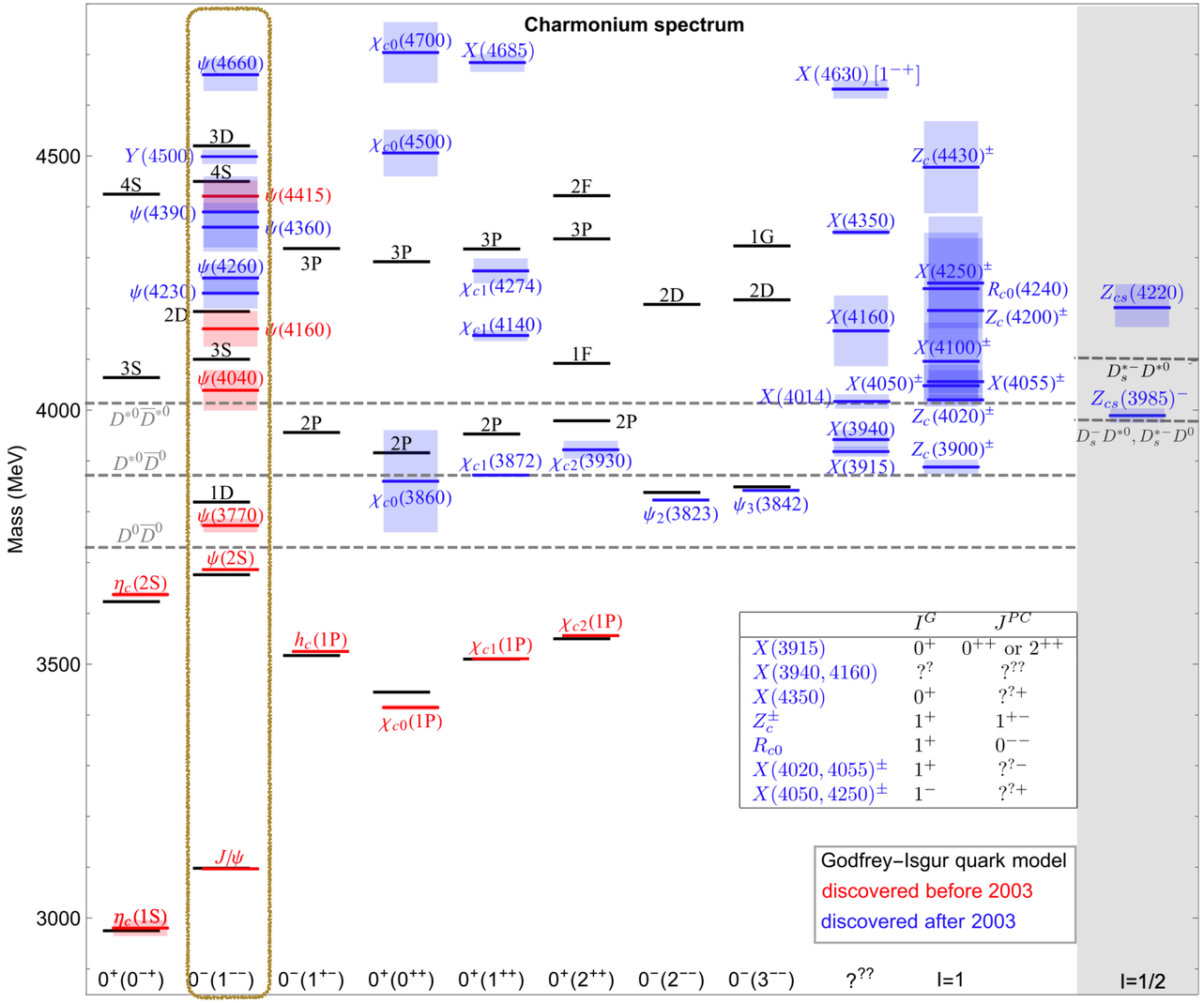
Recent Progress on Vector Charmonium(-like) States

Yuping Guo (郭玉萍)

guoyp@fudan.edu.cn

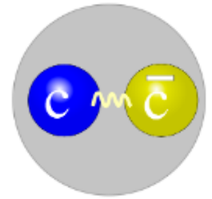
强子物理在线论坛 Hadron Physics Online Forum (HAPOF) 2024.01.19

Charmonium Spectroscopy



	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

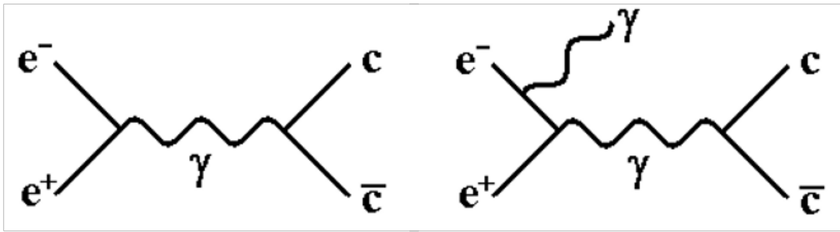


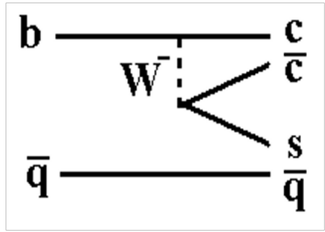
Notation: $n^{2S+1}L_J$

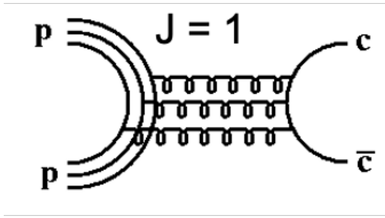
J^{PC}

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

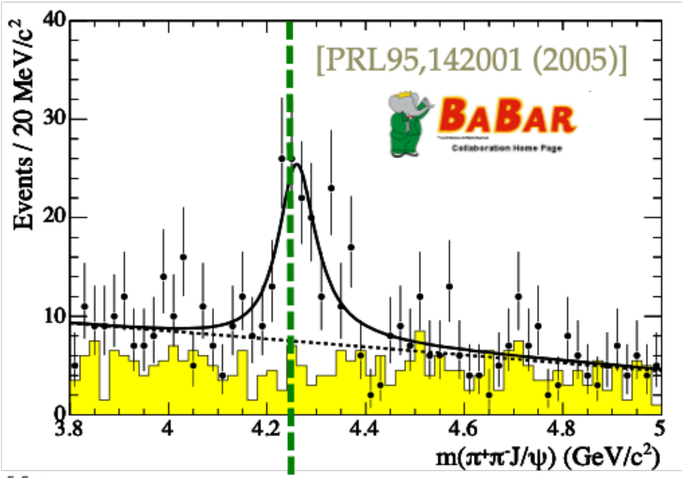


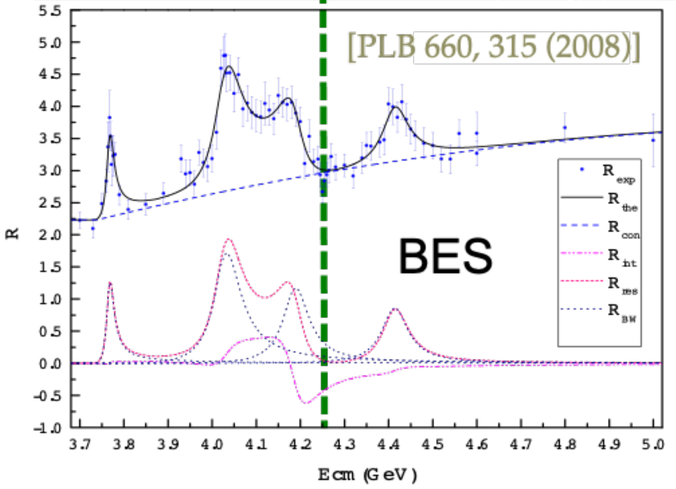


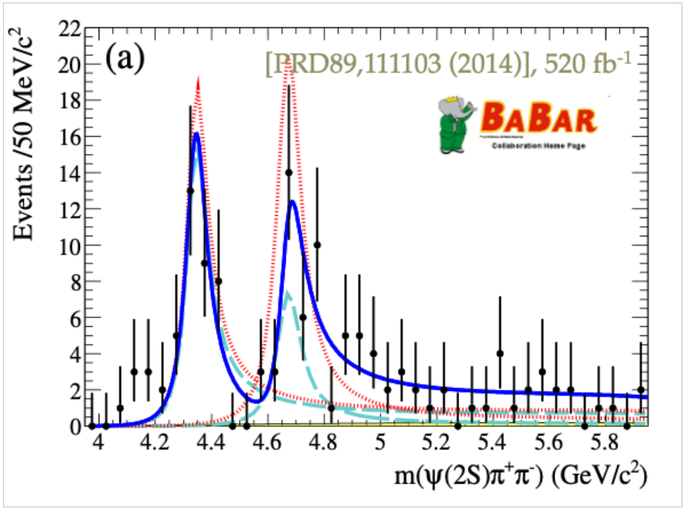


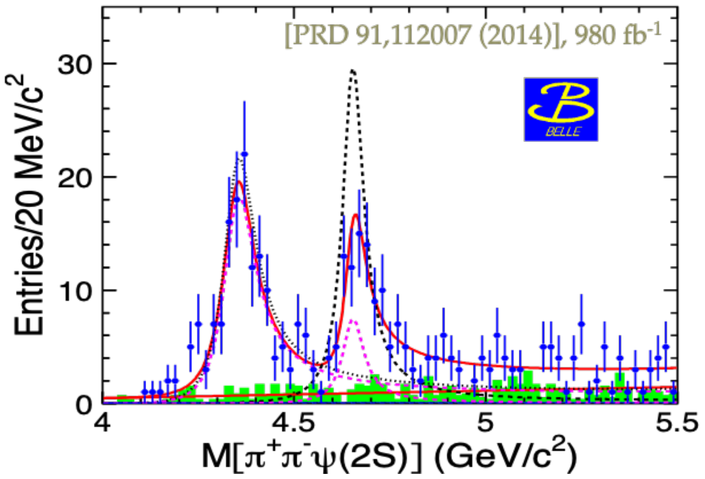
Discovery of Y States

- 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

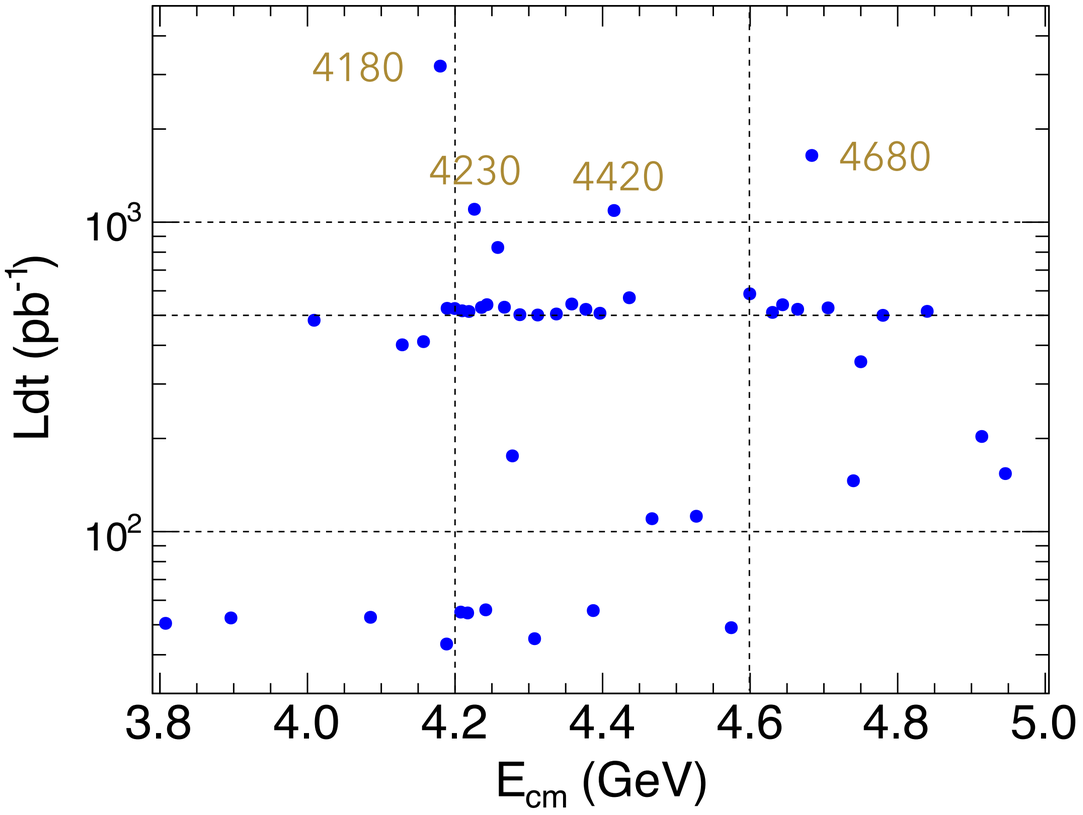




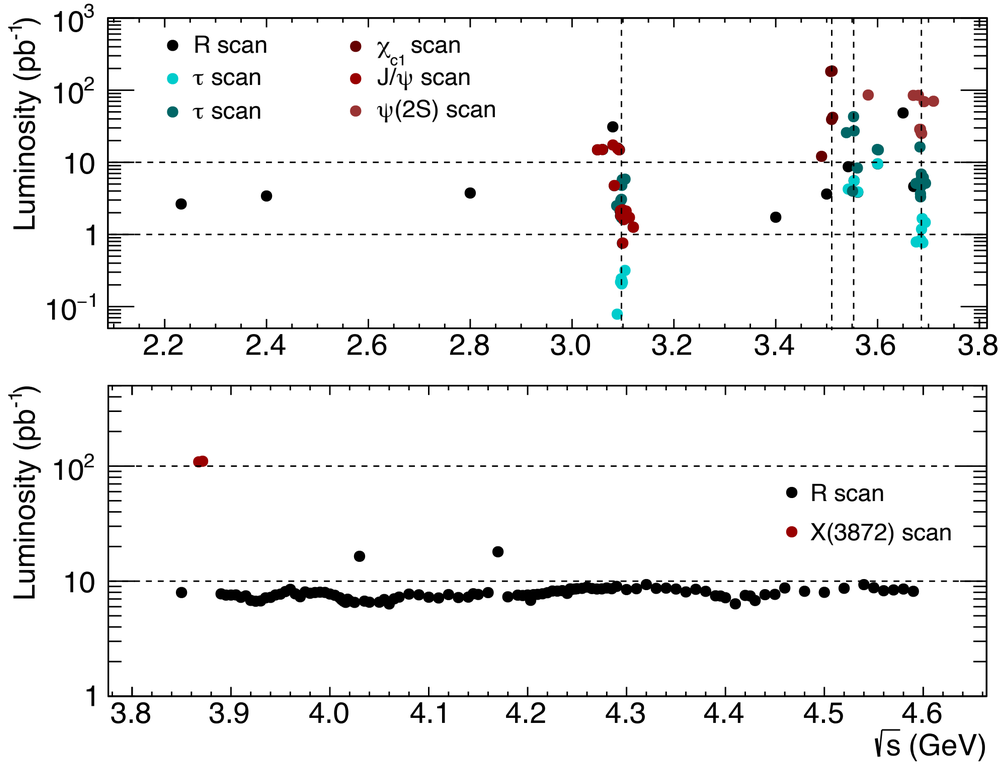




BESIII Data Samples



46 sample, ~22 fb^{-1}

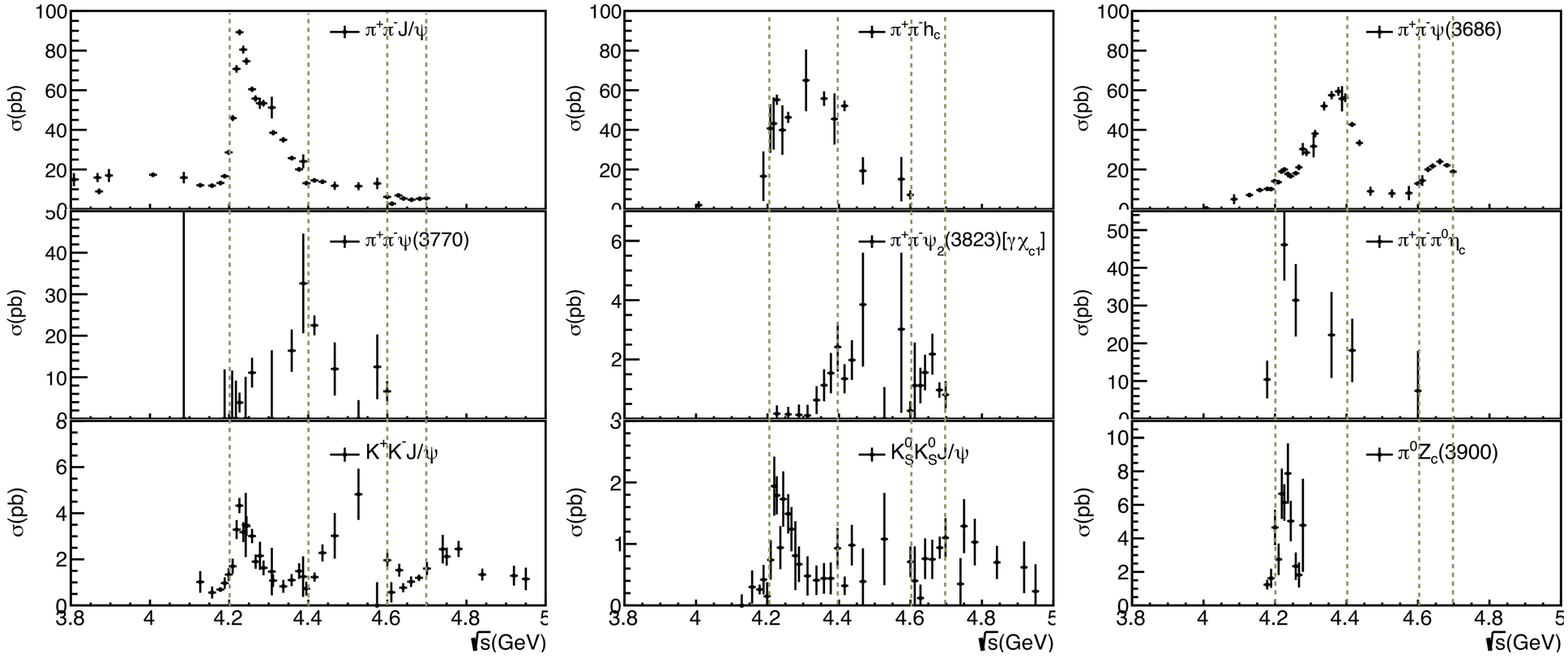


+ Small scan sample, ~2.5 fb^{-1}

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

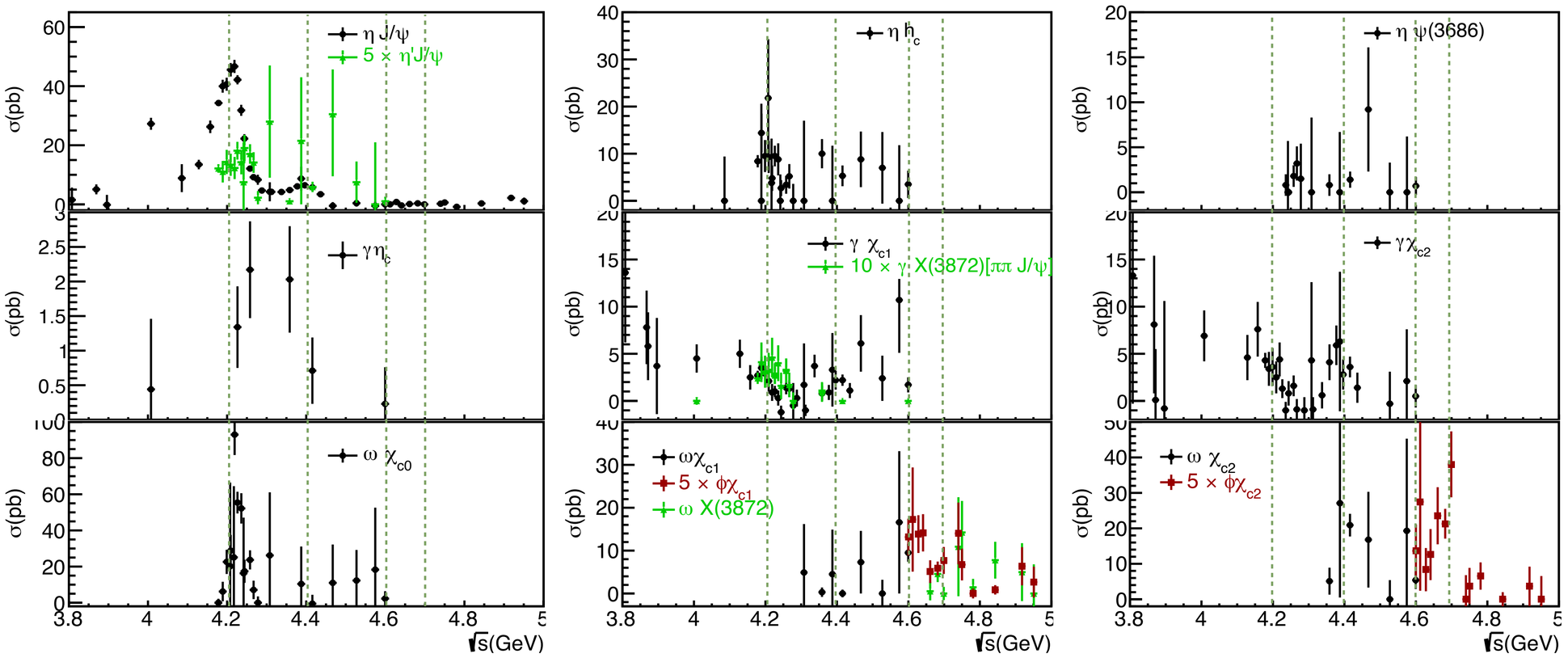
Summary of CS Measurements at BESIII

- Investigated by measuring the cross section as a function of c.m.s $\sigma(\sqrt{s})$
  - Hidden charm processes
  - Open charm processes
  - Light hadron processes



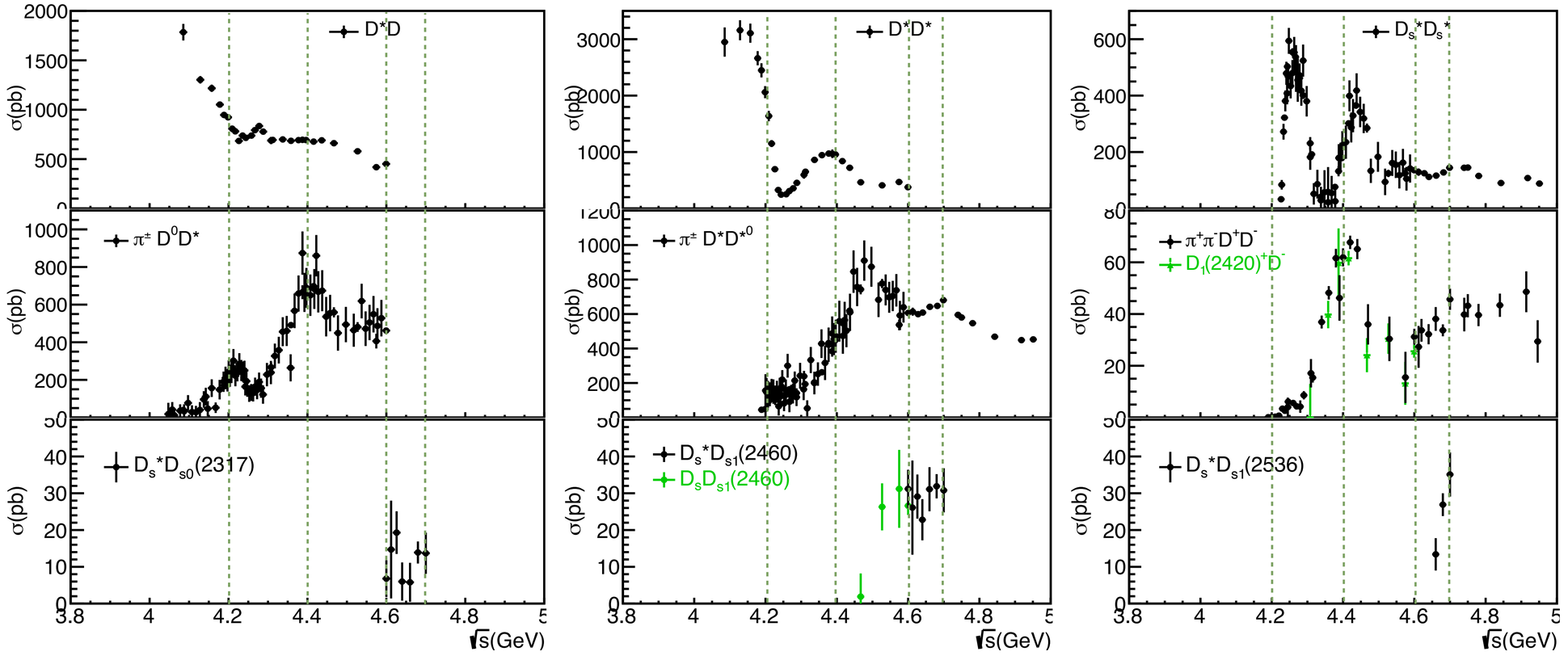
Summary of CS Measurements at BESIII

- Investigated by measuring the cross section as a function of c.m.s $\sigma(\sqrt{s})$
  - Hidden charm processes
  - Open charm processes
  - Light hadron processes



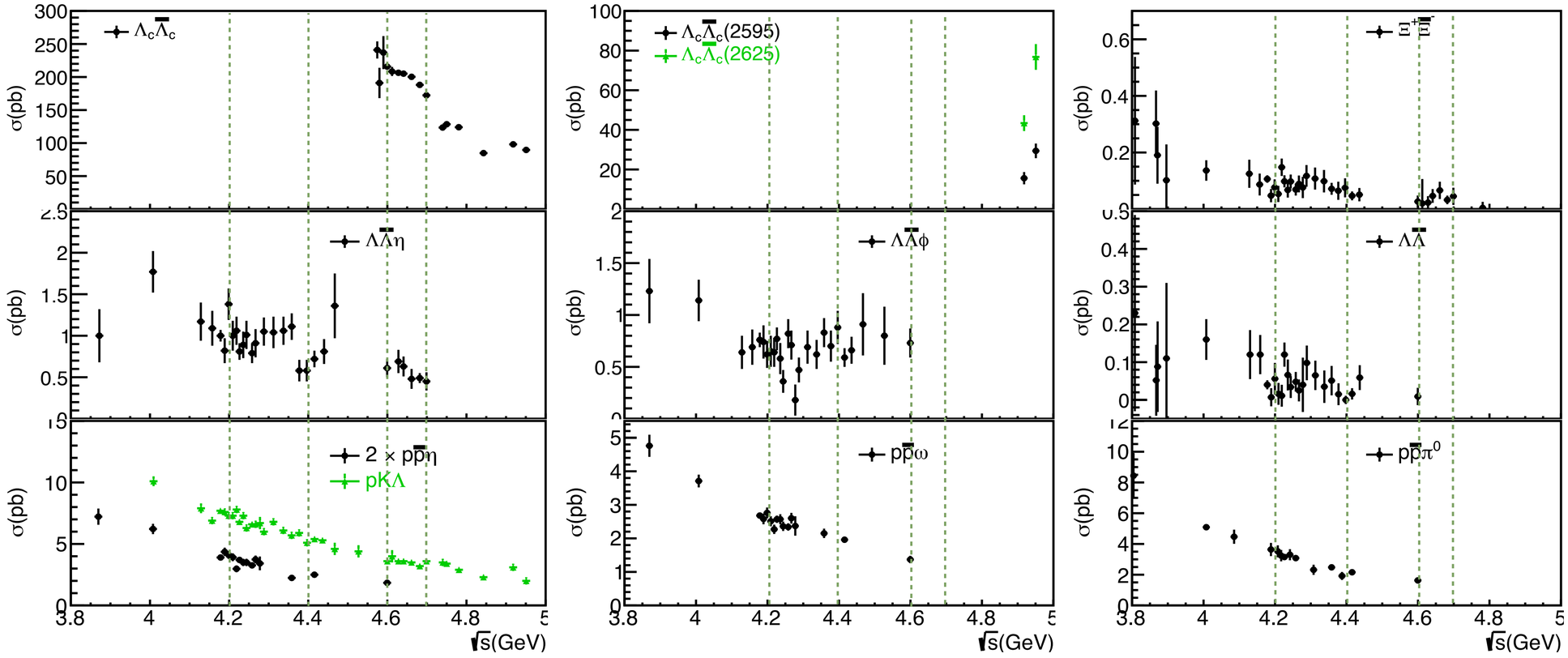
Summary of CS Measurements at BESIII

- Investigated by measuring the cross section as a function of c.m.s $\sigma(\sqrt{s})$
  - Hidden charm processes
  - Open charm processes
  - Light hadron processes



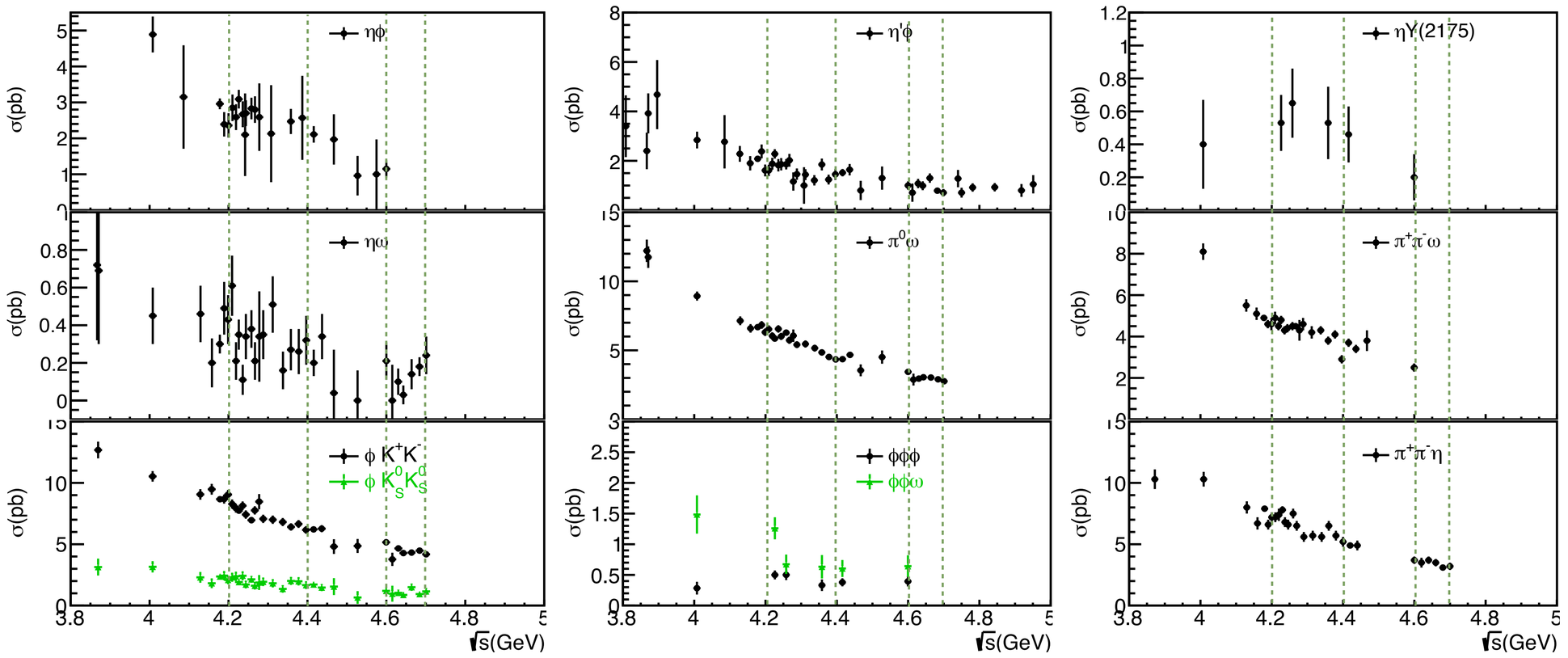
Summary of CS Measurements at BESIII

- Investigated by measuring the cross section as a function of c.m.s $\sigma(\sqrt{s})$
  - Hidden charm processes
  - Open charm processes
  - Light hadron processes



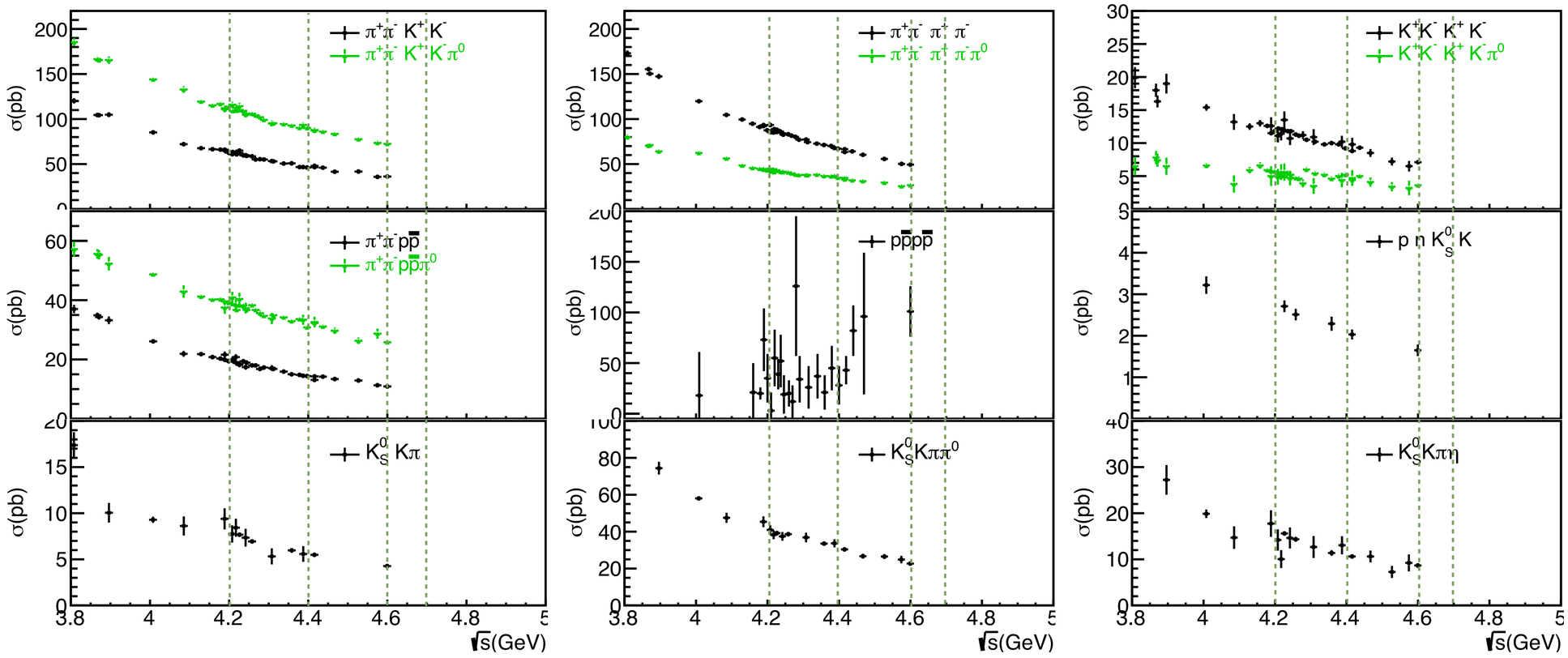
Summary of CS Measurements at BESIII

- Investigated by measuring the cross section as a function of c.m.s $\sigma(\sqrt{s})$
  - Hidden charm processes
  - Open charm processes
  - Light hadron processes

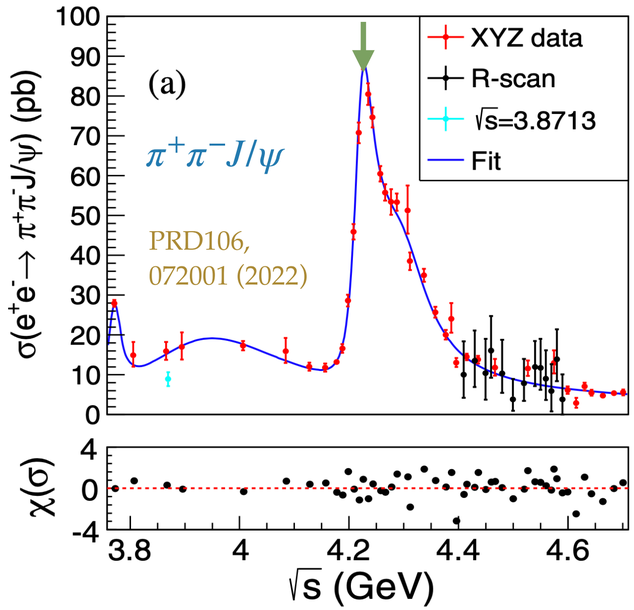


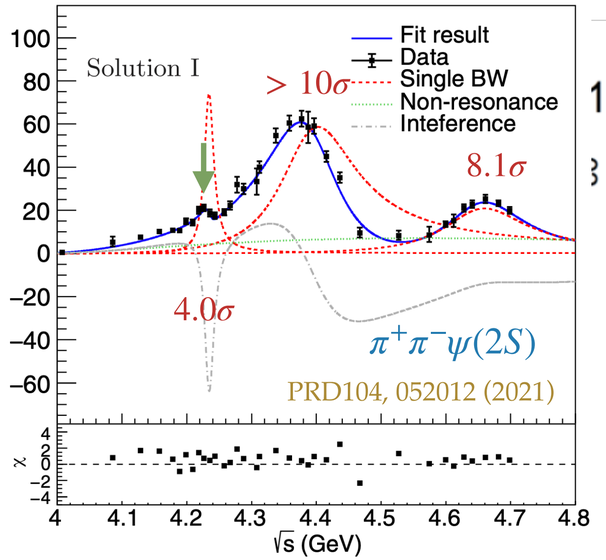
Summary of CS Measurements at BESIII

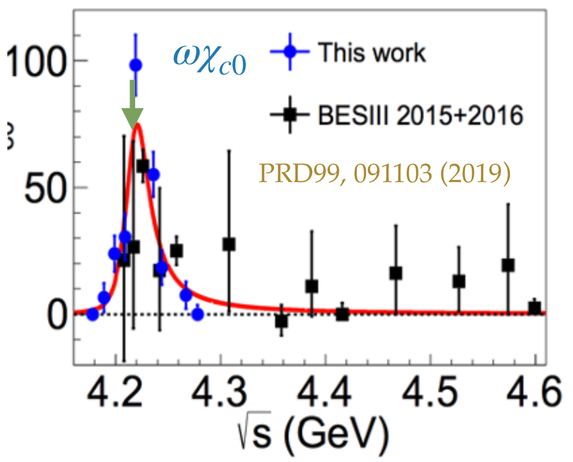
- Investigated by measuring the cross section as a function of c.m.s $\sigma(\sqrt{s})$
  - Hidden charm processes
  - Open charm processes
  - Light hadron processes



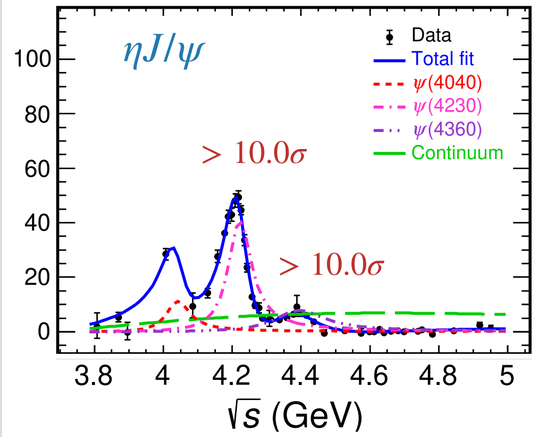
Y(4260) ⇒ Y(4230)

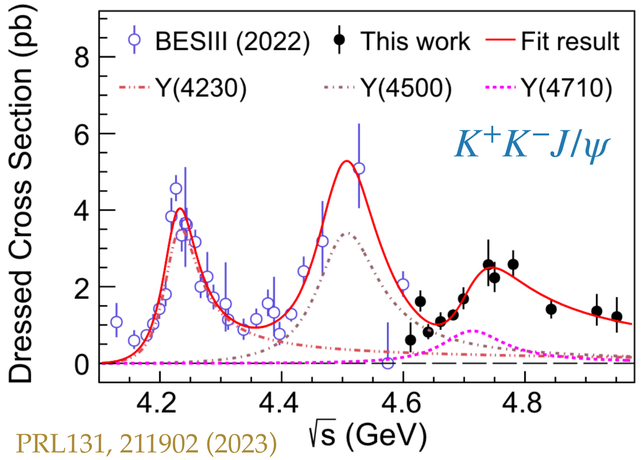




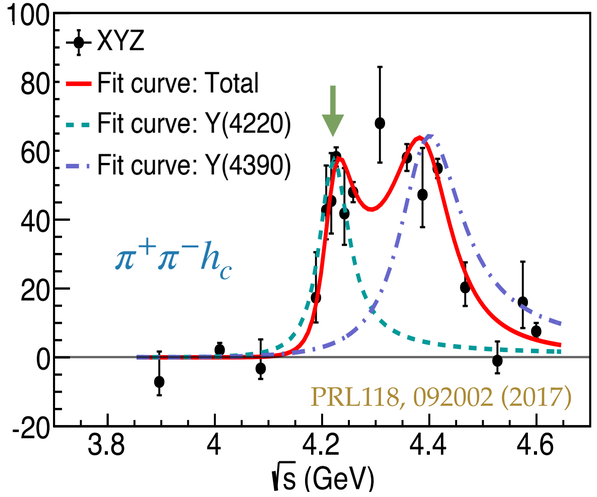


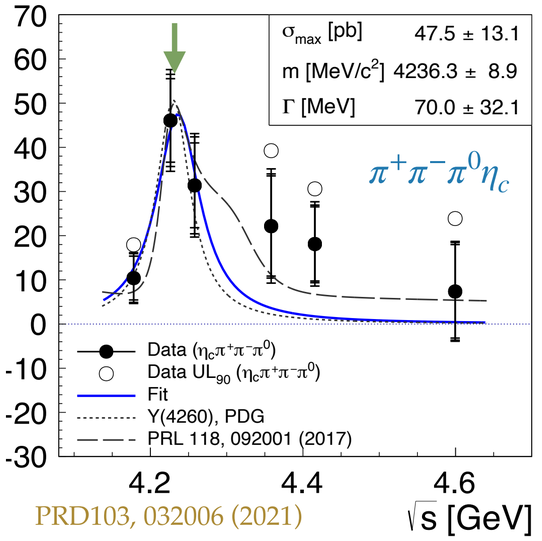
arXiv: 2310.03361



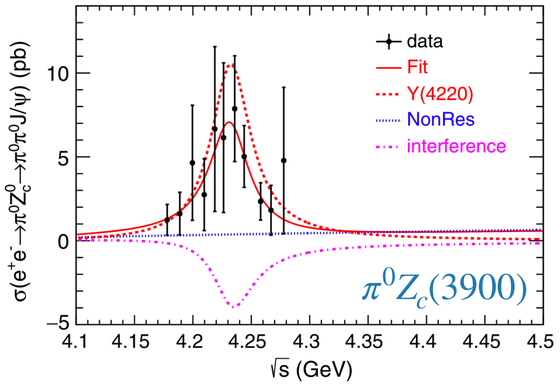


PRL131, 211902 (2023)



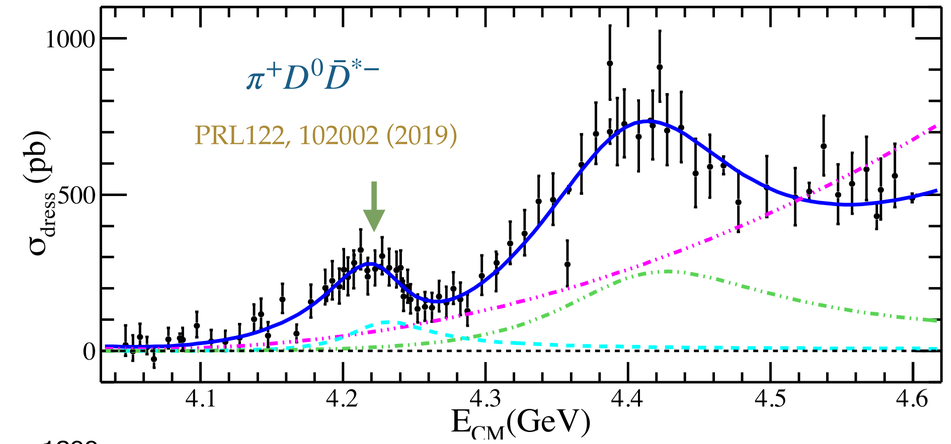


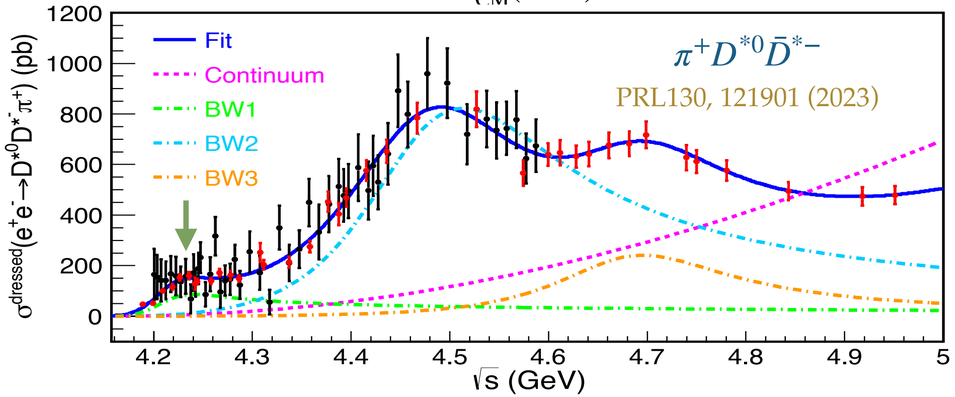
PRD103, 032006 (2021)



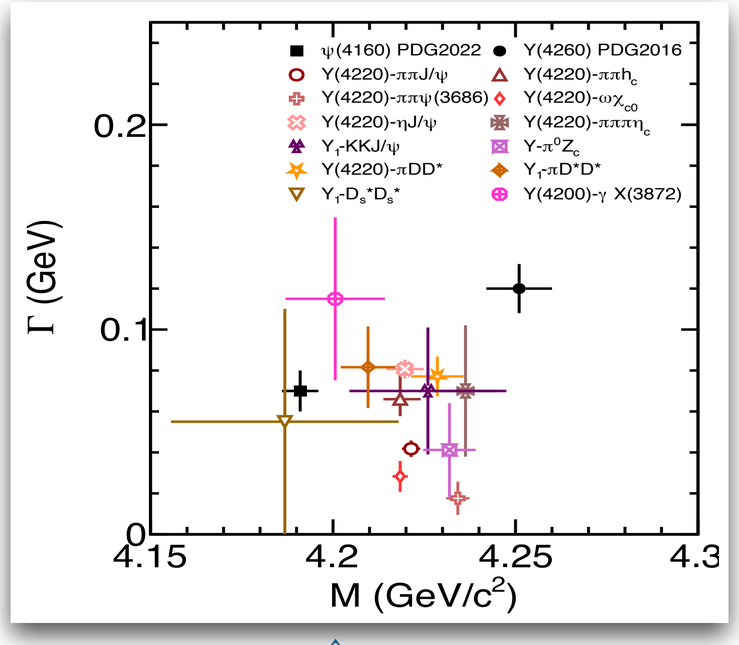
PRD102, 012009 (2020)

Y(4230) in Open Charm Process





Mass and width from different process



⇑

determined with BW parameterization

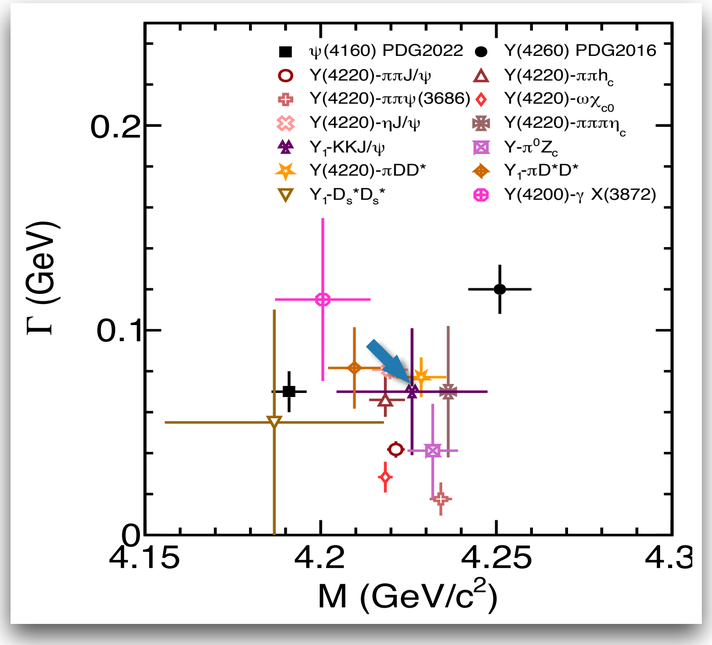
consider possible interference

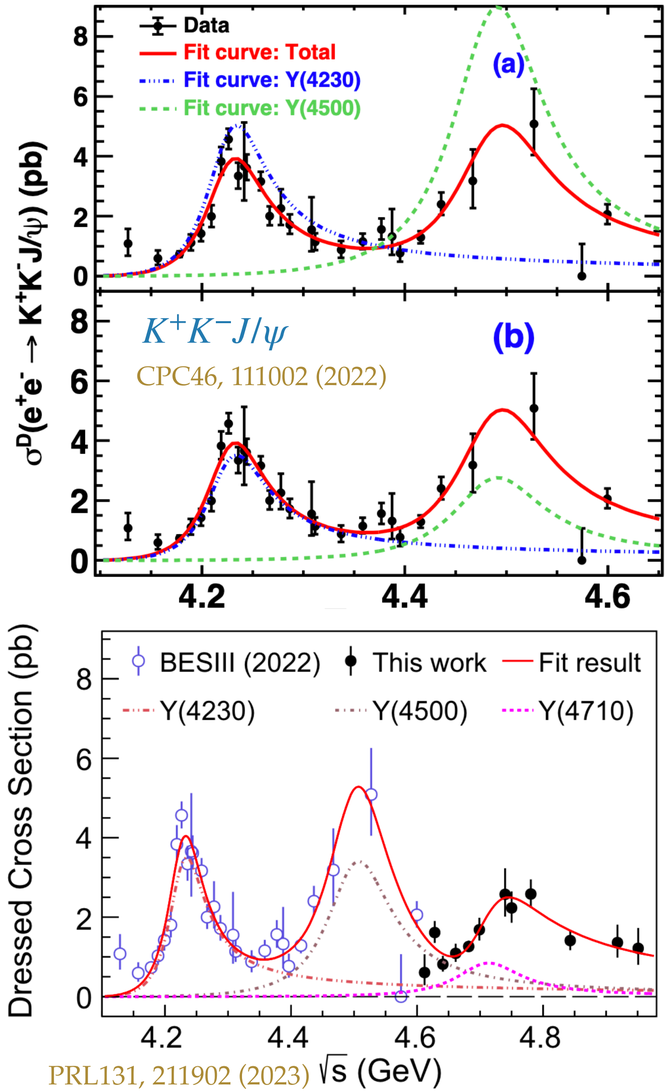
⇓

$\Gamma_{ee}B$(eV)	$\pi^+\pi^-J/\psi$	$\pi^+\pi^-h_c$	$\omega\chi_{c0}$	$\pi^+\pi^-\psi(2S)$	$\eta J/\psi$	K^+K^-J/ψ	$\pi^+\pi^-J/\psi$	$\pi^\pm(D\bar{D}^*)^\mp$	$\pi^\pm(D^*\bar{D}^*)^\mp$
Min	1.7[0.2]	4.6[2.9]	2.5[0.2]	0.02[0.01]	4.0[0.5]	0.29[0.10]	0.22[0.25]	8.6[1.6]	4.8[0.9]
Max	14.6[1.2]			1.64[0.83]	11.9[1.1]	0.42[0.15]	0.53[0.15]	77.4[10.1]	22.4[9.0]

Same Order

Update of K^+K^-J/ψ Cross Section



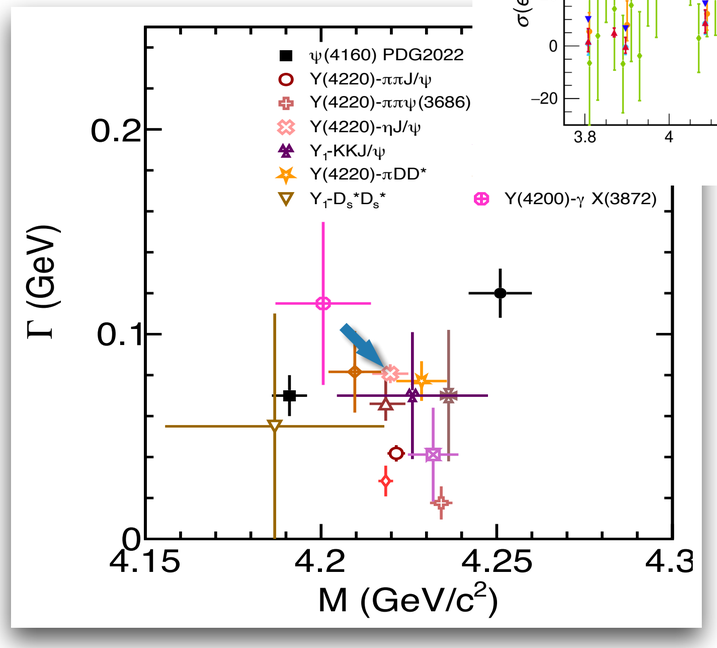


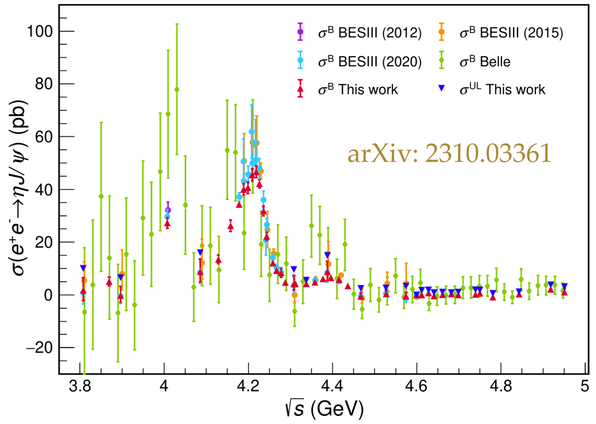
- ML fit with coherent sum of two BWs
- Mass: $4225.3 \pm 2.3 \pm 21.5$ MeV
- Width: $72.9 \pm 6.1 \pm 30.8$ MeV
- Significance $> 5\sigma$

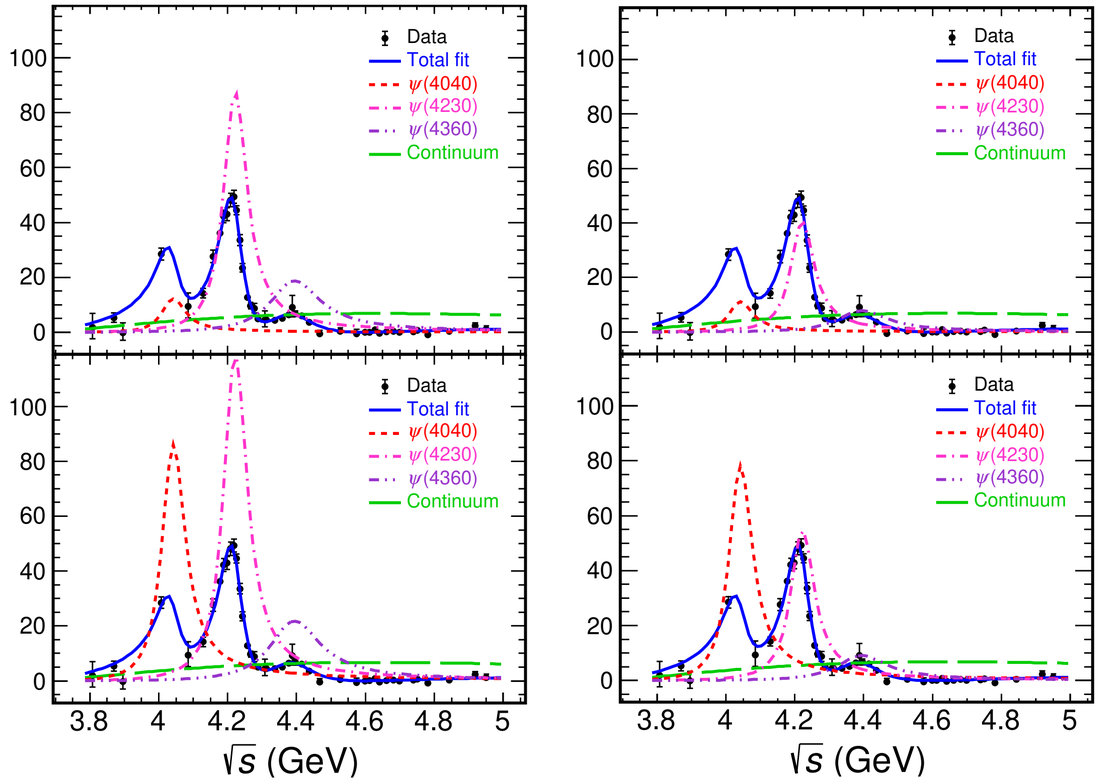
Ratio to $\pi\pi J/\psi$	$K\bar{K}J/\psi$ Sol. I	$K\bar{K}J/\psi$ Sol. II
$\pi\pi J/\psi$ Sol. I	0.17 ± 0.02	0.25 ± 0.04
$\pi\pi J/\psi$ Sol. II	0.097 ± 0.017	0.14 ± 0.03
$\pi\pi J/\psi$ Sol. III	0.035 ± 0.004	0.051 ± 0.007
$\pi\pi J/\psi$ Sol. IV	0.020 ± 0.002	0.028 ± 0.004

- ML fit with coherent sum of three BWs
- Mass: 4226.0 ± 1.4 MeV
- Width: $70.0^{+3.9}_{-3.6}$ MeV

Update of ηJ/ψ Cross Section



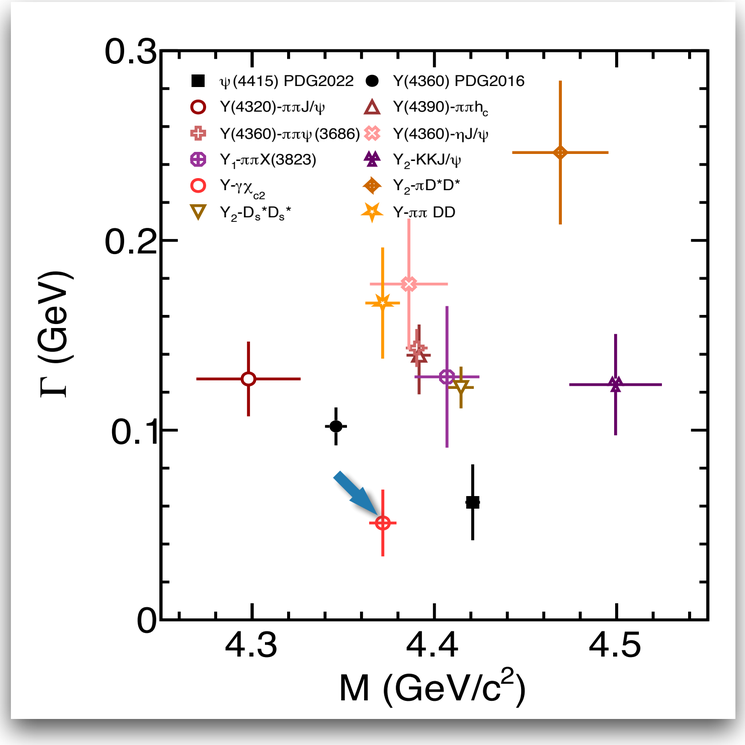


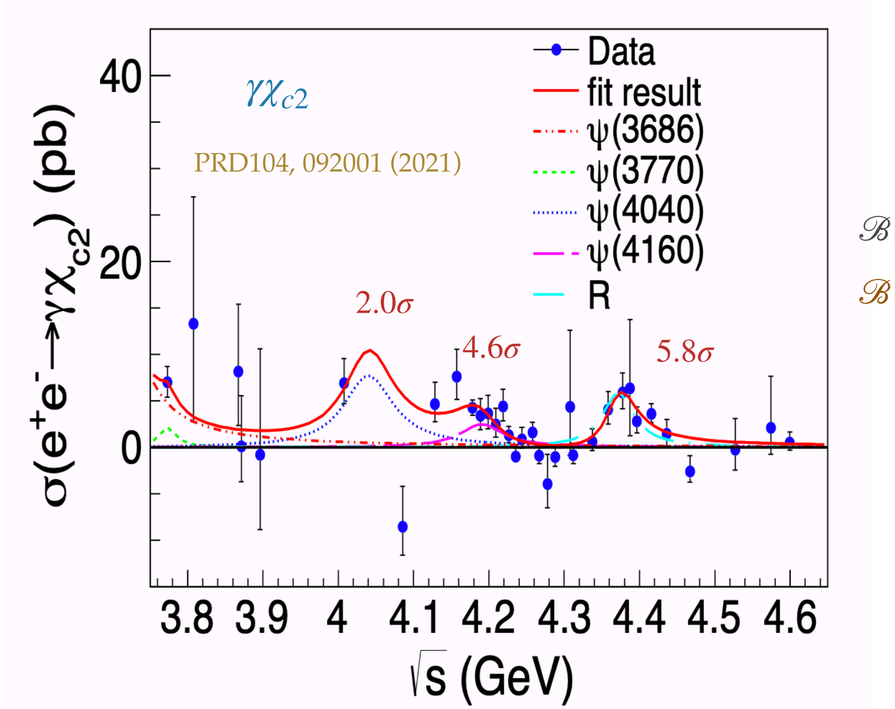


- ML fit with coherent sum of three BWs and a continuum term $(\Phi(\sqrt{s})e^{-p_0 u}p_1)$
- Mass: $4219.7 \pm 2.5 \pm 4.5$ MeV; Width: $80.7 \pm 4.4 \pm 1.4$ MeV
- Take Γ_{ee} to be ~0.63-0.66 keV, $\mathcal{B}[\psi(4230) \to \eta J/\psi) =$ $(6.06 \pm 0.76 \pm 0.17) \times 10^{-3}$ or $(18.89 \pm 1.75 \pm 0.90) \times 10^{-3}$

Between 4300 and 4500

Mass and width from different process





$\mathcal{B}[\psi(4040) \to \gamma\chi_{c2}] = (8.0 - 15.6) \times 10^{-4}$

$\mathcal{B}[\psi(4160) \to \gamma\chi_{c2}] = (4.4 - 14.2) \times 10^{-4}$

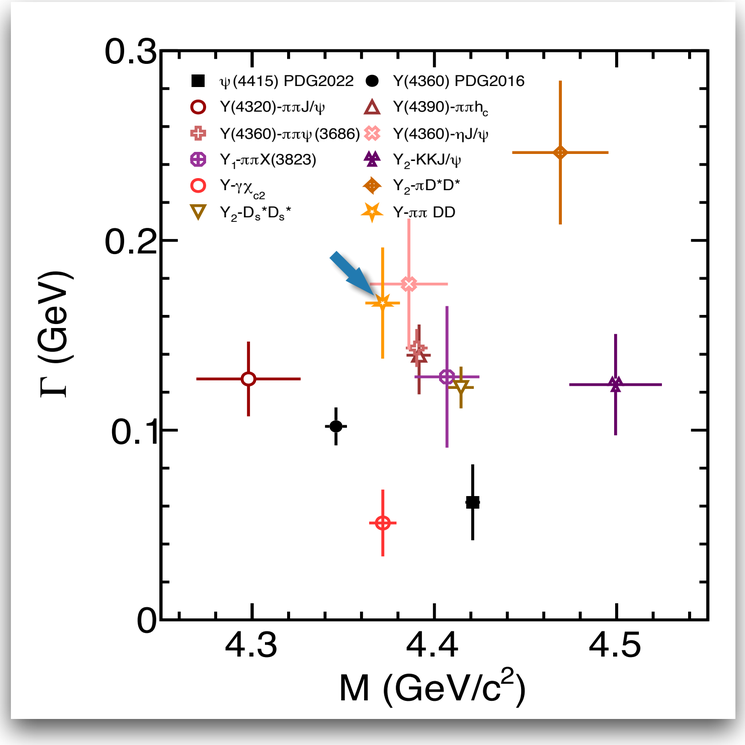
potential model: $\sim 10^{-7}$

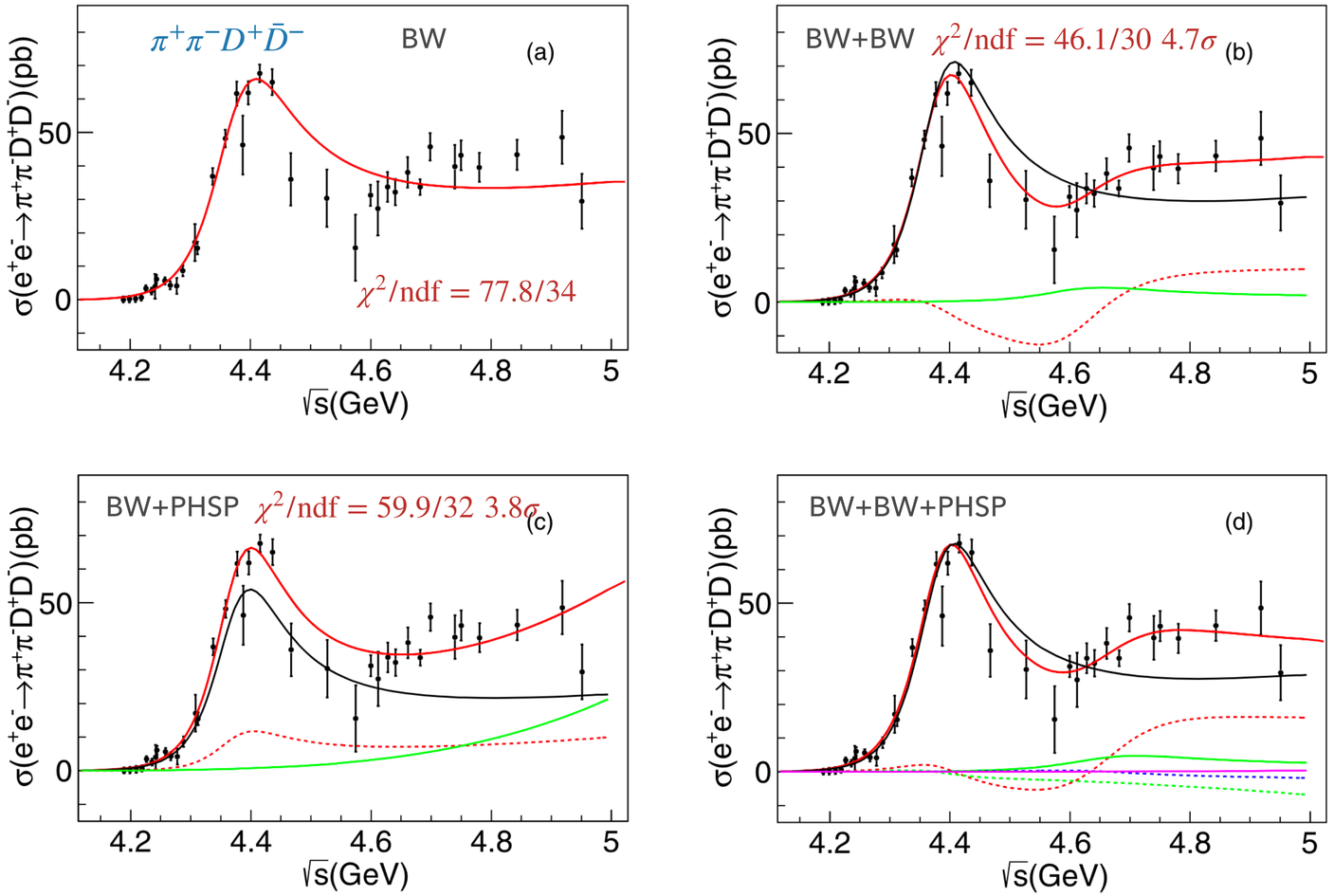
- ML fit with $\psi(3686)$, $\psi(3770)$, and coherent sum of three BWs
- Continuum contribution is not significant ($<1\sigma$)
- Mass: $4371.7 \pm 7.5 \pm 1.8$ MeV
- Width: $51.1 \pm 17.6 \pm 1.9$ MeV

Between 4300 and 4500

PRD106, 052012 (2022)

Mass and width from different process

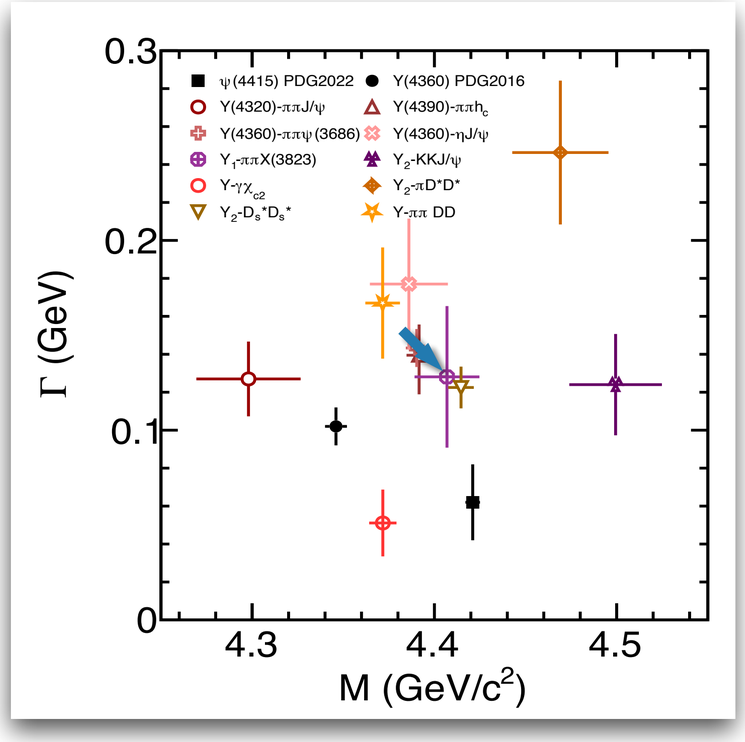


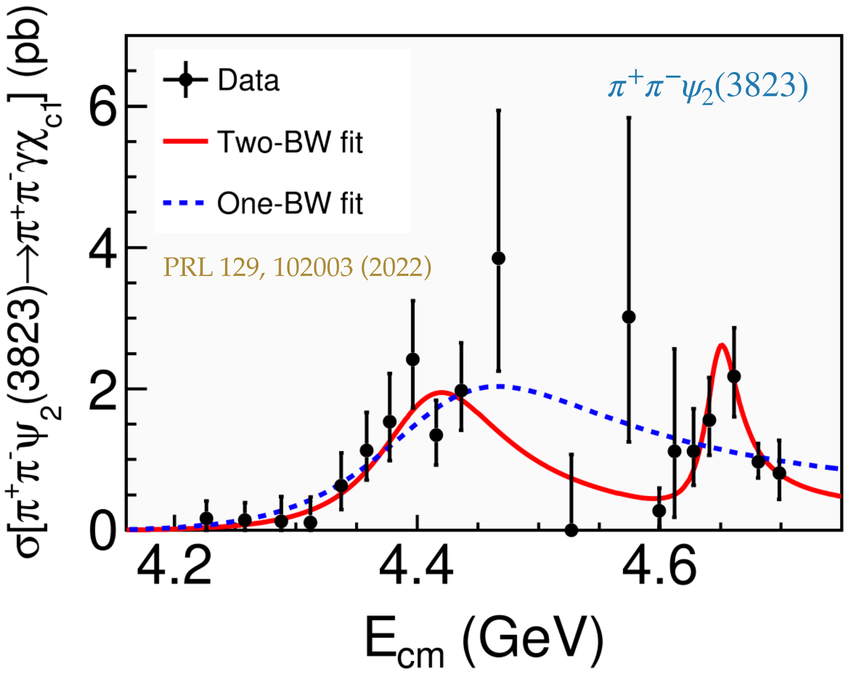


- χ^2 fit; Mass: $4371.6 \pm 2.5 \pm 9.2$ MeV; Width: $167 \pm 4 \pm 29$ MeV

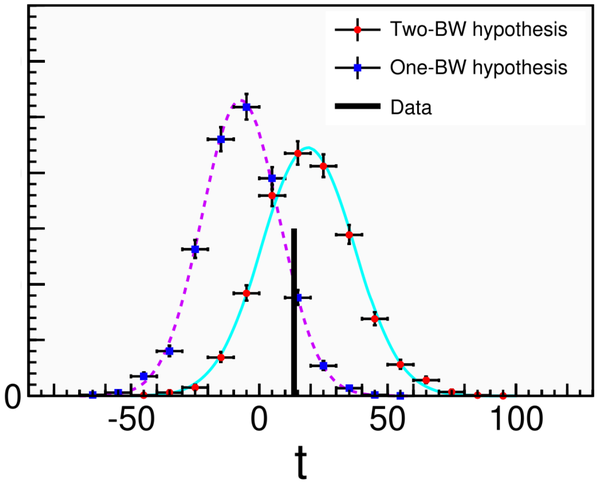
Between 4300 and 4500

Mass and width from different process





Parameters	Solution I	Solution II
$M[R_1]$	$4406.9 \pm 17.2 \pm 4.5$	
$\Gamma_{\rm tot}[R_1]$	$128.1 \pm 37.2 \pm 2.3$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_1}\mathcal{B}_2$	$0.36 \pm 0.10 \pm 0.03$	$0.30 \pm 0.09 \pm 0.03$
$M[R_2]$	$4647.9 \pm 8.6 \pm 0.8$	
$\Gamma_{\rm tot}[R_2]$	$33.1 \pm 18.6 \pm 4.1$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_2}\mathcal{B}_2$	$0.24 \pm 0.07 \pm 0.02$	$0.06 \pm 0.03 \pm 0.01$
ϕ	$267.1 \pm 16.2 \pm 3.2$	$-324.8 \pm 43.0 \pm 5.7$



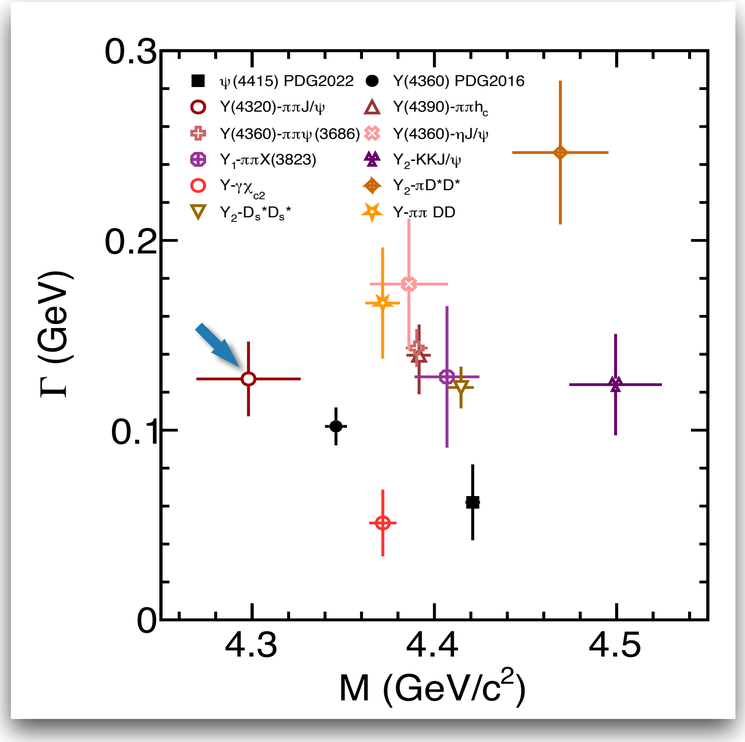
Slightly favor two-BW hypothesis

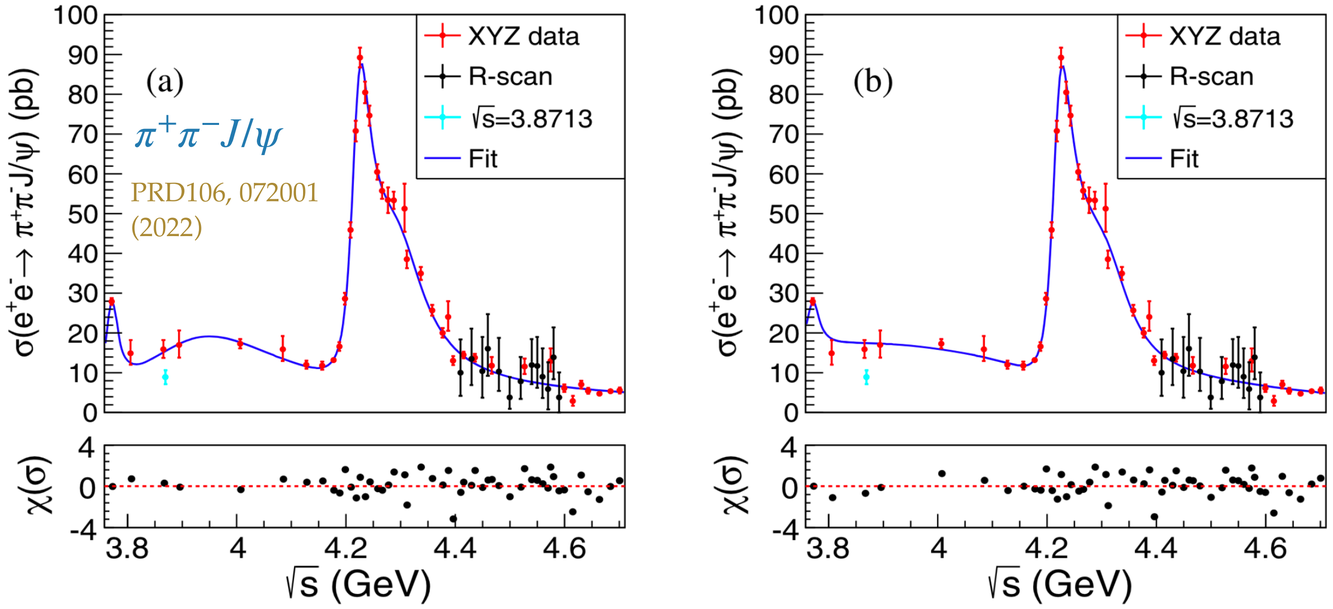
1.7σ

Between 4300 and 4500

FUDAN UNIVERSITY

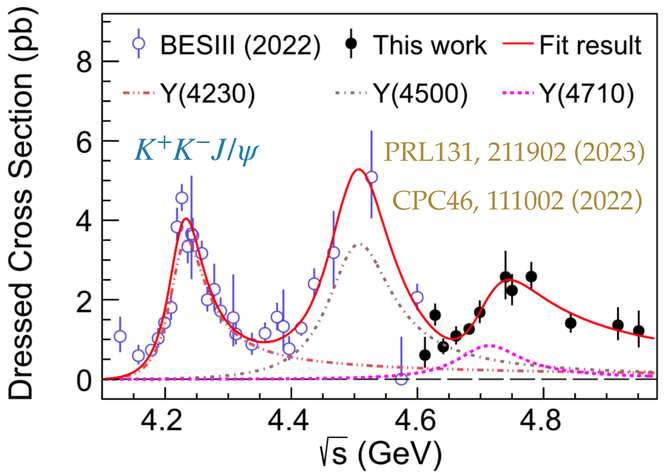
Mass and width from different process



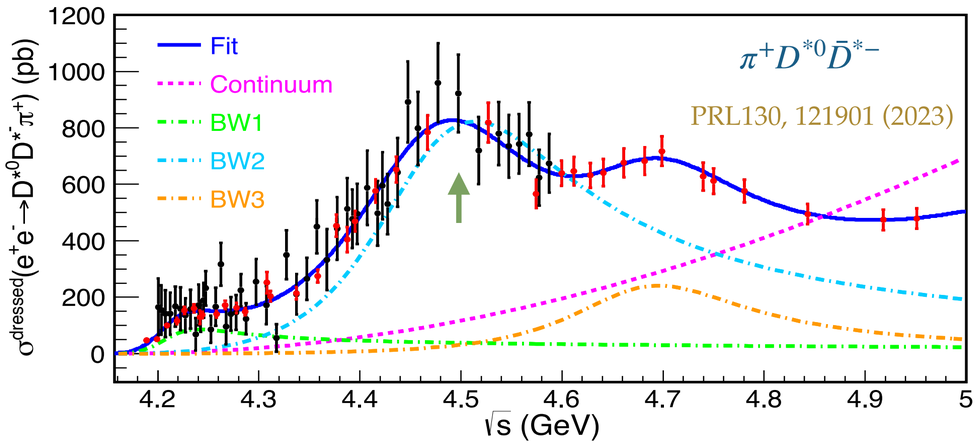


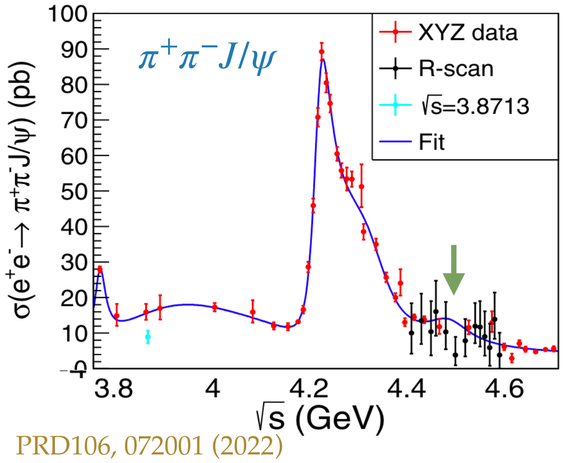
Parameter	Solution I	Solution II	Solution III	Solution IV
$\Gamma^{ee}_{3770}\mathcal{B}(R_{3770})$		$0.6 \pm 0.1 (0.3 \pm 0.1)$		
$M(R_0)$ (p_0)		3905.5 ± 30.1 (4.4 ± 0.3)		
$\Gamma^{tot}_0(R_0)$ (p_1)		346.0 ± 48.5 $((2.7 \pm 0.6) \times 10^{-3})$		
$\Gamma^{ee}_0\mathcal{B}(R_0)$	5.5 ± 0.5 (…)	6.9 ± 0.7 (…)	8.3 ± 0.6 (…)	10.5 ± 0.9 (…)
$M(R_1)$		4221.4 ± 1.5 (4220.1 ± 1.2)		4222.0 ± 3.1 (4220.9 ± 2.9)
$\Gamma^{tot}_1(R_1)$		41.8 ± 2.9 (43.6 ± 2.6)		44.1 ± 4.3 (44.1 ± 3.8)
$\Gamma^{ee}_1\mathcal{B}(R_1)$	$1.7 \pm 0.2 (1.7 \pm 0.2)$	$8.2 \pm 0.9 (8.6 \pm 0.5)$	$3.0 \pm 0.5 (2.5 \pm 0.3)$	$14.6 \pm 1.2 (12.7 \pm 0.8)$
$M(R_2)$		4297.5 ± 12.1 (4316.2 ± 12.4)		4320.0 ± 10.4 (4326.8 ± 10.0)
$\Gamma^{tot}_2(R_2)$		126.6 ± 16.7 (124.3 ± 18.0)		$101.4^{+25.3}_{-19.7}$ $(98.2^{+25.4}_{-19.6})$
$\Gamma^{ee}_2\mathcal{B}(R_2)$	$1.2 \pm 0.3 (0.7 \pm 0.2)$	$2.3 \pm 0.8 (1.1 \pm 0.3)$	$15.6 \pm 2.1 (15.0 \pm 1.2)$	$30.2 \pm 3.3 (23.6 \pm 2.9)$
ϕ_1	$-3.7 \pm 5.4 (24.3 \pm 3.0)$	$-124.6 \pm 11.7 (-78.8 \pm 5.1)$	$87.7 \pm 21.9 (88.0 \pm 12.1)$	$-33.5 \pm 11.2 (-15.1 \pm 7.7)$
ϕ_2	$79.6 \pm 18.5 (130.7 \pm 15.8)$	$35.8 \pm 27.2 (96.6 \pm 19.7)$	$-104.7 \pm 26.9 (-92.5 \pm 6.0)$	$-148.7 \pm 4.5 (-127.6 \pm 2.3)$
χ^2/ndf		54.0/40 (57.3/41)		

Y(4500)



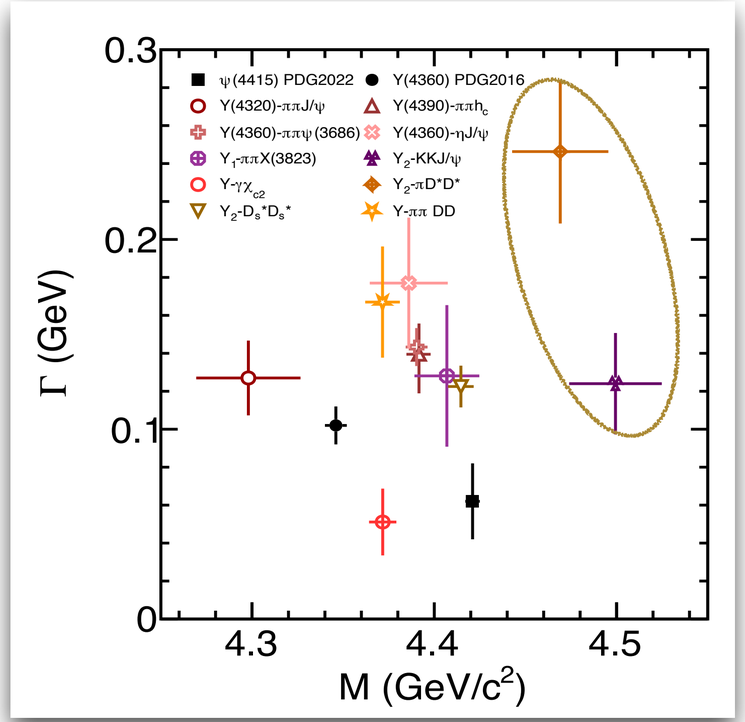
- A 5S-4D mixing state (J. Z. Wang et al. PRD99, 114003 (2019) [Width 2σ larger])
- A heavy-antiheavy hadronic molecule (X. K. Dong et al. Prog. Phys. 41, 65 (2021))
- A $cs\bar{c}\bar{s}$ state from LQCD (T. W. Chiu et al. PRD73, 094510 (2006))
- Indication in $\pi\pi J/\psi$ process
- Assuming structures in KKJ/ψ and $\pi D^*\bar{D}^*$ are the same, $B[Y \to \pi D^*\bar{D}^*]/B[Y \to K\bar{K}J/\psi] \sim 10^2$, inconsistent with hidden-strangeness tetraquark nature (F. Z. Peng et al. PRD107, 016001 (2023))





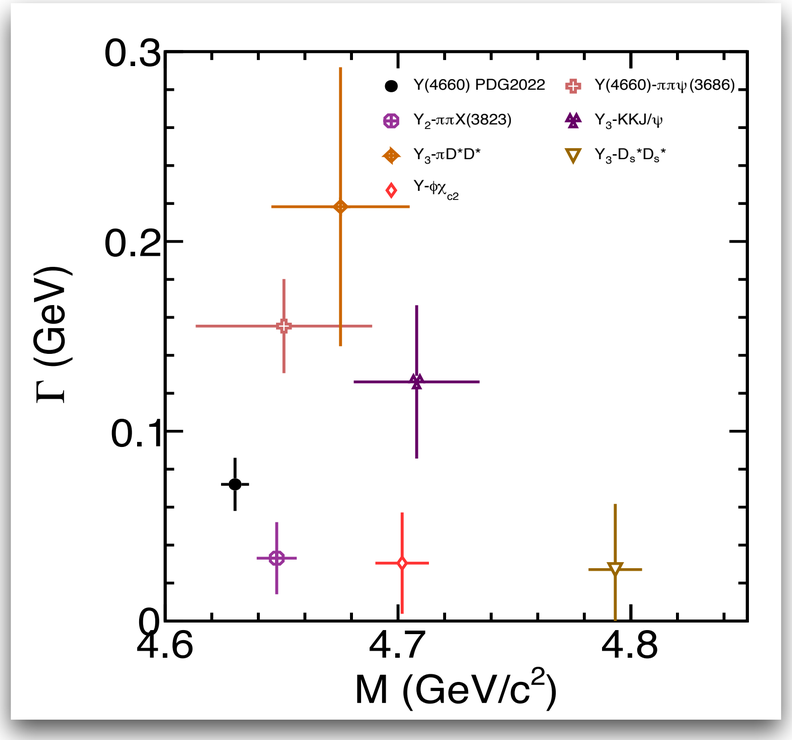
PRD106, 072001 (2022)

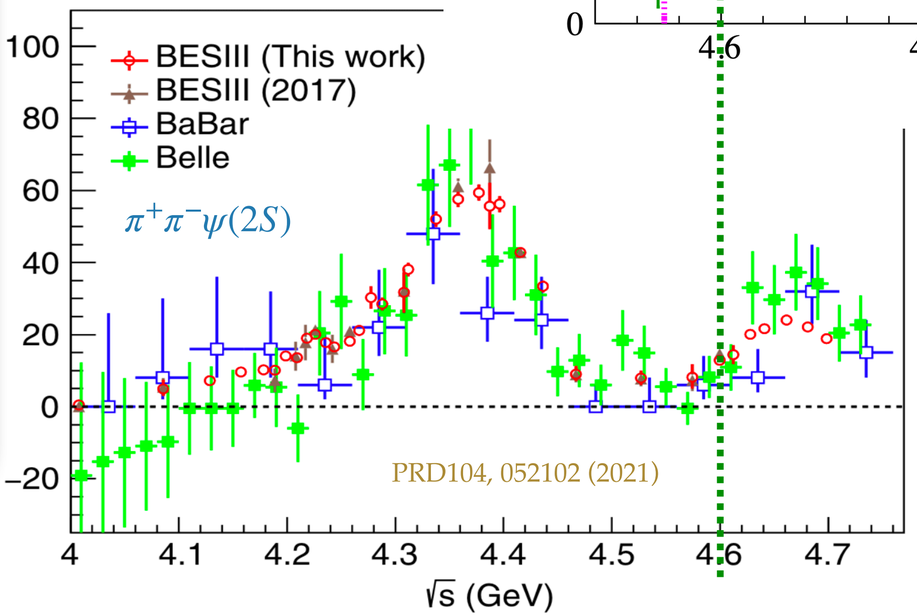
Mass and width from different process

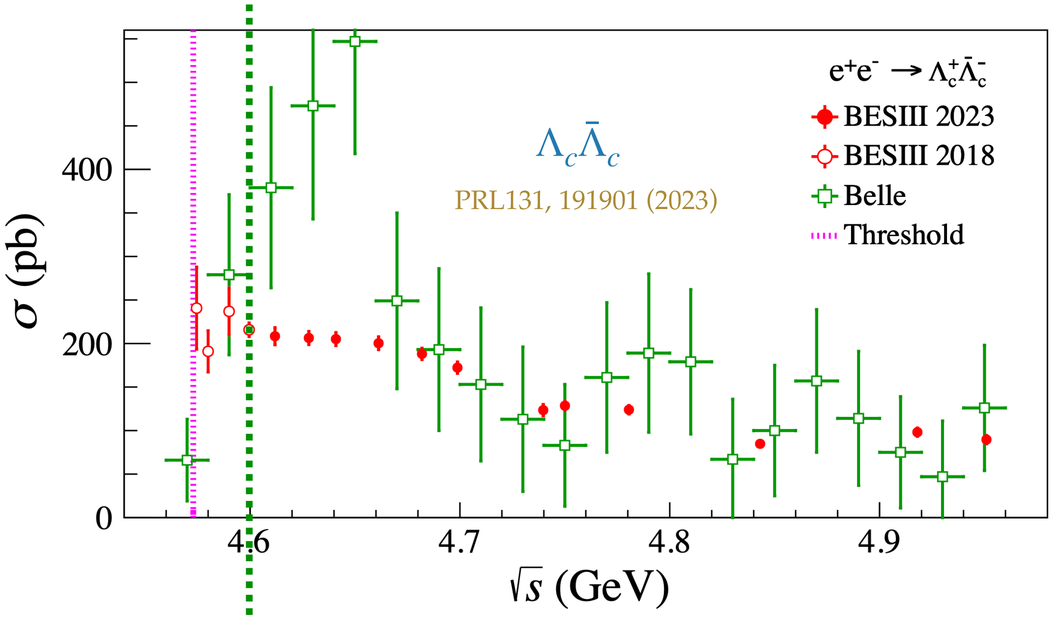


Y(4660) Region

Mass and width from different process



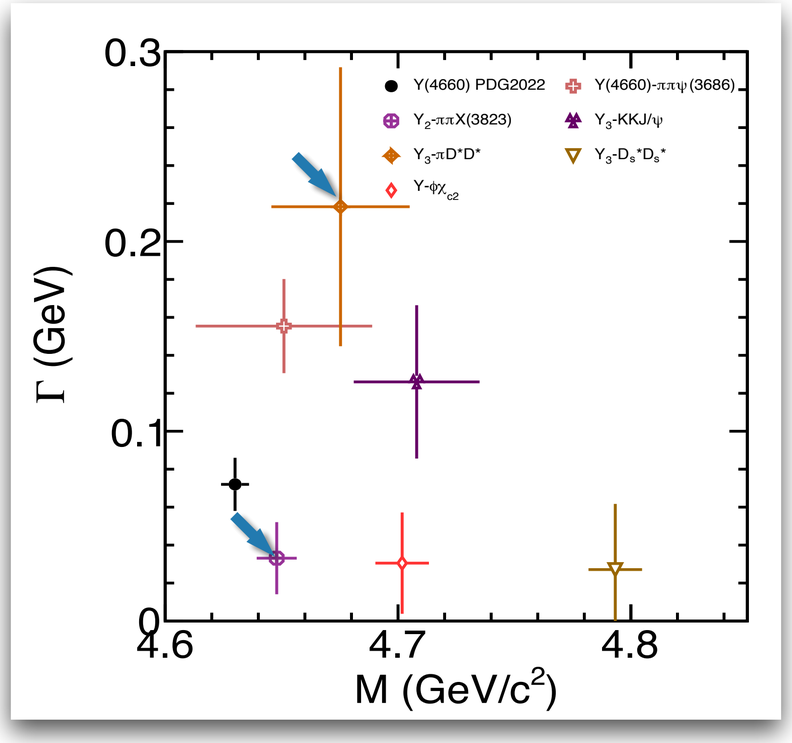


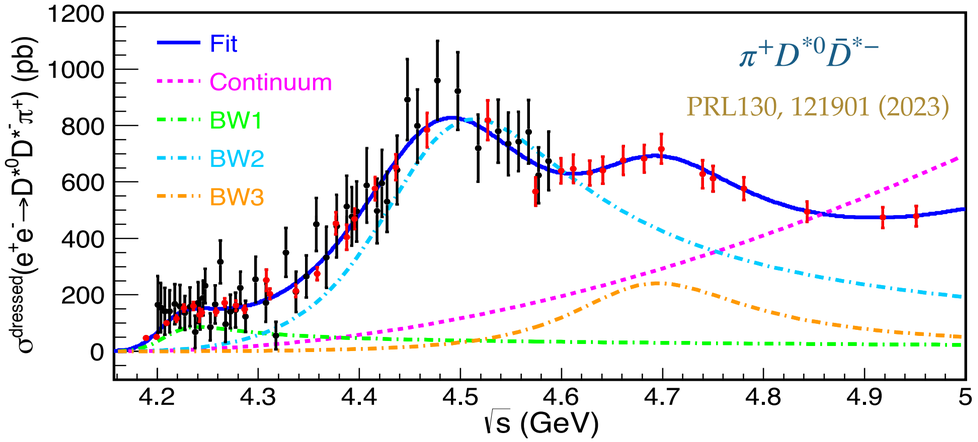


Single Tag and Double Tag to improve precision

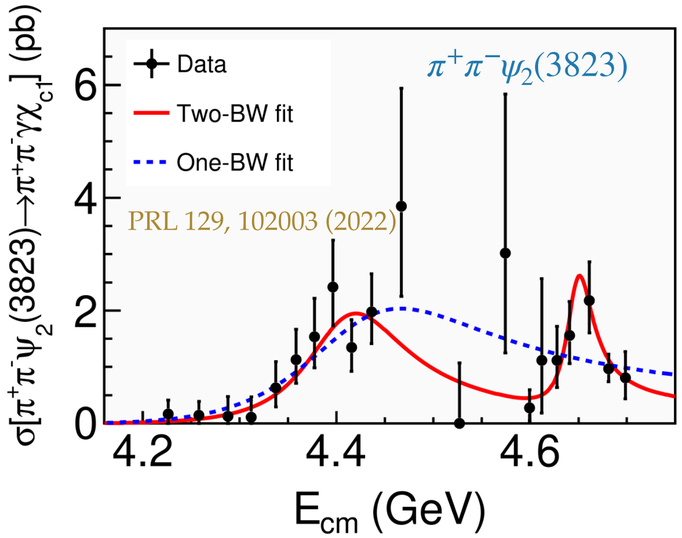
Y(4660) Region

Mass and width from different process





- Mass: 4675.3 ± 29.5 ± 3.5 MeV
- Width: 218 ± 72.9 ± 9.3 MeV
- $\Gamma_{ee}B$: 19.4-2005.3 eV

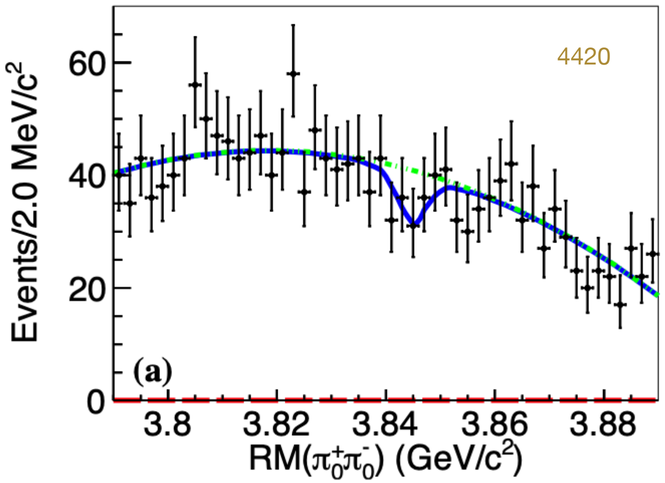


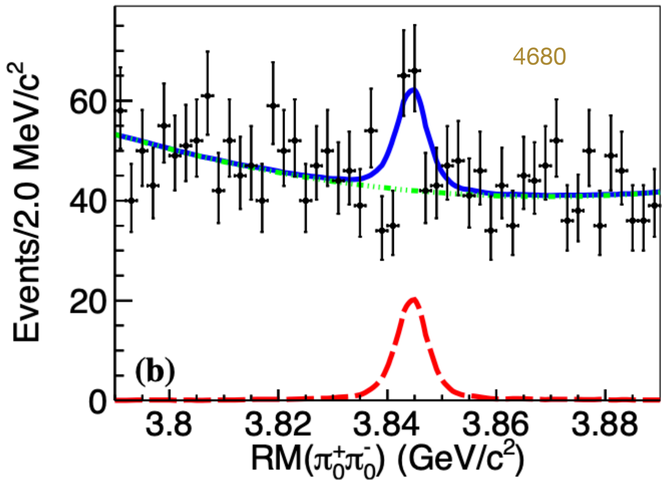
- Mass: 4647.9 ± 8.6 ± 0.8 MeV
- Width: 33.1 ± 18.6 ± 4.1 MeV
- $\Gamma_{ee}B$: 0.06-0.24 eV

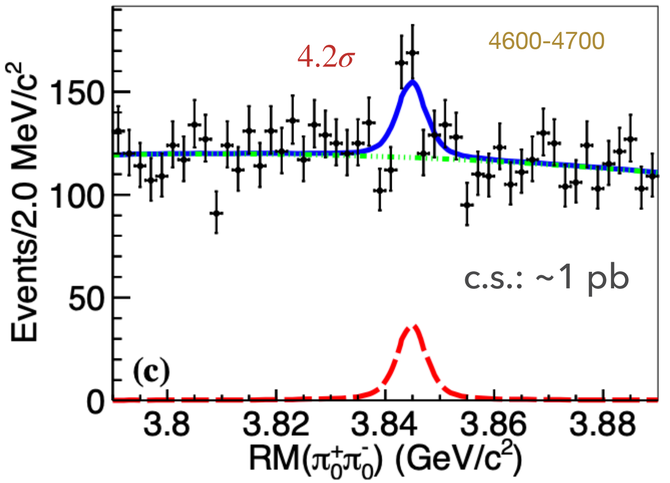
Y(4660) Region

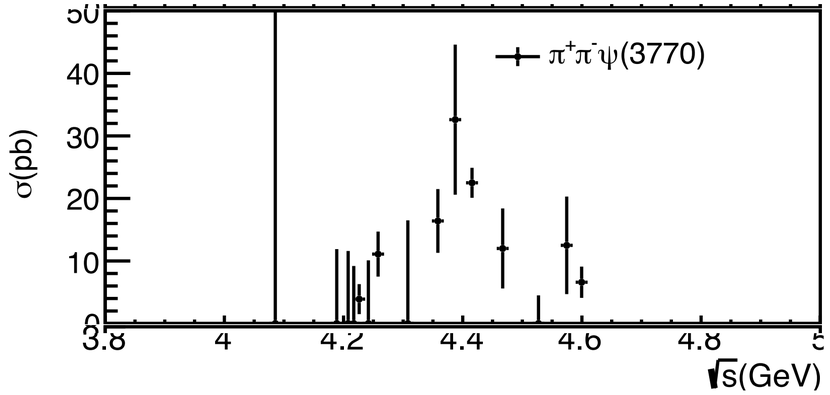
$e^+e^- \to \pi^+\pi^- X(3842) \to \pi^+\pi^- D^+D^-$

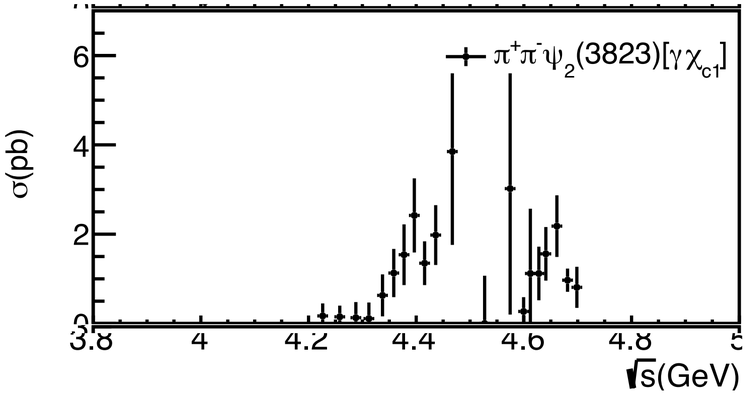
PRD106, 052012 (2022)





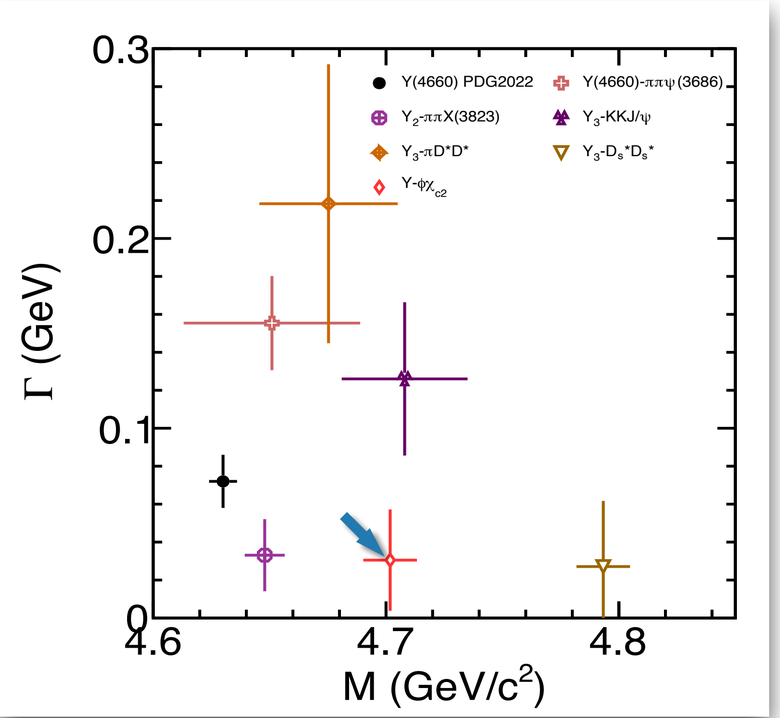




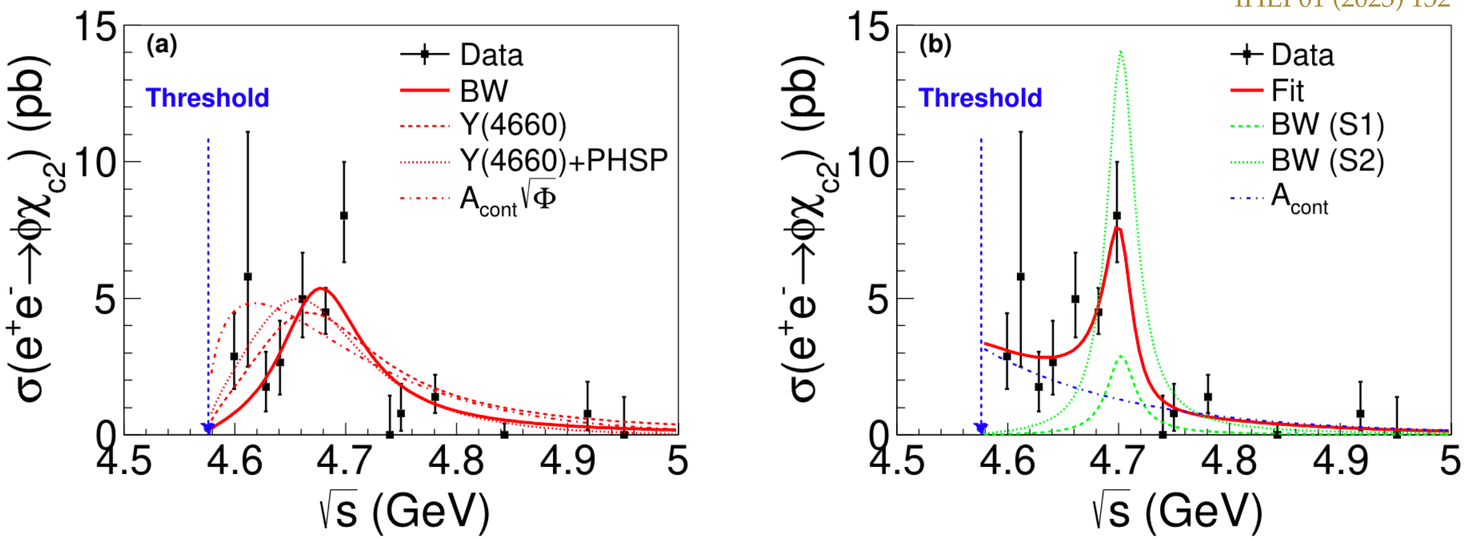


Y(4660) Region

Mass and width from different process



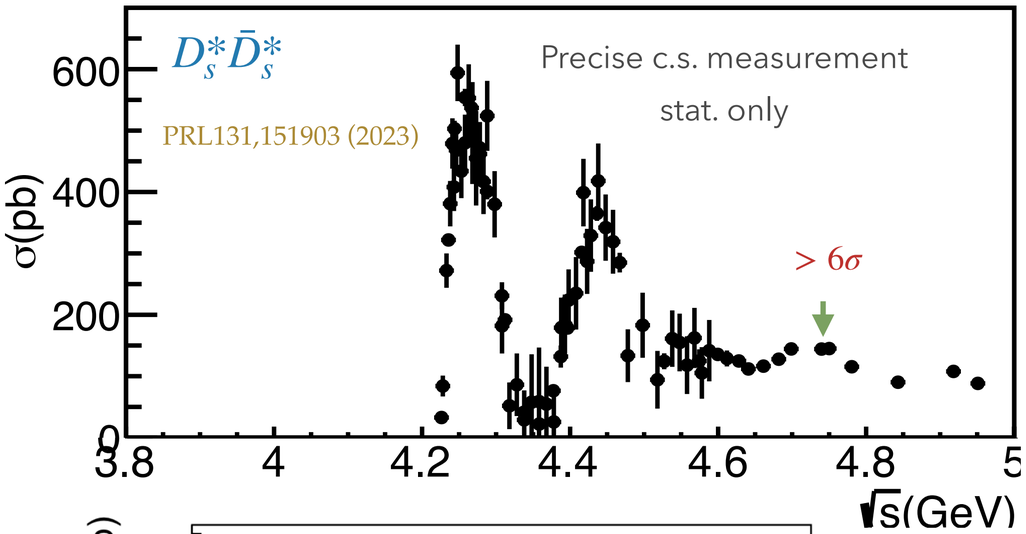
IHEP01 (2023) 132

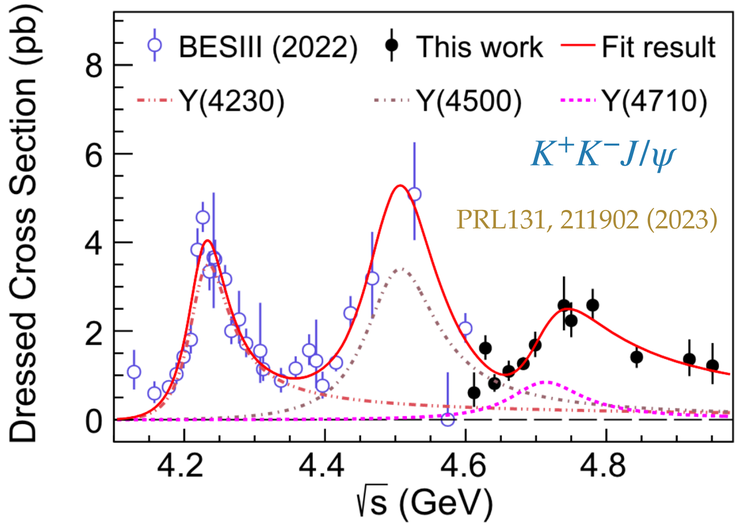


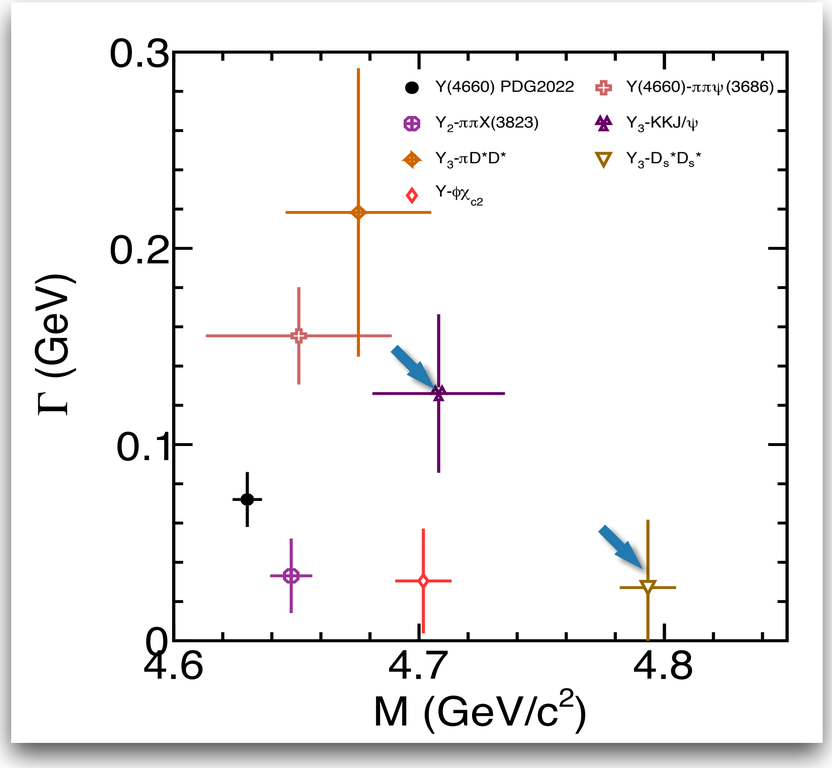
ML fit to the cross section with BW or coherent sum of BW and continuum

- Free BW: $4672.7 \pm 10.8 \pm 3.9$ MeV, $93.2 \pm 19.8 \pm 9.4$ MeV
- One BW assumption over continuum: 3.1σ
- Fix BW parameters to $\psi(4660)$, get comparable fit quality
- Free BW + continuum term: $4710.8 \pm 10.9 \pm 2.7$ MeV, $30.50 \pm 22.33 \pm 14.6$ MeV
- Significance of resonance term: 3.6σ; 2.3σ over one Free BW fit

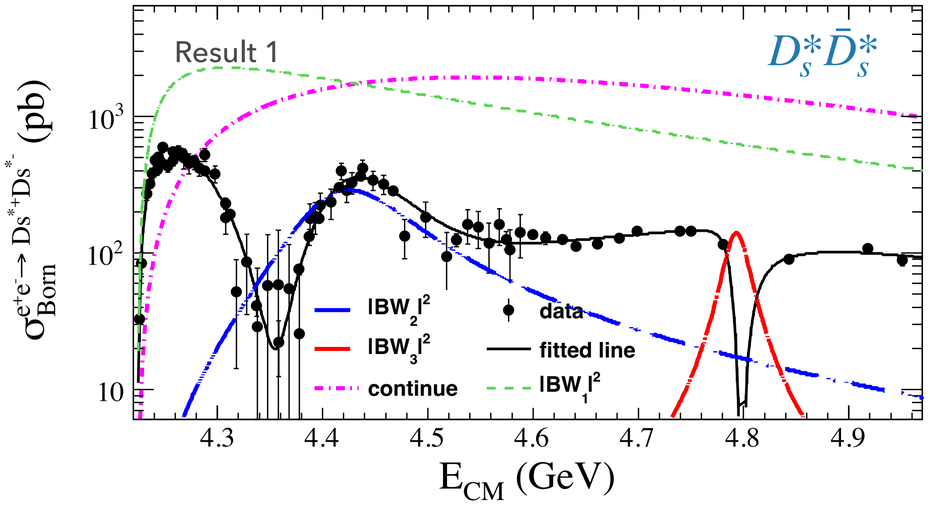
New Structure above 4.7 GeV?

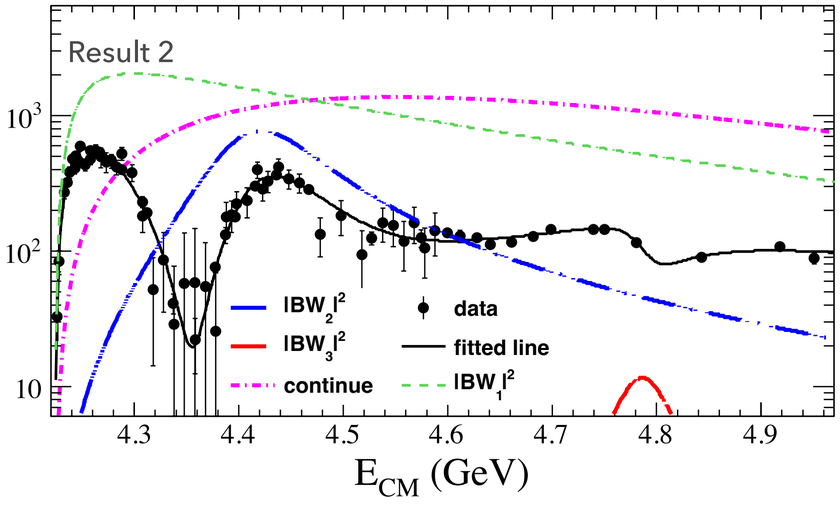




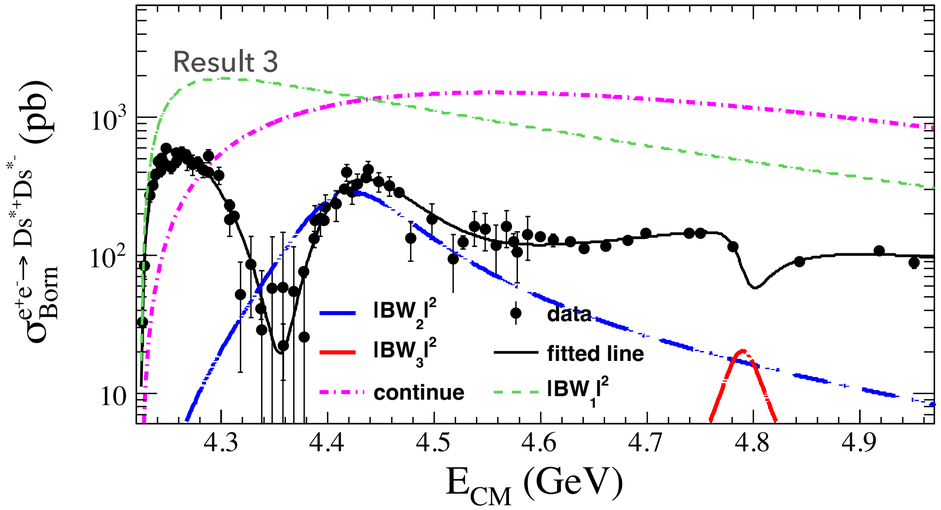


New Structure above 4.7 GeV?





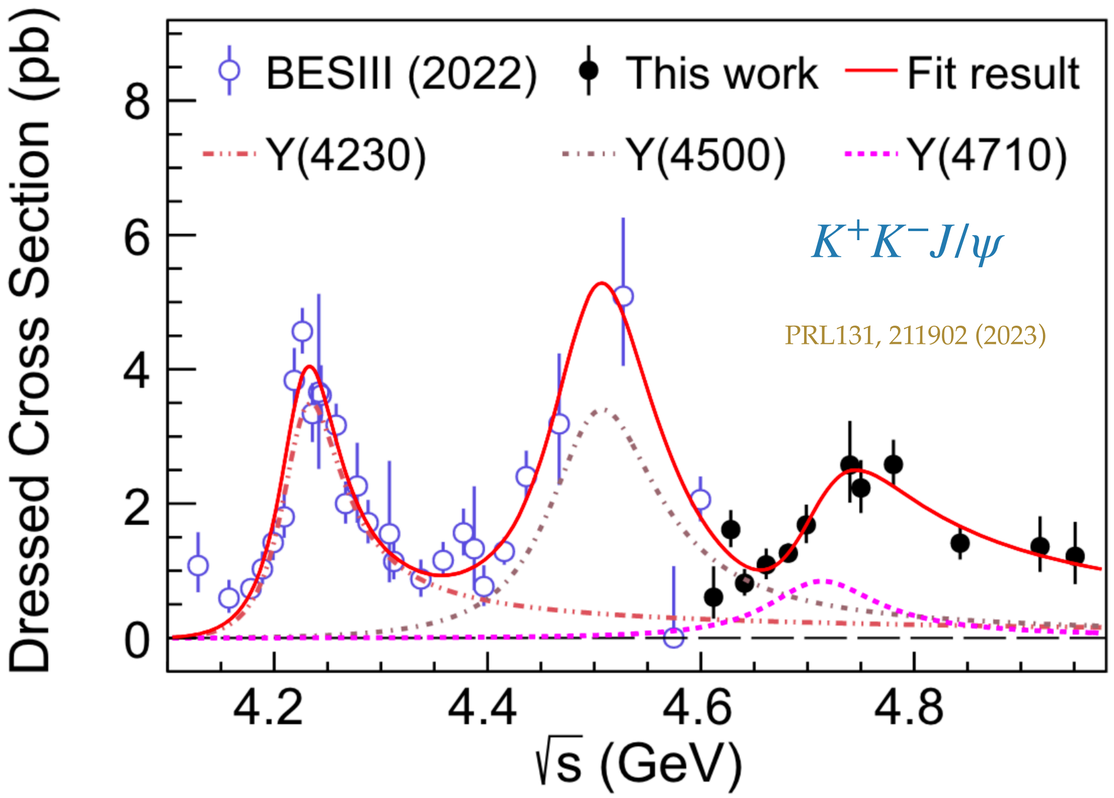
PRL131,151903 (2023)



$$\sigma_{\text{dressed}} = \left| BW_1(E_{\text{c.m.}}) + \sum_{j=2}^{3} BW_j(E_{\text{c.m.}}) e^{i\phi_j} + \frac{a_0\sqrt{\beta^3(E_{\text{c.m.}})}}{E^n_{\text{c.m.}}} e^{i\phi_0} \right|^2,$$

	Result 1	Result 2	Result 3
M_1 (MeV/c^2)	4186.8 ± 8.7	4194.1 ± 6.8	4195.6 ± 6.5
Γ_1 (MeV)	55 ± 15	61.1 ± 8.5	61.7 ± 7.7
M_2 (MeV/c^2)	4414.6 ± 3.4	4411.9 ± 3.2	4411.1 ± 3.2
Γ_2 (MeV)	122.5 ± 7.5	120.2 ± 7.4	119.9 ± 7.3
M_3 (MeV/c^2)	4793.3 ± 6.7	4789.7 ± 8.7	4786.0 ± 9.4
Γ_3 (MeV)	27.1 ± 6.5	42 ± 75	60 ± 34

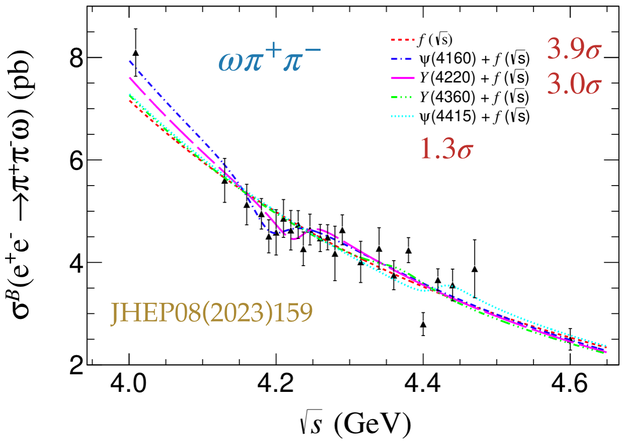
New Structure above 4.7 GeV?

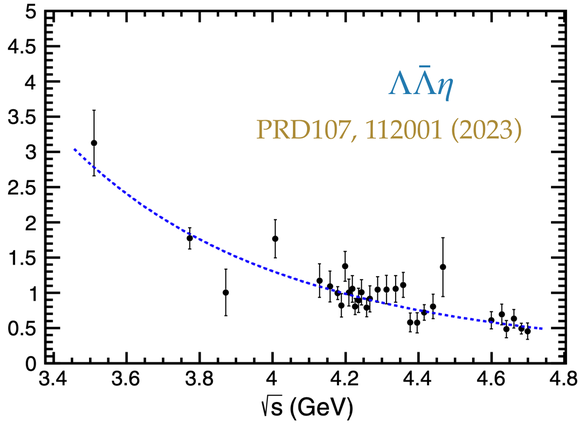


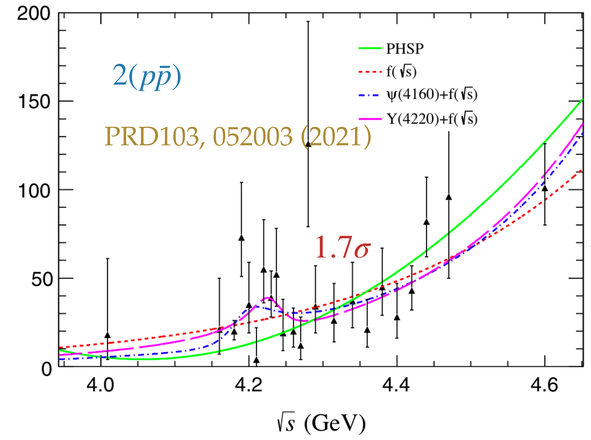
- ML fit with coherent sum of three BWs
- The three-resonance assumption over two is 5.7σ
- PHSP term is not significant, $\Delta(-2\ln L) = 1.2$
- Mass: $4708^{+17}_{-15} \pm 21$ MeV
- Width: $126^{+27}_{-23} \pm 30$ MeV
- Could have significant hybrid component (N.Brambilla et al. PRD107, 054034 (2023), mass higher, consistent with err.)
- Or excited charmonium (PRD 77, 014033 (2008), PRD 90, 054001 (2014), PRD 95, 034026 (2017), PRD 98, 016010 (2018), EPJA 58, 219 (2022), AHEP 2021, 9991152 (2021))
- Or from charmonia mixing (Z.J.Wang and X. Liu, PRD 107, 054016 (2023))

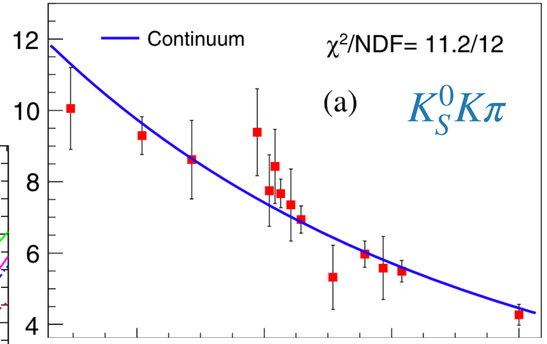
Light Hadron Process

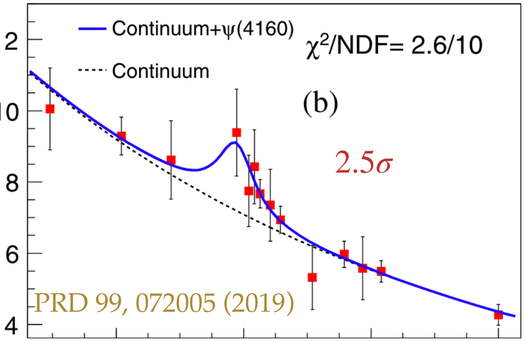
- More than 30 modes, no evident resonances observed (mostly <3σ)

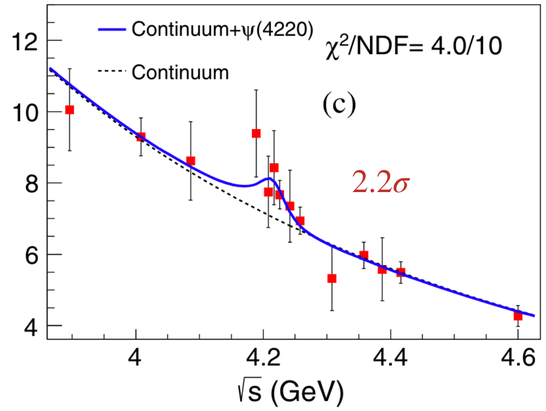


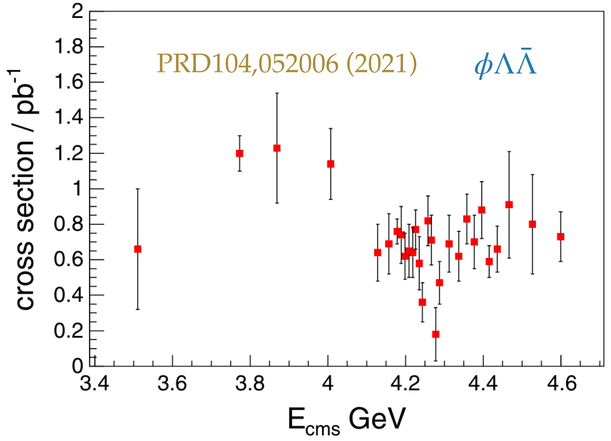


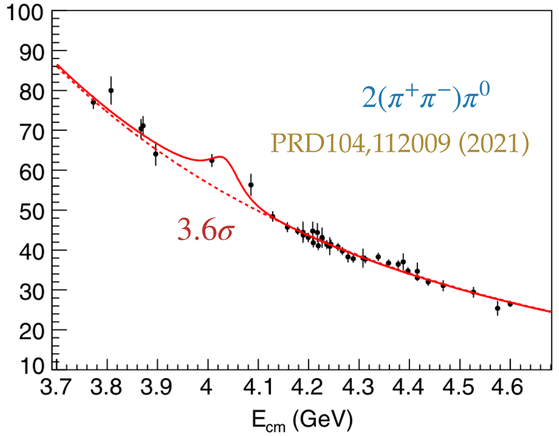


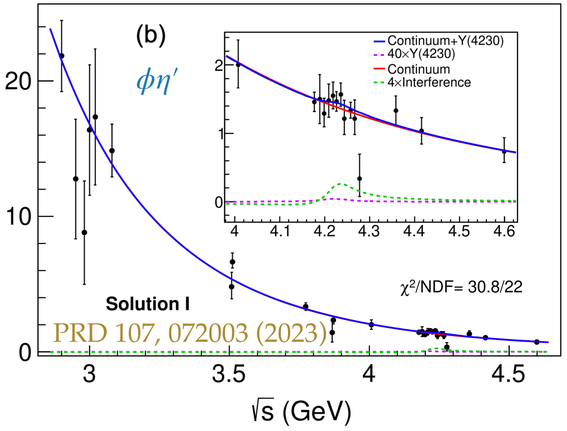




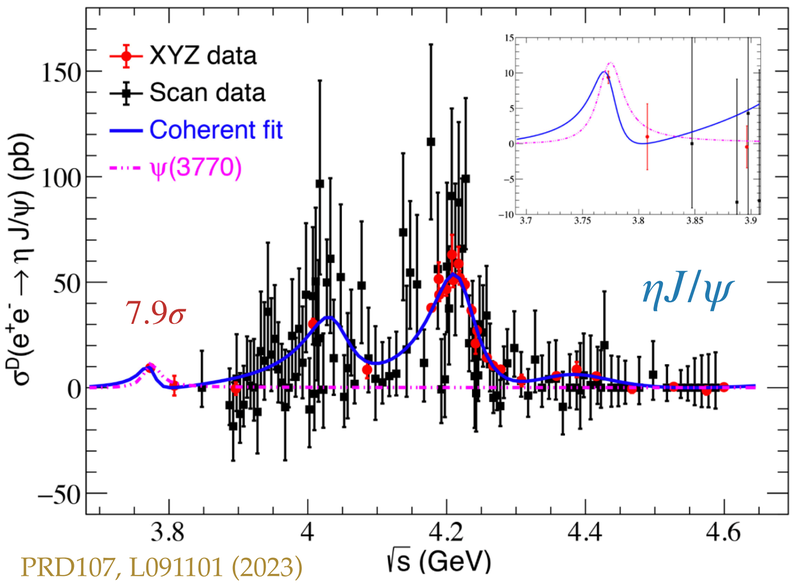


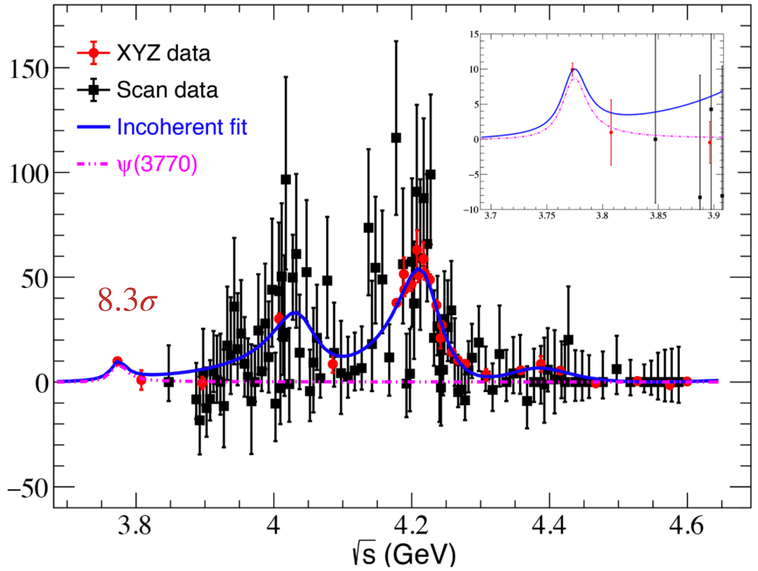






Non-DD Decay of ψ(3770)





PRD107, L091101 (2023)

$\sigma^B = (8.88 \pm 0.87 \pm 0.42)$ pb

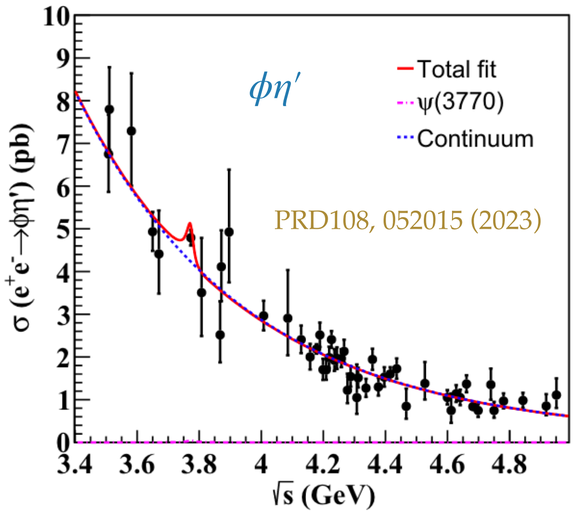
Parameters	Coherent fit Solution1	Solution2	Solution3	Solution4	Incoherent fit
$M_1(\mathrm{MeV}/c^2)$		3773.7 (fixed)			3773.7 (fixed)
$\Gamma_1(\mathrm{MeV})$		27.2 (fixed)			27.2 (fixed)
C_0		13.3 ± 1.9			11.0 ± 1.6
$\mathcal{B}r_1(\times 10^{-4})$	11.3 ± 5.9 ± 1.1	11.6 ± 6.0 ± 1.1	11.2 ± 5.8 ± 1.1	11.5 ± 6.0 ± 1.1	8.7 ± 1.0 ± 0.8
$\phi_1(\mathrm{rad})$	3.9 ± 0.6 ± 0.07	4.2 ± 0.6 ± 0.09	3.7 ± 0.6 ± 0.05	4.1 ± 0.6 ± 0.08	

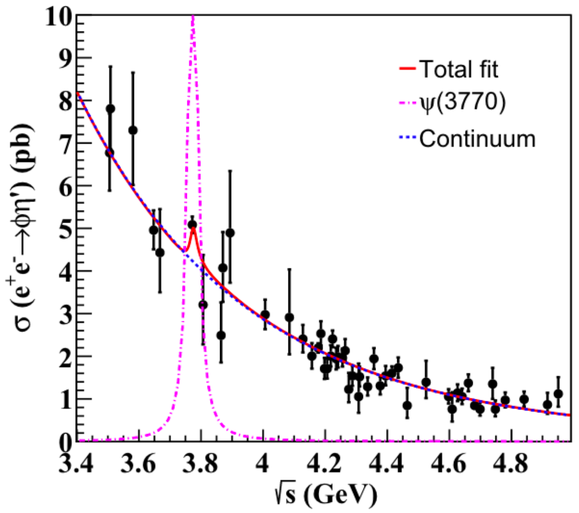
CLEO result: 3.5σ

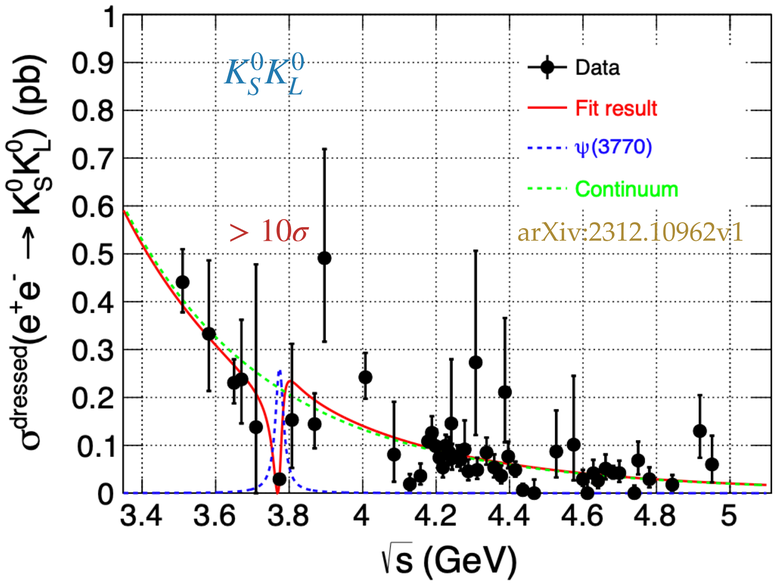
$(8.7 \pm 3.3 \pm 2.2) \times 10^{-4}$

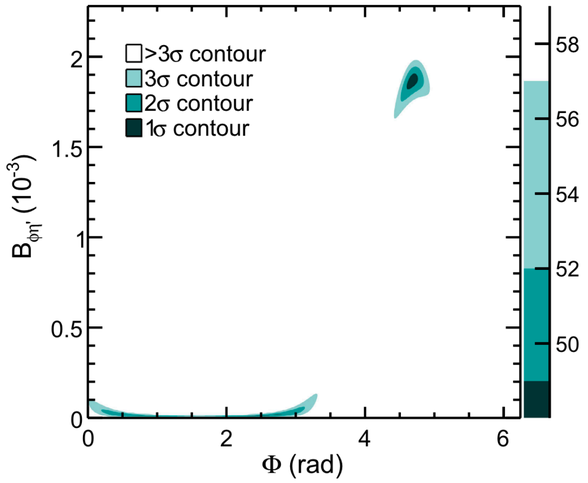
interference between $\psi(3770)$, continuum, and Y states

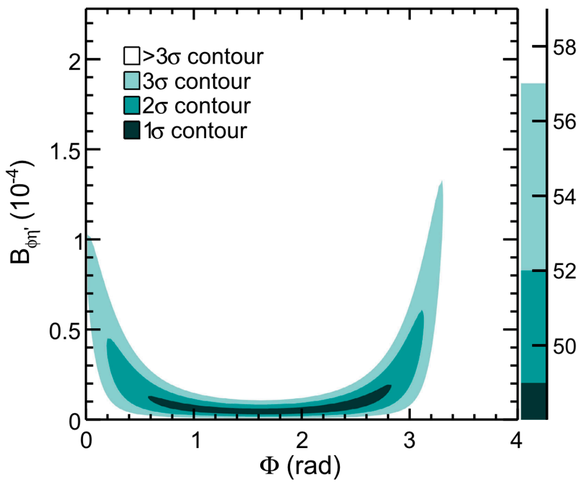
Non-DD Decay of ψ(3770)

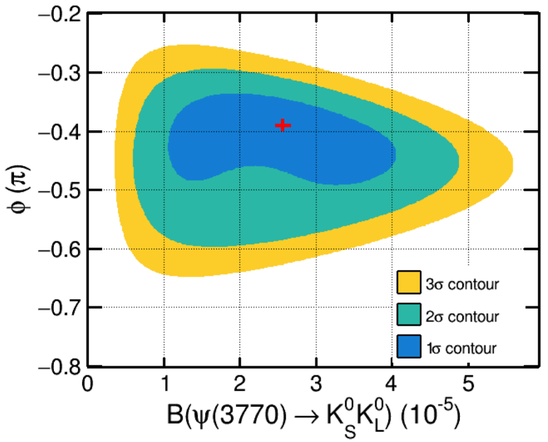




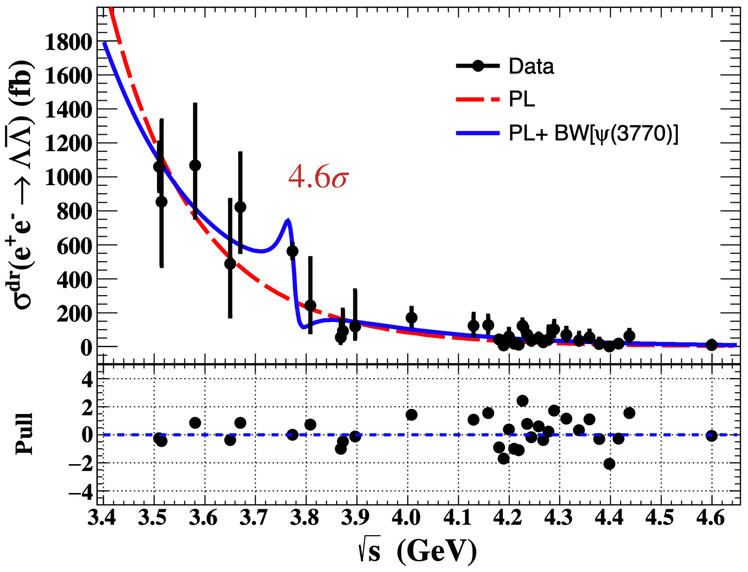




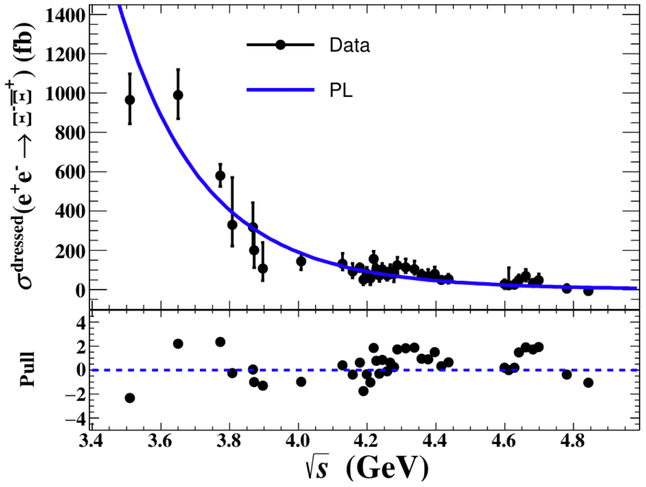


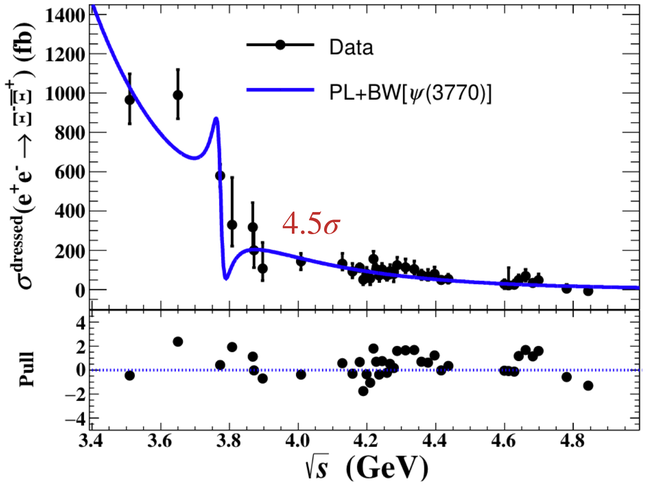


Non-DD Decay of ψ(3770)

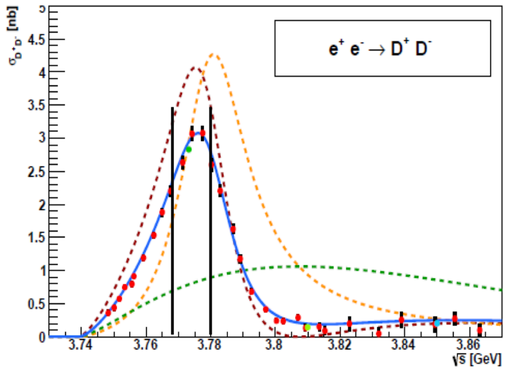


	Fit I	Fit II	
σ_0 (fb)	379 ± 22	320^{+750}_{-340}	
n	8.8 ± 0.4	8.2 ± 0.6	
ϕ (°)	···	183^{+57}_{-40}	240^{+17}_{-115}
σ_ψ (fb)	0 (fixed)	240^{+1470}_{-190}	1440^{+270}_{-1390}
χ^2/ndof	62.0/31	34.6/29	
$\mathcal{B}$ ($\times 10^{-5}$)	···	$2.4^{+15.0}_{-1.9}$	$14.4^{+2.7}_{-14.0}$





Resonance parameter	Solution I	$\chi^2/n.d.f$
$\phi_{\psi(3770)}$ (rad)	-2.1 ± 0.2	
$\Gamma_{ee}\mathcal{B}_{\psi(3770)}$ (10^{-3} eV)	35.5 ± 9.2	$45.0/(38-4)$
$\mathcal{B}[\psi(3770)\to\Xi^-\bar{\Xi}^+]$ (10^{-6})	136.0 ± 35.2	



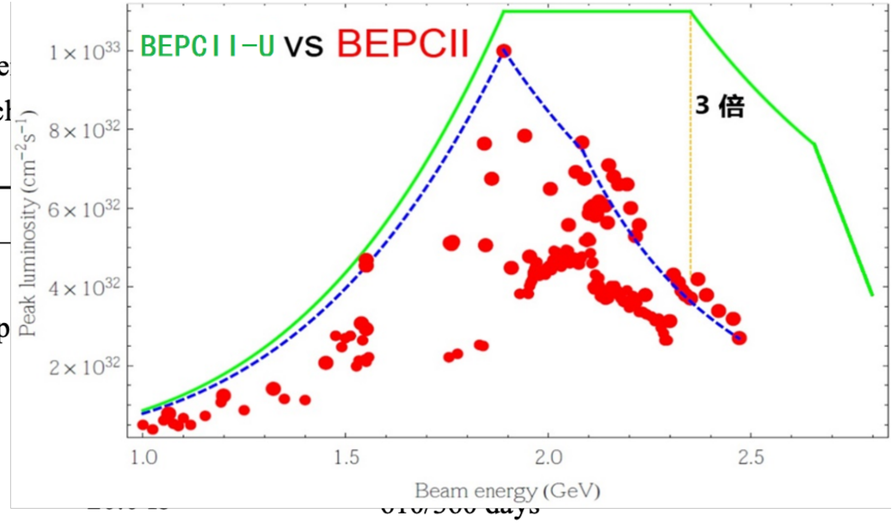
Two more data samples around $\psi(3770)$ this year!

500/pb for each point

Future Data Samples

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

Energy	Physics motivations	Current data	Comp		
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}			
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



Pentaquark: 4.86 GeV - $p\bar{p}\eta_c$ threshold; 4.97 GeV - $p\bar{p}J/\psi$ threshold

Summary

- Properties of vector states have been investigated using various processes, including hidden charm, open charm, and light hadronic final states
  - Y(4230) is seen in 10 decay modes
  - Rich structures in the cross section line shapes above 4.3 GeV, more data samples are needed around 4.5 GeV and 4.7 GeV
  - No evident structure is seen in light hadron process
  - Hard to get a unified picture with current used strategy [use simply formula to fit cross section], require joint effort/better modeling ⇒ combined fit with K-matrix?
  - Interference effect need to be considered properly

Thank You!