Recent progress of vector Charmonium-like States at BESIII

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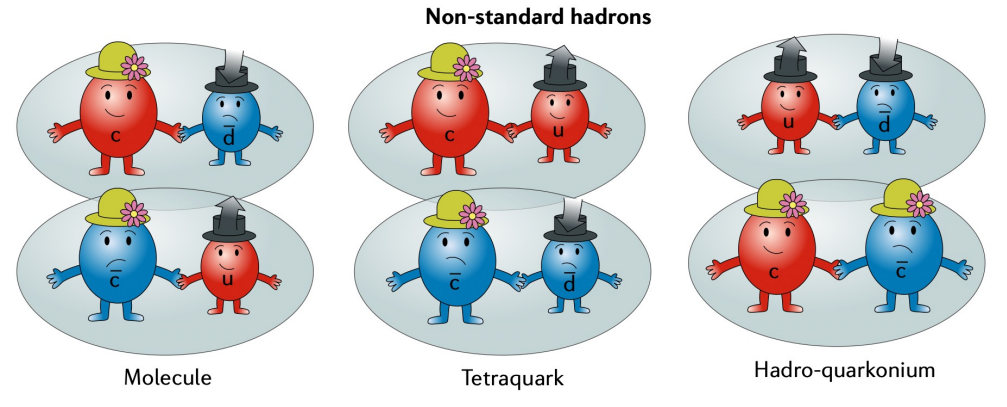
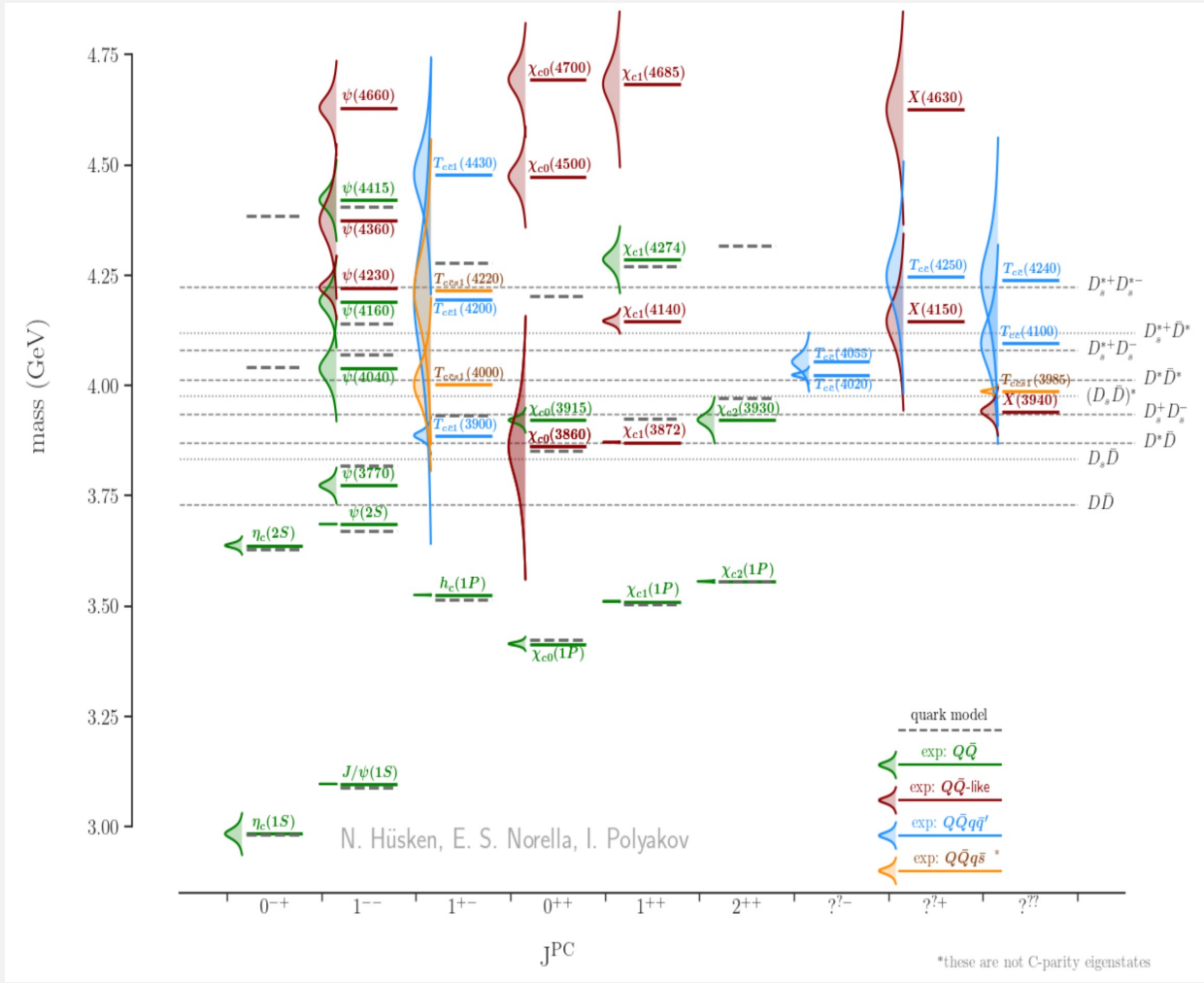
Introduction

- Since the discovery of J/ψ, the charmonium energy region has been an active area of research
- Exotic hadrons (XYZ states) challenge traditional quark models and deepen our understanding of nonperturbative QCD



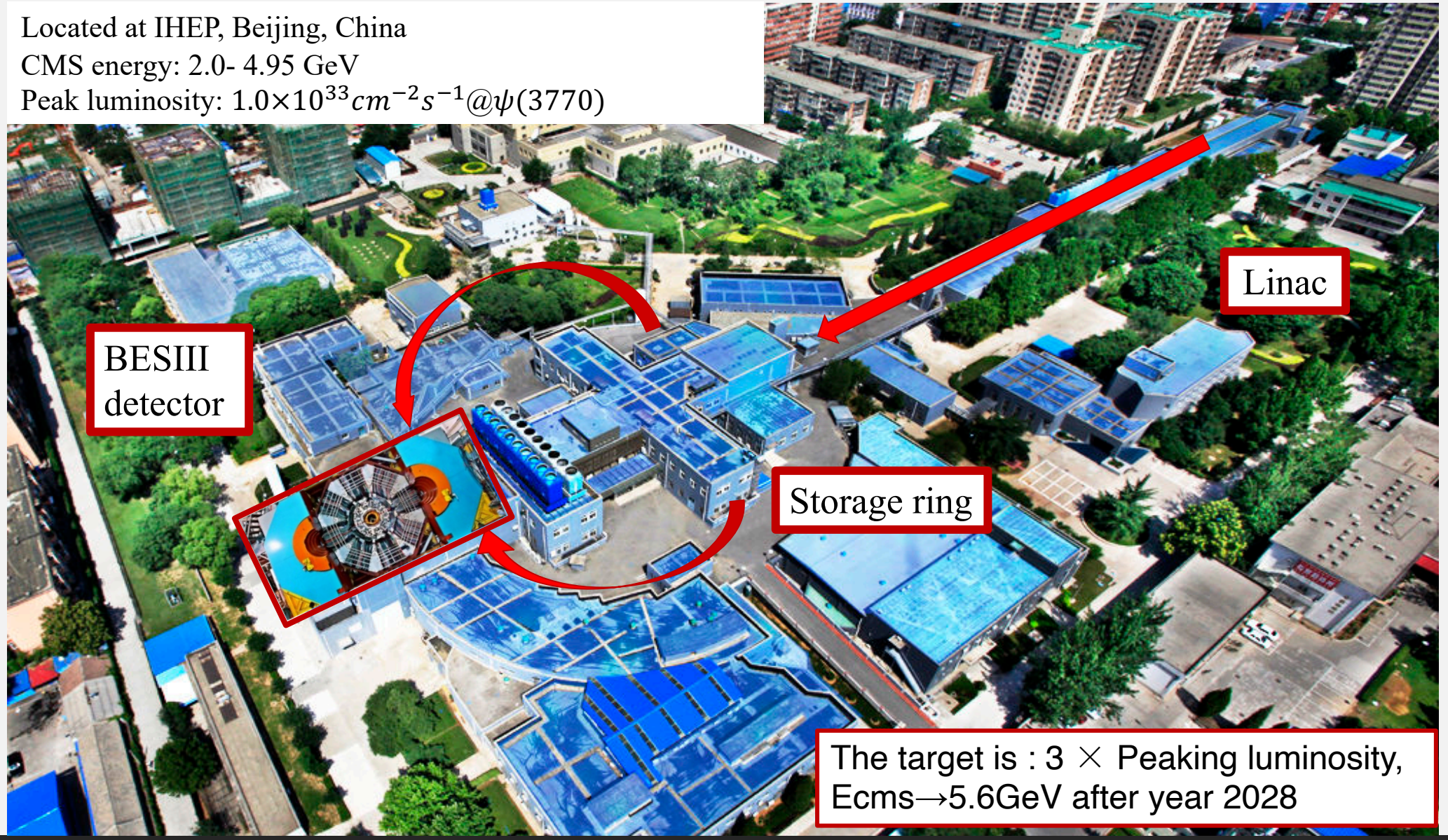
Nature Rev. Phys. 1, 480–494 (2019).

Mod. Phys. Lett. A 40 (2025) 17n18, 2530002



BEPCII and BESIII

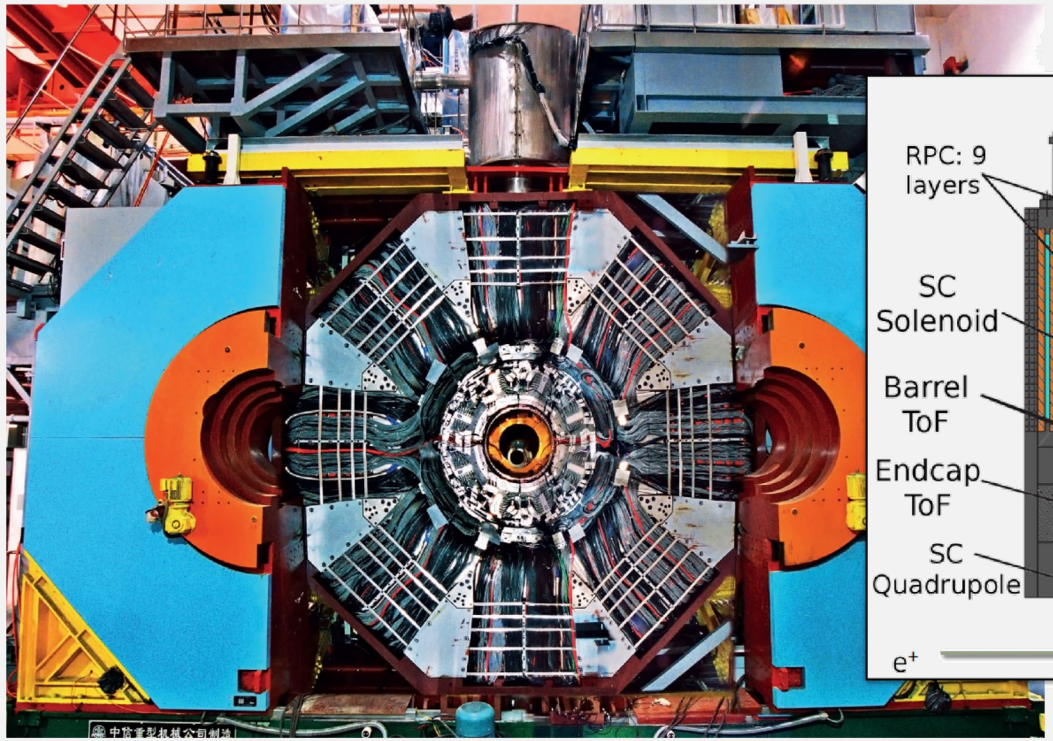
Located at IHEP, Beijing, China
CMS energy: 2.0- 4.95 GeV
Peak luminosity: $1.0\times10^{33}cm^{-2}s^{-1}@\psi(3770)$

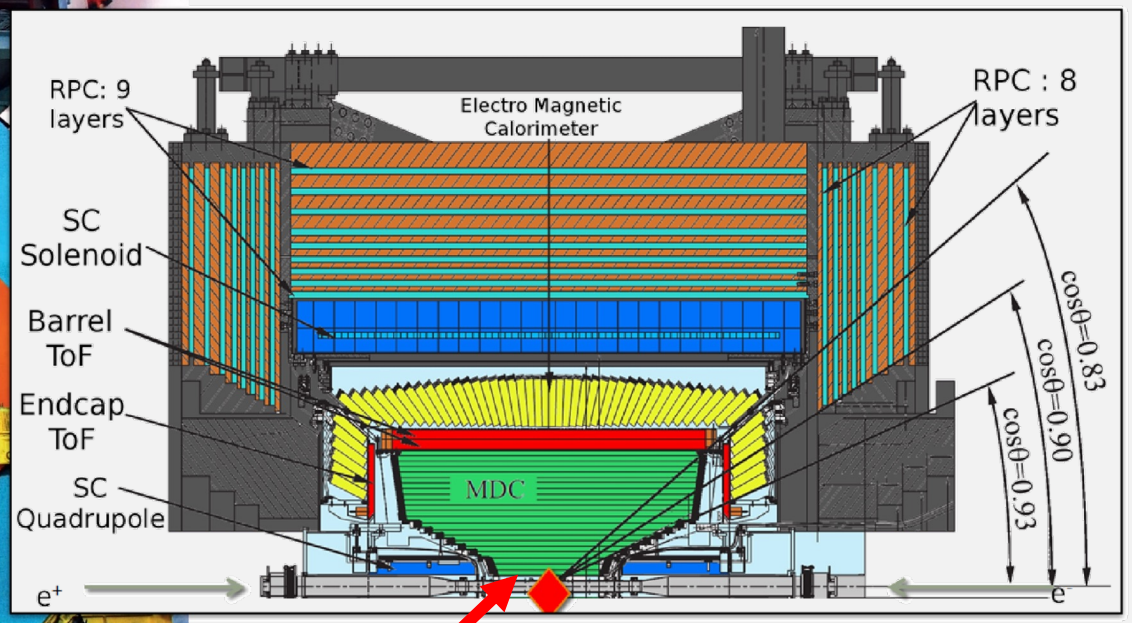


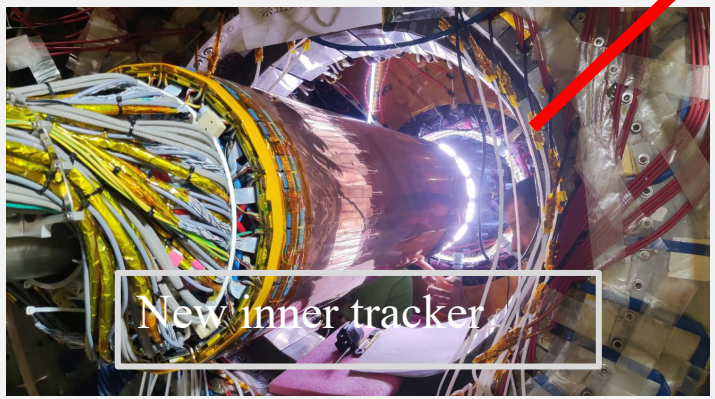
BEPCII

BEPCII-U

BEPCII and BESIII







The inner MDC has been replaced with a 3 layers of Cylindrical Gas Electron Multiplier (CGEM) at Oct. 2024

MUC $\sigma_{R\Phi}$: 2 cm

TOF

σ_T :80 ps
110 ps (60 ps)

MDC

dE/dx: 6%

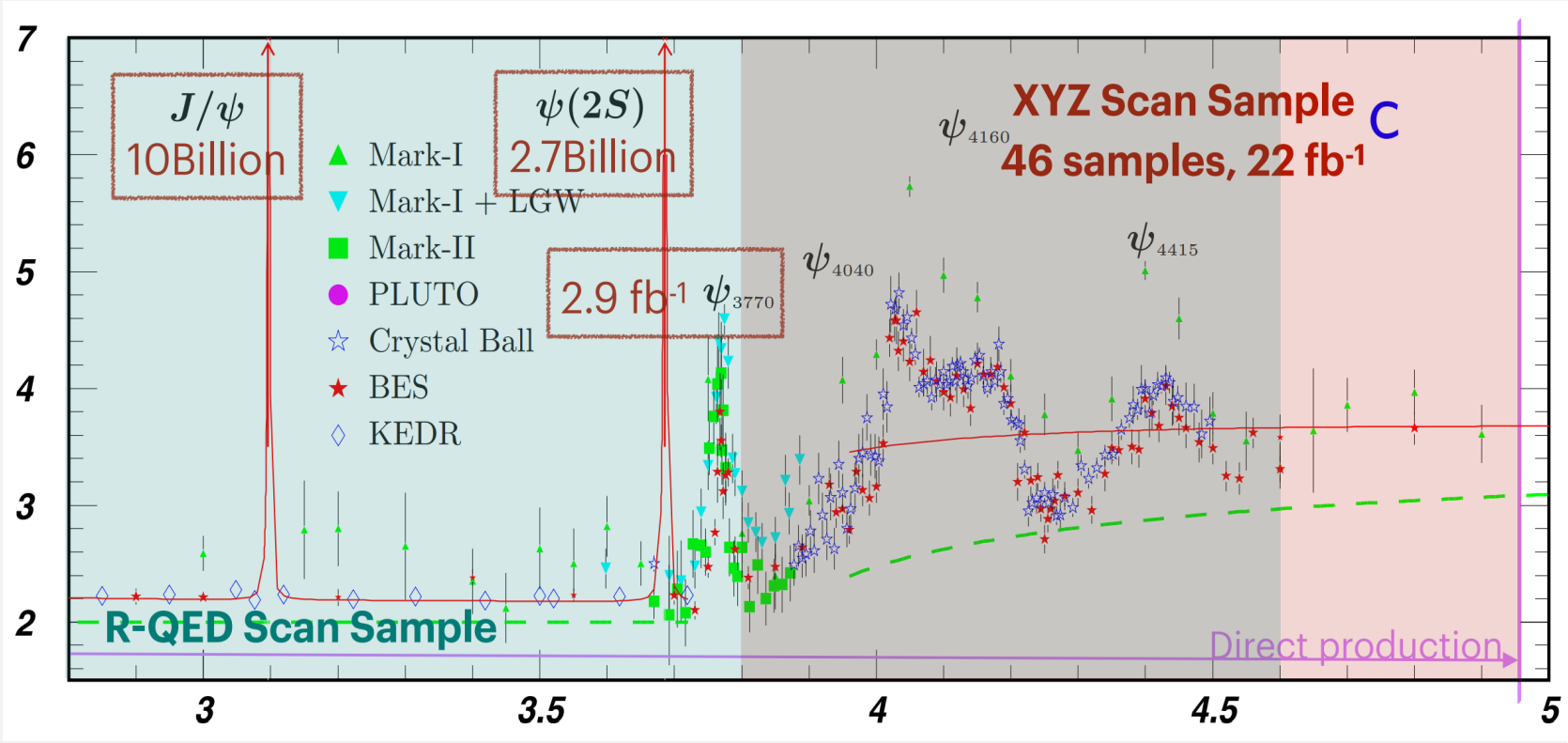
σ_p/p: 0.5% at 1GeV/c

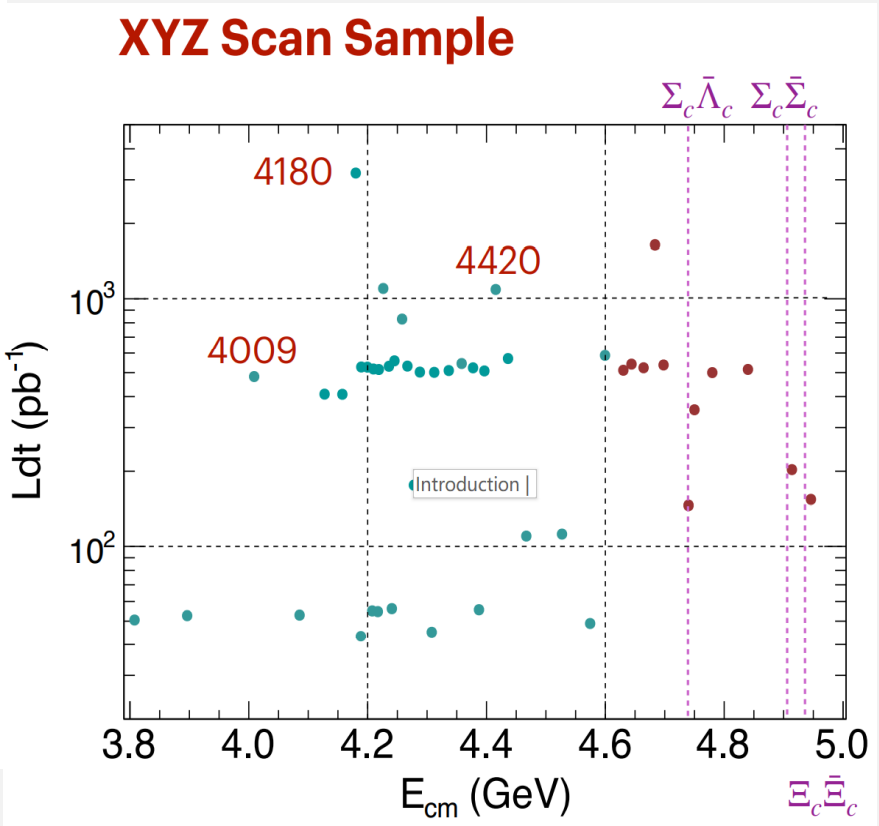
EMC

ΔE/E: at 1GeV
2.5%
5.0%

σ_Z: 0.6 cm/√E

BESIII data samples



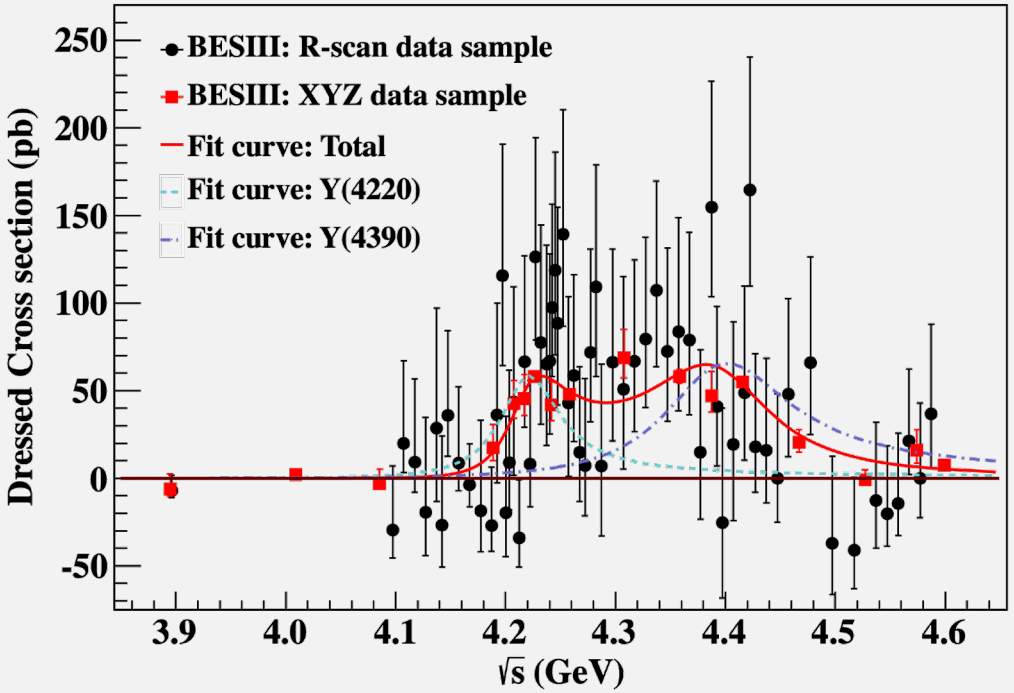


Rich datasets in the XYZ region luminosity of around 22fb^{-1}

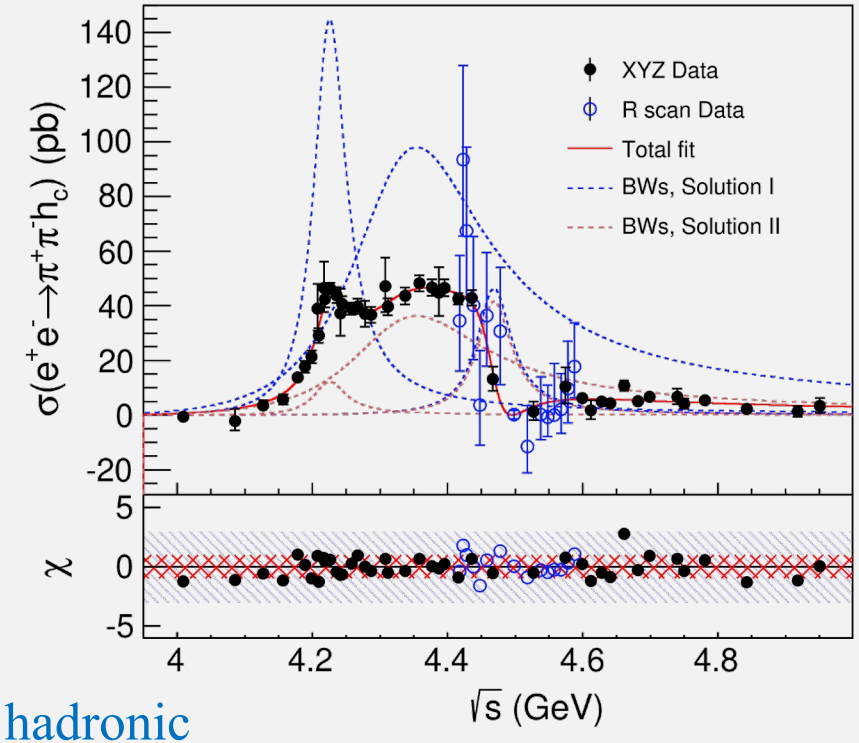
- spectroscopy of charmonium(-like) states
- open-charm decays
- charmed baryons
- …

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

BESIII: PhysRevLett.118.092002(2017)



BESIII: PhysRevLett.135.071901(2025)



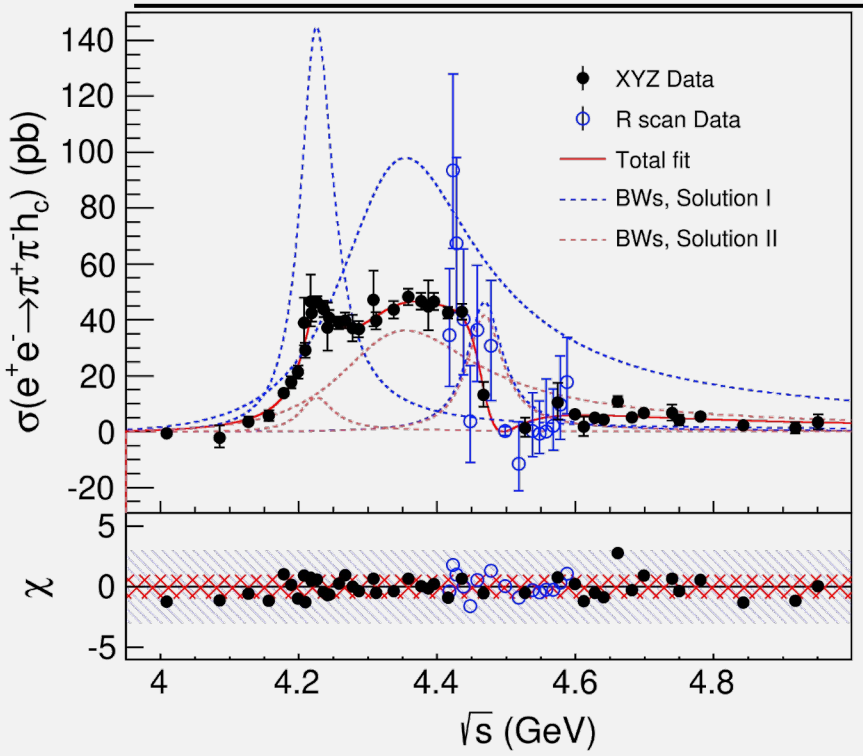
$h_c \to \gamma\eta_c$, 16 exclusive hadronic channel to reconstruct η_c

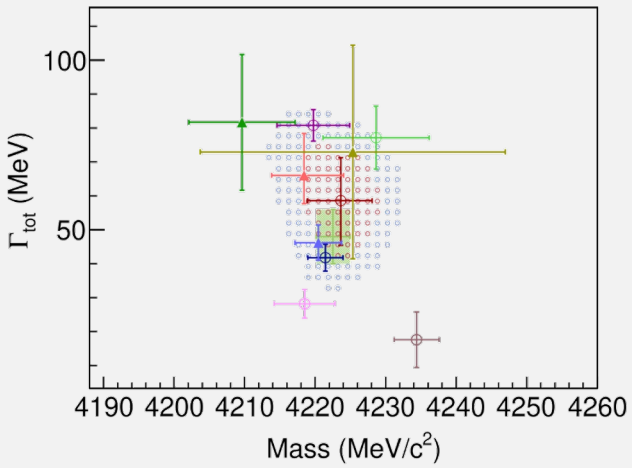
- 17 XYZ data points+62 R-scan points
- Fitted with coherent sum of two Breit-Wigner

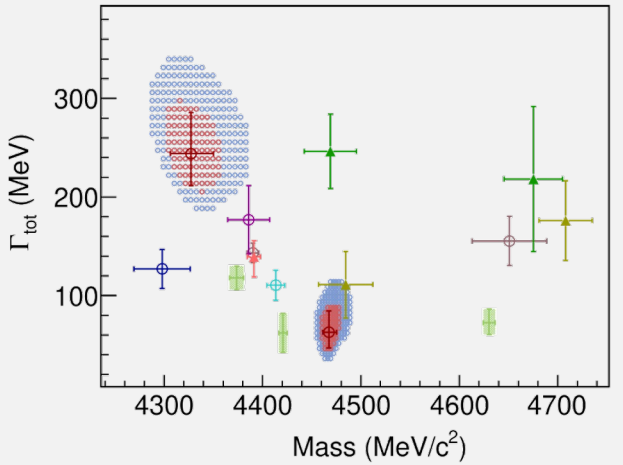
- 44 XYZ data points+15 R-scan points
- Fitted with coherent sum of three Breit-Wigner

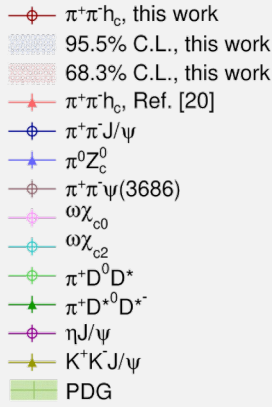
Measurement of $e^+e^- \to \pi^+\pi^- h_c(1P)$

BESIII: PhysRevLett.135.071901(2025)









Overpopulated states need careful classification

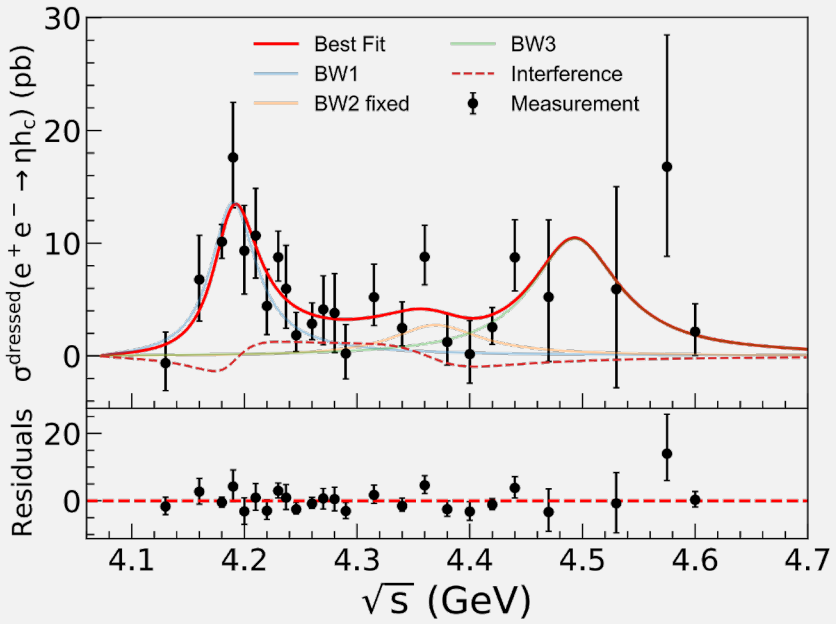
- Different fit strategies are tested
- Three Breit-Wigner model provides best fit quality
  - ✓ Parameters of Y(4230) are consistent with each other
  - ✓ Mass of R_2 is consistent with Y(4360), but width is about 100 MeV larger
  - ✓ R_3 is consistent with Y(4500) observed in $e^+e^- \to K^+K^-J/\psi$

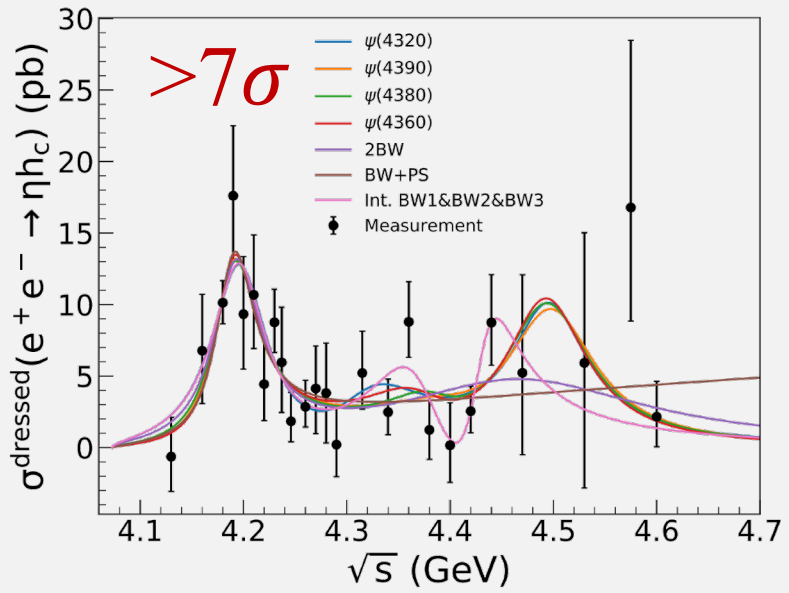
	Y(4230)	Y(4360)	5.4σ Y(4500)
Parameter	R_1	R_2	R_3
M (MeV/c^2)	$4223.6^{+3.6+2.6}_{-3.7-2.9}$	$4327.4^{+20.1+10.7}_{-18.8-9.3}$	$4467.4^{+7.2+3.2}_{-5.4-2.7}$
Γ (MeV)	$58.5^{+10.8+6.7}_{-11.4-6.5}$	$244.1^{+34.0+24.2}_{-27.1-18.3}$	$62.8^{+19.2+9.9}_{-14.4-7.0}$
$\Gamma_{ee} \cdot \mathcal{B}(R \to \pi^+\pi^- h_c)$ (eV)	$10.2^{+1.2+1.4}_{-1.5-1.4}$ $(0.9^{+0.4+0.3}_{-0.4-0.2})$	$29.1^{+5.7+4.4}_{-3.9-3.4}$ $(10.8^{+2.5+1.9}_{-1.8-1.5})$	$3.9^{+3.5+1.7}_{-1.7-0.5}$ $(3.5^{+3.0+1.5}_{-1.6-0.7})$
ϕ (rad)	···	$3.6^{+0.1+0.1}_{-0.1-0.1}$ $(0.7^{+0.3+0.2}_{-0.3-0.2})$	$0.7^{+0.3+0.1}_{-0.3-0.2}$ $(-2.2^{+0.3+0.2}_{-0.3-0.1})$

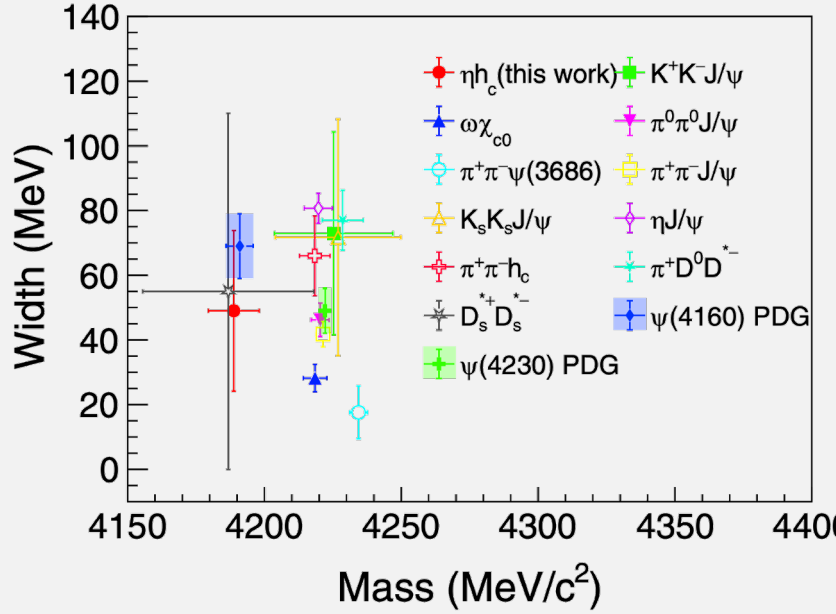
$$|BW_1(\sqrt{s}) + e^{i\phi_2} BW_2(\sqrt{s}) + e^{i\phi_3} BW_3(\sqrt{s})|^2$$

Measurement of $e^+e^- \to \eta h_c$

BESIII: PhysRevD.111.L011101(2025)







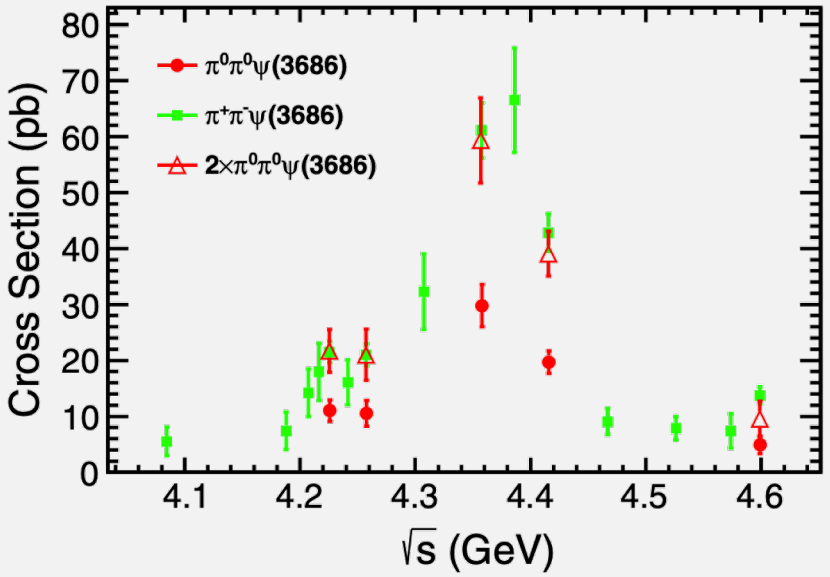
$$\sigma^{\rm dressed}(s) = \left|{\rm BW}_1(s) + {\rm BW}_2(s)e^{i\phi}\right|^2 + \left|{\rm BW}_3(s)\right|^2$$

- The interference between BW1, BW2 and BW3 is neglected due to limited sample size
- The parameters of second BW are fixed to Y(4360)
- First resonance is stable in other hypotheses
- First resonance is consistent with $\psi(4160)$ in PDG, mass is lower than Y(4230)

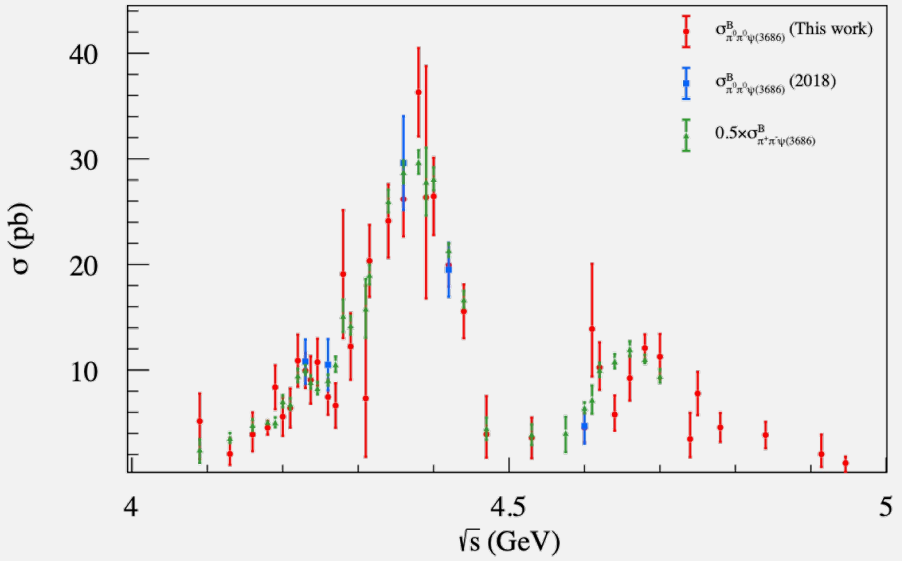
$\Gamma_{ee}\mathcal{B}$ (eV)	M (MeV/c^2)	$\Gamma_{\rm tot}$ (MeV)
$0.80 \pm 0.19 \pm 0.45$	$4188.8 \pm 4.7 \pm 8.0$	$49 \pm 16 \pm 19$

Measurement of $e^+e^- \to \pi^0\pi^0\psi(3686)$

BESIII: PhysRevD. 97. 052001 (2018)



BESIII: arXiv: 2601.02136

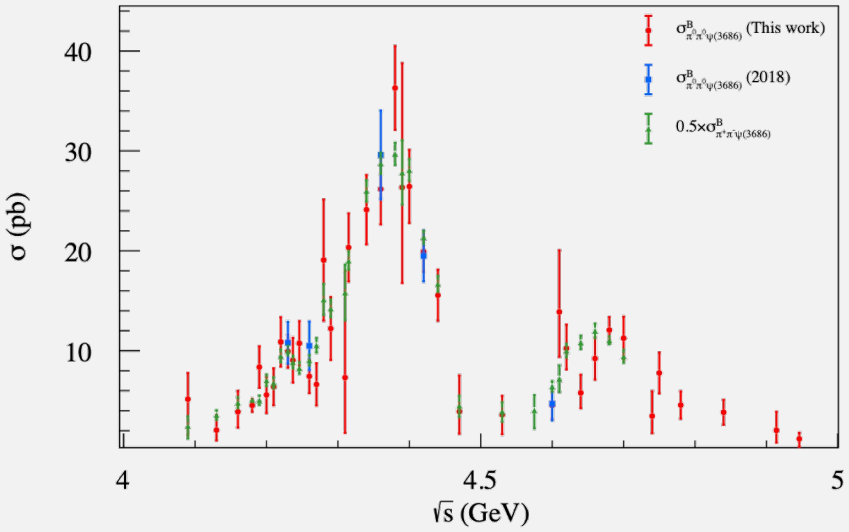


- Previous work: 16 energy points, ~5.2 fb^{-1} in total, only 5 energy points have observable signal events
- Updated work: 41 energy points, ~22.1 fb^{-1} in total
- Cross sections consistent with expectation from isospin symmetry
- Clear structures can be observed

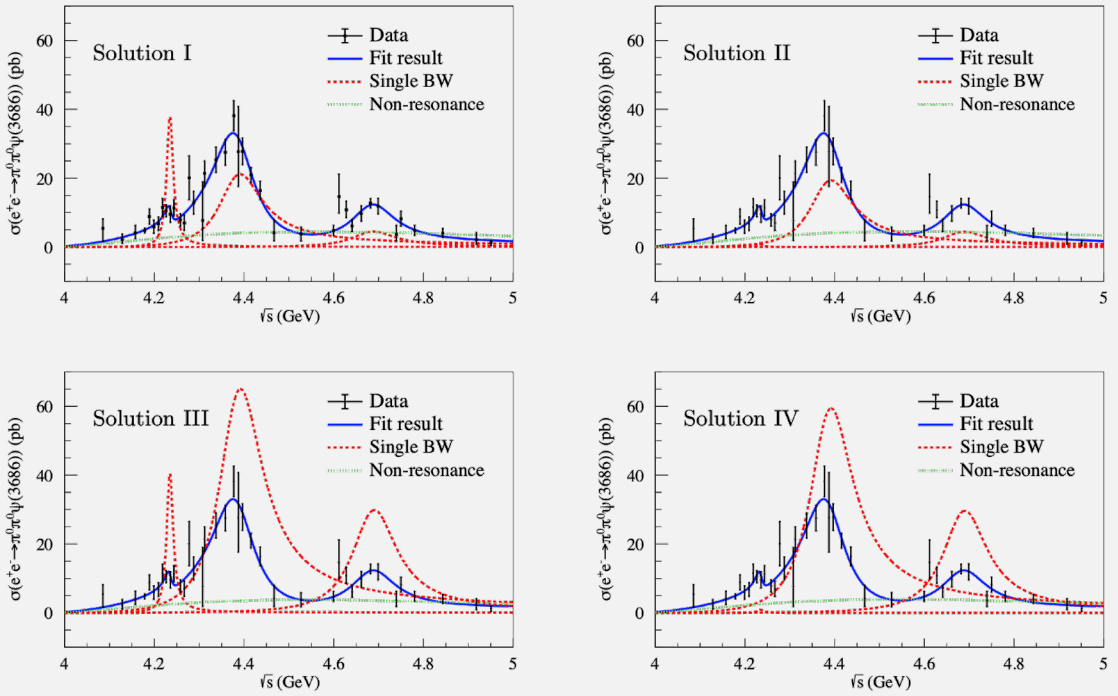
$$\sigma^B_{\pi^0\pi^0\psi(3686)} \sim 0.5\sigma^B_{\pi^+\pi^-\psi(3686)}$$

Measurement of $e^+e^- \to \pi^0\pi^0\psi(3686)$

BESIII: arXiv: 2601.02136



$$\sigma^{\text{fit}}(\sqrt{s}) = \left| \sum_k e^{i\phi_k} \cdot BW_k(s) + e^{i\phi_{\text{cont}}} \cdot \psi_{\text{cont}} \right|^2$$

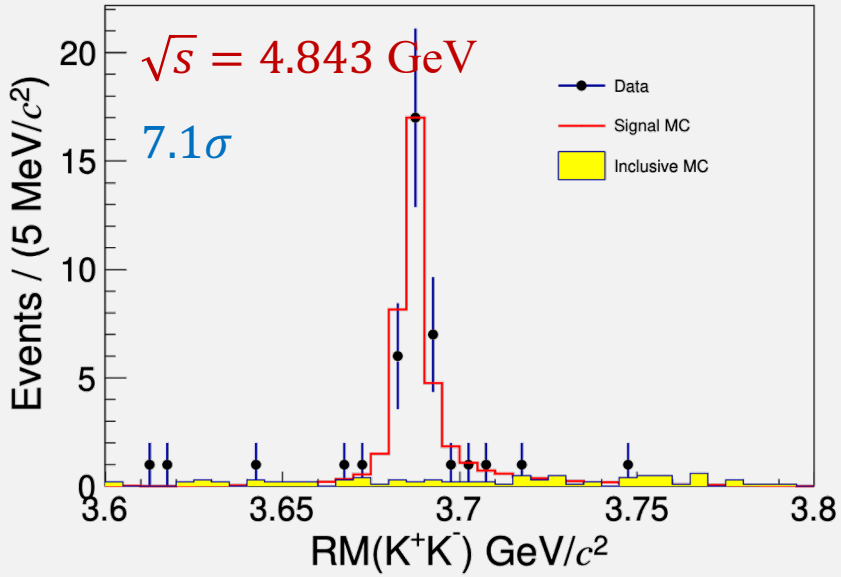


- Same model is used as charged channel $\pi^+\pi^-\psi(3686)$
- Y(4230) (1.9σ) fixed to $\pi^+\pi^-\psi(3686)$ parameters
- Confirm the existence of Y(4390) (11.4σ) and Y(4660) (5.7σ)

Parameter	Solution I	Solution II	Solution III	Solution IV
$M(Y4230)$ (MeV/c^2)	4234.4 (fixed)			
$\Gamma^{\text{tot}}(Y4230)$ (MeV)	17.6 (fixed)			
$\mathcal{B}\Gamma^{ee}(Y4230)$ (eV)	$0.81 \pm 0.07 \pm 0.37$	$0.02 \pm 0.01 \pm 0.01$	$0.87 \pm 0.08 \pm 0.43$	$0.02 \pm 0.01 \pm 0.01$
$M(Y4390)$ (MeV/c^2)	$4383.0 \pm 8.6 \pm 1.9$			
$\Gamma^{\text{tot}}(Y4390)$ (MeV)	$117.4 \pm 20.7 \pm 4.8$			
$\mathcal{B}\Gamma^{ee}(Y4390)$ (eV)	$3.18 \pm 1.21 \pm 0.57$	$2.92 \pm 1.07 \pm 0.36$	$9.90 \pm 1.42 \pm 0.76$	$9.03 \pm 1.22 \pm 0.09$
$M(Y4660)$ (MeV/c^2)	$4684.0 \pm 17.3 \pm 1.9$			
$\Gamma^{\text{tot}}(Y4660)$ (MeV)	$119.5 \pm 47.1 \pm 9.1$			
$\mathcal{B}\Gamma^{ee}(Y4660)$ (eV)	$0.80 \pm 0.73 \pm 0.14$	$0.79 \pm 0.70 \pm 0.13$	$5.36 \pm 1.60 \pm 0.39$	$5.31 \pm 1.58 \pm 0.23$
$\phi_{Y(4230)}$ (rad)	2.03 ± 0.25	6.14 ± 0.41	1.23 ± 0.18	5.35 ± 0.52
$\phi_{Y(4660)}$ (rad)	5.99 ± 0.40	5.93 ± 0.40	5.28 ± 0.46	5.22 ± 0.46
ϕ_{cont} (rad)	3.87 ± 0.36	3.69 ± 0.33	2.23 ± 0.27	2.06 ± 0.24
a ($\times 10^5$)	4.2 ± 9.5	3.3 ± 8.0	5.3 ± 22.8	4.9 ± 22.6
n	8.7 ± 1.8	8.6 ± 1.8	8.9 ± 3.6	8.9 ± 3.6

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

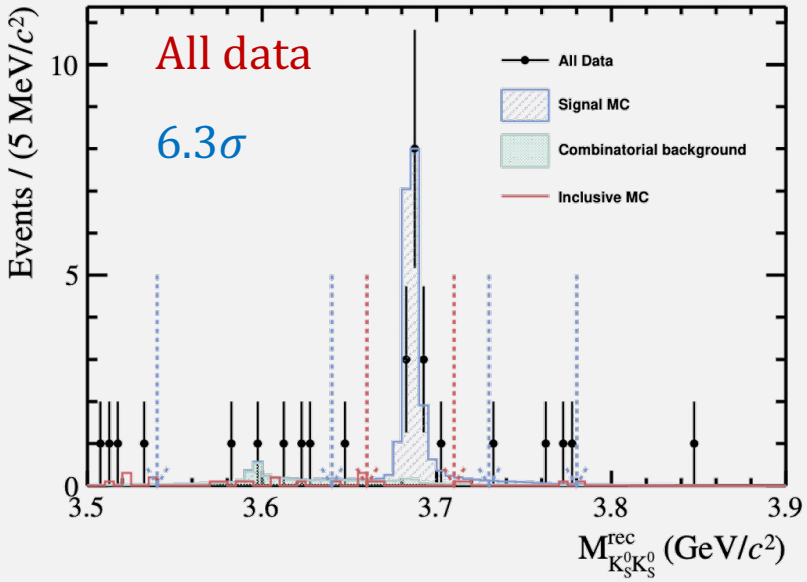
BESIII: arXiv: 2407.20009



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

- $\psi(3686) \to J/\psi$+X, $J/\psi \to l^+l^-$
- $\psi(3686) \to J/\psi\pi^+\pi^-$, $J/\psi \to l^+l^-$, missing one Kaon
- $\psi(3686) \to l^+l^-$
- $\psi(3686) \to l^+l^-$, missing one Kaon

BESIII: JHEP 02 (2025) 120



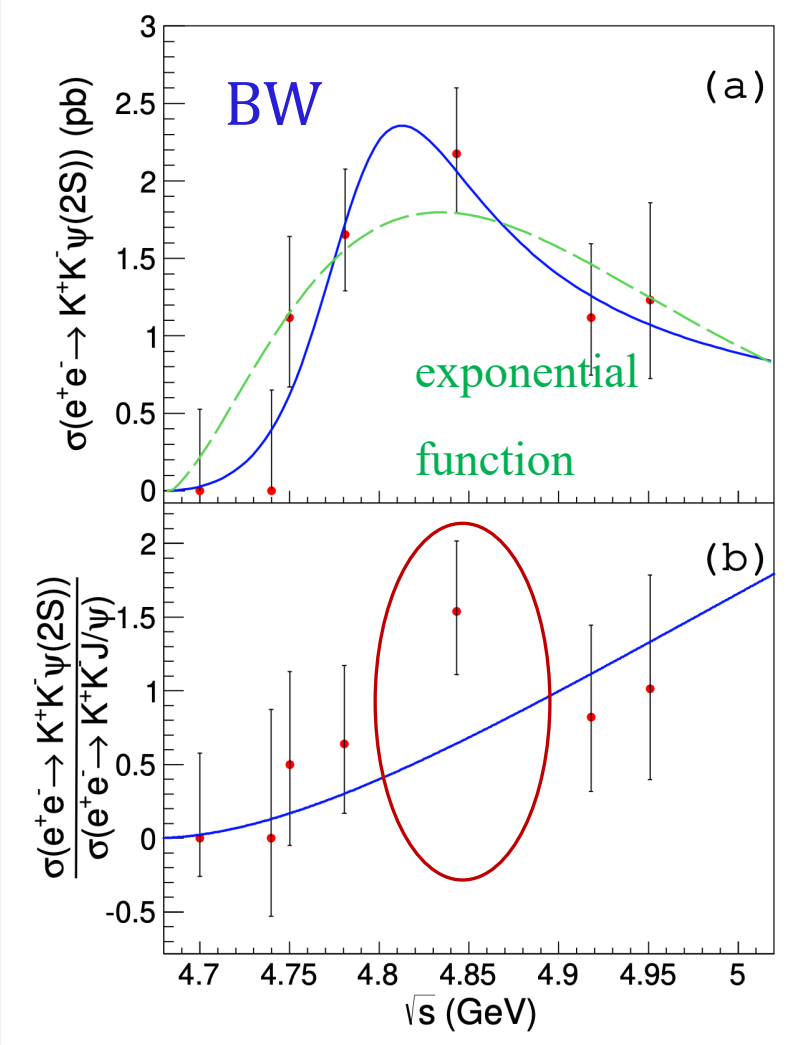
channel: $e^+e^- \to K_S^0K_S^0\psi(3686)$

- $\psi(3686) \to J/\psi$+X, $J/\psi \to l^+l^-$
- Both $K_S^0 \to \pi^+\pi^-$

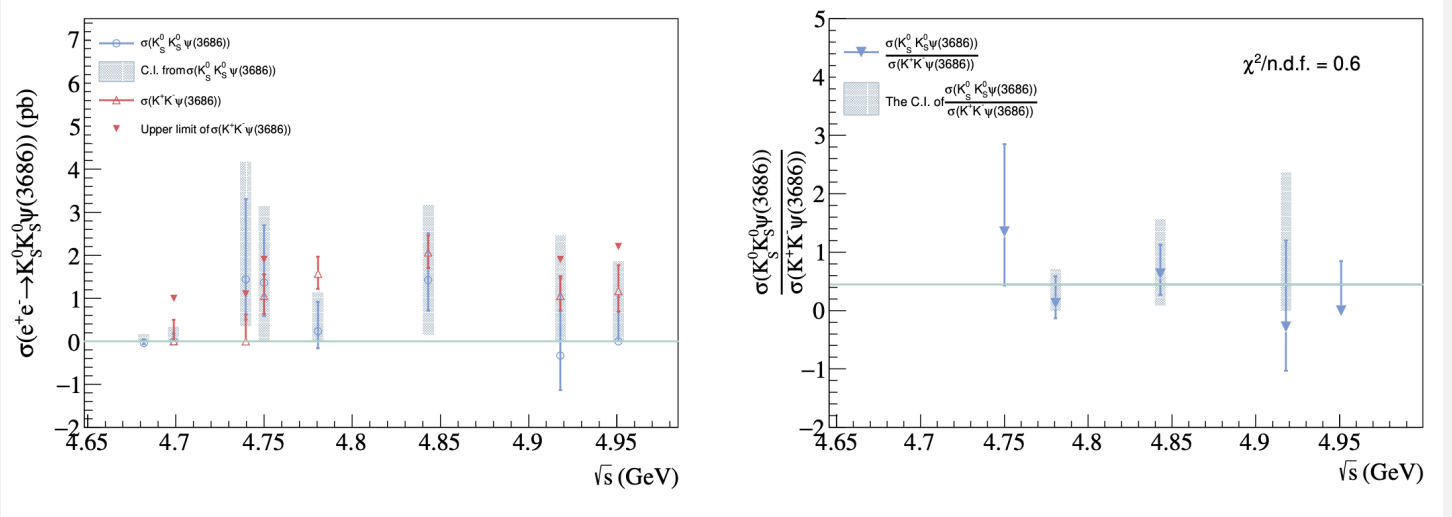
Both charged and neutral channel are observed

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

BESIII: arXiv: 2407.20009



BESIII: JHEP 02 (2025) 120



- Cross section line shape of $e^+e^- \to K^+K^-\psi(3686)$
  - ✓ Breit-Wigner or an exponential function produce similar fit quality
  - ✓ Cross section ratio $K^+K^-\psi(3686)/\ K^+K^-J/\psi$ above PHSP of 2.0σ at $\sqrt{s} = 4.843$ GeV
- Cross section line shape of $e^+e^- \to K_S^0K_S^0\psi(3686)$
  - ✓ Consistent with the expectation from isospin symmetry

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

Prompt inclusive J/ψ and $\psi(3686)$ production

BESIII: PhysRevD.111.052007(2025)

- Nonrelativistic QCD can describe charmonium production
  - ✓ Inclusive J/ψ production at B-factory($\sqrt{s} = 10.6$ GeV) can be described with next-to-leading order NRQCD
  - ✓ Extrapolation to lower energies, cross sections prediction(Chinese Phys. C 43 083104) are smaller than results of $e^+e^- \to \pi^+\pi^- J/\psi$ process measured by BESIII
    - ➢ Perturbative calculations not applicable close to the J/ψ production threshold
- New experimental results on inclusive charmonium production in e^+e^- annihilation at low energies
  - ✓ Useful to understand the limits of applicability of NRQCD
  - ✓ Provide information about the properties of exotic charmoniumlike states

channel: $e^+e^- \to J/\psi + X$

- $J/\psi \to \mu^+\mu^-$, only state directly from e^+e^- annihilation are treated as signal
- Background: $\gamma_{ISR}\, J/\psi$, $\psi(3686) \to \pi^+\pi^- J/\psi$, $\chi_{c1,2} \to \gamma J/\psi$

channel: $e^+e^- \to \psi(3686) + X$

- $\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-/e^+e^-$, only state directly from e^+e^- annihilation are treated as signal
- Background: $\gamma_{ISR}\, \psi(3686)$

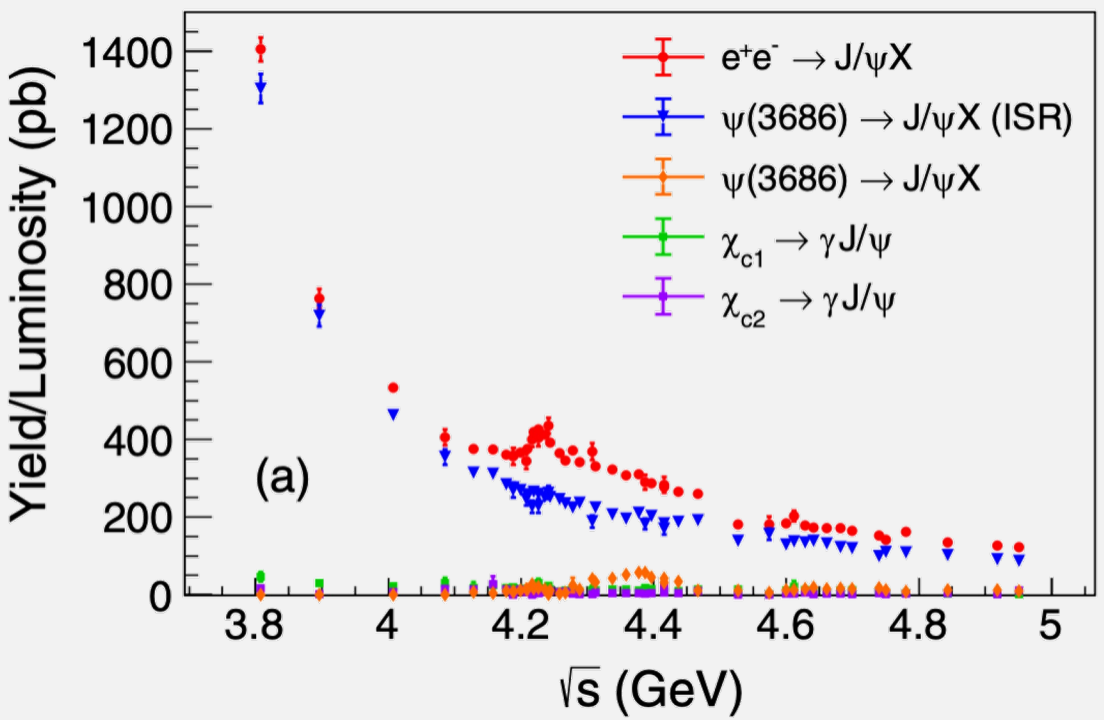
Prompt inclusive J/ψ and $\psi(3686)$ production

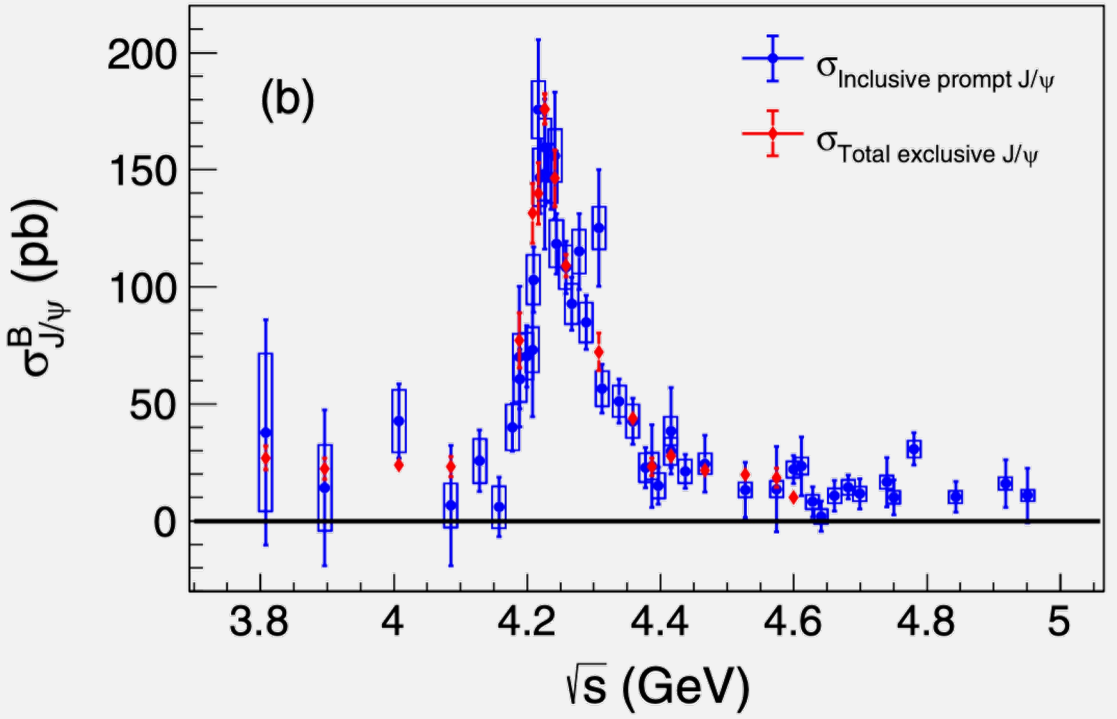
BESIII: PhysRevD.111.052007(2025)

- Inclusive prompt J/ψ cross section is in good agreement with sum of exclusive processes, such as

  $e^+e^- \to \pi^+\pi^- J/\psi, \pi^0\pi^0 J/\psi,\ K^+K^- J/\psi,\ K^0K^0 J/\psi,\ \eta J/\psi,\ \pi^0 J/\psi,\ \eta' J/\psi$

- No evidence of hidden decays involving the J/ψ meson
- Peaking structure is dominantly a superposition of contributions of the $\mathrm{Y}(4230)$ and $\mathrm{Y}(4360)$

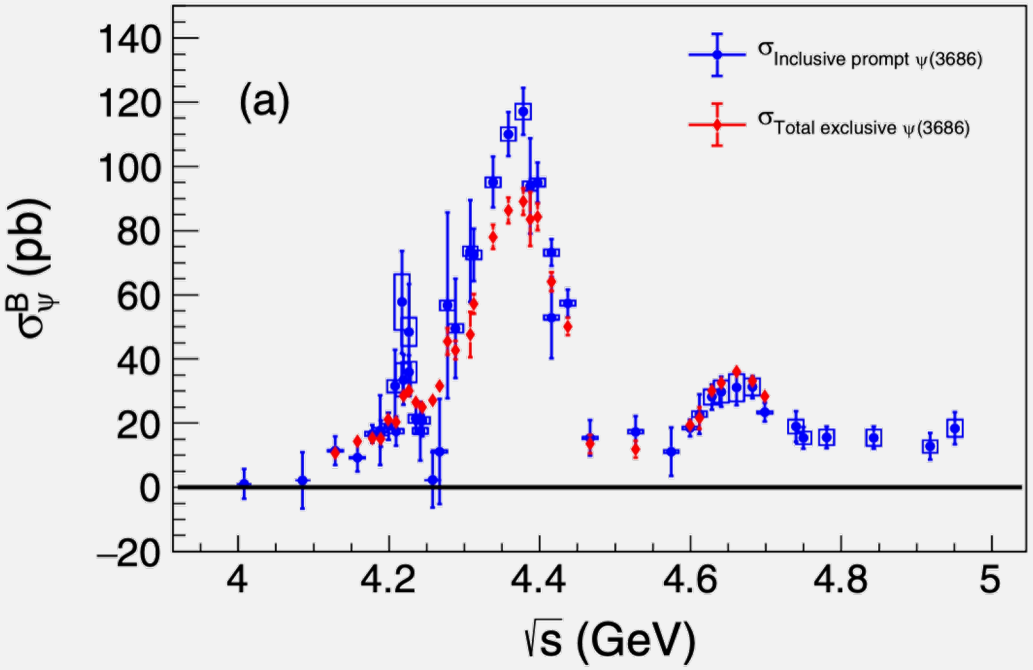


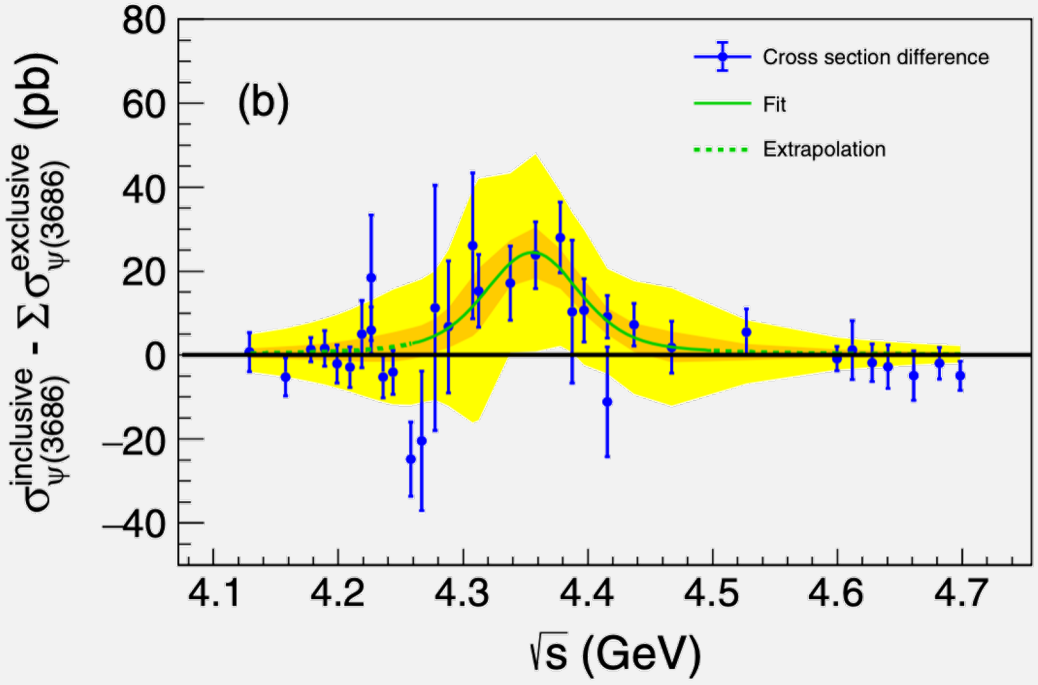


Prompt inclusive J/ψ and $\psi(3686)$ production

BESIII: PhysRevD.111.052007(2025)

- Comparison between inclusive prompt $\psi(3686)$ cross section and sum of exclusive processes, such as $e^+e^- \to \pi^+\pi^-\psi(3686),\ \eta\psi(3686)$
  - ✓ Contribution of $e^+e^- \to \pi^+\pi^-\psi(3686)$ is scaled 1.5 times to consider $e^+e^- \to \pi^0\pi^0\psi(3686)$
- Clear structures of $\mathrm{Y}(4230)$, $\mathrm{Y}(4360)$ and $\mathrm{Y}(4660)$
- Unknown process at the $\mathrm{Y}(4360)$ peak is about 23% of inclusive $\psi(3686)$ cross section





Summary

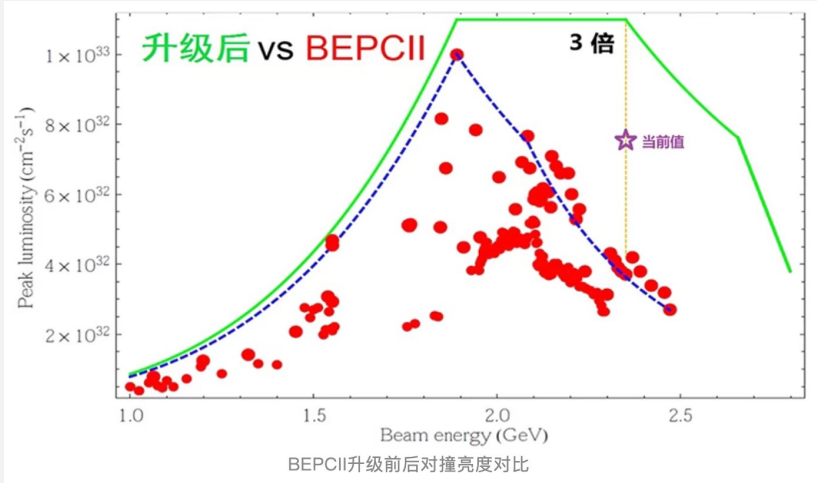
- Fine energy scan at BESIII from √s=3.8 to 4.95 GeV studying vector charmonium-like states
- Cross section measurement of some exclusive channels
  - ✓ $e^+e^- \to \pi^+\pi^- h_c, e^+e^- \to \eta h_c, e^+e^- \to \pi^0\pi^0\psi(3686)$
  - ✓ Final states with strange quark: $e^+e^- \to K\bar{K}\psi(3686)$
- Cross section measurement of inclusive J/ψ and $\psi(3686)$
- The abundant structure observed in this energy region at different processes need careful classification

2026/03/17 18:05:53

Luminosity 7.35 E32/cm^2/s

	e+	e−
Energy [GeV]	2.3516	2.3515
Current [mA]	630.40	587.87
Lifetime [hr]	2.11	2.40
Inj.Rate [mA/min]	0.00	0.00

BEPCII实时运行状态与束流参数



BEPCII升级前后对撞亮度对比

THANK YOU!