Charmonium-like States BESIII Collaboration

Ben Moses, Indiana University
Lepton-Photon Conference, August 2025
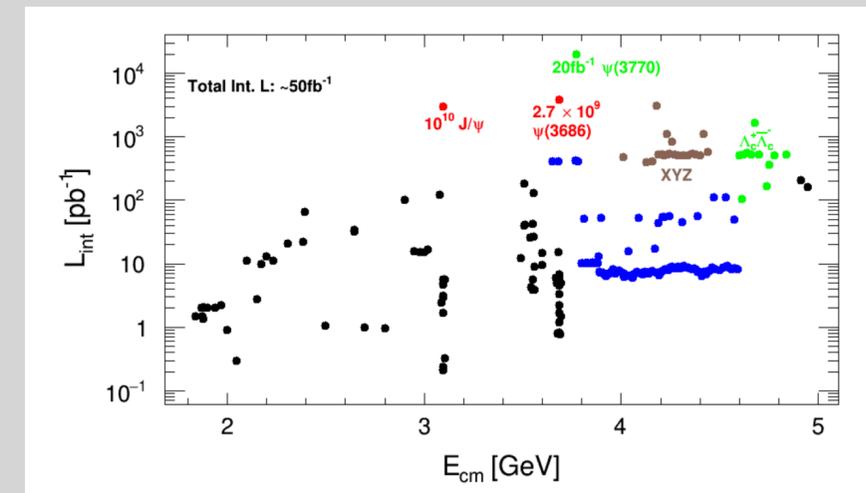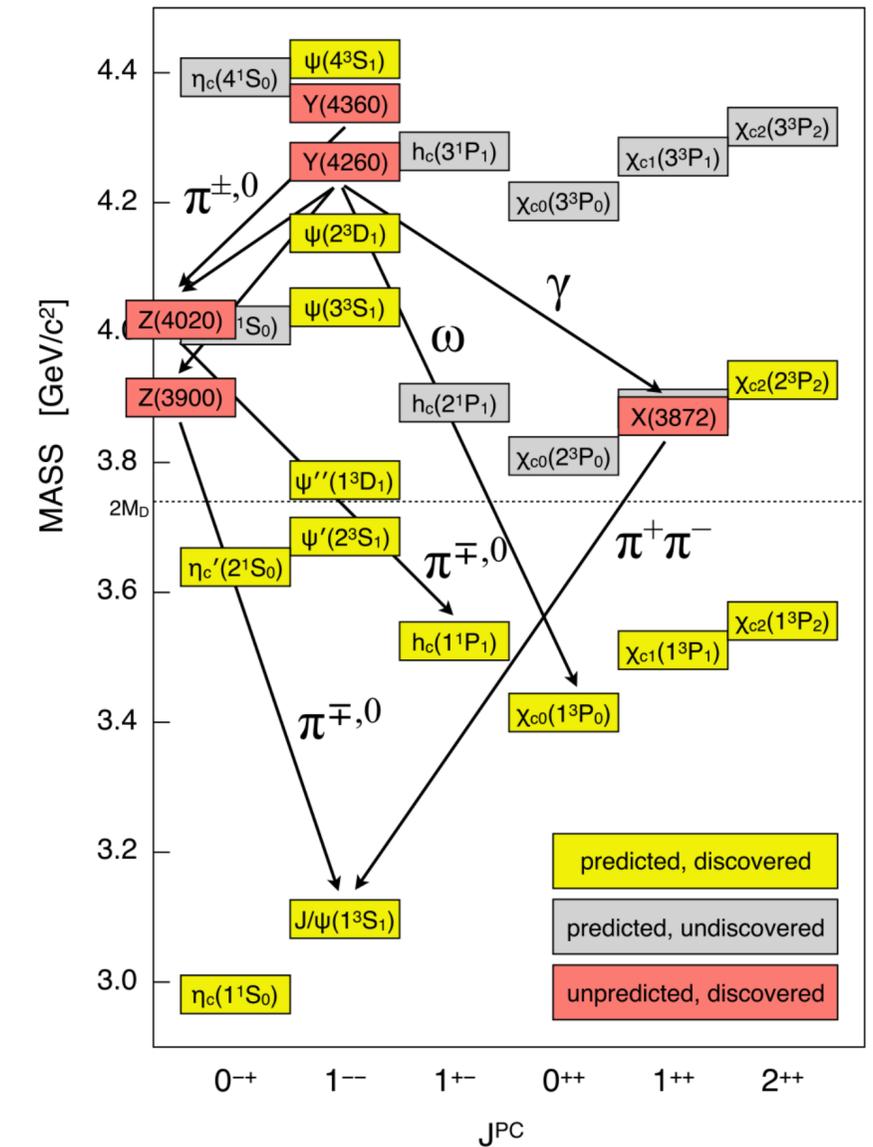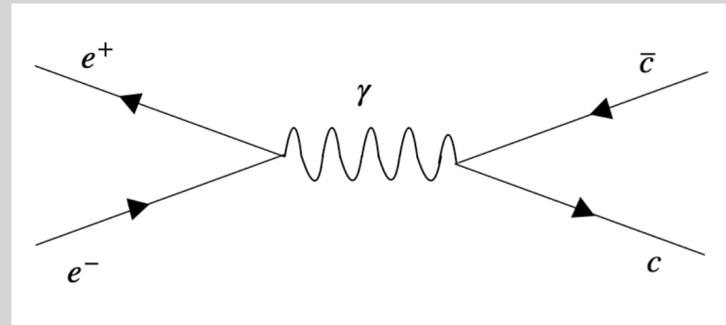
BESIII and the BEPCII Collider

- e^+e^- mainly annihilate into a virtual photon, with quantum numbers $J^{PC} = 1^{--} \rightarrow$ Direct production of 1^{--} vector meson states

- BESIII: $E_{CM} = 1.85 - 4.95$ GeV, $\mathscr{L}_{\text{peak}} = 1.0 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ at 3.773 GeV

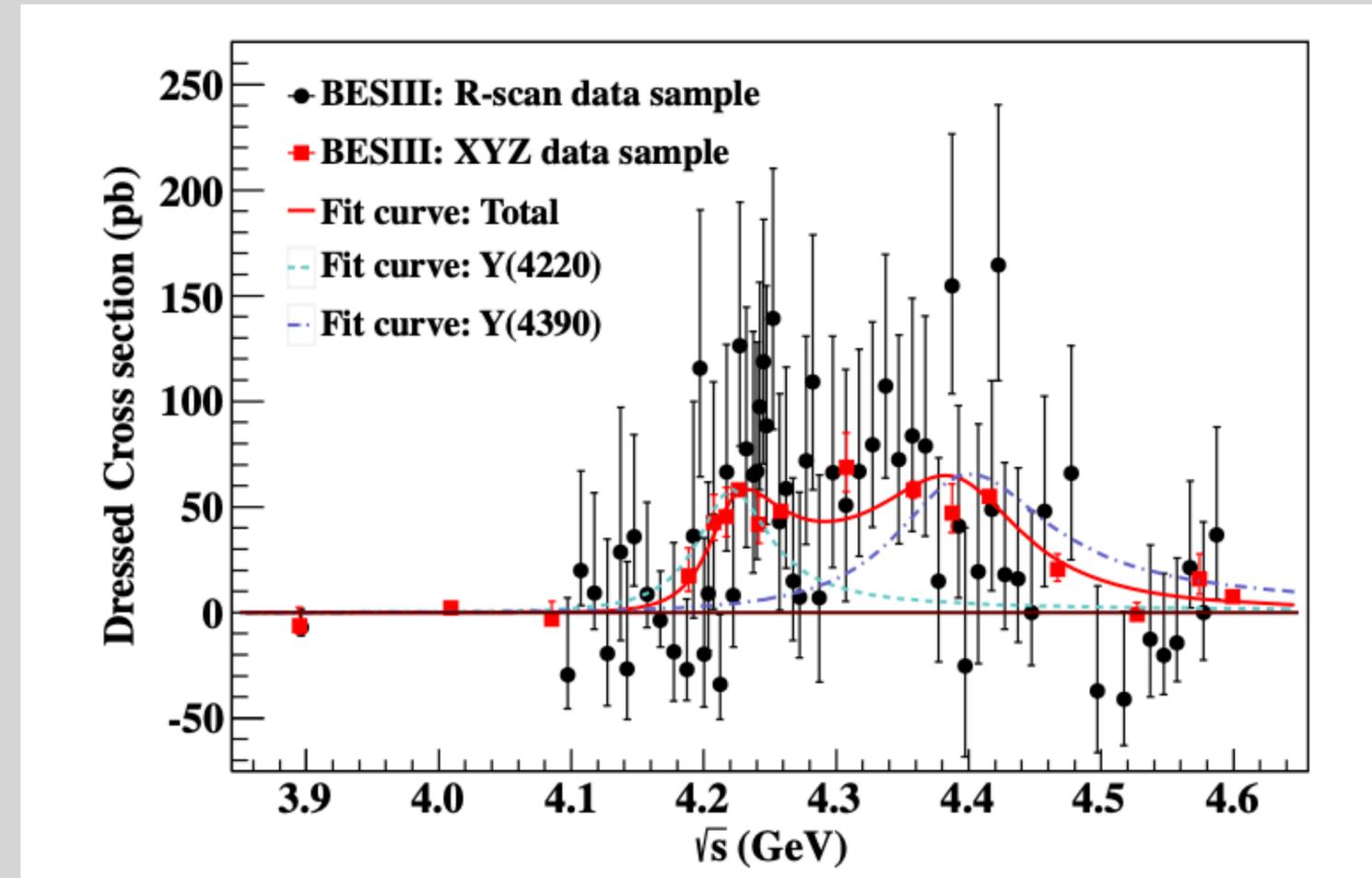Recent Analyses:

- $e^+e^- \rightarrow \pi^+\pi^- h_c$

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

- $e^+e^- \rightarrow \Omega^-\overline{\Omega}^+$

- Prompt Inclusive production of J/ψ and $\psi(2S)$

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

Three Resonance Structure in $e^+e^- \to \pi^+\pi^- h_c$

- Y states (1^{--} charmonium(-like) states) numerous and not well understood

- Y(4220), Y(4390) observed in $e^+e^- \to \pi^+\pi^- h_c$ previously at BESIII

- Hybrid? Tetraquark? Excited charmonia? etc. $\to$ precise measurements needed

- Strong coupling from (supposed) vector charmonium states to h_c would indicate exotic internal structure

BESIII Phys. Rev. Lett. 118, 092002 (2017)

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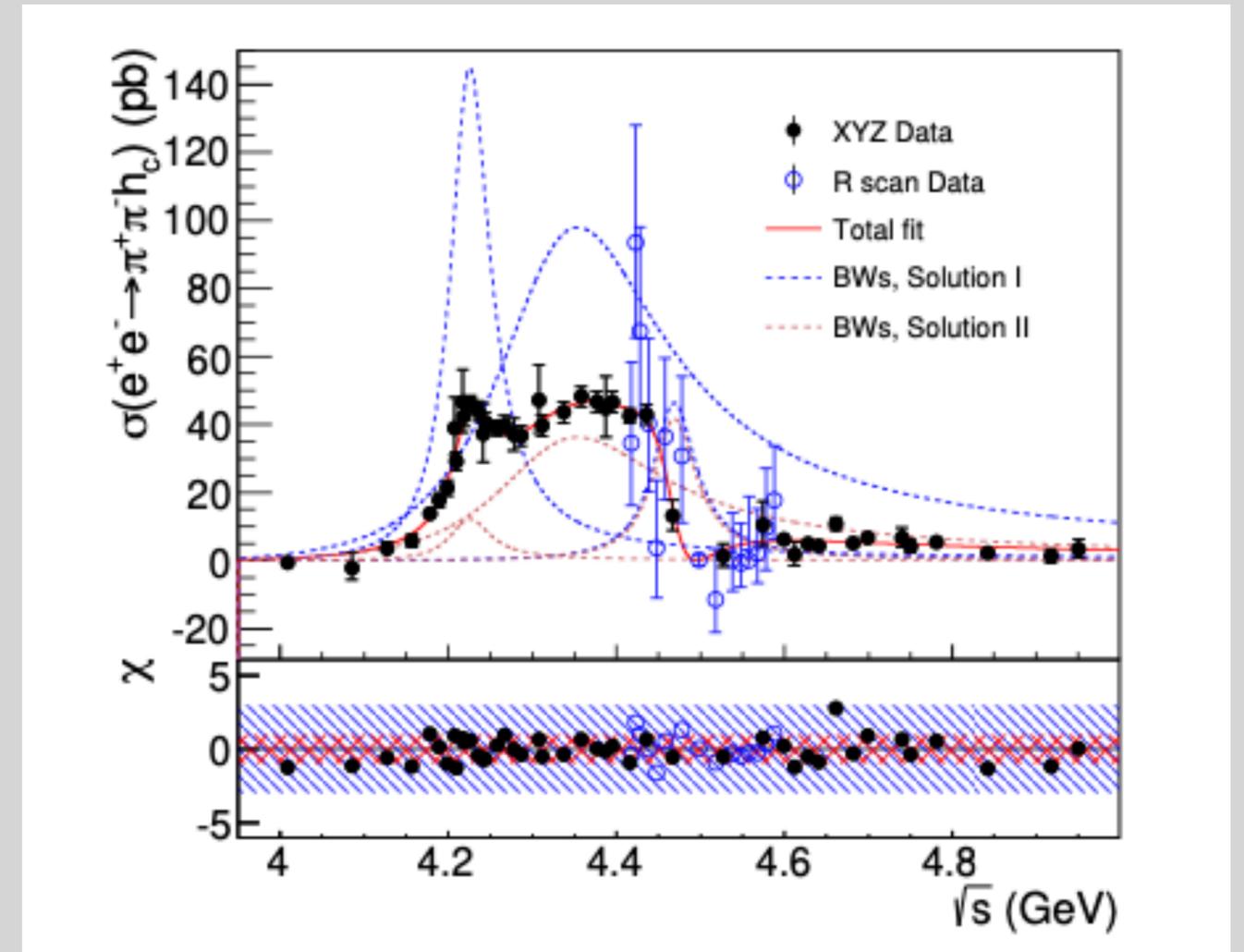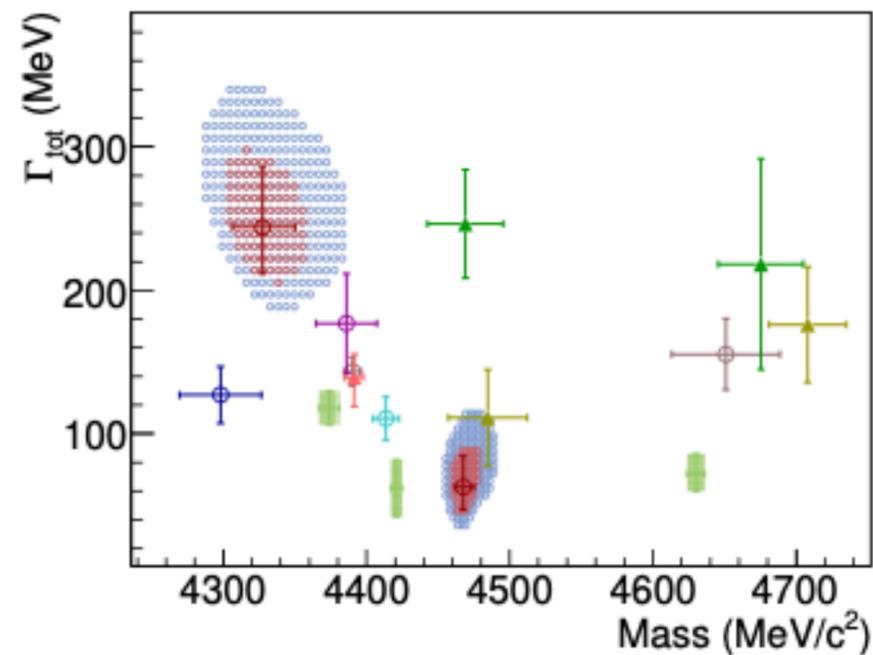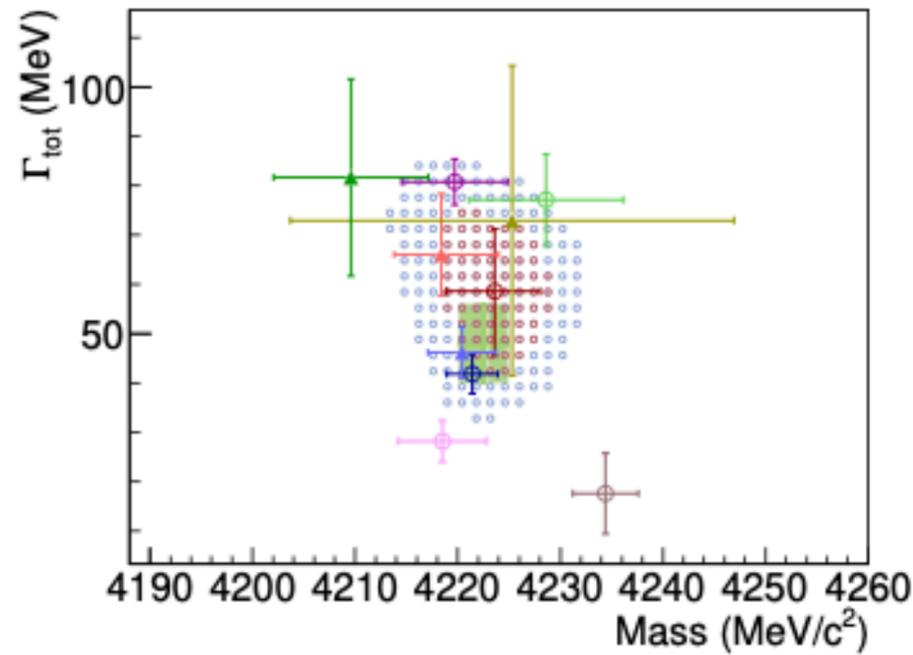- Strong coupling from (supposed) vector charmonium states to h_c would indicate exotic internal structure

BESIII arXiv:2504.04096v2
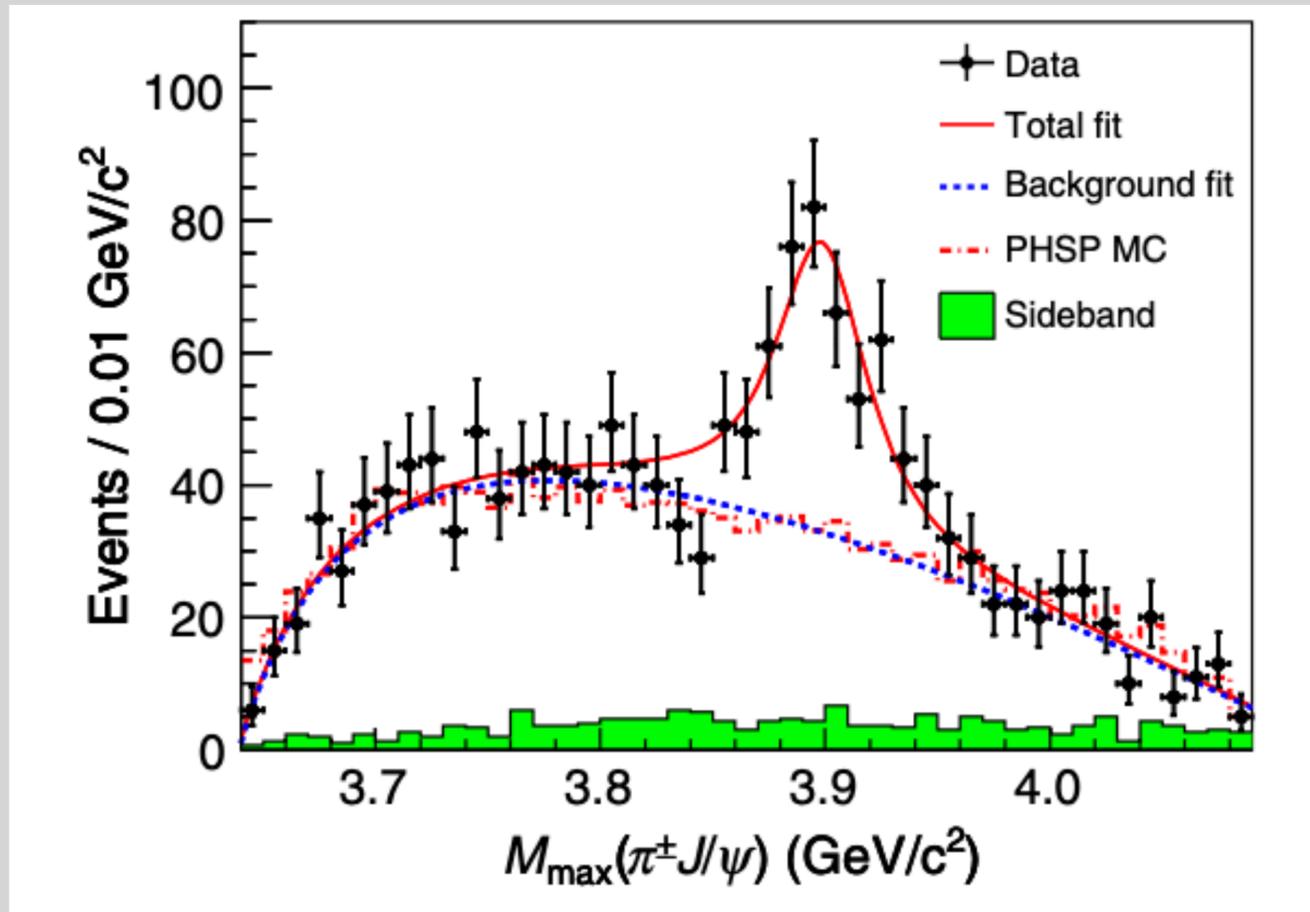
$e^+e^- \to \pi^+\pi^- h_c$: **Resonance Parameters**

Resonance	Parameter	this measurement (3BW)	this measurement (2BW)	previous measurement
R_1	M (MeV/c^2)	$4223.6^{+3.6+2.6}_{-3.7-2.9}$	4219.7 ± 3.4	$4218.4 \pm 4.0 \pm 0.9$
	Γ_{tot} (MeV)	$58.5^{+10.8+6.7}_{-11.4-6.5}$	83.8 ± 5.5	$66.0 \pm 9.0 \pm 0.4$
R_2	M (MeV/c^2)	$4327.4^{+20.1+10.7}_{-18.8-9.3}$	4382.6 ± 6.0	$4391.6 \pm 6.3 \pm 1.0$
	Γ_{tot} (MeV)	$244.1^{+34.0+23.9}_{-27.1-18.0}$	163.1 ± 10.4	$139.5 \pm 16.1 \pm 0.6$
R_3	M (MeV/c^2)	$4467.4^{+7.2+3.2}_{-5.4-2.7}$	$-$	4421 ± 4
	Γ_{tot} (MeV)	$62.8^{+19.2+9.8}_{-14.4-6.6}$	$-$	62 ± 20 (from PDG)
	χ^2/ndf	$41.9/70$	$78.5/66$	$-$

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

- $Z_c(3900)^{\pm}$ observed simultaneously by BESIII and Belle in $\pi^{\pm}J/\psi$

- If molecular/tetraquark state, strong correlation between $Y(4220)$ and $\pi Z_c(3900)$ system

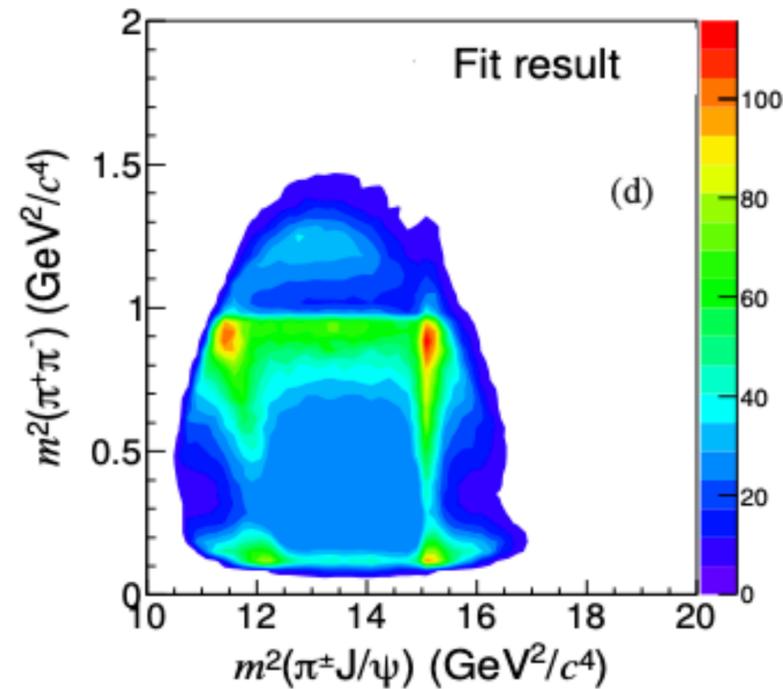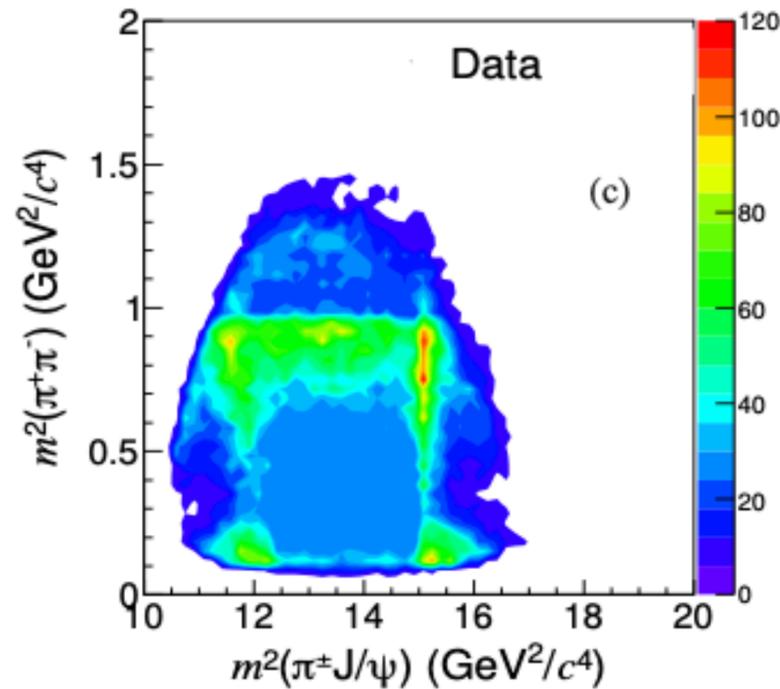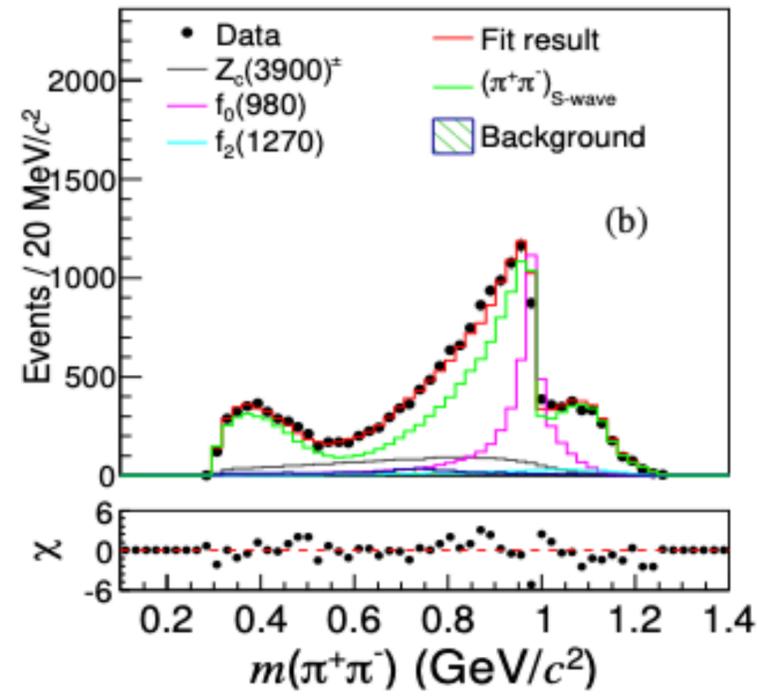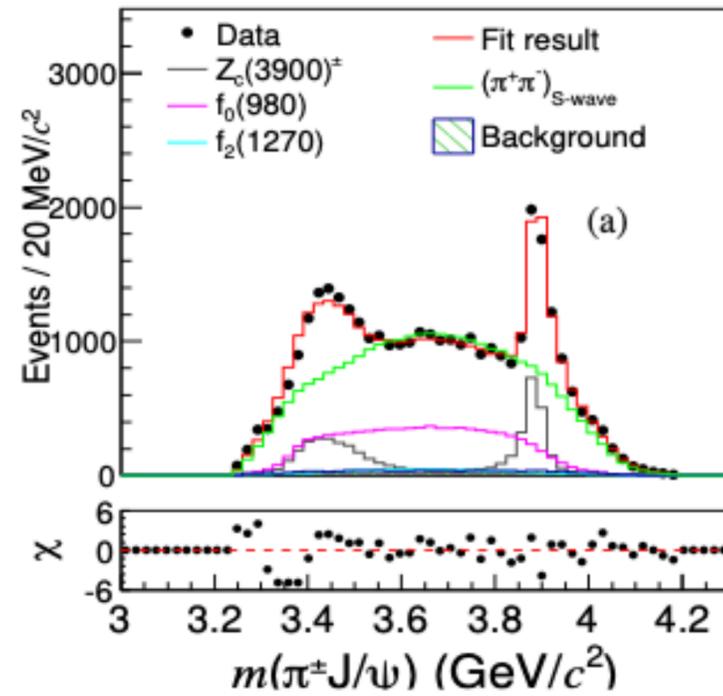- Promising to study relationship between $Z_c(3900)^{\pm}$ and Y states, as well as $\pi^+\pi^-$ resonances and Y states to understand internal structure of $Z_c(3900)$
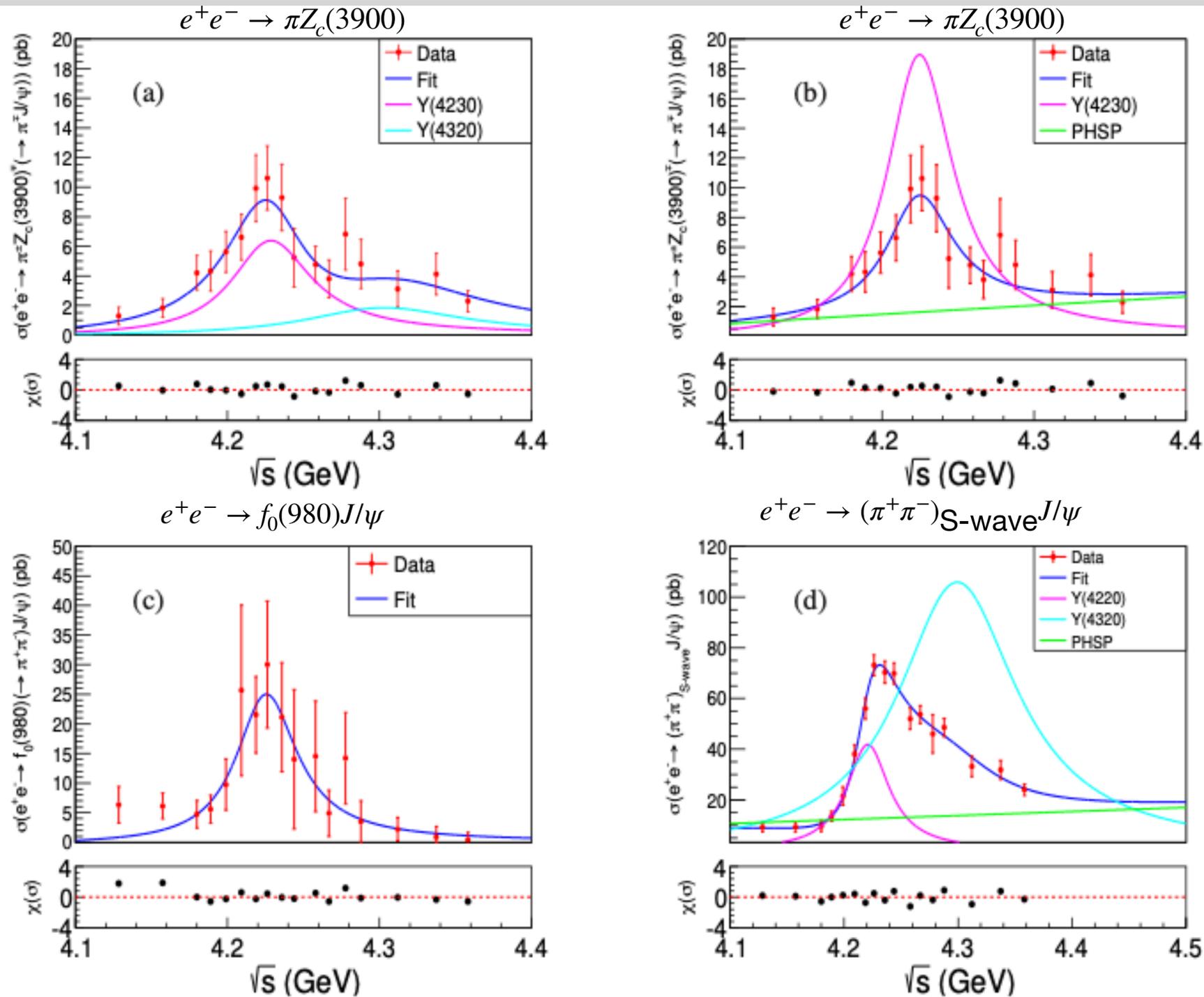
PWA of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$: Invariant Mass Distributions

- Fits to $\pi^{\pm} J/\psi$ and $\pi^+\pi^-$ for combined datasets between 4.127 - 4.358 GeV

- Mass and width results from Breit-Wigner $Z_c(3900)$ fit shown below

- Initial BES measurements:
  $M = 3899.0 \pm 3.6 \pm 4.9$,
  $\Gamma = 46 \pm 10 \pm 20$ MeV

- Current PDG average:
  $M = 3887.1 \pm 2.6$, $\Gamma = 28.4 \pm 2.6$ MeV

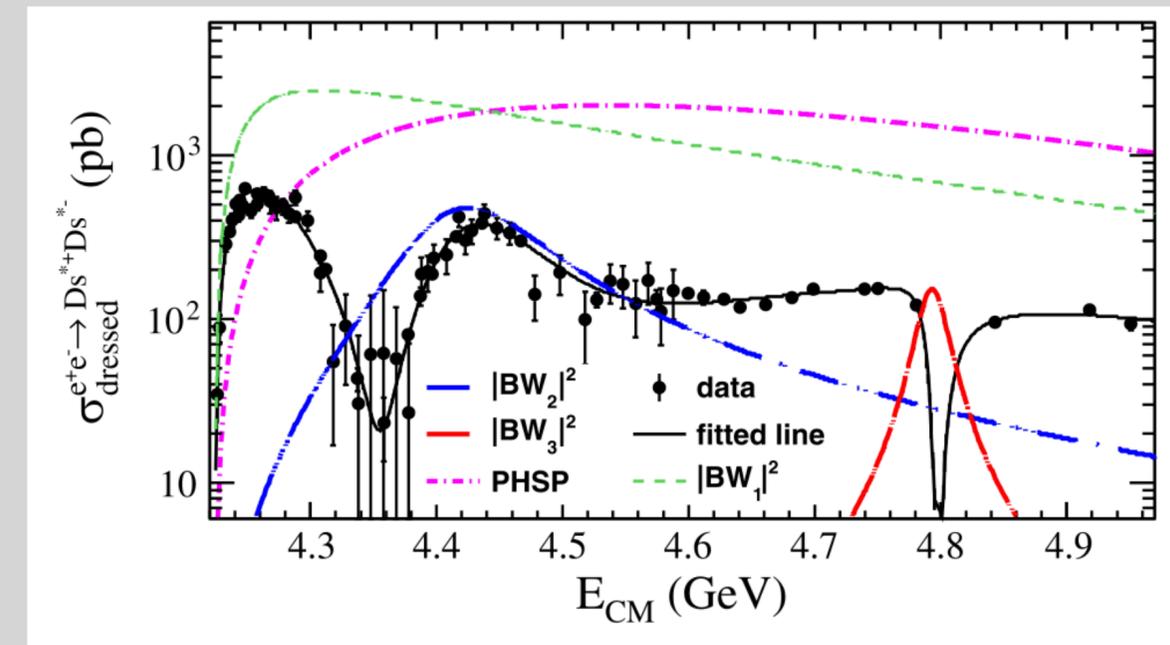| Sample	M (MeV/c^2)	Γ (MeV)
$4.1567 - 4.1989$	3883.5 ± 1.6	38.6 ± 3.6
$4.2091 - 4.2357$	3884.0 ± 1.0	37.8 ± 1.6
$4.2438 - 4.2776$	3884.9 ± 1.8	34.2 ± 3.3
$4.2866 - 4.3583$	3890.0 ± 2.3	36.1 ± 4.2
Average	$3884.6 \pm 0.7 \pm 3.3$	$37.2 \pm 1.3 \pm 6.6$

PWA of $e^+e^- \to \pi^+\pi^- J/\psi$: Cross Section Fits

- Cross sections of sub processes $e^+e^- \to \pi^\pm Z_c(3900)^\pm, f_0(980)J/\psi, (\pi^+\pi^-)_{\text{S-wave}}J/\psi$ measured for the first time

- Process $e^+e^- \to \pi^+\pi^- J/\psi$ seen to be dominated by $(\pi^+\pi^-)_{\text{S-wave}}J/\psi$ final state

- Observation of $Y(4220)$ in sub process cross sections

- $M = 4225.8 \pm 4.2 \pm 3.1$ MeV, $\Gamma = 55.3 \pm 9.5 \pm 11.1$ MeV

- Significance of $Y(4220)$ in $\sigma(e^+e^- \to (\pi^+\pi^-)_{\text{S-wave}}J/\psi)$ $\sim 12.2\sigma$

Resonance Observation in $e^+e^- \to \Omega^-\overline{\Omega}^+$

- Recent work at BESIII suggests strong coupling of Y states to final states containing strange quarks; also interesting to look at charmless decays of Y states

- Further: (believed) conventional charmonium state, $\psi(3770)$, has significantly larger non $D\overline{D}$ branching fraction than predicted

- Investigating $\Omega^-\overline{\Omega}^+$ near 3.773 GeV can help understand all of these things
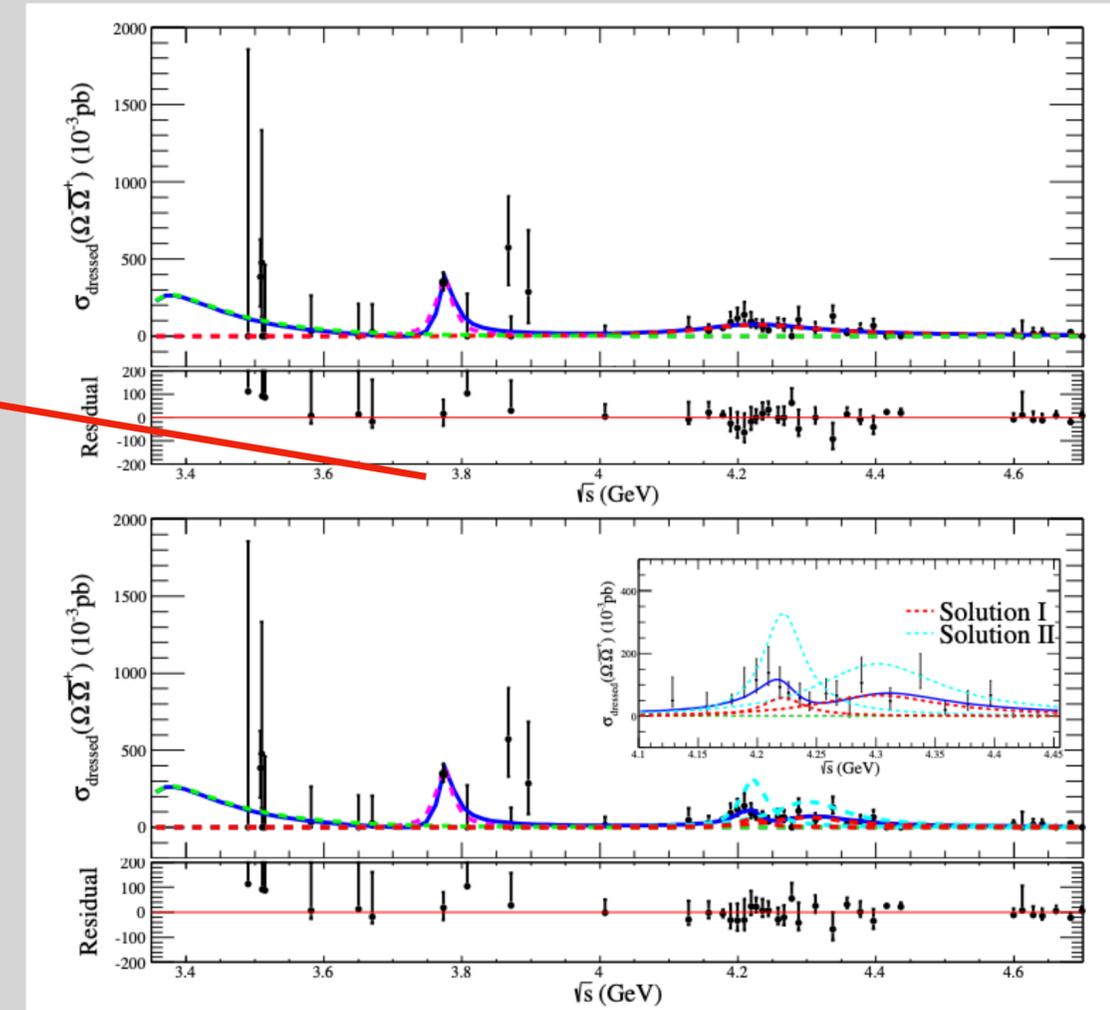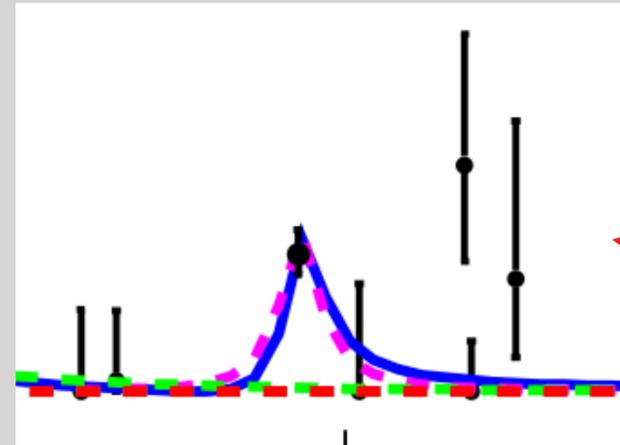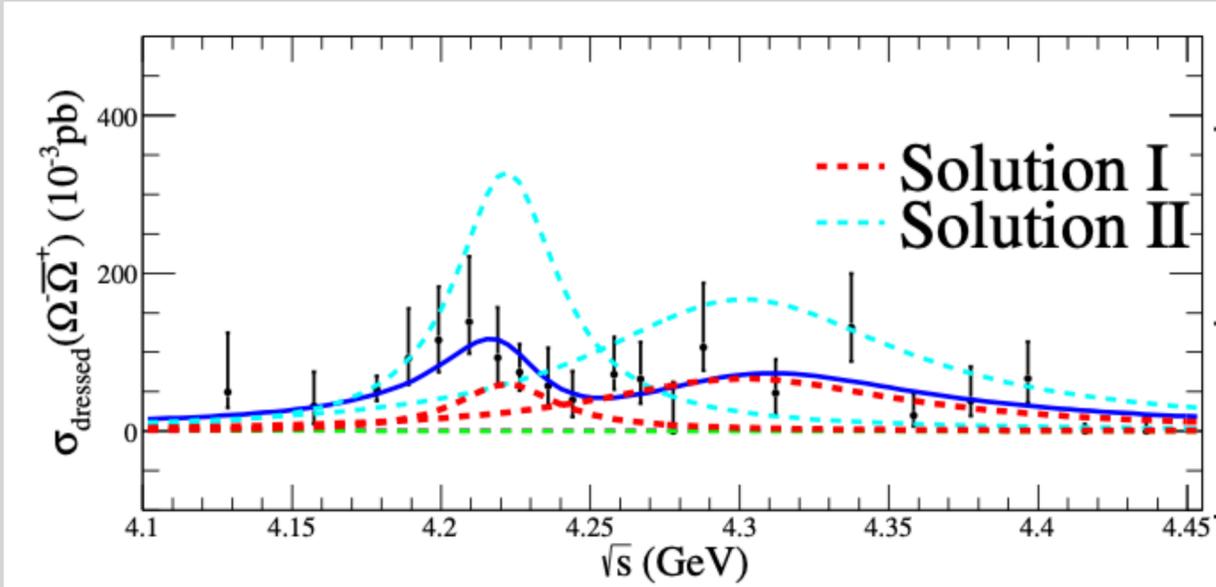
BESIII PHYSICAL REVIEW LETTERS 131, 151903 (2023)

BESIII PHYSICAL REVIEW LETTERS 133, 261902 (2024)

Resonance Observation in $e^+e^- \to \Omega^-\overline{\Omega}^+$: Cross Section

- $\sigma(e^+e^- \to \Omega^-\overline{\Omega}^+)$ fit for data taken between 3.7 and 4.7 GeV

- Line shape: combination of three Breit-Wigners ($\psi(3770), Y(4230), Y(4320)$) with an energy power function
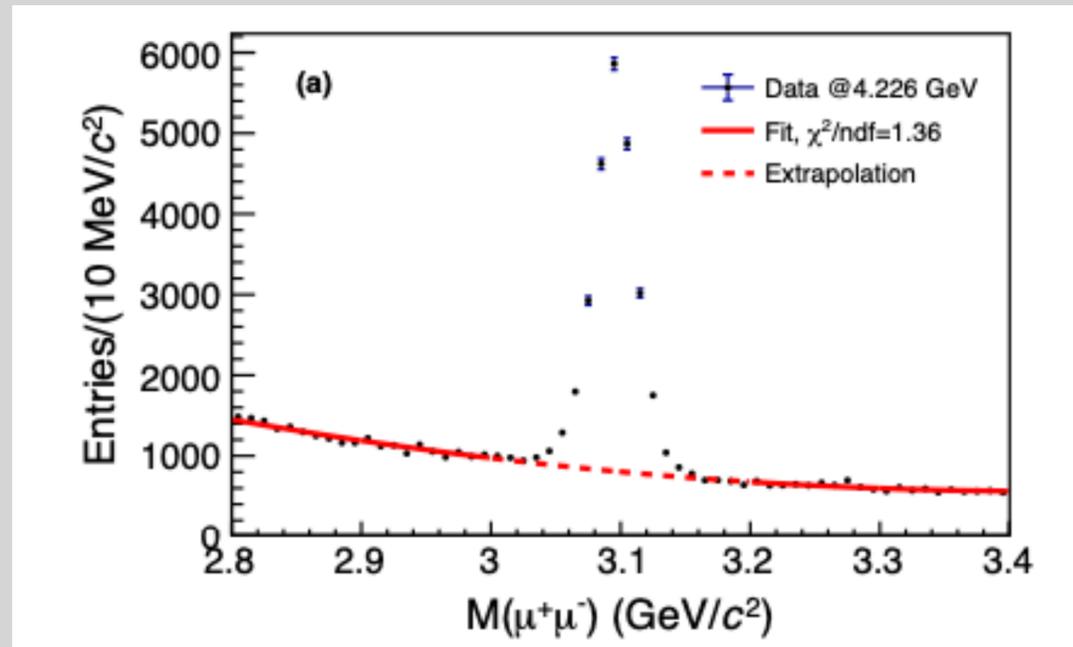
- Y states exhibit significance $> 10\sigma$

Parameters	SolutionI	SolutionII
M_1 (MeV/c^2)	3773.7 (fixed)	
Γ_1 (MeV)	27.2 (fixed)	
M_2 (MeV/c^2)	4221.4 (fixed)	
Γ_2 (MeV)	41.8 (fixed)	
M_3 (MeV/c^2)	4298.0 (fixed)	
Γ_3 (MeV)	127.0 (fixed)	
$\Gamma_{ee}\mathcal{B}(\psi(3770))$ (10^{-3}eV)	10.5±2.5±1.4	
$\Gamma_{ee}\mathcal{B}(Y(4230))$ (10^{-3}eV)	3.0±1.2±0.8	16.6±2.4±9.2
$\Gamma_{ee}\mathcal{B}(Y(4320))$ (10^{-3}eV)	10.6±2.8±5.4	26.6±3.8±14.9
ϕ_1 (rad)	-0.3±0.7±0.1	
ϕ_2 (rad)	-0.3±0.3±0.8	-2.2±0.1±0.3

- Large dataset at 3.773 GeV allows measurement of branching fraction
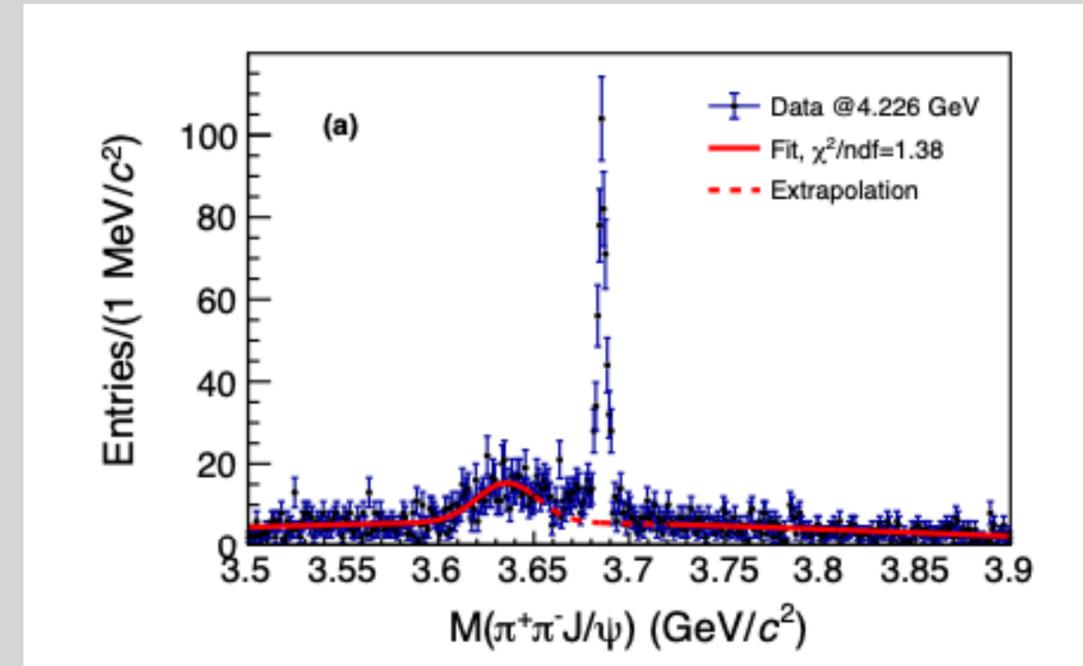$\mathcal{B}(\psi(3770) \to \Omega^-\overline{\Omega}^+) = (4.0 \pm 1.0 \pm 0.6) \times 10^{-5}$

BESIII arXiv:2505.03180v1

Inclusive Production Cross Sections of J/ψ and $\psi(2S)$

- Double charmonium production cross sections from B factories larger than expected $\rightarrow$ hidden states/processes?

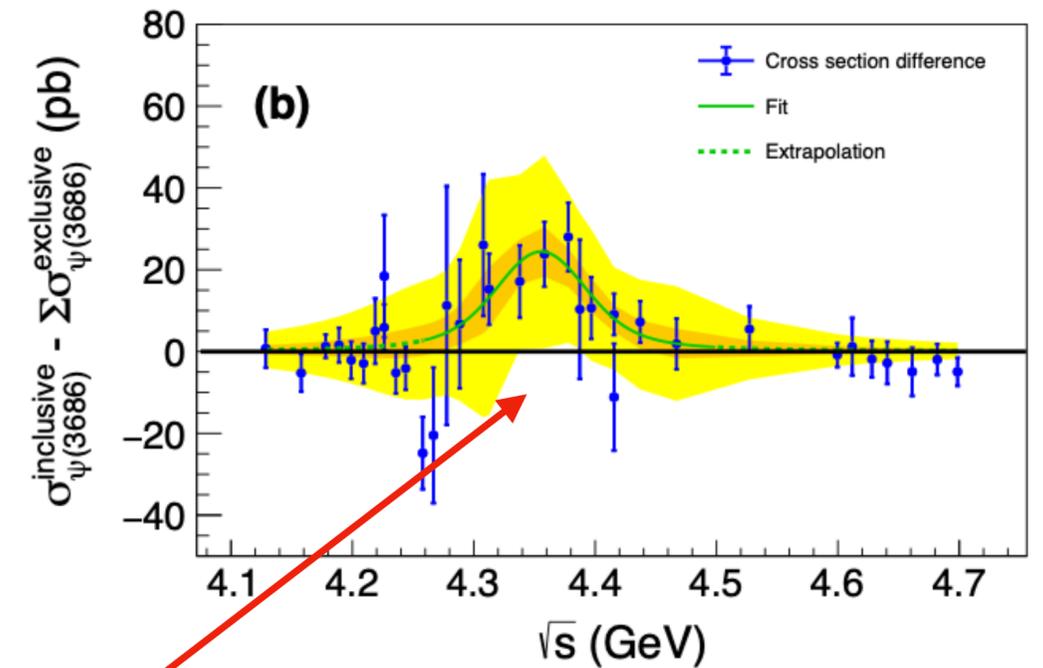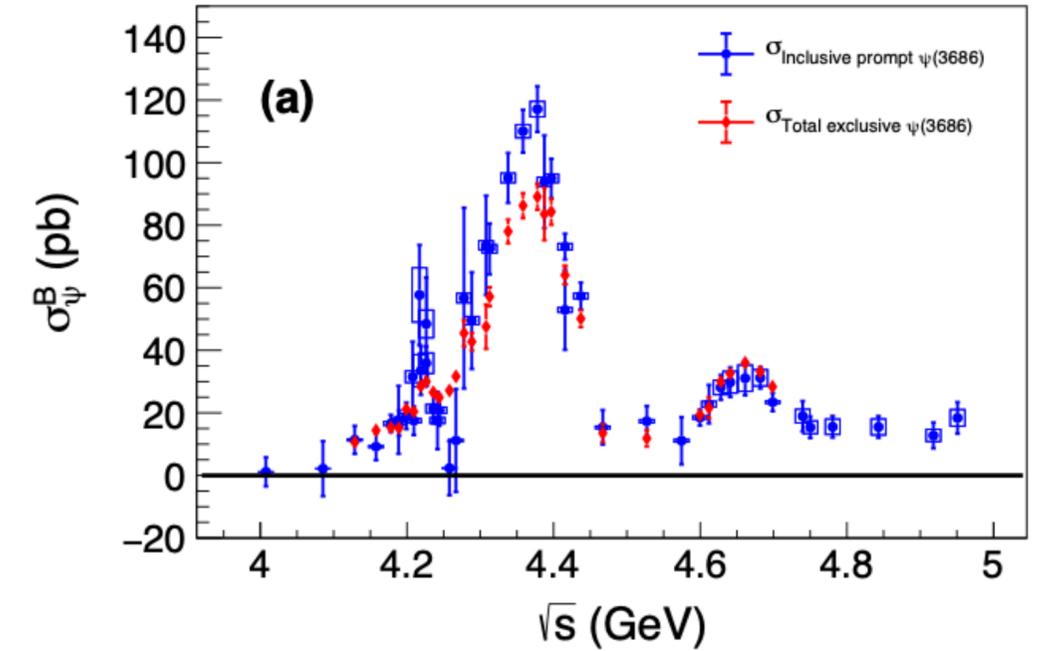- Can investigate by studying prompt $J/\psi X$ and $\psi(2S)X$ production below $\psi c\bar{c}$ threshold at BESIII

- Reconstruct $J/\psi \rightarrow \mu^+\mu^-$

- Subtract ISR production / conventional charmonium decays (e.g. $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$)

- Reconstruct $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$ with $J/\psi \rightarrow l^+l^-$ ($l = e, \mu$)

- ISR production also subtracted

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Inclusive Production Cross Sections of J/ψ and $\psi(2S)$

- Unknown decays of $\psi(4360) \rightarrow \psi(2S)X$ $\sim 23\%$ of discrepancy here

$e^+e^- \rightarrow K^+K^-\psi(2S)$ Cross Section Measurement

- $Y(4710)$ state observed at BESIII in $\sigma(e^+e^- \rightarrow K^+K^-J/\psi)$

- One of the heaviest charmonium-like states observed to date

- Natural extension to study $e^+e^- \rightarrow K^+K^-\psi(2S)$

- Derivation $\sim 2\sigma$ from phase space ratio around 4.843 GeV

BESIII arXiv: 2407.20009

BESIII PHYSICAL REVIEW LETTERS 131, 211902 (2023)

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$e^+e^- \to K^+K^-\psi(2S)$: **Search for** $Z_{cs}^\pm \to K^\pm\psi(2S)$

- Hidden charm, hidden strange tetraquark candidate $Z_{cs}(3985)$ observed in BESIII in K^+ recoil mass from $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-}D^0)$

- LHCb then observed $Z_{cs}(4000) \to J/\psi K$ in $B^+ \to J/\psi\phi K^+$
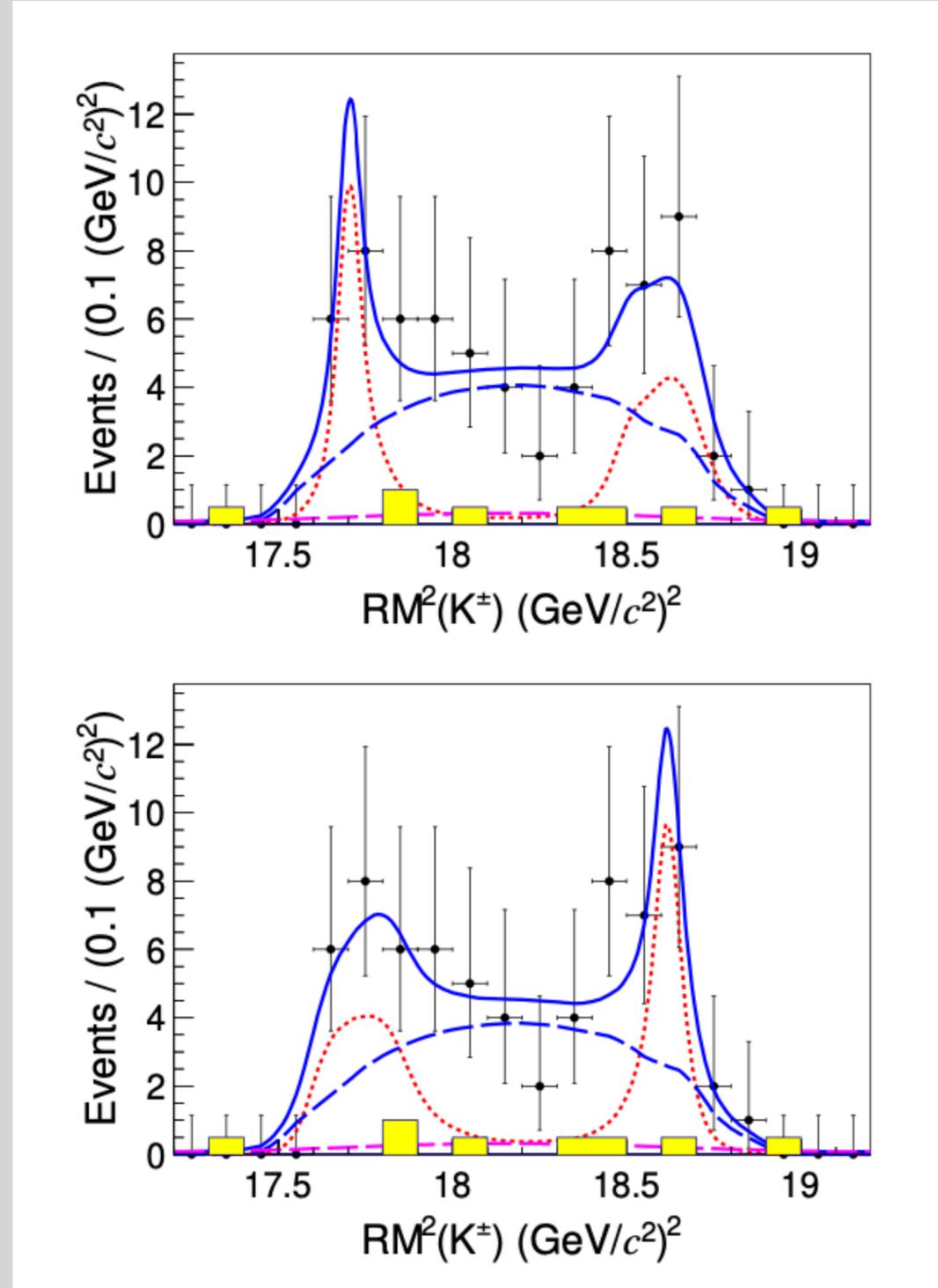
- Two states have similar masses but very different widths (~ 7.7 and ~ 131 MeV respectively)

- Natural for BESIII to search for $Z_{cs} \to K^\pm J/\psi$ and $Z_{cs} \to K^\pm\psi(2S)$

- 2 fits performed with Z_{cs} mass ~ 4.205 and ~ 4.315 GeV

- Global significances of 1.2σ and 1.1σ

BESIII arXiv: 2407.20009

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Summary / Future Outlook

- Many ongoing efforts at BESIII into identifying and describing charmonium-like states

- Updated results on $\sigma(e^+e^- \to \pi^+\pi^- h_c)$:

  - Better fit including third resonance to describe shape between 4.3 — 4.5 GeV

- New Partial Wave Analysis of $e^+e^- \to \pi^+\pi^- J/\psi$:

  - Additional measurement of $Z_c(3900)$ parameters; cross section measurement of subprocess $e^+e^- \to \pi^\pm Z_c(3900)^\pm$ and $e^+e^- \to f_0(980)J/\psi$; $Y(4220)$ observation in $e^+e^- \to (\pi^+\pi^-)_{\text{S-wave}}J/\psi$

- $> 10\sigma$ observations of $Y(4230)$ and $Y(4320)$ in $e^+e^- \to \Omega^-\overline{\Omega}^+$

- Measurements of inclusive J/ψ and $\psi(2S)$ production cross sections to test strong interaction theory

- First measurements of $\sigma(e^+e^- \to K^+K^-\psi(2S))$; higher statistics necessary to search for charged Z_{cs}

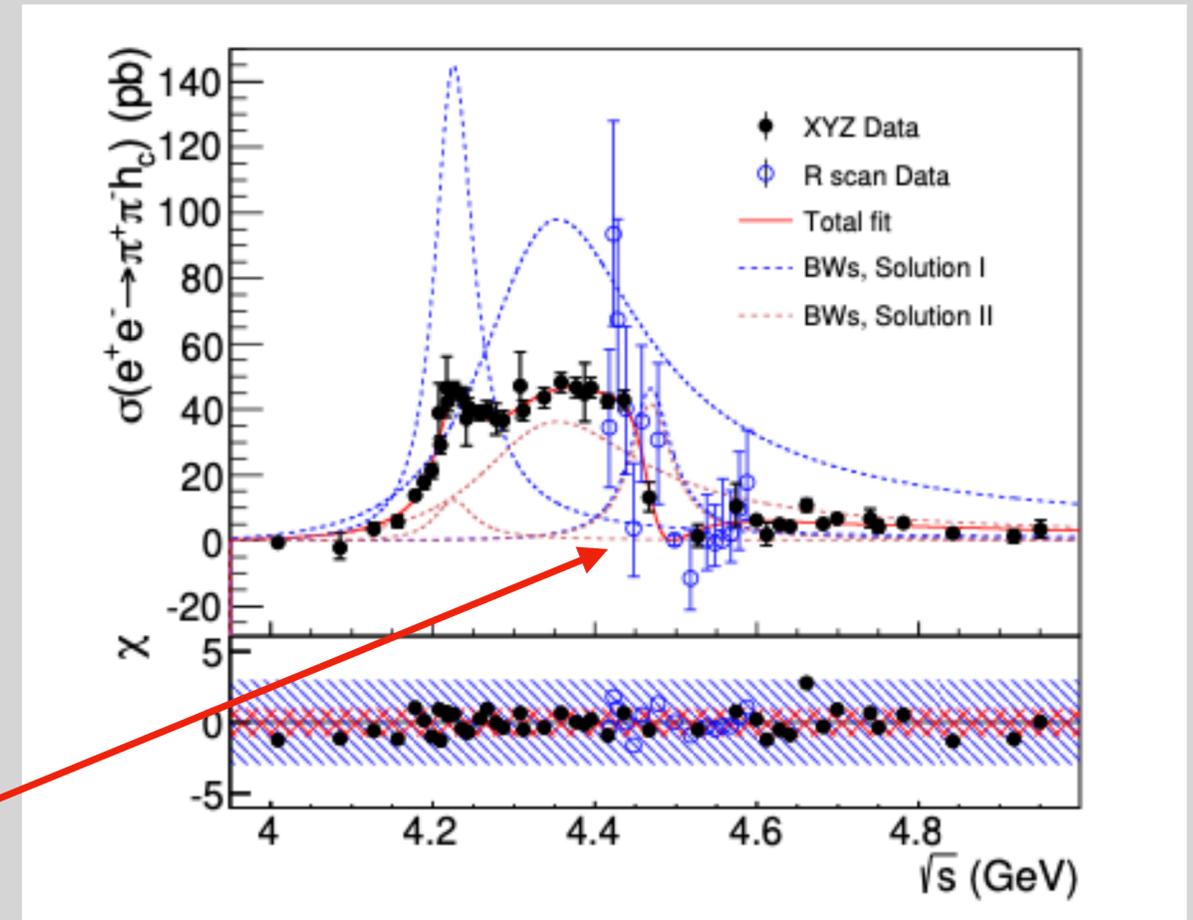- **Future Plans:** New CGEM detector installed, increasing maximum E_{CM}, more XYZ data
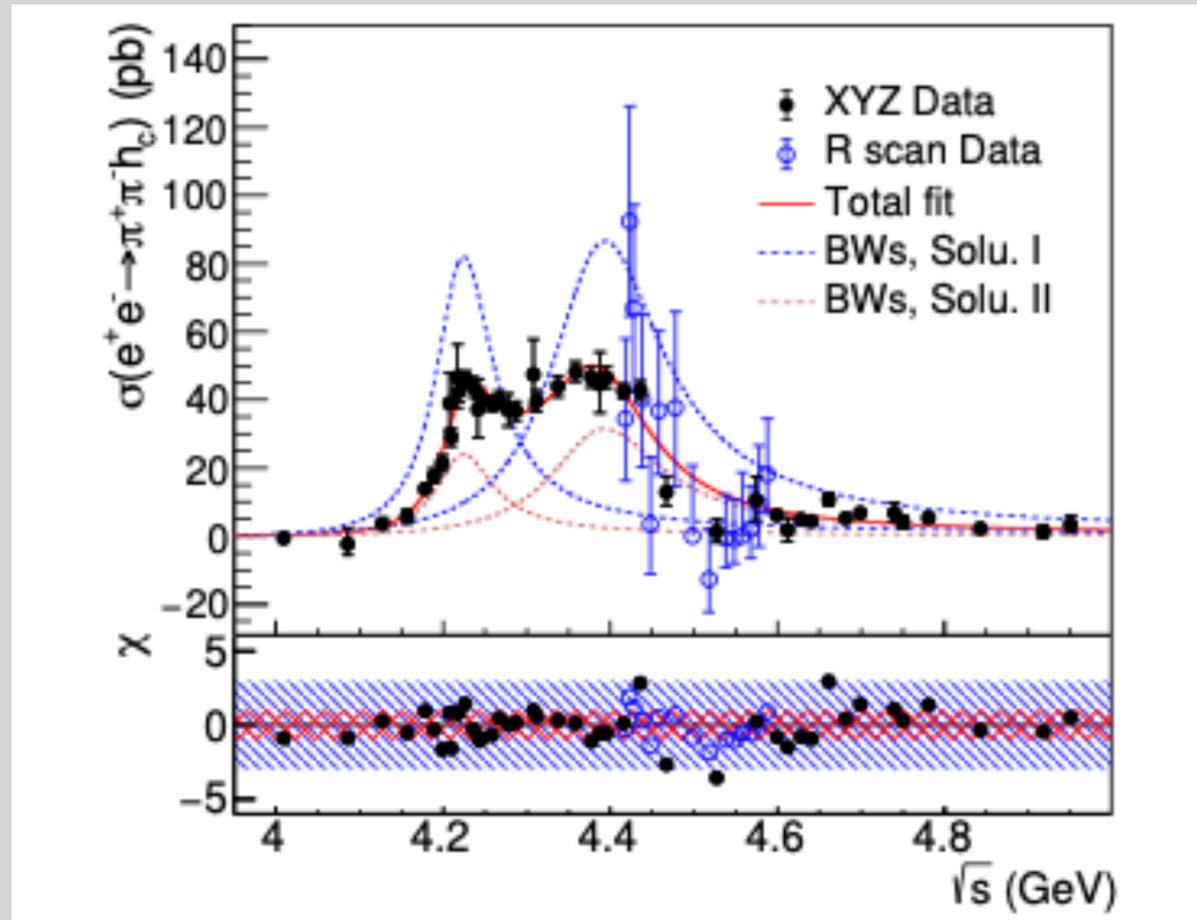
BACKUP

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$e^+e^- \to \pi^+\pi^- h_c$: **Cross Section Fits**

- Cross Section fit as coherent sum of 2 Breit-Wigners

- Better fit including third BW resonance

- Significance $\sim 5.4\sigma$

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Resonance Observation in $e^+e^- \to \Omega^-\overline{\Omega}^+$: EFF and Branching Fraction Measurement

- Evidence of decay $\psi(3770) \to \Omega^-\overline{\Omega}^+$ with significance 4.4σ from cross section measurement

- Branching fraction determined to be:
$\mathscr{B}(\psi(3770) \to \Omega^-\overline{\Omega}^+) = (4.0 \pm 1.0 \pm 0.6) \times 10^{-5}$

- Larger by at least an order of magnitude than prediction

- Suggests non-negligible $\psi(3770)$ resonance contribution in the cross section $e^+e^- \to \Omega^-\overline{\Omega}^+$

- Results provide strong evidence for the first observed baryonic decay mode of the charmonium-like Y states

- Ω^- energy-dependent effective form factor can be calculated from Born cross section results

- Results compared with earlier work from CLEO-c (blue), and theoretical prediction; consistent with theoretical prediction with discrepancy $< 1\sigma$

$$|G_{\text{eff}}(s)| = \sqrt{\frac{3s\sigma^{\text{B}}}{4\pi\alpha^2\mathcal{C}\beta(1 + \frac{2m_\Omega^2}{s})}},$$

BESIII arXiv:2505.03180v1