ was found by CLEO at $\sqrt{s}$=4.17 GeV $[3\sigma]$ *PRL 107, 041803 (2011)*
- The process $e^+e^- \to \eta h_c$ was observed for the first time at $\sqrt{s}$=4.226 GeV by BESIII, a hint of a resonance around 4.2 GeV was observed *PRD 96, 012001 (2017)*
- New data (15 fb^{-1}) between $\sqrt{s}$=4.13 to 4.6 GeV has been collected by BESIII



⇒



Update of $\sigma[e^+e^- \to \eta h_c]$

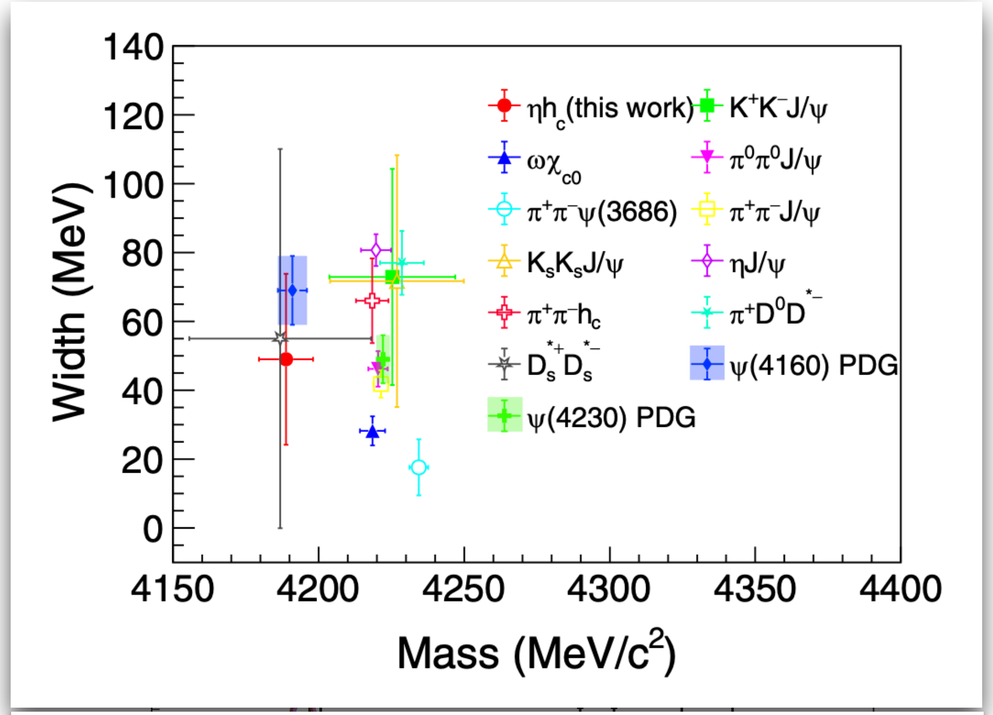


- $\sigma^{\text{dressed}} = |BW_1 + BW_2 e^{i\phi}|^2 + |BW_3|^2$
  - Mass and Width of BW_2 fixed to $Y(4360)$
  - $M_1 = 4188.8 \pm 4.7 \pm 8.0$ MeV/c^2

    $\Gamma_1 = 49 \pm 16 \pm 19$ MeV

    $\Gamma_{ee}\mathcal{B} = 0.80 \pm 0.19 \pm 0.45$ eV
  - Alternative parameterizations:
    - Fix parameters of the second resonance to $Y(4320)/Y(4380)/Y(4390)$
    - Remove BW_2
    - Use sum of a BW and phase space
    - Coherent sum of three BWs
    - Statistical significance of BW_1 in all cases >7σ

Update of $\sigma[e^+e^- \to \eta h_c]$



The first resonance:

- ☆ **Parameters consistent with** $\psi(4160)$
- ☆ Mass consistent with hybrid with a mass of (4.15 ± 0.15) GeV/c^2

PRD92, 114019 (2015)

- $\sigma^{\text{dressed}} = |BW_1 + BW_2 e^{i\phi}|^2 + |BW_3|^2$
  - Mass and Width of BW_2 fixed to $Y(4360)$
  - $M_1 = 4188.8 \pm 4.7 \pm 8.0$ MeV/c^2

    $\Gamma_1 = 49 \pm 16 \pm 19$ MeV

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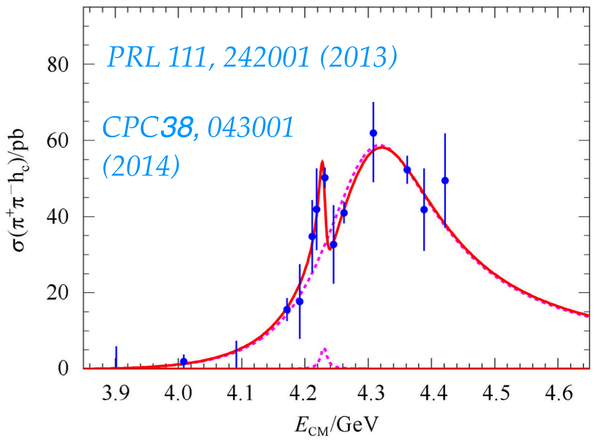
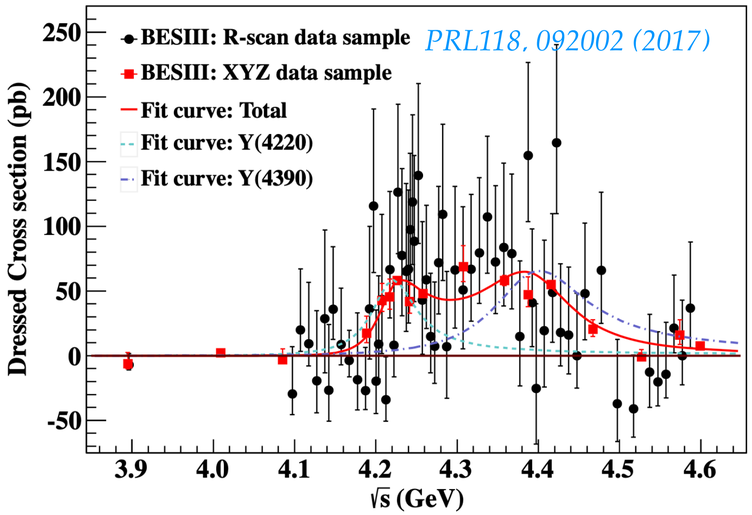
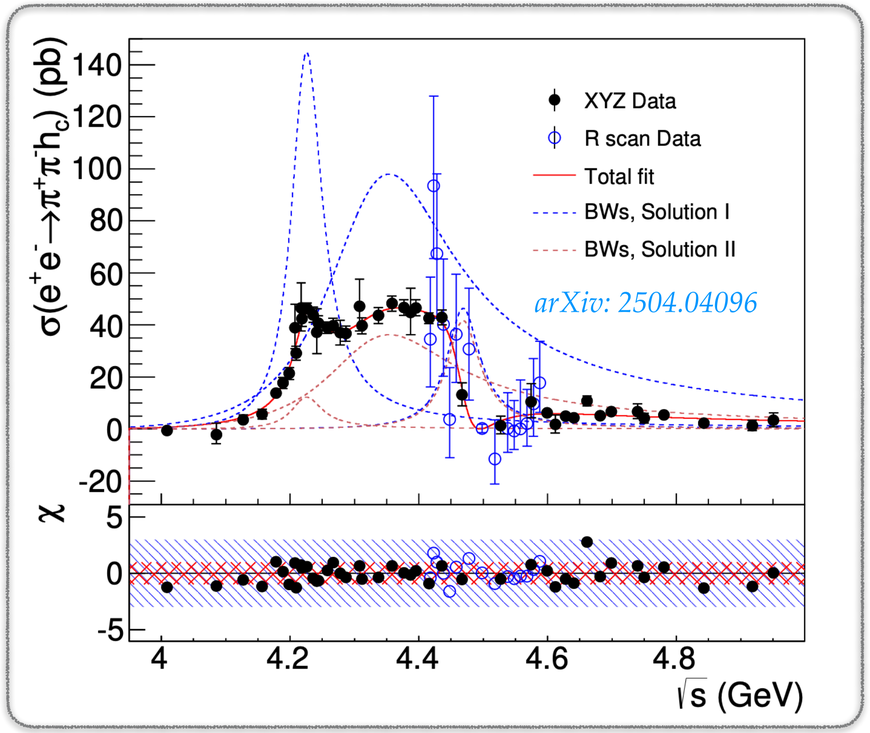
    - Coherent sum of three BWs
    - Statistical significance of BW_1 in all cases >7σ

Update of $\sigma[e^+e^- \to \pi^+\pi^- h_c]$

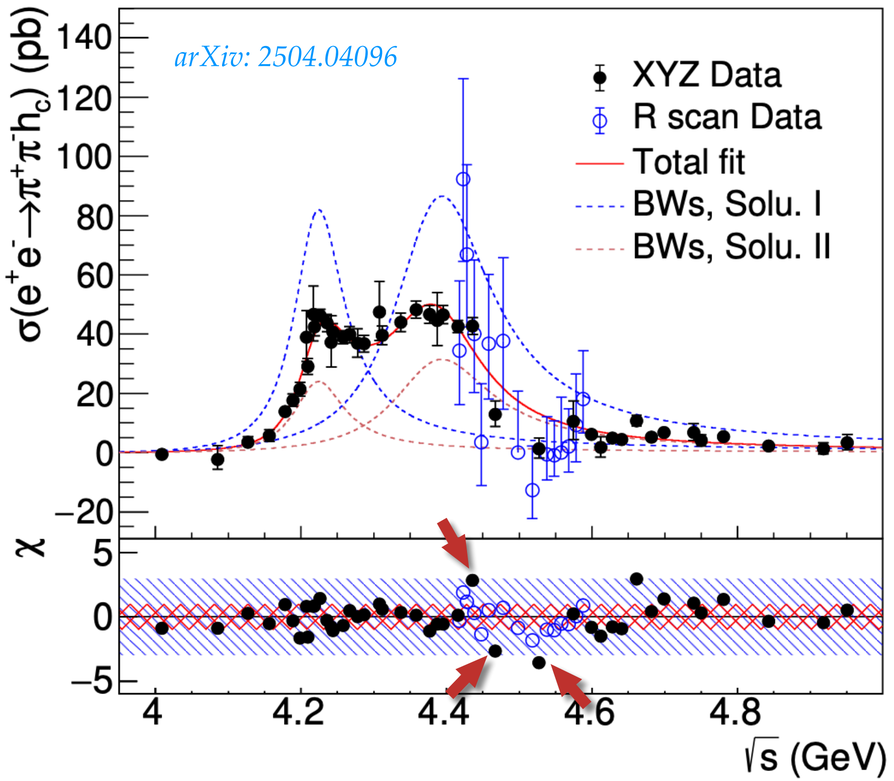
- The $e^+e^- \to \pi^+\pi^- h_c$ process was observed by CLEO at $\sqrt{s}$=4.17 GeV $[10\sigma]$ *PRL107, 041803 (2011)*
- The cross section of $e^+e^- \to \pi^+\pi^- h_c$ was measured by BESIII at $\sqrt{s}$ from 3.9 to 4.6 GeV, two resonant structures was observed *PRL118, 092002 (2017)*
- New data (27 data samples) between $\sqrt{s}$=4.18 to 4.95 GeV has been collected by BESIII





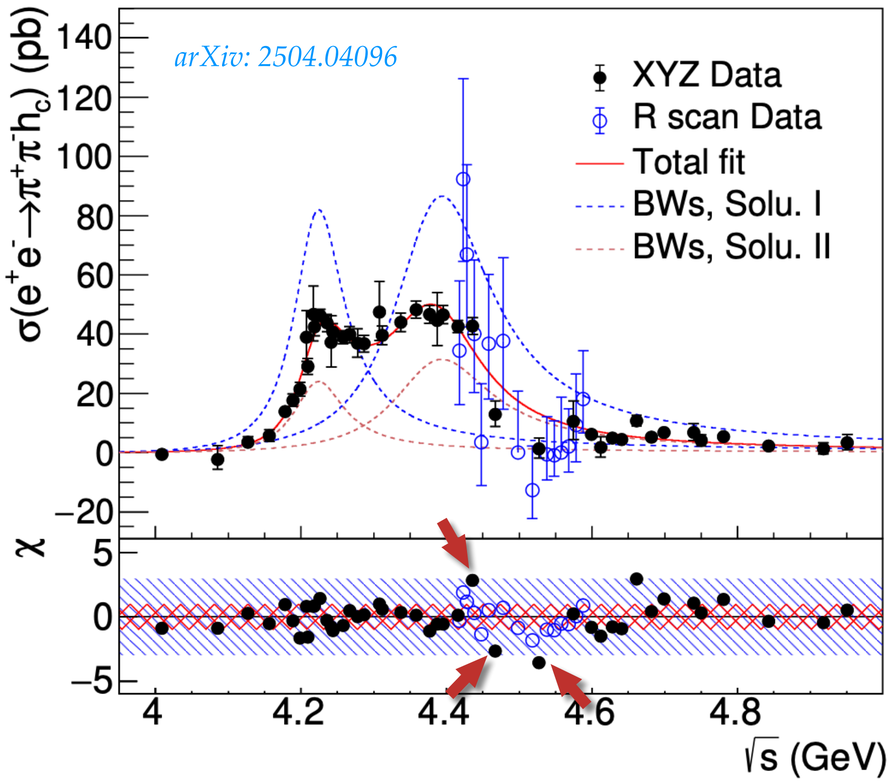


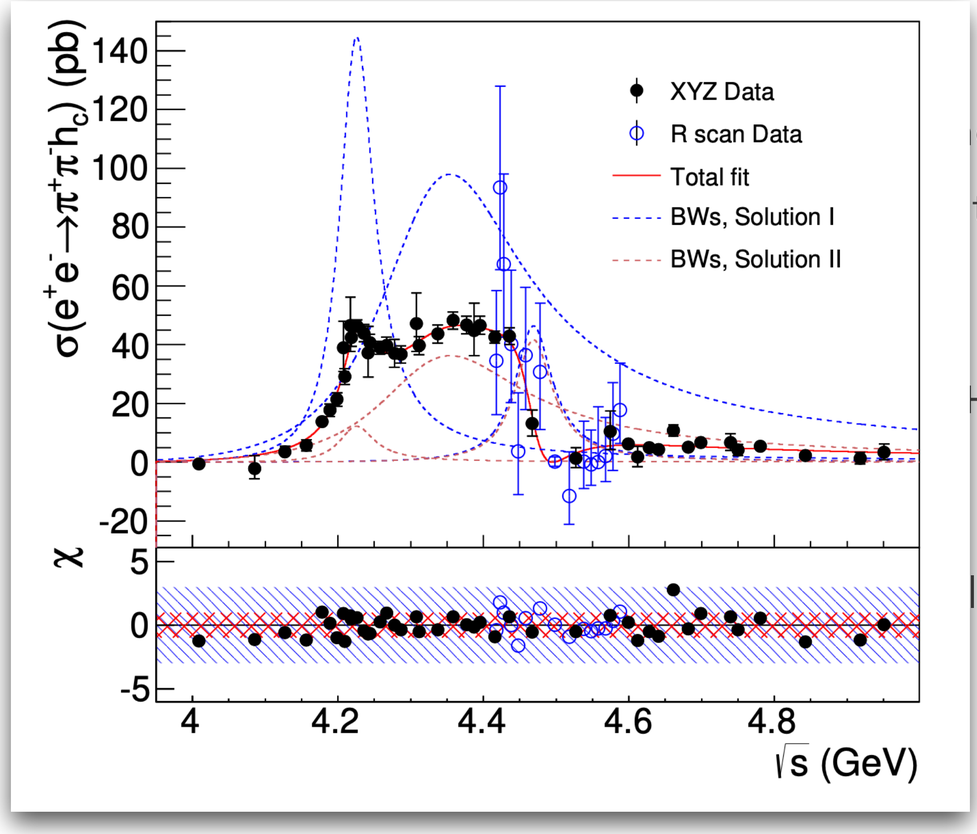
Update of $\sigma[e^+e^- \to \pi^+\pi^- h_c]$



- Test of resonance structures:
  - Starting with two coherent BWs, add one more BW, two more BWs, one more BW and a continuum termt
  - Check significance of each addtional term
  - Baseline model: $\sigma^{\text{dressed}} = |BW_1 + BW_2 e^{i\phi_2} + BW_3 e^{i\phi_3}|^2$
  - Significance of the third resonance: 5.4σ
  - Significance of addtional contribution smaller than 1σ

Update of $\sigma[e^+e^- \to \pi^+\pi^- h_c]$





ore BW, two

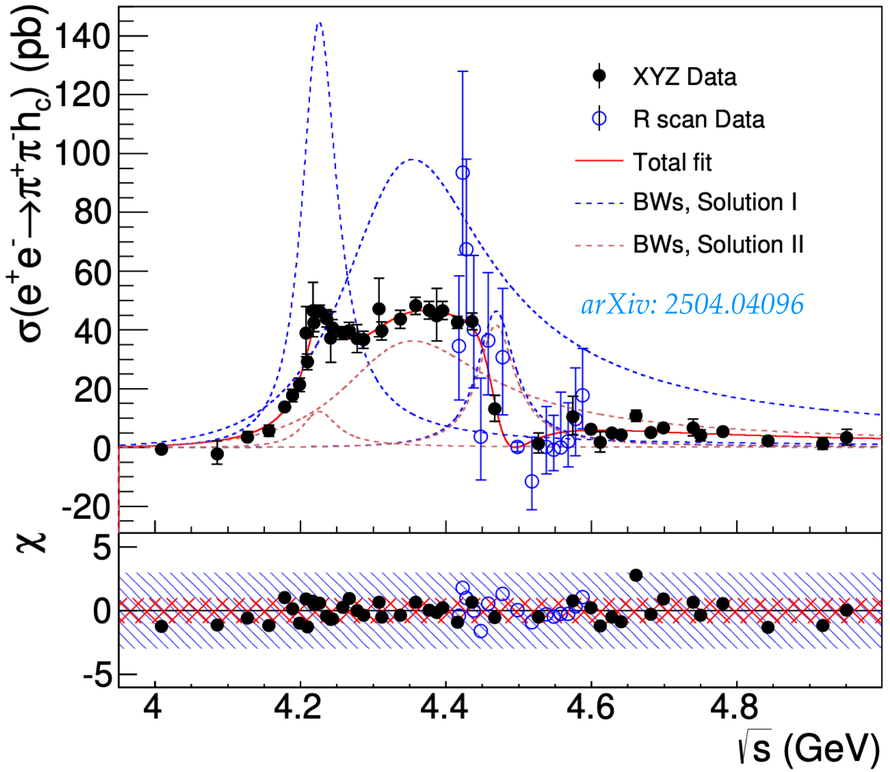
termt

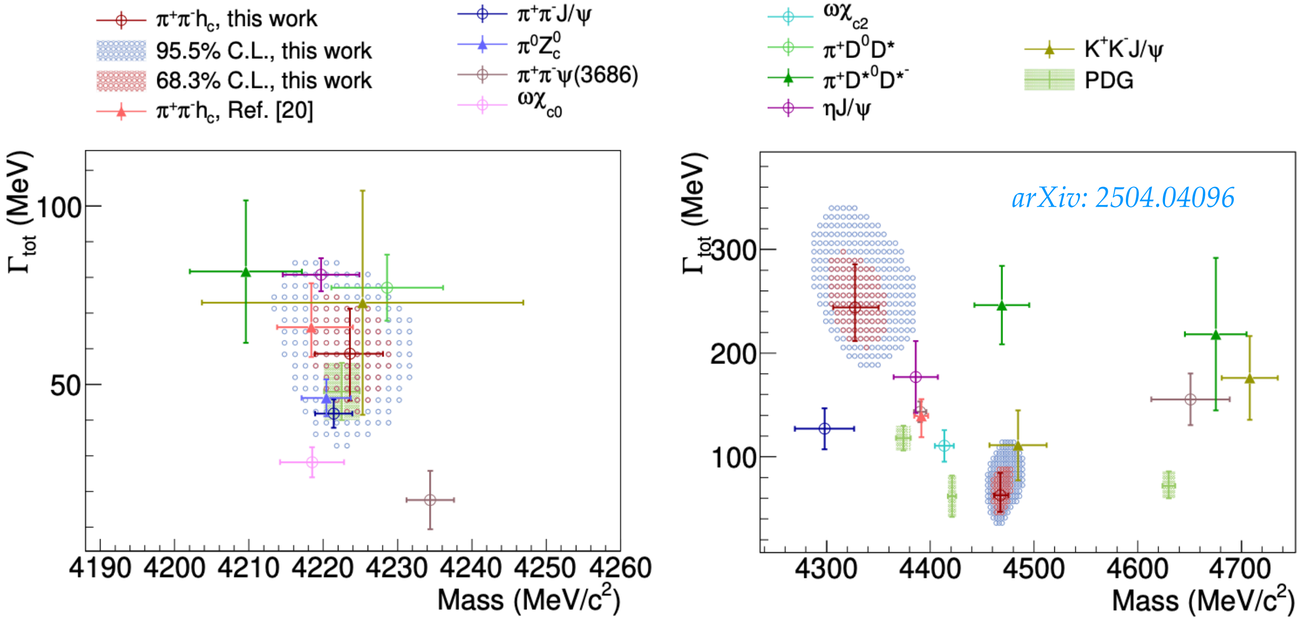
$- BW_3 e^{i\phi_3}|^2$

ler than 1σ

Cannot be described by two coherent BWs

Update of $\sigma[e^+e^- \to \pi^+\pi^- h_c]$

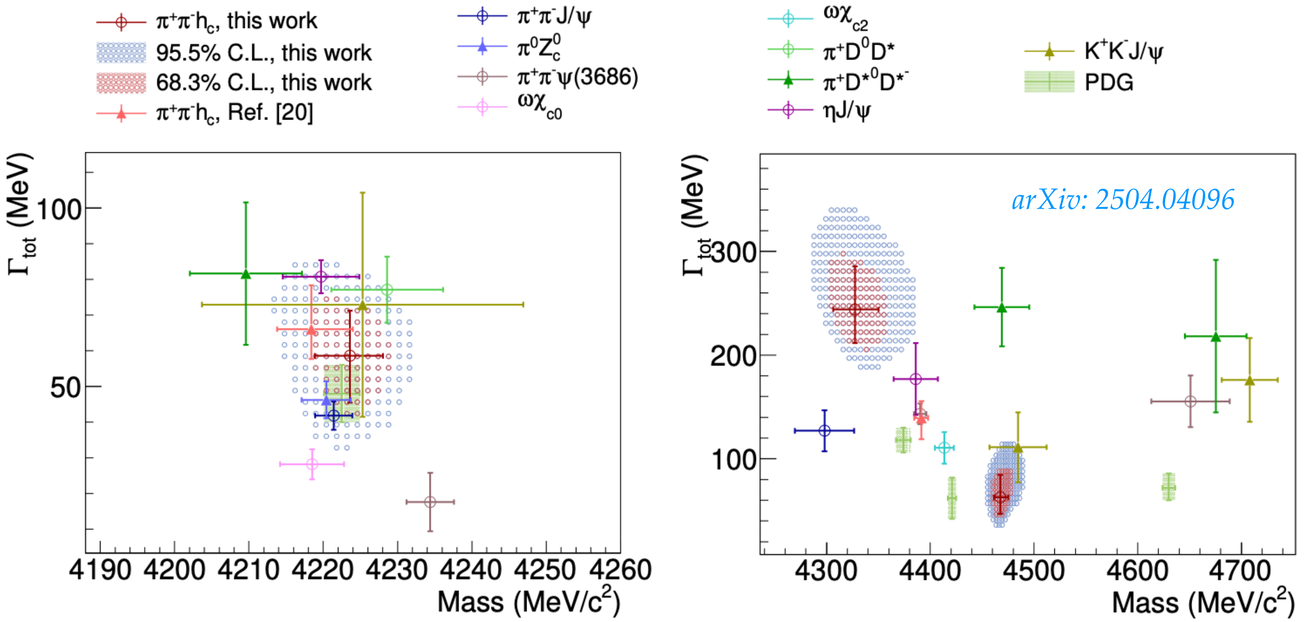




Resonance	Parameter	this measurement (3BW)	this measurement (2BW)	previous measurement
R_1	M (MeV/c^2)	$4223.6^{+3.6+2.6}_{-3.7-2.9}$	4219.7 ± 3.4	$4218.4 \pm 4.0 \pm 0.9$
	$\Gamma_{\rm tot}$ (MeV)	$58.5^{+10.8+6.7}_{-11.4-6.5}$	83.8 ± 5.5	$66.0 \pm 9.0 \pm 0.4$
R_2	M (MeV/c^2)	$4327.4^{+20.1+10.7}_{-18.8-9.3}$	4382.6 ± 6.0	$4391.6 \pm 6.3 \pm 1.0$
	$\Gamma_{\rm tot}$ (MeV)	$244.1^{+34.0+23.9}_{-27.1-18.0}$	163.1 ± 10.4	$139.5 \pm 16.1 \pm 0.6$
R_3	M (MeV/c^2)	$4467.4^{+7.2+3.2}_{-5.4-2.7}$	–	4421 ± 4
	$\Gamma_{\rm tot}$ (MeV)	$62.8^{+19.2+9.8}_{-14.4-6.6}$	–	62 ± 20 (from PDG)
	χ^2/ndf	41.9/70	78.5/66	–

Update of $\sigma[e^+e^- \to \pi^+\pi^- h_c]$

- Parameters of R_1 consistent with previous measurement and $\psi(4230)$
- Mass of R_2 consistent with $\psi(4360)$, but width much broader
- Parameters of R_3 consistent with $\psi(4500)$, and a hybrid state *PRD107, 054034 (2023)*
- No obvious resonance structure is found at around $\psi(4660)$
- In $S-D$ mixing scheme, $4S-3D$, $5S-4D$ states are located in this mass region, only three stuctures are observed in this mode *PRD99, 114003 (2019)*
- Mass of R_2/R_3 compatible with $\psi(3D)$ *PRD100, 074016 (2019)*



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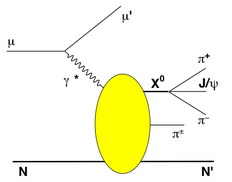
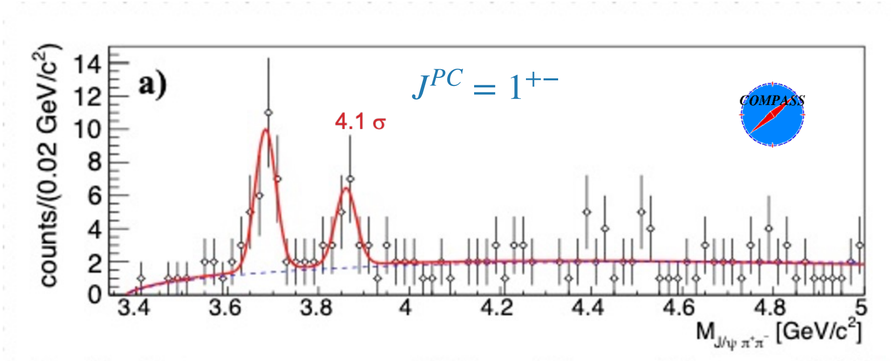
Search for $\tilde{X}(3872)$ in $e^+e^- \to \eta\tilde{X}$

- 8.9 fb^{-1} data sample from 4.288 to 4.951 GeV



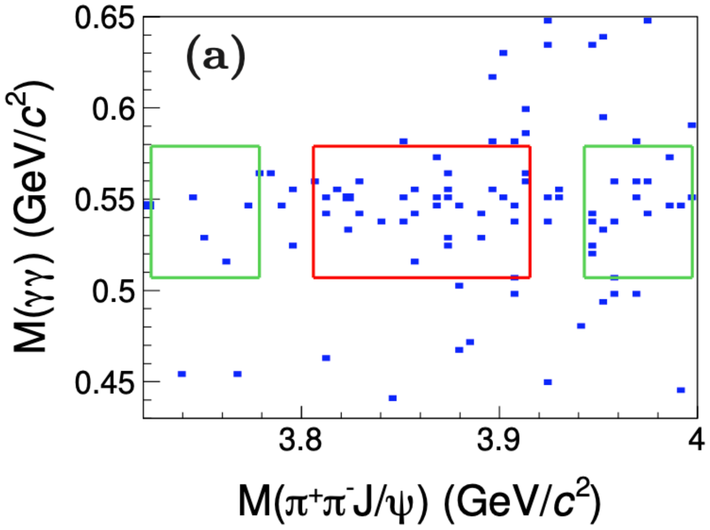
$\gamma^* N \to X[\to \pi^+\pi^- J/\psi]\pi^\pm N'$

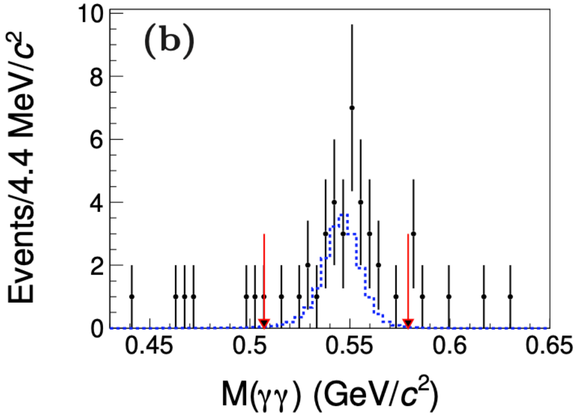
PLB 783, 334-340 (2018)

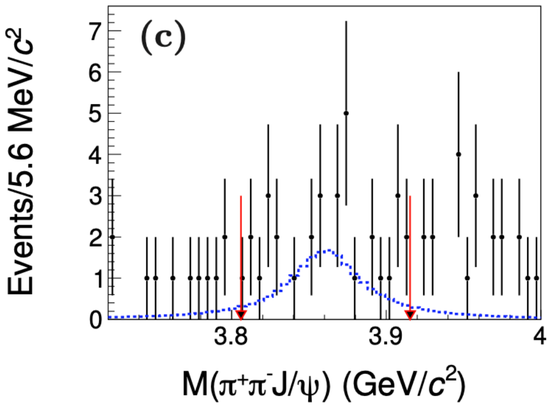


$[(3860.0 \pm 10.4)\ \mathrm{MeV}/c^2,\ \ < 51\ \mathrm{MeV}]$

PRD109, 112004 (2024)

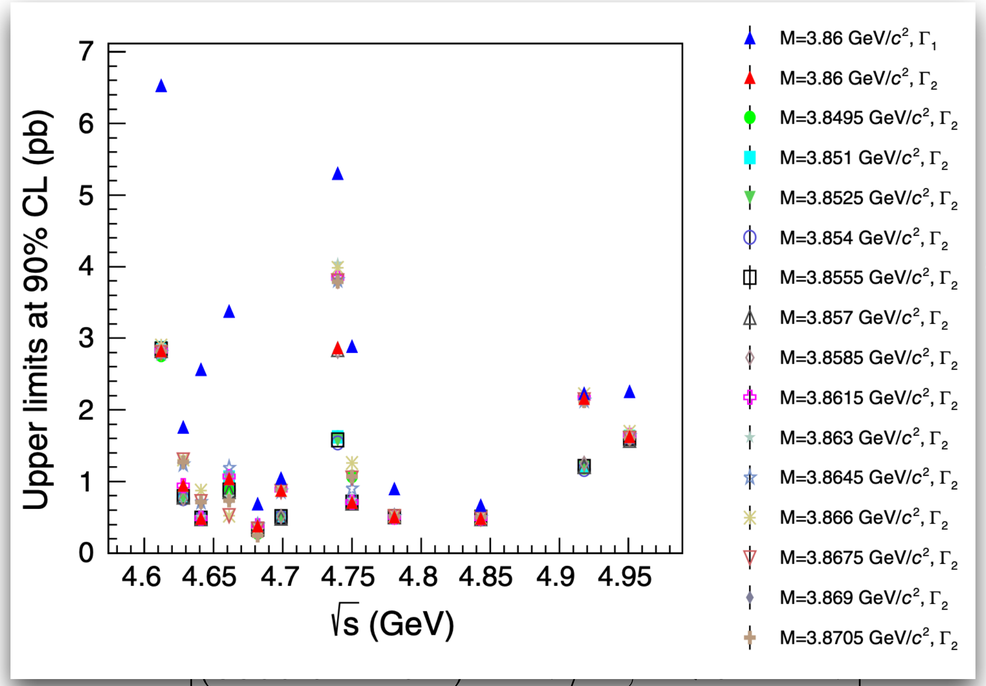






Search for $\tilde{X}(3872)$ in $e^+e^- \to \eta\tilde{X}$

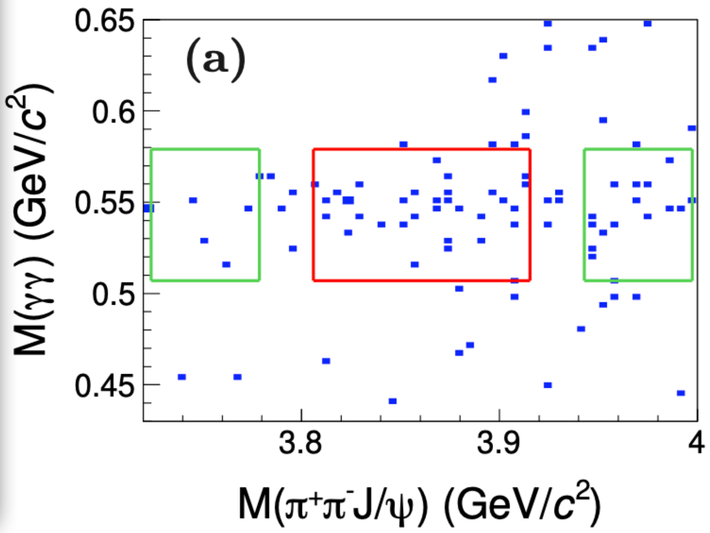
- 8.9 fb^{-1} data sample from 4.288 to 4.951 GeV

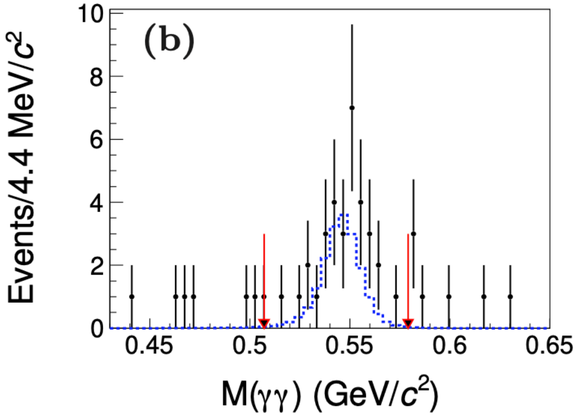


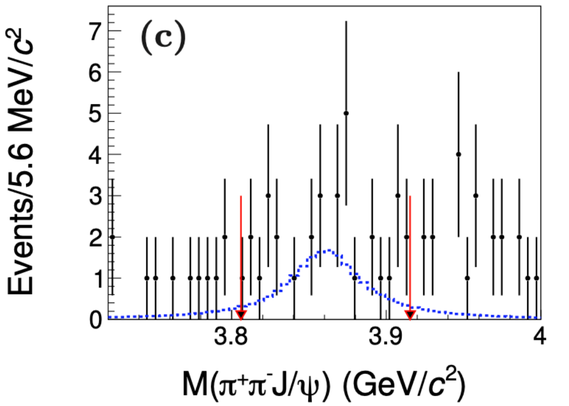
$\Gamma_1 = 51$ MeV, COMPASS U.L.

$\Gamma_2 = 1.19$ MeV, $X(3872)$

PRD109, 112004 (2024)



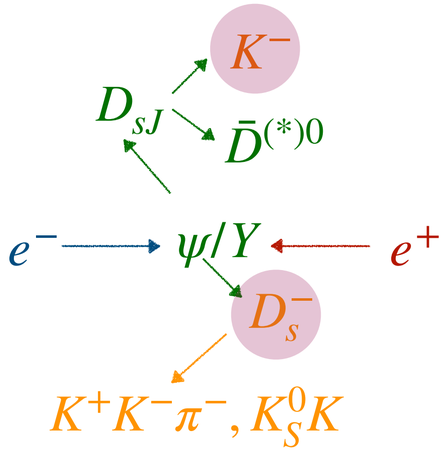




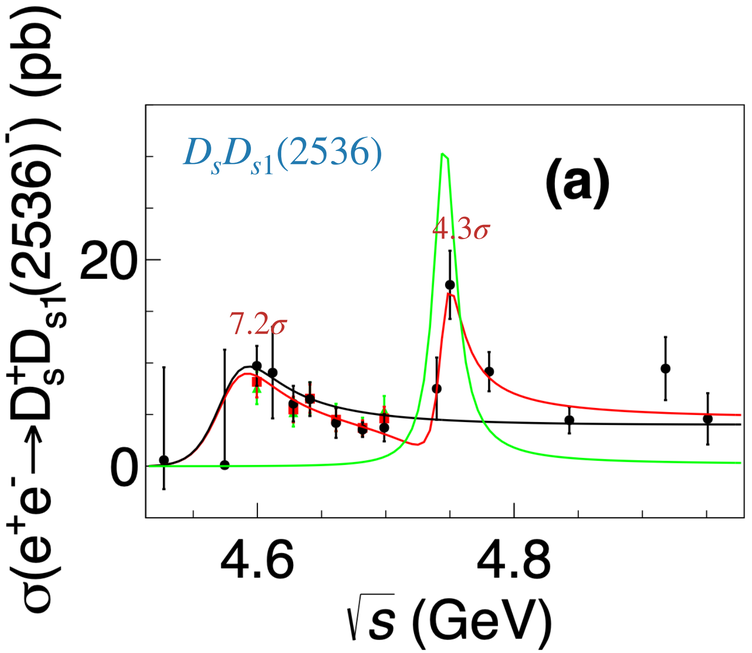
$e^+e^- \to D_sD_{s1}(2536)$ and $D_sD^*_{s2}(2573)$

- 15 data samples corresponding to a total integrated lum. of 6.6 fb^{-1} from $\sqrt{s}$=4.53 to 4.95 GeV

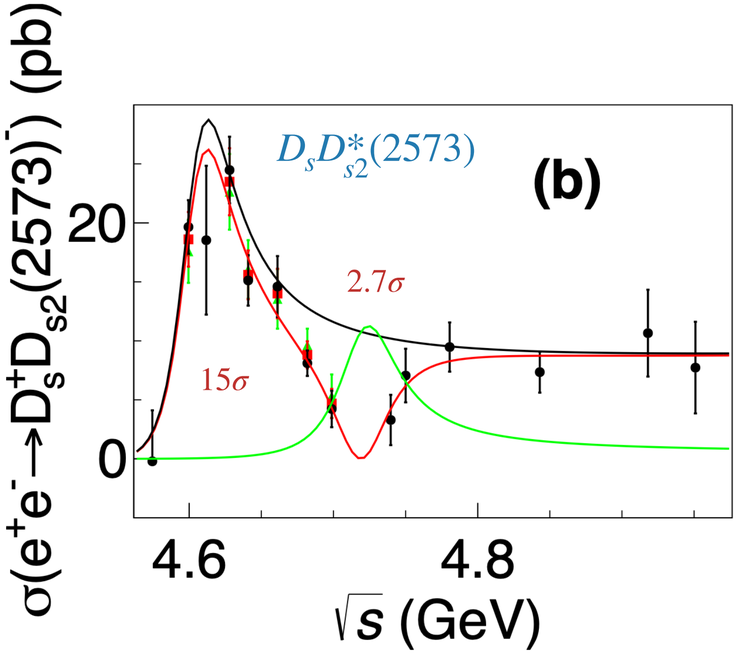
Partial reconstruction



PRL 133, 171903 (2024)



	R1	R2
Mass (MeV/c²)	4584[14, 68]	4749.9[8.2, 6.7]
Width (MeV)	57[12, 211]	24.9[8.0, 7.8]

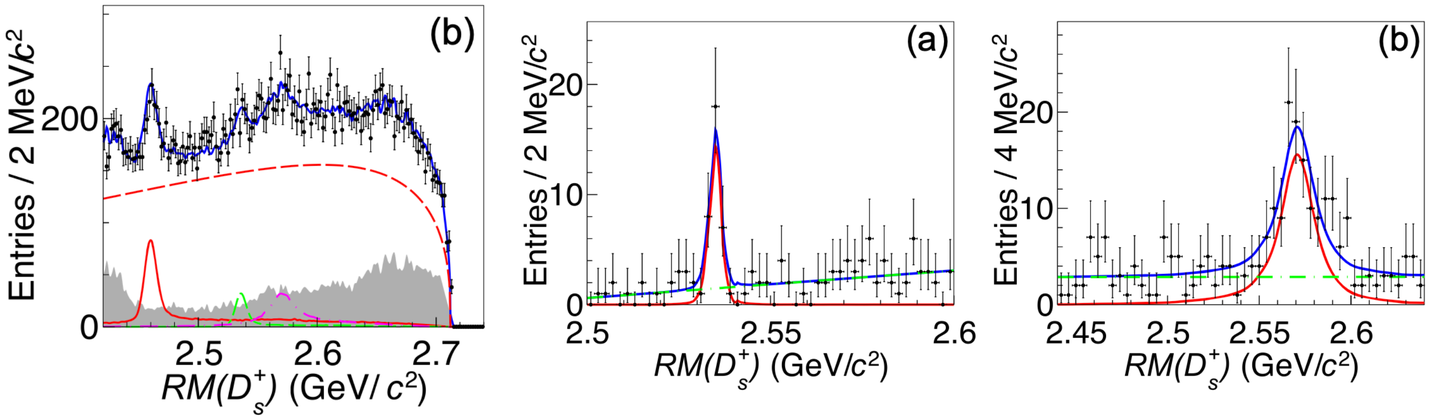


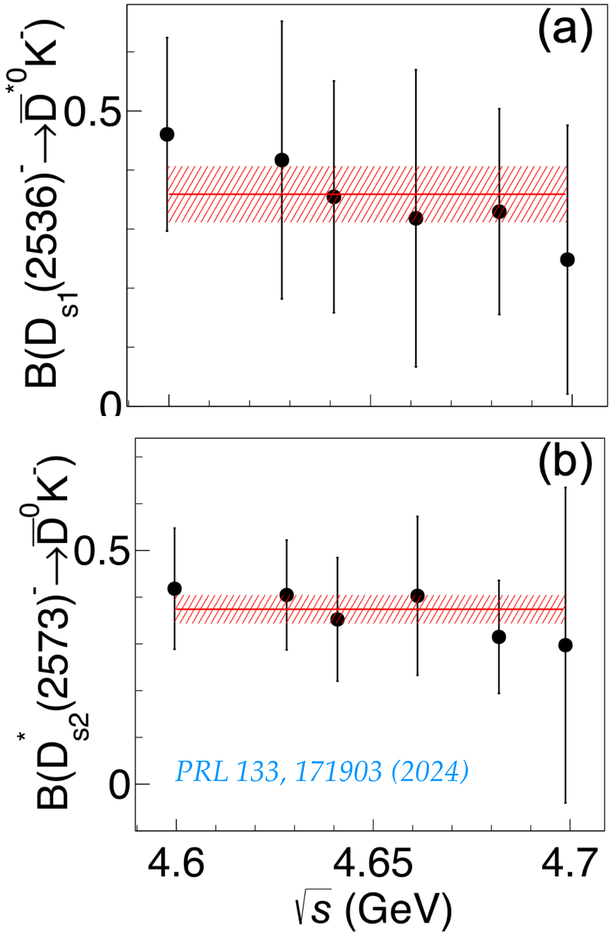
	R1	R2
Mass (MeV/c²)	4603.1[3.9, 0.8]	4720[13, 2]
Width (MeV)	45.2[5.7, 0.7]	50[12, 1]

Decay Property of $D_{s1}(2536)$ and $D^*_{s2}(2573)$

- ML fit to the exclusive and inclusive CS: $L_i(\sigma^{\rm inc}_{i,j}, \delta^{\rm inc}_{i,j}, \sigma^{\rm exc}_{i,j}, \delta^{\rm exc}_{i,j}; \sigma_{i,j}, B_i) = \Pi^6_{j=1} L^{\rm inc}_{i,j} L^{\rm exc}_{i,j}$
- The absolute branching fractions are:
  - $B(D_{s1}(2536)^- \to \bar{D}^{*0}K^-) = (35.9 \pm 4.8 \pm 3.5)\,\%$
  - $B(D_{s2}(2573)^{*-} \to \bar{D}^0 K^-) = (37.4 \pm 3.1 \pm 4.6)\,\%$
  - In tension with predictions based on the assumption that they are dominated by a bare $c\bar{s}$ component

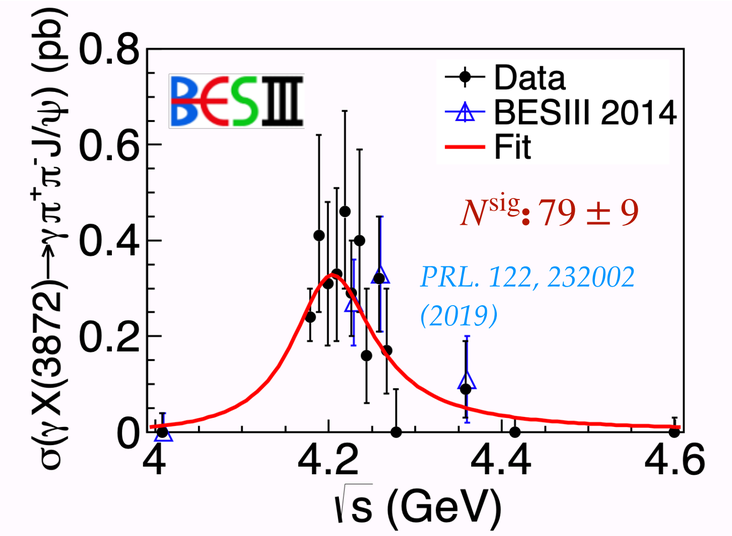
PRD93, 034035 (2016); PRL 128, 112001 (2022)

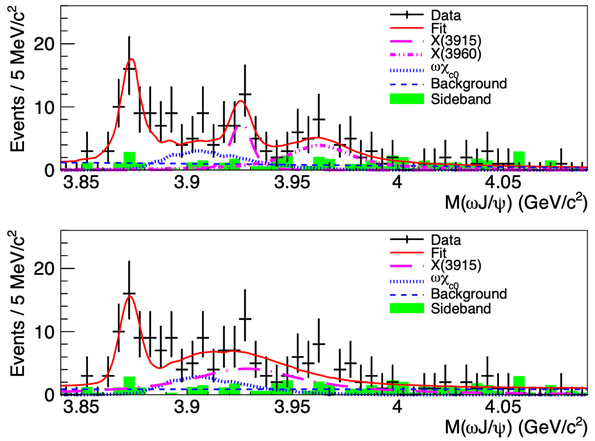




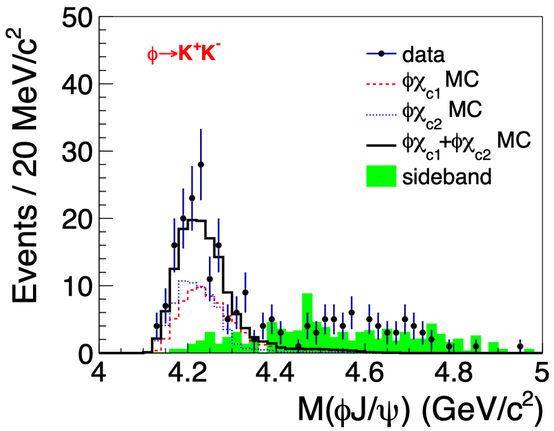
C-even States

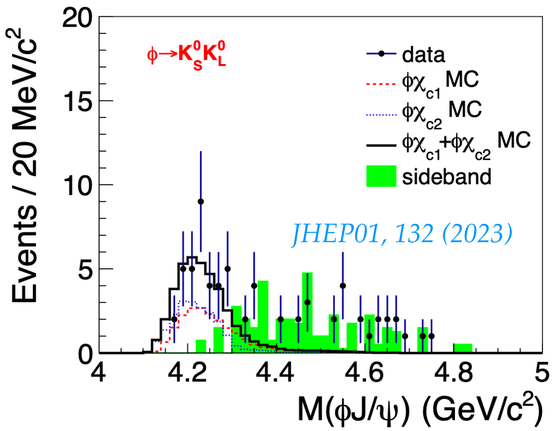
- Small production rate in radiative transition process
- Radiative and hadronic transitions to X(3872) are observed at BESIII
- Several decay modes of X(3872) have been searched: $\pi^0\chi_{c1}$ [observed], $\pi\pi\chi_{c0,1,2}$, $\pi\chi_{c0,2}$, $\pi\pi\eta$, $\gamma\psi_2(3823)$ [not found]
- Found evidence of X(3915)/X(3960) [$\omega J/\psi$ mode] , no obvious signal for X(4140), X(4274), X(4500) [$\phi J/\psi$ mode], no evidence of $X_2(4013)$ [$D\bar{D}$ mode]





PRL 122, 232002 (2019)





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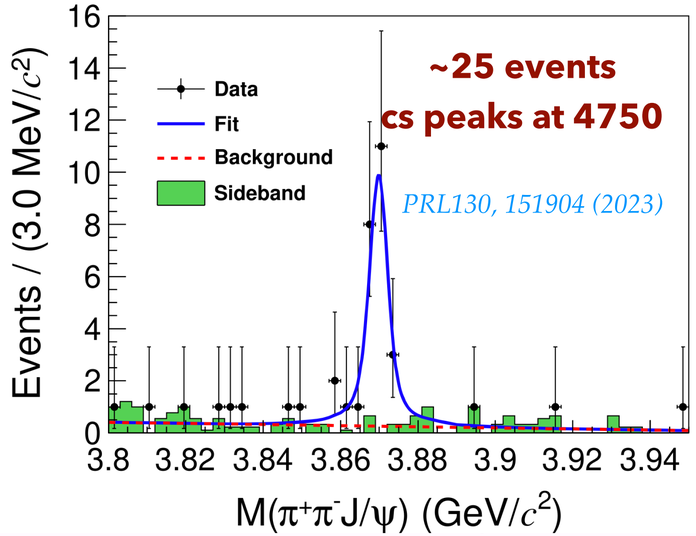
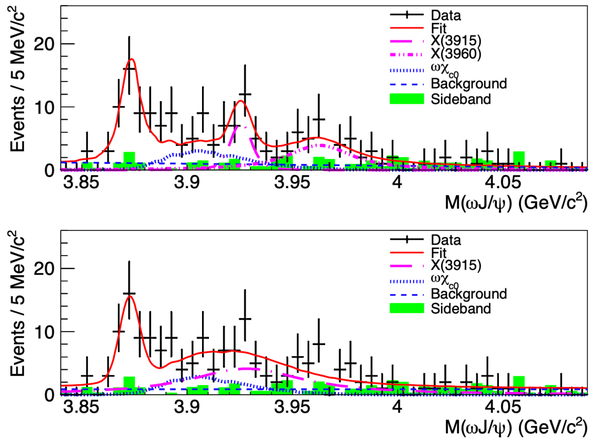
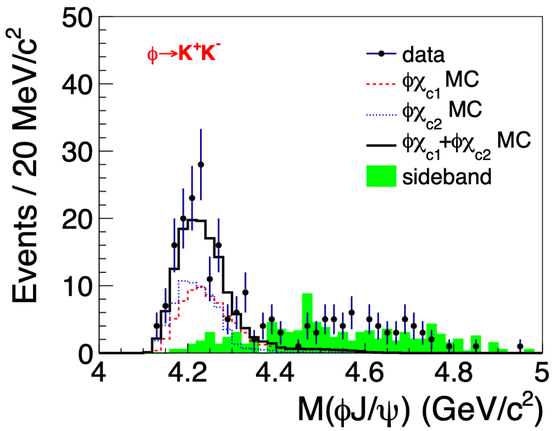
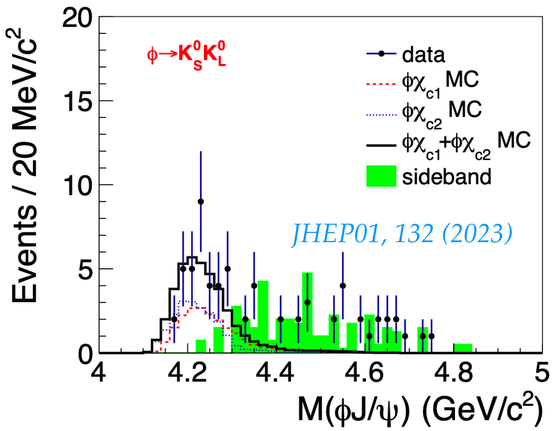
- Found evidence of X(3915)/X(3960) [$\omega J/\psi$ mode] , no obvious signal for X(4140), X(4274), X(4500) [$\phi J/\psi$ mode], no evidence of $X_2(4013)$ [$D\bar{D}$ mode]





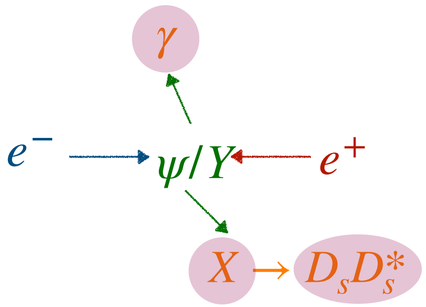
PRL 122, 232002 (2019)



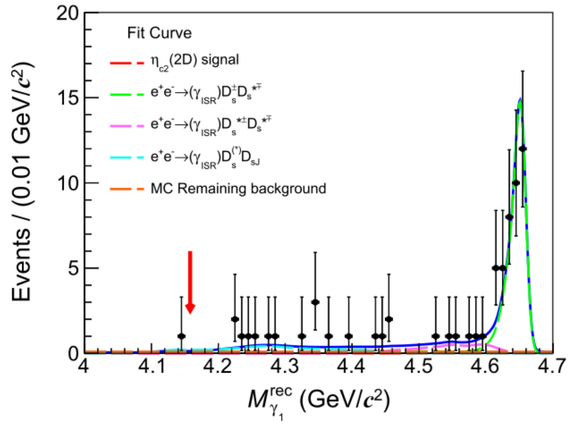


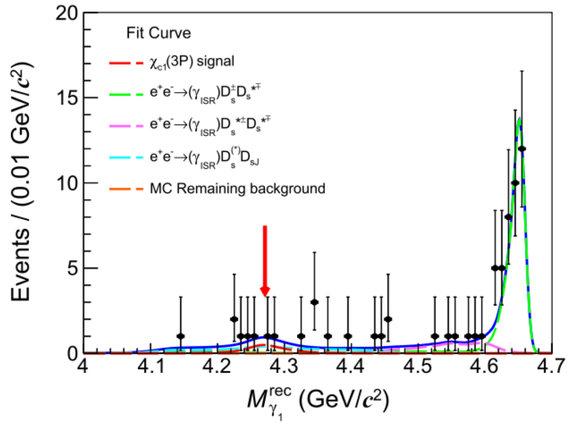
C-even States in $e^+e^- \to \gamma D_s^{\pm} D_s^{*\mp}$

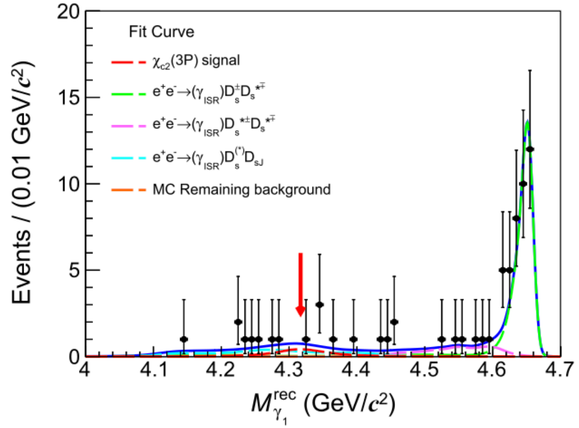
- Full reconstruction method, $D_s^* \to \gamma D_s$, $D_s \to K^+K^-\pi, K_S^0 K$, 4680 data sample

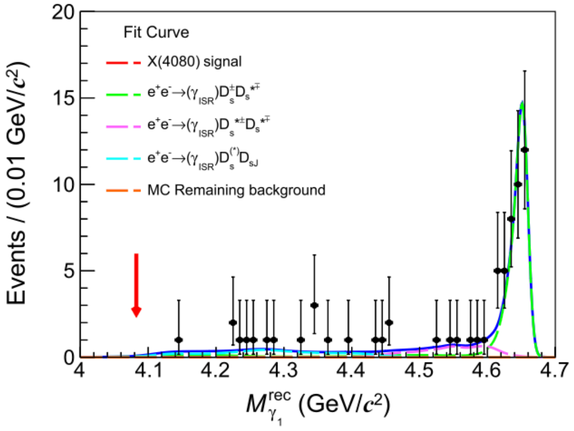


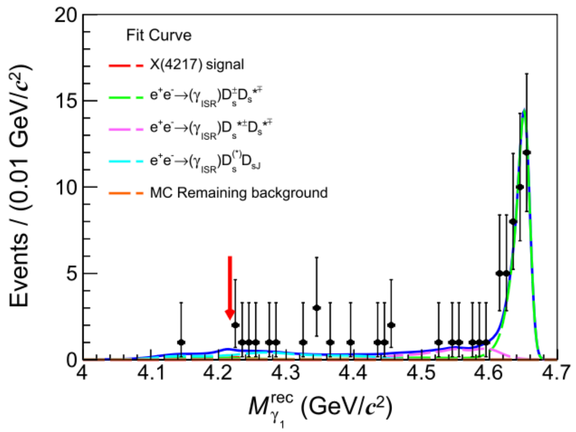
State	J^{PC}
$\eta_{c2}(2D)$ [4]	2^{-+}
$\chi_{c1}(3P)$ [4]	1^{++}
$\chi_{c2}(3P)$ [4]	2^{++}
$X(4080)$ [9]	1^{++}
$X(4217)$ [10–12]	1^{-+}
$X(4279)$ [10–12]	0^{-+}

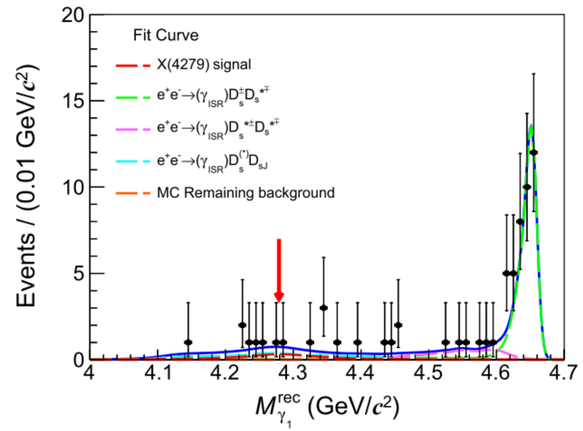










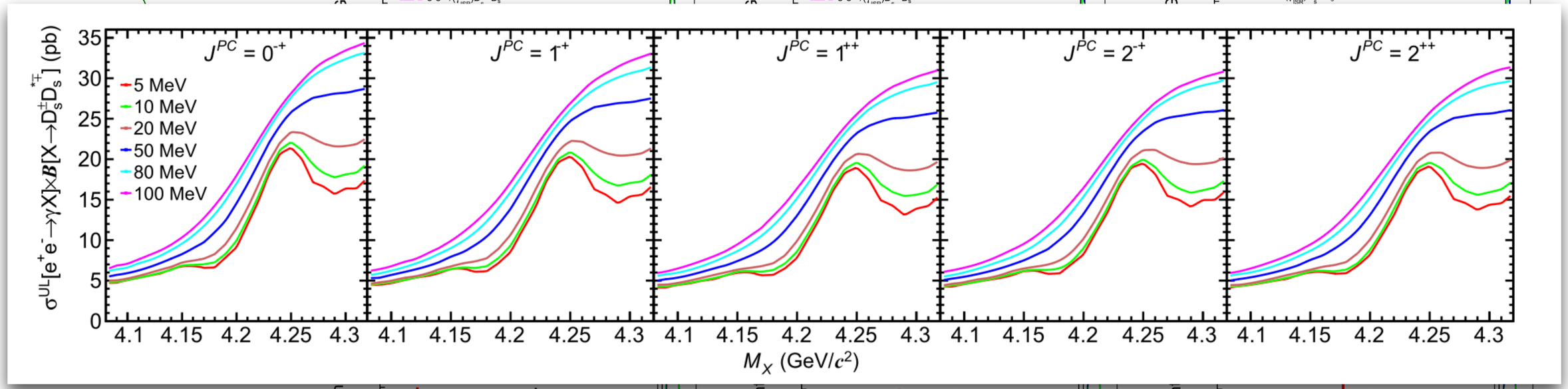


[4] PRD 72, 054026 (2005)
[9] Progr. Phys. 41, 65 (2021)
[10] JHEP 07 (2012) 126
[11] JHEP 12 (2016) 089
[12] PRD 102, 014023 (2020)

PRD110, 032017 (2024)

C-even States in $e^+e^- \to \gamma D_s^{\pm} D_s^{*\mp}$

- Full reconstruction method, $D_s^* \to \gamma D_s$, $D_s \to K^+K^-\pi, K_S^0 K$, 4680 data sample



[4] PRD 72, 054026 (2005)
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PRD110, 032017 (2024)

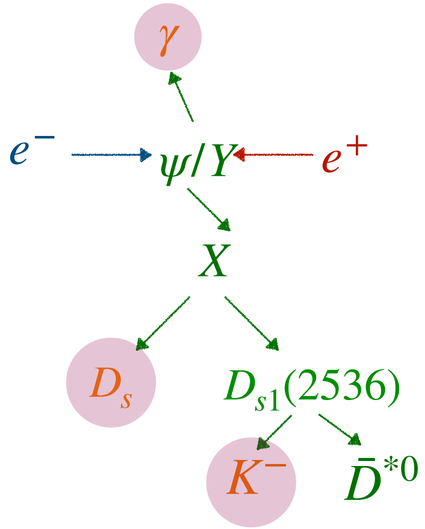
C-even States in $e^+e^- \to \gamma D_s^{\pm} D_{s1}^{\mp}(2536)$

- Search for molecular state with $J^{PC} = 1^{-+}$

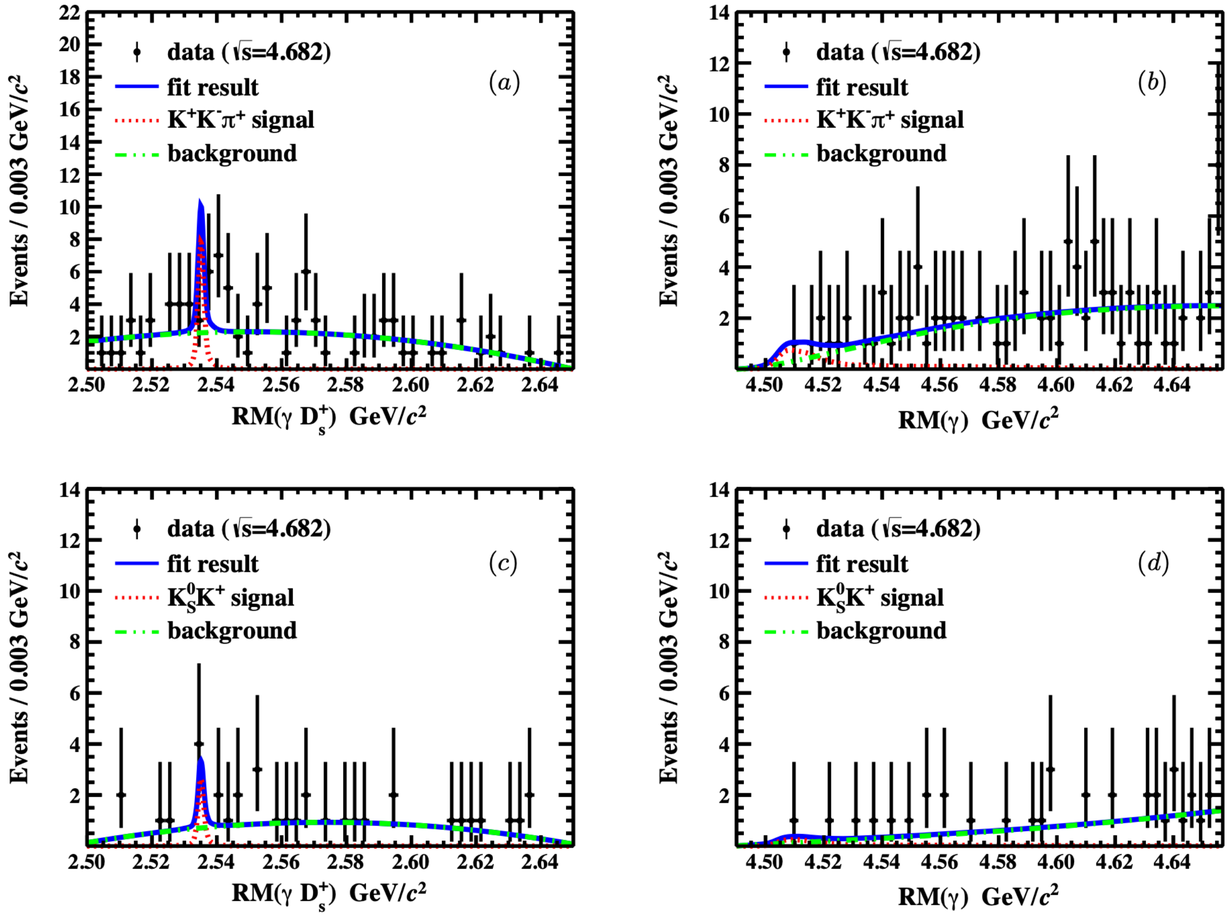
  PRD89, 114013 (2014)

- Partial reconstruction method, 5.8 fb^{-1}, $\sqrt{s} = 4.61 - 4.95$ GeV

- Mass of X set to 4.503 GeV



arXiv:2503.11015



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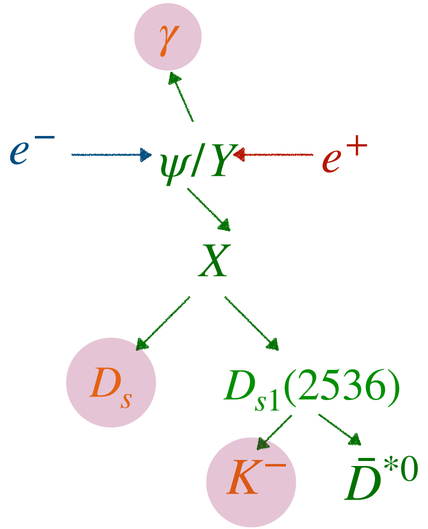

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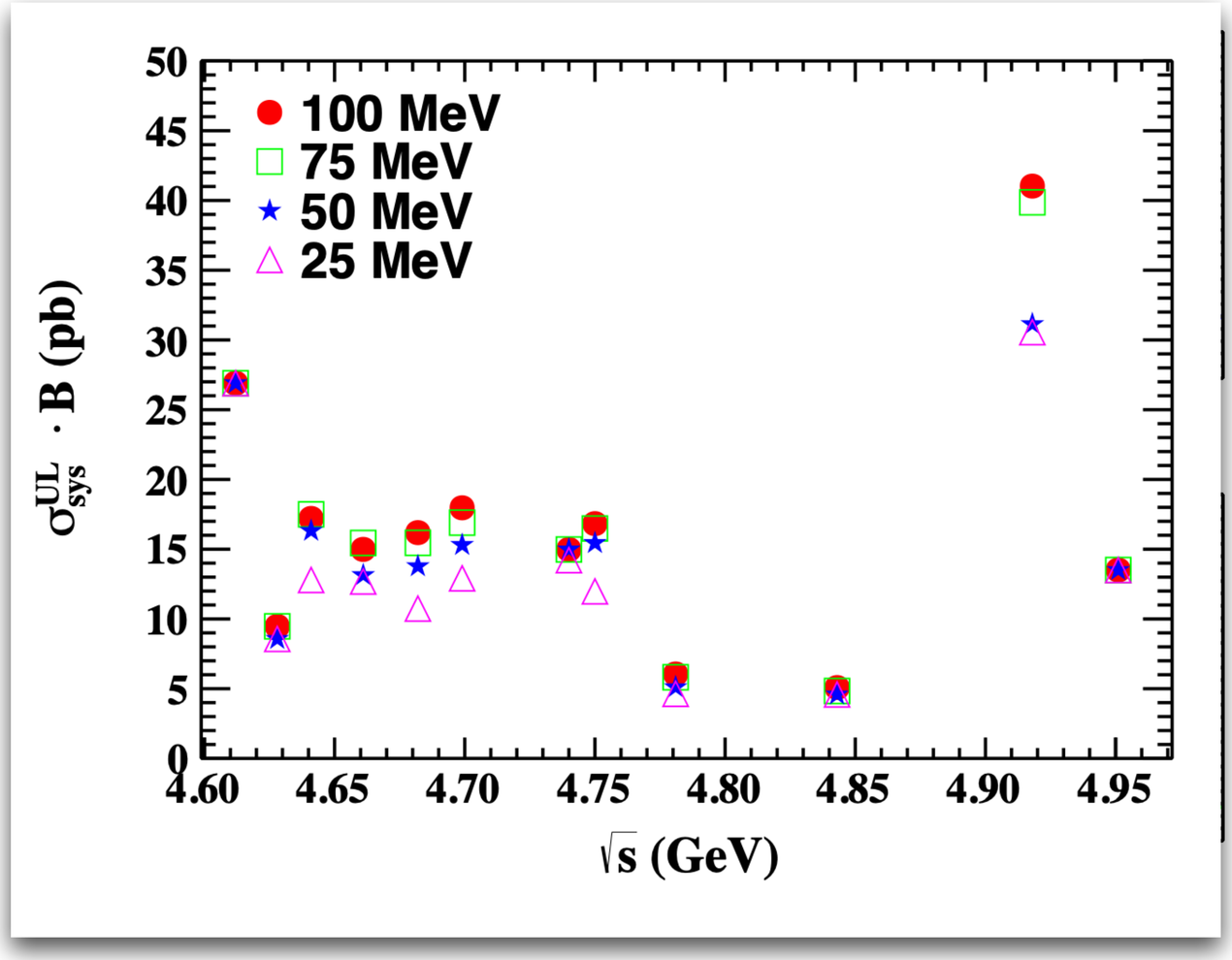

Summary

- Benefit from the fine scan data samples collected between $\sqrt{s}$=3.8 to 4.95 GeV, good performance of BEPCII and BESIII, the properties of charmonium and charmoniumlike states have been studied
  - $Y(4260)$ has fine structure, cross section enhancement around $Y(4230)$ is observed in more than 10 decay modes: $\pi^+\pi^- J/\psi$, $\pi^+\pi^- h_c$, $\pi^+\pi^-\psi(2S)$, $\omega\chi_{c0}$, $\eta J/\psi$, $\pi^+\pi^-\pi^0\eta_c$, $K^+K^- J/\psi$, $\pi^0 Z_c(3900)$, πDD^*, πD^*D^*, ηh_c, $\gamma X(3872)$
  - Discovered new charmonium-like states $Y(4500)$ and $Y(4710)/Y(4790)$
  - Cross section of $e^+e^- \to \pi^+\pi^- h_c$ has been measured with improved precision up tp 4.95 GeV, the cross section betwen 4.3 and 4.45 GeV exhibits a plateau-like shape and drops sharply around 4.5 GeV
  - Enhancement around 4.2 GeV observed from the cross section of $e^+e^- \to \eta h_c$
  - The cross-section line shapes are very complicated, more sophisticate d analysis may determine the pole positions of these states better and help to understand their nature
  - Study of C-even states from radiative/hadronic transition process suffers from low statistics
- BEPCII is upgrading, increase the luminosity at $\sqrt{s}$=4.7 GeV by a factor of 3, and extend the $\sqrt{s}$ up to 5.6 GeV starting from 2028, more exciting results are expected!

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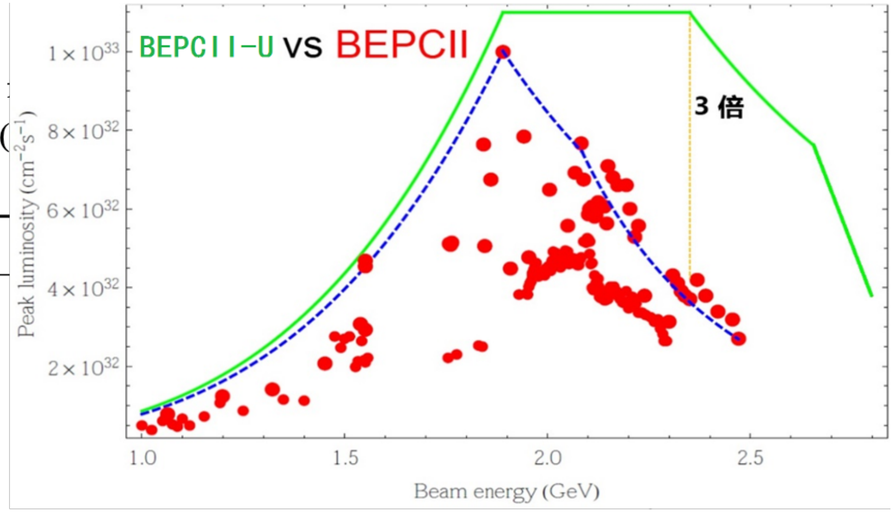
Thank You!

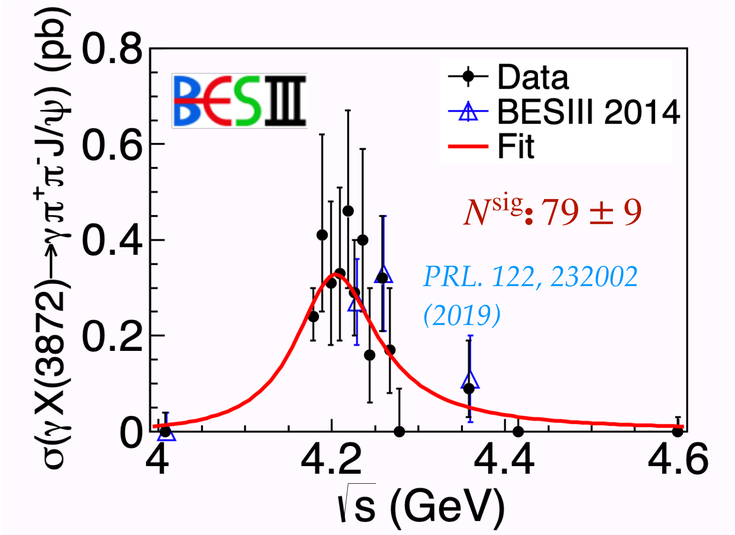
Future Data Samples

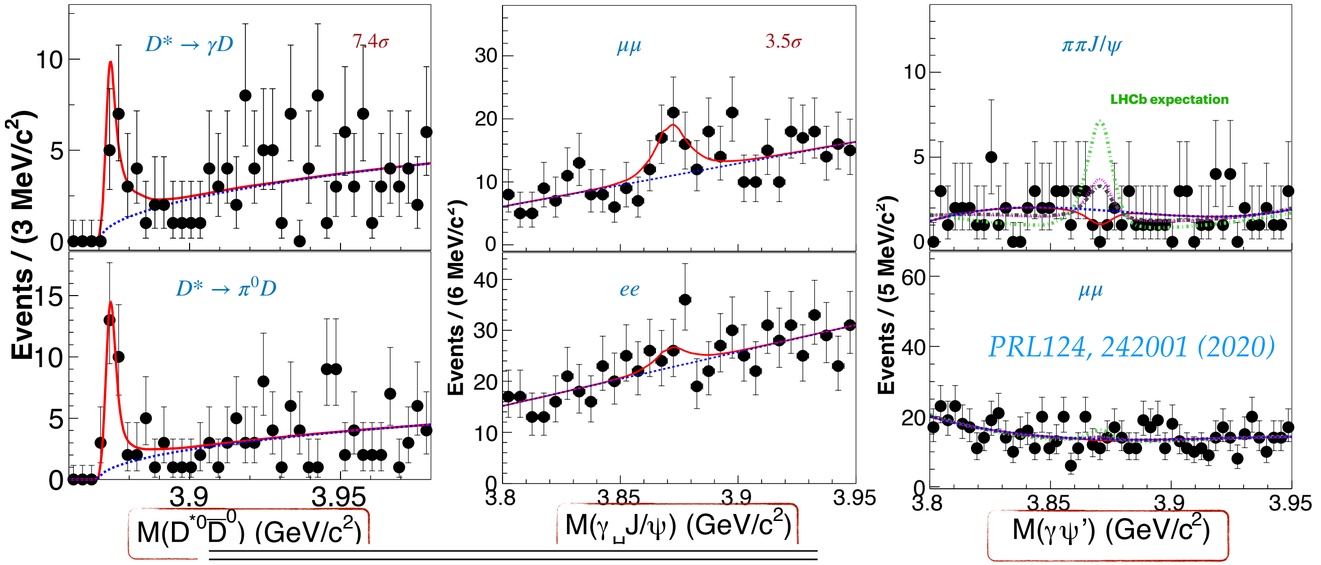
Table 7.1. List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples
most column shows the number of required data taking days with the current (T_C) and upgraded (
implementation and beam current increase.

Energy	Physics motivations	Current data		
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A		
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)		
J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)		
$\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (0.45 billion)		
$\psi(3770)$ peak	$D^0/D^{\pm}$ decays	2.9 fb^{-1}	20.0 fb^{-1}	610/360 days
3.8 - 4.6 GeV	R values XYZ/Open charm	Fine scan (105 energy points)	No requirement	N/A
4.180 GeV	D_s decay XYZ/Open charm	3.2 fb^{-1}	6 fb^{-1}	140/50 days
4.0 - 4.6 GeV	XYZ/Open charm Higher charmonia cross-sections	16.0 fb^{-1} at different $\sqrt{s}$	30 fb^{-1} at different $\sqrt{s}$	770/310 days
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days



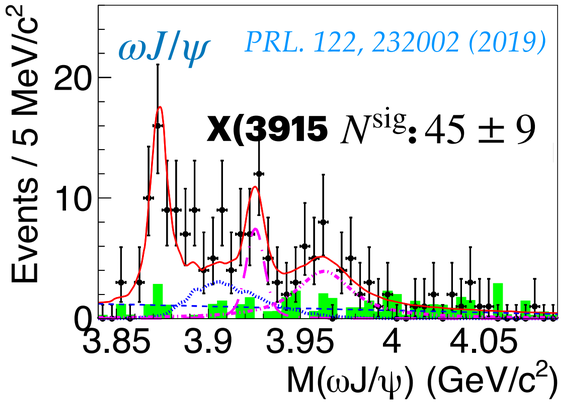
X(3872) Decay Property

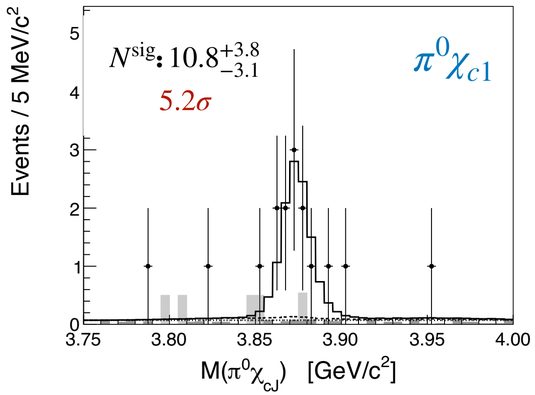




mode	ratio	UL
$\gamma J/\psi$	0.79 ± 0.28	-
$\gamma\psi'$ 2.8σ lower	-0.03 ± 0.22	< 0.42
$\gamma D^0 \bar{D}^0$	0.54 ± 0.48	< 1.58
$\pi^0 D^0 \bar{D}^0$	-0.13 ± 0.47	< 1.16

mode	ratio	UL
$D^{*0}\bar{D}^0 + c.c.$	11.77 ± 3.09	-
$\gamma D^+ D^-$	$0.00^{+0.48}_{-0.00}$	< 0.99
$\omega J/\psi$	$1.6^{+0.4}_{-0.3} \pm 0.2$ [18]	-
$\pi^0\chi_{c1}$	$0.88^{+0.33}_{-0.27} \pm 0.10$ [31]	-





PRL 122, 202001 (2019)

Ratio	90% C.L Upper Limit
$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	3.6
$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}$	4.5
$\frac{\mathcal{B}(X(3872)\to\pi^+\pi^-\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	0.56
$\frac{\mathcal{B}(X(3872)\to\pi^0\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	1.7

PRD 105, 072009 (2022)