Recent Progress on XYZ states from BESIII

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On Behalf of BESIII Collaboration

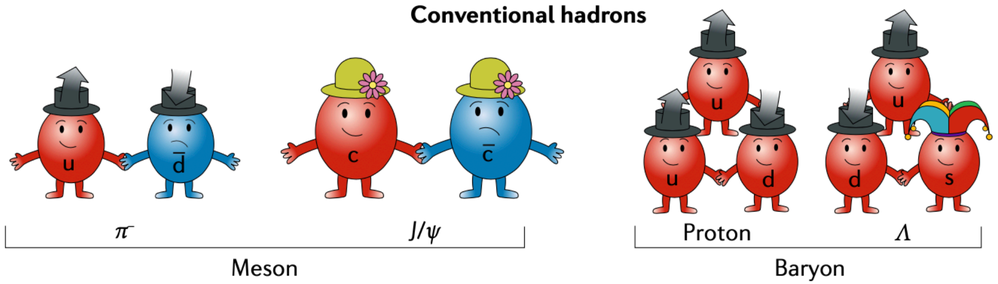
第七届全国重味物理与量子色动力学研讨会

南京　2025.04.21

Hadrons

- **Quark Model** [1964 by Gell-Mann and Zweig]

Lowest Configuration!



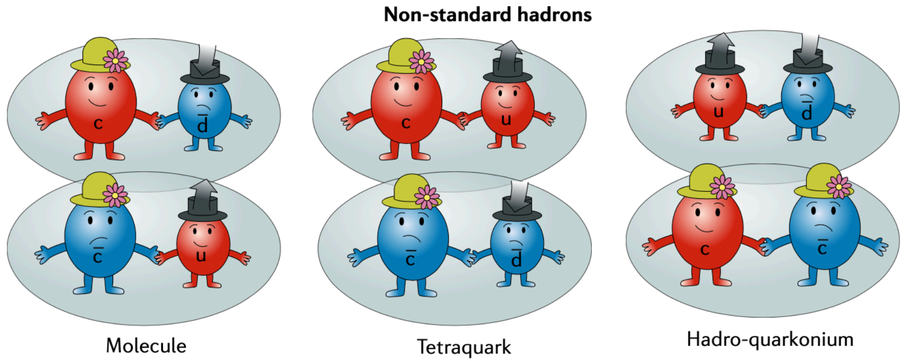
A SCHEMATIC MODEL OF BARYONS AND MESONS *

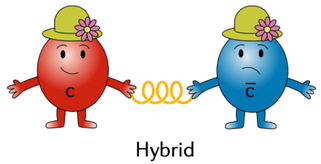
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

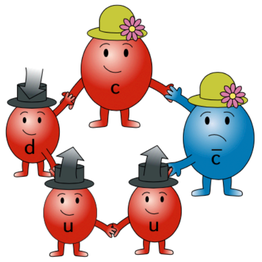
anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

- **Exotic hadrons:**

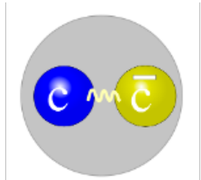


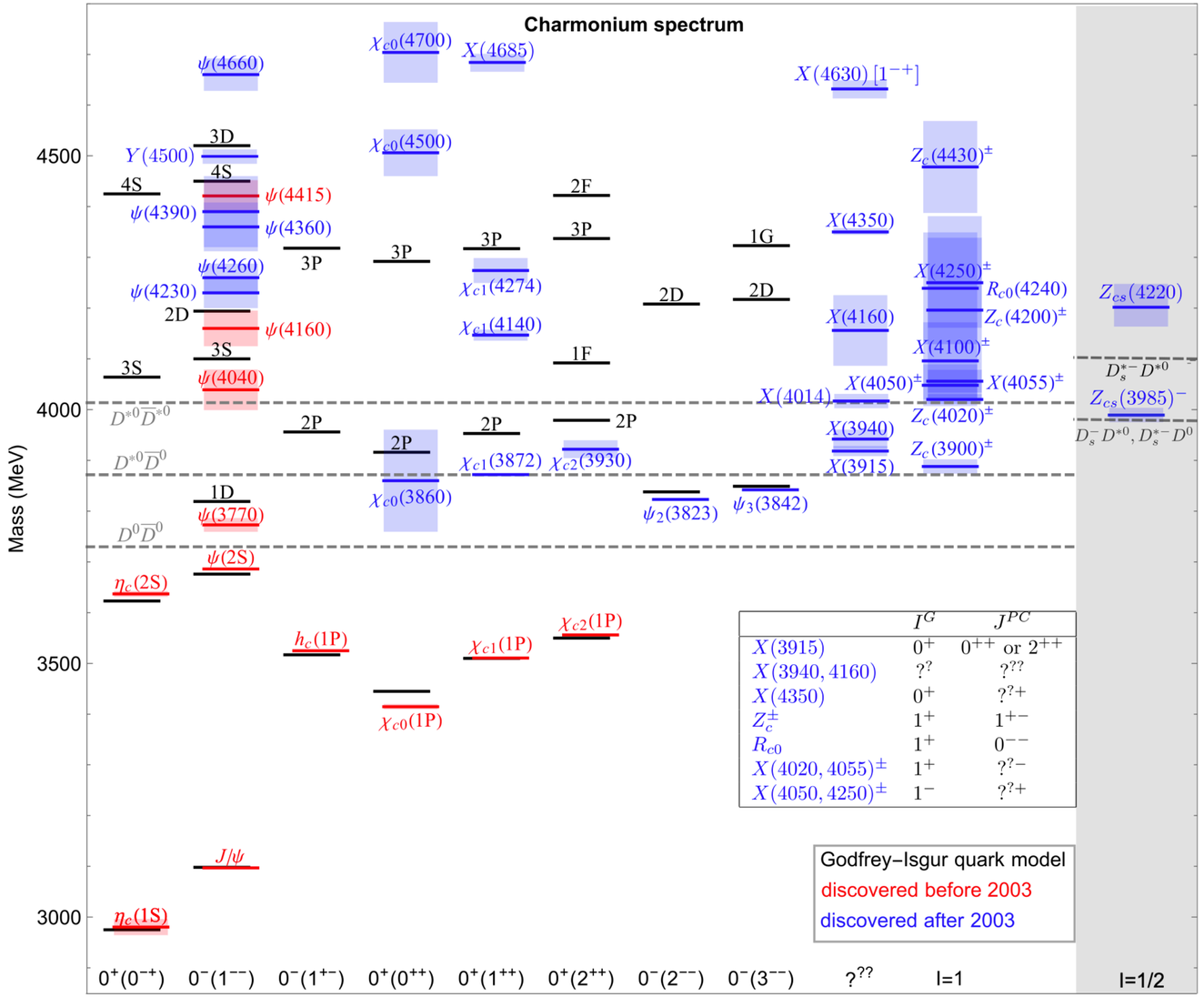



Glueball



Charmonium Spectroscopy





from F. K. Guo

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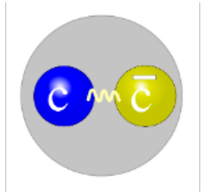
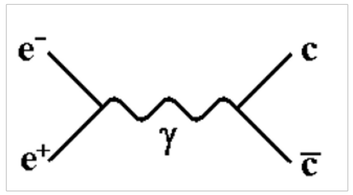
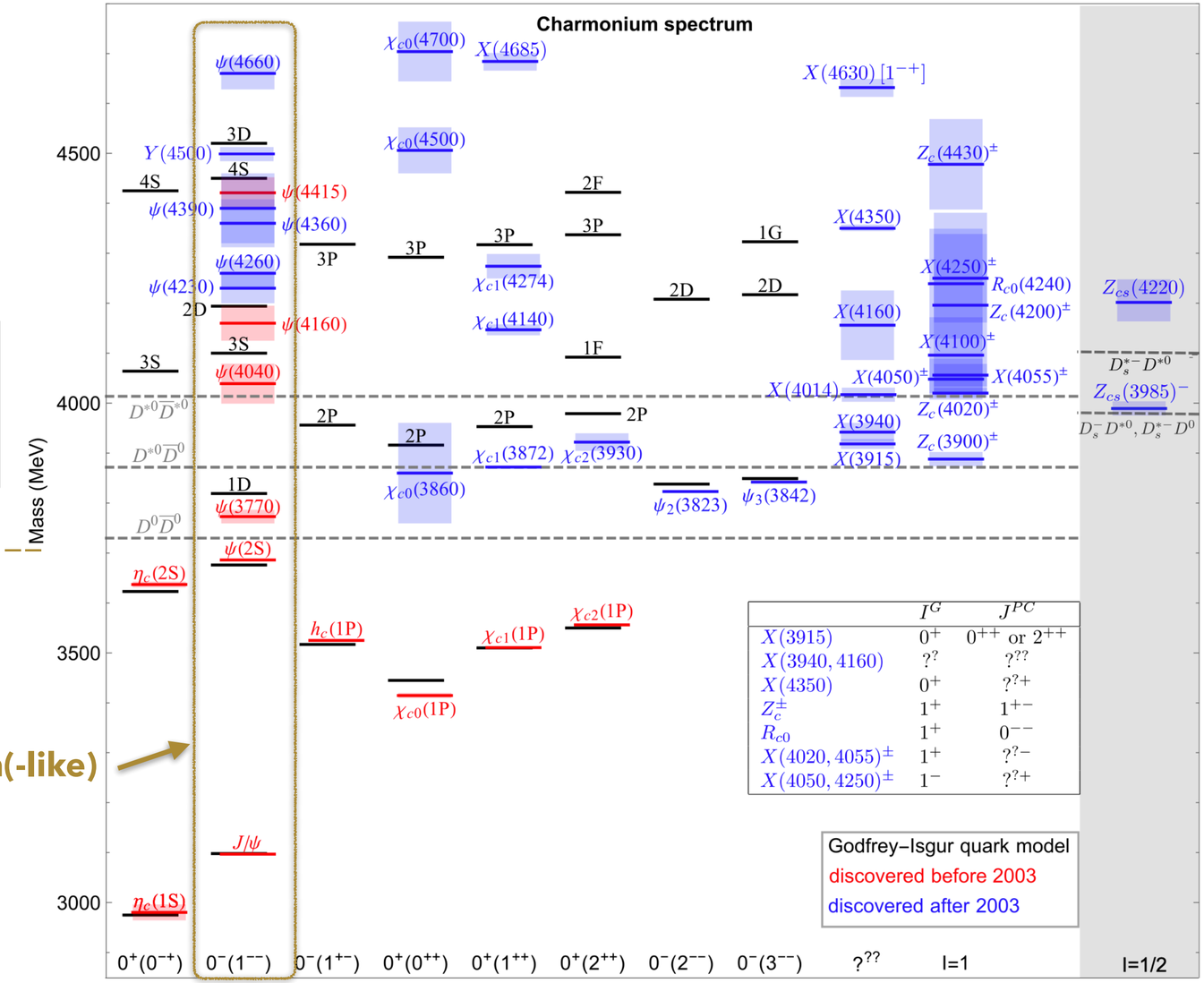




$J^{PC} = 1^{--}$

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

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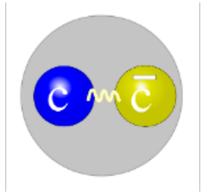

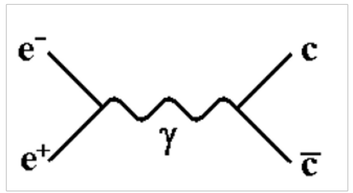

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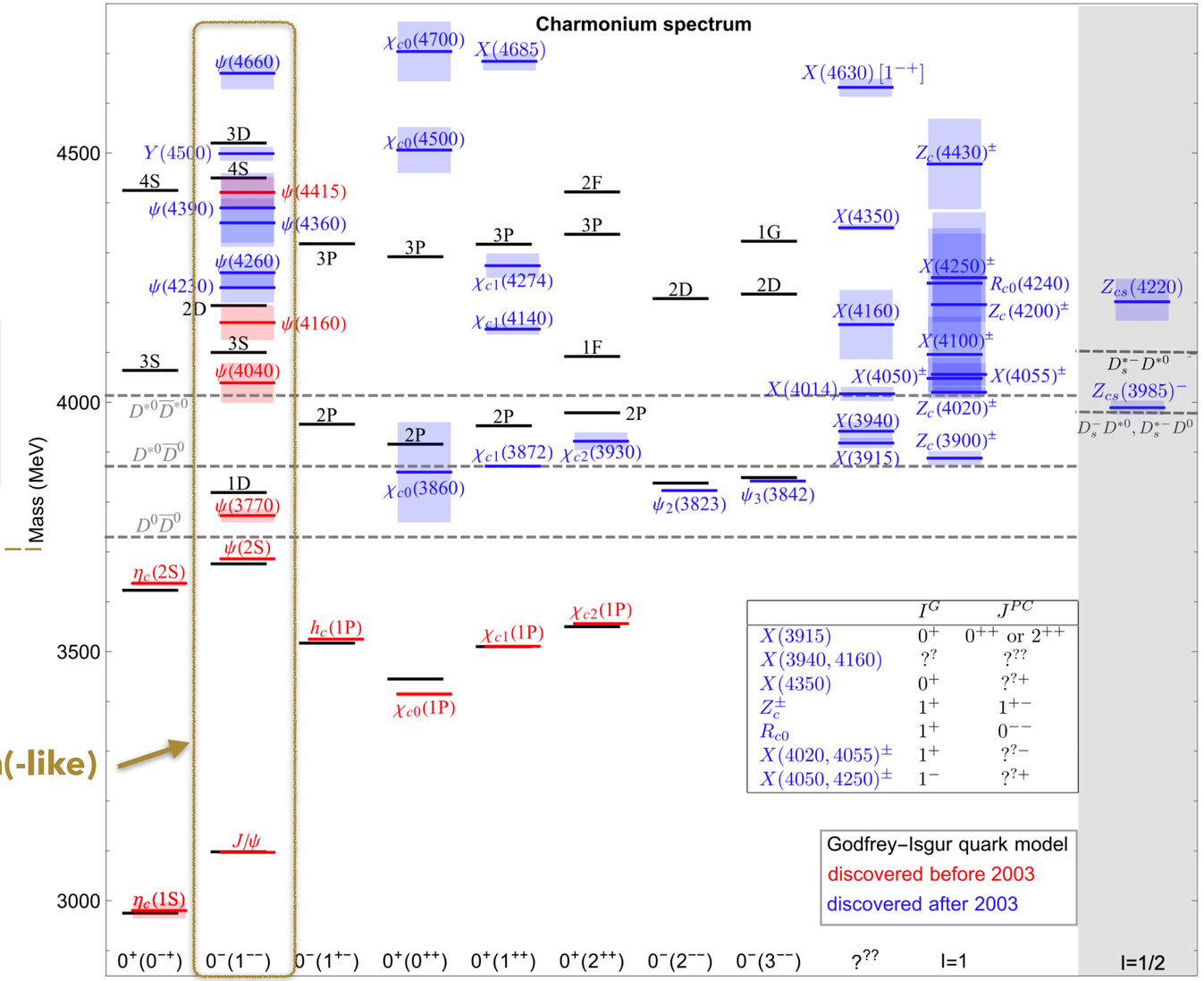

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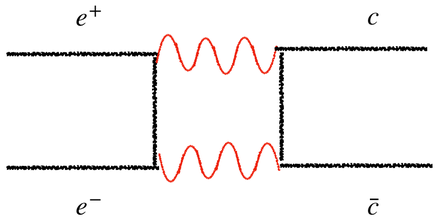
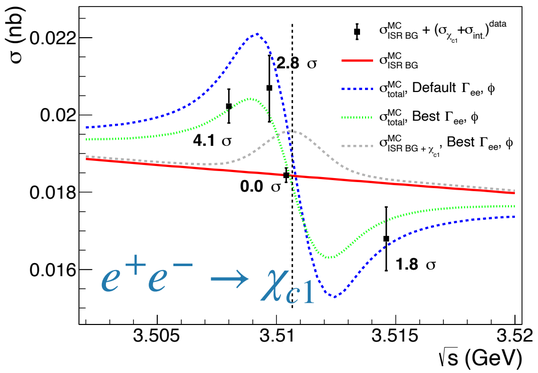
C-even states



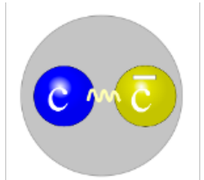
PRL129, 122001 (2022)

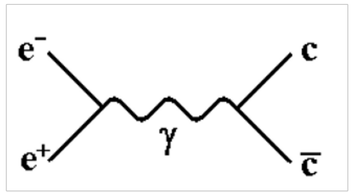


from F. K. Guo

$\Gamma_{ee} = (0.12^{+0.13}_{-0.08})$ eV

Charmonium Spectroscopy





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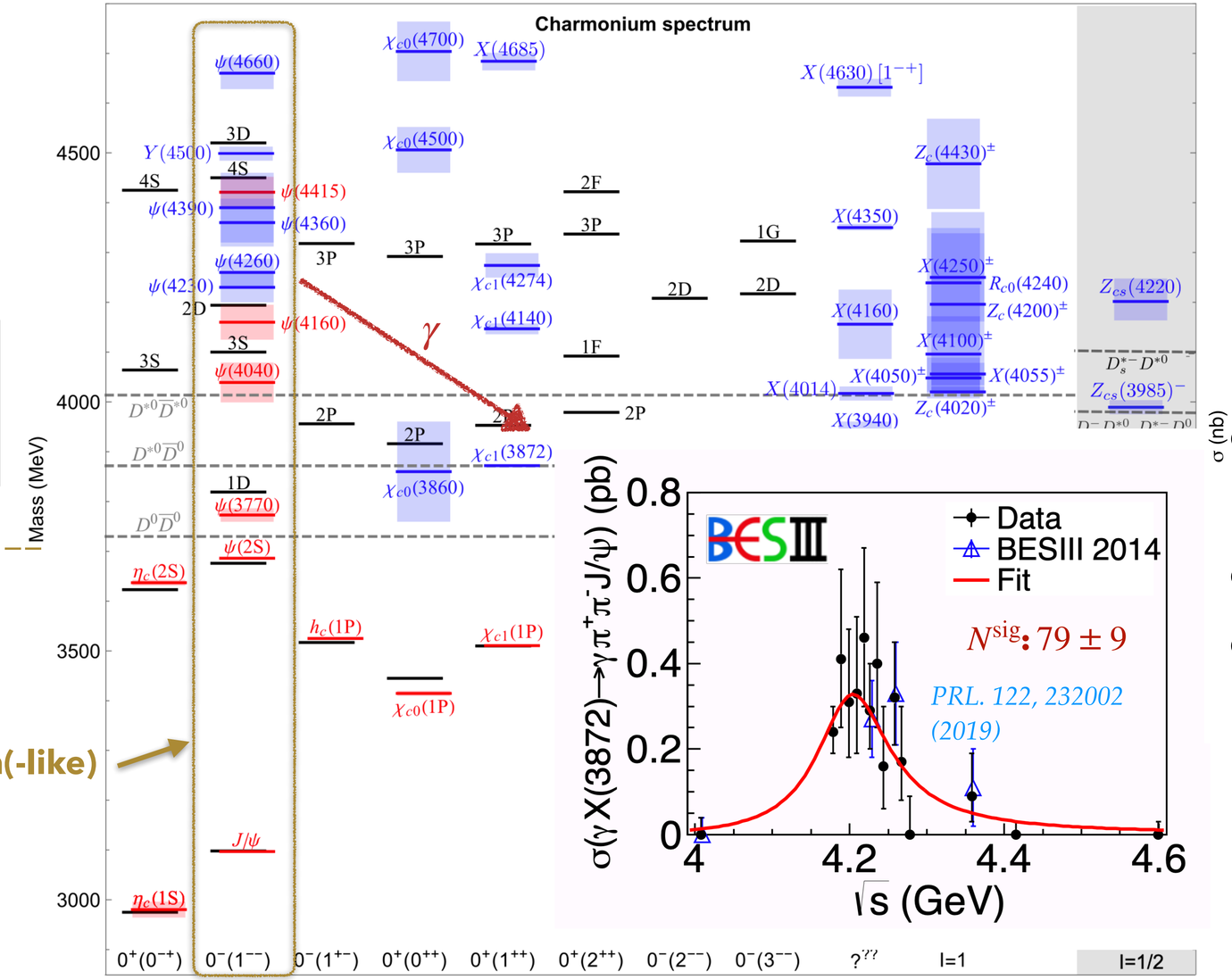

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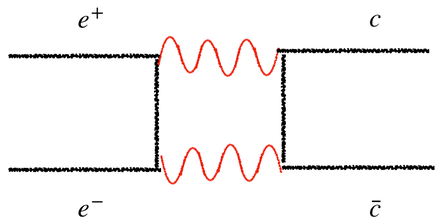

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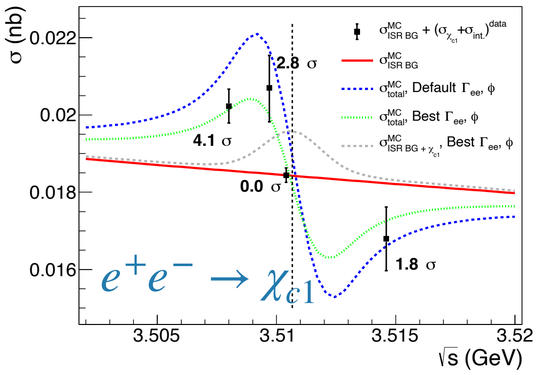

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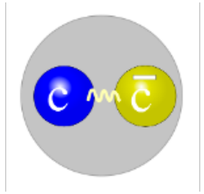

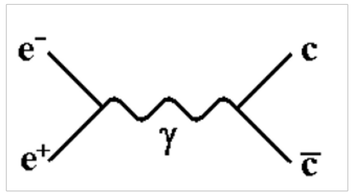

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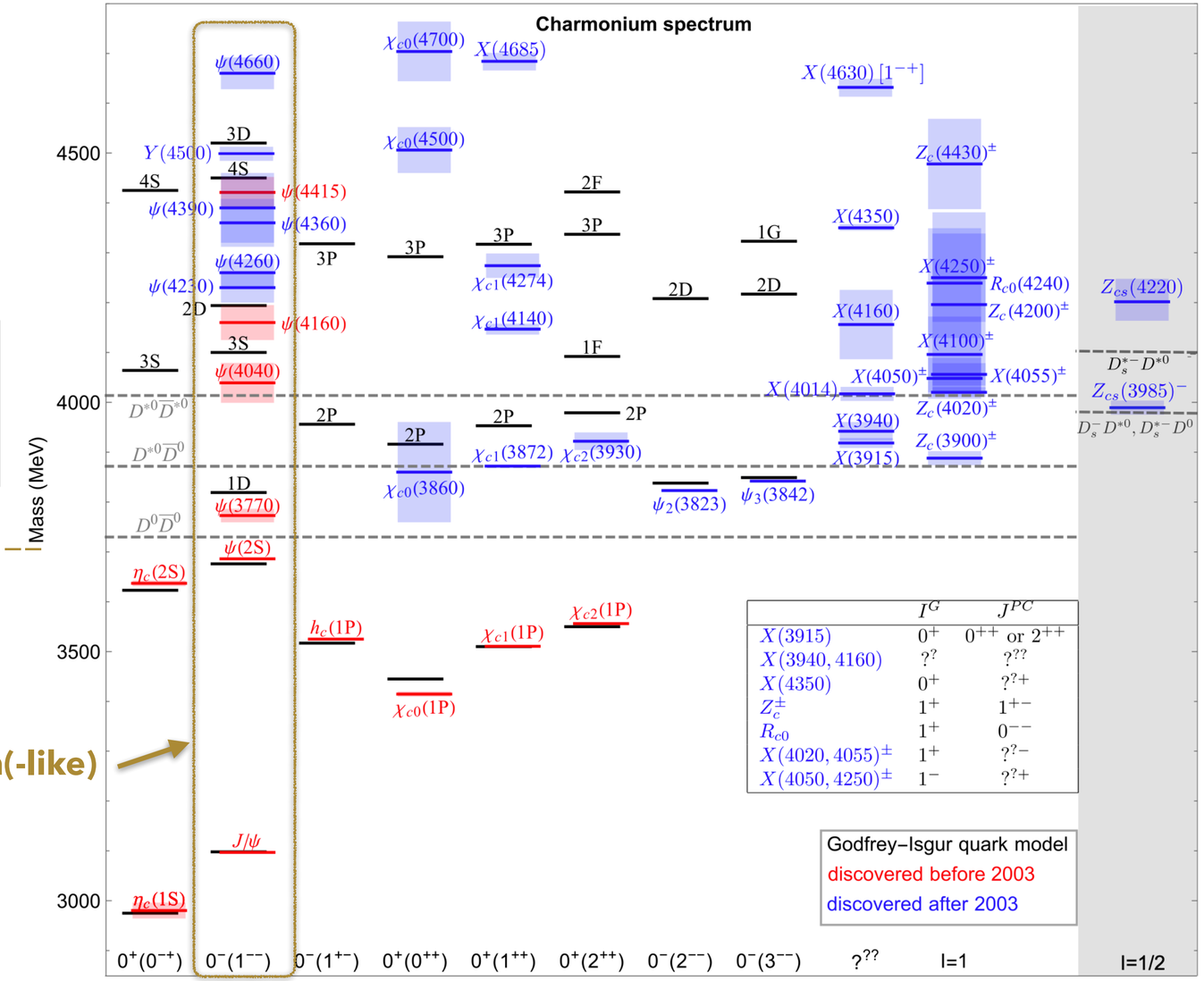

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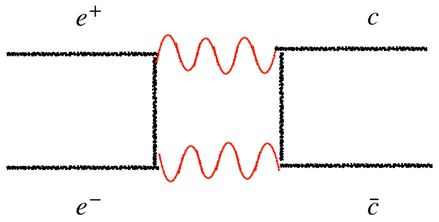

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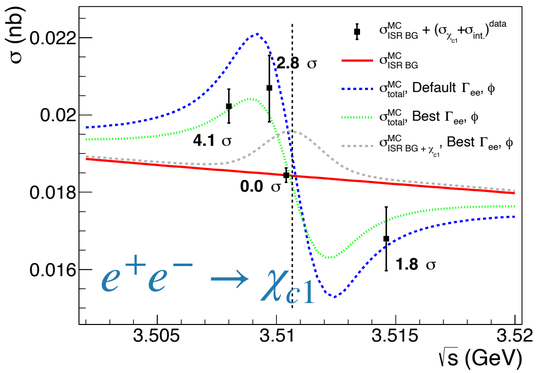

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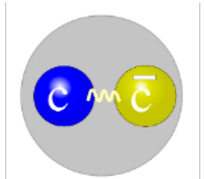

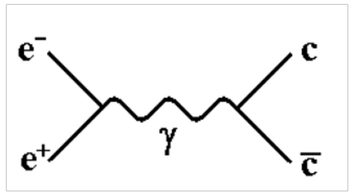

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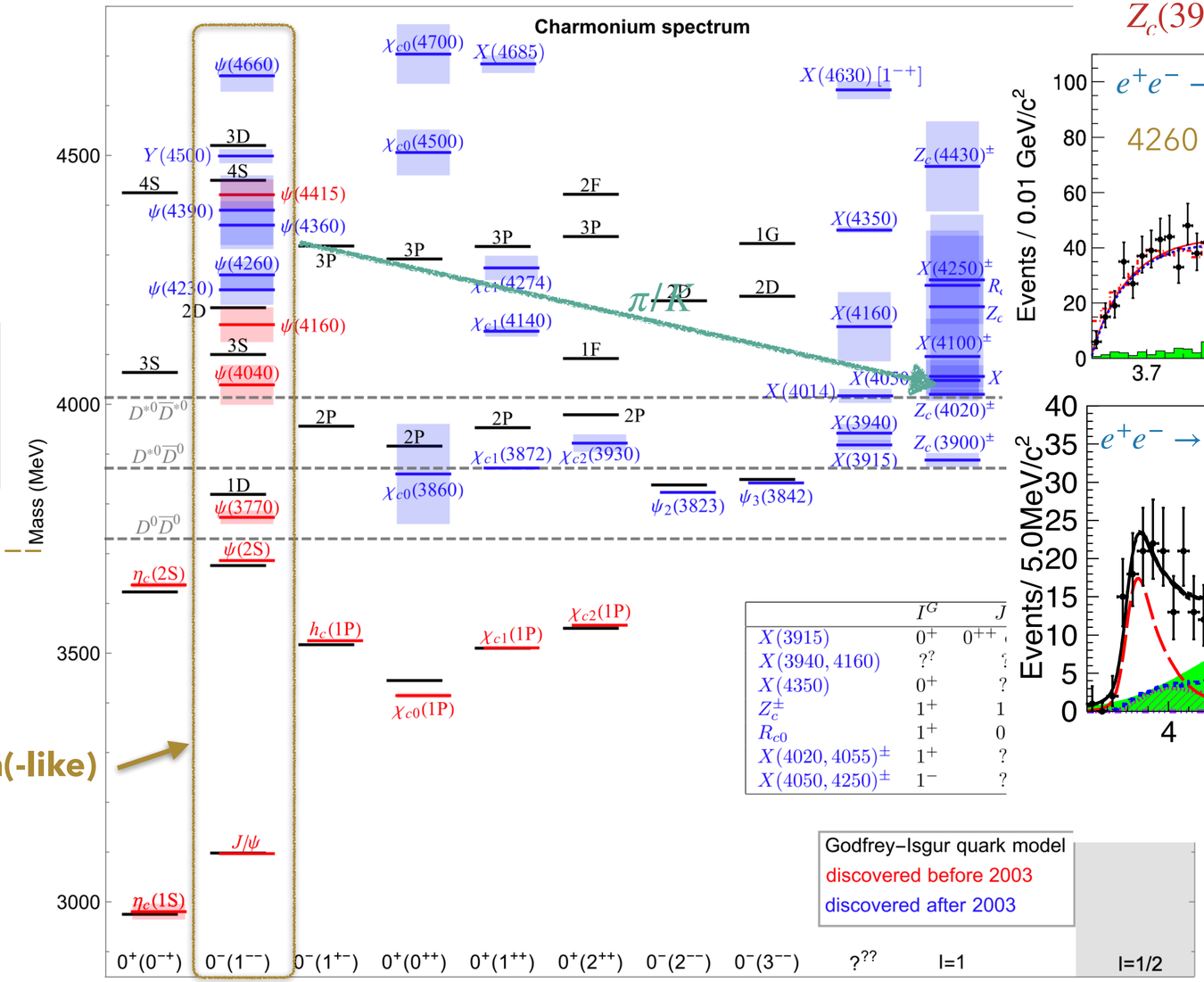
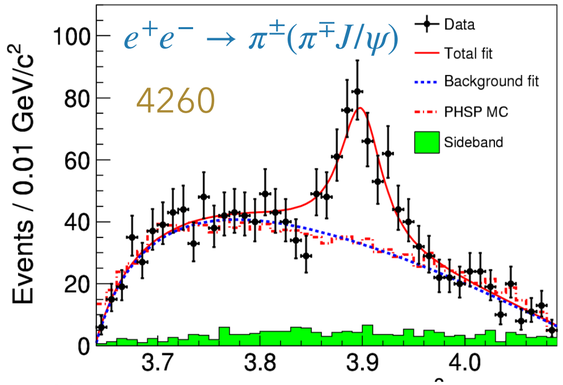
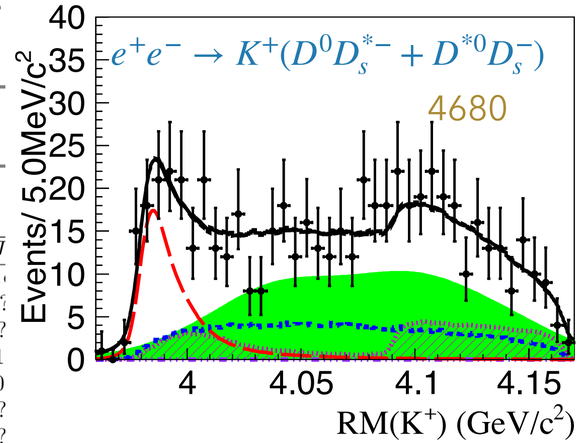


	I^G	J
$X(3915)$	0^+	0^{++}
$X(3940, 4160)$	$?^?$	?
$X(4350)$	0^+	?
$Z_c^{\pm}$	1^+	1
R_{c0}	1^+	0
$X(4020, 4055)^{\pm}$	1^+	?
$X(4050, 4250)^{\pm}$	1^-	?

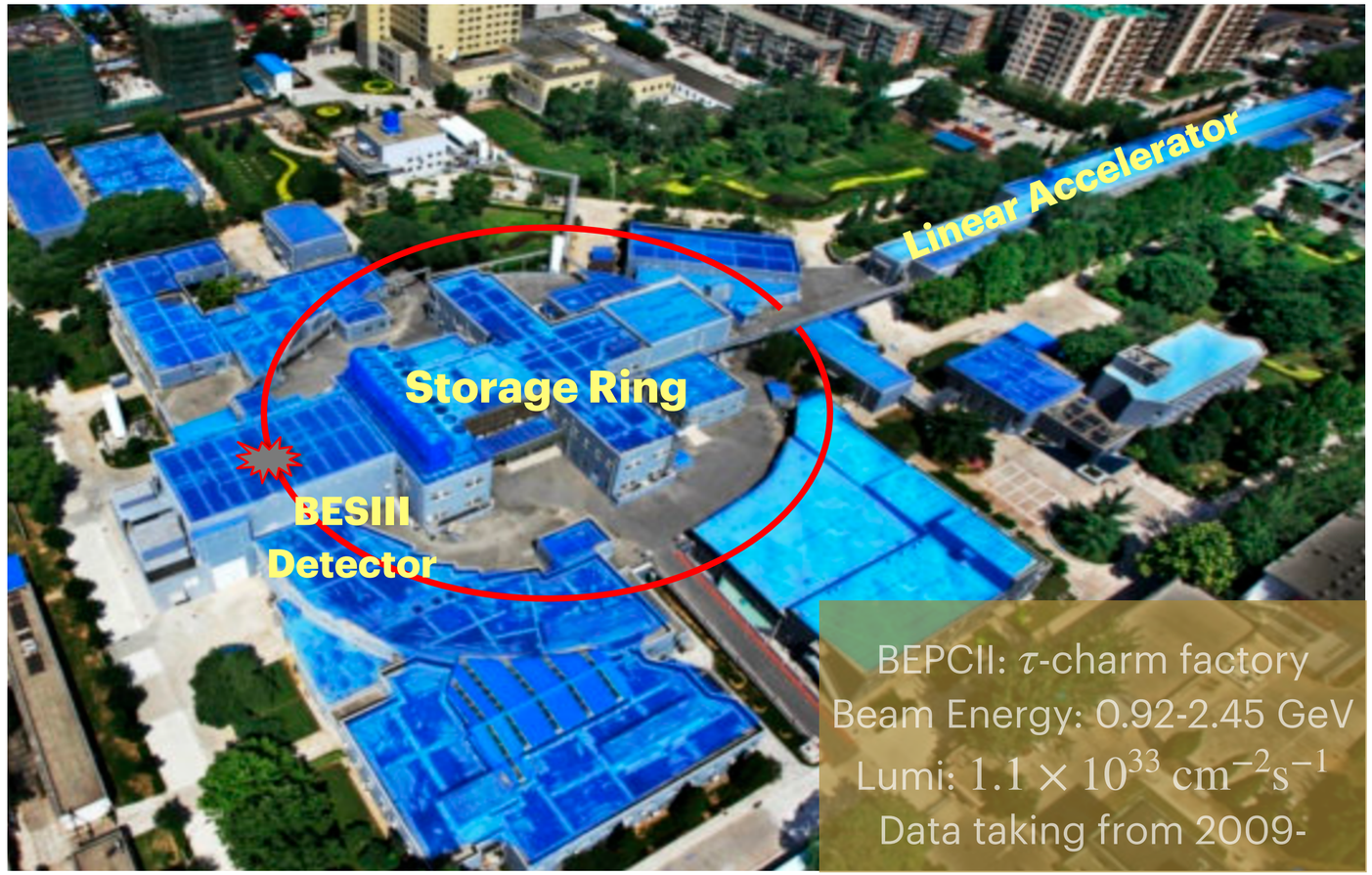
$Z_c(3900)/Z_c(4020)/Z_c(3885)$





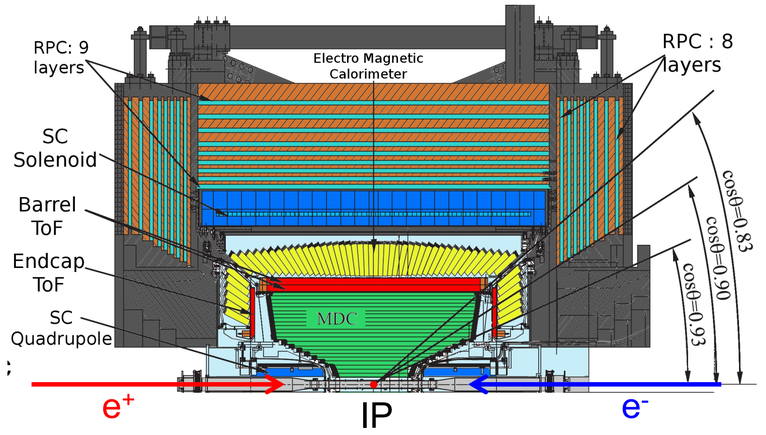
from F. K.

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



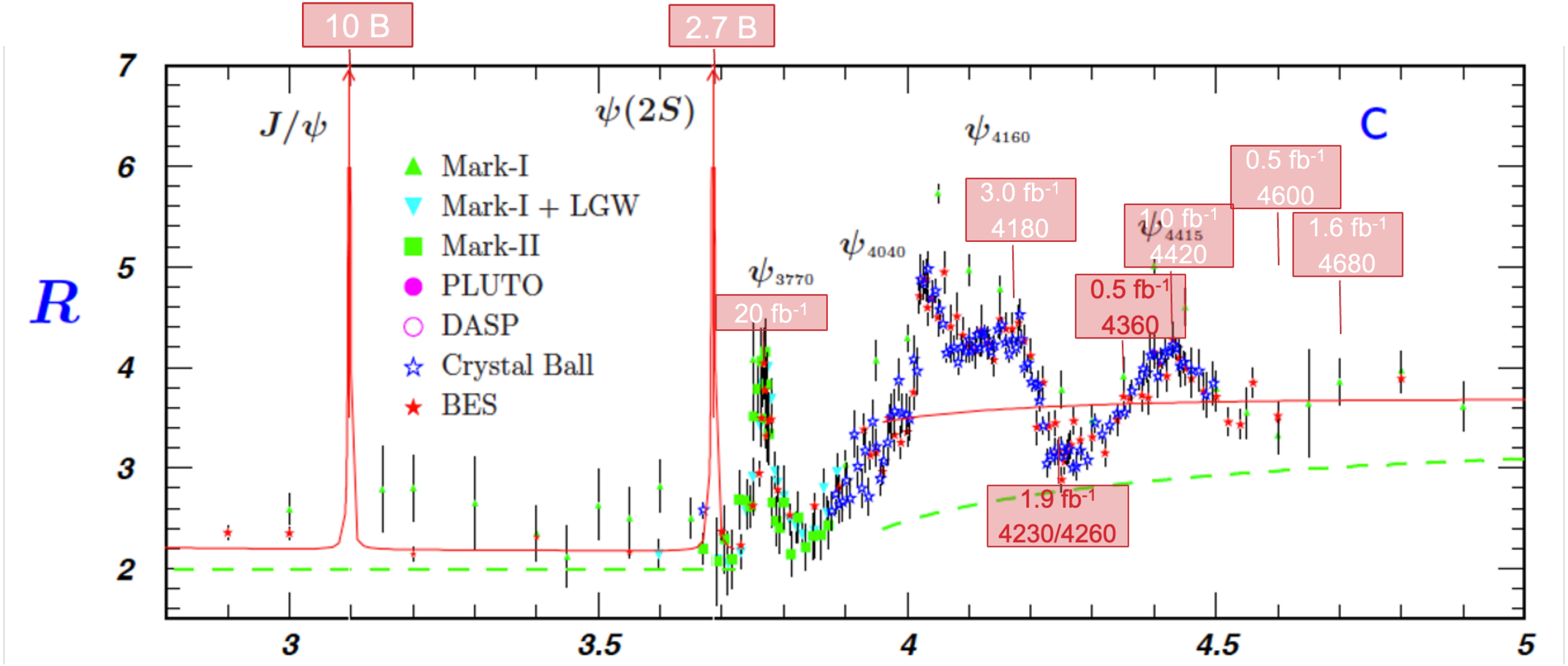
MUC $\sigma_{R\Phi}$: 2 cm

TOF
σ_T :80 ps
110 ps (60 ps)

MDC
dE/dx: 6%
σ_p/p: 0.5% at 1GeV/c

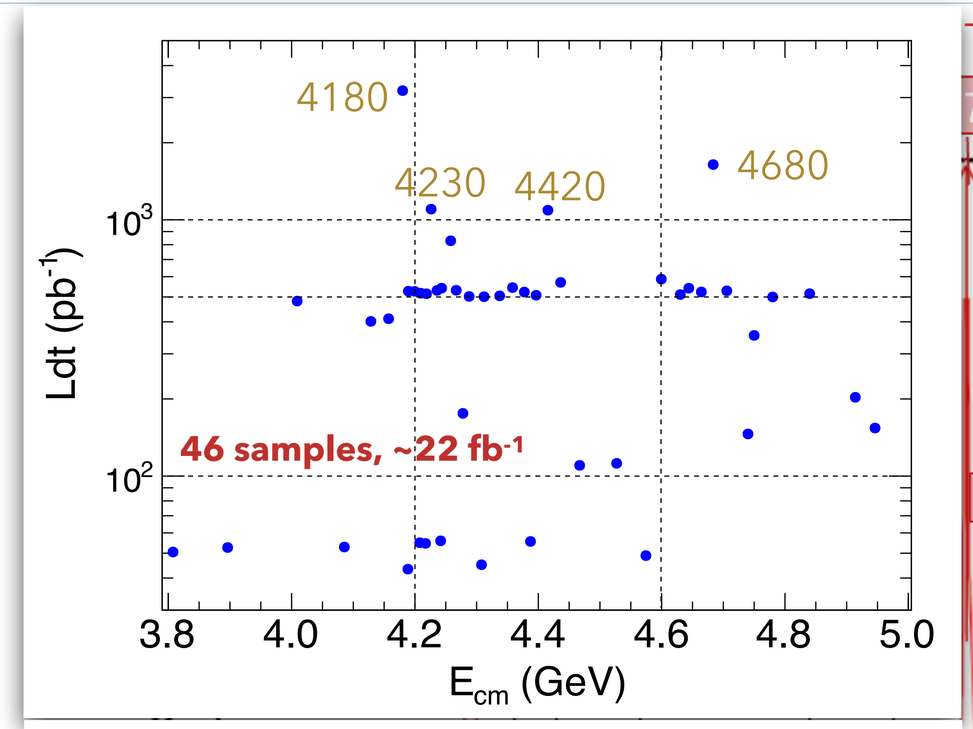
EMC
$\Delta E/E$: at 1GeV
2.5%
5.0%
σ_Z: 0.6 cm/$\sqrt{E}$

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

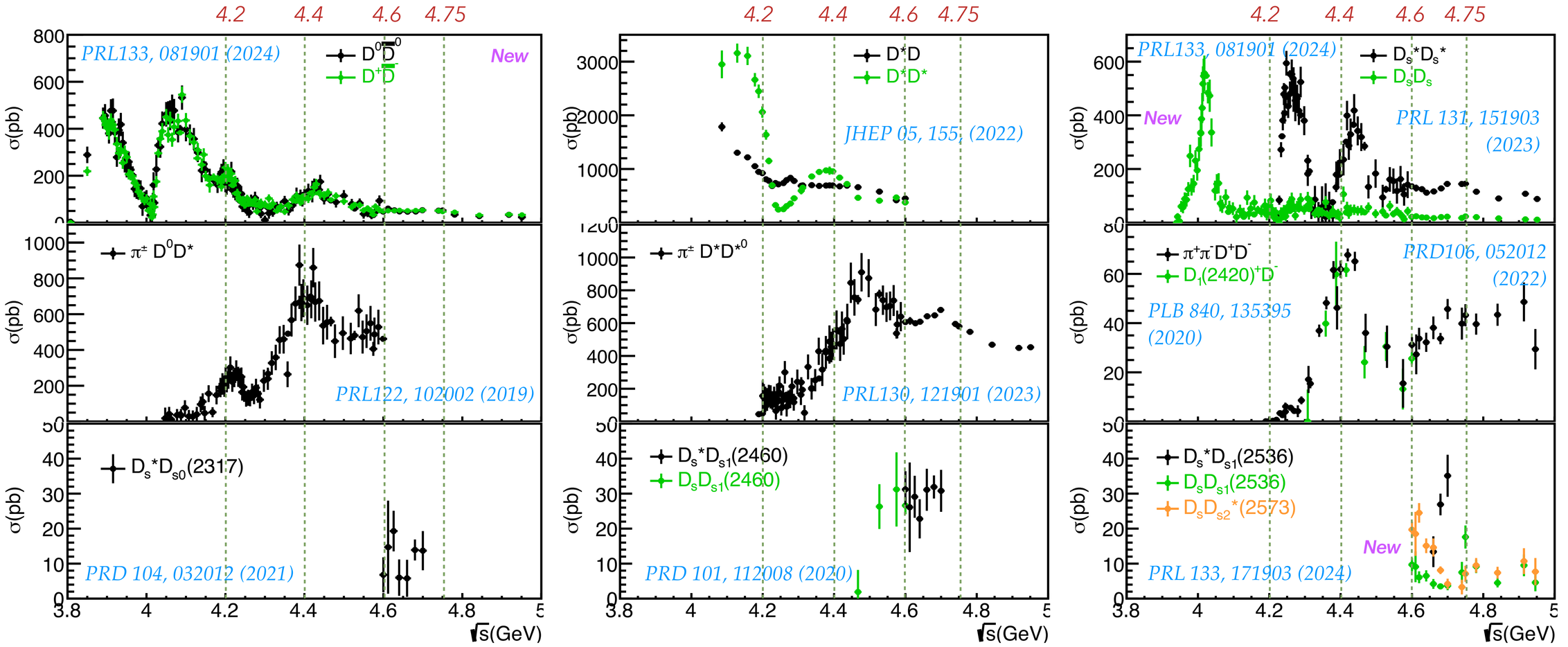


+ Samll scan samples, 151 points from 3.8 to 4.6 GeV, ~3.5 fb^{-1}

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

Overview of CS measurements at BESIII

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



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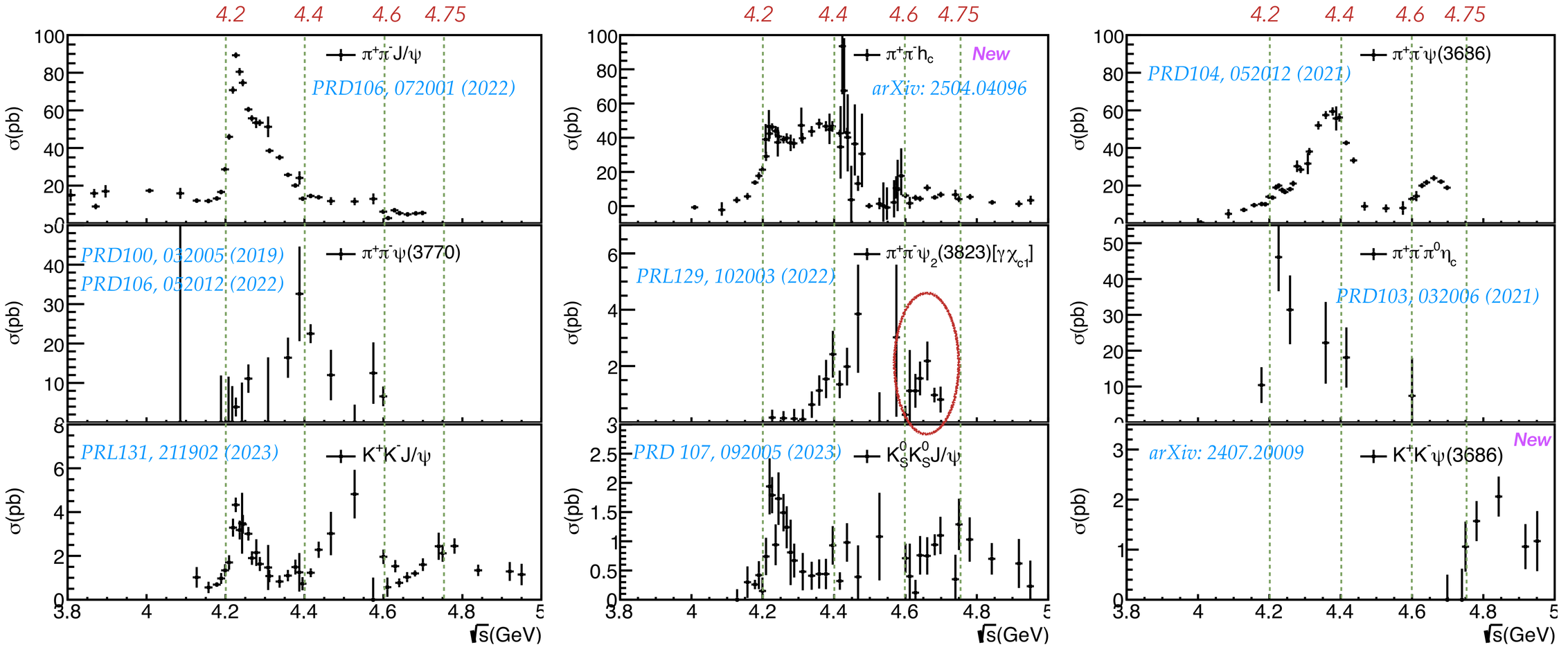

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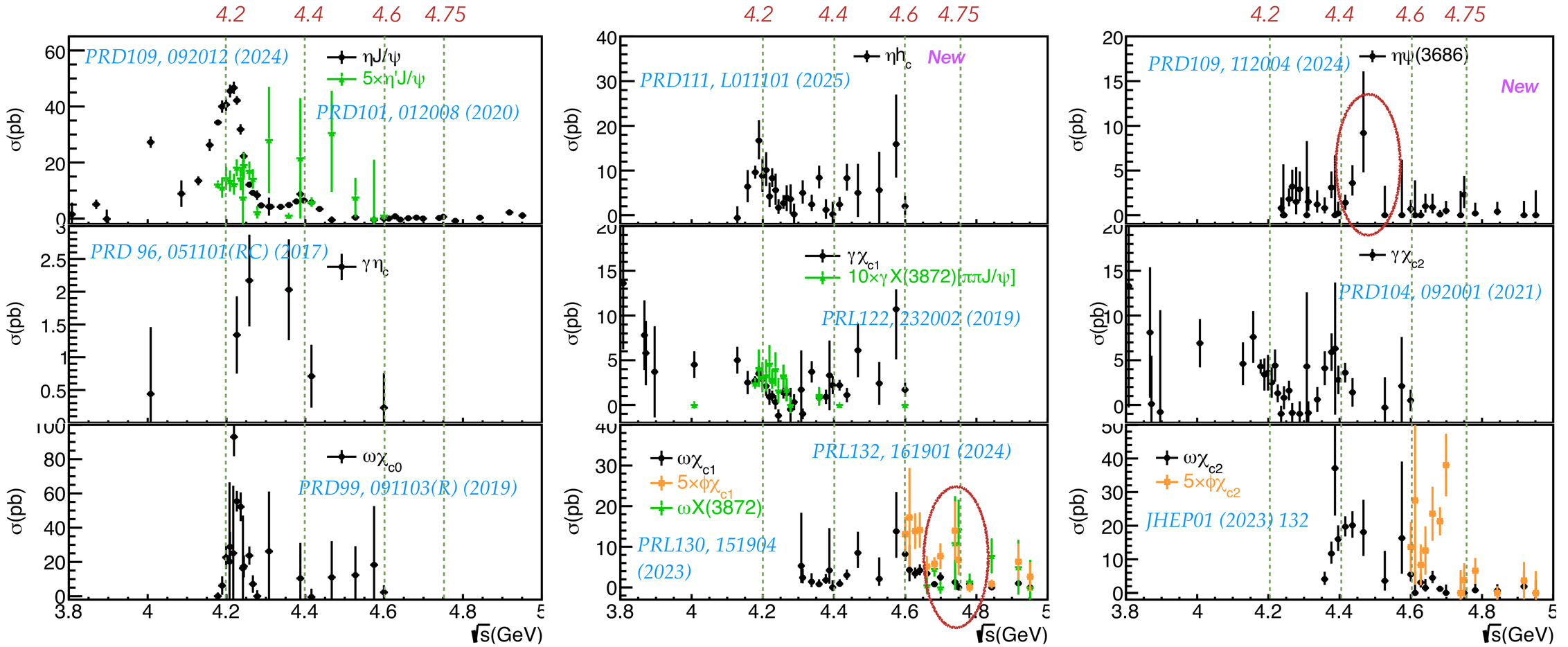
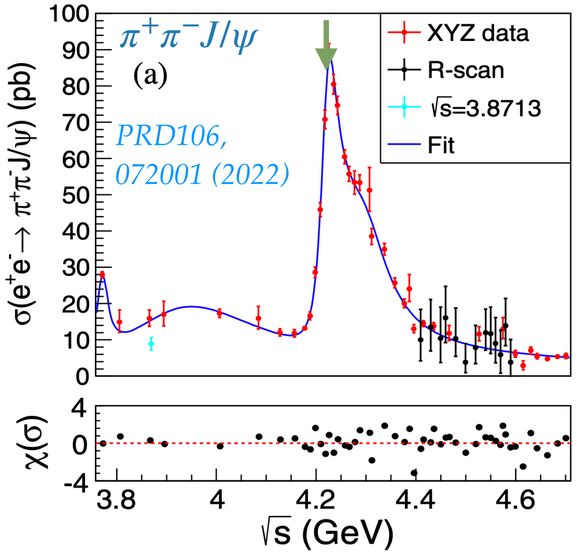
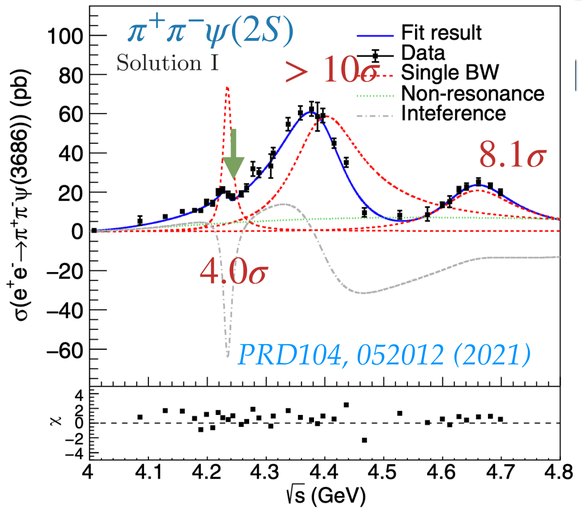
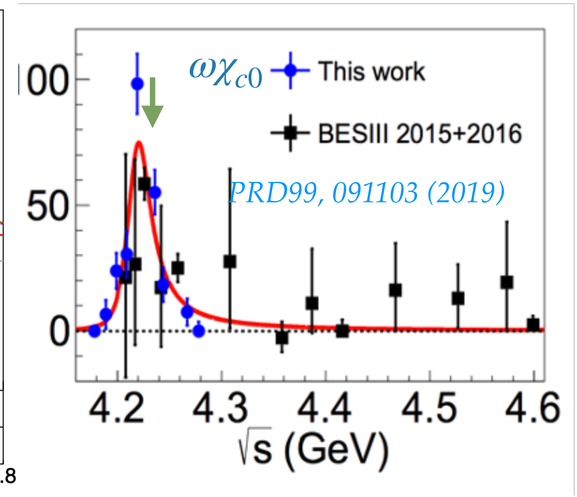


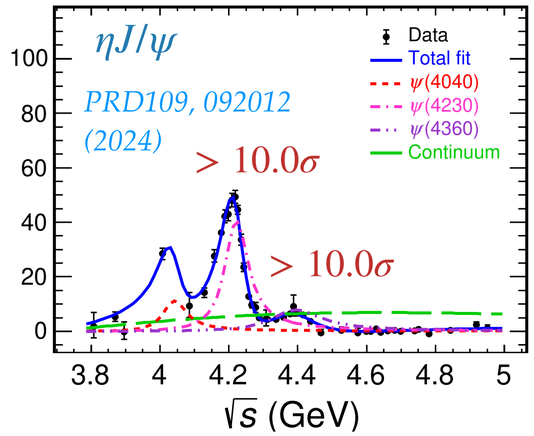
Y(4260)⇒Y(4230)

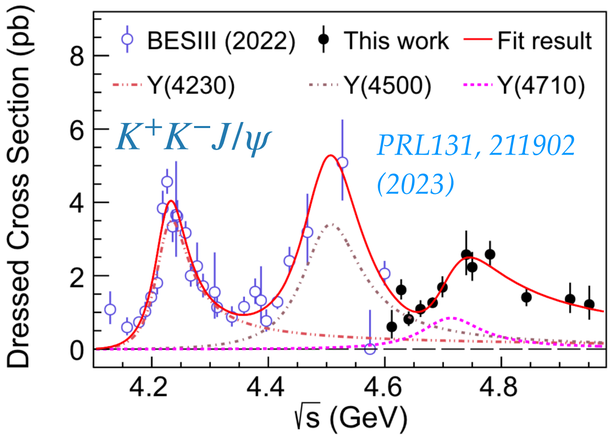
- Seen in more than 10 decay modes, including open charm final states

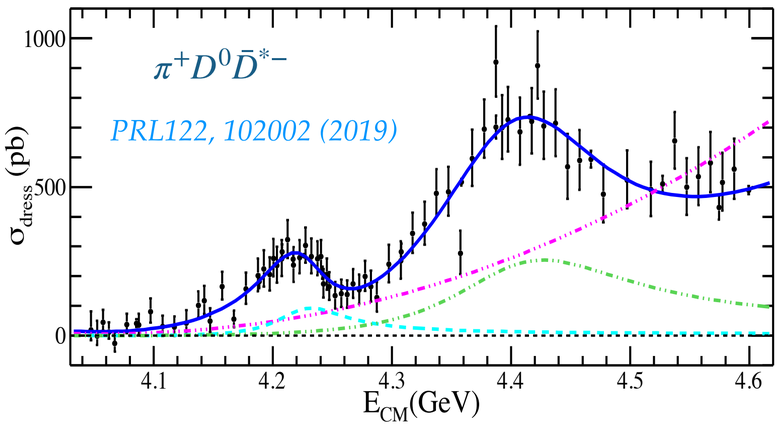


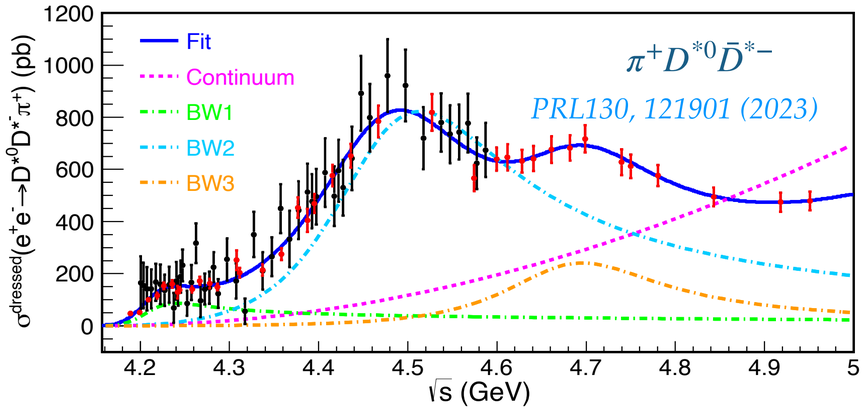












Y(4260)⇒Y(4230)

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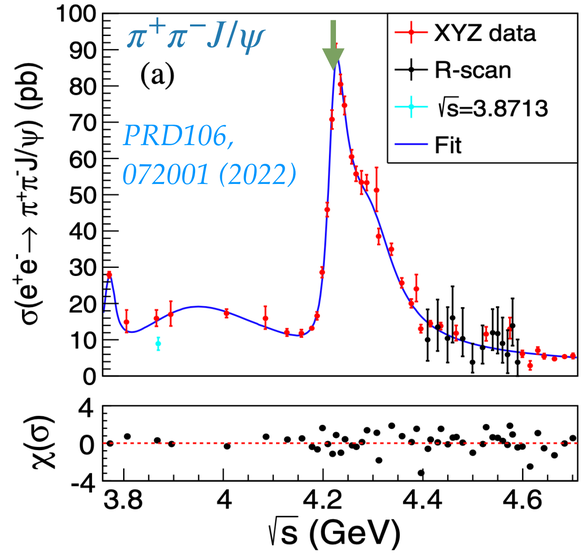
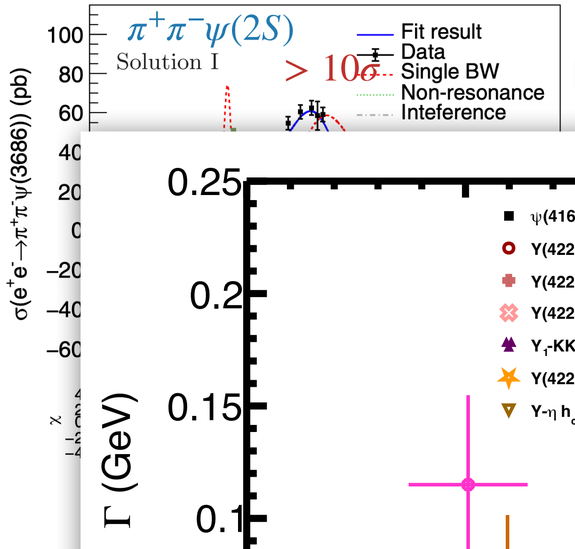
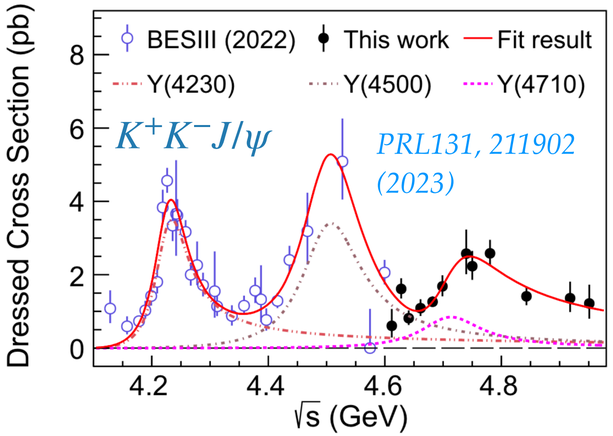
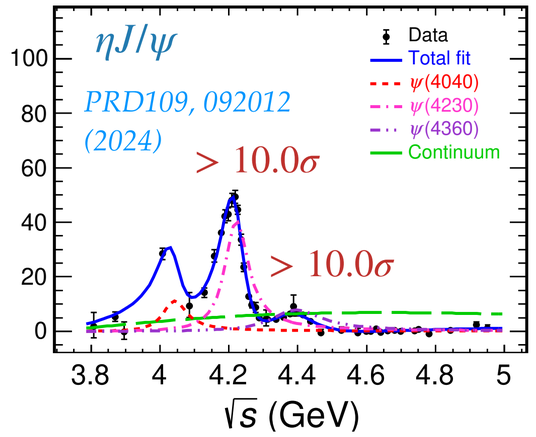
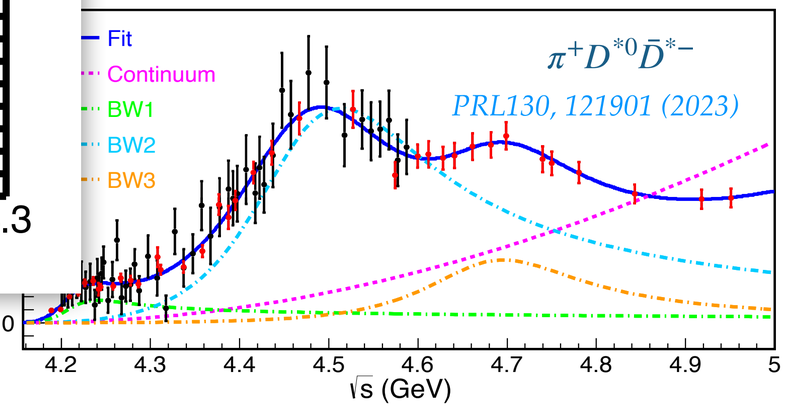




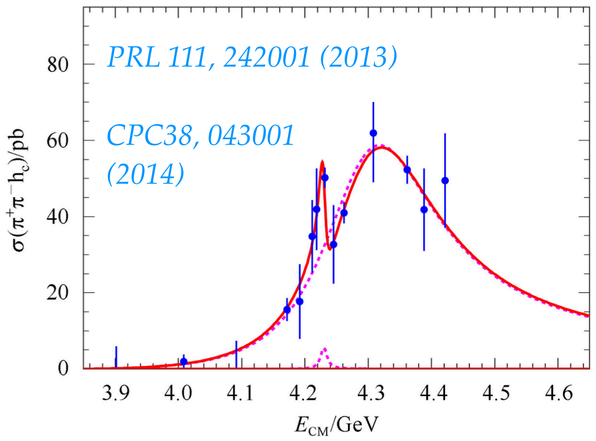


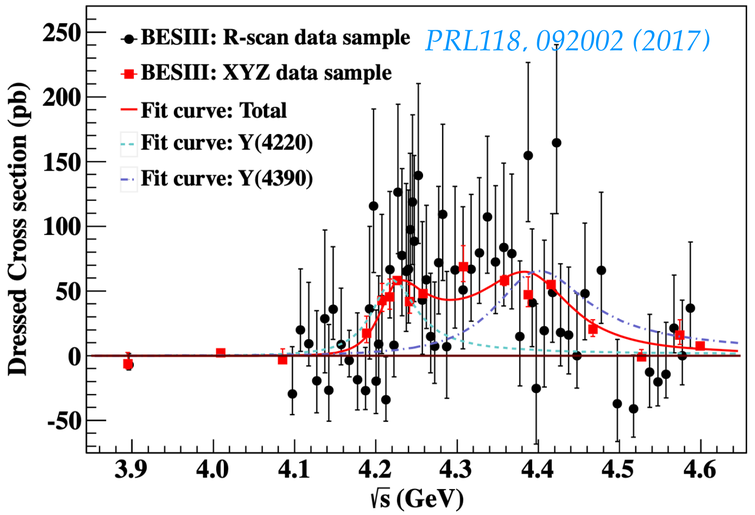


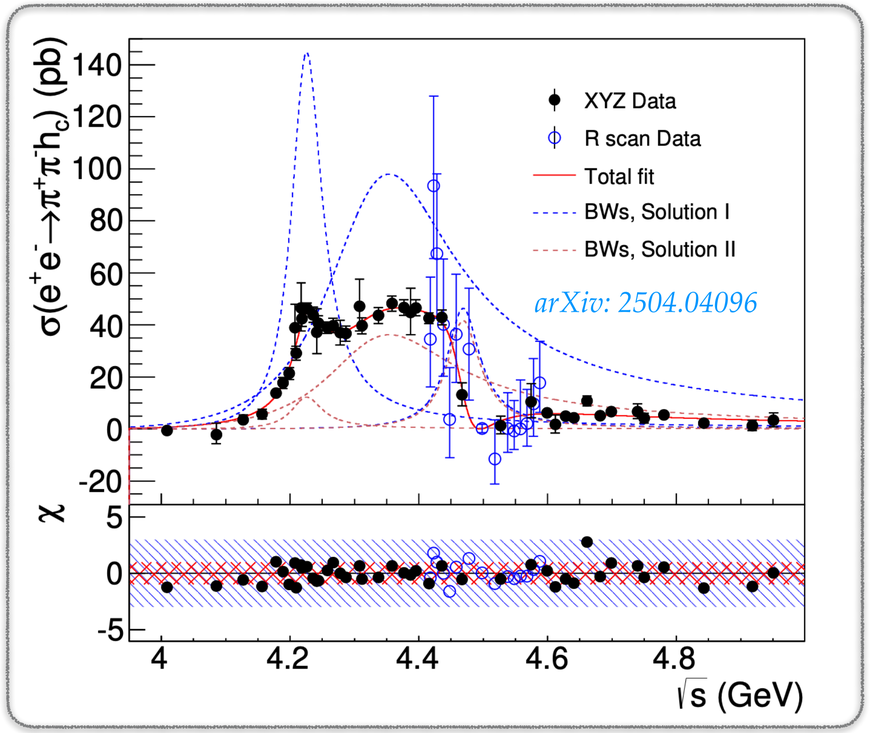


Update of $\sigma[e^+e^- \to \pi^+\pi^- h_c]$

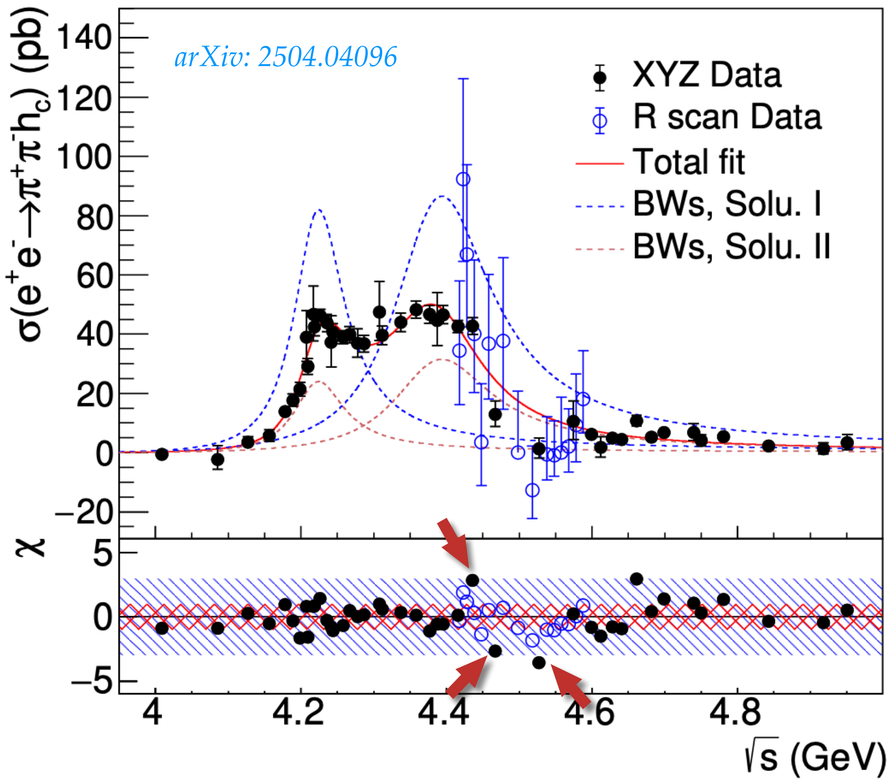
- The $e^+e^- \to \pi^+\pi^- h_c$ process was observed by CLEO at $\sqrt{s}$=4.17 GeV $[10\sigma]$ *PRL107, 041803 (2011)*
- The cross section of $e^+e^- \to \pi^+\pi^- h_c$ was measured by BESIII at $\sqrt{s}$ from 3.9 to 4.6 GeV, two resonant structures was observed *PRL118, 092002 (2017)*
- New data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





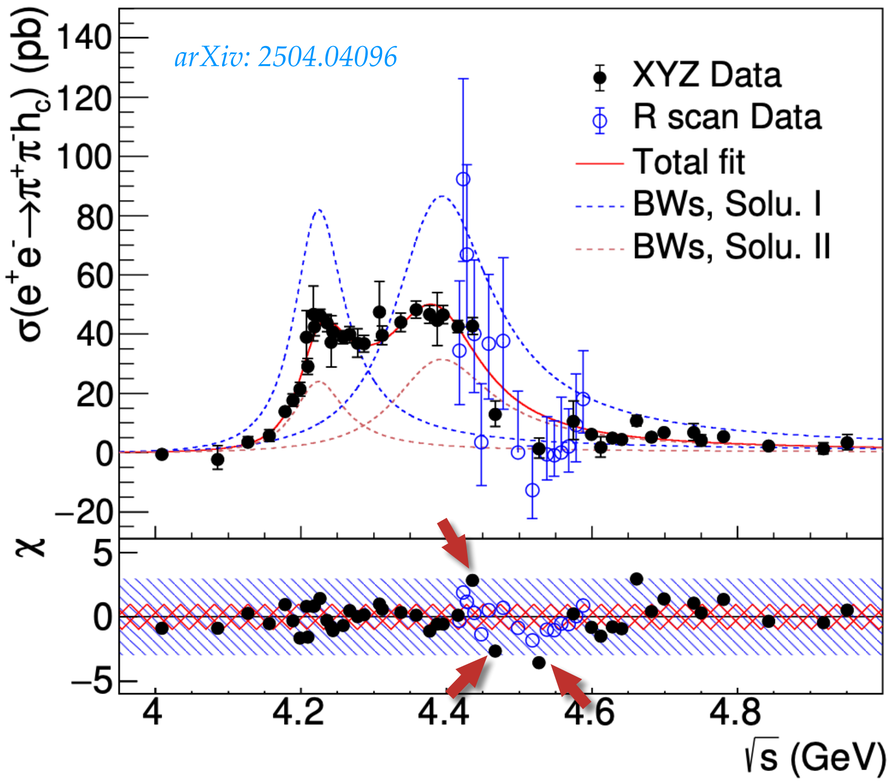


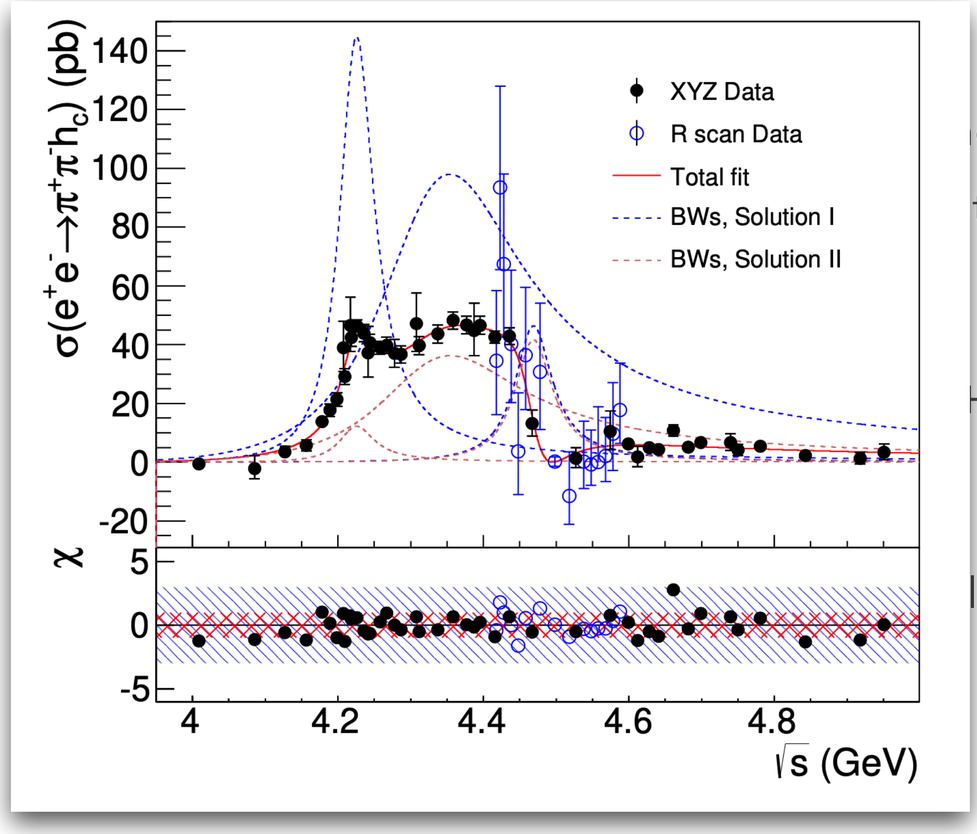
Update of $\sigma[e^+e^- \to \pi^+\pi^- h_c]$



- 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

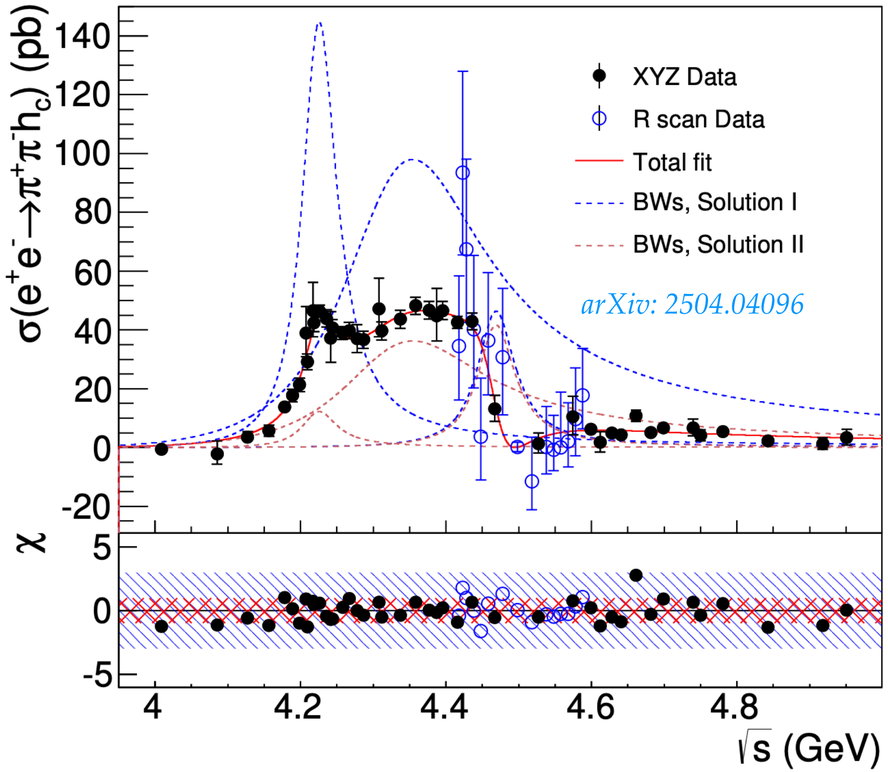
termt

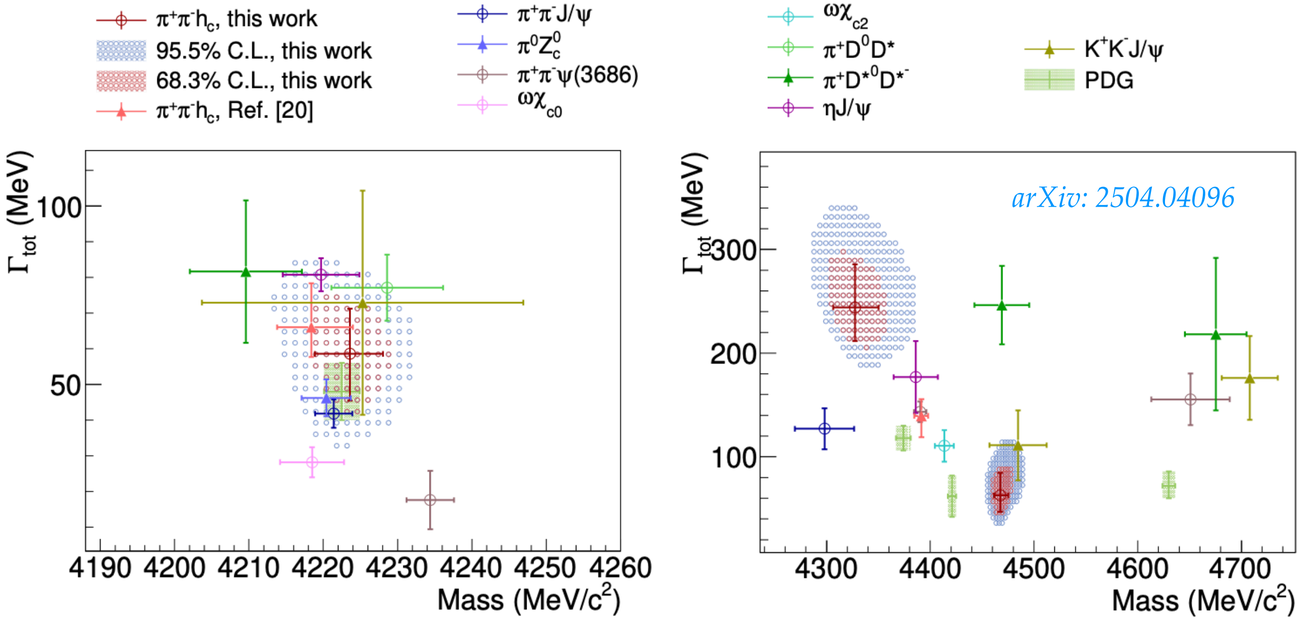
$- BW_3 e^{i\phi_3}|^2$

ler than 1σ

Cannot be described by two coherent BWs

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

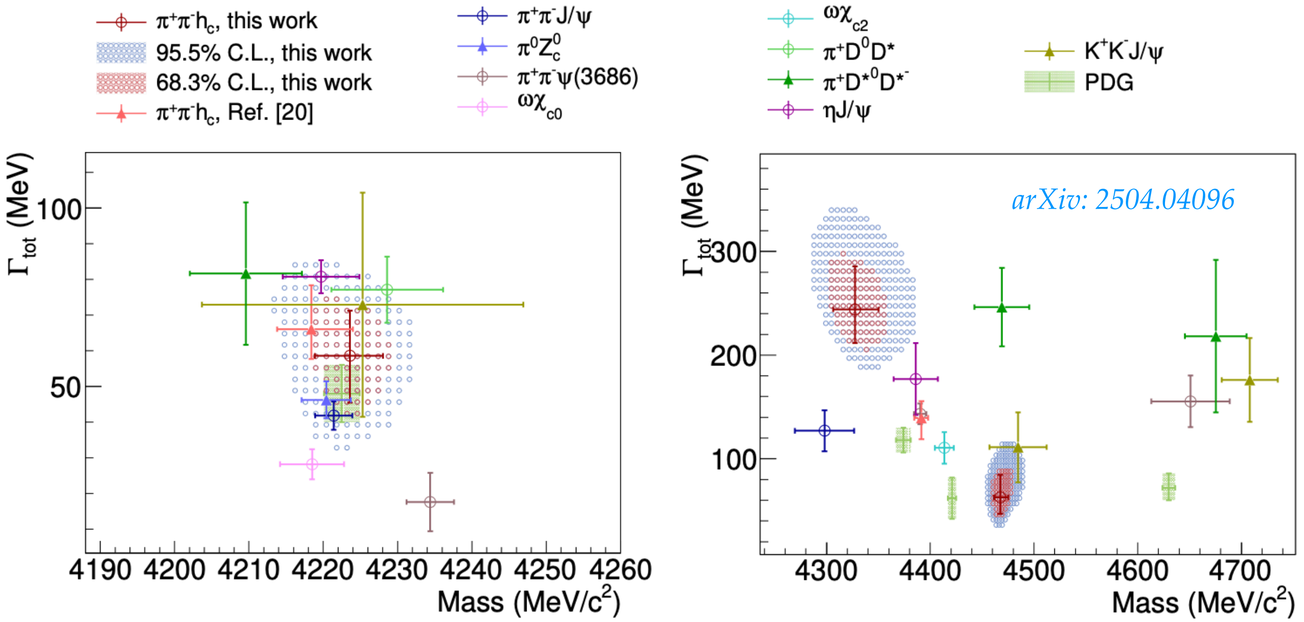




Resonance	Parameter	this measurement (3BW)	this measurement (2BW)	previous measurement
R_1	M (MeV/c^2)	$4223.6^{+3.6+2.6}_{-3.7-2.9}$	4219.7 ± 3.4	$4218.4 \pm 4.0 \pm 0.9$
	$\Gamma_{\rm tot}$ (MeV)	$58.5^{+10.8+6.7}_{-11.4-6.5}$	83.8 ± 5.5	$66.0 \pm 9.0 \pm 0.4$
R_2	M (MeV/c^2)	$4327.4^{+20.1+10.7}_{-18.8-9.3}$	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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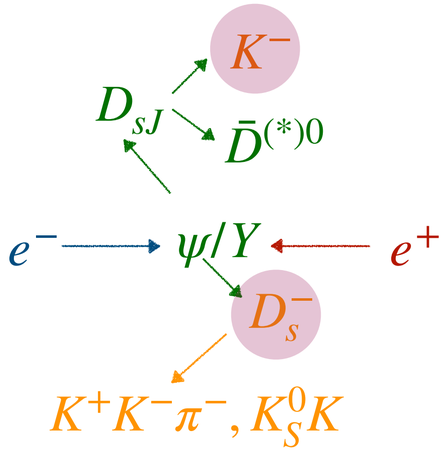
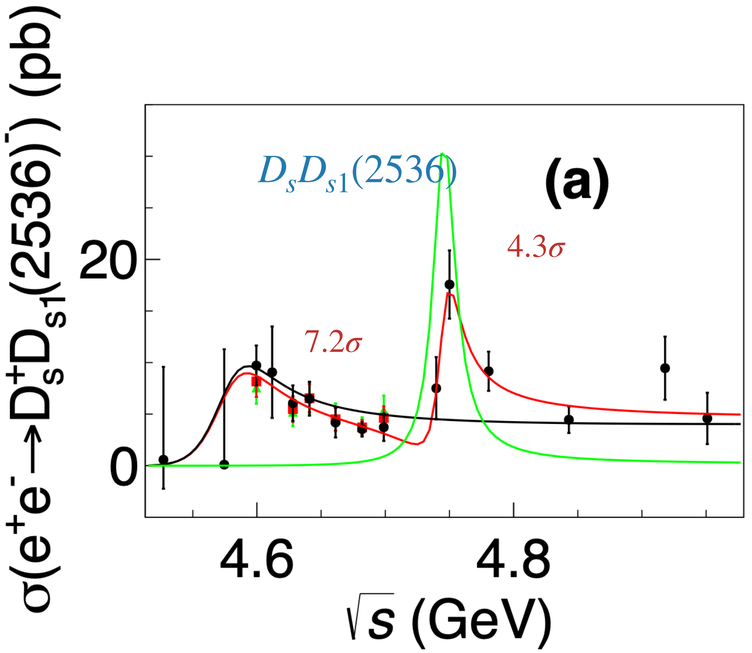
	χ^2/ndf	41.9/70	78.5/66	–

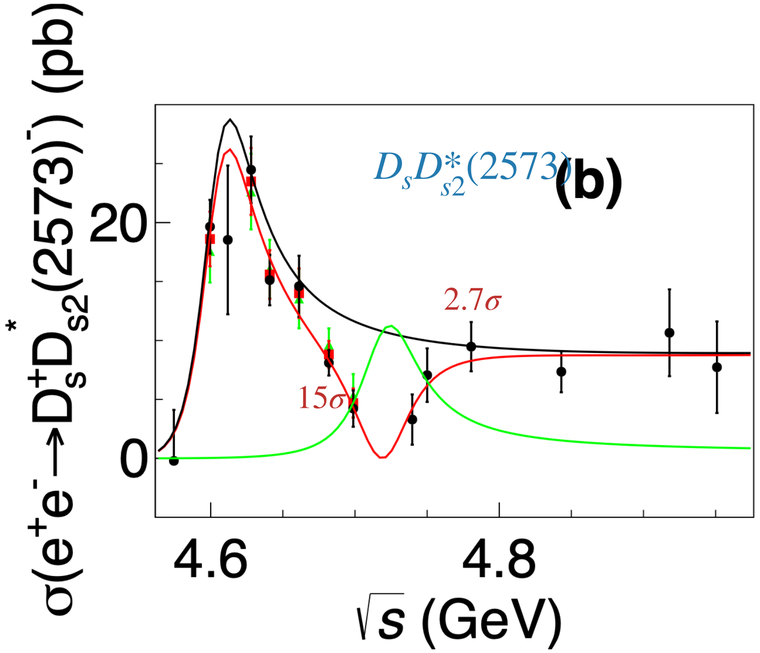
$e^+e^- \to D_sD_{s1}(2536)$ and $D_sD_{s2}^*(2573)$

- 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







	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]

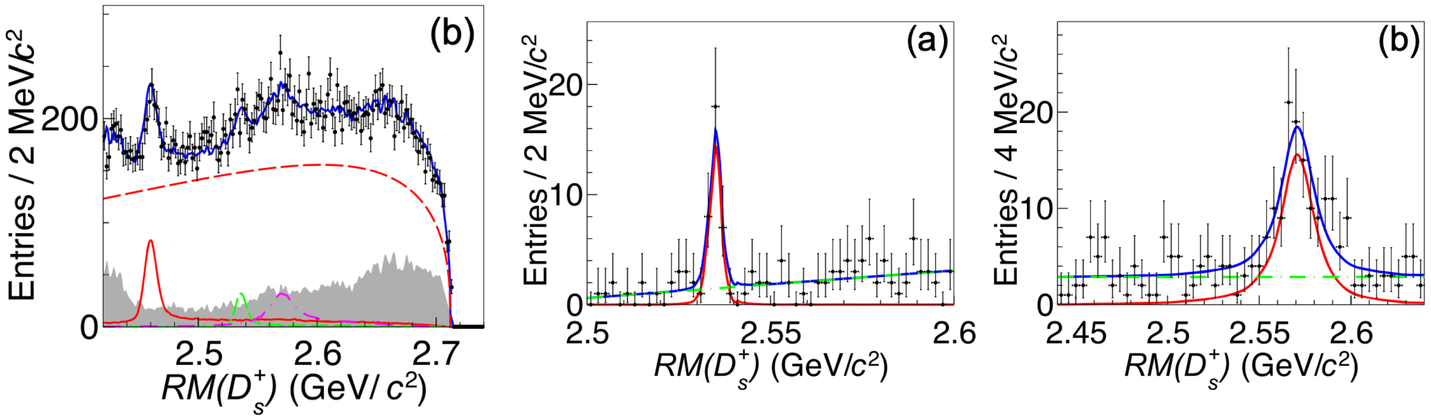
	R1	R2
Mass (MeV/c²)	4603.1[3.9, 0.8]	4720[13, 2]
Width (MeV)	45.2[5.7, 0.7]	50[12, 1]

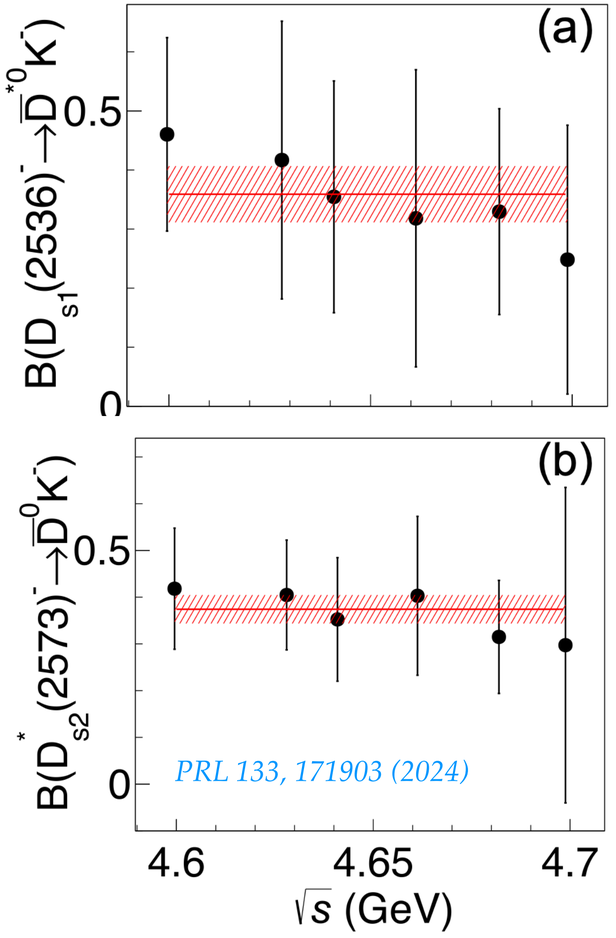
PRL 133, 171903 (2024)

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

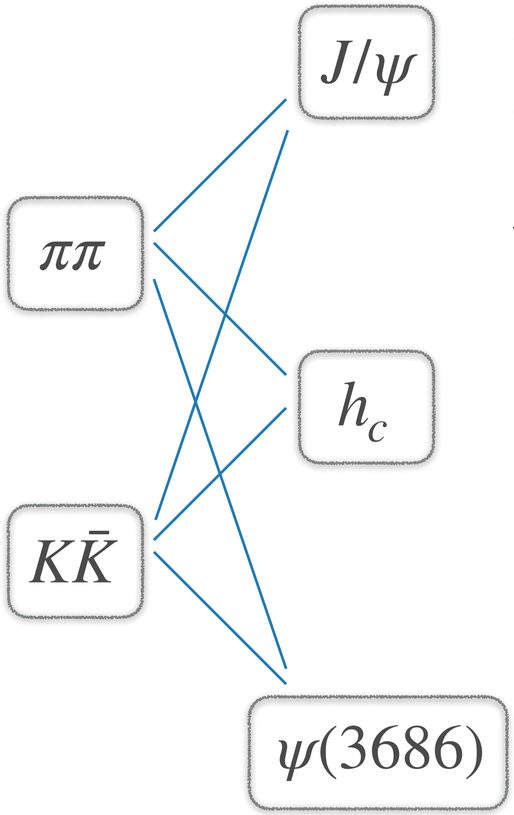
- ML fit to the exclusive and inclusive CS: $L_i(\sigma^{\rm inc}_{i,j}, \delta^{\rm inc}_{i,j}, \sigma^{\rm exc}_{i,j}, \delta^{\rm exc}_{i,j}; \sigma_{i,j}, B_i) = \Pi^6_{j=1} L^{\rm inc}_{i,j} L^{\rm exc}_{i,j}$
- The absolute branching fractions are:
  - $B(D_{s1}(2536)^- \to \bar{D}^{*0}K^-) = (35.9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

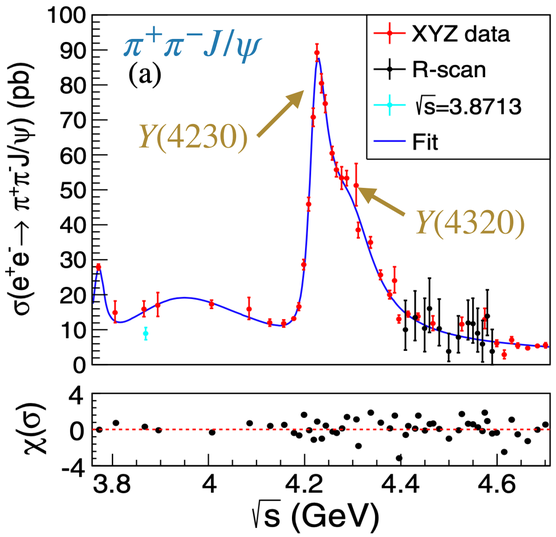
PRD93, 034035 (2016);
PRL 128, 112001 (2022)

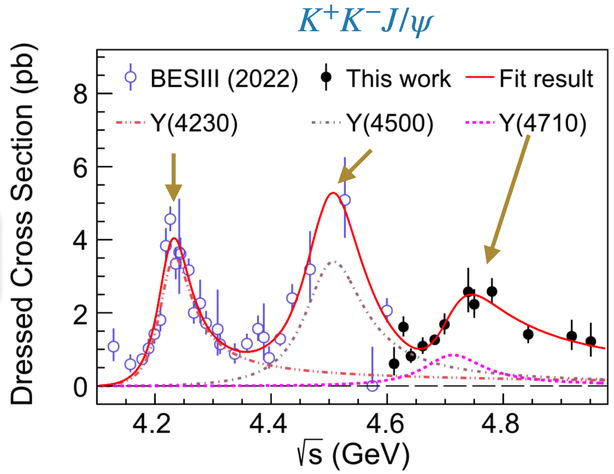


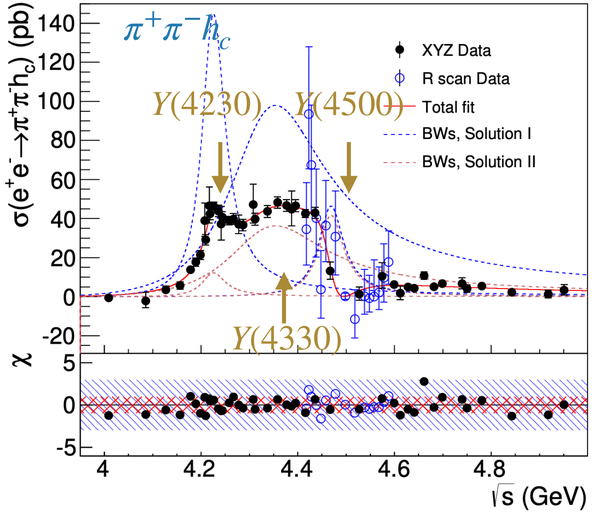


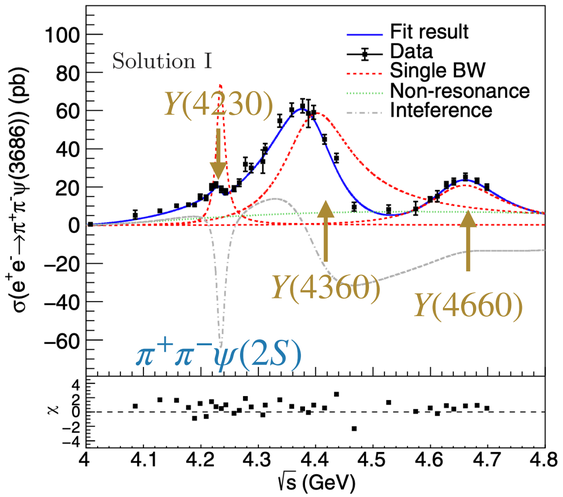
Study of $e^+e^- \to K\bar{K} + c\bar{c}$











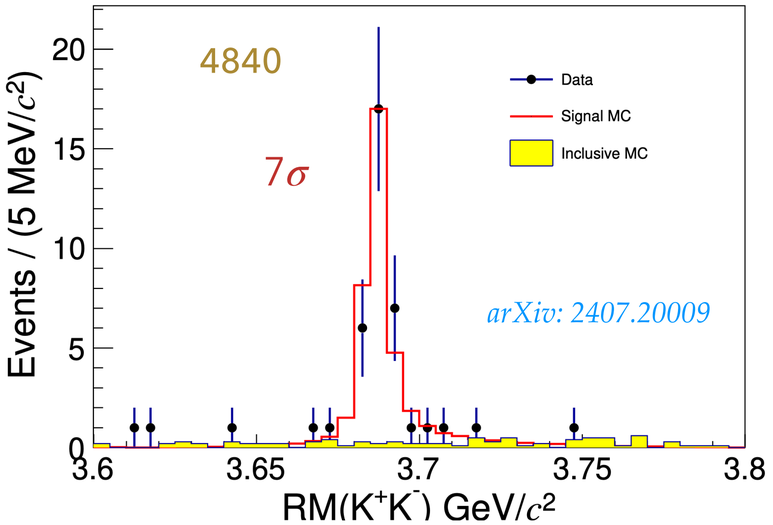
$K\bar{K}h_c$

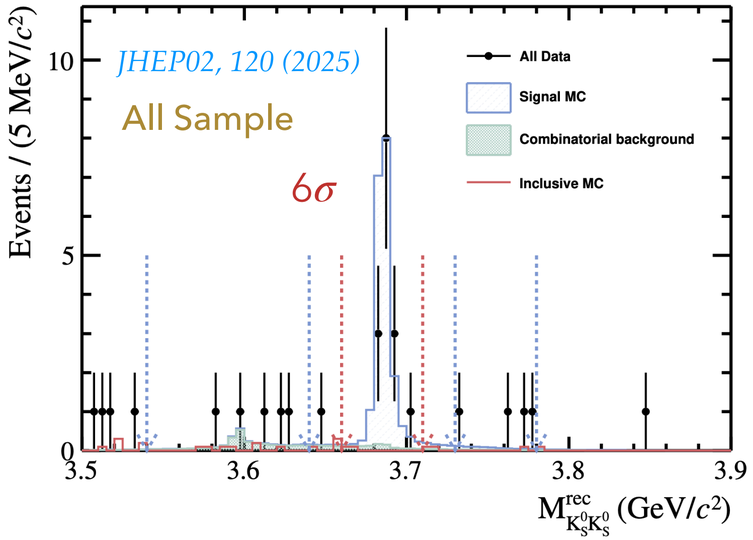
$K\bar{K}\psi(2S)$

Mass threshold: ~4.513 GeV, 4.673 GeV

Study of $e^+e^- \to K\bar{K}\psi(3686), K\bar{K}h_c$

- Partial reconstruction technique to improve the reconstruction efficiency
  - $K^+K^-\psi(3686)$: data sample at $\sqrt{s} = 4.669$ to 4.951 GeV, 2.5 fb^{-1}
    - $e^+e^- \to K^+K^-\psi(3686)$, $\psi(3686) \to J/\psi + X$, $J/\psi \to l^+l^-$
    - $e^+e^- \to K^+K^-\psi(3686)$, $\psi(3686) \to J/\psi\pi^+\pi^-$, $J/\psi \to l^+l^-$, missing one Kaon
    - $e^+e^- \to K^+K^-\psi(3686)$, $\psi(3686) \to l^+l^-$
    - $e^+e^- \to K^+K^-\psi(3686)$, $\psi(3686) \to l^+l^-$, missing one Kaon
  - $K^0_SK^0_S\psi(3686)$: data sample at $\sqrt{s} = 4.682$ to 4.951 GeV, 4.1 fb^{-1}
    - $e^+e^- \to K^0_SK^0_S\psi(3686)$, $\psi(3686) \to J/\psi + X$, $J/\psi \to l^+l^-$, $K^0_S \to \pi^+\pi^-$
  - $K^0_SK^0_Sh_c$:data sample at $\sqrt{s} = 4.6$ to 4.951 GeV, 6.4 fb^{-1}
    - $e^+e^- \to K^0_SK^0_S + h_c$, $h_c \to \gamma\eta_{c'}$ tag $K^0_SK^0_S + \gamma$





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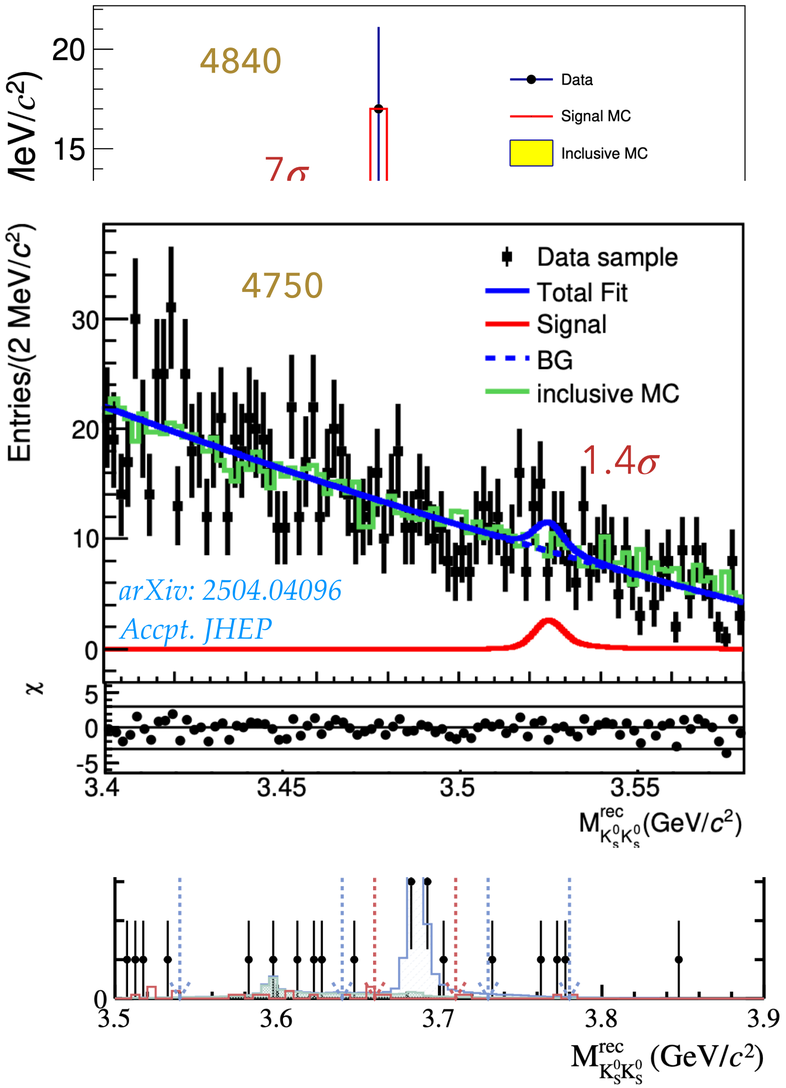
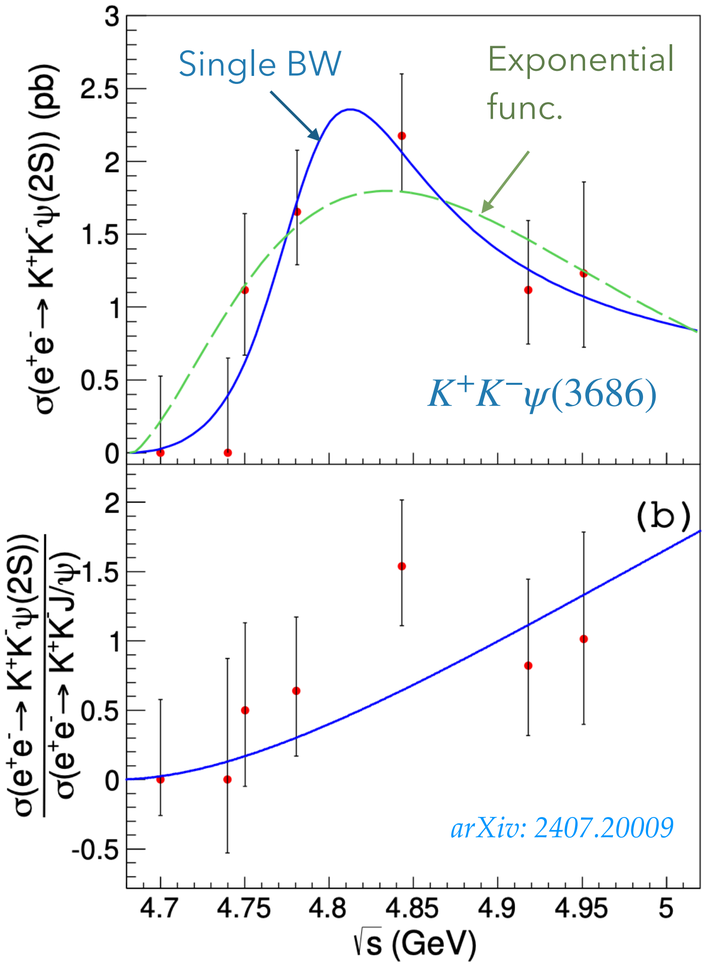
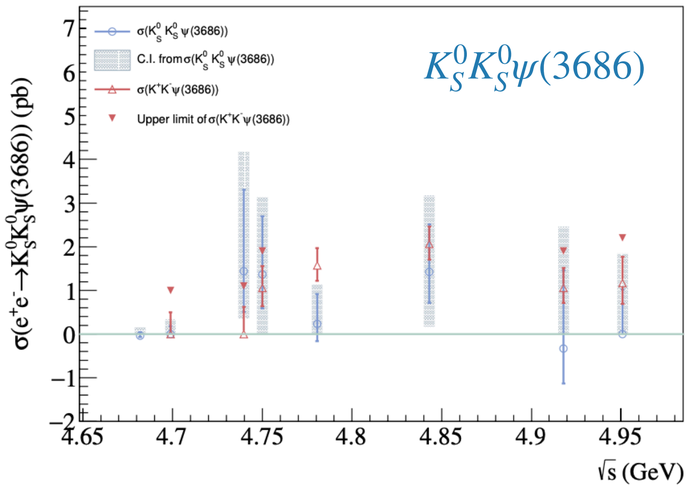
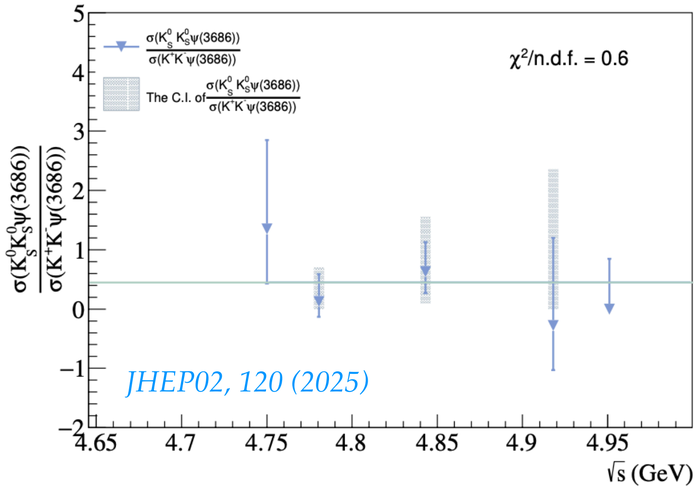
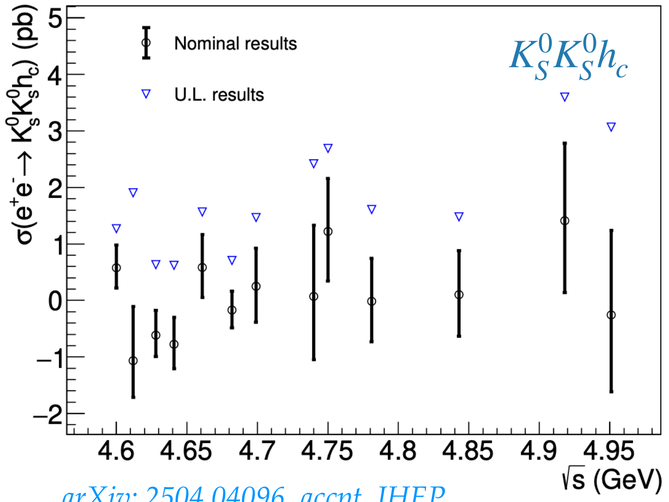


Study of $e^+e^- \to K\bar{K}\psi(3686), K\bar{K}h_c$









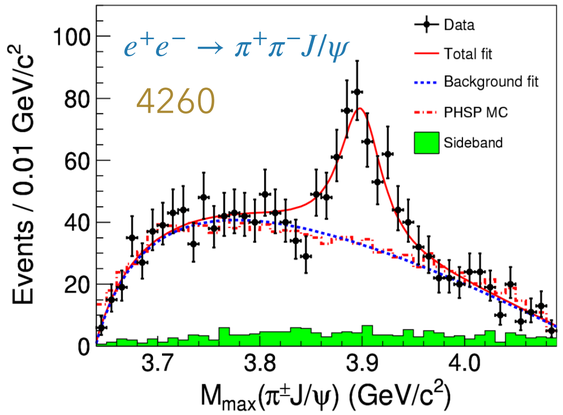
arXiv: 2504.04096, accpt. JHEP

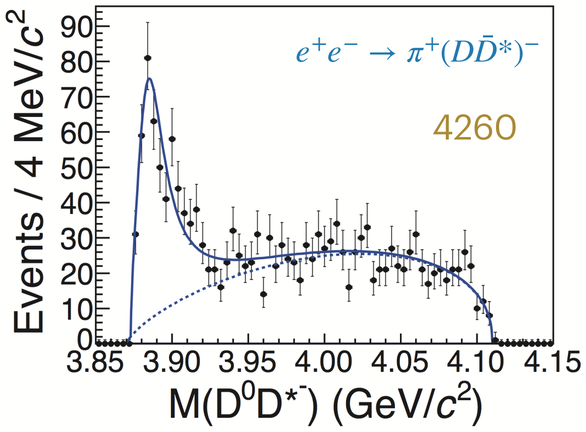
$$R = \frac{\sigma[e^+e^- \to K^0_S K^0_S \psi(3686)]}{\sigma[e^+e^- \to K^+K^-\psi(3686)]} = 0.45 \pm 0.25$$

$M = 4787.7 \pm 17.7\ \mathrm{MeV}/c^2, \Gamma = 110.3 \pm 33.9\ \mathrm{MeV}$

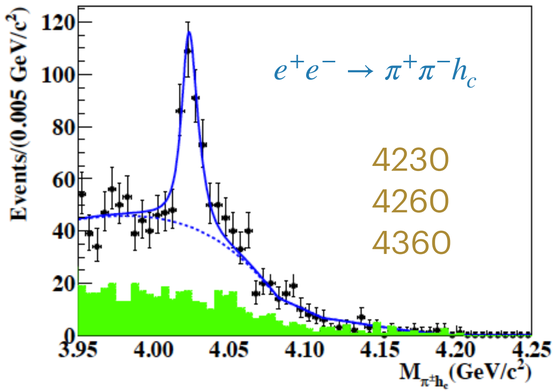
Z_{cs} in $e^+e^- \to K\bar{K} + c\bar{c}$

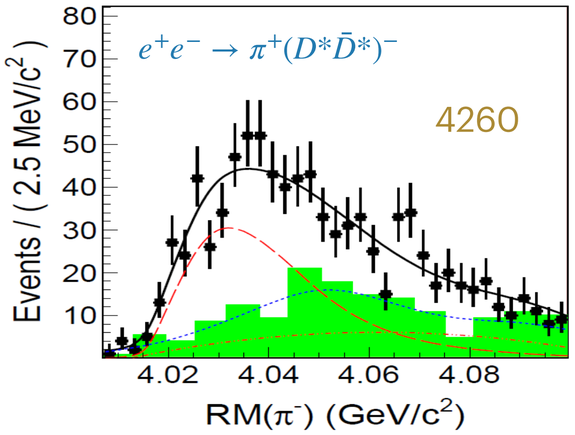
$Z_c(3900)/Z_c(3885)$

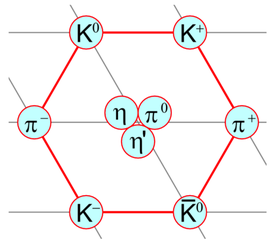




$Z_c(4020)/Z_c(4025)$



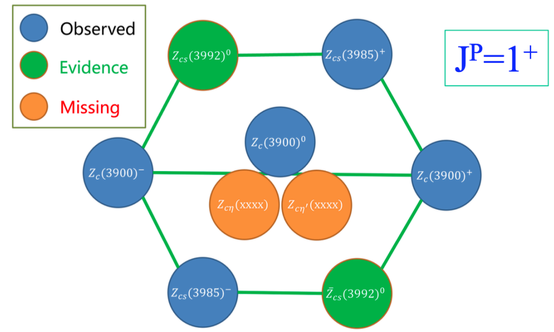


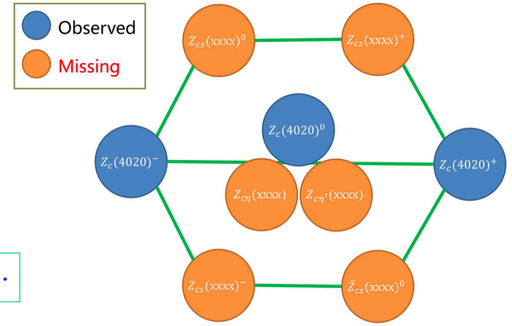


+ J/ψ

+ h_c

+ $\psi(2S)$, ⋯



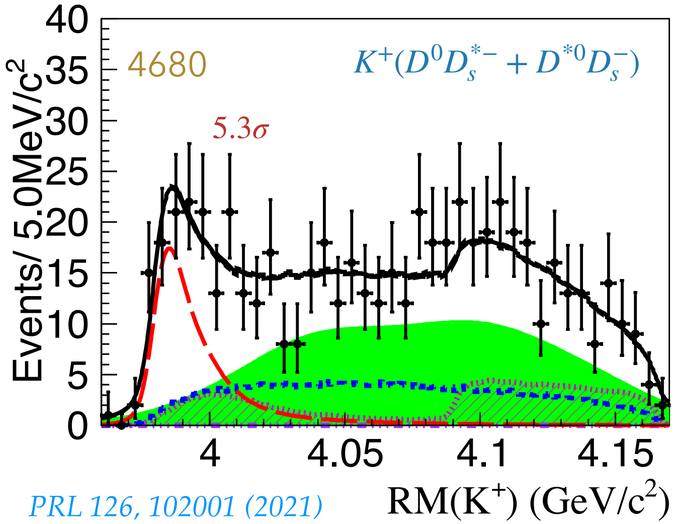


PRL110, 252001 (2013) PRL112, 022001 (2014)
PRL111, 242001 (2013) PRL112, 132001 (2014)

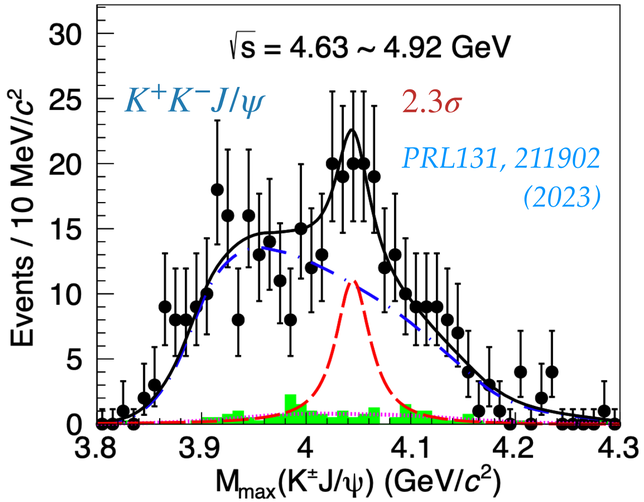
PRL115, 112003 (2015) PRL115, 222002 (2015)
PRL113, 212002 (2014) PRL115, 182002 (2015)

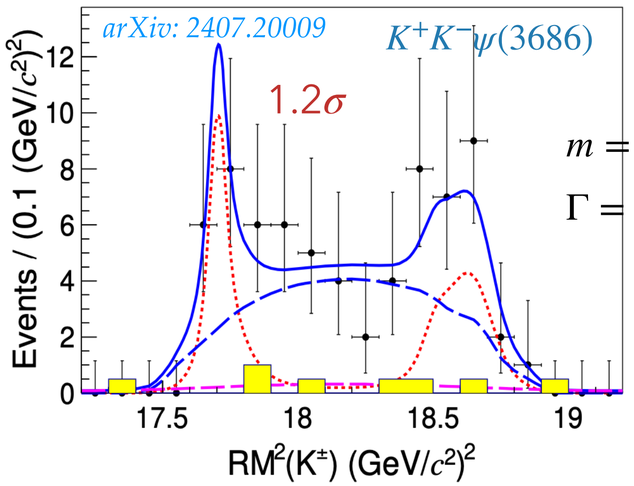
Seen in both charged and neutral modes

Z_{cs} in $e^+e^- \to K\bar{K} + c\bar{c}$



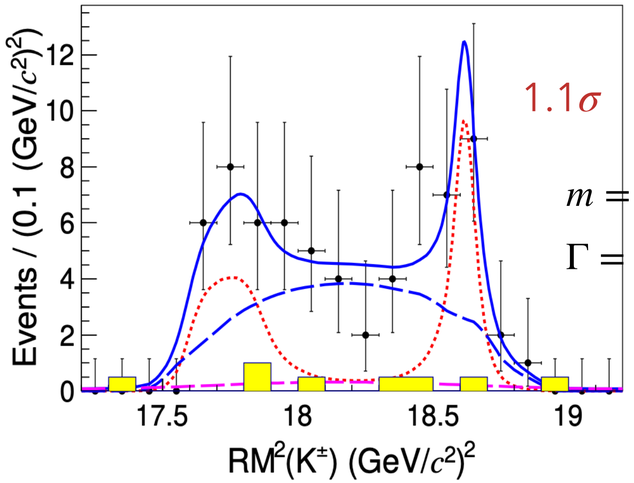
PRL 126, 102001 (2021)





$m = 4208.4 \pm 3.1$ MeV/c^2

$\Gamma = 6.1 \pm 5.7$ MeV



$m = 4316.0 \pm 2.7$ MeV/c^2

$\Gamma = 9.0 \pm 8.6$ MeV

$Z_{cs}(3985)$:

$m = 3985^{+2.1}_{-2.0} \pm 1.7$ MeV/c^2

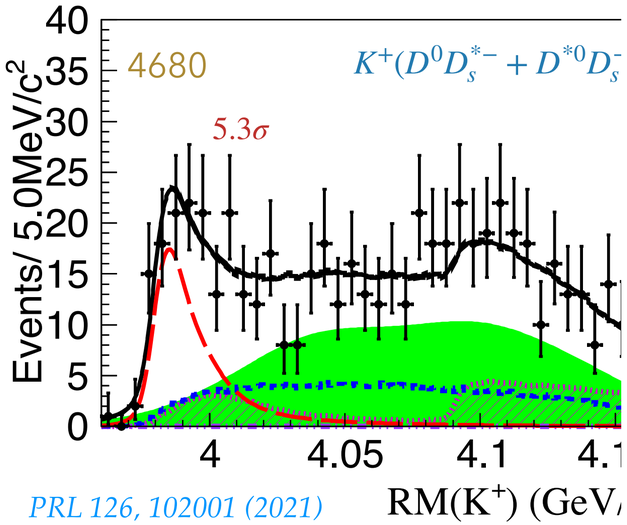
$\Gamma = 13.8^{+8.1}_{-5.2} \pm 4.9$ MeV

$m = 4044 \pm 6$ MeV/c^2

$\Gamma = 36 \pm 16$ MeV

$$R \equiv \frac{B[Z_{cs}(3985) \to KJ/\psi]}{B[Z_{cs}(3985) \to (\bar{D}^0 D_s^* + \bar{D}^{*0} D_s)]} < 0.03 \text{ at } 90\% \text{ C. L.}$$

Z_{cs} in $e^+e^- \to K\bar{K} + c\bar{c}$



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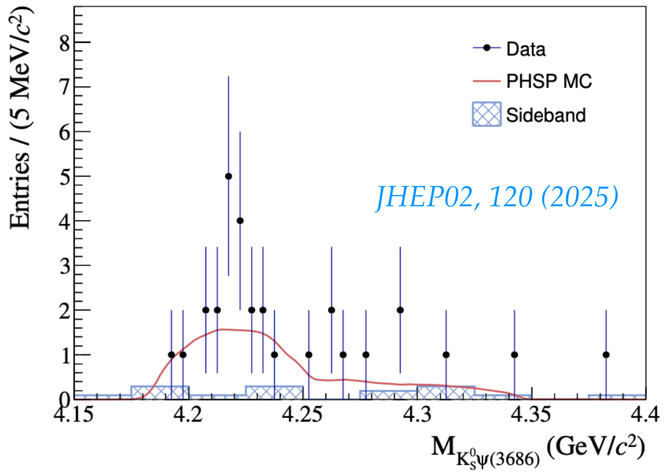
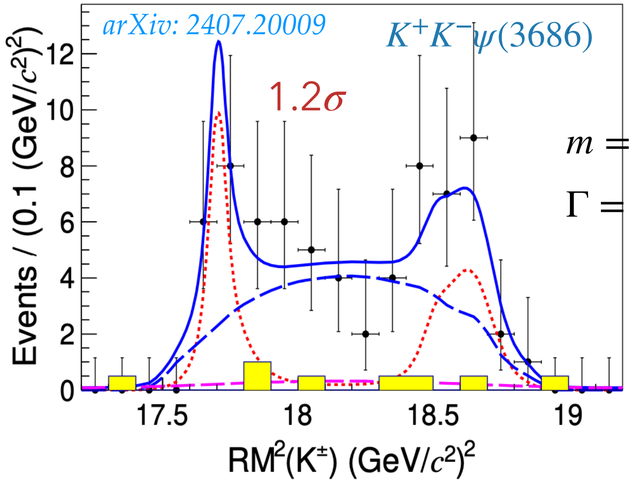




$m = 4208.4 \pm 3.1$ MeV/c^2

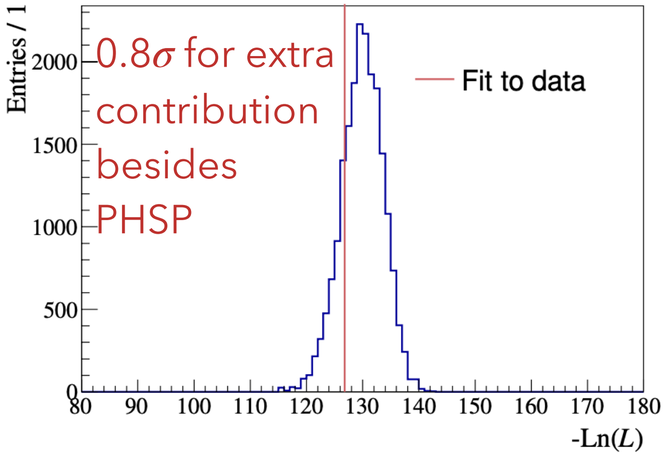
$\Gamma = 6.1 \pm 5.7$ MeV

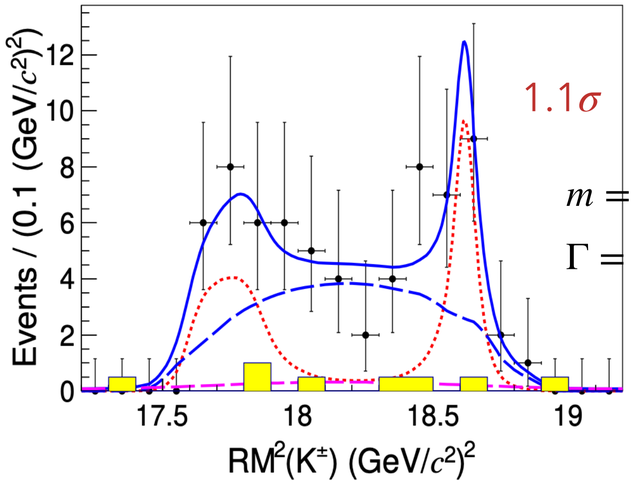
$Z_{cs}(3985)$:

$m = 3985^{+2.1}_{-2.0} \pm 1.7$ MeV/c^2

$\Gamma = 13.8^{+8.1}_{-5.2} \pm 4.9$ MeV

$$R \equiv \frac{B[Z_{cs}(3985)}{B[Z_{cs}(3985) \to (\bar{D}}$$





$m = 4316.0 \pm 2.7$ MeV/c^2

$\Gamma = 9.0 \pm 8.6$ MeV

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 4.6 and 4.75 GeV observed in $D_s D_{s1}(2536)$ and $D_s D_{s2}^*(2573)$ cross section
  - Y and Z_{cs} studies at $K\bar{K} + c\bar{c}$ final state, need more statistics
- BEPCII finished upgrade, 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!

Summary

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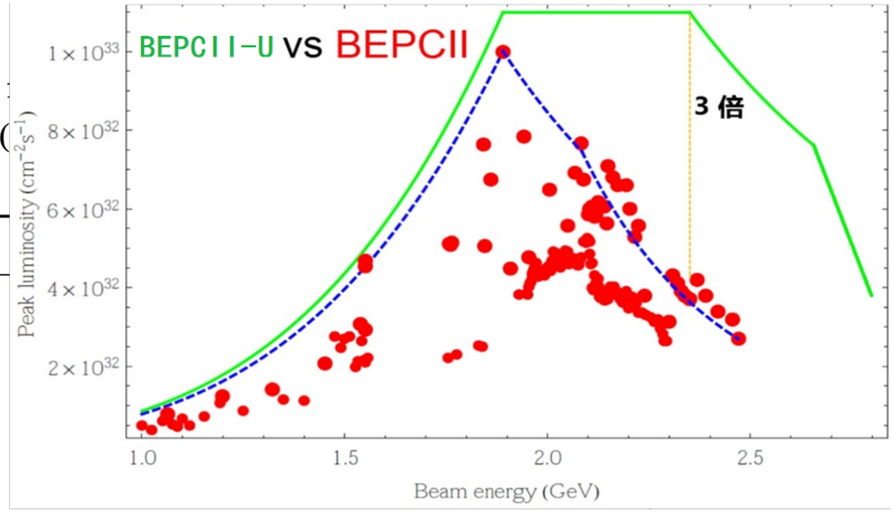
Thank You!

Future Data Samples

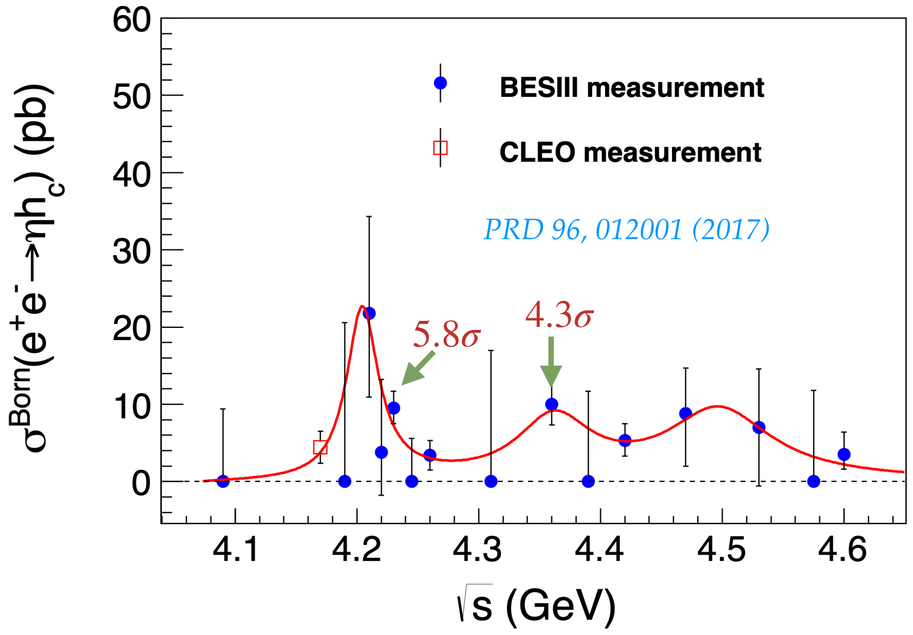
Table 7.1. List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples
most column shows the number of required data taking days with the current (T_C) and upgraded (
implementation and beam current increase.

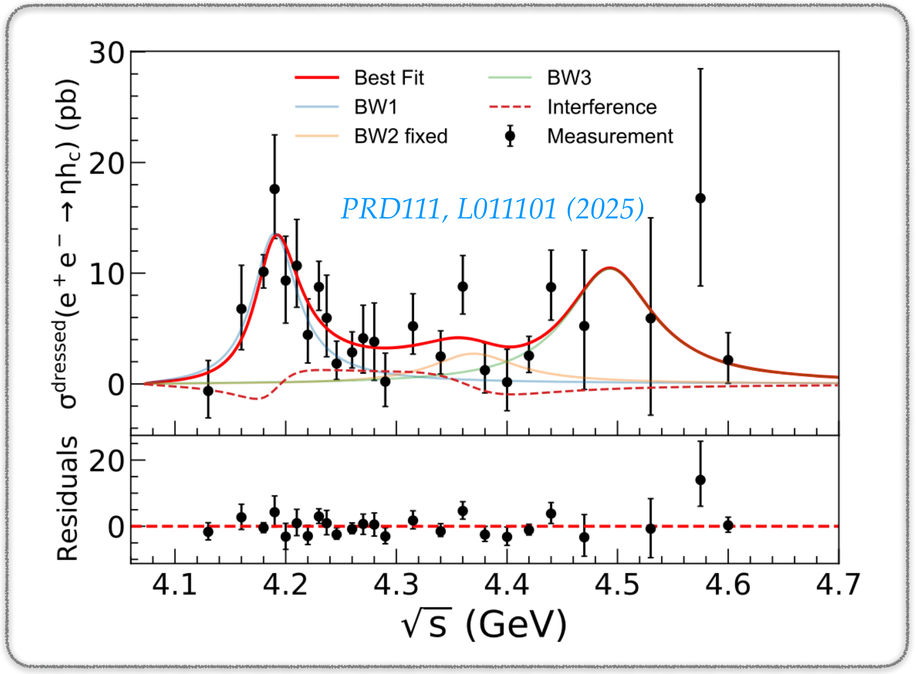
Energy	Physics motivations	Current data		
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A		
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)		
J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)		
$\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (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



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





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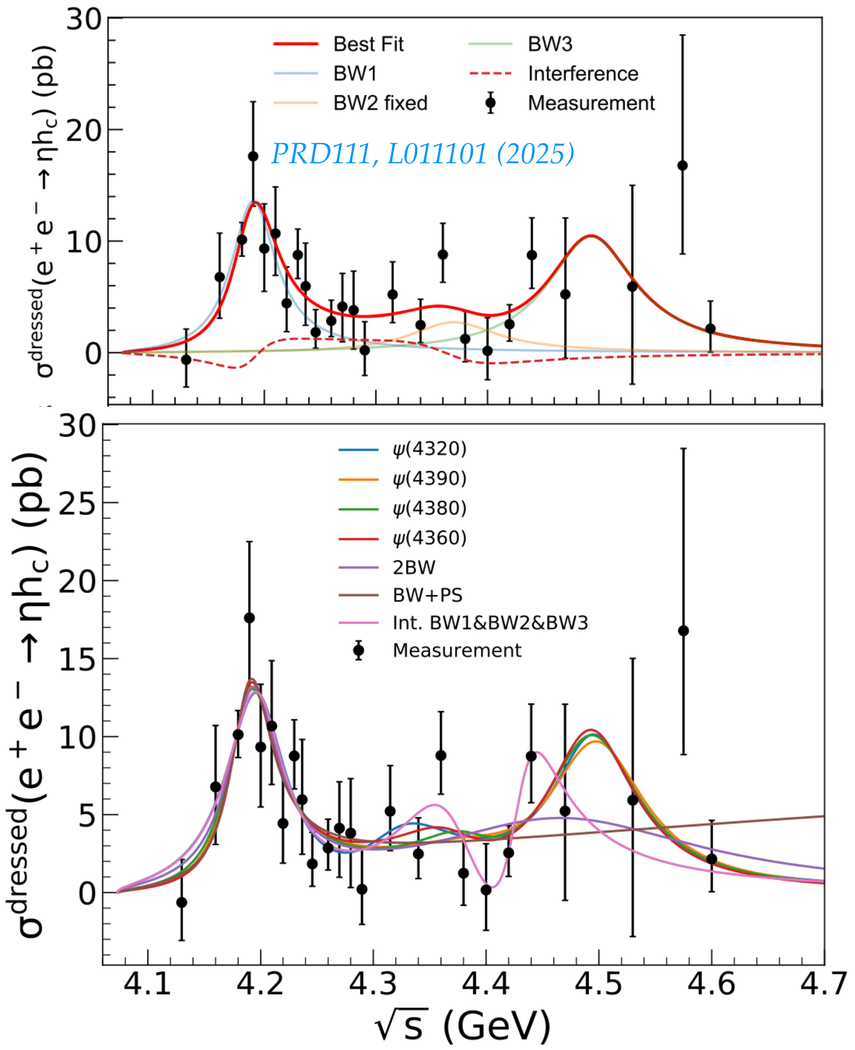
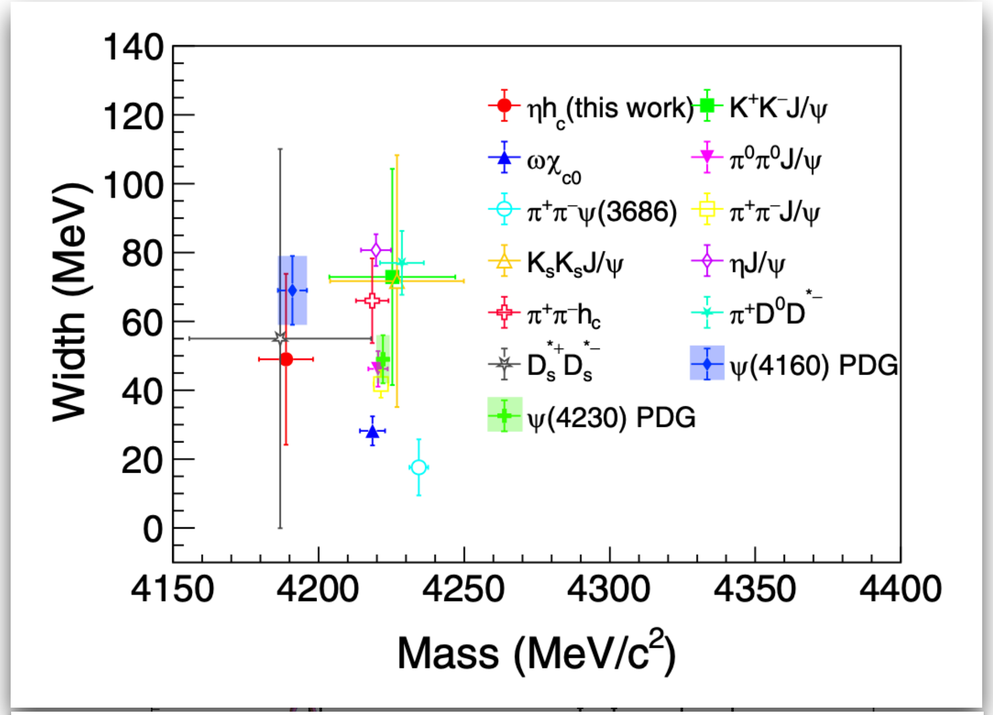


- $\sigma^{\text{dressed}} = |BW_1 + BW_2 e^{i\phi}|^2 + |BW_3|^2$
  - Mass and Width of BW_2 fixed to $Y(4360)$
  - $M_1 = 4188.8 \pm 4.7 \pm 8.0$ MeV/c^2

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

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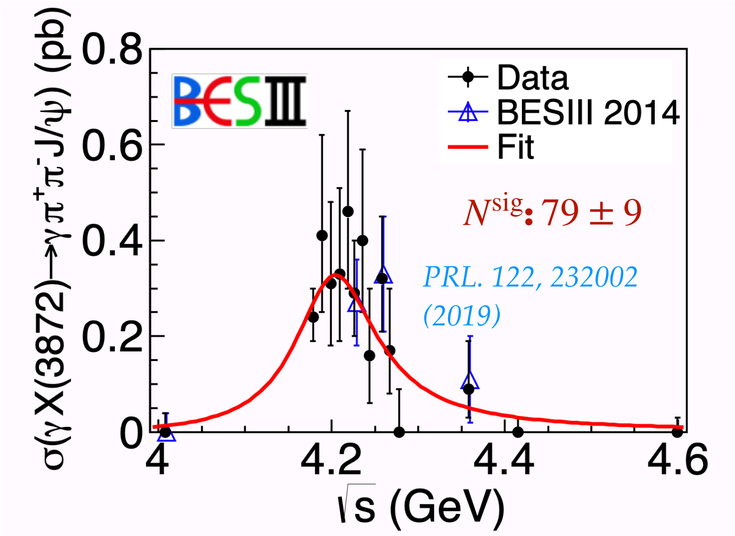
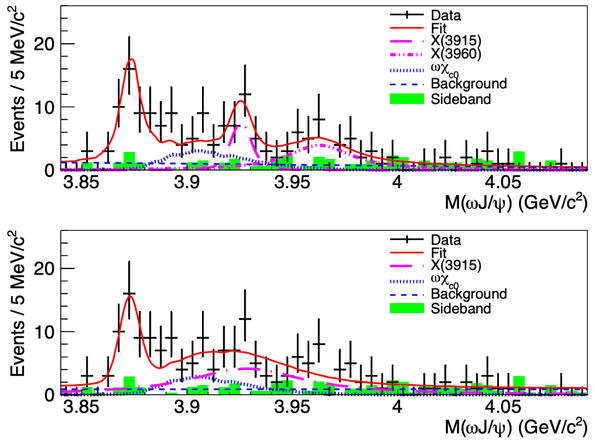
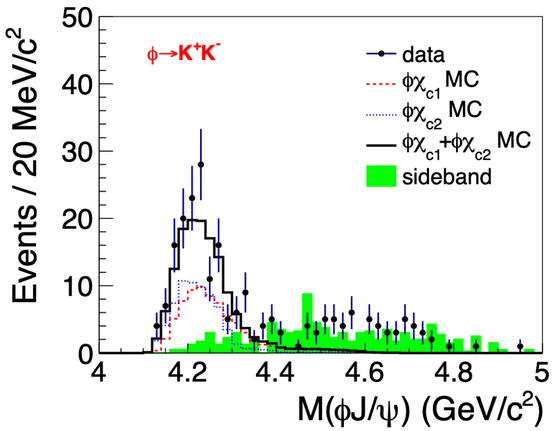
C-even States

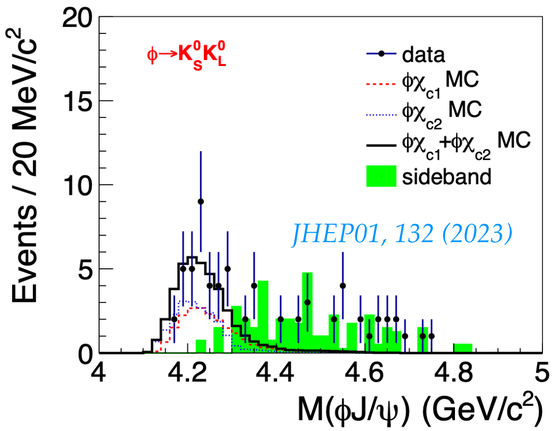
- Small production rate in radiative transition process
- Radiative and hadronic transitions to X(3872) are observed at BESIII
- Several decay modes of X(3872) have been searched: $\pi^0\chi_{c1}$ [observed], $\pi\pi\chi_{c0,1,2}$, $\pi\chi_{c0,2}$, $\pi\pi\eta$, $\gamma\psi_2(3823)$ [not found]
- Found 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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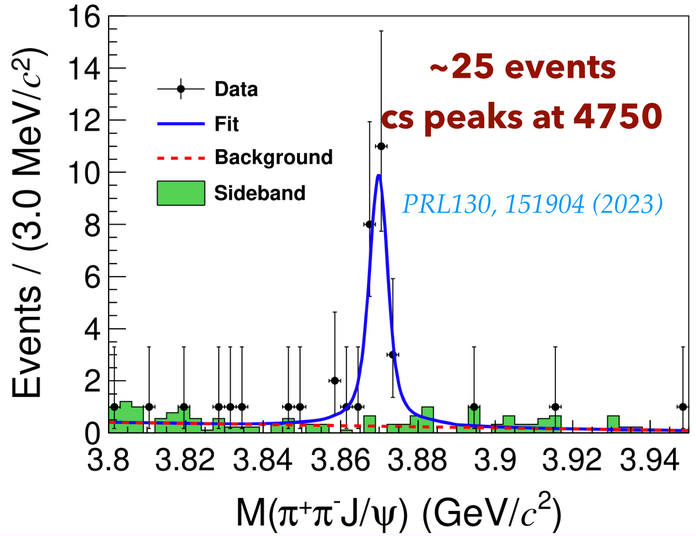
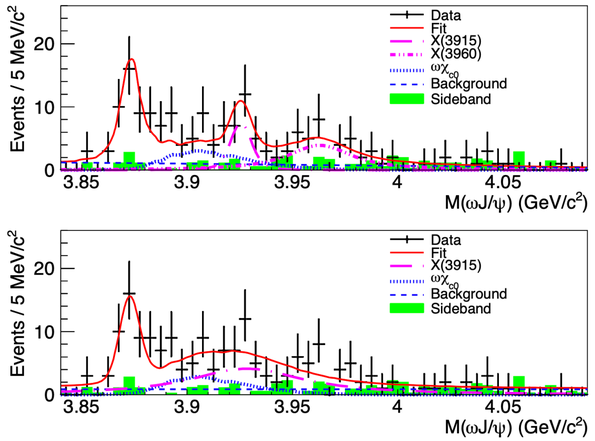
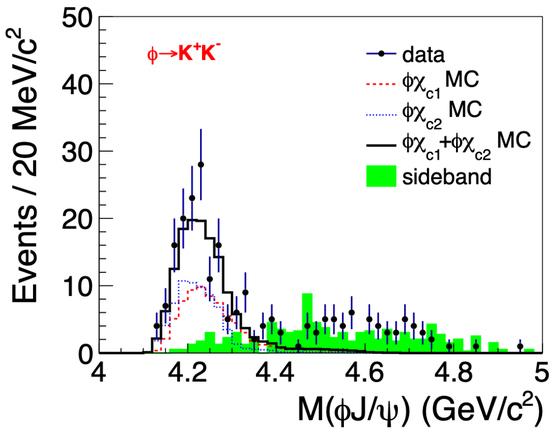
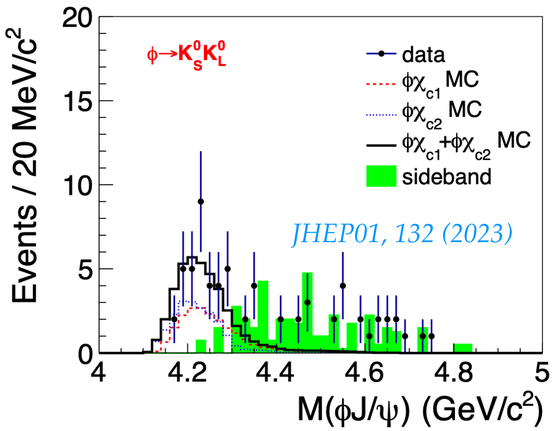


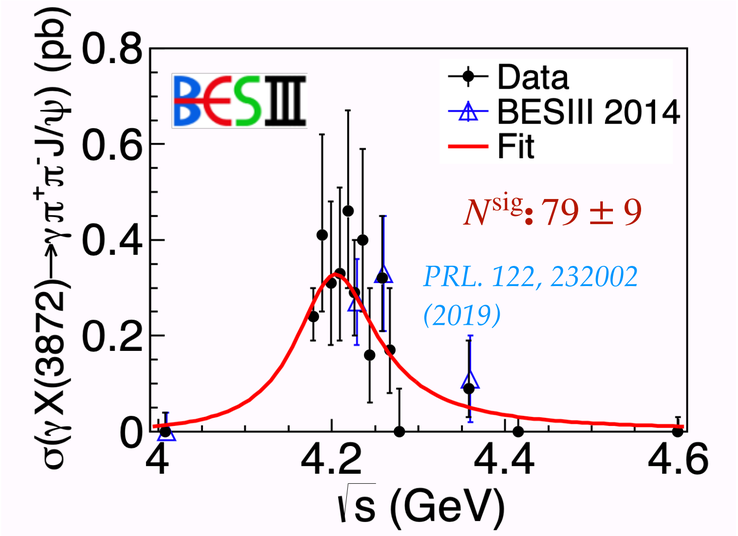


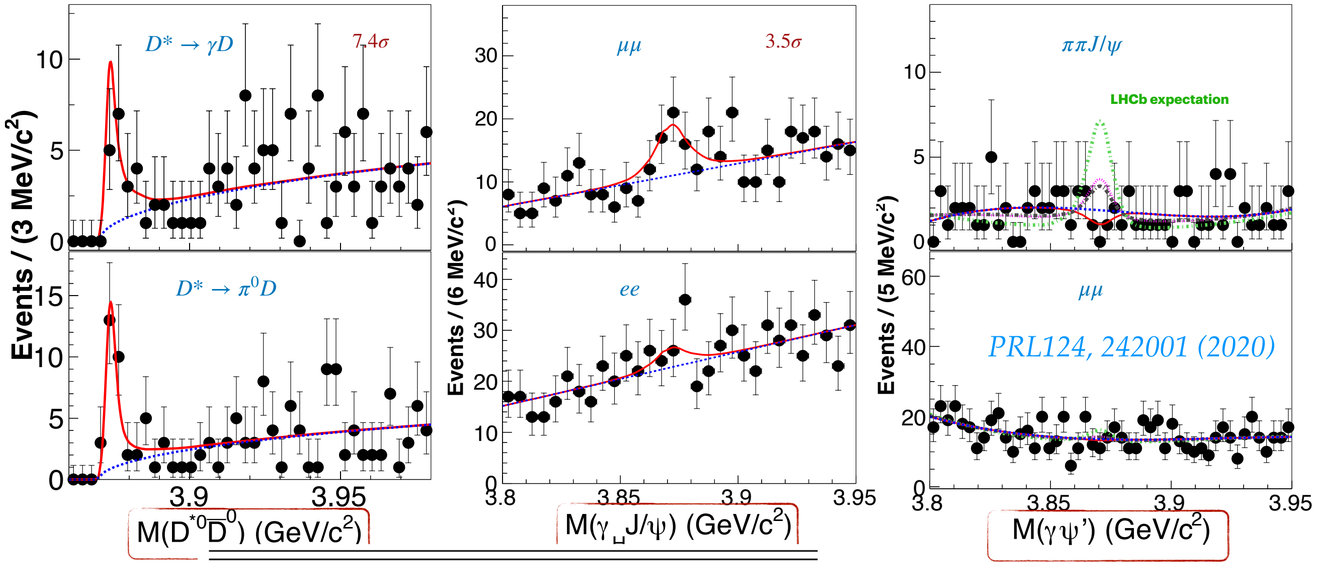
PRL 122, 232002 (2019)





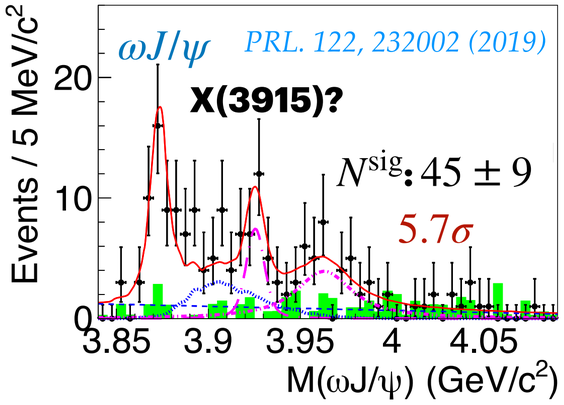
X(3872) Decay Property

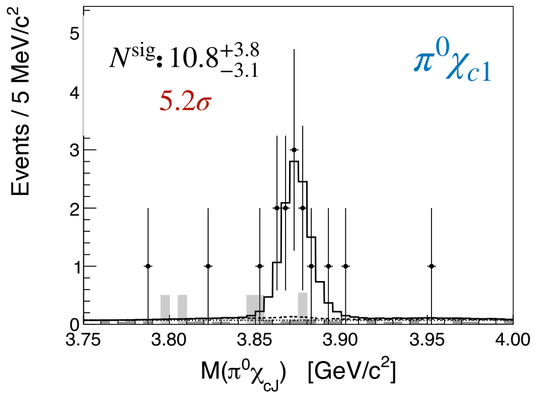




mode	ratio	UL
$\gamma J/\psi$	0.79 ± 0.28	-
$\gamma\psi'$ 2.8σ lower	-0.03 ± 0.22	< 0.42
$\gamma D^0 \bar{D}^0$	0.54 ± 0.48	< 1.58
$\pi^0 D^0 \bar{D}^0$	-0.13 ± 0.47	< 1.16

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)