EPS-HEP 2025

# Recent Highlights on Charmonium-(like) Physics at BESIII


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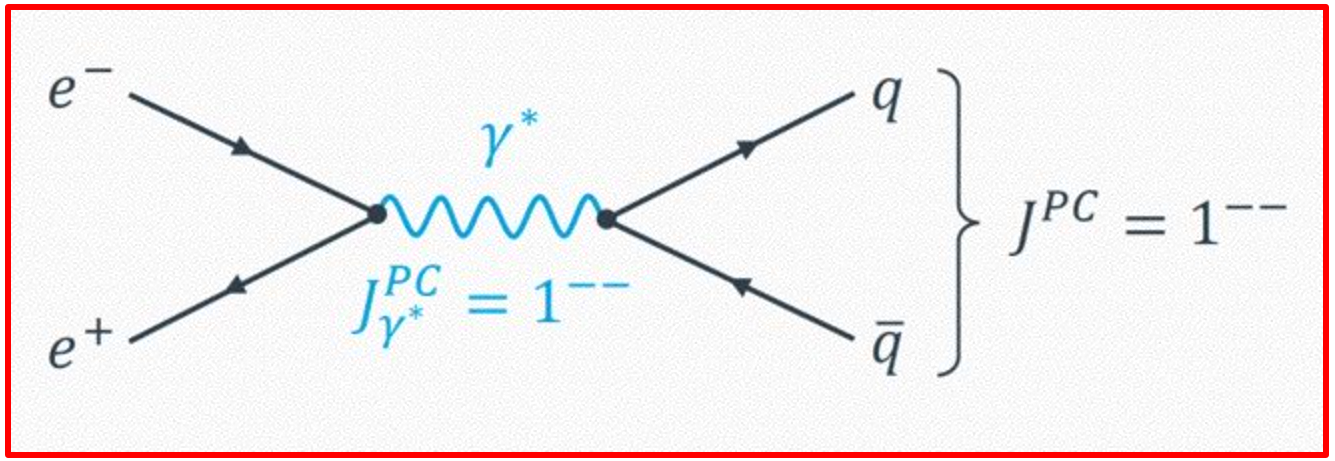
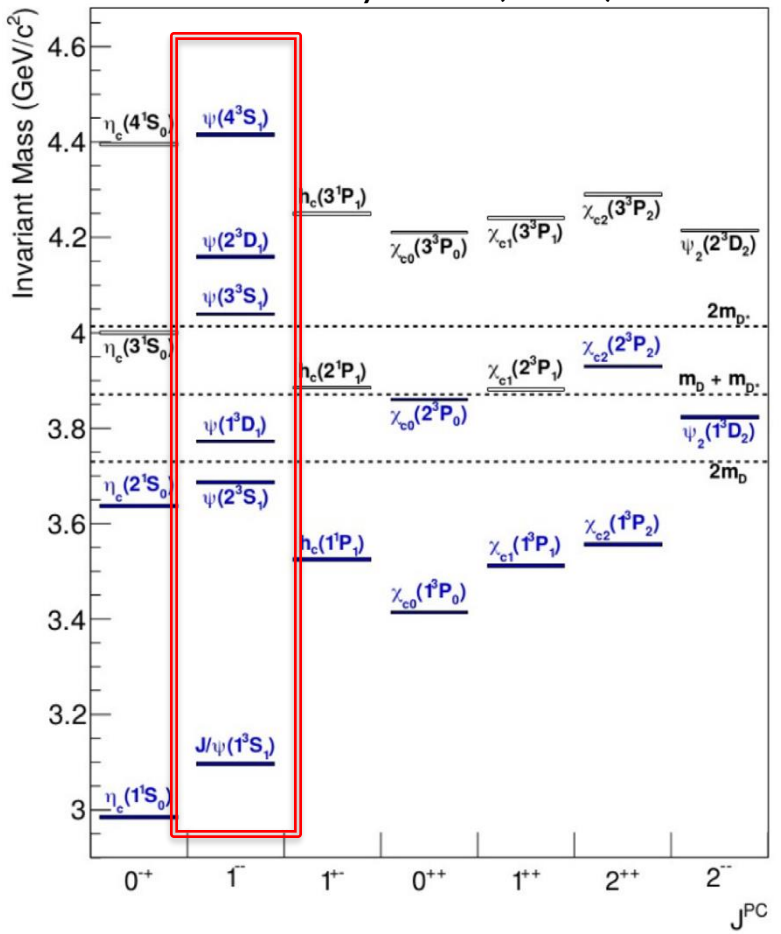
8 July 2025

# Hadron production in $e^+e^-$ collisions




- $e^+e^-$ pairs mainly annihilate into one virtual photon
- The virtual photon can decay into quark-antiquark pairs
- Direct production of vector meson states with $J^{PC} = 1^{--}$
- Energy scan to estimate the line shape and decay width

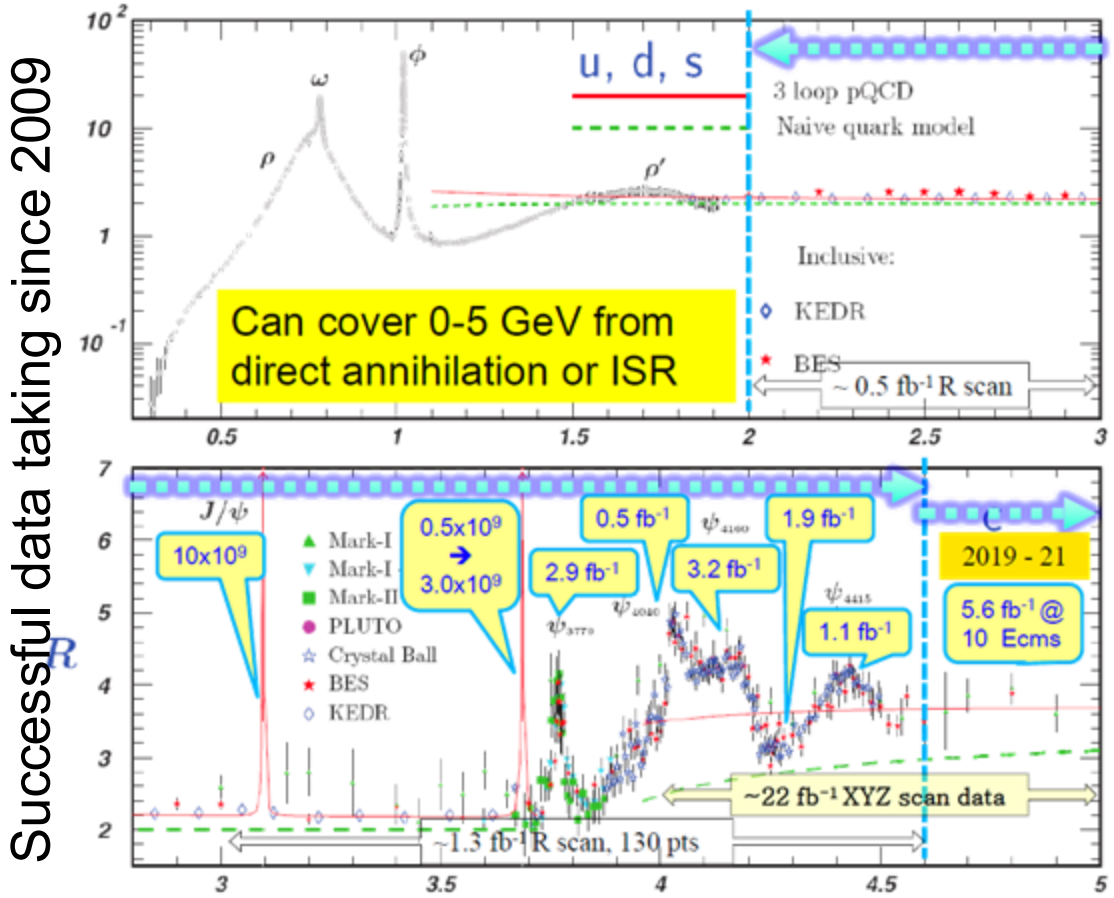
Reviews in Physics 8 (2022) 100070

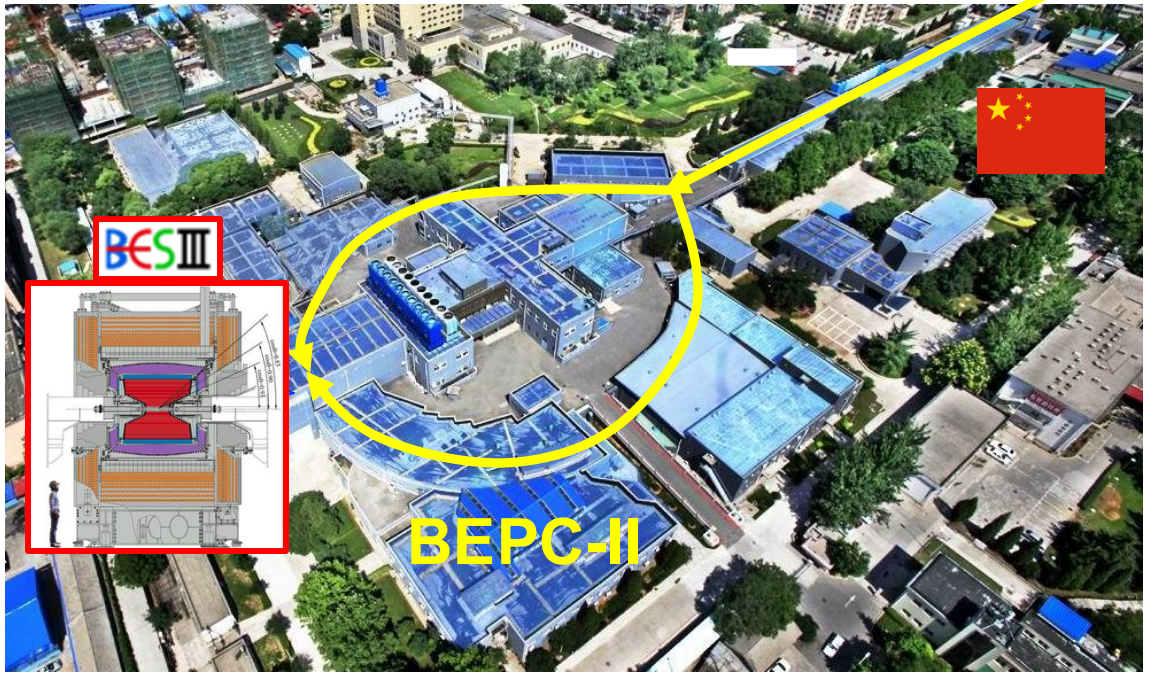


# $e^+e^-$ collisions with BEPC-II and BESIII

$E_{CM}$ = 2 - 4.95 GeV (so far)

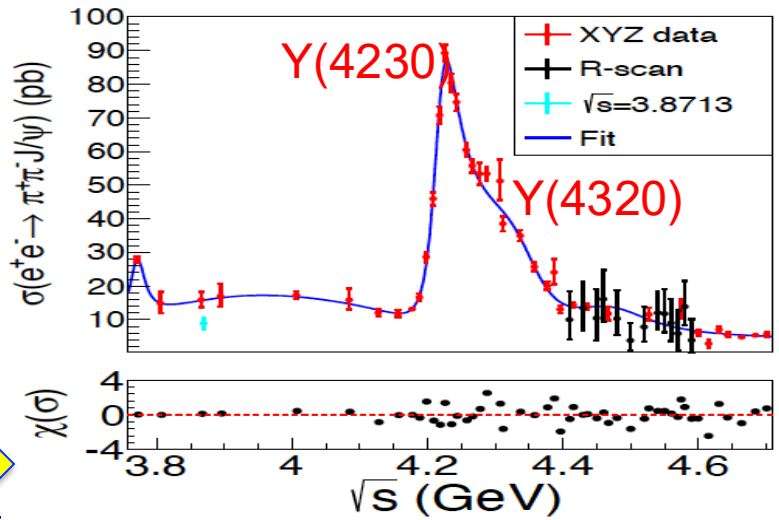
$L_{peak}$ = 1.0 x $10^{33}/cm^2s^{-1}$




Charmonium Spectroscopy

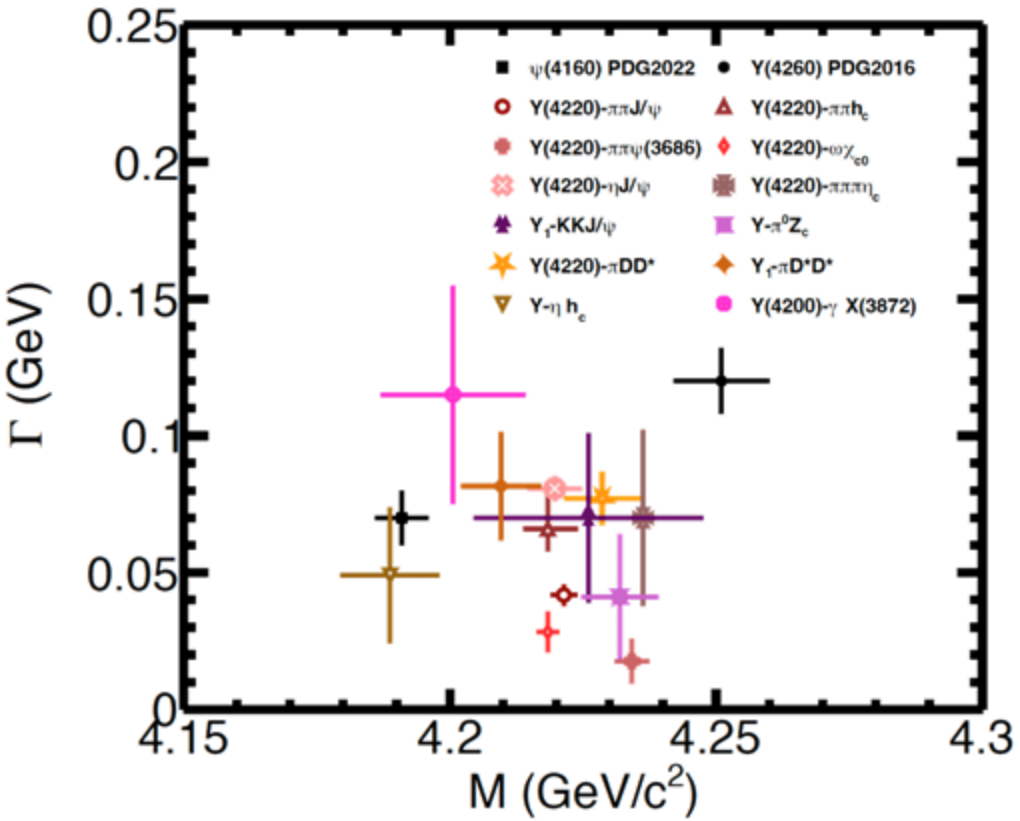
Conventional & Unconventional



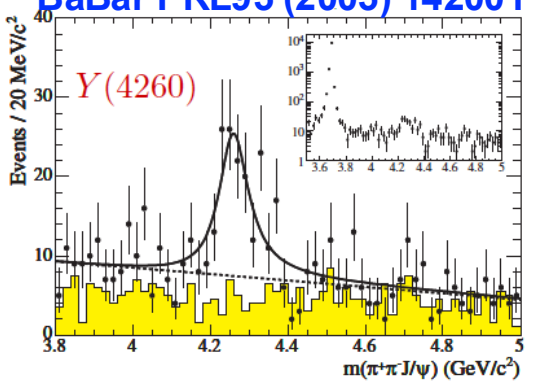
# Spectroscopy of $1^{--}$ Charmonium(-like) states

Y(4260) firstly seen by BaBar searching for X(3872), afterwards split into two states Y(4230) and Y(4360) by BESIII

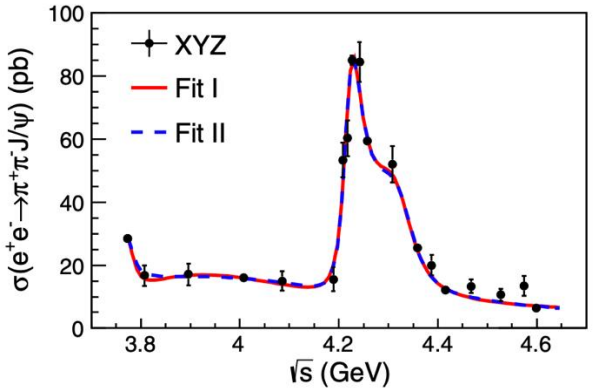
…now called ψ(4230) and ψ(4360) by PDG




**BaBar PRL95 (2005) 142001**



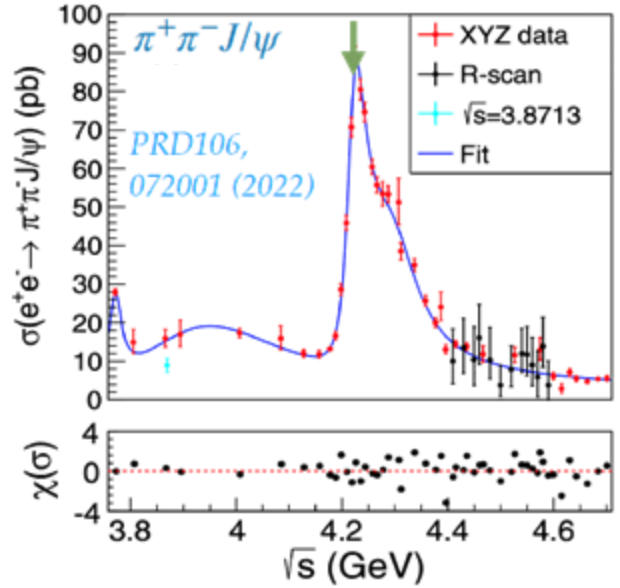

**BESIII PRL118 (2017) 092001**

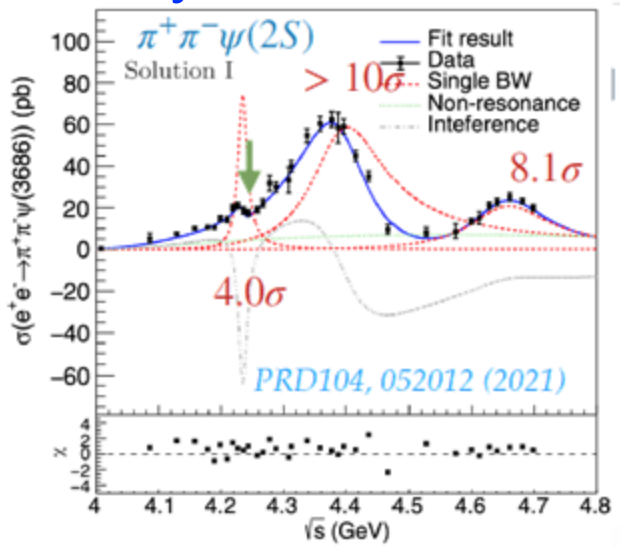


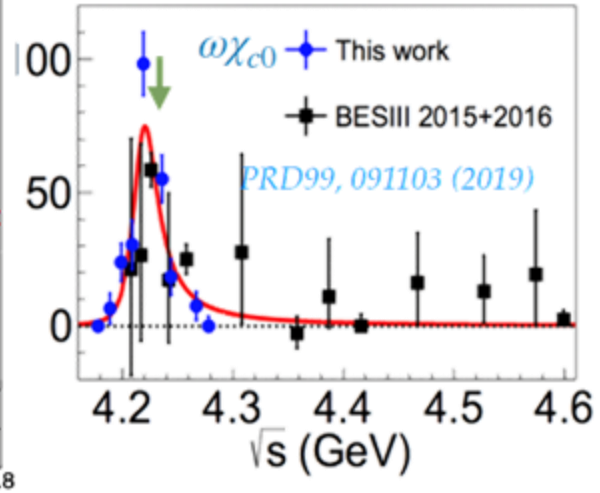

- Inconsistent with all $1^{--}$ quark model states
- Very suppressed open charm decays
- Candidates for exotic matter
  - ? Hybrids?
  - ? Tetraquark?
  - ? Hadronic molecules?
- Well established
- Experimentally easy to produce using $e^+e^-$ collisions → Initial State Radiation

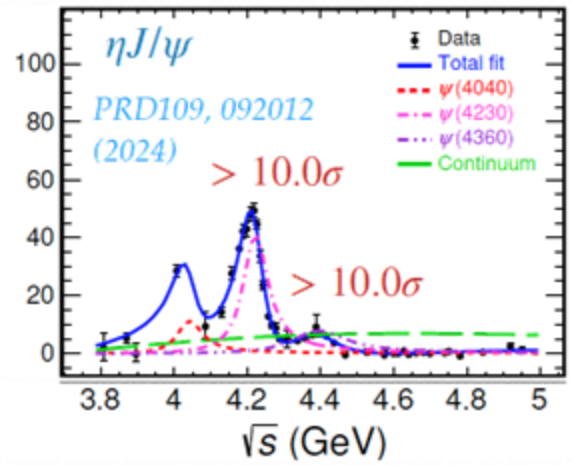
# From Y(4260) to Y(4230)

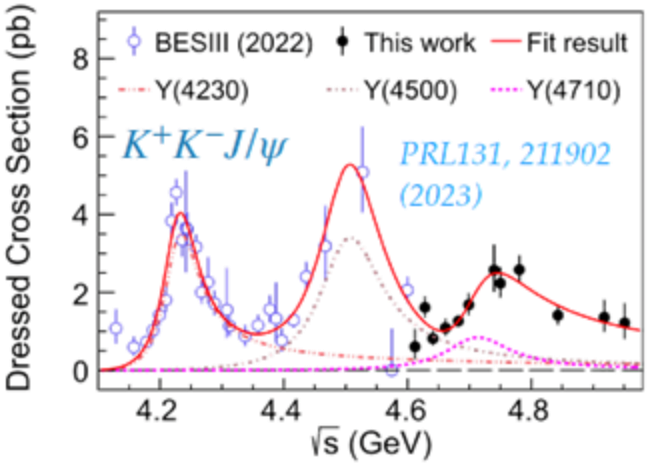
## Seen in more than ten decay modes, into charmonia and into open charm final states

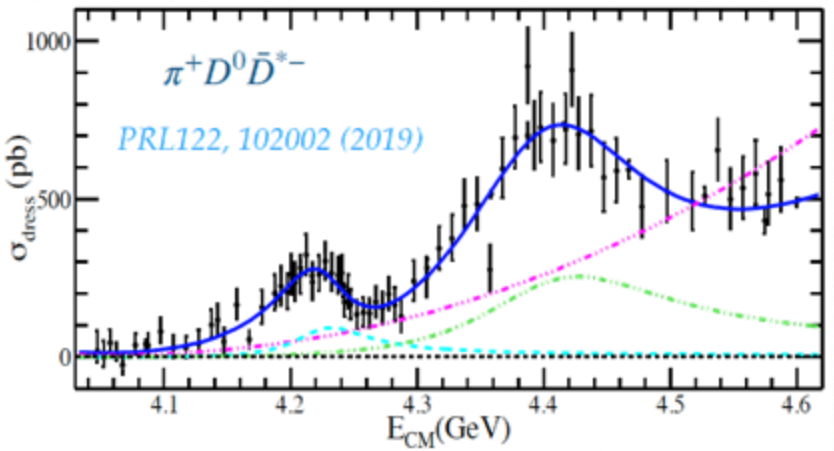


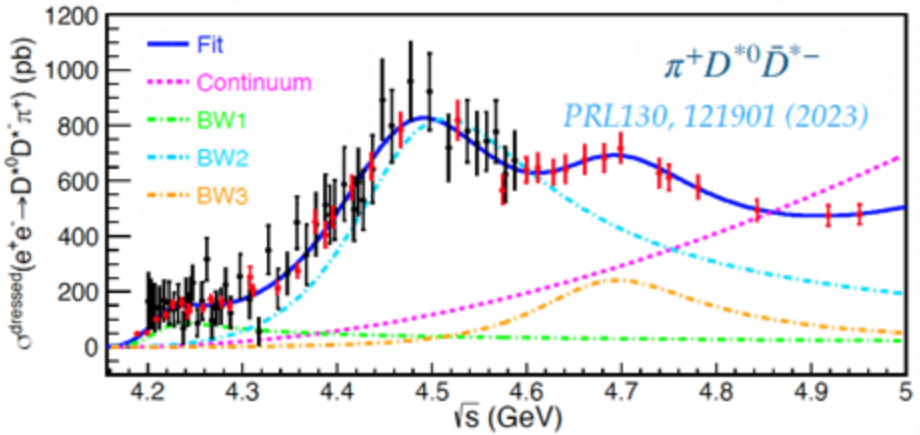




## Searching for what is still missing

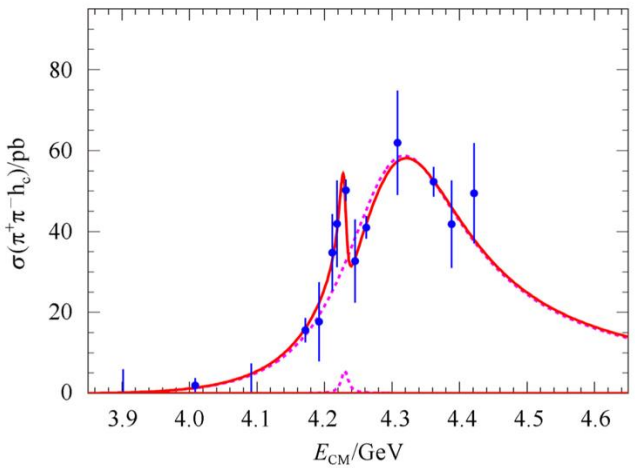
# Precise Measurement of $e^+e^- \to \pi^+\pi^- h_c(1P)$

Initially observed by CLEO-c at √s=4.17 GeV PRL107, 041803 (2011)

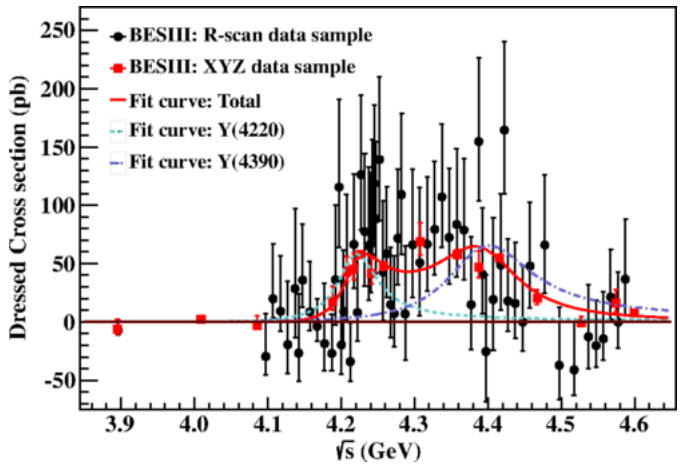
$e^+e^- \to \pi^+\pi^- h_c(1P)$ cross section by BESIII at √s=3.9-4.6 GeV, found two structures

PRL118, 092002 (2017)

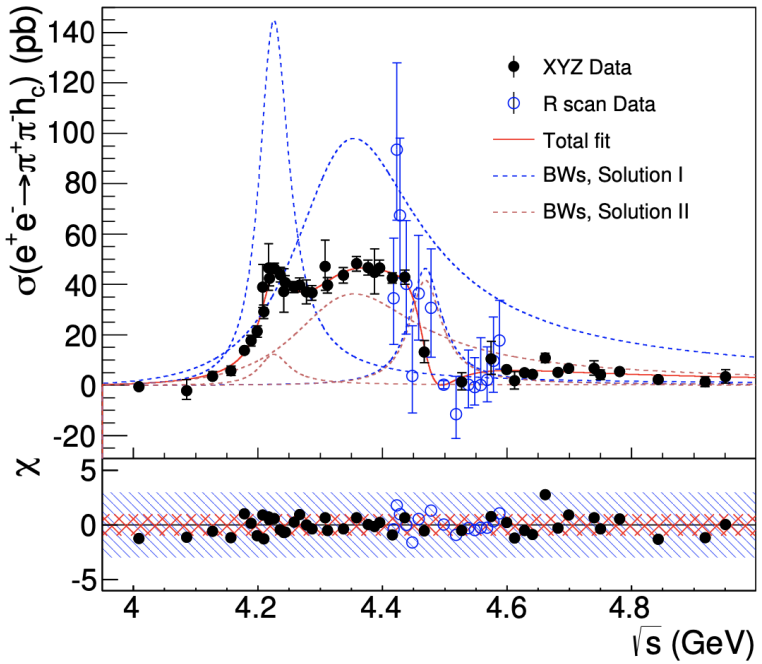
New data collected by BESIII √s=4.18-4.95 GeV (27 data samples)




PRL107, 041803 (2011) – CLEO-c
PRL111, 242001 (2013) – BESIII
CPC 38, 043001 (2014)



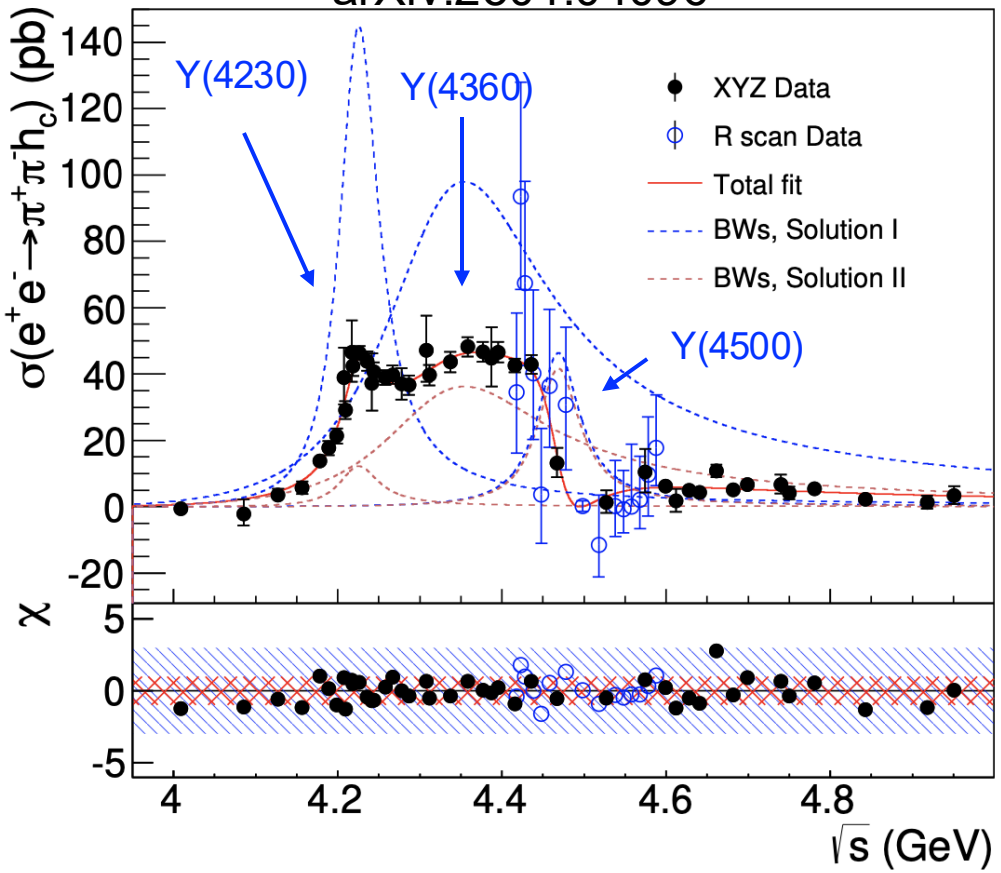

PRL118, 092002 (2017) - BESIII




arXiv:2504.04096 - BESIII

# Precise Measurement of $e^+e^- \to \pi^+\pi^- h_c(1P)$

arXiv:2504.04096




- Tested different combinations of resonance structures
- Starting from two BWs, adding more BWs and continuum
- Checked significance of each additional term

Best description: coherent sum of three BW functions

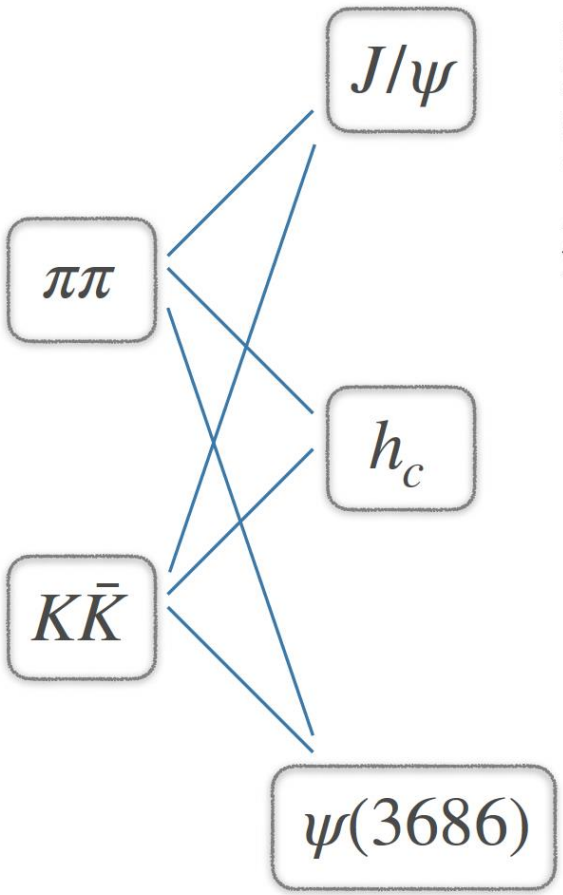
| | Y(4230) | Y(4360) | >5σ Y(4500) |
|---|---|---|---|
| Parameter | $R_1$ | $R_2$ | $R_3$ |
| $M$ (MeV/c²) | $4223.6^{+3.6+2.6}_{-3.7-2.9}$ | $4327.4^{+20.1+10.7}_{-18.8-9.3}$ | $4467.4^{+7.2+3.2}_{-5.4-2.7}$ |
| $\Gamma$ (MeV) | $58.5^{+10.8+6.7}_{-11.4-6.5}$ | $244.1^{+34.0+24.2}_{-27.1-18.3}$ | $62.8^{+19.2+9.9}_{-14.4-7.0}$ |

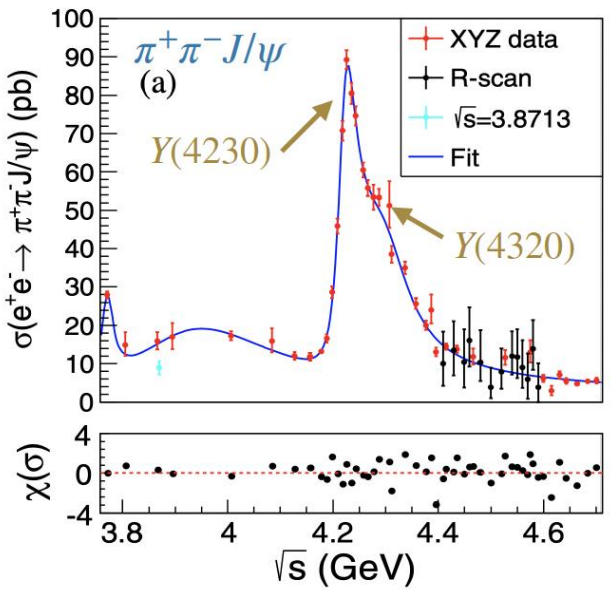
a bit larger width
$\Gamma_{Y(4360)}$= 120±21 MeV

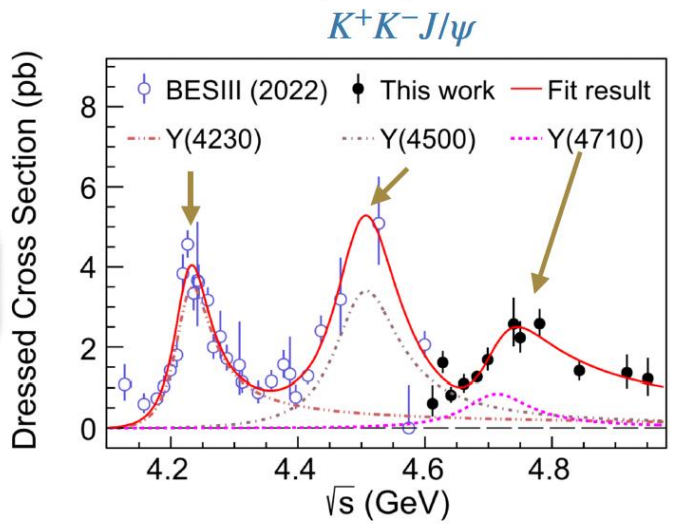
No Y(4660) structure present in data, in tension with P-wave tetraquark assumption EPJC78, 29(2018)

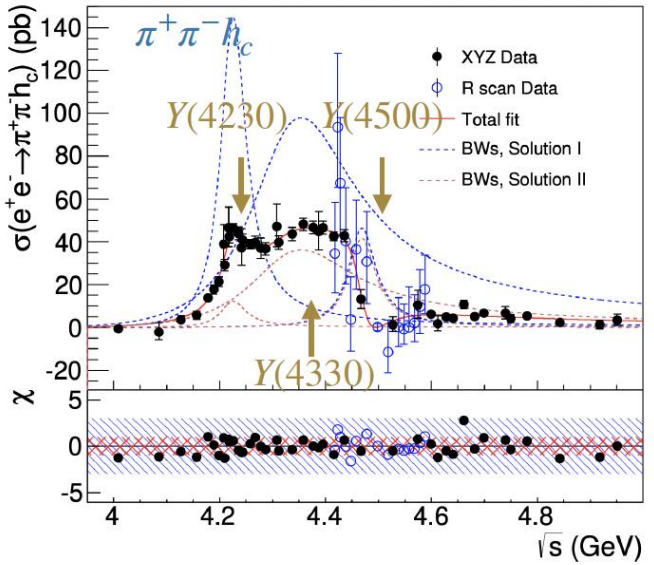
In S-D mixing scheme, 4S–3D, 5D – 4D states located in this region, observed only three PRD99, 114003 (2019)

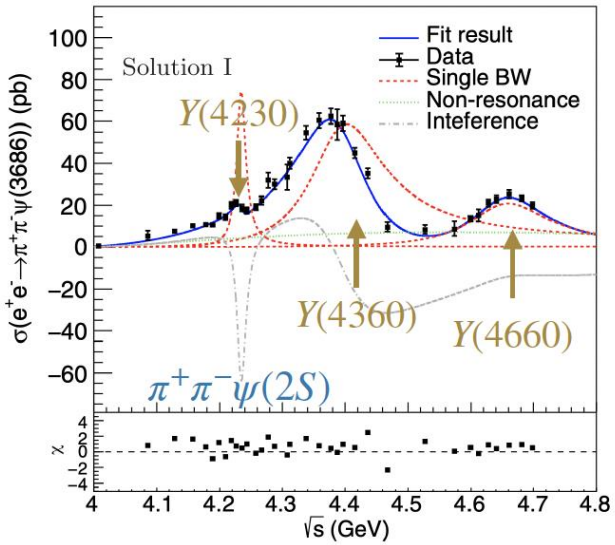
# Checking strange content of charmonium-like states?




$K\bar{K}h_c$

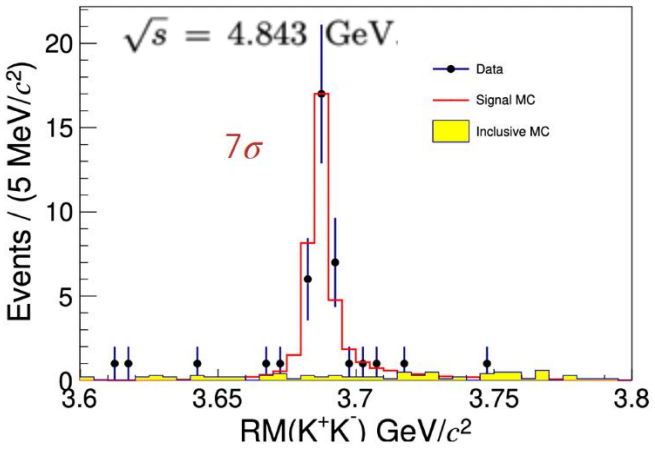
$K\bar{K}\psi(2S)$

Mass threshold: ~4.513 GeV, 4.673 GeV

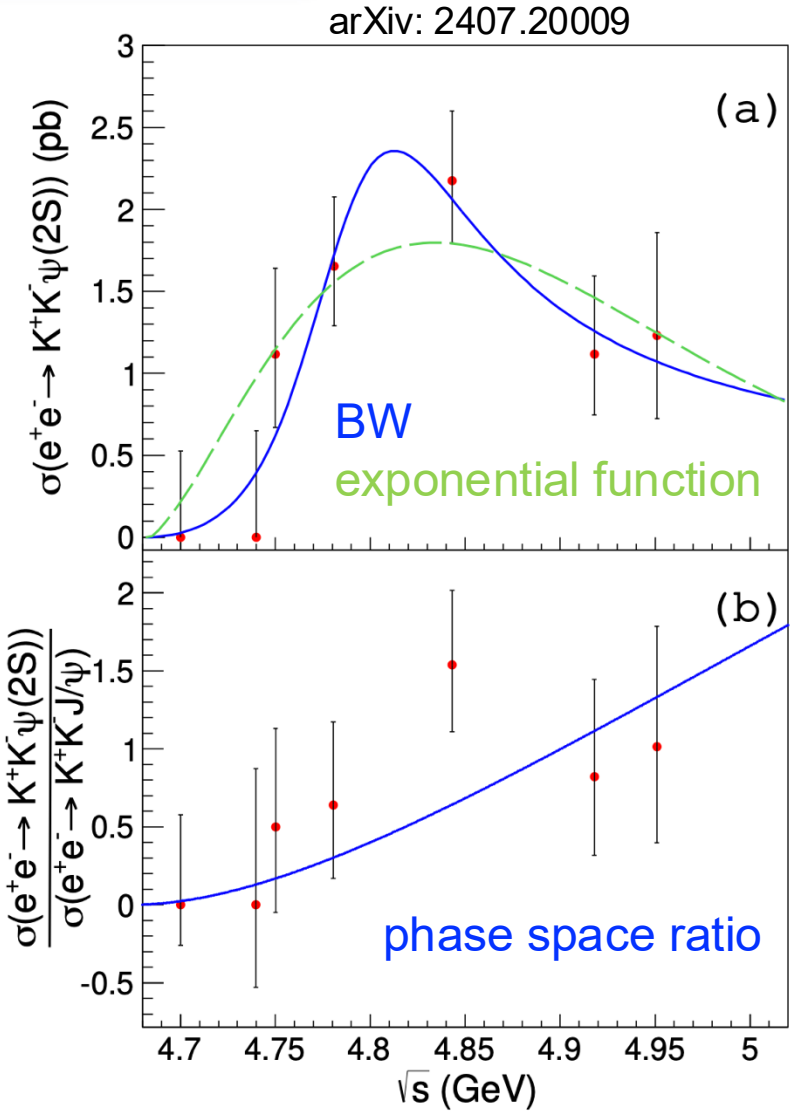
## Partial reconstruction to improve signal efficiency

- $K^+K^-\psi(3686)$: 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
- $K_S^0K_S^0\psi(3686)$: data sample at $\sqrt{s} = 4.682$ to $4.951$ GeV, 4.1 fb$^{-1}$
  - $e^+e^- \to K_S^0K_S^0\psi(3686)$, $\psi(3686) \to J/\psi + X$, $J/\psi \to l^+l^-$, $K_S^0 \to \pi^+\pi^-$
- $K_S^0K_S^0h_c$ :data sample at $\sqrt{s} = 4.6$ to $4.951$ GeV, 6.4 fb$^{-1}$
  - $e^+e^- \to K_S^0K_S^0 + h_c$, $h_c \to \gamma\eta_c$, tag $K_S^0K_S^0 + \gamma$

# Measurement of $e^+e^- \to K^+K^-\psi(3686)$ cross section




Clear $e^+e^- \to K^+K^-\psi(3686)$ signal




The cross section can be fitted similarly:

- either assuming the decay of a vector state (BW)

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

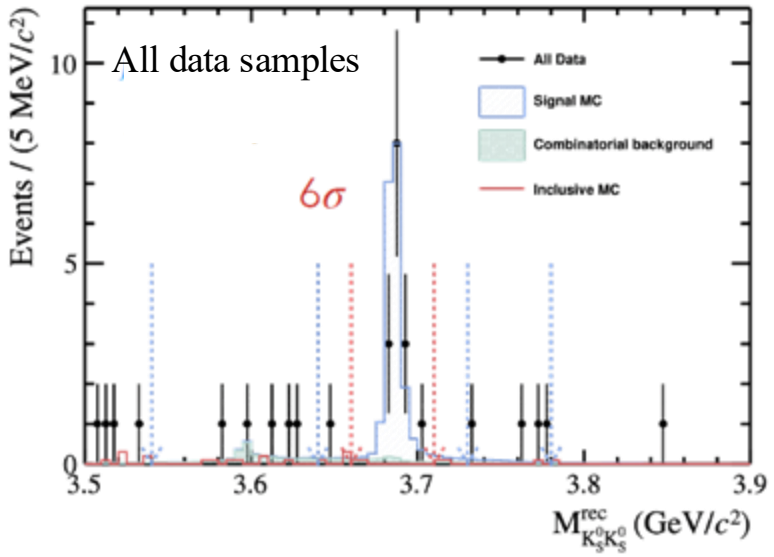
- either as a tail of the decay of a lower mass resonance ($Y(4710)$?)

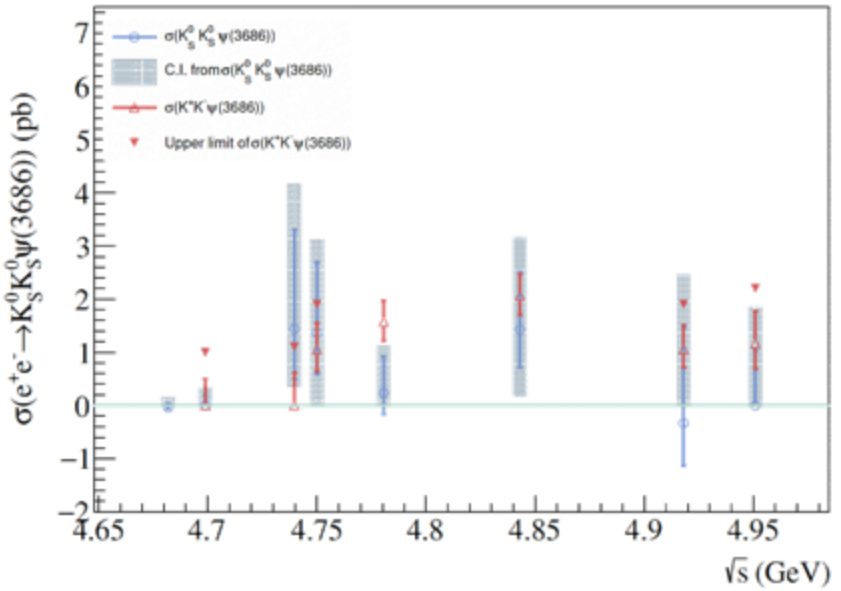
$$\sigma(\sqrt{s}) = p_1 \cdot \Phi(\sqrt{s}) e^{p_0(\sqrt{s} - M_{\text{th}})}$$

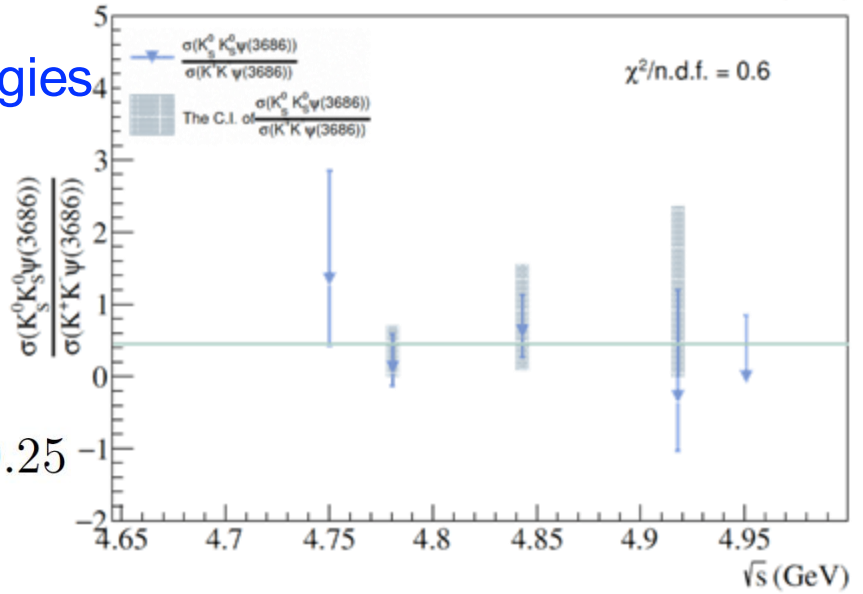
Cross section ratio $K^+K^-\psi(3686)$ / $K^+K^-J/\psi$ above phase space of ~2σ

- Hint that some different production mechanism could be present

# Measurement of $e^+e^- \to K\bar{K}\psi(3686)$ cross section



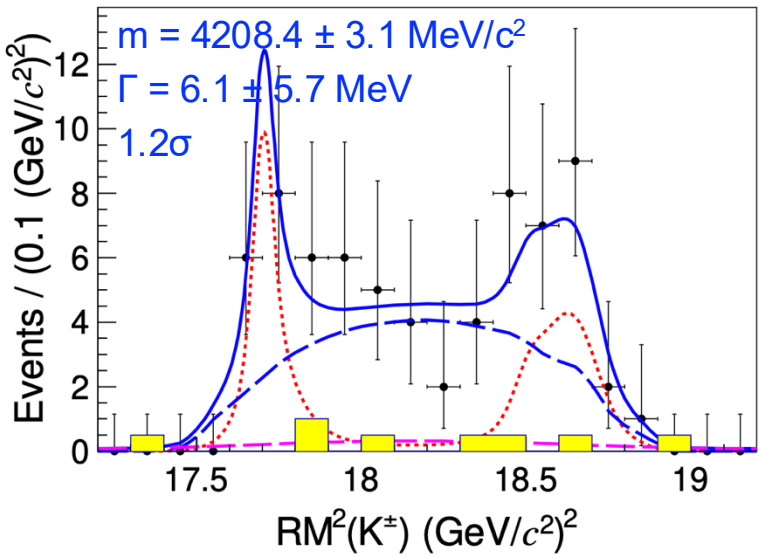



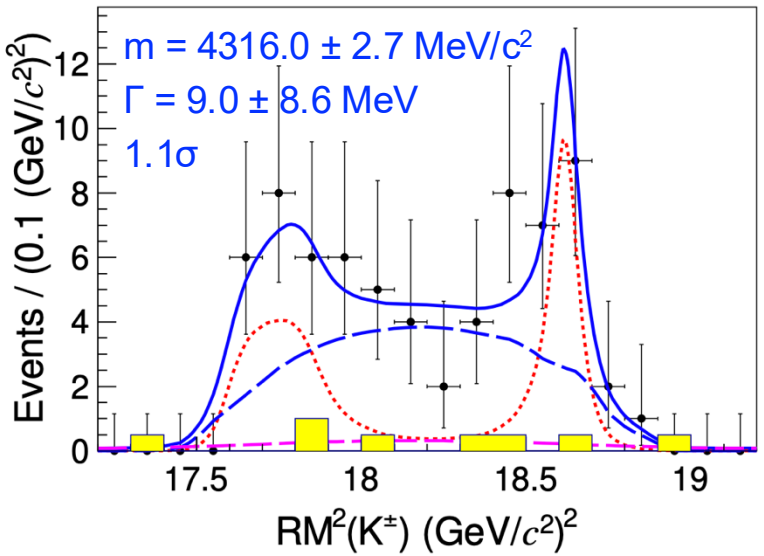

JHEP02, 120 (2025)

- First measurement of $K\bar{K}\psi(3686)$ cross section at different energies
- Significance 6.3σ summing up the complete data sample
- Cross section ratio $K\bar{K}\psi(3686)/K^+K^-\psi(3686)$ consistent with isospin expectations

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

# Searching for strange tetraquark states $Z_{cs}$

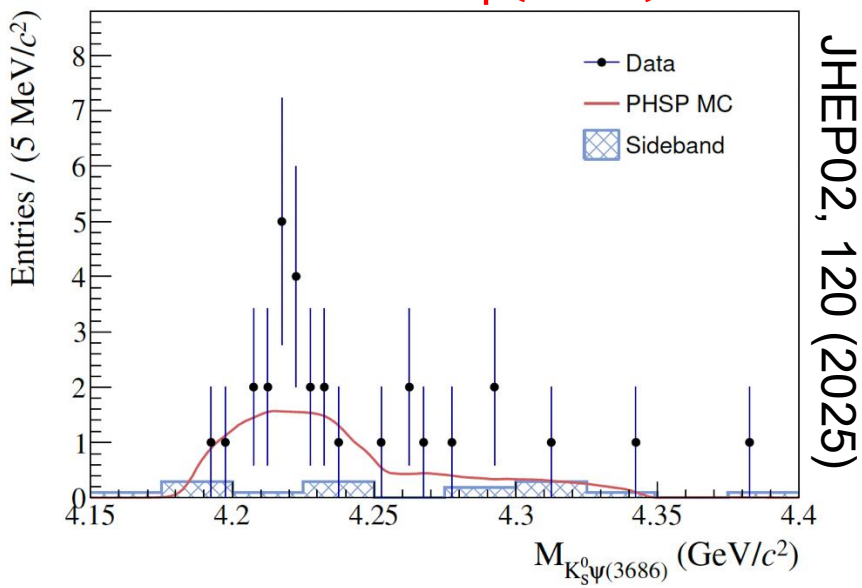



$e^+e^- \to K^+K^-\psi(3686)$

- Two best fit results assuming the presence of a $Z_{cs}$ structure
- $Z^{\pm}_{cs}$ masses around 4.208 GeV/c² and 4.315 GeV/c²
- Structure around 4.208 GeV/c² close to $Z_{cs}(4220)$ reported by LHCb
- ~1σ significance

$e^+e^- \to K\bar{K}\psi(3686)$




JHEP02, 120 (2025)

Consistent with three-body phase space

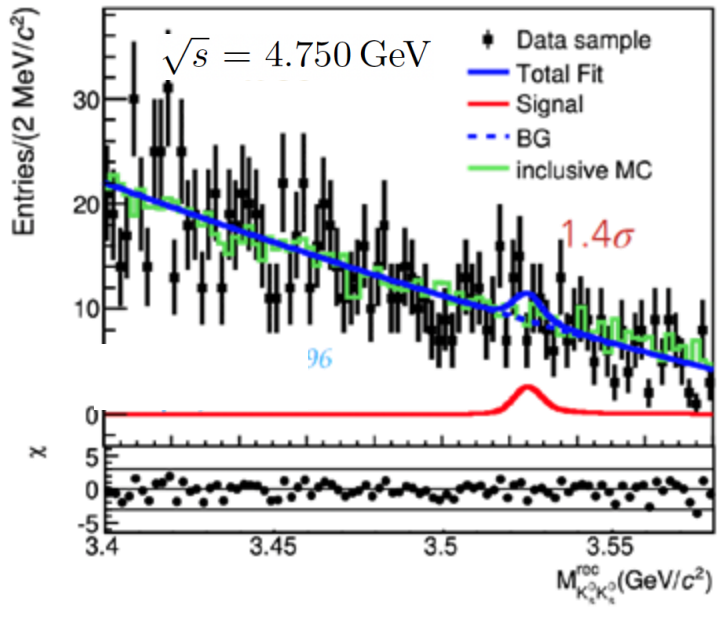
No evidence of $Z_{cs}$ states

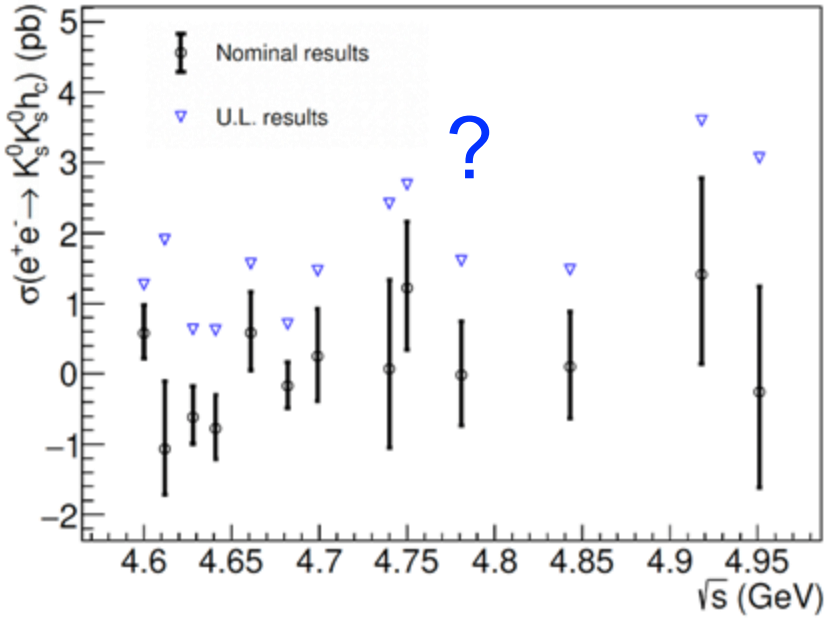
arXiv: 2407.20009

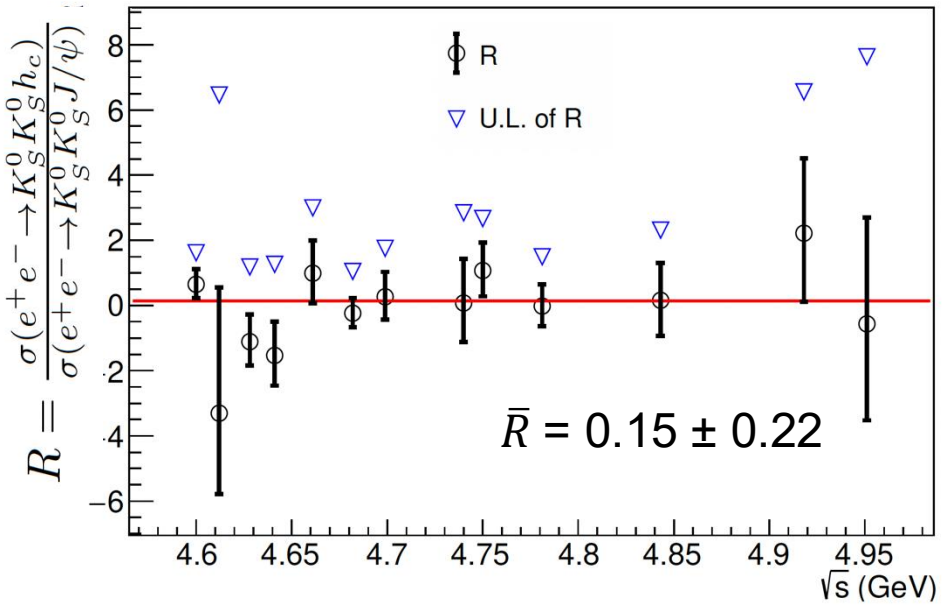
# Measurement of $e^+e^- \to K\bar{K}h_c(1P)$

- Search for $e^+e^- \to K\bar{K}h_c$ using 13 energy points at $\sqrt{s}$=4.60-4.95 GeV
- Significance below 2σ for each energy point, estimated upper limits
- Slight enhancement at 4.75 GeV but no definitive conclusions
- Cross section ratio $\sigma(e^+e^- \to K\bar{K}h_c)/\sigma(e^+e^- \to K\bar{K}J/\psi)$ quite small, different from $\sigma(e^+e^- \to \pi^+\pi^- h_c)/\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ measured at 4.2 < $\sqrt{s}$ < 4.4 GeV

JHEP05(2025)144



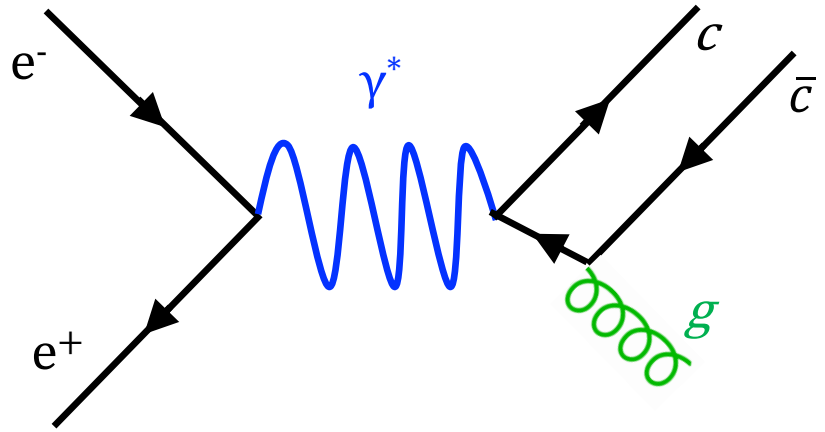



# Prompt inclusive charmonium production

## Nonrelativistic QCD can describe charmonium production

- Perturbative short-term coefficients describe the $c\bar{c}$ production
- Nonperturbative Long-Distance Matrix Elements define the probability to evolve in a defined state




- Double-charmonium production cross section from B-factories larger than expected
- Below the $J/\psi c\bar{c}$ threshold (~6 GeV) check of the contribution from color-octet

  Non-zero if σ > 10 pb at $\sqrt{s}$ = 4.6~5.6 GeV EPJC77(2017)597

- Search for unknown states/processes

# Prompt inclusive J/ψ and ψ(3686) production

Data: $\mathcal{L}$ = 22 fb$^{-1}$
$\sqrt{s}$ = 3.81 - 4.95 GeV

## Signal channels

- $J/\psi X, J/\psi \to \mu^+\mu^-$
- $\psi(3686)X, \psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-/e^+e^-$

## Non prompt background

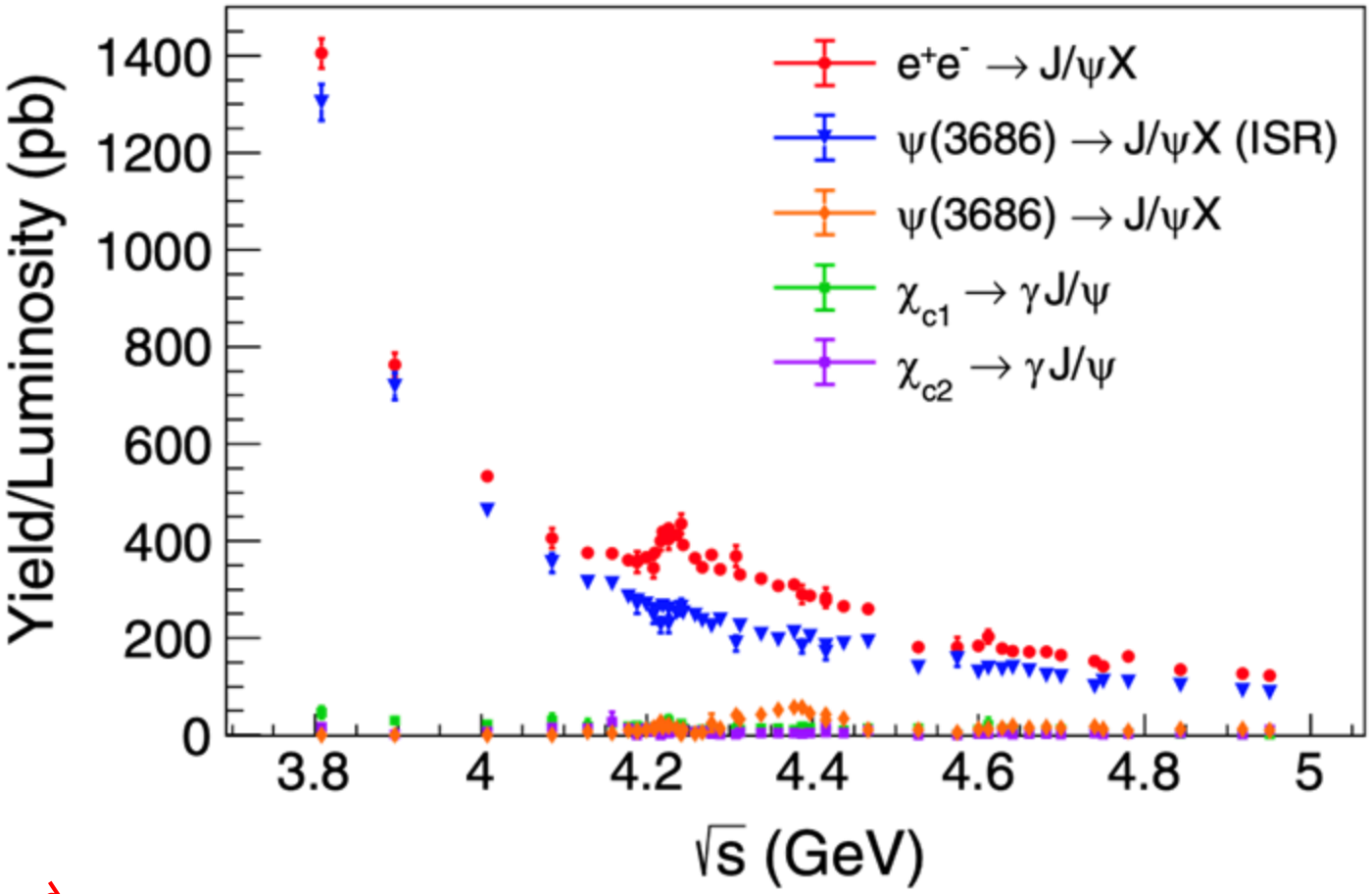
J/ψ from conventional charmonia

- $\psi(3686) \to \pi^+\pi^- J/\psi, \chi_{c1,2} \to \gamma J/\psi$, etc.

ISR production

- $\gamma_{ISR}\, J/\psi$; $\gamma_{ISR}\, \psi(3686)$

to be subtracted




PHYS REV D 111, 052007 (2025)

# Inclusive and exclusive J/ψ production

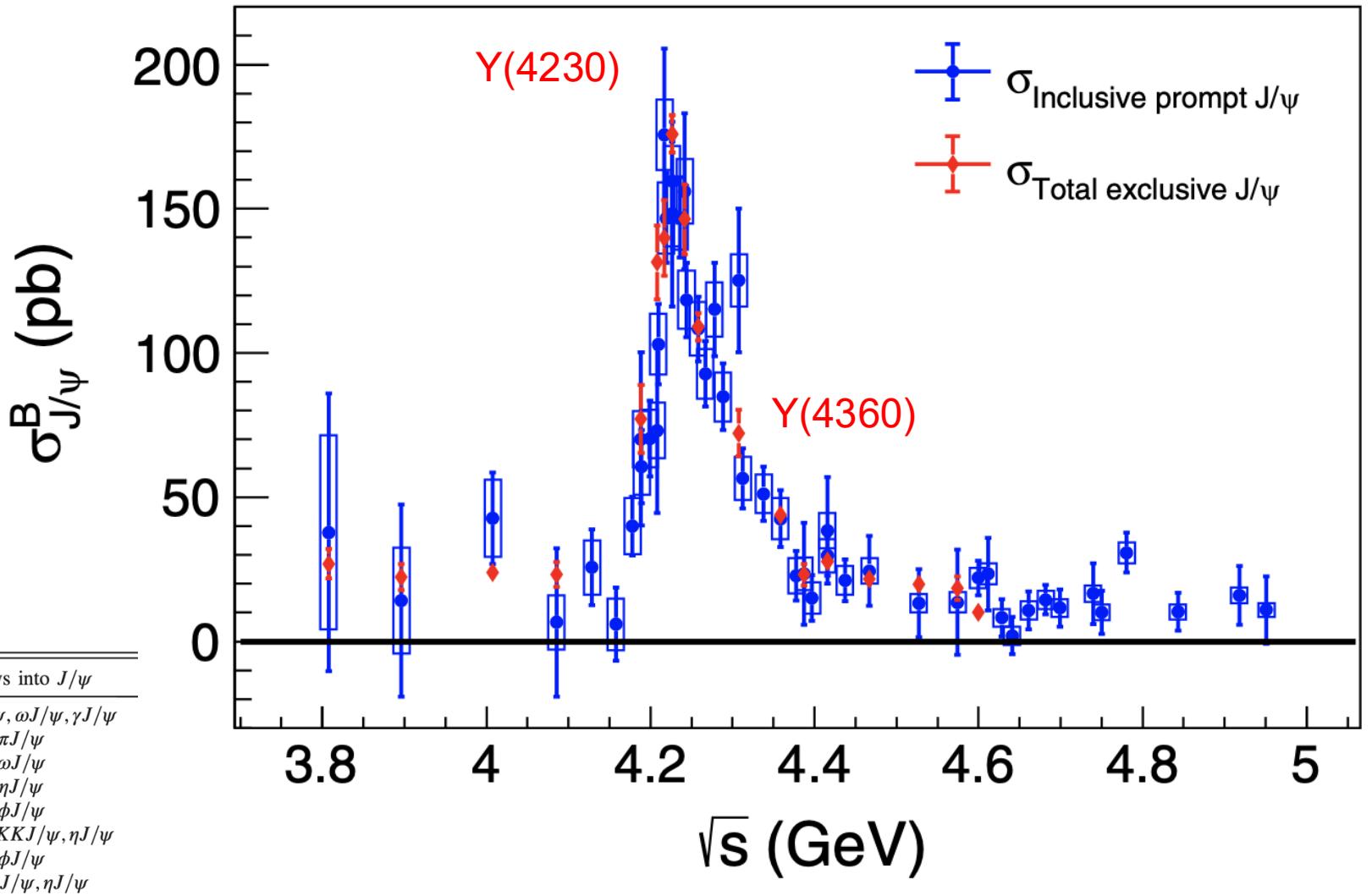
no evidence of hidden decays involving the J/ψ meson

Average value of J/ψ cross section in the region √s=4.53 to 4.95 GeV

$\sigma = 14.0 \pm 1.7_{stat} \pm 3.1_{syst}$ pb

(in the no-resonance hypothesis)

| $c\bar{c}$ Meson | Mass (MeV) | Width (MeV) | Decays into $J/\psi$ |
|---|---|---|---|
| $\chi_{c1}(3872)$ | $3871.7 \pm 0.1$ | $1.2 \pm 0.2$ | $\pi^+\pi^- J/\psi, \omega J/\psi, \gamma J/\psi$ |
| $Z_c(3900)$ | $3887.1 \pm 2.6$ | $28.4 \pm 2.6$ | $\pi J/\psi$ |
| $\chi_{c0}(3915)$ | $3921.7 \pm 1.8$ | $18.8 \pm 3.5$ | $\omega J/\psi$ |
| $\psi(4040)$ | $4039.0 \pm 1.0$ | $80 \pm 10$ | $\eta J/\psi$ |
| $X(4160)$ | $4153 \pm 23$ | $136 \pm 60$ | $\phi J/\psi$ |
| $\psi(4230)$ | $4222.7 \pm 2.6$ | $49.0 \pm 8.0$ | $\pi\pi J/\psi, KK J/\psi, \eta J/\psi$ |
| $X(4350)$ | $4350.6 \pm 5.2$ | $13 \pm 18$ | $\phi J/\psi$ |
| $\psi(4360)$ | $4372.0 \pm 9.0$ | $115 \pm 13$ | $\pi^+\pi^- J/\psi, \eta J/\psi$ |
| $Y(4500)$ | $4485 \pm 28$ | $111 \pm 34$ | $K^+K^- J/\psi$ |
| $\psi(4660)$ | $4630.0 \pm 6.0$ | $72 \pm 14$ | $\cdots$ |
| $Y(4710)$ | $4704 \pm 87$ | $183 \pm 149$ | $K^0K^0 J/\psi$ |




PHYS REV D 111, 052007 (2025)

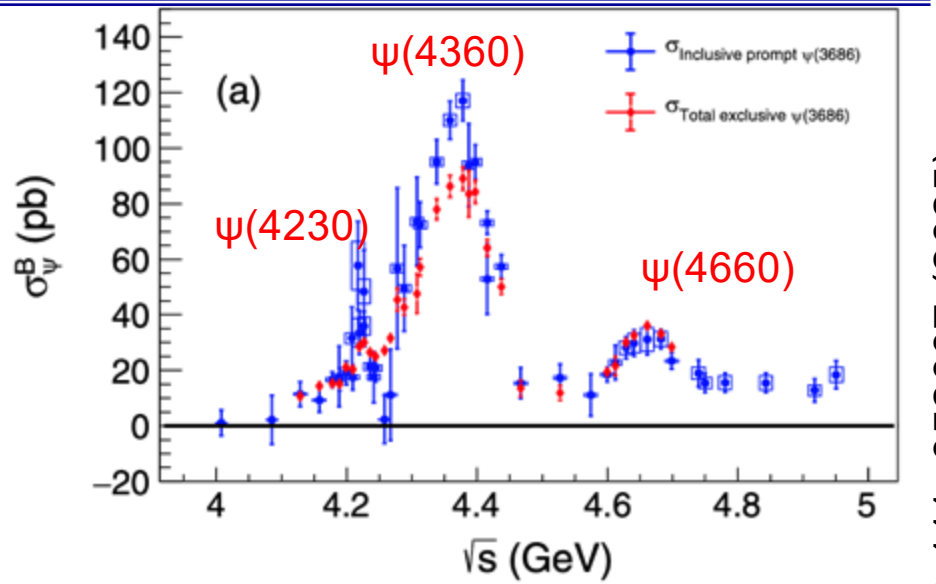
# Inclusive and exclusive ψ(3686) production

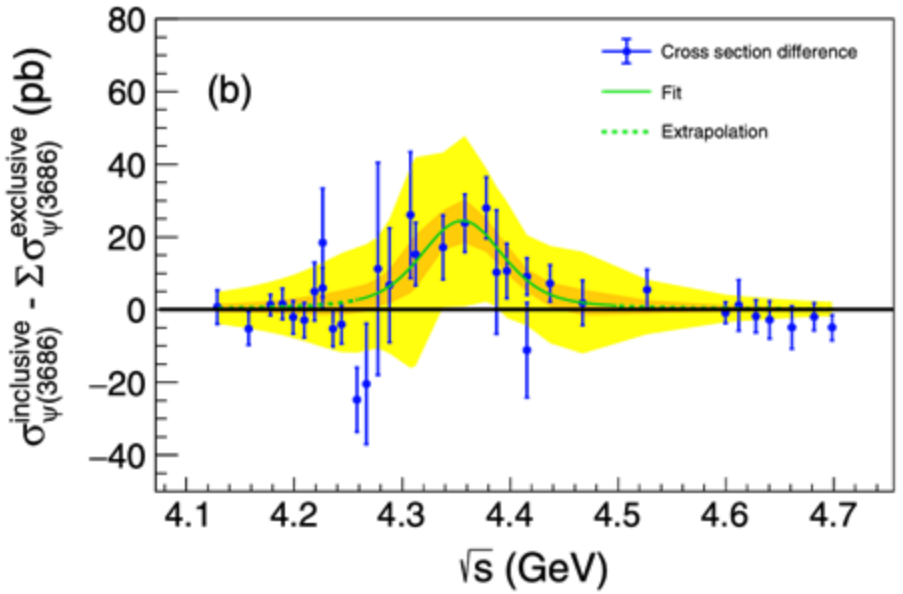
Missing exclusive processes around the ψ(4360) region

Excess ~ 23% of the $\psi(4360)_{prompt}$ inclusive cross section

Average value of ψ(3686) cross section
in the region √s=4.84 to 4.95 GeV
σ = 15.3 ± 3.0 pb
(in the no-resonance hypothesis)

| $c\bar{c}$ Meson | Mass (MeV) | Width (MeV) | Decays into $\psi(3686)$ |
|---|---|---|---|
| $\chi_{c1}(3872)$ | $3871.7 \pm 0.1$ | $1.2 \pm 0.2$ | $\gamma\psi(3686)$ |
| $Z_c(3900)$ | $3887.1 \pm 2.6$ | $28.4 \pm 2.6$ | ··· |
| $\chi_{c0}(3915)$ | $3921.7 \pm 1.8$ | $18.8 \pm 3.5$ | ··· |
| $\psi(4040)$ | $4039.0 \pm 1.0$ | $80 \pm 10$ | ··· |
| $X(4160)$ | $4153 \pm 23$ | $136 \pm 60$ | ··· |
| $\psi(4230)$ | $4222.7 \pm 2.6$ | $49.0 \pm 8.0$ | $\pi^+\pi^-\psi(3686)$ |
| $X(4350)$ | $4350.6 \pm 5.2$ | $13 \pm 18$ | ··· |
| $\psi(4360)$ | $4372.0 \pm 9.0$ | $115 \pm 13$ | $\pi^+\pi^-\psi(3686)$ |
| $Y(4500)$ | $4485 \pm 28$ | $111 \pm 34$ | ··· |
| $\psi(4660)$ | $4630.0 \pm 6.0$ | $72 \pm 14$ | $\pi^+\pi^-\psi(3686)$ |
| $Y(4710)$ | $4704 \pm 87$ | $183 \pm 149$ | ··· |

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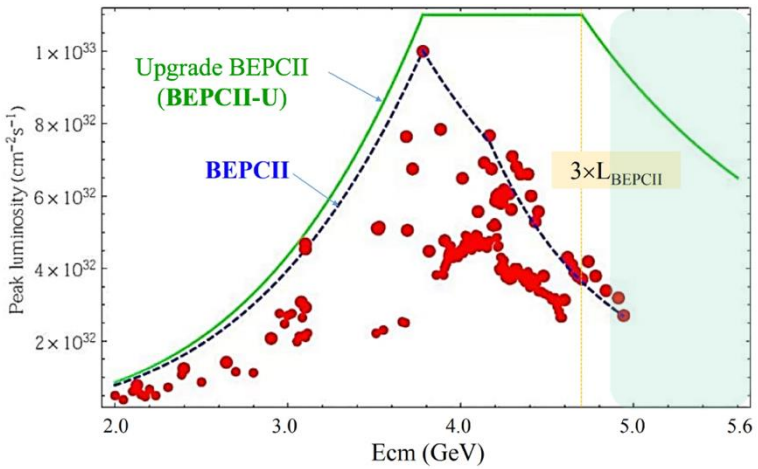
# In Summary

Fine energy scan at BESIII from $\sqrt{s}$=3.8 to 4.95 GeV studying $J^{PC} = 1^{--}$ states

- Improved precision in $e^+e^- \to \pi^+\pi^- h_c(1P)$ cross section measurement,

  plateau-like shape between 4.3 and 4.5 GeV
- First measurement of $e^+e^- \to K^+K^-\psi(3686)$ and $e^+e^- \to K\bar{K}\psi(3686)$ processes
- Search for $Z_{cs}$ states in $K\bar{K} + c\bar{c}$ final states, more statistics is needed
- Search for $e^+e^- \to K\bar{K}h_c(1P)$, no significant signal observed
- Prompt inclusive charmonium production measurements for testing theory of strong interaction




Starting from this year improved BESIII capabilities with crucial updates

- Increase in maximum CMS energy up to 5.6 GeV
- Increase in integrated luminosity in XYZ region
- New CGEM inner tracker