



# Study of charmonium-like states via $e^+e^- \rightarrow$ hidden charm final states at BESIII

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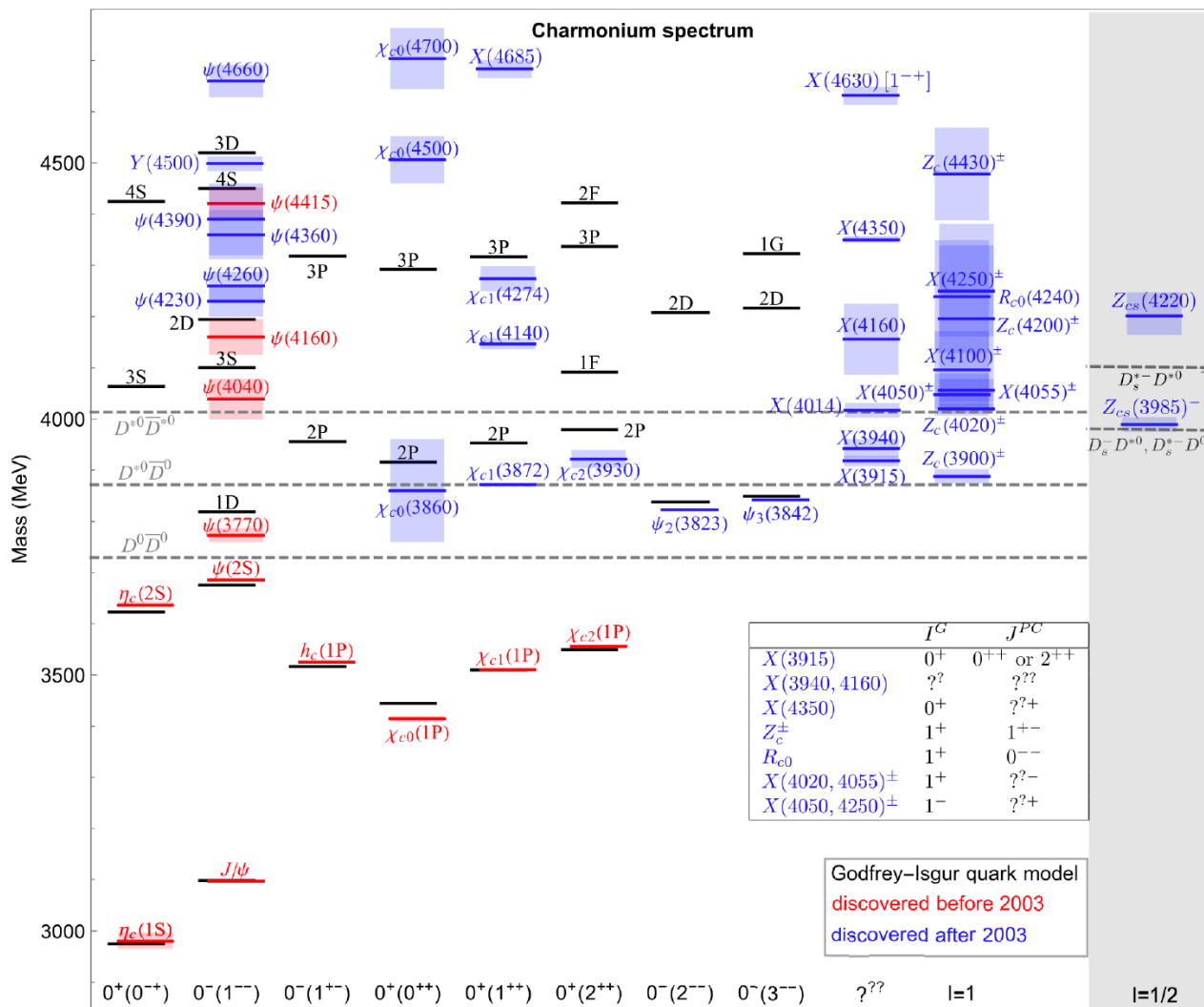
(On behalf of BESIII Collaboration)

Shandong University of Technology, China

The 14<sup>th</sup> International Workshop on  $e^+e^-$  Collisions from Phi to Psi  
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## Charmonium(-like) States Mass Spectrum



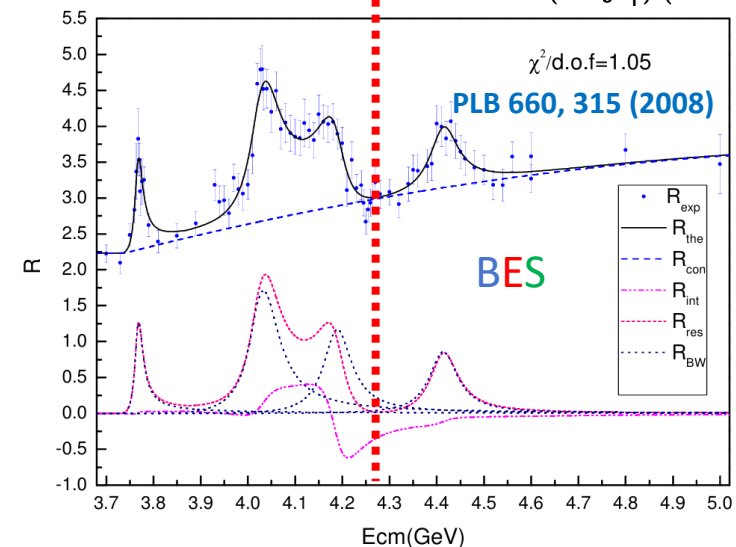
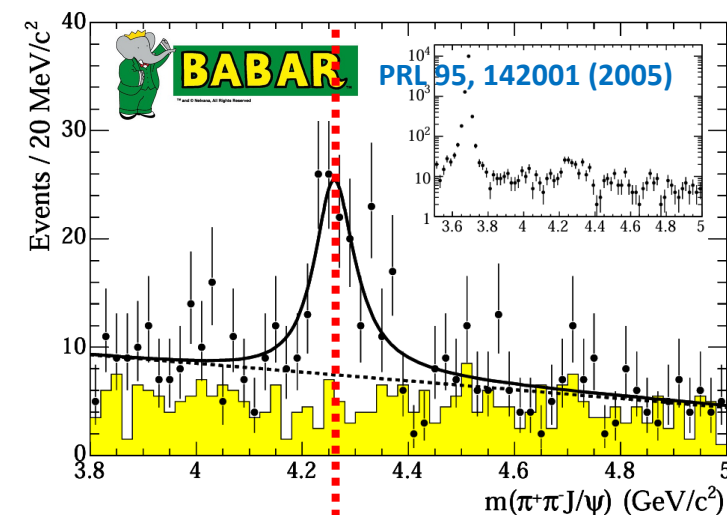
from F. K. Guo

- Bellow  $D\bar{D}$  mass threshold
  - ✓ Theoretical predictions match well with experimental observations
- Above  $D\bar{D}$  mass threshold
  - ✓ A series of new particles are observed beyond theoretical predictions  
 → **Good candidates of exotic states:** hybrid states, hadron molecule, compact tetra-quark, etc.
- Roughly classified to 3 categories
  - ✓  $X$ : Iso-spin  $I = 0$  with quantum number other than  $1^{--}$
  - ✓  $Y$ : Iso-spin  $I = 0$ , vector states with quantum number equal to  $1^{--}$
  - ✓  $Z$ : Iso-spin larger than 0

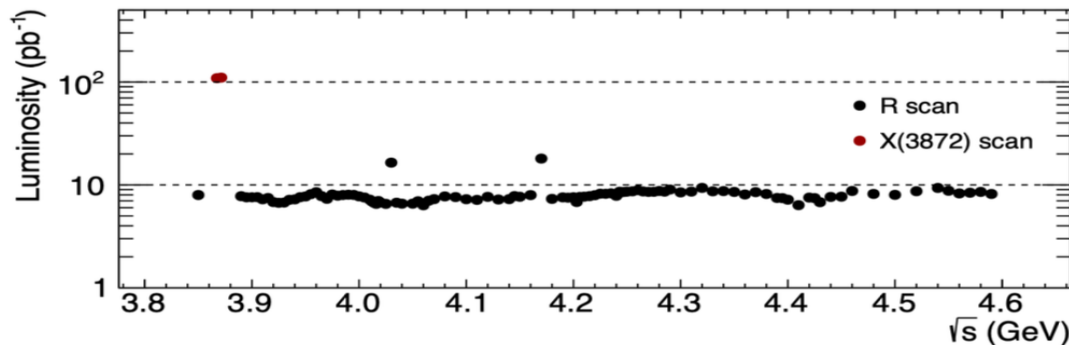
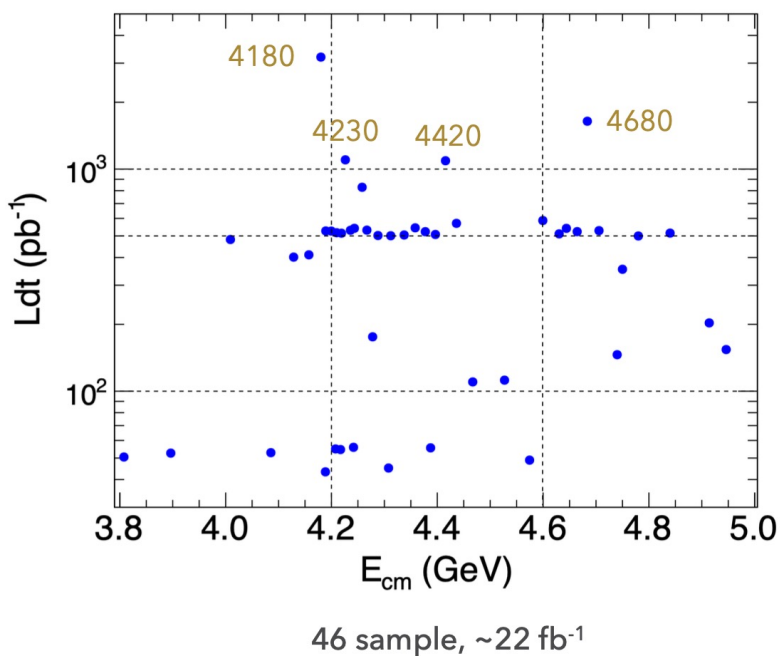


## Discovery of $Y$ States

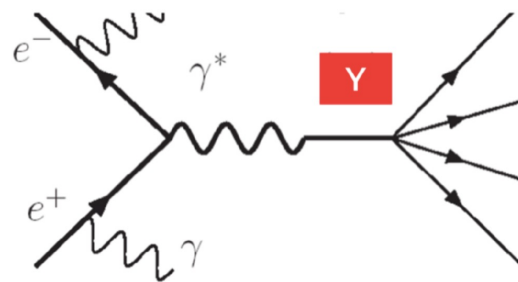
- $Y(4260)$ 
  - ✓ Discovered with ISR process at *BaBar* in  $\pi^+\pi^-J/\psi$  final states
  - ✓ Confirmed by CLEO and Belle latterly
  - ✓ Mass  $> 4$  GeV, above  $D\bar{D}$  threshold
  - ✓ Not observed in inclusive hadron cross section:  
→ **disfavor charmonium state**
- Interpretation
  - ✓ Is  $Y(4260)$  hybrid?
  - ✓ According to lattice QCD simulation, both the  $1^{--}$  and  $1^{-+}$  hybrid charmonium lie around 4.26 GeV
- Family Members
  - ✓ Latterly, evidence of  $Y(4360)$  was found at *BaBar*,  $Y(4660)$  was discovered at Belle, both in  $\pi^+\pi^-\psi(2S)$  final states
- **More measurements is necessary to pin down its nature!**



## Production and Decays of $Y$ States at BESIII



+ Small scan sample,  $\sim 2.5 \text{ fb}^{-1}$



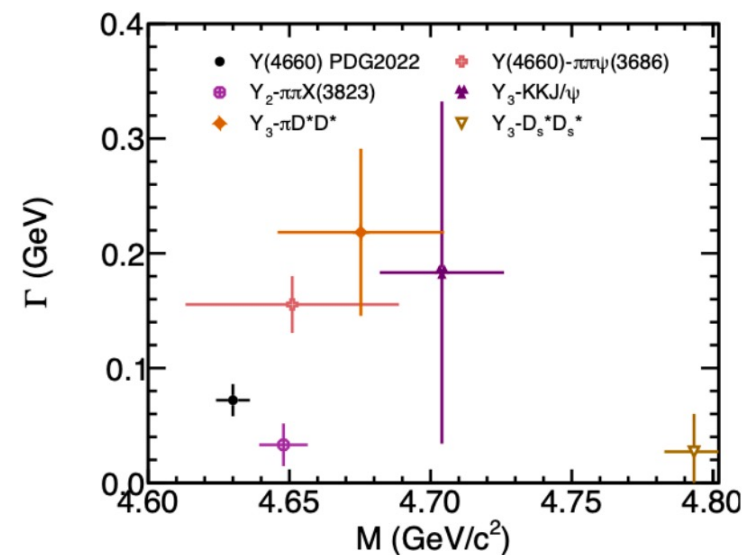
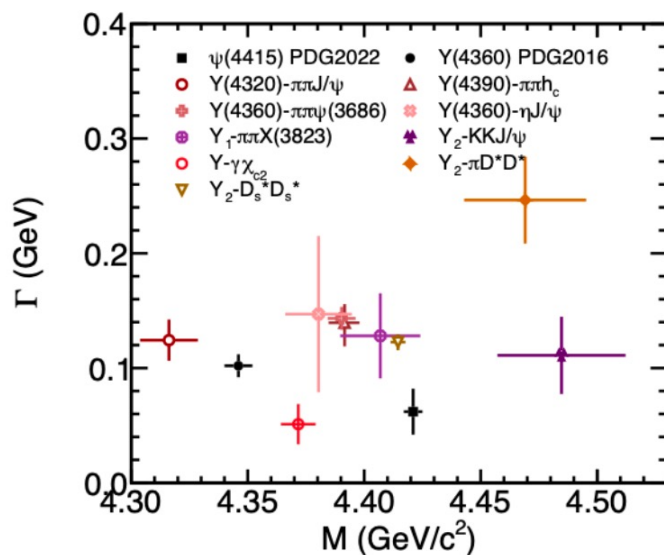
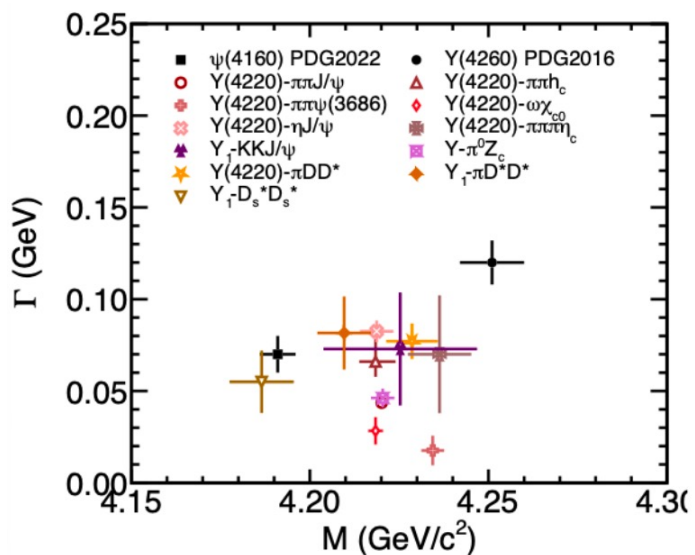
- BESIII can directly generate  $Y$  states by  $e^+e^-$  annihilation
- BESIII accumulate  $\sim 24.5 \text{ fb}^{-1}$  collision data events from 3.8~5.0 GeV
- Search for more  $Y$  states, study their properties and new decay modes
  - ✓ Hidden-charm final states
  - ✓ Open charm final states
  - ✓ Baryon and light hadron final states



## Observation of $Y$ States

- Lots of progresses of the charmonium-like states have been made in hidden charm final states
  - ✓ More than those in open charm, baryon, and light hadron final states
  - ✓ Ways to search for:
    - Combinations of **Light particles** and **hidden charm mesons**:

$$(\pi\pi/K\bar{K}/\eta/\eta' \dots) + (J/\psi/\psi(2S)/\eta_c/X(3872)/\chi_{cJ} \dots)$$



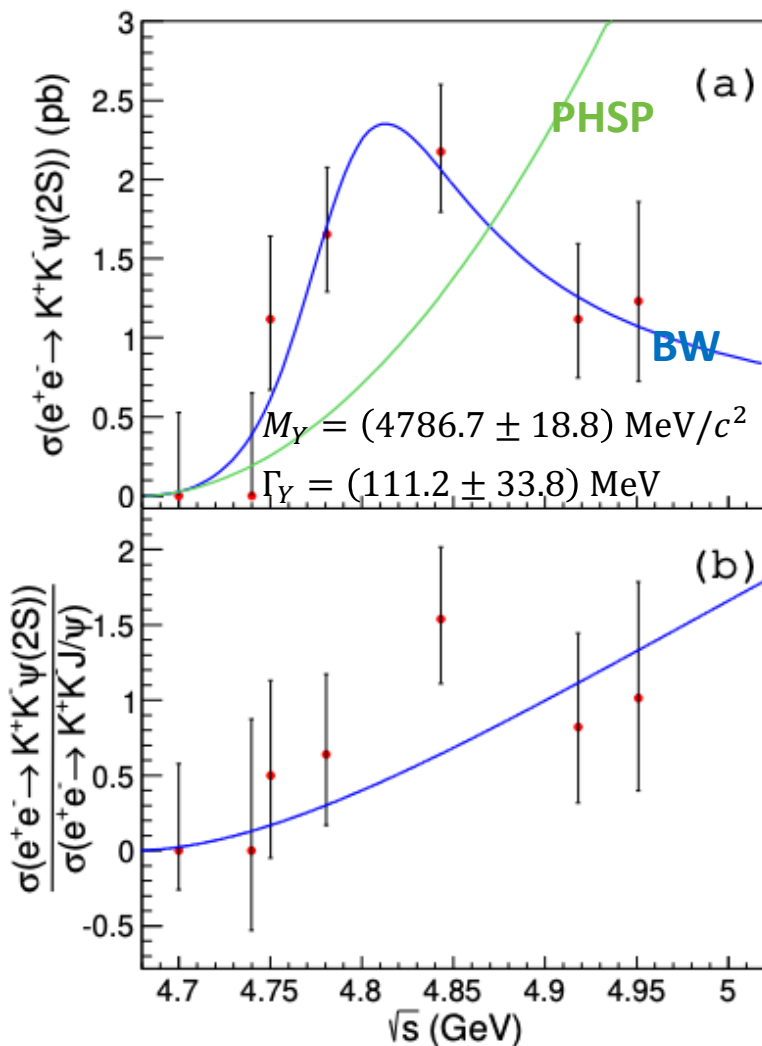


## Recent Progresses at BESIII

- $e^+e^- \rightarrow K^+K^-\psi(2S)$  *arxiv:2407.20009*
- $e^+e^- \rightarrow K^0K^-\pi^+J/\psi + c.c.$  *arxiv:2510.13274 (Accepted by JHEP)*
- $e^+e^- \rightarrow \pi^+\pi^-h_c$  *PRL 135, 071901 (2025)*
- $e^+e^- \rightarrow \eta\eta J/\psi$  *arxiv:2601.15882*
- $e^+e^- \rightarrow \eta\eta\psi(2S)$  *PRD 113, 092013 (2026)*
- $e^+e^- \rightarrow \pi^0\pi^0\psi(2S)$  *arxiv:2601.02136*

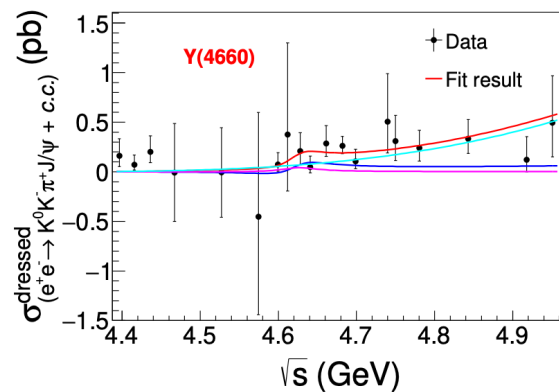
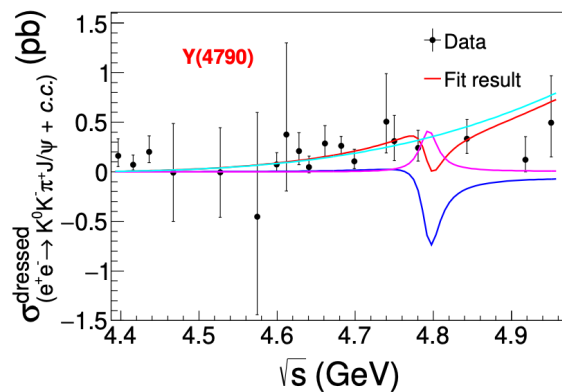
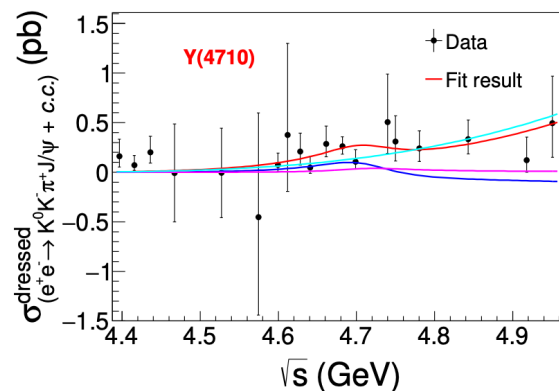
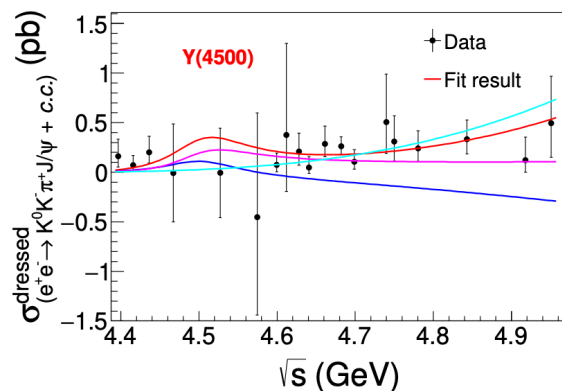


$e^+e^- \rightarrow K^+K^-\psi(2S)$  arxiv:2407.20009



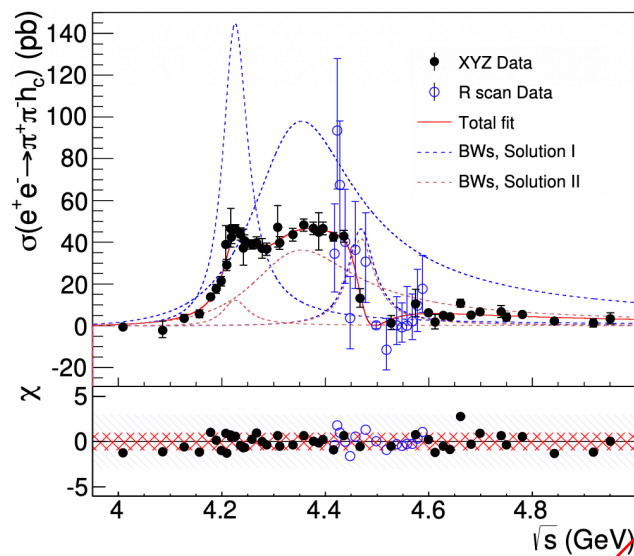
- $\sqrt{s}$ : 4.669~4.950 GeV,  $2.5 \text{ fb}^{-1}$
- Reconstruction method
  - ✓  $K^+$ ,  $K^-$ , and  $J/\psi$ , reconstruct  $\psi(2S)$  with  $K^+K^-$  recoiling mass
  - ✓  $K^+$  or  $K^-$ ,  $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$ , missing the untagged  $K$
  - ✓  $K^+$ ,  $K^-$ , and  $\psi(2S) \rightarrow e^+e^-/\mu^+\mu^-$
  - ✓  $K^+$  or  $K^-$ ,  $\psi(2S) \rightarrow e^+e^-/\mu^+\mu^-$ , missing the untagged  $K$
- The  $\sqrt{s}$  dependent cross section: → **No solid conclusion**
  - ✓ Can be well-described by a BW with free mass and width
  - ✓ Can also be described with  $Y(4710)$  (with mass and width fixed) and continuum process
- The  $\sqrt{s}$  dependent  $R = \frac{\sigma(e^+e^- \rightarrow K^+K^-\psi(2S))}{\sigma(e^+e^- \rightarrow K^+K^-J/\psi)}$ .
  - ✓ If  $e^+e^- \rightarrow K^+K^-\psi(2S)$  and  $e^+e^- \rightarrow K^+K^-J/\psi$  proceed with the same mechanism,  $R$  should be similar to trend of phase space
  - ✓ At 4.843 GeV, a deviation of about  $2\sigma$  with respect to the phase spaces is found → **A distinct production mechanism for  $e^+e^- \rightarrow K^+K^-\psi(2S)$ ?**

$e^+e^- \rightarrow K^0 K^- \pi^+ J/\psi + c. c.$  arxiv:2510.13274 (Accepted by JHEP)

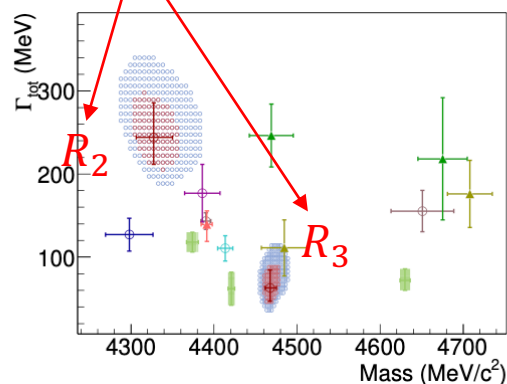
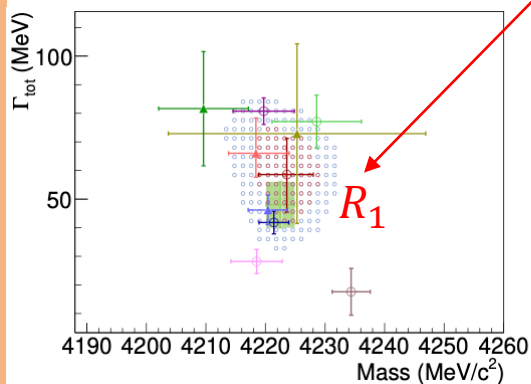


- $\sqrt{s}$ : 4.396 ~ 4.950 GeV,  $8.86 \text{ fb}^{-1}$
- $e^+e^- \rightarrow K_L^0 K^- \pi^+ J/\psi + c. c.$ 
  - ✓ Missing a  $K_L^0 (K^0/\bar{K}^0)$ :  $K^- \pi^+ l^+ l^- (l = e, \mu)$
- $e^+e^- \rightarrow K_S^0 K^- \pi^+ J/\psi + c. c.$ 
  - ✓ Full  $K_S^0 (\rightarrow \pi^+ \pi^-) K^- \pi^+ l^+ l^-$
  - ✓ Missing a  $K^\pm$  or  $\pi^\mp$ :  $K_S^0 (\rightarrow \pi^+ \pi^-) (K^-/\pi^+) l^+ l^-$
  - ✓ Miss a  $K_S^0 (K^0/\bar{K}^0)$ :  $K^- \pi^+ l^+ l^-$
- **The process is observed for the first time:**
  - 9.4 $\sigma$  statistical significance with all data samples summed up
- The cross section line-shape is tried to be described with a coherent sum of BW and PHSP:
  - The significance of resonance contribution is less than  $2\sigma$  in all fits
- No any intermediate states in  $K\pi, K\bar{K}, K\bar{K}\pi, KJ/\psi, \pi J/\psi$ , or  $K\pi J/\psi$  system are observed

$e^+e^- \rightarrow \pi^+\pi^-h_c$  PRL 135, 071901 (2025)



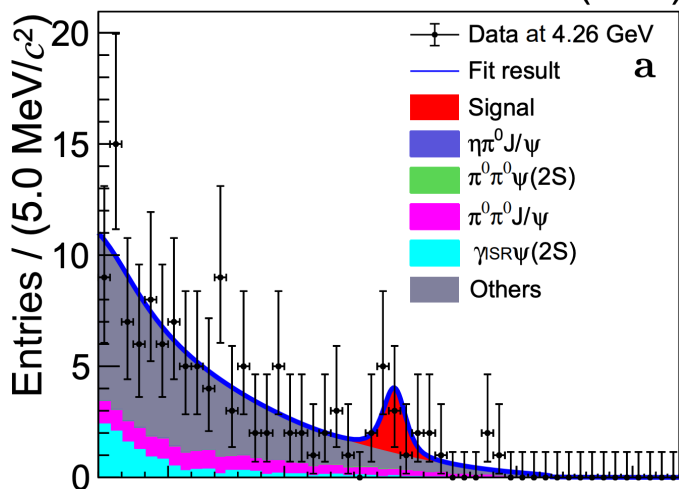
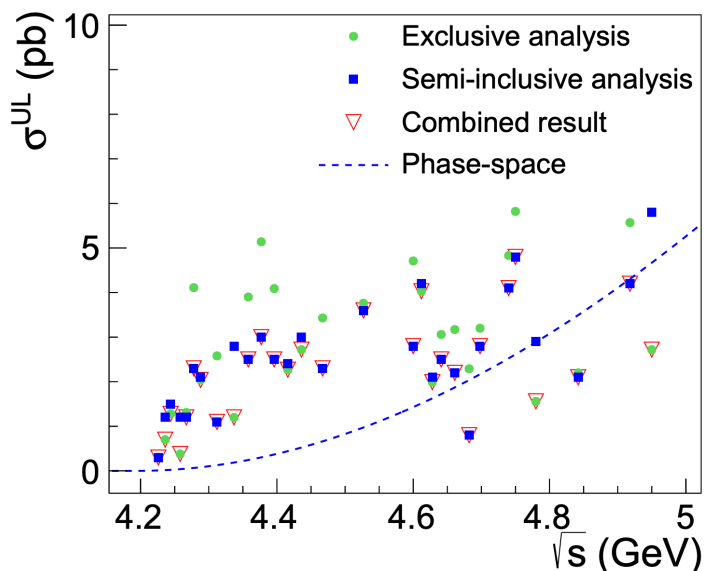
- $\sqrt{s}$ : 4.009 ~ 4.950 GeV, 22.2 fb<sup>-1</sup>
- $\pi^+\pi^-h_c$ ,  $h_c \rightarrow \gamma\eta_c$ ,  $\eta_c \rightarrow 16$  hadronic final states
- Cross Section: A plateau like shape between 4.3 and 4.45 GeV drops sharply around 4.5 GeV → cannot be described by two resonances only
- The inclusion of the relatively narrower third component proves crucial for reproducing the drop at around 4.5 GeV
- The statistical significance of three BWs model over two BWs model is greater than 5 $\sigma$
- The mass and width of  $R_1$  are consistent with  $Y(4230)$
- The mass of  $R_2$  is consistent with  $\psi(4360)$ , but with width ~100 MeV broader
- The mass and width of  $R_3$  are consistent with  $Y(4500)$  in  $K^+K^-J/\psi$



- ◆  $\pi^+\pi^-h_c$ , this work
- 95.5% C.L., this work
- 68.3% C.L., this work
- ◆  $\pi^+\pi^-h_c$ , Ref. [20]
- ◆  $\pi^+\pi^-J/\psi$
- ◆  $\pi^0Z^0$
- ◆  $\pi^+\pi^-\psi(3686)$
- ◆  $\omega\chi_{c0}$
- ◆  $\omega\chi_{c2}$
- ◆  $\pi^+D^0D^*$
- ◆  $\pi^+D^{*0}D^*$
- ◆  $\eta J/\psi$
- ◆  $K^+K^-J/\psi$
- PDG

✓ No obvious structure is observed at  $Y(4660)$ : intension with the hidden charm  $P$ -wave tetraquark model prediction

$e^+e^- \rightarrow \eta\eta J/\psi$  arxiv:2601.15882

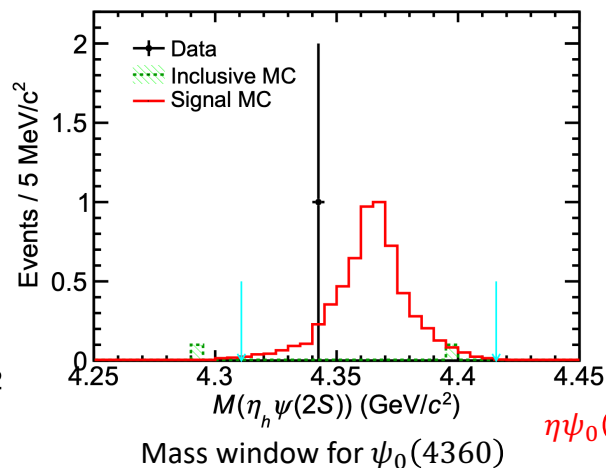
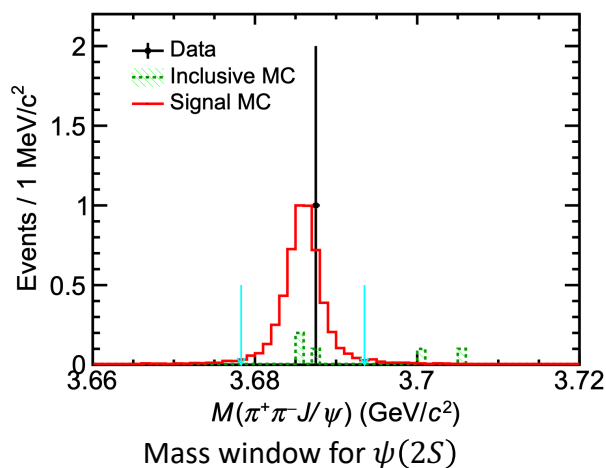


- $\sqrt{s}$ : 4.226 ~ 4.950 GeV, 15.1 fb<sup>-1</sup>
- Exclusively reconstructing  $\eta\eta + J/\psi \rightarrow l^+l^-$ :  $\eta \rightarrow \gamma\gamma/\pi^+\pi^-\pi^0$ 
  - ✓ An observation with significance larger than  $5\sigma$ : 4.682 GeV ( $5.7\sigma$ ) and 4.750 GeV ( $8.9\sigma$ )
- Inclusively reconstructing  $\eta\eta(\text{missing}) + J/\psi \rightarrow l^+l^-$ :  $\eta \rightarrow \gamma\gamma$ 
  - ✓ No observation with significance larger than  $5\sigma$
- Upper limits of cross sections are set with 90% confidence level
- The combined upper limits show a strong deviation from phase space around 4.4 GeV, however, no clear structures are visible
- The isospin partner to  $Z_c(3900)$  is searched for, but no significant signals are found
- The statistical significance is low: the upper limits for  $e^+e^- \rightarrow \eta\eta J/\psi$  also serves as that for  $e^+e^- \rightarrow \eta Z_c, Z_c \rightarrow \eta J/\psi$
- More data samples are needed to draw solid conclusion



## $e^+e^- \rightarrow \eta\eta\psi(2S)$ PRD 113, 092013 (2026)

- $\sqrt{s}$ : 4.840 ~ 4.950 GeV,  $0.9 \text{ fb}^{-1}$
- Partial reconstruction of  $\eta\eta(\text{missing}) + \psi(2S) (\rightarrow \pi^+\pi^-J/\psi (\rightarrow l^+l^-) (l = e, \mu))$ :  $\eta \rightarrow \gamma\gamma$
- $\psi_0(4360)$ 
  - ✓ The exotic charmonium-like state with  $J^{PC} = 0^{--}$
  - ✓ A bound system of  $D^*\bar{D}_1(2420)$
  - ✓ Distinguished from  $1^{--}$  vector charmonium states with the angular distribution of the outgoing  $\eta$
- No significant signal of the  $\psi_0(4360)$  is observed
- The upper limit of  $\sigma(e^+e^- \rightarrow \eta\psi_0(4360)) * \mathcal{B}(\psi_0(4360) \rightarrow \eta\psi(2S))$  and  $\sigma(e^+e^- \rightarrow \eta\eta\psi(2S))$  are set with 90% confidence level



U. L. of  $\sigma(e^+e^- \rightarrow \eta\eta\psi(2S))$

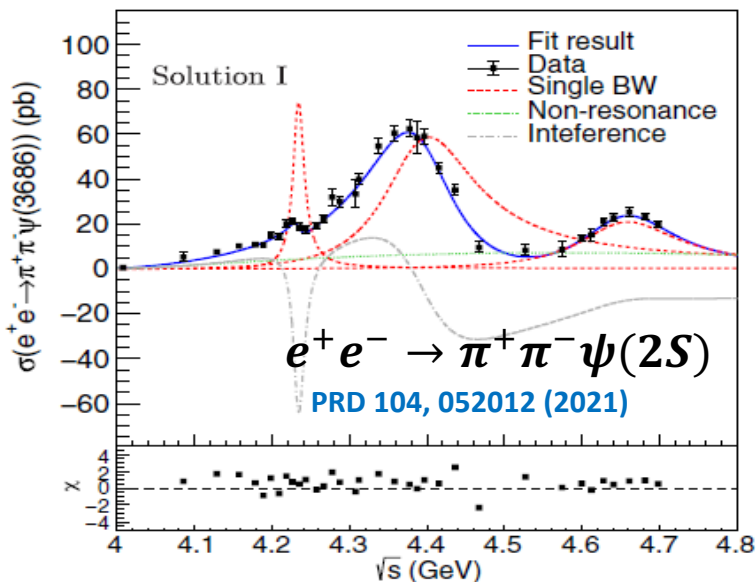
$\sqrt{s}$ (MeV)	$\mathcal{L}$ ( $\text{pb}^{-1}$ )	$N_{\text{obs}}$	$N_{\text{sig}}$	$N^{\text{UL}}$	$(1 + \delta_{\text{ISR}}^{\text{sig}})$	$(1 + \delta_{\text{VP}})$	$\epsilon$ (%)	$\sigma^{\text{Born}}$ (pb)	$\sigma^{\text{UL}}$ (pb)
4843.07	525.16	0	$0.0_{-0.0}^{+1.0}$	$< 2.0$	0.706	1.056	10.7	$0.0_{-0.0}^{+1.1}$	$< 2.3$
4918.02	207.82	0	$0.0_{-0.0}^{+1.0}$	$< 2.0$	0.750	1.056	9.7	$0.0_{-0.0}^{+2.9}$	$< 6.0$
4950.93	159.28	1	$1.0_{-0.7}^{+1.4}$	$< 3.6$	0.762	1.056	9.5	$3.9_{-2.7}^{+5.5} \pm 0.2$	$< 15$

U. L. of  $\sigma(e^+e^- \rightarrow \eta\psi_0(4360)) * \mathcal{B}(\psi_0(4360) \rightarrow \eta\psi(2S))$

$\sqrt{s}$ (MeV)	$\mathcal{L}$ ( $\text{pb}^{-1}$ )	$N^{\text{UL}}$	$(1 + \delta_{\text{ISR}}^{\text{sig}})$	$(1 + \delta_{\text{VP}})$	$\epsilon$ (%)	$\sigma^{\text{UL}} \cdot \mathcal{B}$ (pb)
4918.02	207.82	$< 2.0$	0.676	1.056	9.6	$< 6.8$
4950.93	159.28	$< 3.6$	0.687	1.056	9.8	$< 16$

$\eta\psi_0(4360)$  threshold  $\rightarrow 4.9$  GeV: highly suppressed due to the limited phase space

$e^+e^- \rightarrow \pi^0\pi^0\psi(2S)$  arxiv:2601.02136



$$M_{Y(4230)} = (4234.4 \pm 3.2 \pm 0.2) \text{ MeV}/c^2$$

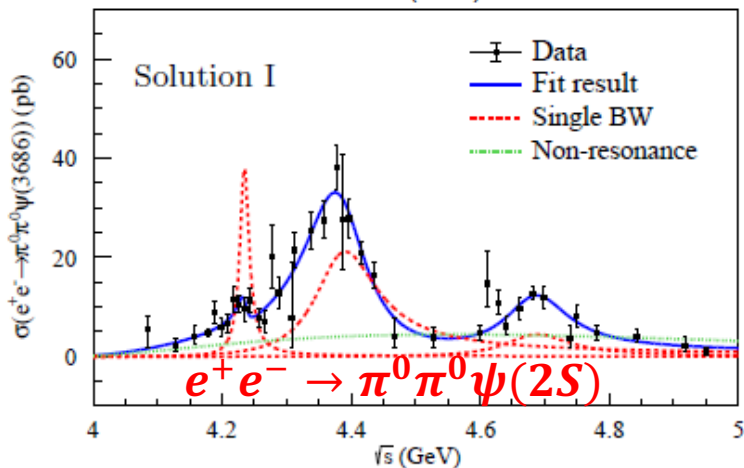
$$\Gamma_{Y(4230)} = (17.6 \pm 8.1 \pm 0.9) \text{ MeV}$$

$$M_{Y(4390)} = (4390.3 \pm 6.0 \pm 0.7) \text{ MeV}/c^2$$

$$\Gamma_{Y(4390)} = (143.3 \pm 10.0 \pm 0.5) \text{ MeV}$$

$$M_{Y(4660)} = (4651.0 \pm 37.8 \pm 2.1) \text{ MeV}/c^2$$

$$\Gamma_{Y(4660)} = (155.4 \pm 24.8 \pm 0.8) \text{ MeV}$$



$$M_{Y(4230)} = (4234.4) \text{ MeV}/c^2 \text{ (fix)}$$

$$\Gamma_{Y(4230)} = (17.6) \text{ MeV (fix)}$$

$$M_{Y(4390)} = (4383.0 \pm 8.6 \pm 1.9) \text{ MeV}/c^2$$

$$\Gamma_{Y(4390)} = (117.4 \pm 20.7 \pm 4.8) \text{ MeV}$$

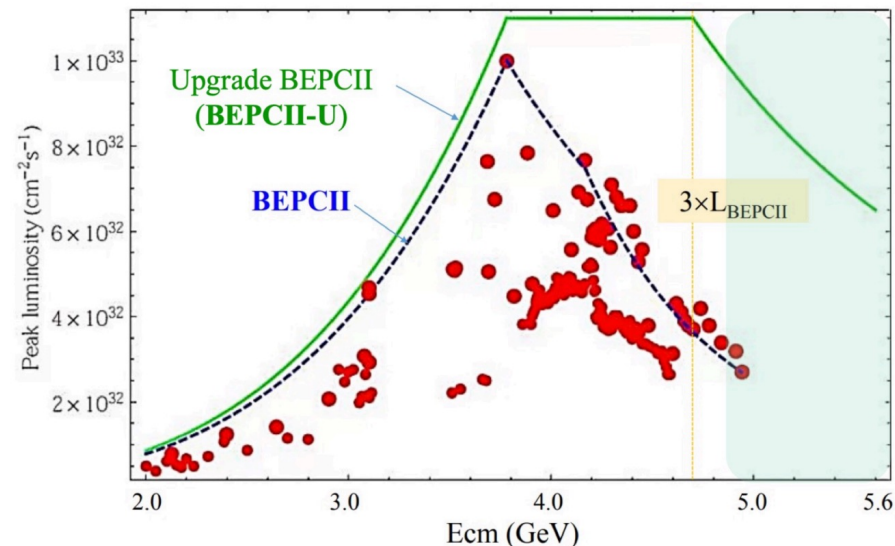
$$M_{Y(4660)} = (4684.0 \pm 17.3 \pm 1.9) \text{ MeV}/c^2$$

$$\Gamma_{Y(4660)} = (119.5 \pm 47.1 \pm 9.1) \text{ MeV}$$

- $\sqrt{s}$ : 4.008 ~ 4.950 GeV, 22.1 fb<sup>-1</sup>
- $\pi^0(\rightarrow \gamma\gamma)\pi^0(\rightarrow \gamma\gamma)\psi(2S)(\rightarrow \pi^+\pi^-J/\psi)$ ,  $J/\psi \rightarrow l^+l^- (l = e, \mu)$
- The obtained cross sections are found to be ~one-half of those in charged mode → **Consistent with isospin symmetry expectation**
- Fit with a coherent sum of  $Y(4230) + Y(4390) + Y(4660) + \text{Non-resonant contribution}$
- Resonance parameters are consistent between charged and neutral modes
- The parameters of  $Y(4390)$  ( $> 5\sigma$ ) are consistent with previous measurements
- The parameters of  $Y(4660)$  ( $> 5\sigma$ ) are roughly consistent with previous measurements

## Summary

- BESIII has made new progresses on  $Y$  states in hidden charm final states
  - ✓  $e^+e^- \rightarrow K^+K^-\psi(2S)$
  - ✓  $e^+e^- \rightarrow K^0K^-\pi^+J/\psi + c.c.$
  - ✓  $e^+e^- \rightarrow \pi^+\pi^-h_c$
  - ✓  $e^+e^- \rightarrow \eta\eta J/\psi$
  - ✓  $e^+e^- \rightarrow \eta\eta\psi(2S)$
  - ✓  $e^+e^- \rightarrow \pi^0\pi^0\psi(2S)$
- There are still puzzles in  $Y$  states
- BESIII has a good opportunity to contribute more
  - ✓ BEPCII upgraded in 2024:
    - Higher luminosity in the XYZ region
    - $\sqrt{s}$  up to 5.6 GeV
- More analysis on charmonium-like states in hidden charm final states will come out in the future



Thanks for your attention!

厚德·博学·笃行·至善



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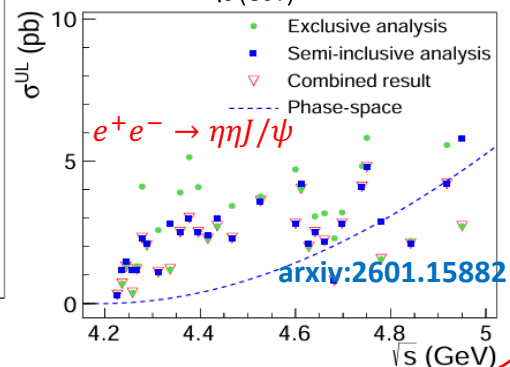
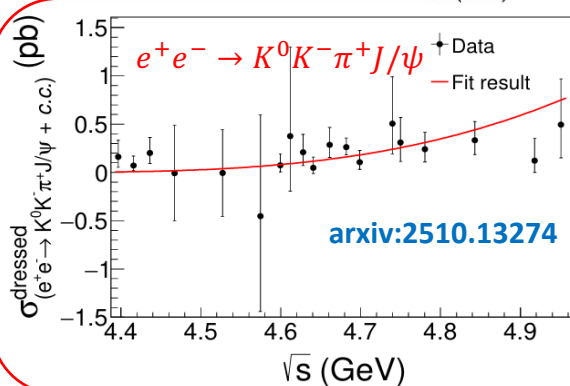
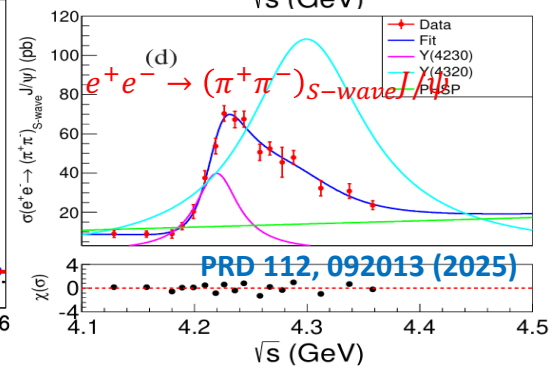
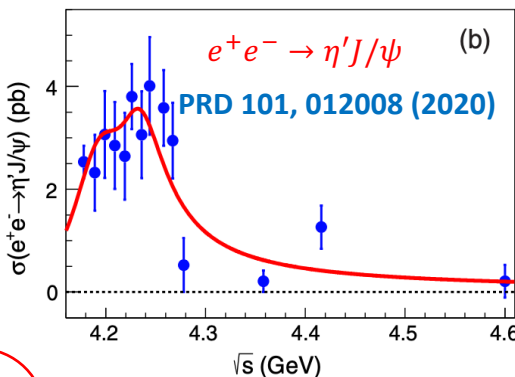
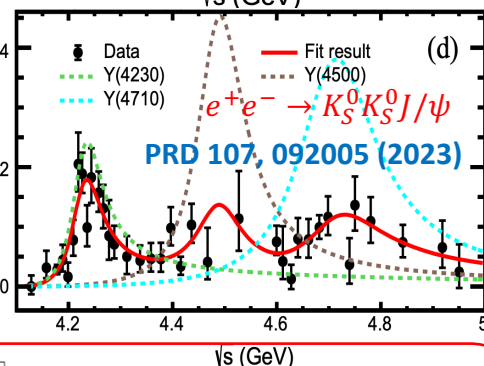
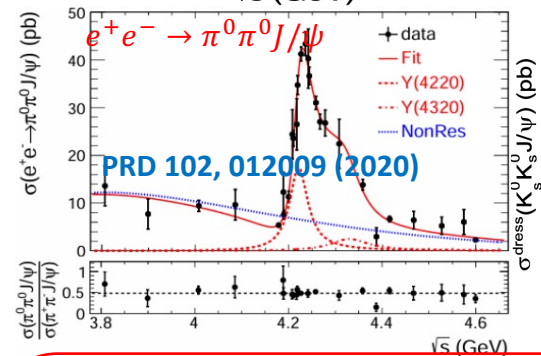
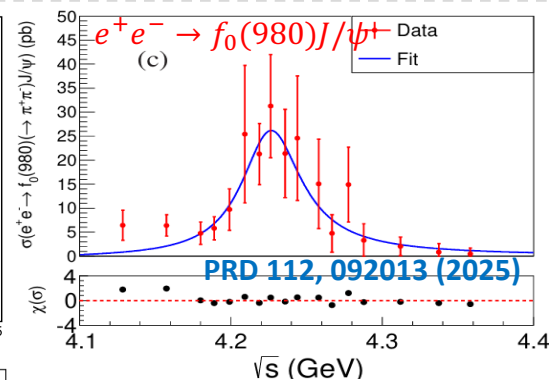
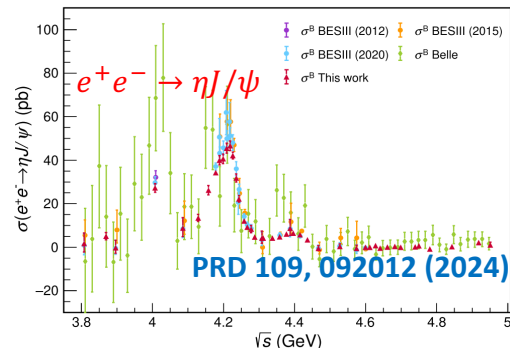
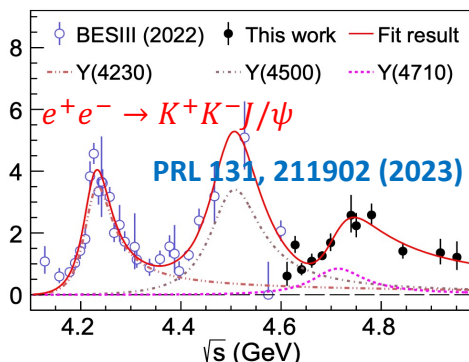
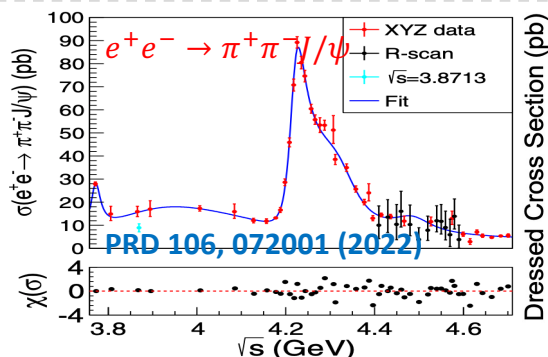
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Back Up



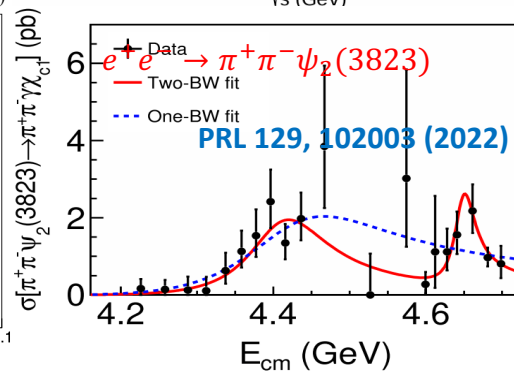
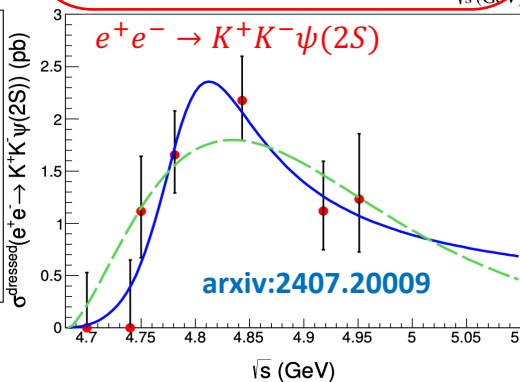
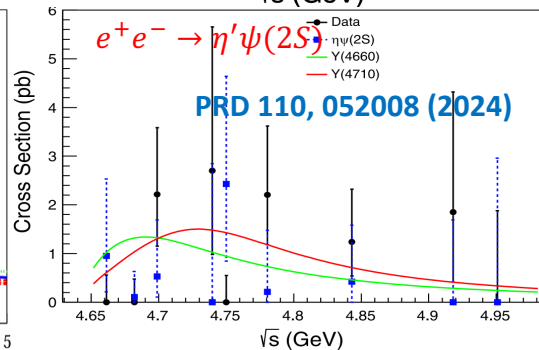
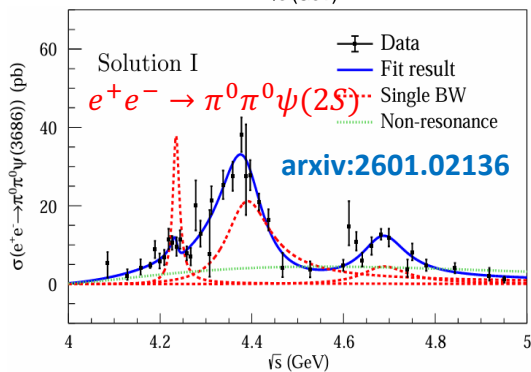
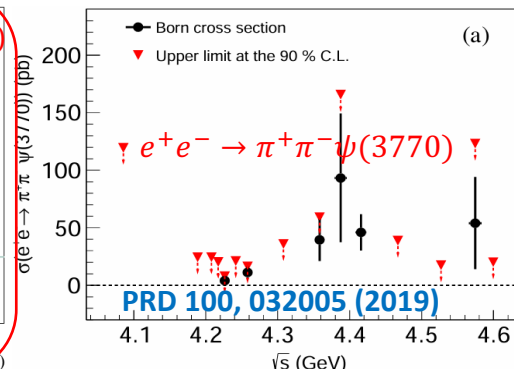
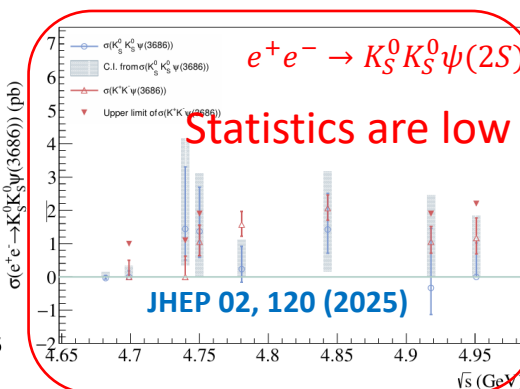
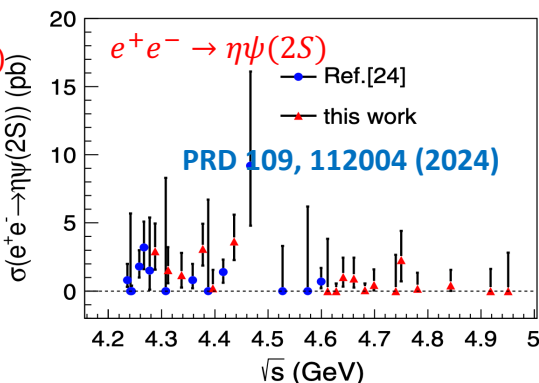
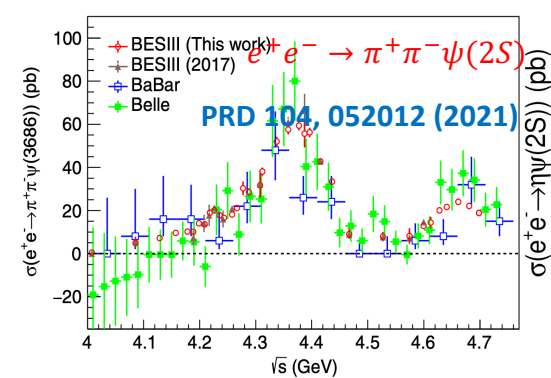
# Summary of $\sigma(e^+e^- \rightarrow J/\psi + X)$



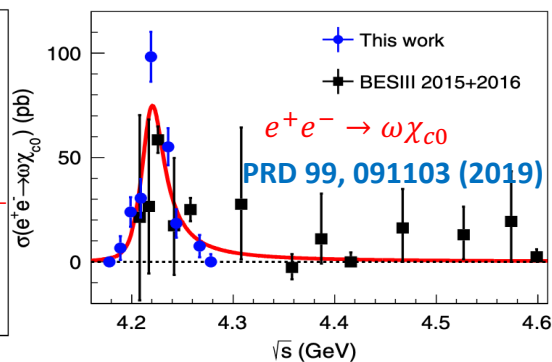
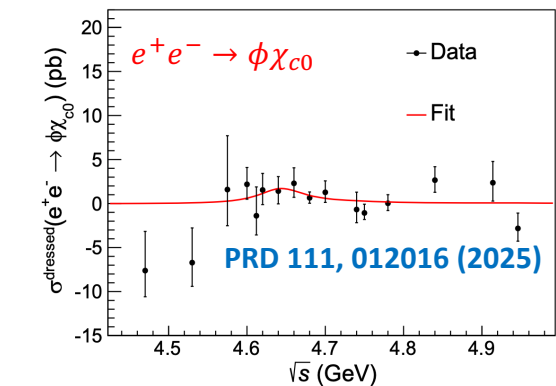
Statistics are low



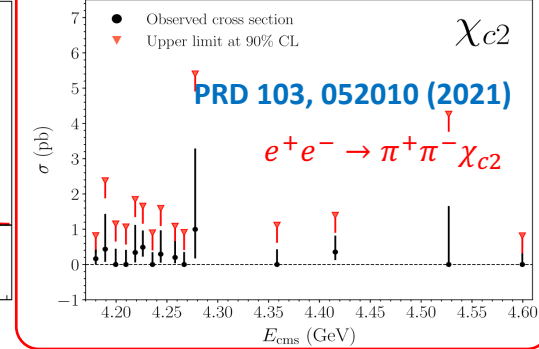
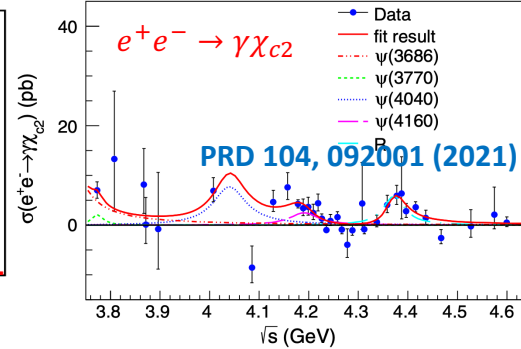
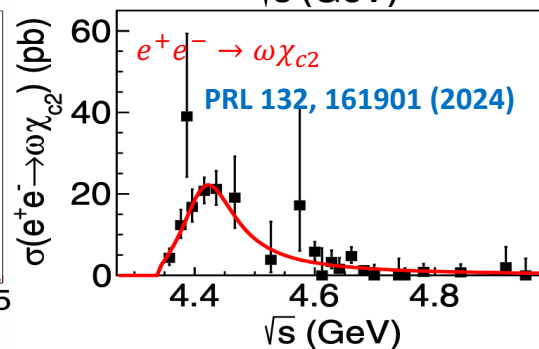
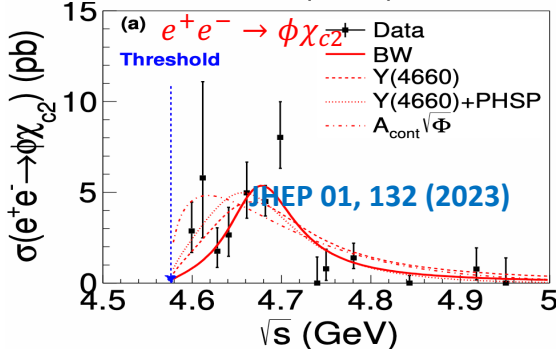
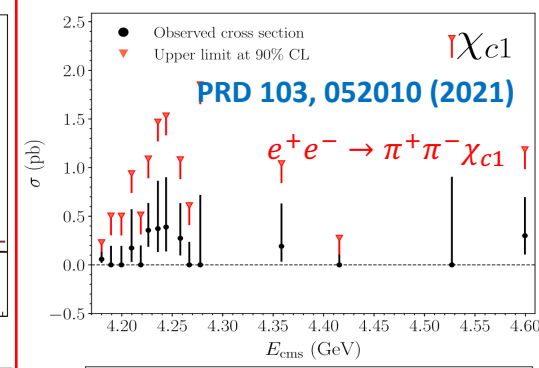
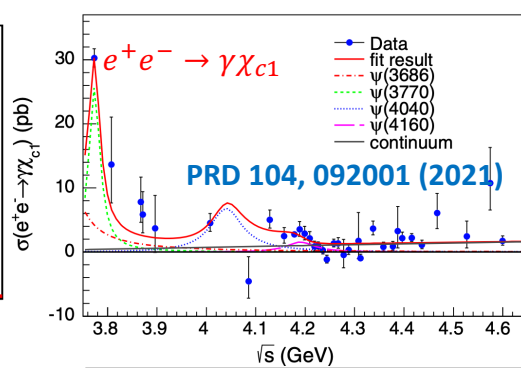
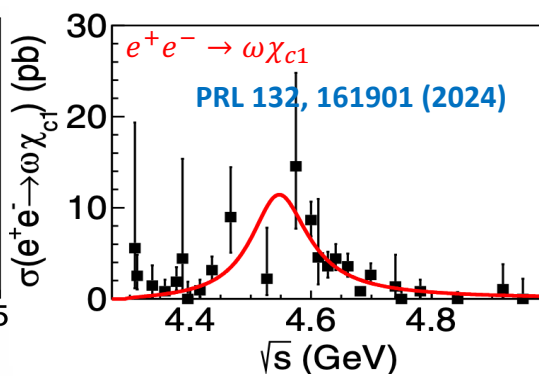
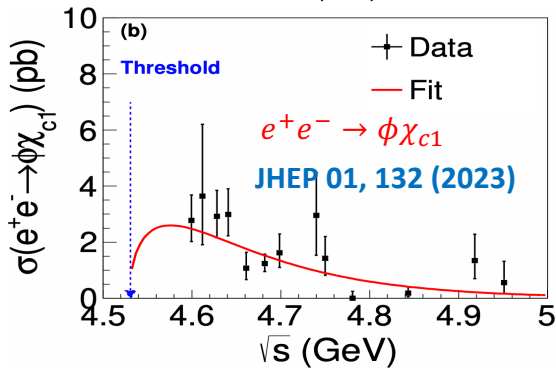
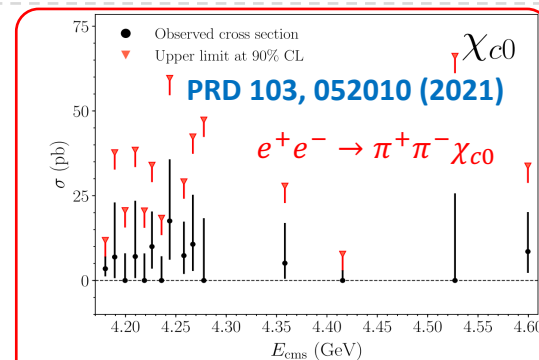
# Summary of $\sigma(e^+e^- \rightarrow \psi(2S)/\psi(3770)/\psi_2(3823) + X)$



# Summary of $\sigma(e^+e^- \rightarrow \chi_{cJ} + X)$

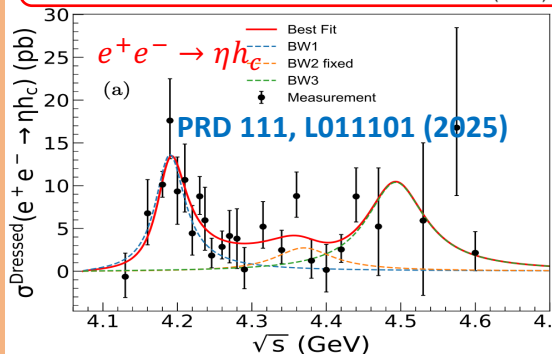
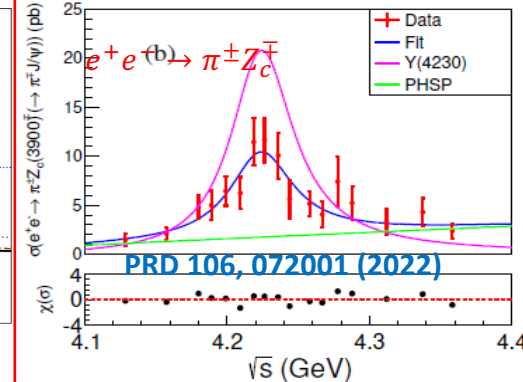
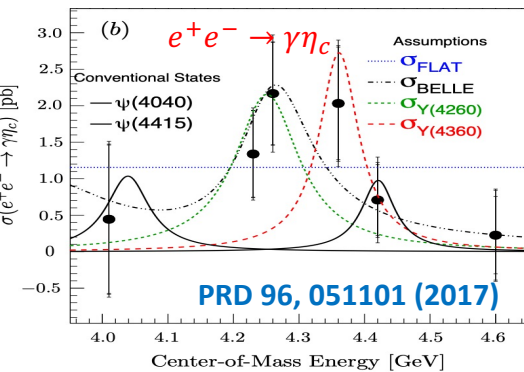
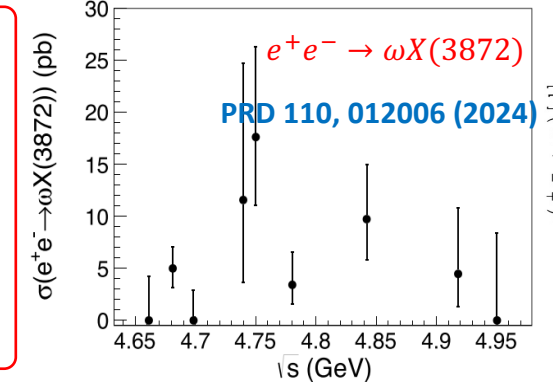
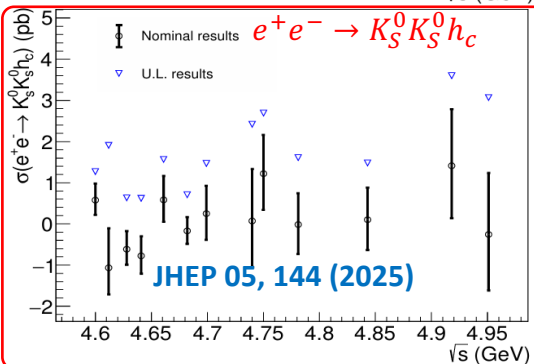
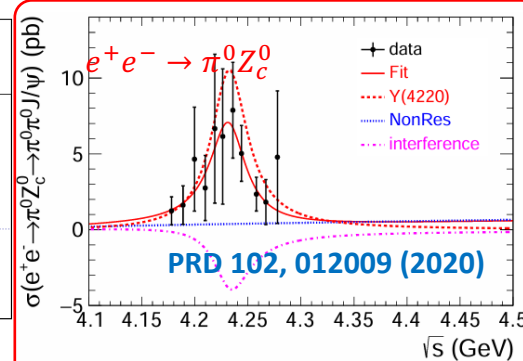
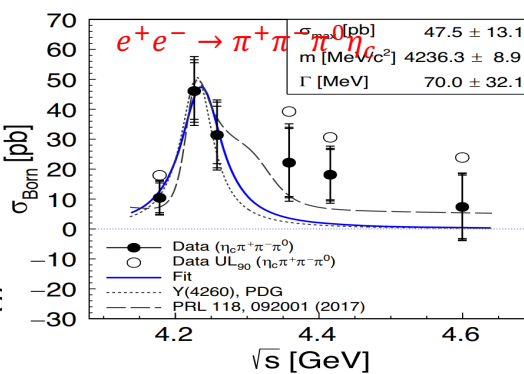
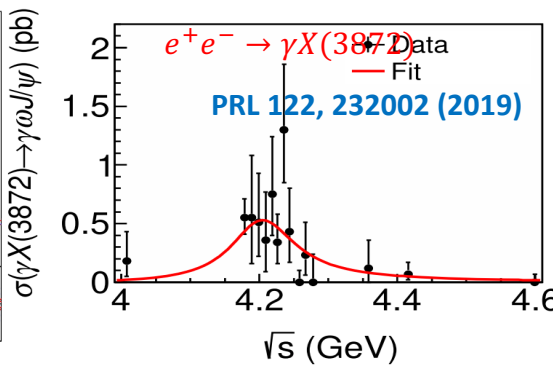
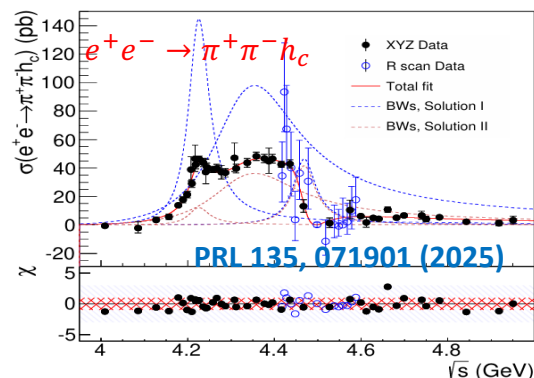


Statistics are low





# Summary of $\sigma(e^+e^- \rightarrow h_c/X(3872)/\eta_c/Z_c+X)$



Statistics are low

From PWA of  $e^+e^- \rightarrow \pi\pi J/\psi$