Recent Progress on
Vector Charmonium(-like) States From BESIII

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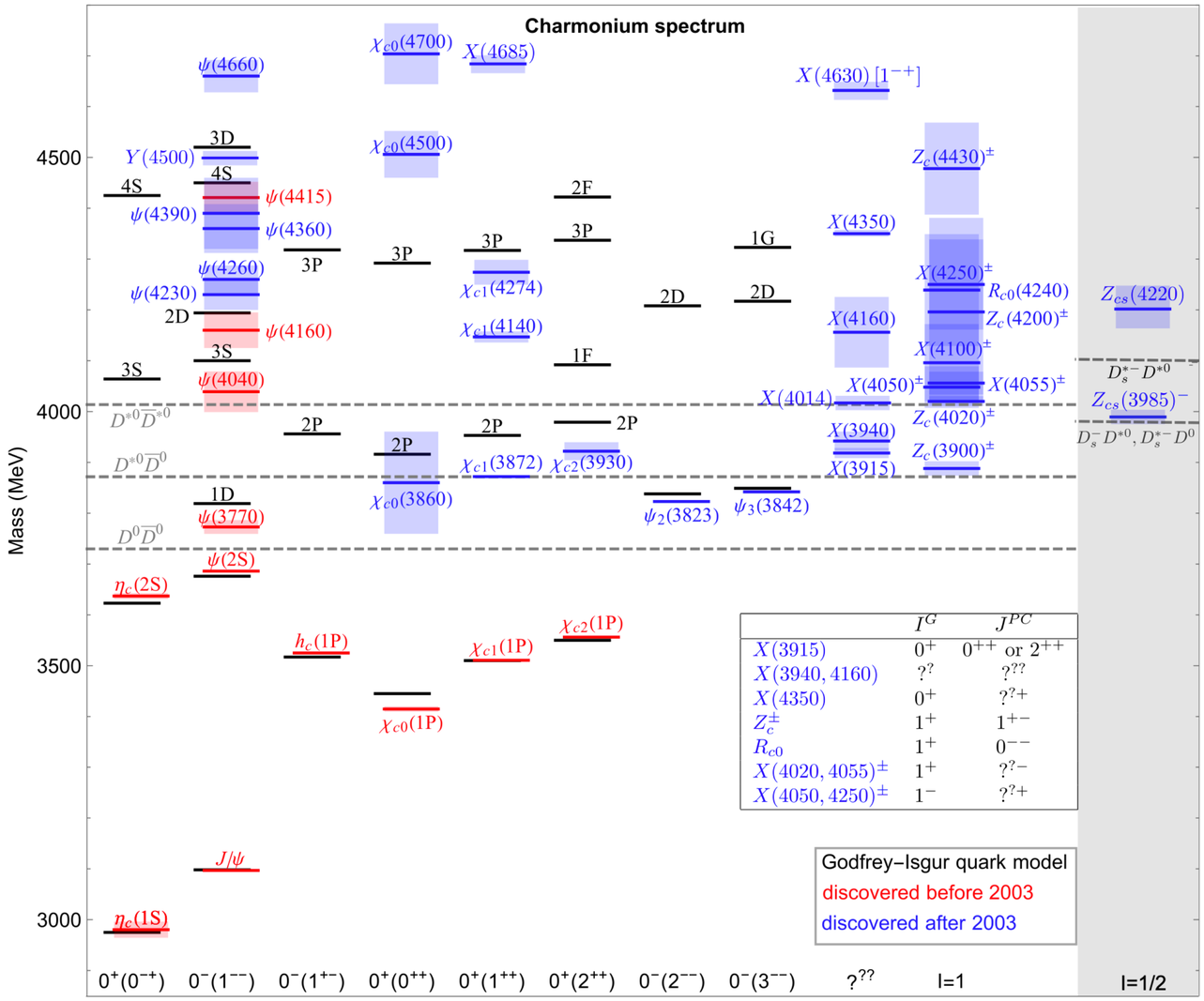
On behalf of the BESIII collaboration

QWG 2024 - IISER Mohali

The exotic states @ Charmonium sector

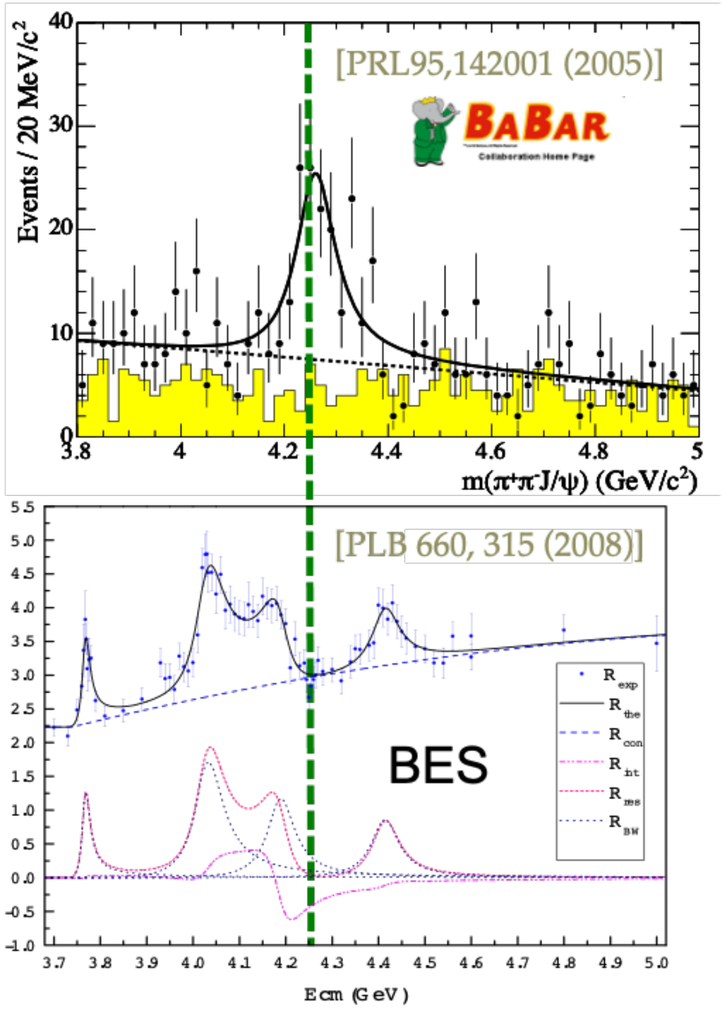


from F. K. Guo

- Since the new century, a series of new particles have been discovered experimentally above the open-charm threshold.
- Their properties indicate that they are good candidates of exotic states: Hybrid states, Hadron molecule, Compact tetra-quark, etc.
- They can be classified to 3 categories (roughly):
- **X: Iso-spin I=0 with quantum number other than 1^{--}**
- **Y: Iso-spin I=0, vector states**
- **Z: Iso-spin larger than 0**

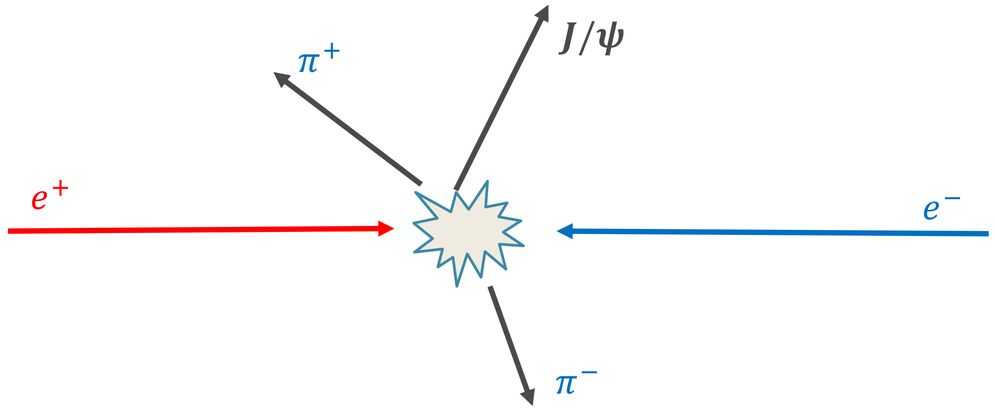
Discovery of Y States

- 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 $D\overline{D}$ threshold
  - Not observed in inclusive hadron cross section, **disfavor charmonium state**
- Interpratation
  - Is Y(4260) hybrid?
  - Strongly couple to the low-lying charmonium.
  - According to lattice QCD simulation, both the 1^{--} and 1^{-+} hybrid charmonium lie around 4.26 GeV
- Family members
  - 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
  - More measurements is necessary to pin down its nature!!



Production and decays of Y states at BESIII

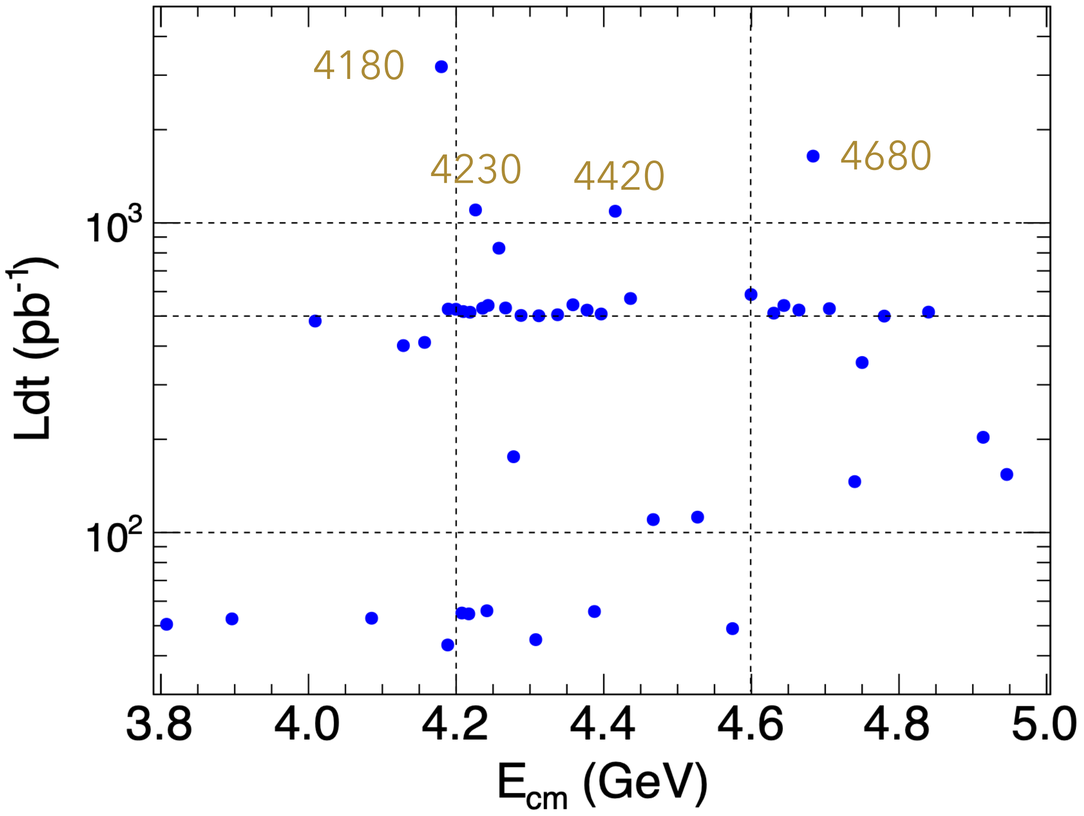
Can be produced from electron positron annihilation directly, good opportunity to study Y states at BESIII



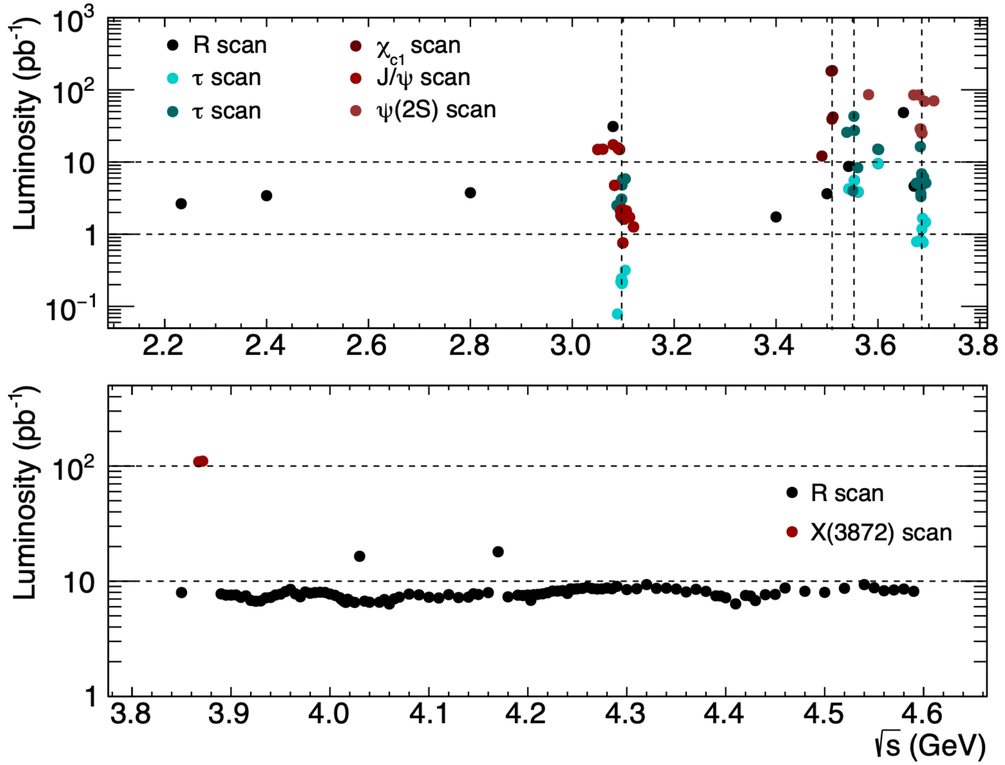
We can study Y state via various processes:

- *Hidden charm final state => disfavored by charmonium state, crucial to reveal their inner structure*
- Open charm final state
- Baryon and Light hadron final state

BESIII Data Samples



46 sample, ~22 fb^{-1}

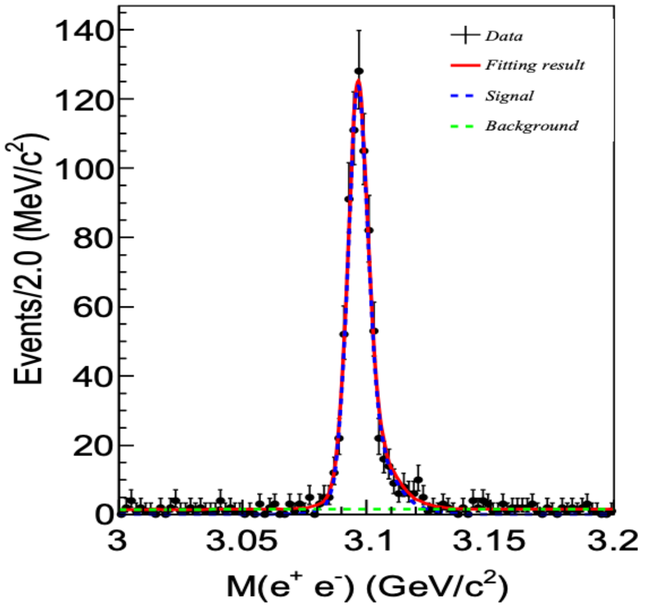


+ Small scan sample, ~2.5 fb^{-1}

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

The method to study Y states @ BESIII

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ [PRD106, 072001 (2022)]



- Tag event at each cm energy

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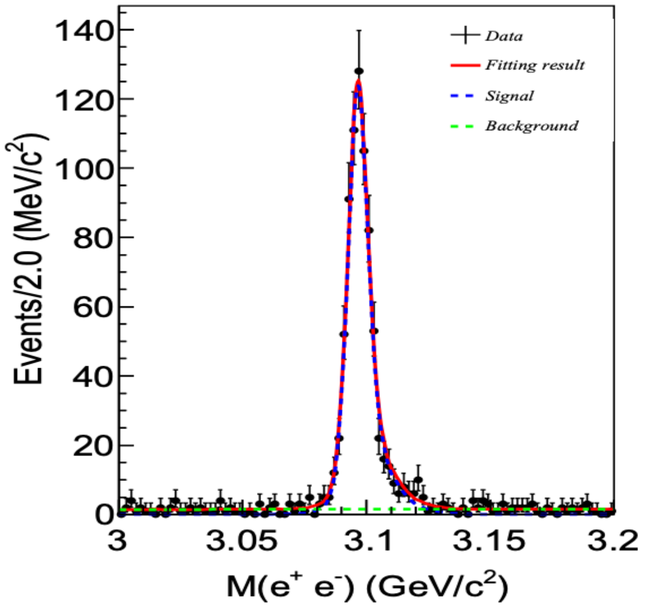

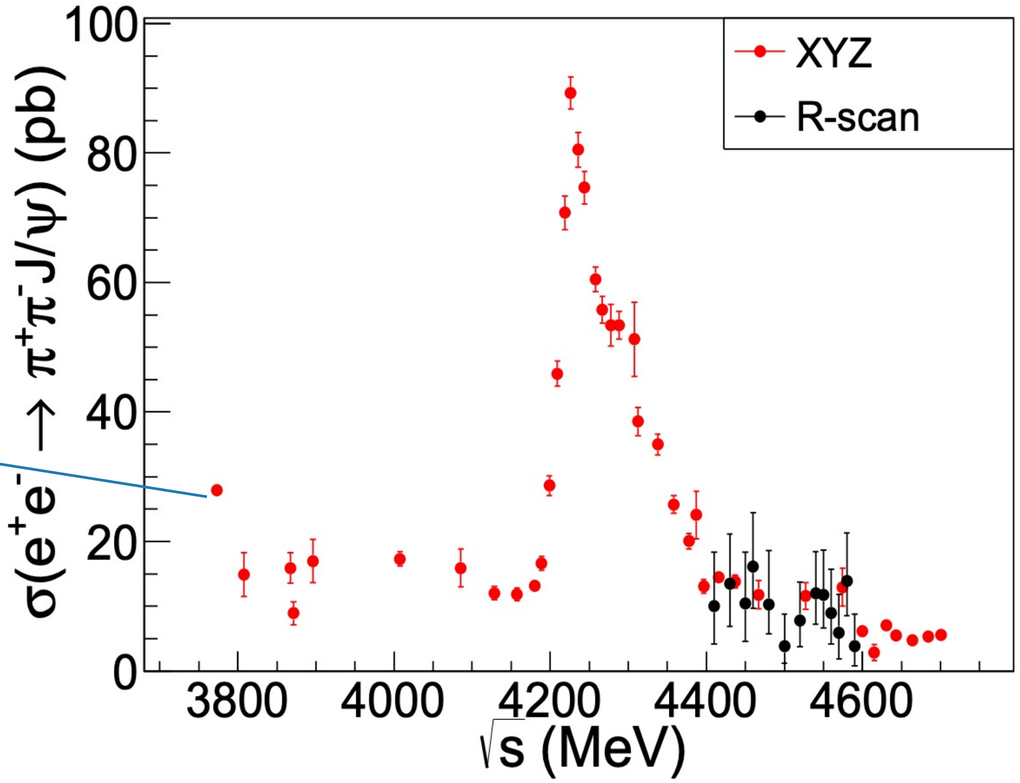

- Tag event at each cm energy
- Calculate the cross section at each $\sqrt{s}$ by: $\sigma = \frac{Nsig}{L*(1+\delta)*|1+\Pi|^2 Br*\varepsilon}$

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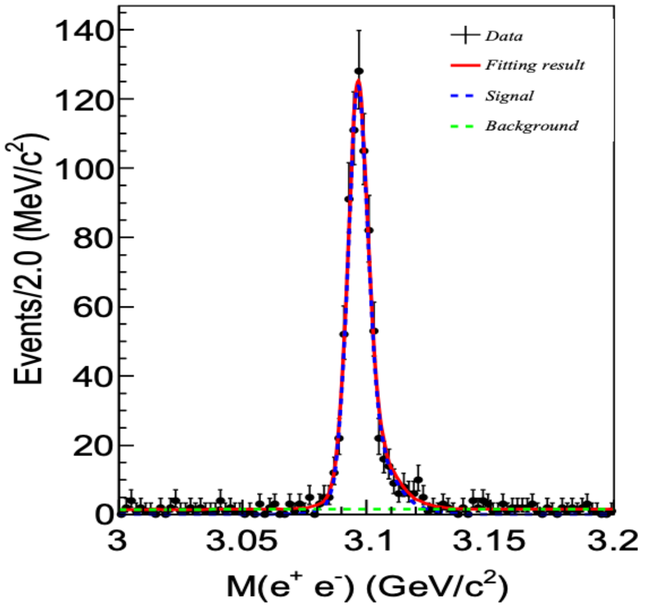
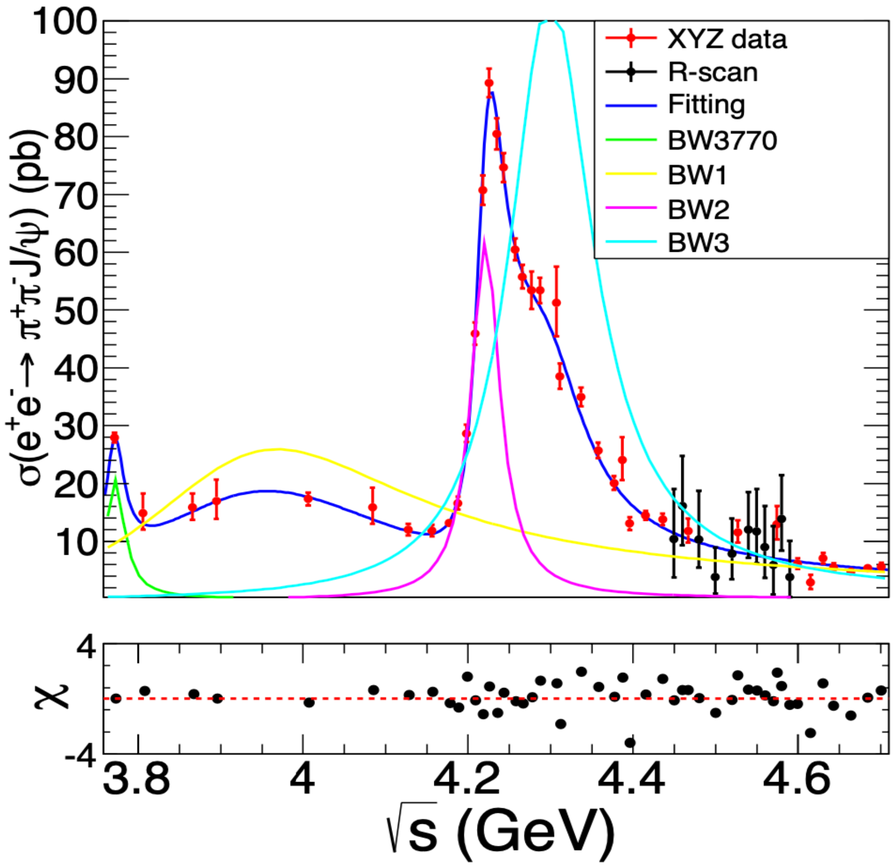
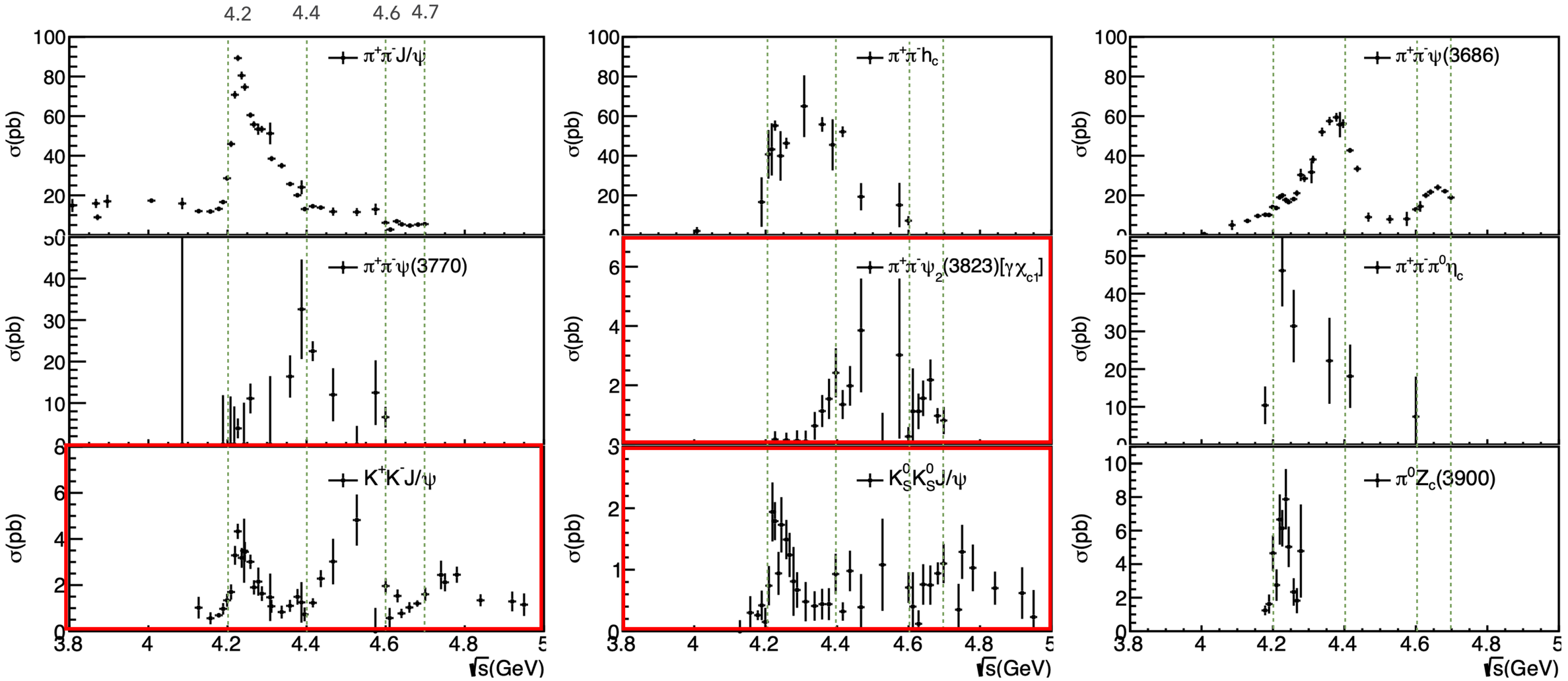


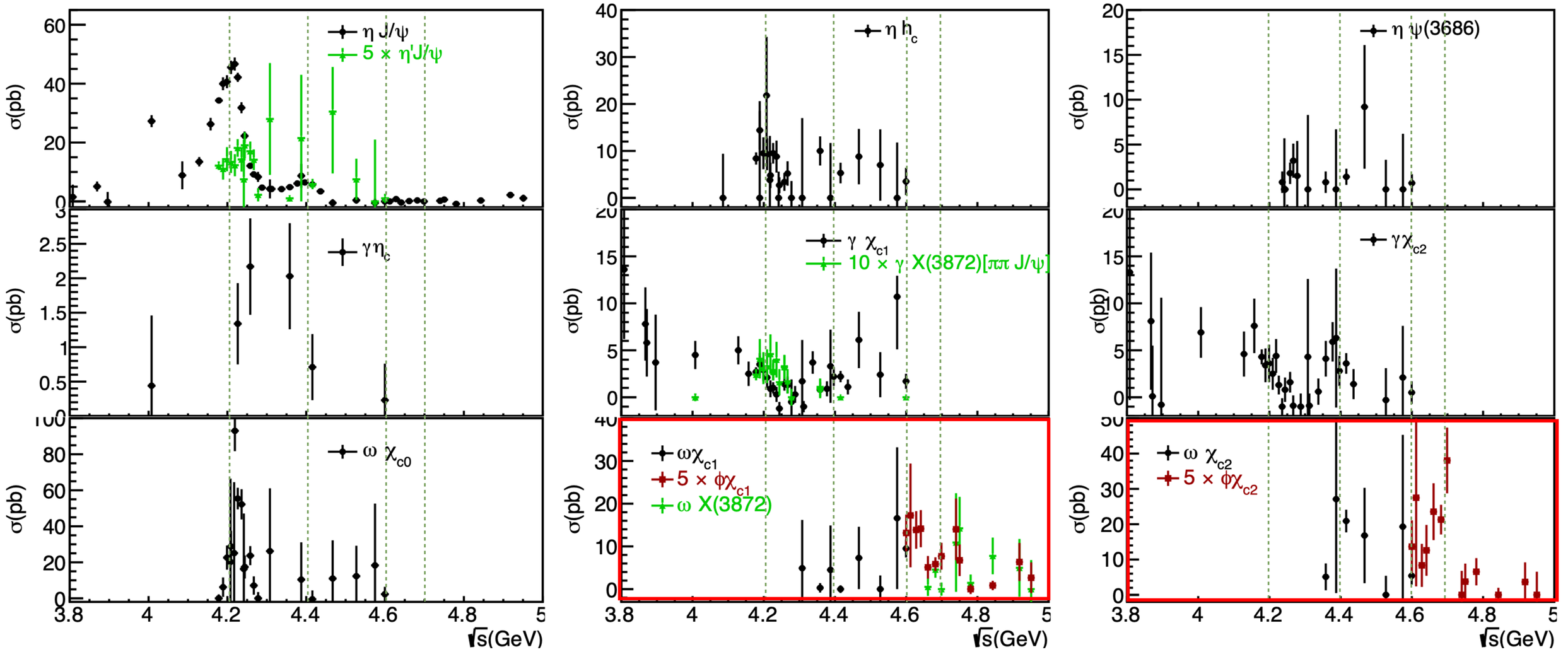


- Tag event at each cm energy
- Calculate the cross section at each $\sqrt{s}$ by: $\sigma = \frac{Nsig}{L*(1+\delta)*|1+\Pi|^2 Br*\varepsilon}$
- Fit to the lineshap of cross section with model, e.g.: $\sigma(s) = |BW1(s) + BW2(s)*e^{i\phi} + BW3(s)*e^{i\phi'}|^2$

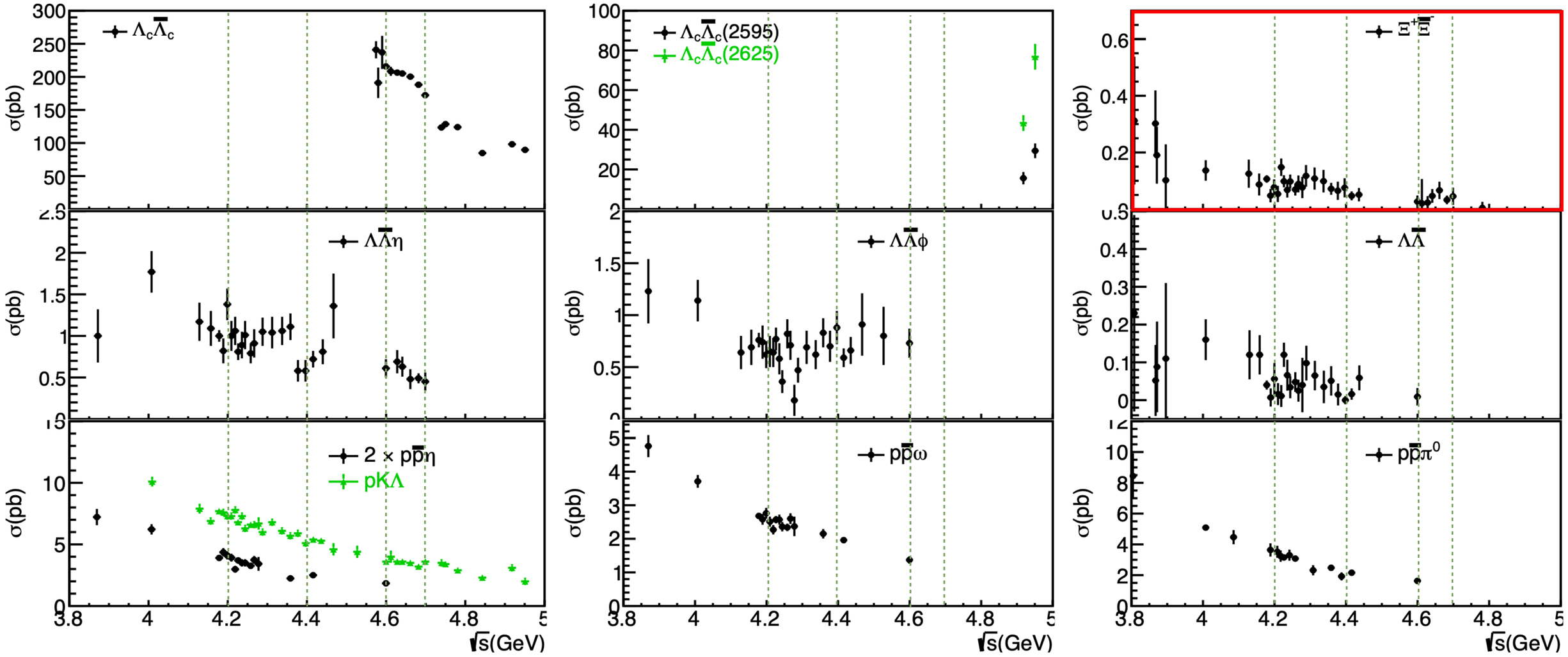
Summary of $\sigma(e^+e^- \to \pi\pi/KK + charmonium)$



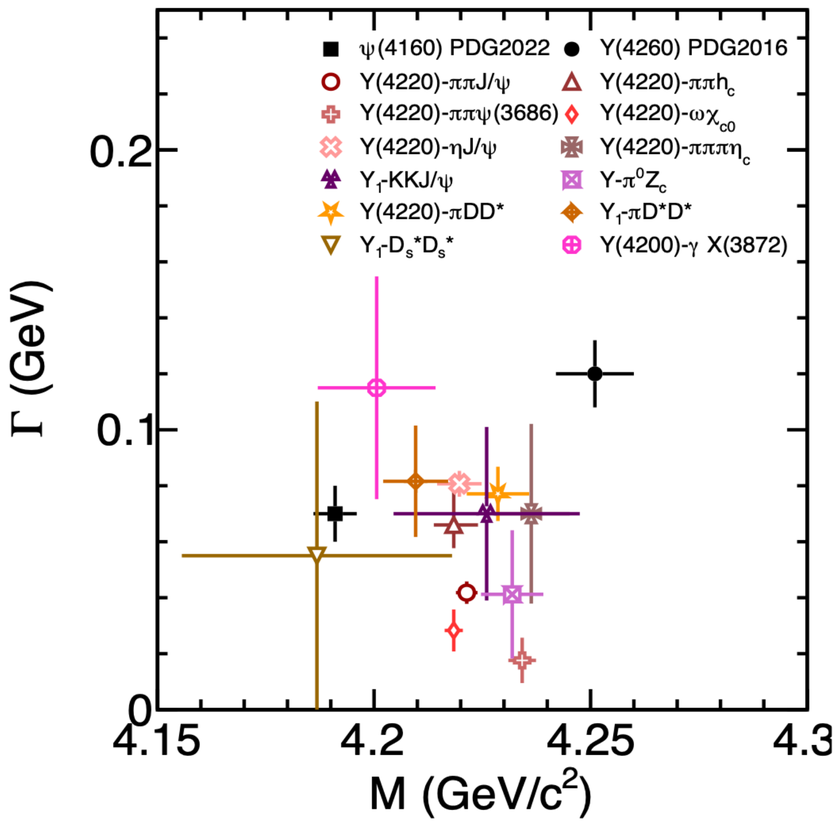
Summary of $\sigma(e^+e^- \to \eta/\gamma\,/\omega + charmonium)$

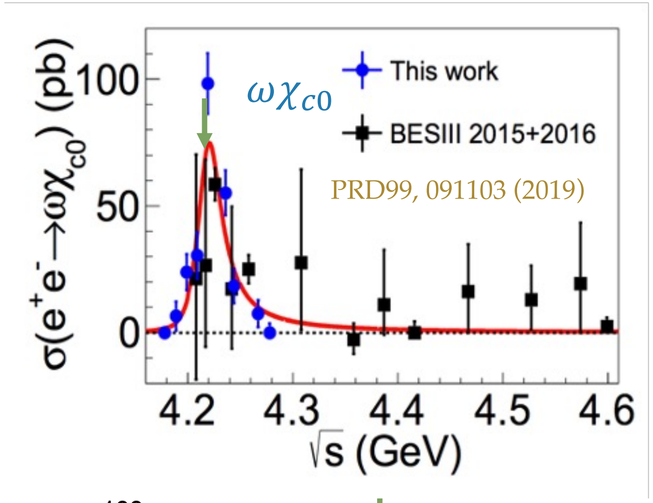


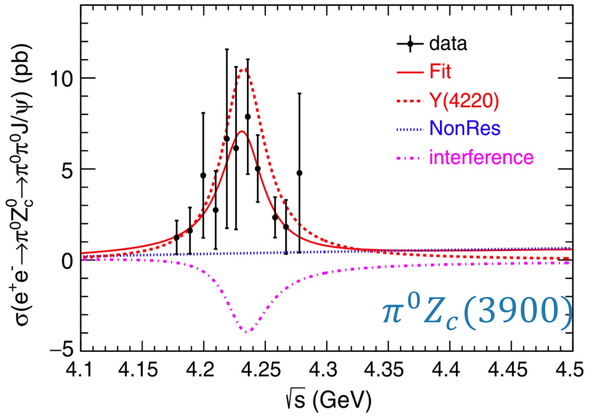
Summary of $\sigma(e^+e^- \to Baryon + (light\ meson))$

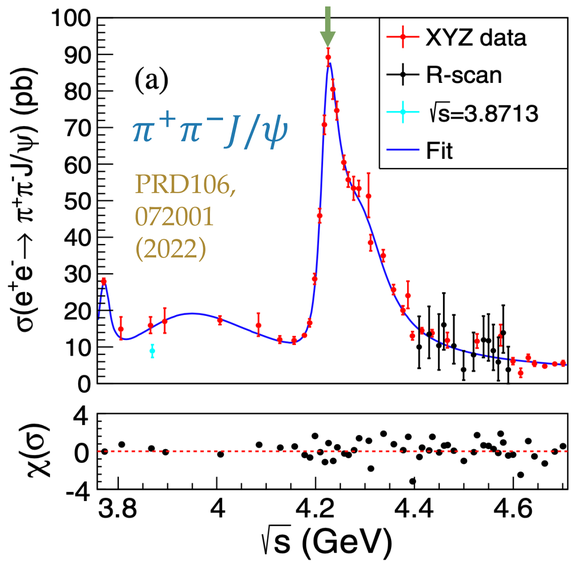


Conclusions from these measurment: 1. Y(4260) ⇒ Y(4230)

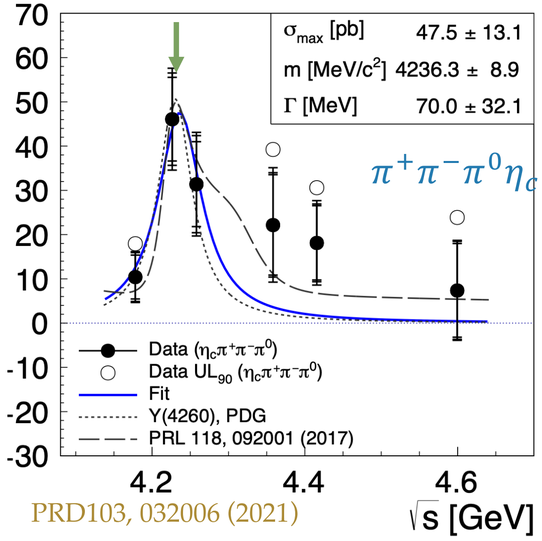






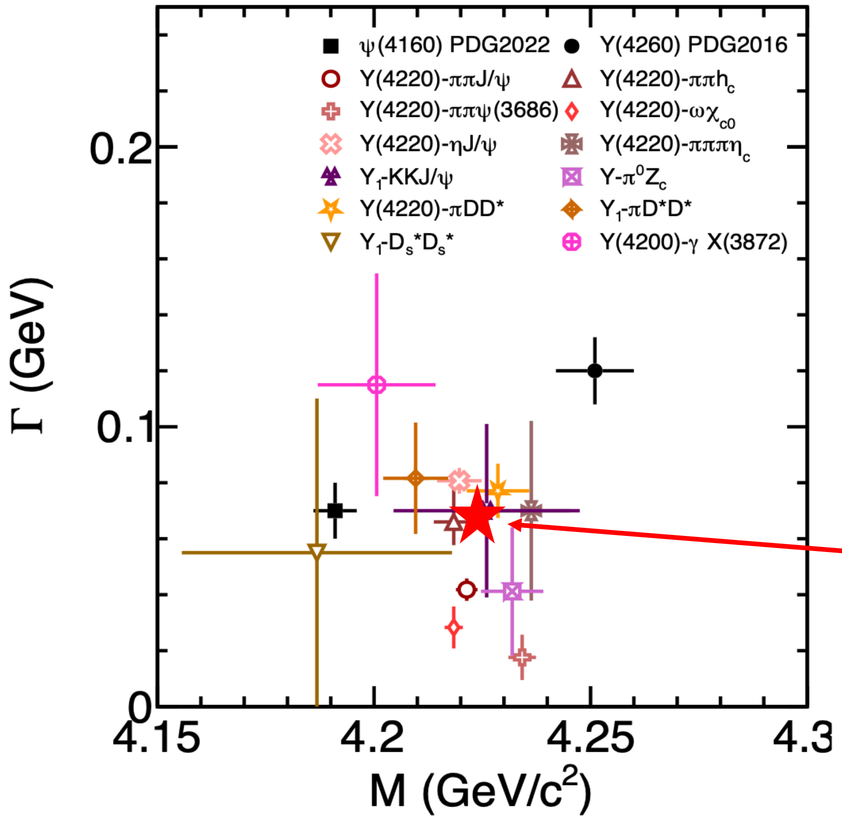


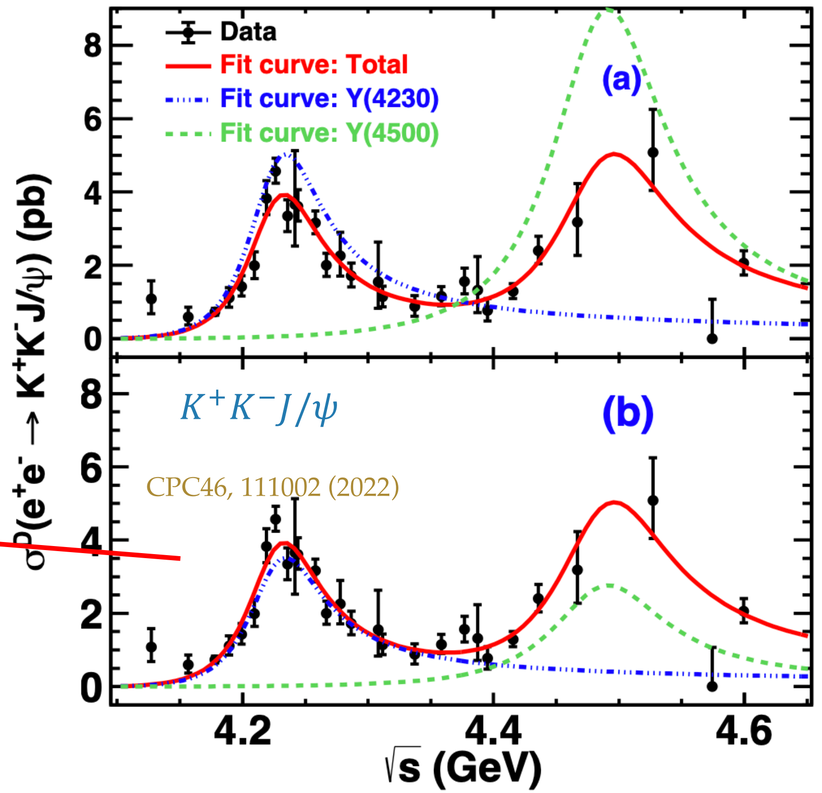
PRD102, 012009 (2020)



PRD103, 032006 (2021)

Update of K^+K^-J/ψ Cross Section





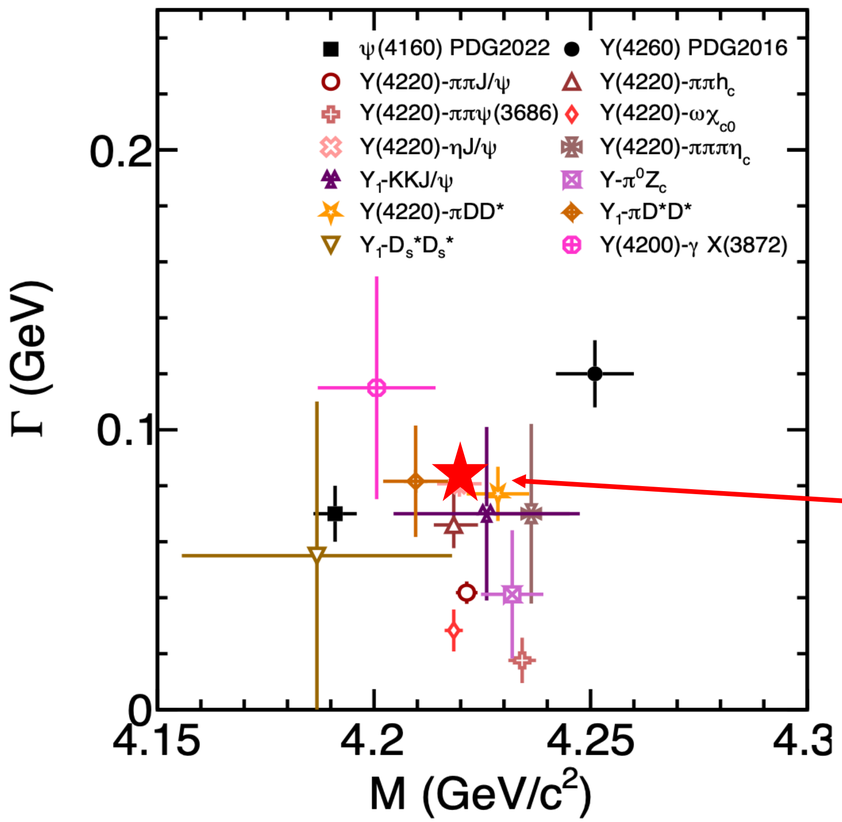
- ML fit with coherent sum of two BWs
- **Mass: $4225.3 \pm 2.3 \pm 21.5$ MeV**
- **Width: $72.9 \pm 6.1 \pm 30.8$ MeV**
- Significance > 5σ

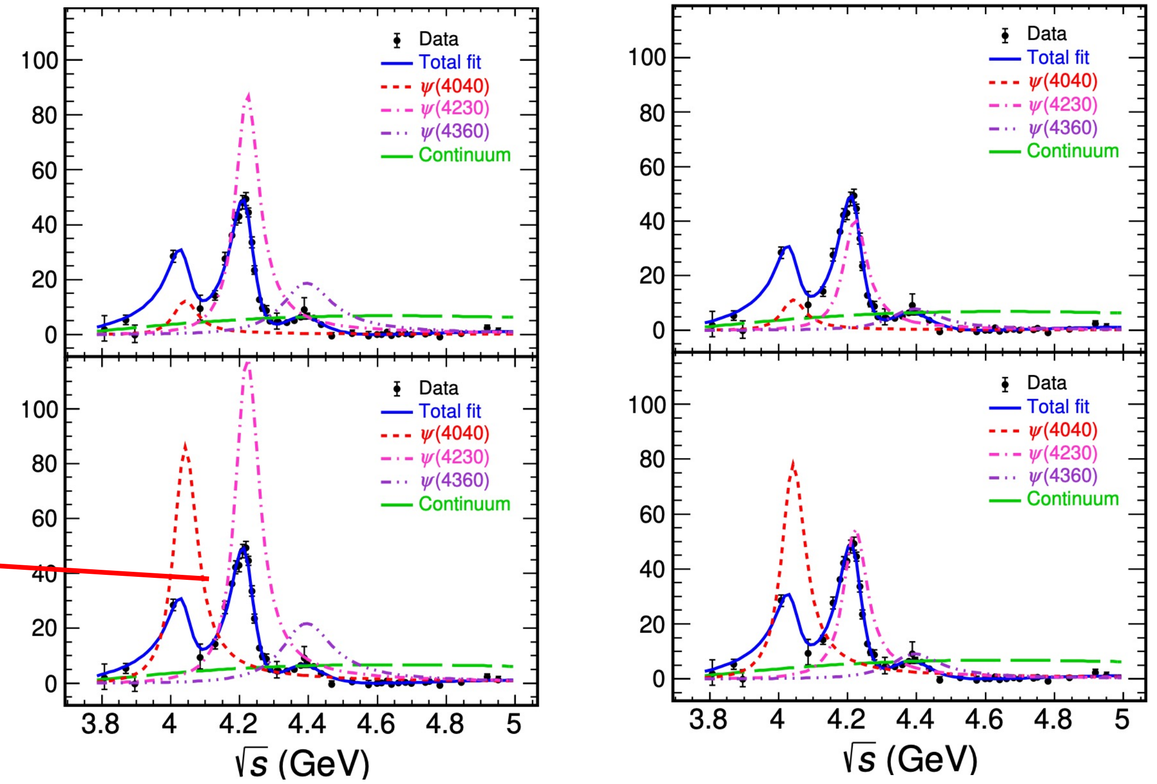
Ratio to $\pi\pi J/\psi$

	$K\bar{K}J/\psi$ 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

Update of ηJ/ψ Cross Section

arXiv: 2310.03361

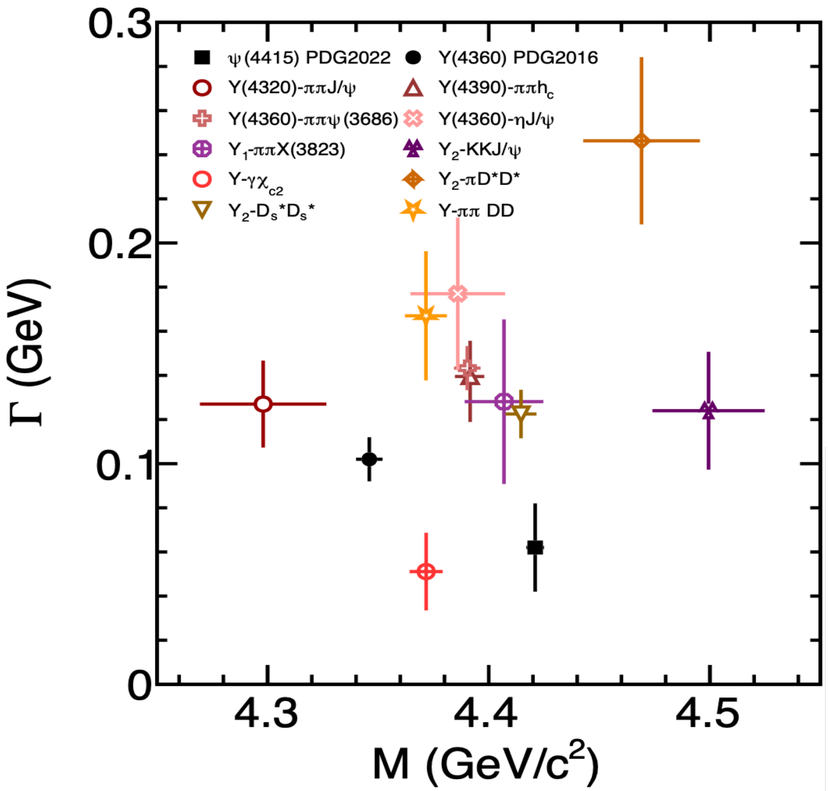


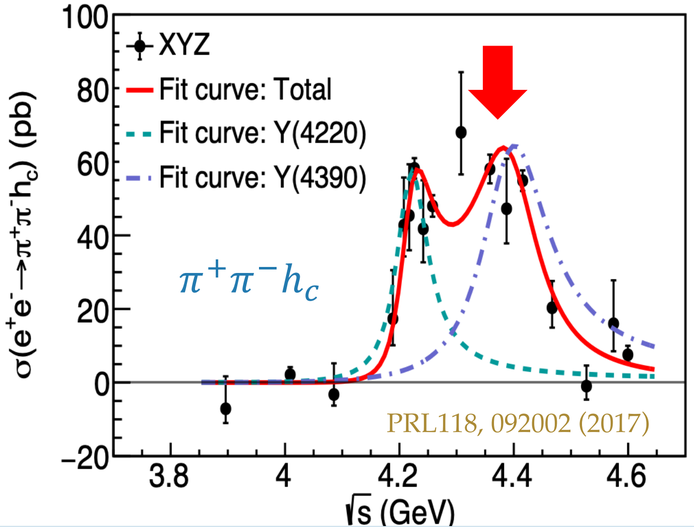


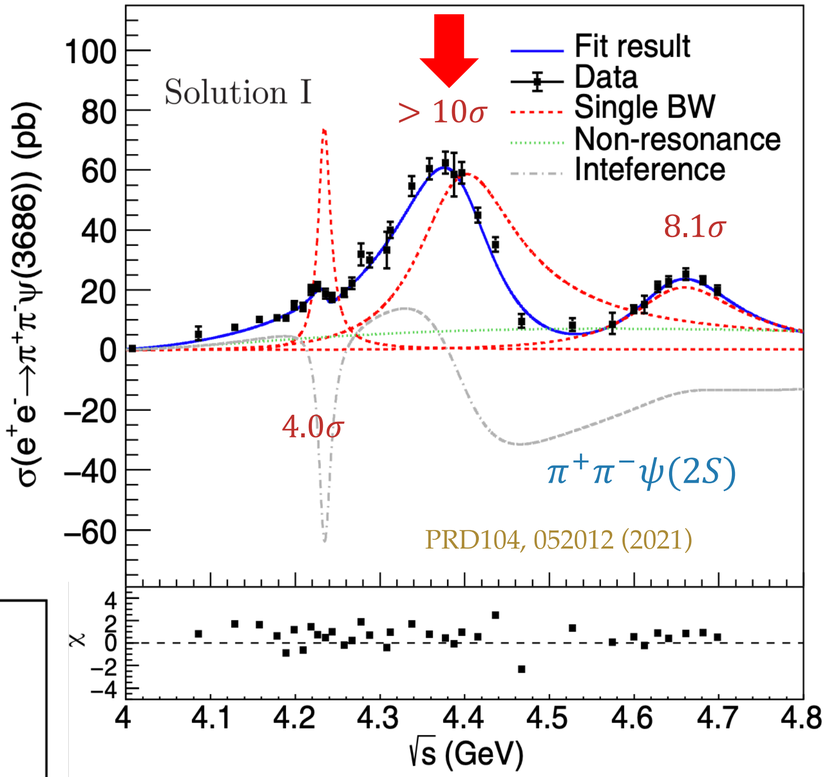
- ML fit with coherent sum of three BWs and a continuum term ($\Phi(\sqrt{s})e^{-p_0 u}p_1$)
- **Mass: $4219.7 \pm 2.5 \pm 4.5$ MeV; Width: $80.7 \pm 4.4 \pm 1.4$ MeV**
- Take Γ_{ee} to be ~0.63-0.66 keV, $\mathcal{B}[\psi(4230) \to \eta J/\psi) = (6.06 \pm 0.76 \pm 0.17)\times10^{-3}$ or $(18.89 \pm 1.75 \pm 0.90)\times10^{-3}$

Conclusions from these measurements: 2. new state in [4300 4500] MeV

Mass and width from different process







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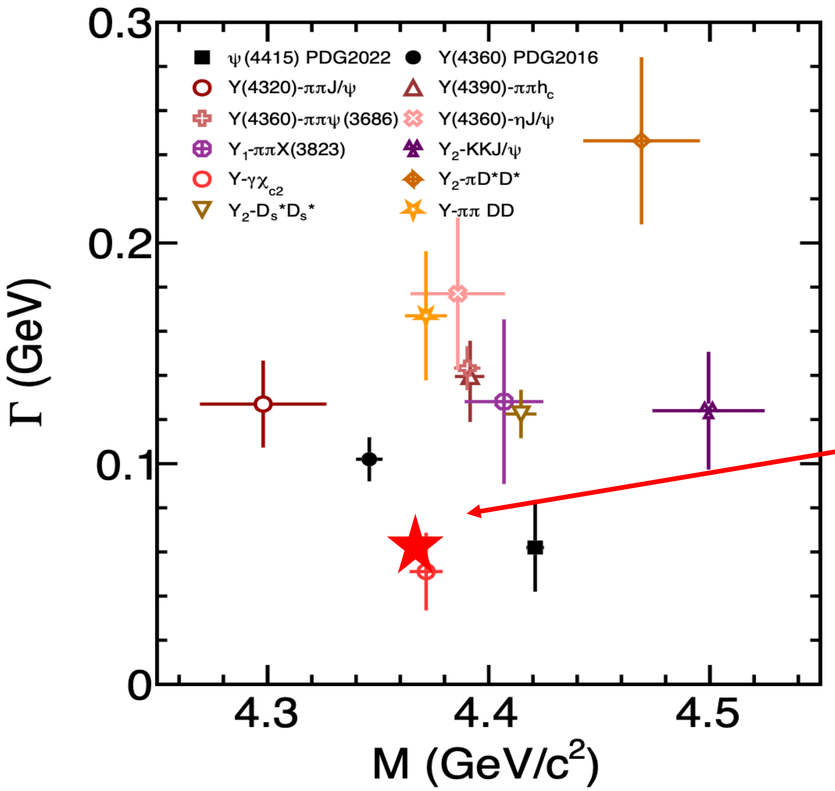
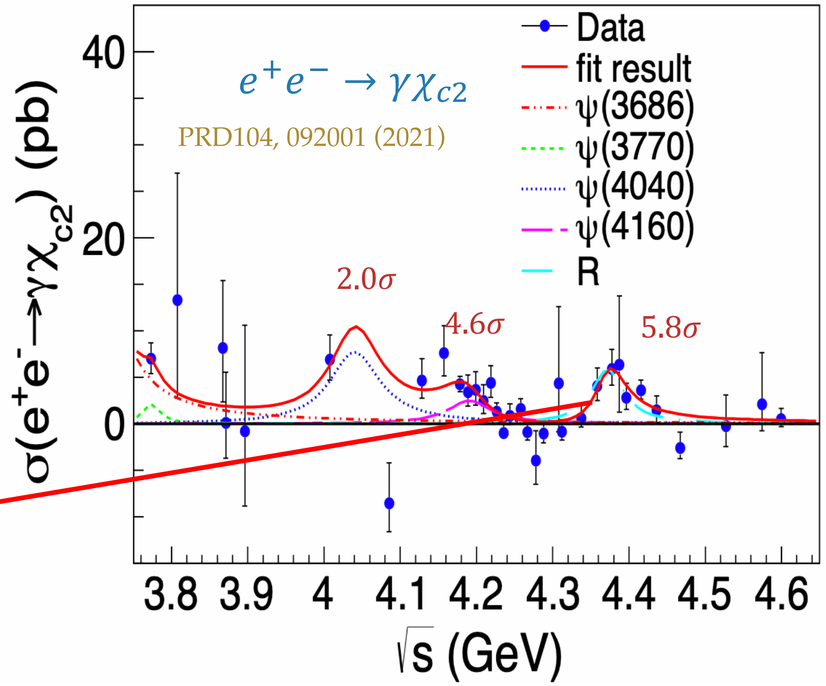




$\mathcal{B}[\psi(4040) \to \gamma\chi_{c2}] = (8.0 - 15.6)\times10^{-4}$

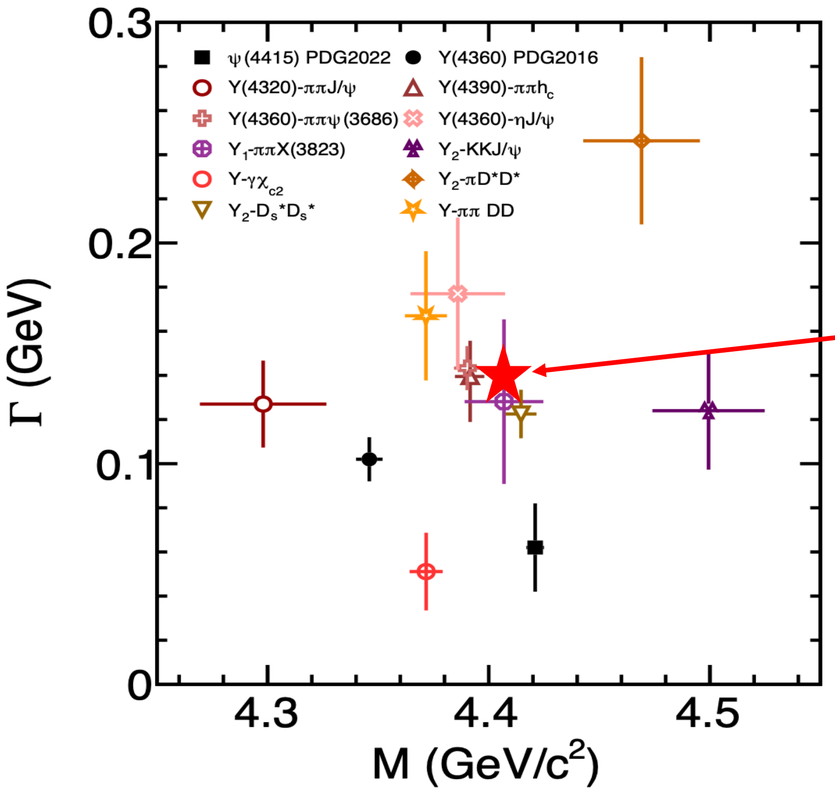
$\mathcal{B}[\psi(4160) \to \gamma\chi_{c2}] = (4.4 - 14.2)\times10^{-4}$

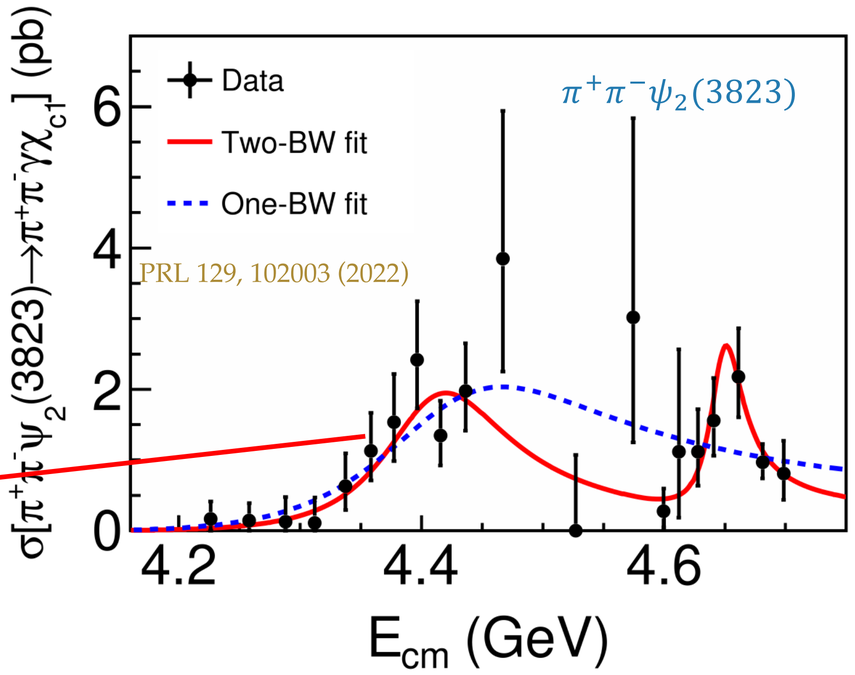
potential model:~ 10^{-7}

- 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**

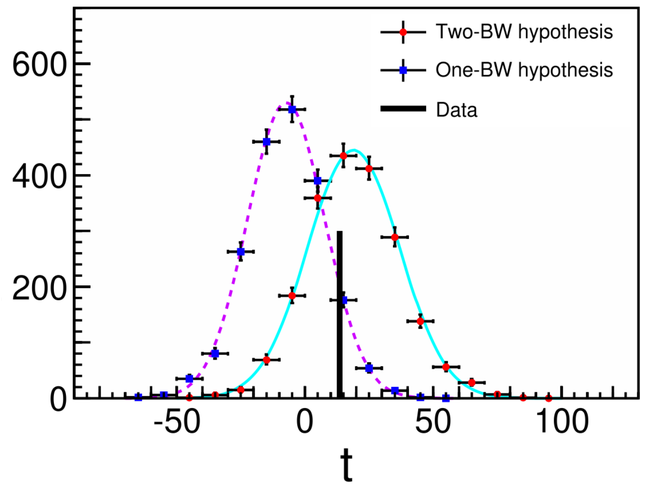
Conclusions from these measurements: 2. new state in [4300 4500] MeV

Mass and width from different process





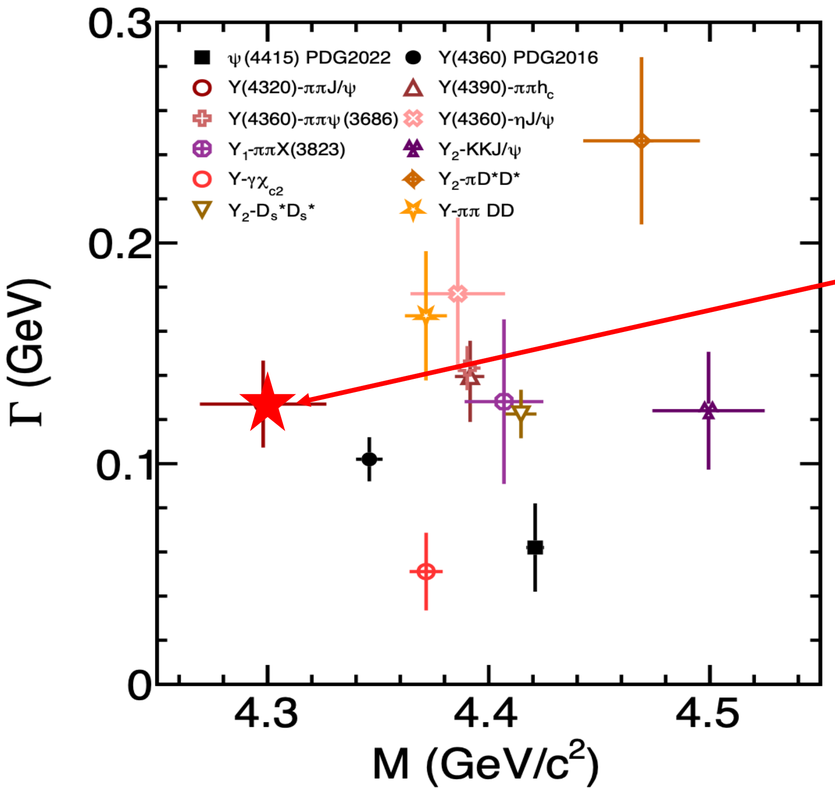
Parameters	Solution I	Solution II
$M[R_1]$	$4406.9 \pm 17.2 \pm 4.5$	
$\Gamma_{\rm tot}[R_1]$	$128.1 \pm 37.2 \pm 2.3$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_1}\mathcal{B}_2$	$0.36 \pm 0.10 \pm 0.03$	$0.30 \pm 0.09 \pm 0.03$
$M[R_2]$	$4647.9 \pm 8.6 \pm 0.8$	
$\Gamma_{\rm tot}[R_2]$	$33.1 \pm 18.6 \pm 4.1$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

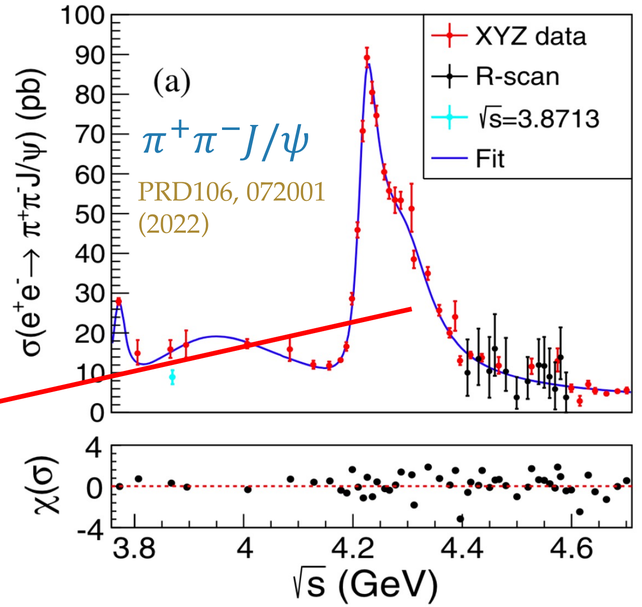


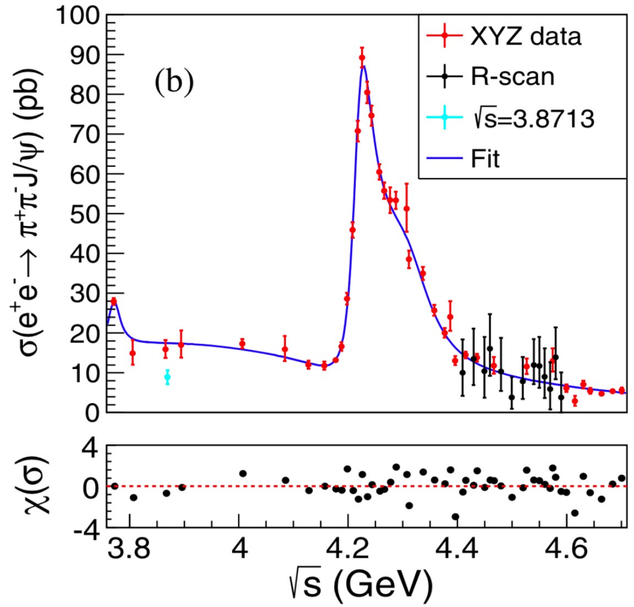
Slightly favor two-BW hypothesis
1.7σ

Conclusions from these measurements: 2. new state in [4300 4500] MeV

Mass and width from different process



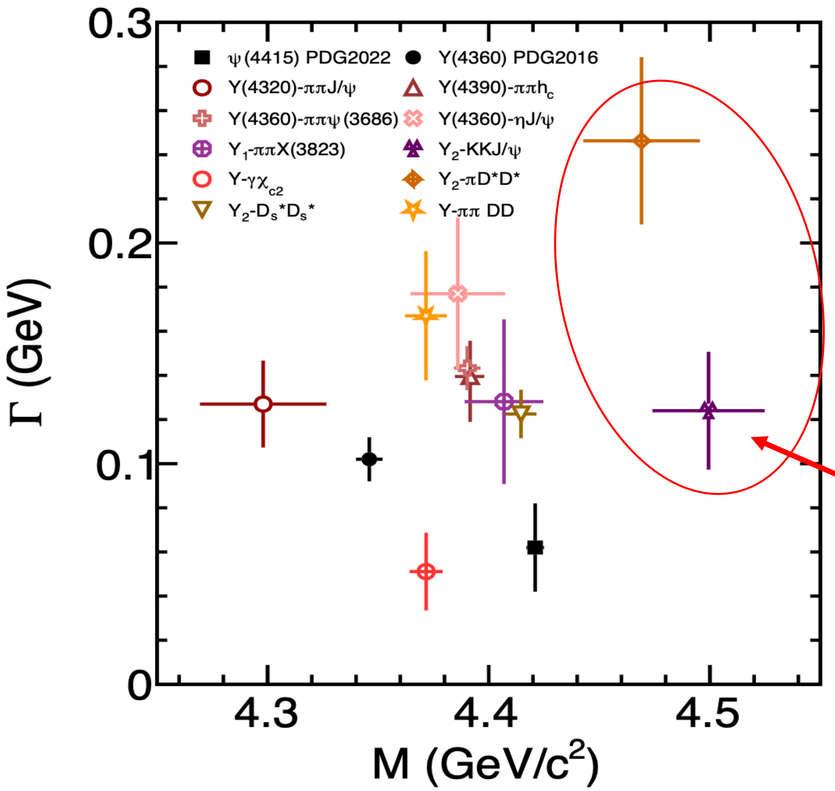




Parameter	Solution I	Solution II	Solution III	Solution IV
$\Gamma^{ee}_{3770}\mathcal{B}(R_{3770})$		$0.6 \pm 0.1 (0.3 \pm 0.1)$		
$M(R_0)$ (p_0)		3905.5 ± 30.1 (4.4 ± 0.3)		
$\Gamma^{tot}_0(R_0)$ (p_1)		346.0 ± 48.5 $((2.7 \pm 0.6) \times 10^{-3})$		
$\Gamma^{ee}_0\mathcal{B}(R_0)$	5.5 ± 0.5 (…)	6.9 ± 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)		

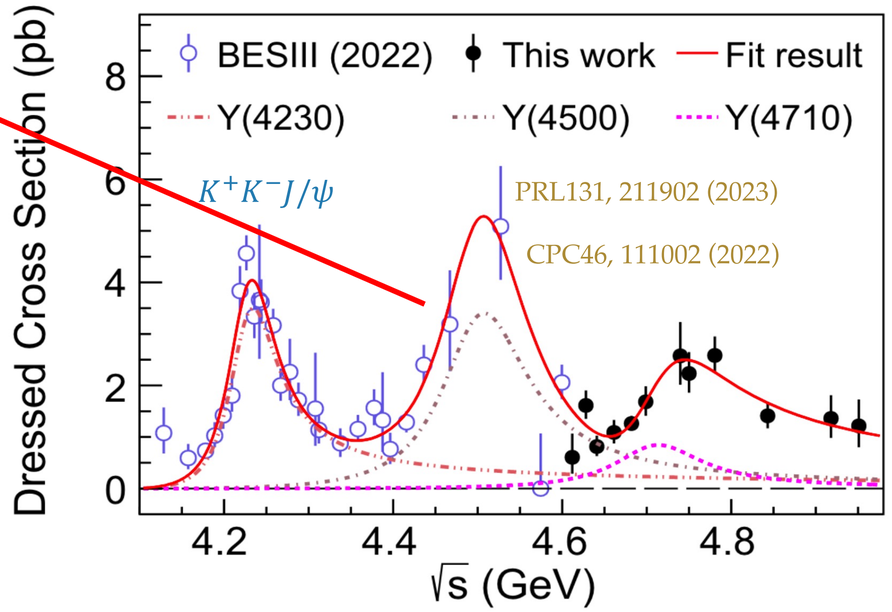
Conclusions from these measurements: 2. new state in [4300 4500] MeV

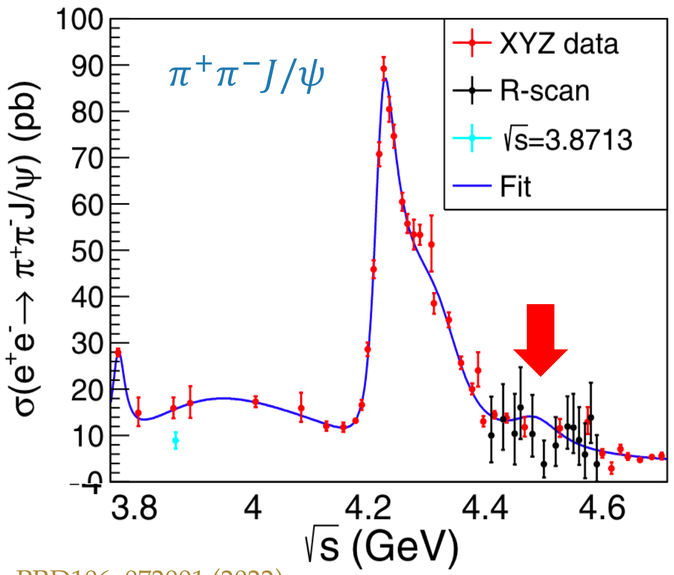
Mass and width from different process



Theoretical interpretations

- 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 $cs\overline{cs}$ state from LQCD (T. W. Chiu et al. PRD73, 094510 (2006))
- $B[Y \to \pi D^* \overline{D}^*]/B[Y \to K\overline{K}J/\psi]$~$10^2$, inconsistent with hidden-strangeness tetraquark nature (F. Z. Peng et al. PRD107, 016001 (2023))





PRD106, 072001 (2022)

Conclusions from these measurements: 2. new state in [4300 4500] MeV

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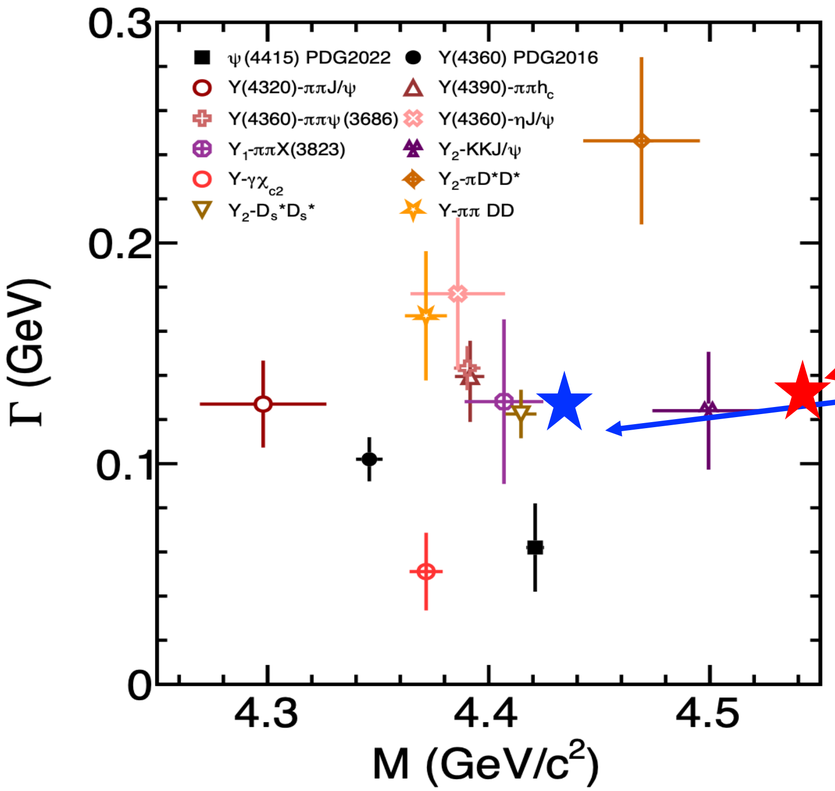
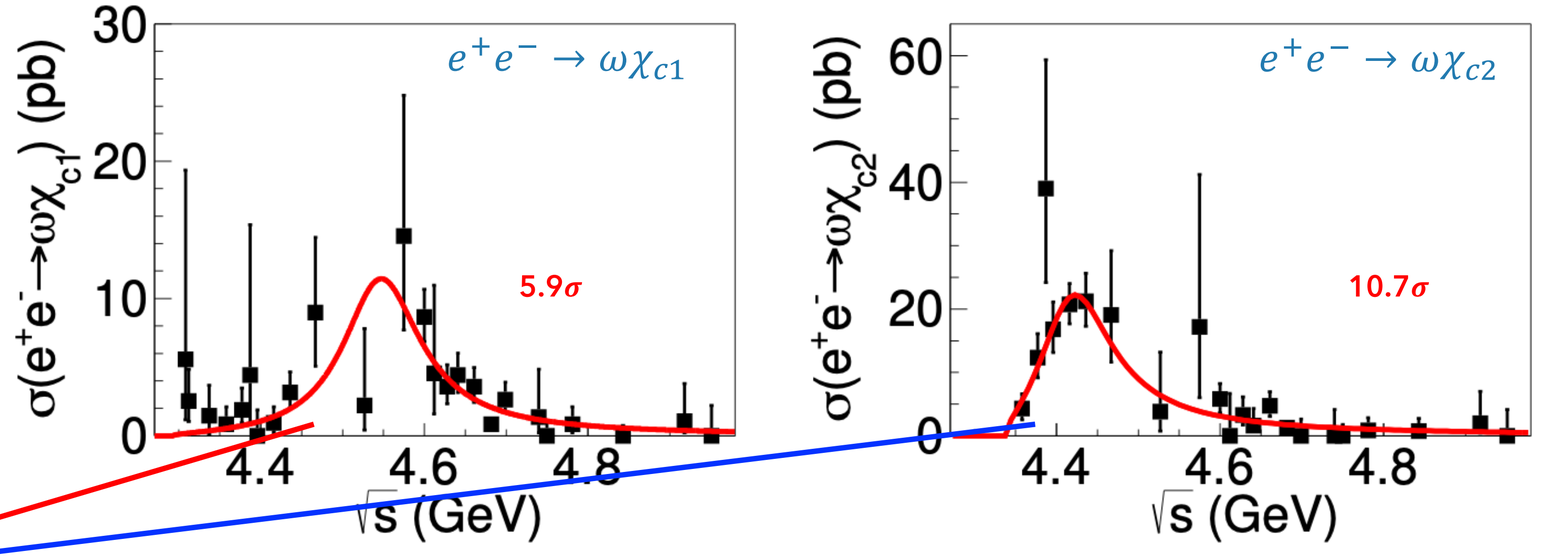




Recently, BESIII reports two structures from $e^+e^- \to \omega\chi_{c1/2}$ Processes.

From $\omega\chi_{c1}$:

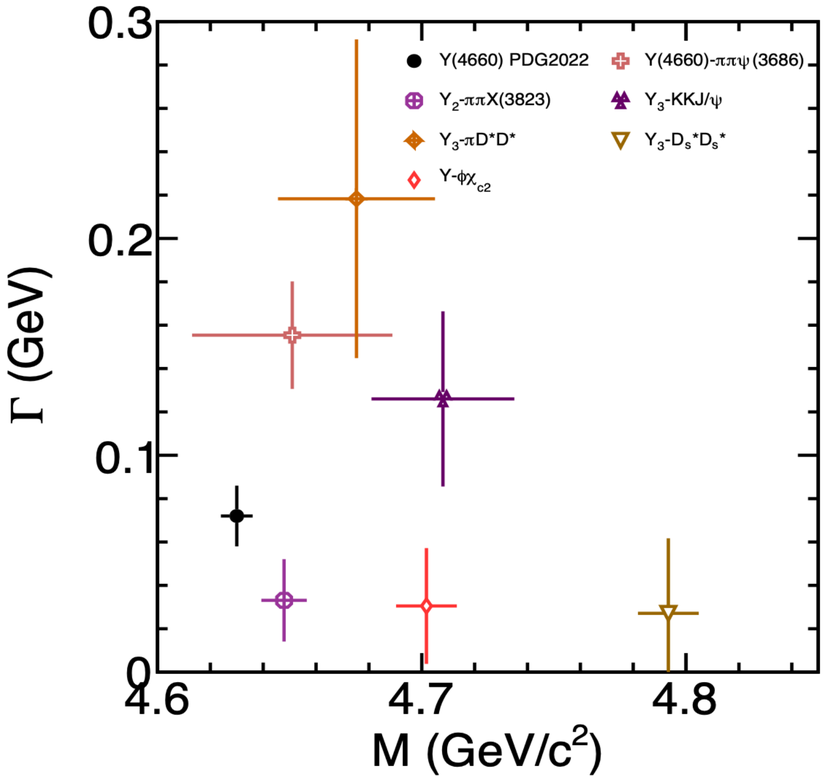
- **Mass: 4544.2 ± 18.7 ± 1.7 MeV**
- **Width: 116.1 ± 33.5 ± 1.7 MeV**

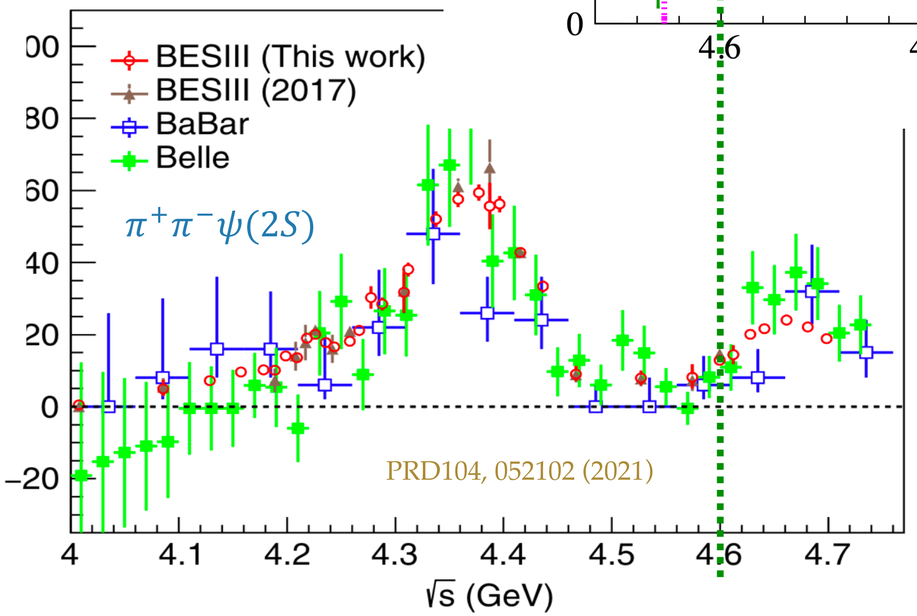
From $\omega\chi_{c2}$:

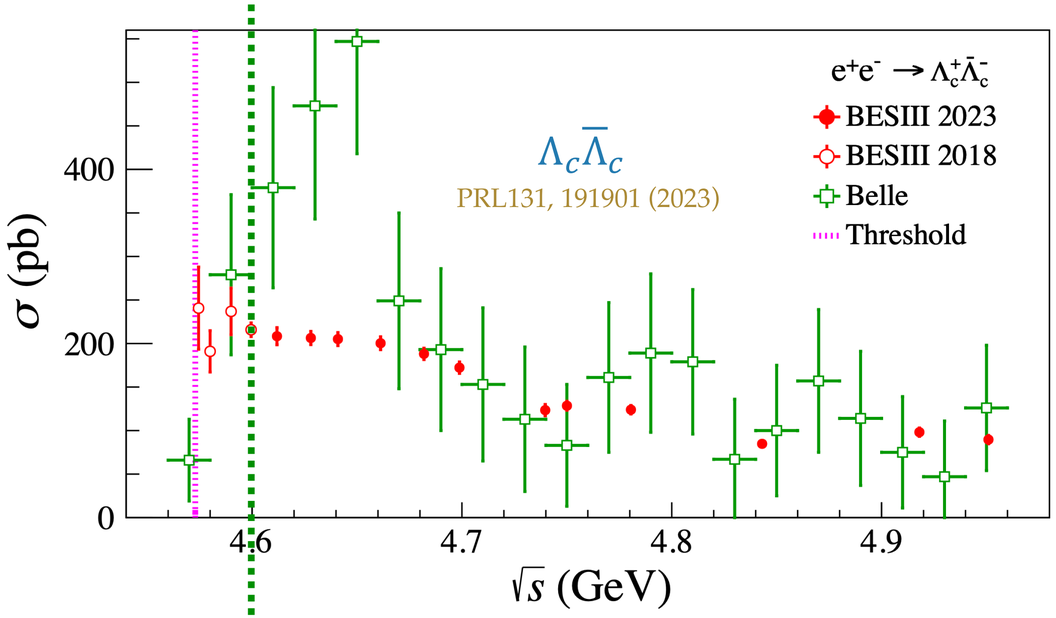
- **Mass: 4413.6 ± 9.0 ± 0.8 MeV**
- **Width: 110.5 ± 15.0 ± 2.9 MeV**

Conclusions from these measurements: 3. the Y(4660)

Mass and width from different process



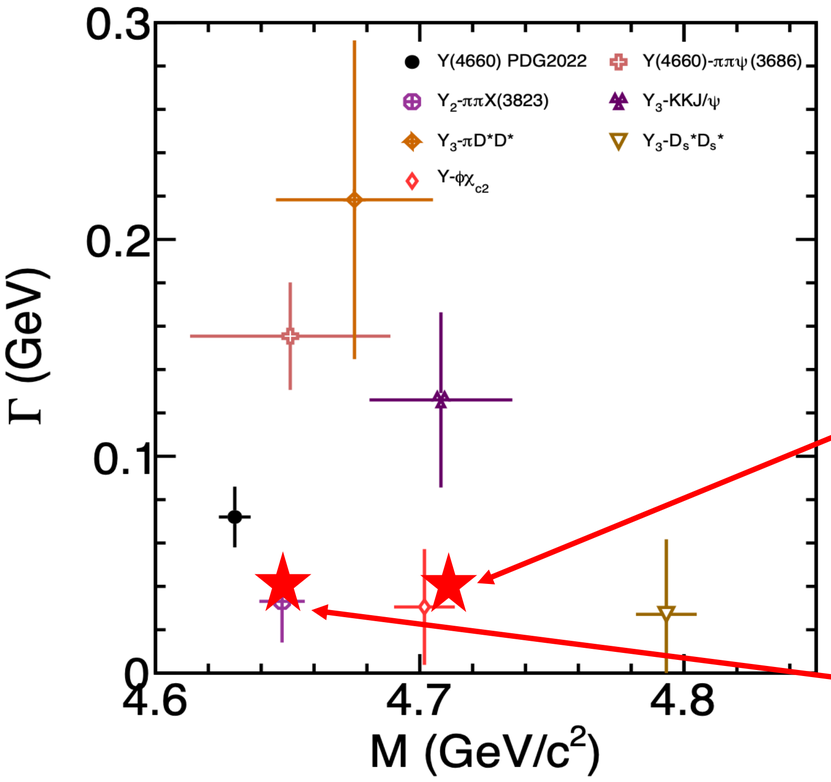




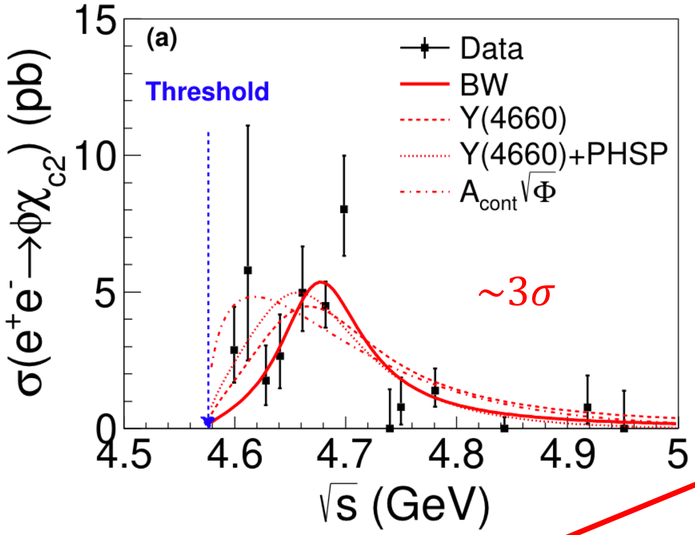
Single Tag and Double Tag to improve precision

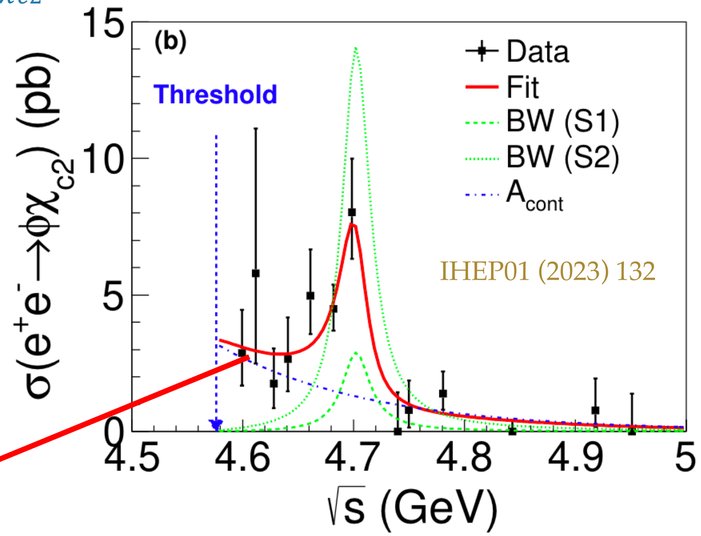
The Y(4660)

Mass and width from different process



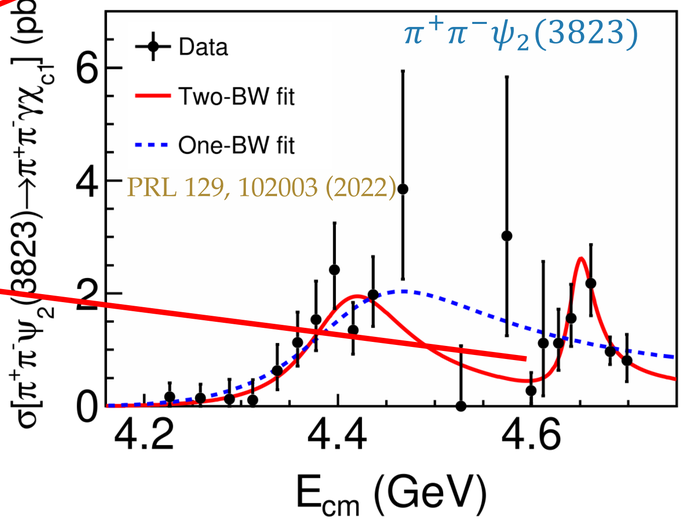
$e^+e^- \to \phi\chi_{c2}$





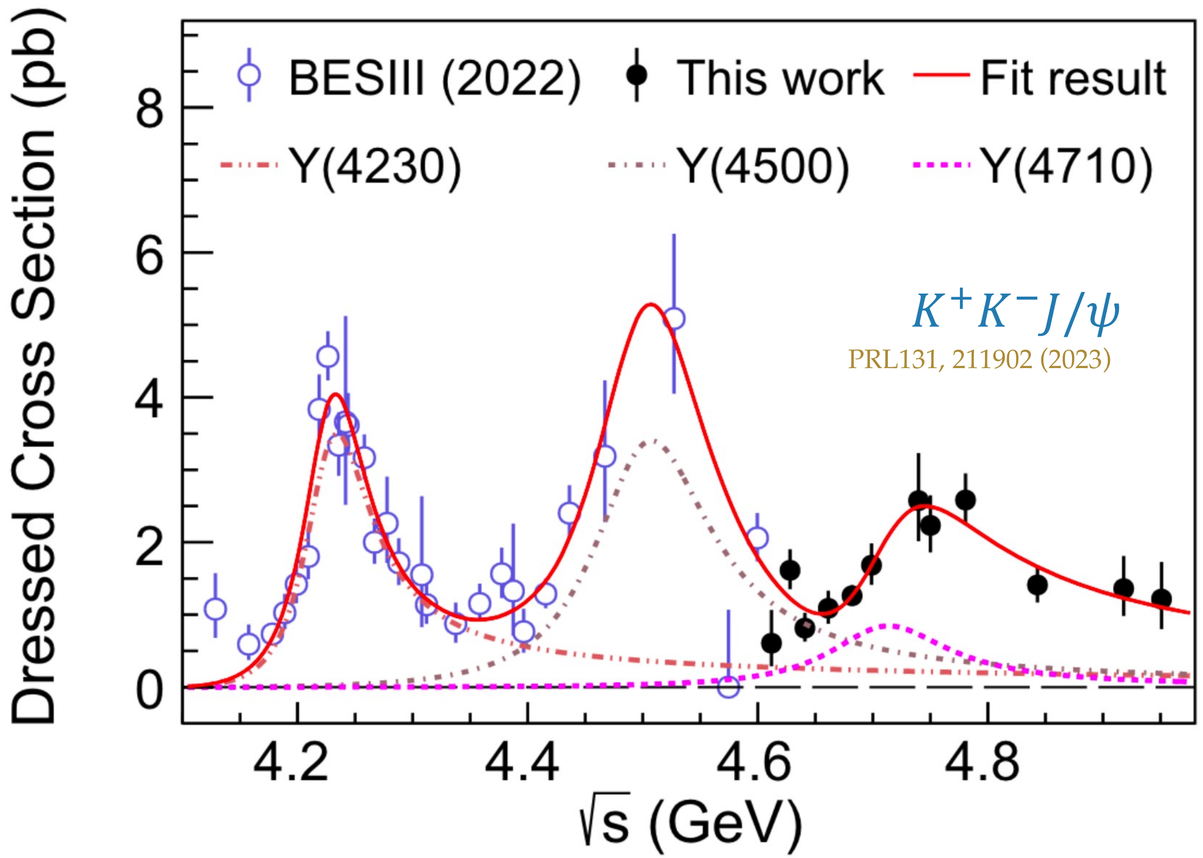
ML fit to the cross section with BW or coherent sum of BW and continuum

- Free BW: $4672.7 \pm 10.8 \pm 3.9$ MeV, $93.2 \pm 19.8 \pm 9.4$ MeV
- Free BW + continuum term: $4710.8 \pm 10.9 \pm 2.7$ MeV, $30.50 \pm 22.33 \pm 14.6$ MeV



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

New Structure above 4.7 GeV?

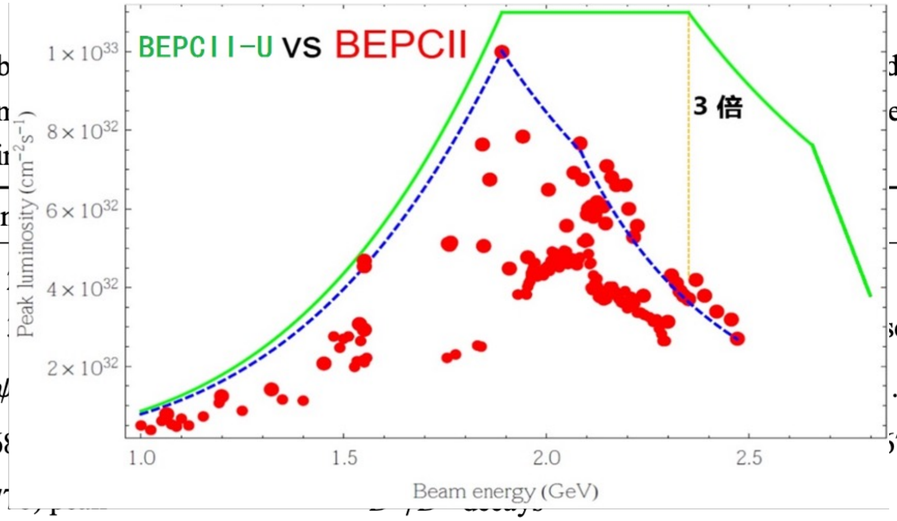


- The three-resonance assumption over two is 5.7σ
- **Mass: $4708^{+17}_{-15} \pm 21$ MeV**
- **Width: $126^{+27}_{-23} \pm 30$ MeV**

Theoretical interpretations

- 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))

Future Data Samples



Tab … d the proposed samples for the remainder of the physics program. The right-
n … ent (T_C) and upgraded (T_U) machine. The machine upgrades include top-up
i…

Er…		Current data	Expected final data	T_C / T_U
1.8 - …		N/A	0.1 fb^{-1} (fine scan)	60/50 days
2.0 - …		…scan (20 energy points)	Complete scan (additional points)	250/180 days
J/ψ		….2 fb^{-1} (10 billion)	3.2 fb^{-1} (10 billion)	N/A
ψ(368…		…57 fb^{-1} (0.45 billion)	4.5 fb^{-1} (3.0 billion)	150/90 days
ψ(37…		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

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 at BESIII

- Several resonant structures are found at: ~4220 MeV, 4300~4500 MeV, 4660 MeV and 4700 MeV
- The measured parameters from different processes are different , therefore no clear conclusion can be drawn: are they the same state? And their natures?
- The possible reasons:
  - Due to low statistics
  - The way to extract their parameters from data
- More efforts, e.g. more data, better model, are necessary !

Thank you!