# Recent Charmonium and XYZ Studies at BESIII

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第6届重味物理与量子色动力学研讨会

中国海洋大学&山东大学 青岛

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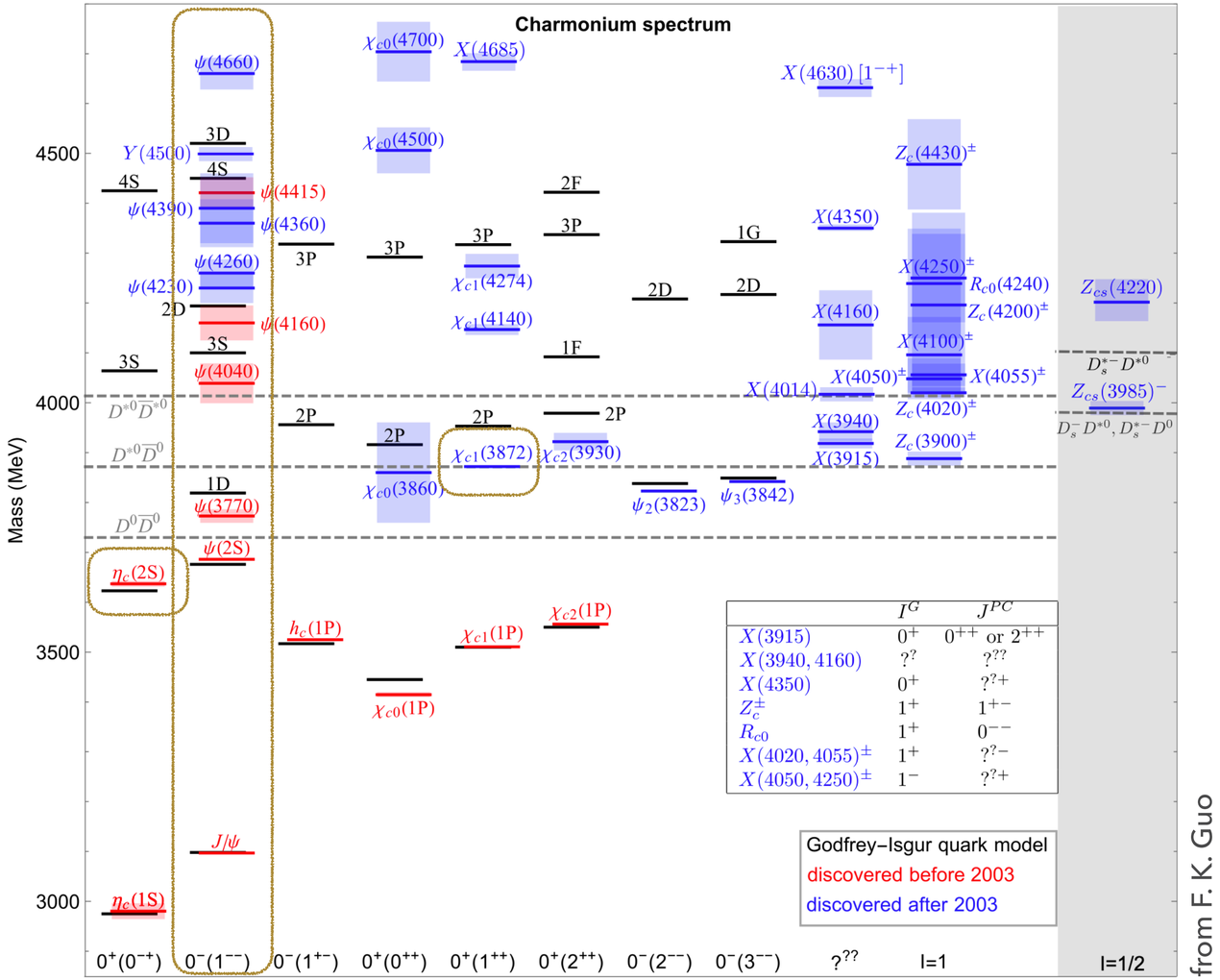
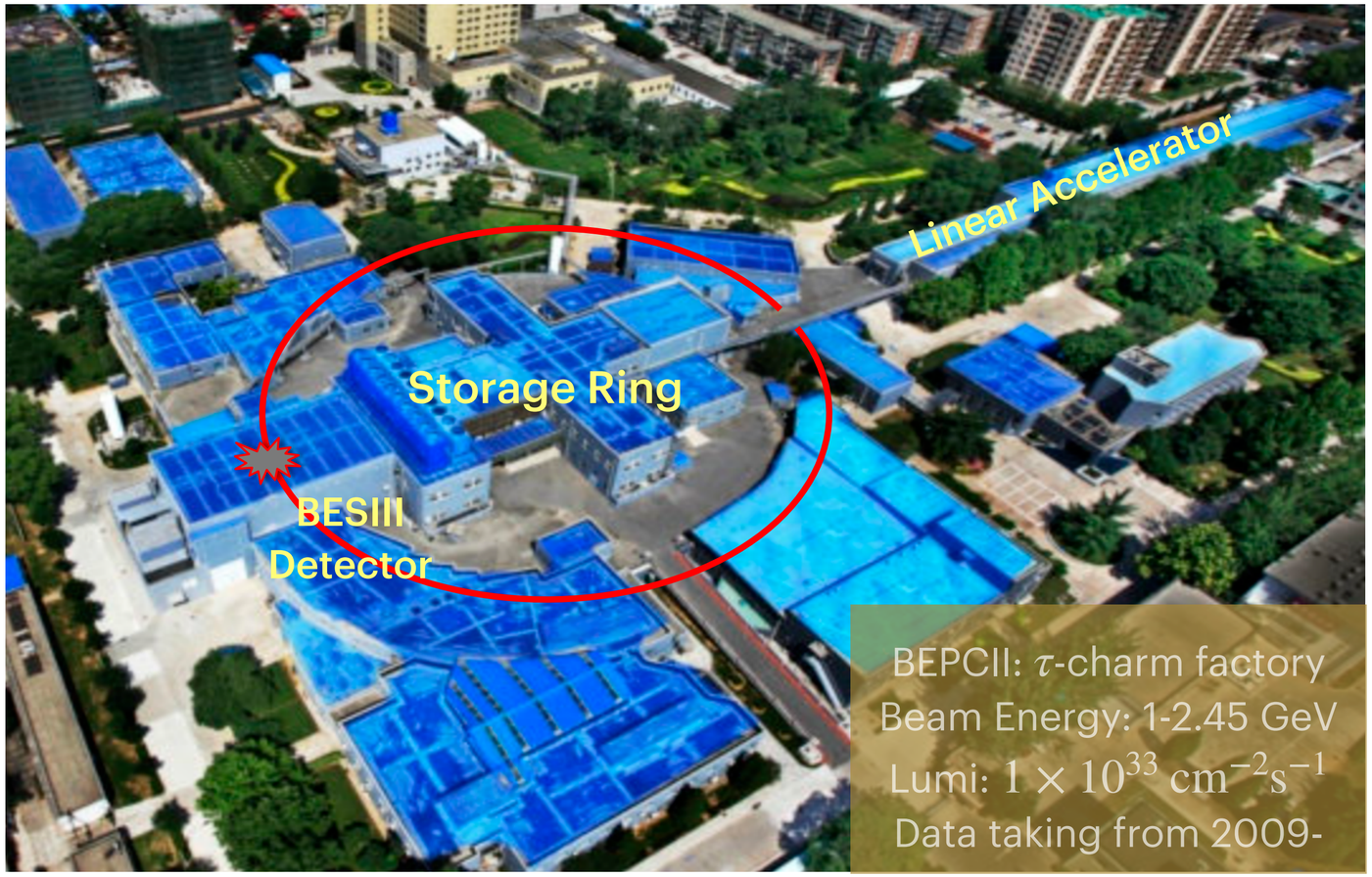
# Charmonium Spectroscopy




from F. K. Guo

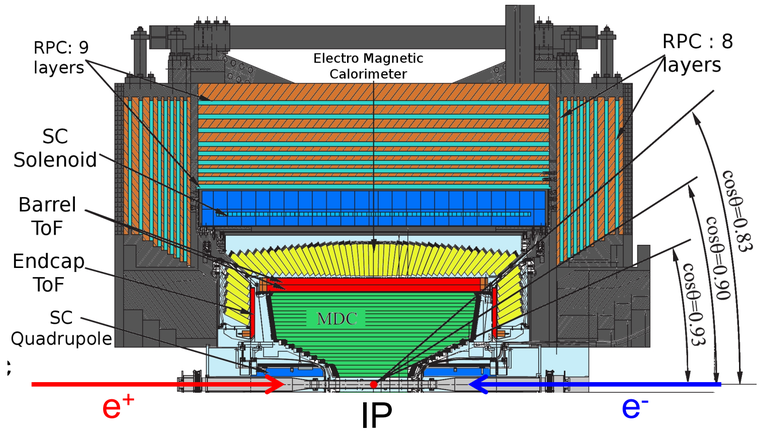
- Selected topics in this talk:
  - Vector charmonium(-like) states
    - Hadronic transitions
    - Precise measurement of the open charm processes
    - Non-$D\bar{D}$ decays of $\psi(3770)$
  - New measurements of $X(3872)$
  - Radiative transition in search for C-even states
  - Hadronic decays of spin-singlet charmonium states

# Beijing Electron Positron Collider II and BESIII




BEPCII: $\tau$-charm factory
Beam Energy: 1-2.45 GeV
Lumi: $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$
Data taking from 2009-

Solenoid Magnet: 0.9/1.0 T



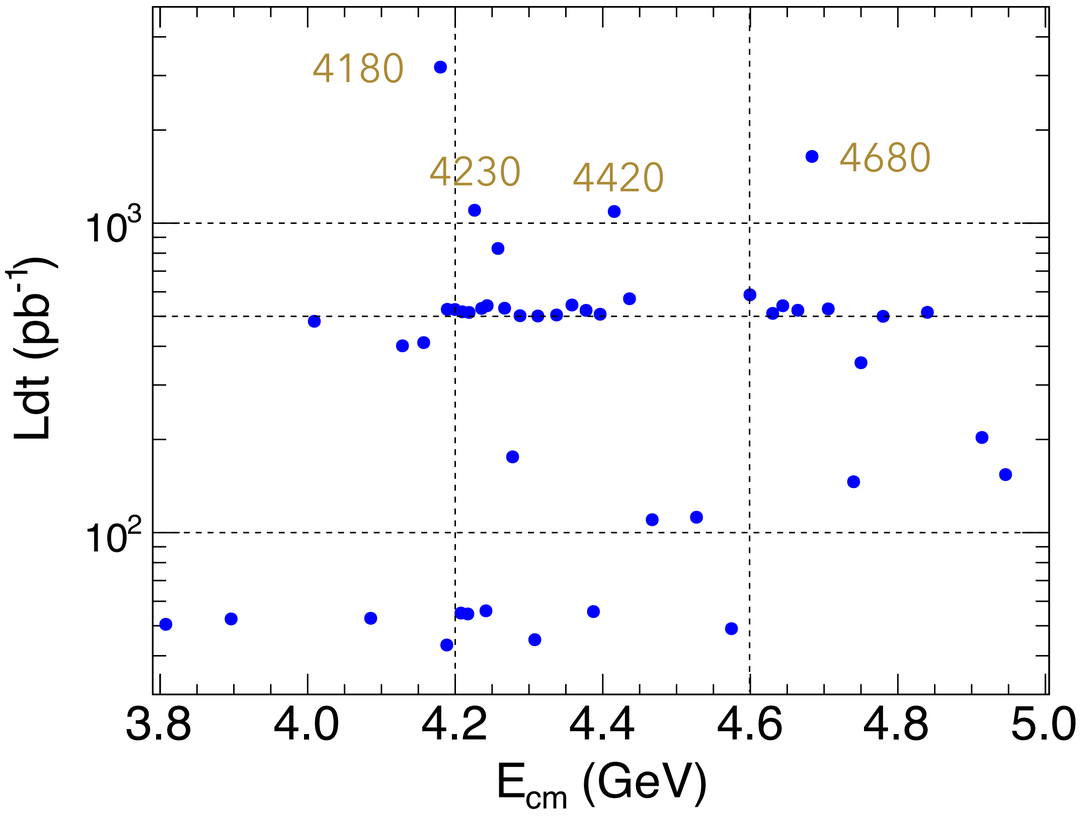

**MUC** $\sigma_{R\Phi}$: 2 cm

**TOF**
$\sigma_T$ :80 ps
110 ps (60 ps)

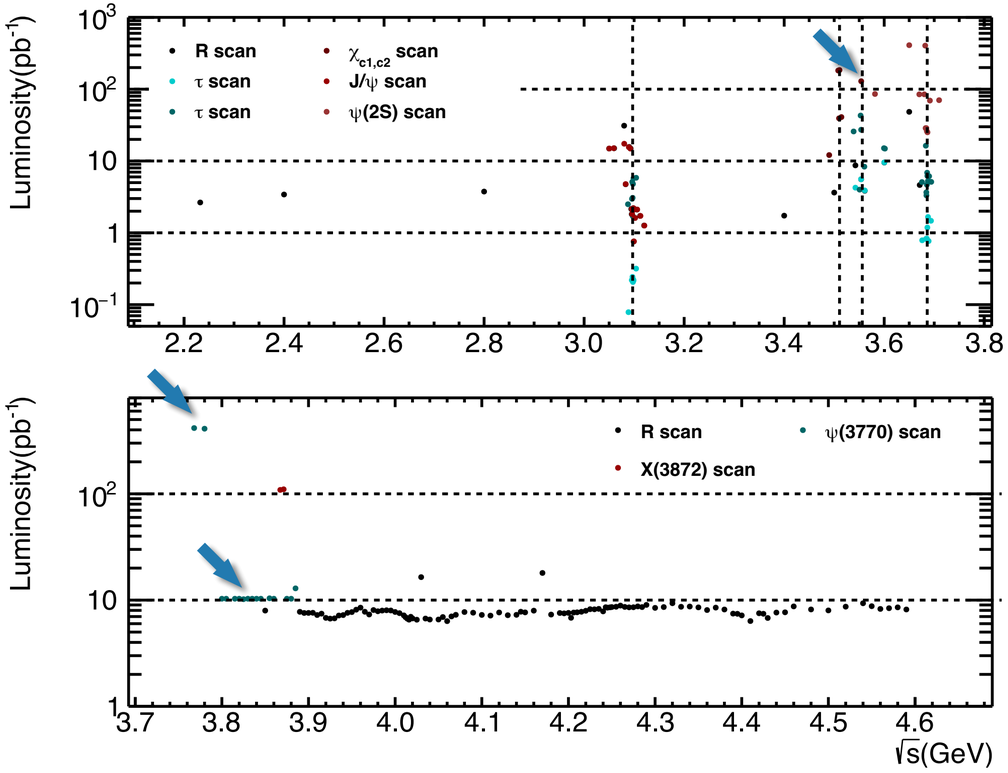
**MDC**
dE/dx: 6%
$\sigma_p/p$: 0.5% at 1GeV/c

**EMC**
$\Delta E/E$: at 1GeV
2.5%
5.0%
$\sigma_Z$: 0.6 cm/$\sqrt{E}$

# BESIII Data Samples




46 sample, ~22 fb$^{-1}$

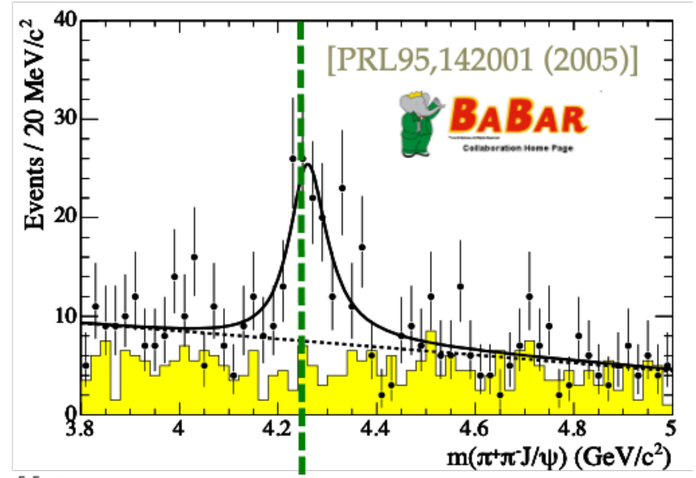


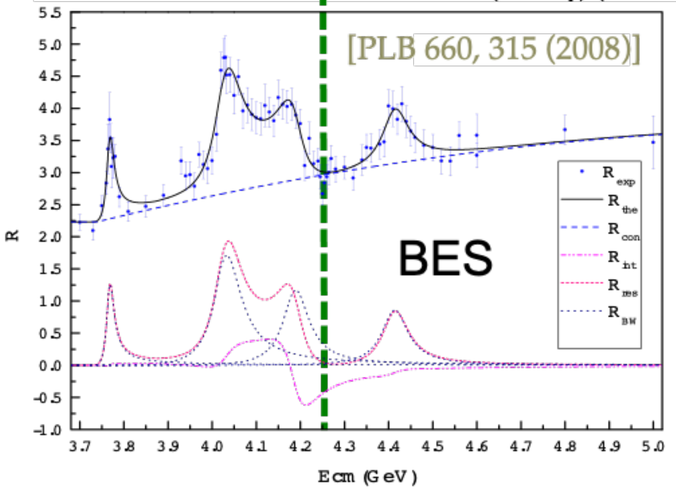

+ Small scan sample, ~3.5 fb$^{-1}$

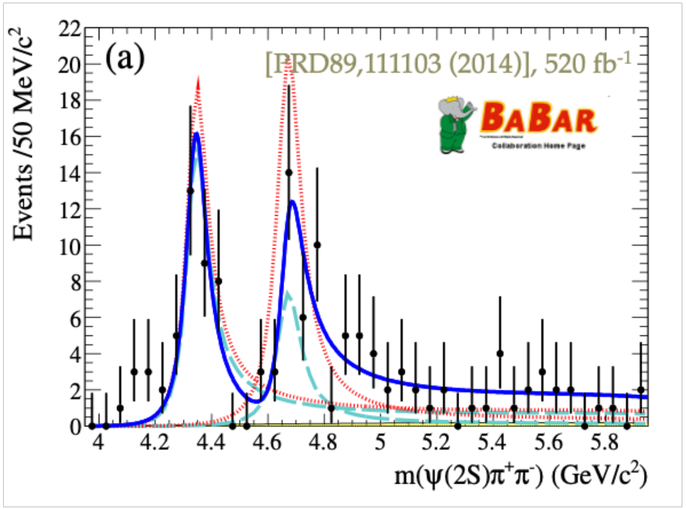
+ 10 Billion $J/\psi$, 2.7 Billion $\psi(3686)$, 20 fb$^{-1}$ $\psi(3770)$

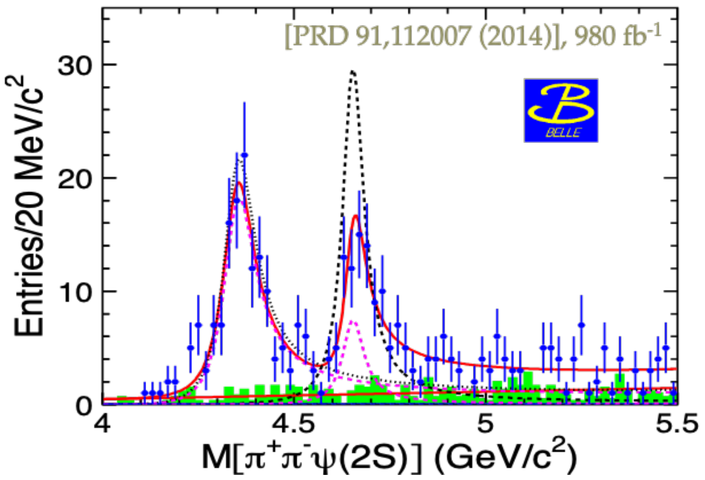
# Discovery of Y States

- 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 $D\bar{D}$ threshold
  - Not observed in inclusive hadron cross section
  - Not observed in open charm pair cross section
- 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



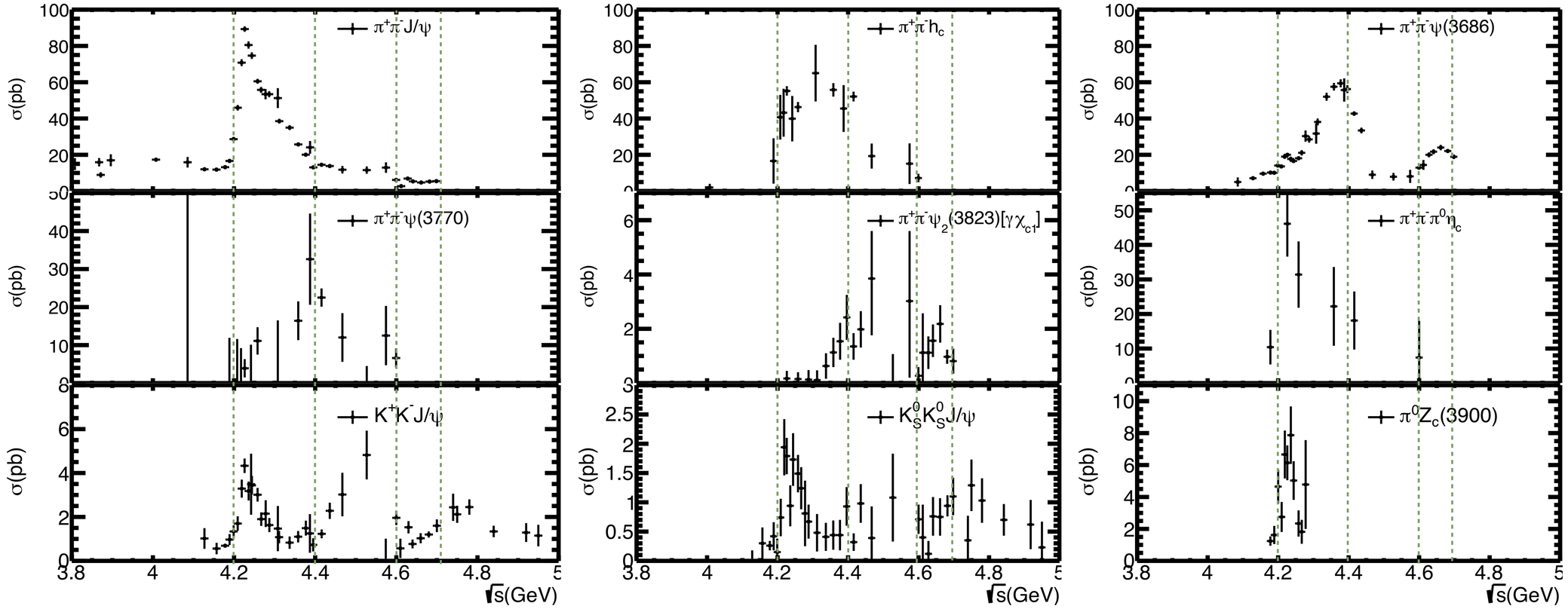



# Summary of CS Measurements at BESIII

- Investigated by measuring the cross section as a function of c.m.s $\sigma(\sqrt{s})$

  - Hidden charm processes
  - Open charm processes
  - Light hadron processes



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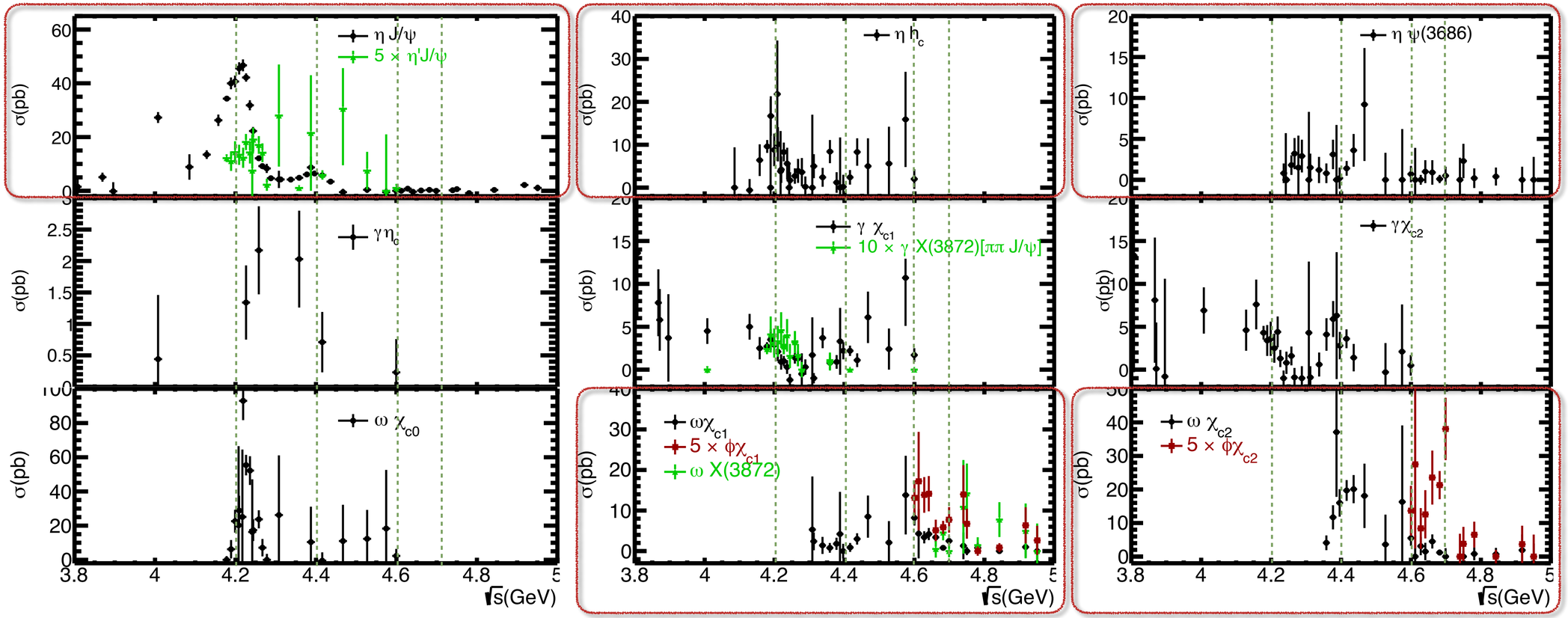

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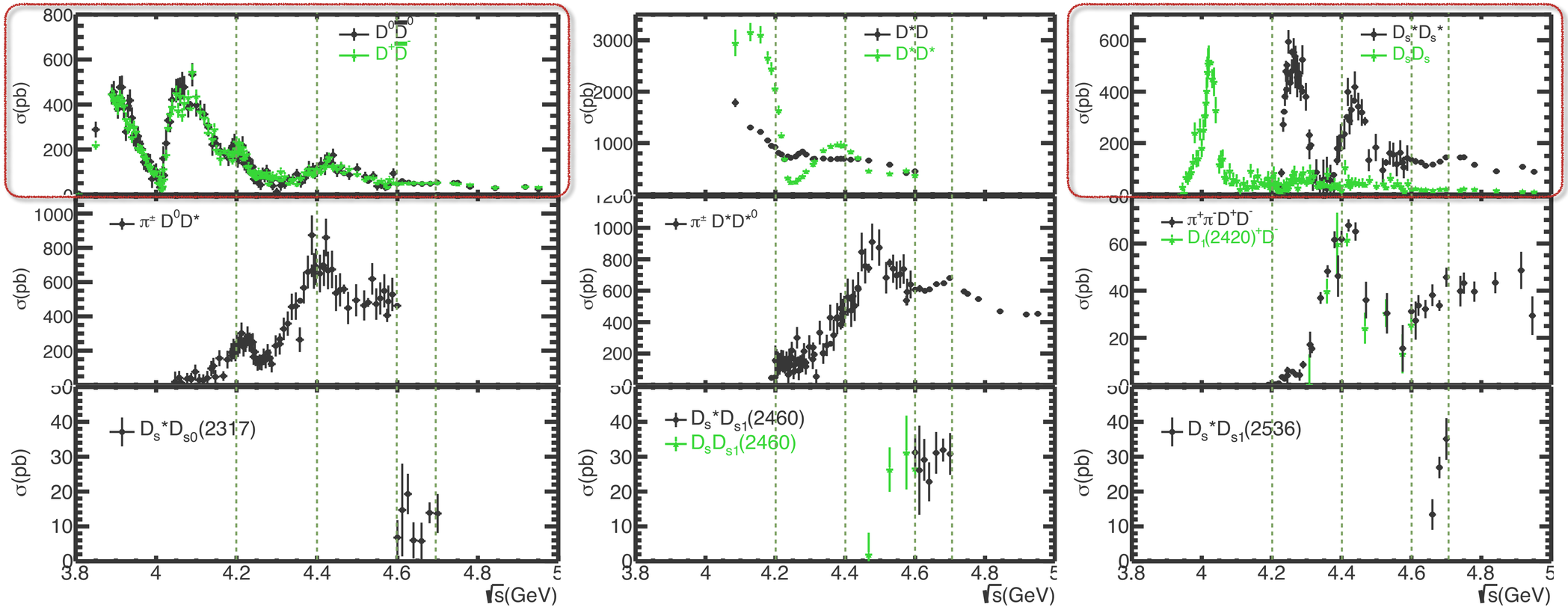
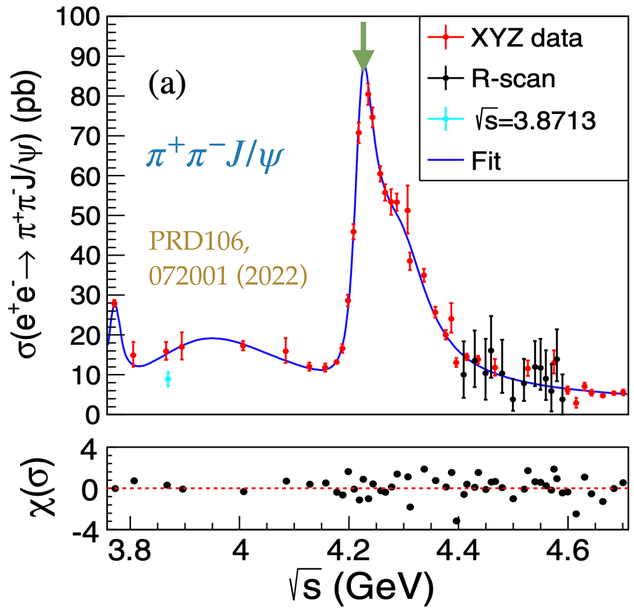
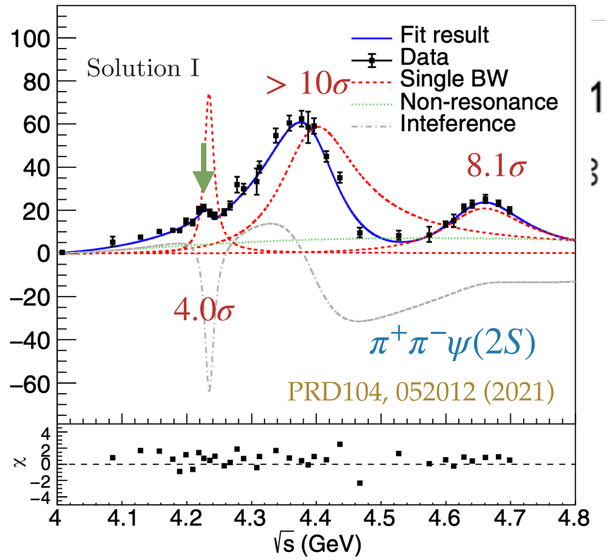
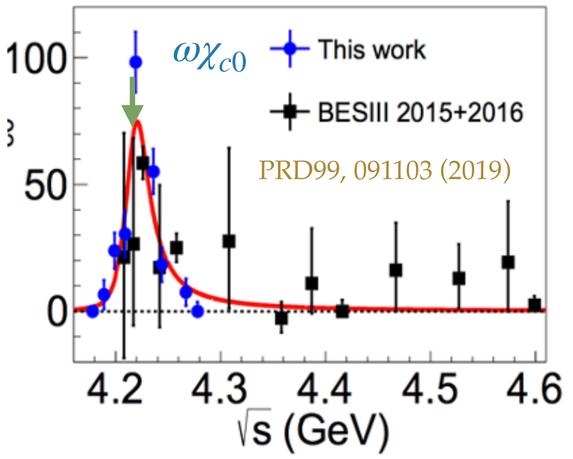


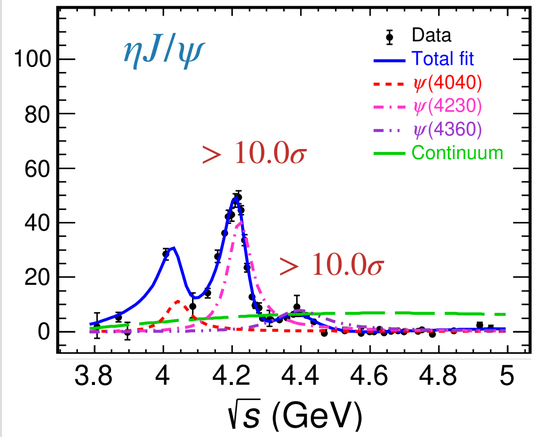
# Y(4260) ⇒ Y(4230)

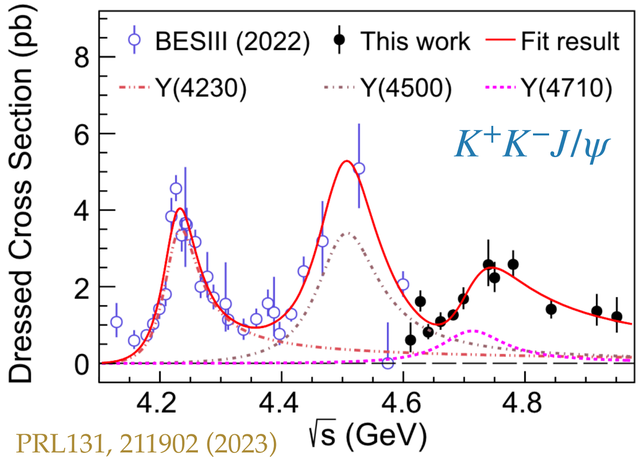


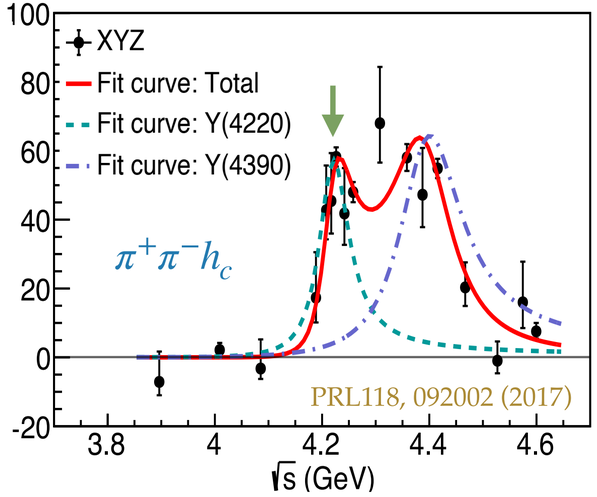



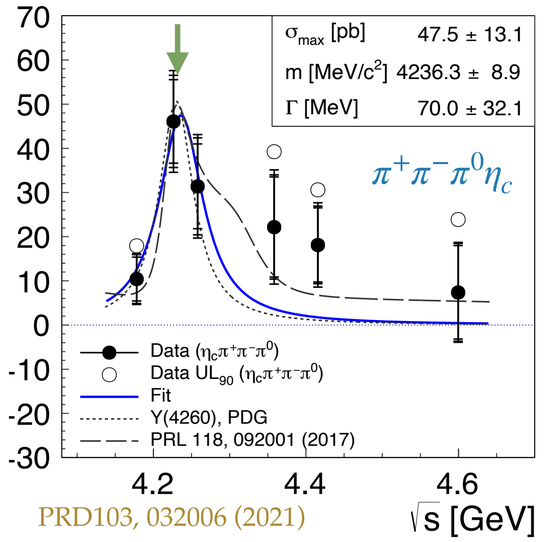

arXiv: 2310.03361



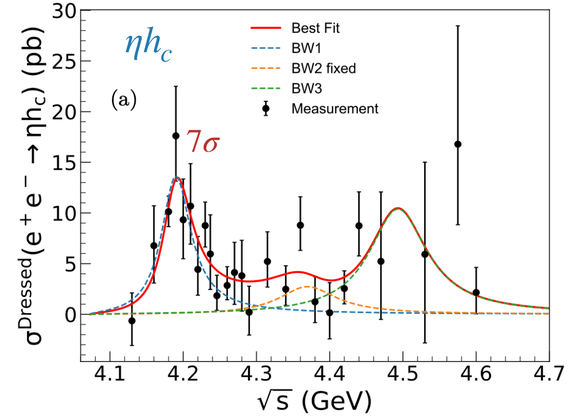




PRL131, 211902 (2023)



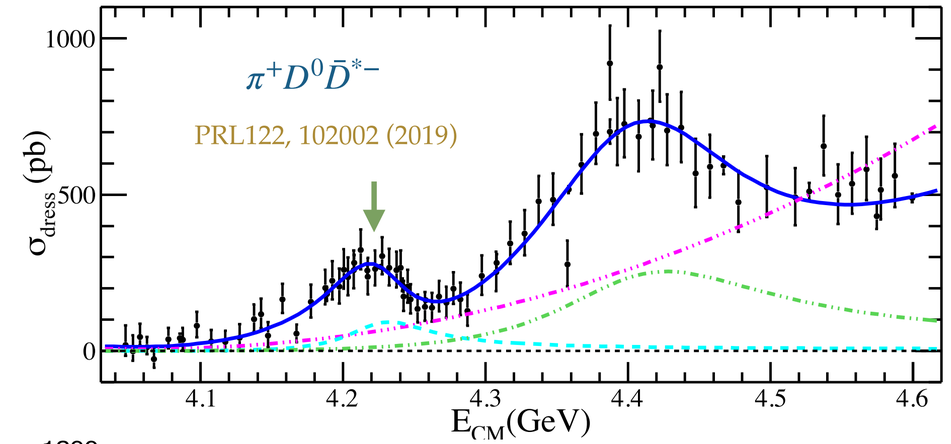




PRD103, 032006 (2021)

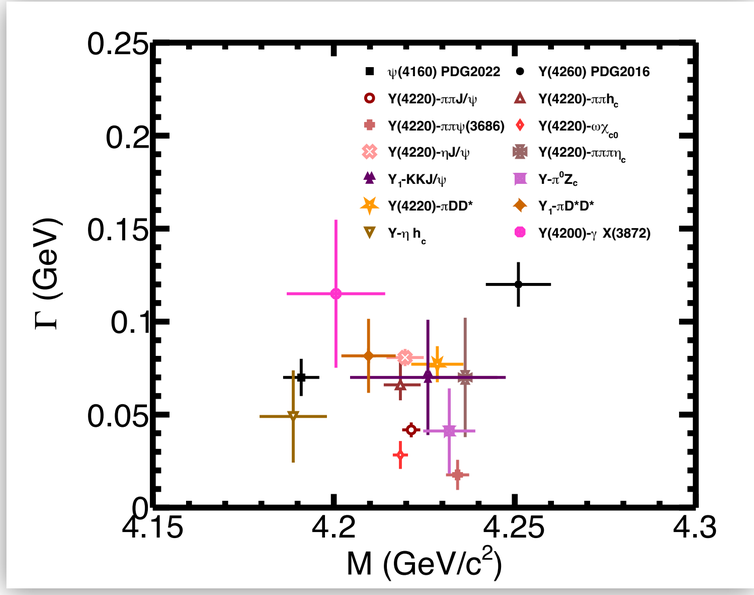



arXiv:2404.06718

# Y(4230) in Open Charm Process




## Mass and width from different process




⇑

determined with BW parameterization

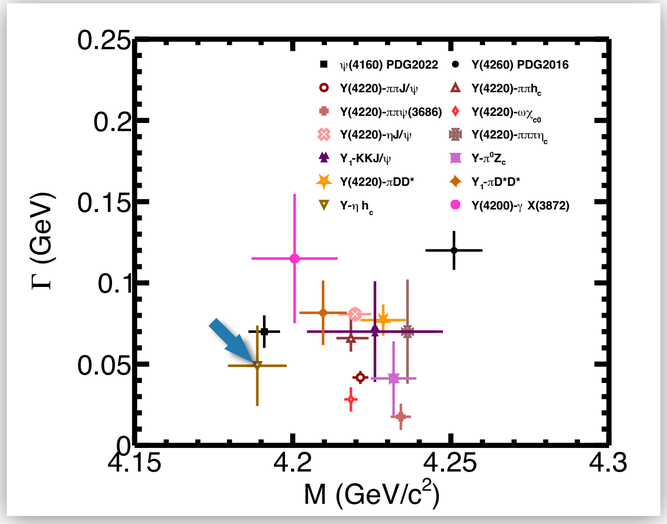
consider possible interference

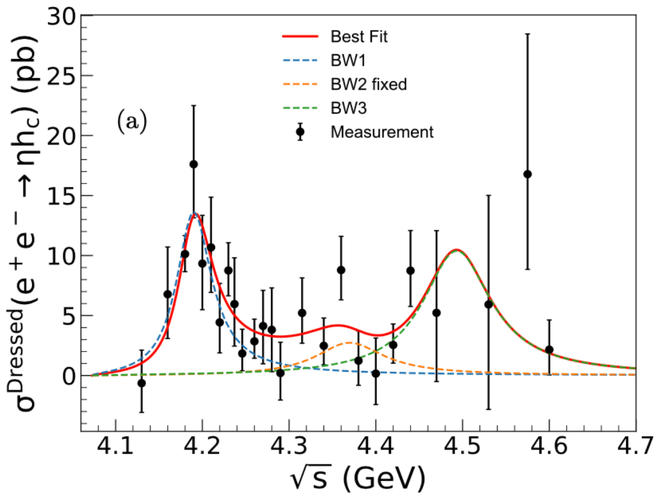
⇓

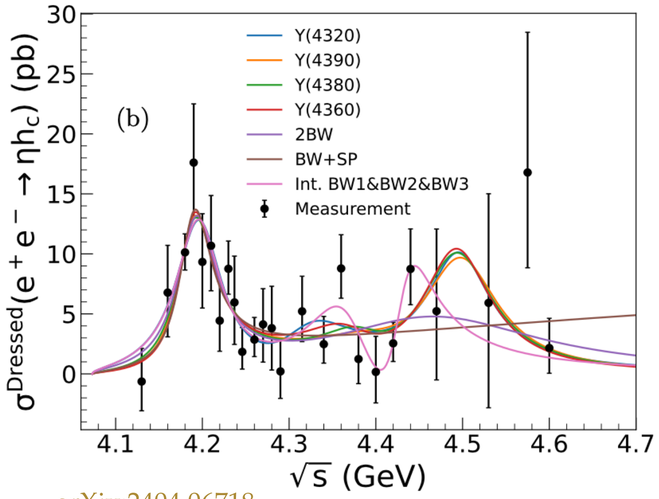
| $\Gamma_{ee}B$(eV) | $\pi^+\pi^-J/\psi$ | $\pi^+\pi^-h_c$ | $\omega\chi_{c0}$ | $\pi^+\pi^-\psi(2S)$ | $\eta J/\psi$ | $K^+K^-J/\psi$ | $\pi^+\pi^-J/\psi$ | $\pi^\pm(D\bar{D}^*)^\mp$ | $\pi^\pm(D^*\bar{D}^*)^\mp$ |
|---|---|---|---|---|---|---|---|---|---|
| Min | 1.7[0.2] | 4.6[2.9] | 2.5[0.2] | 0.02[0.01] | 4.0[0.5] | 0.29[0.10] | 0.22[0.25] | 8.6[1.6] | 4.8[0.9] |
| Max | 14.6[1.2] | | | 1.64[0.83] | 11.9[1.1] | 0.42[0.15] | 0.53[0.15] | 77.4[10.1] | 22.4[9.0] |

Same Order

# Update of $\eta h_c$ Cross Section



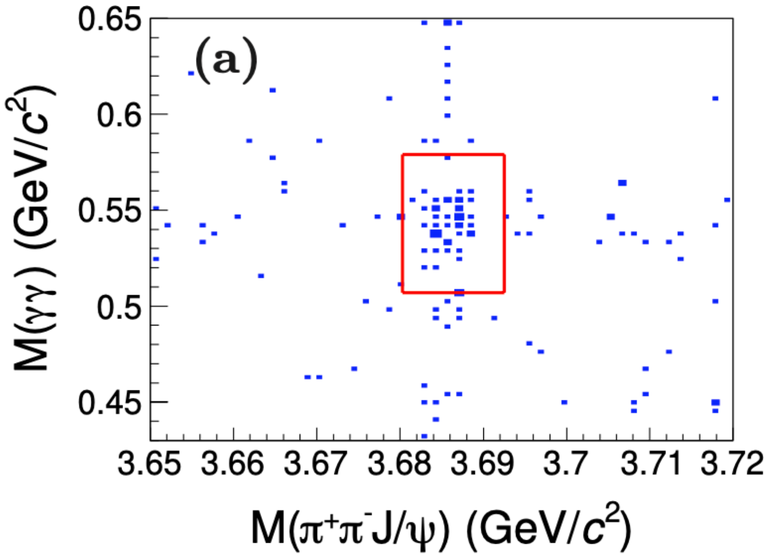



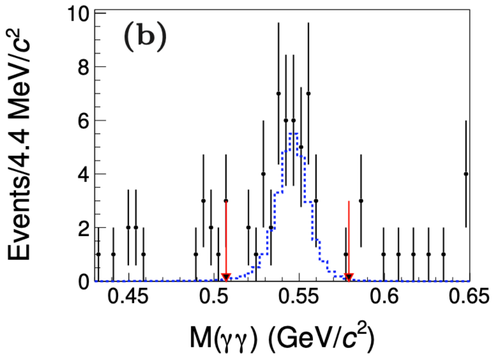

arXiv:2404.06718

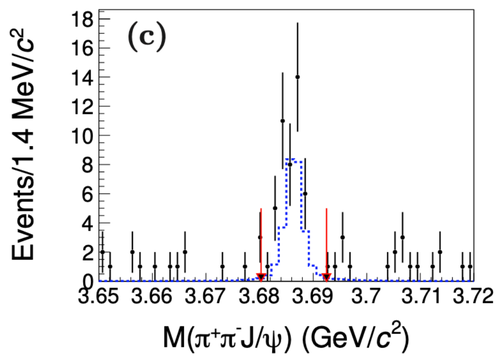
- 15 fb$^{-1}$ data sample from 4.129 to 4.600 GeV
- $\sigma^{\text{dressed}} = |BW_1 + BW_2 e^{i\phi}|^2 + |BW_3|^2$
  - Mass and Width of $BW_2$ fixed to Y(4360)
  - $M_1 = 4188.8 \pm 4.7 \pm 8.0$ MeV/$c^2$
    $\Gamma_1 = 49 \pm 16 \pm 19$ MeV
    $\Gamma_{ee}\mathcal{B} = 0.80 \pm 0.19 \pm 0.45$ eV
- Alternative parameterizations:
  - fix parameters of the second resonance to Y(4320), Y(4380), Y(4390)
  - remove $BW_2$
  - use sum of a $BW$ and phase space
  - coherent sum of three $BW$s
  - statistical significance of $BW_1$ in all cases > $7\sigma$

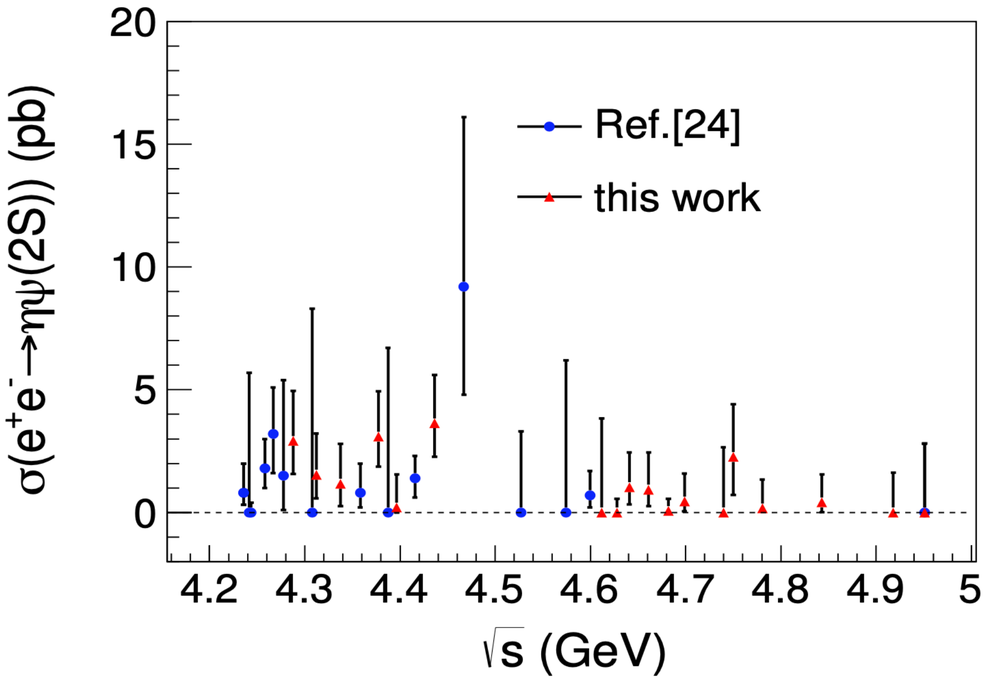
# Update of ηψ(3686) and Search for $\tilde{X}(3872)$

- 8.9 $fb^{-1}$ data sample from 4.288 to 4.951 GeV




significance > 5$\sigma$

combing previous data samples

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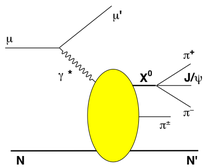
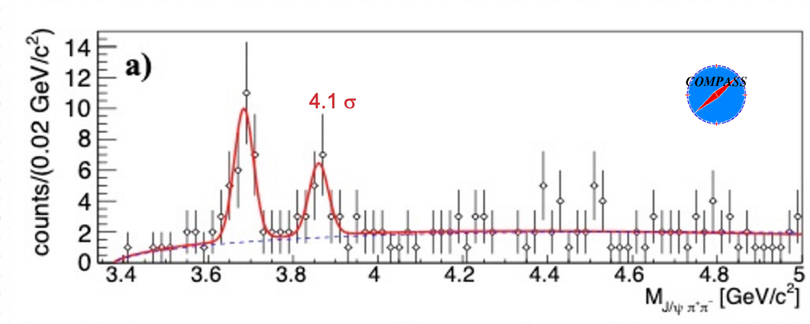


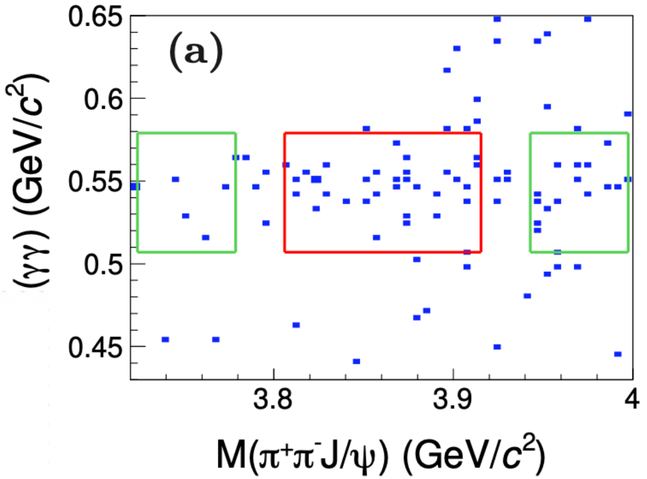

$\gamma^* N \to X[\to \pi^+\pi^- J/\psi]\pi^\pm N'$

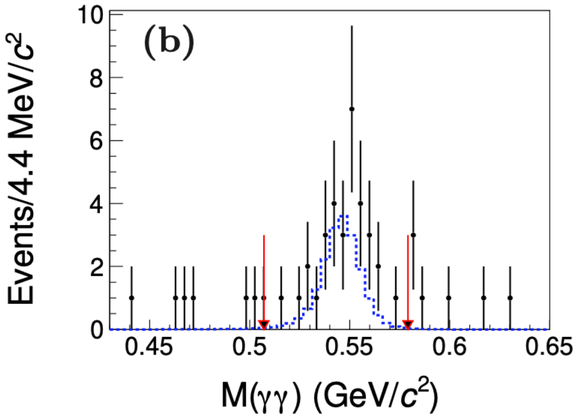
PLB 783, 334-340 (2018)

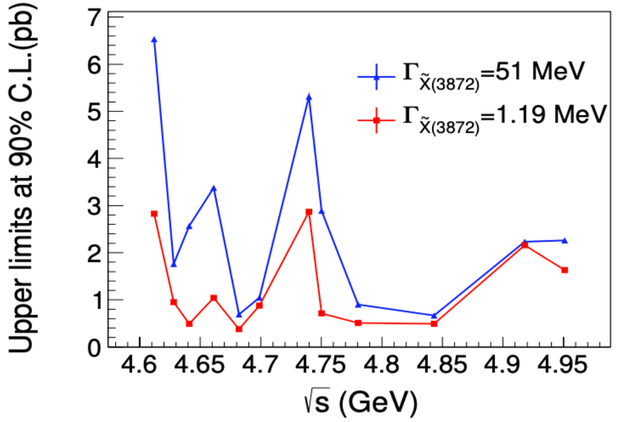


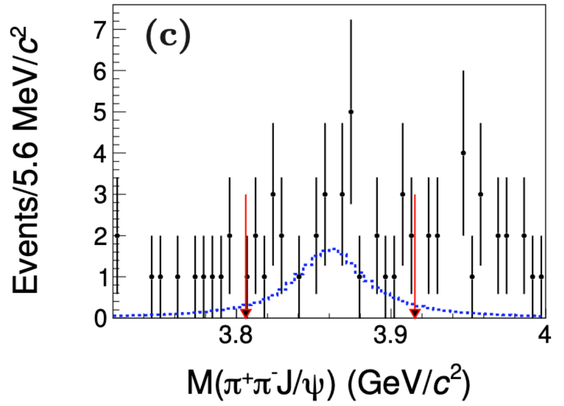

$[(3860.0 \pm 10.4)\ \mathrm{MeV}/c^2,\ \ < 51\ \mathrm{MeV}]$

arXiv:2403.16811



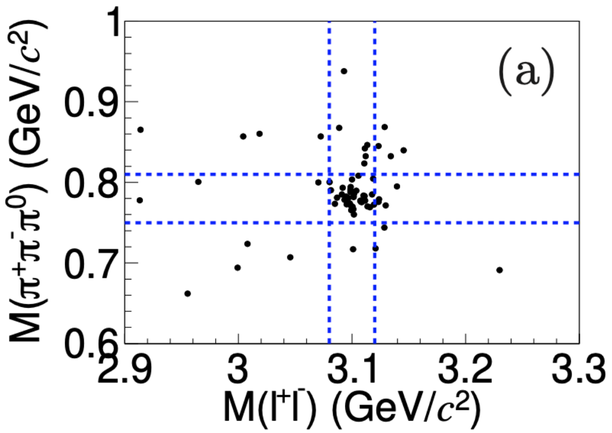



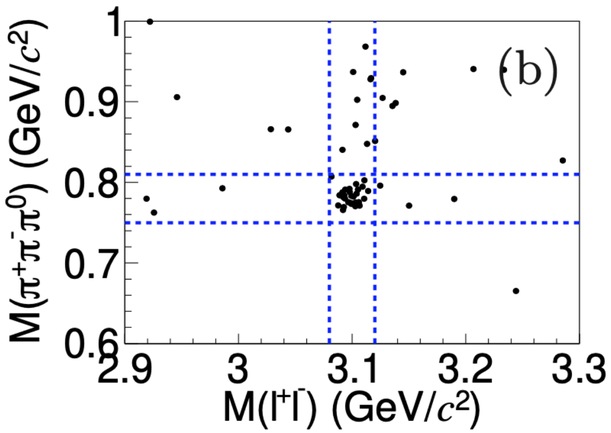
# Observations in $\omega\chi_{c1}$ and $\omega\chi_{c2}$

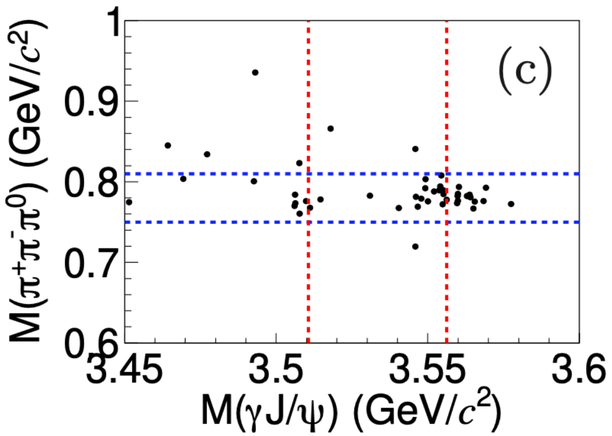
- 11.0 fb$^{-1}$ data sample from 4.308 to 4.951 GeV

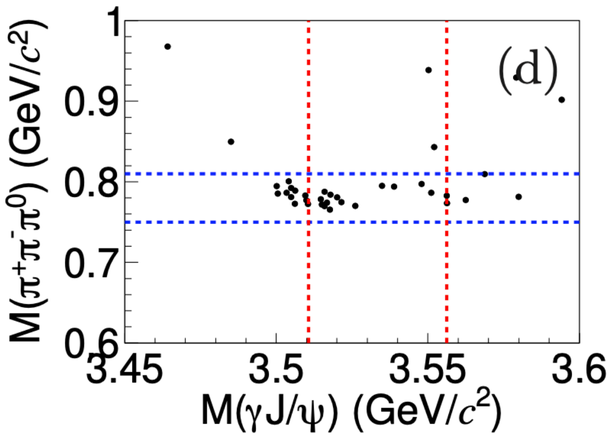
4436 sample

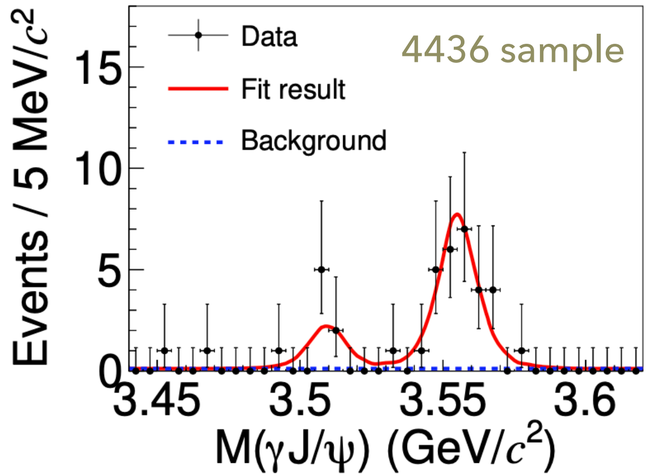


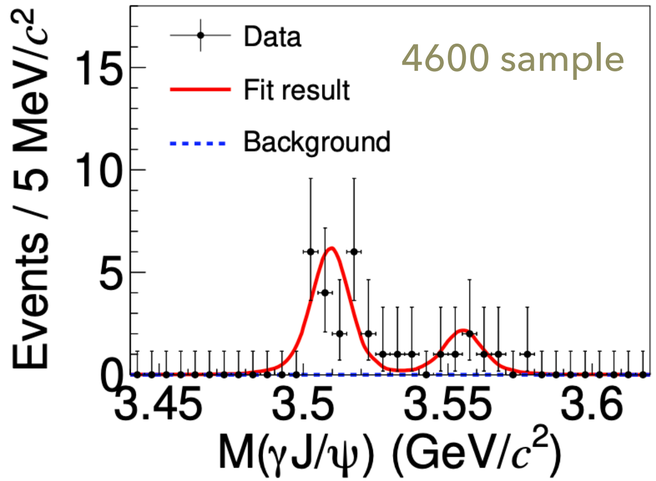

4600 sample



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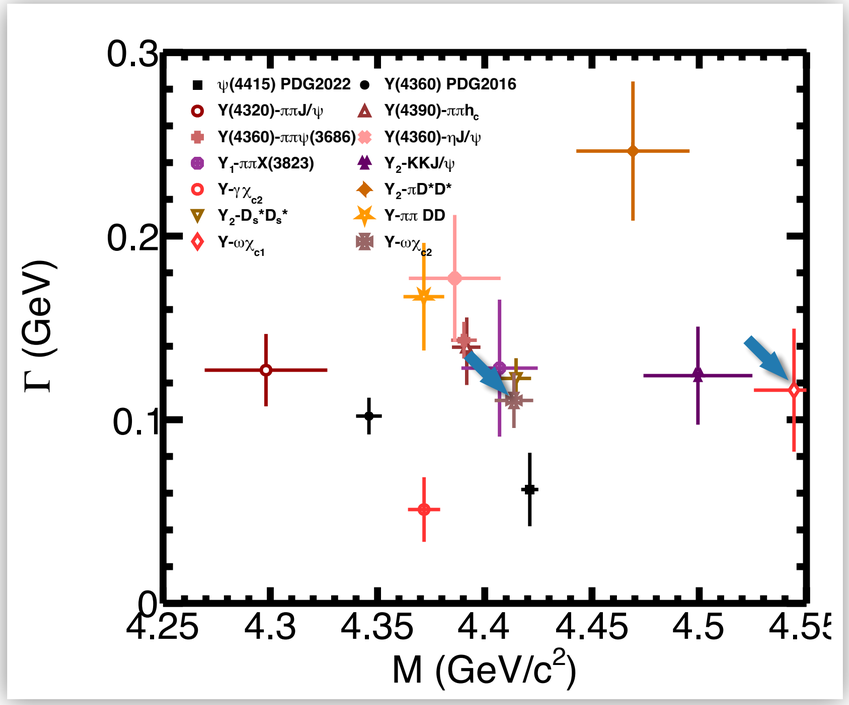
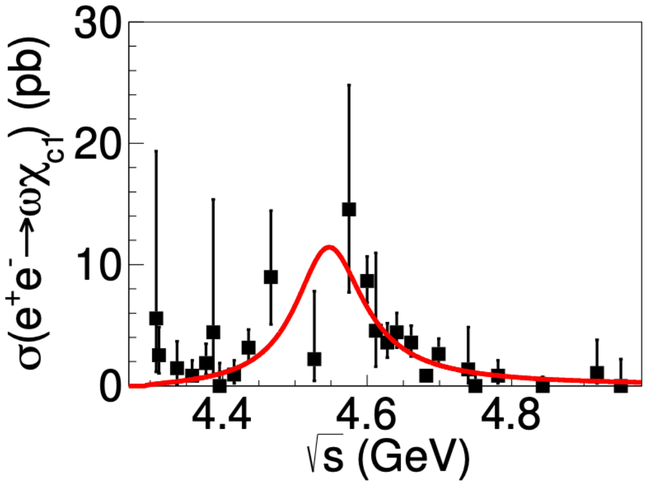
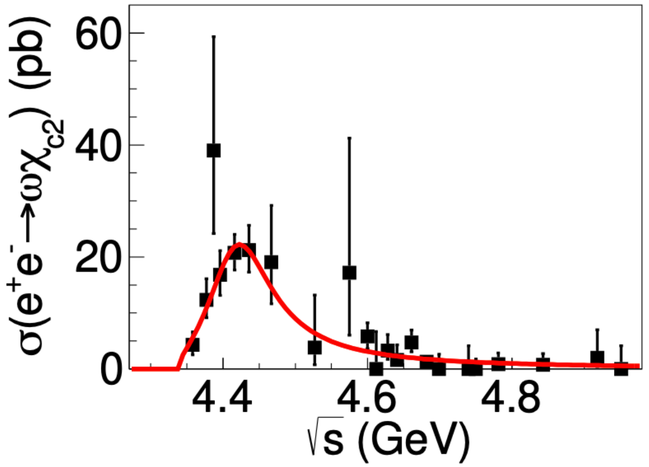


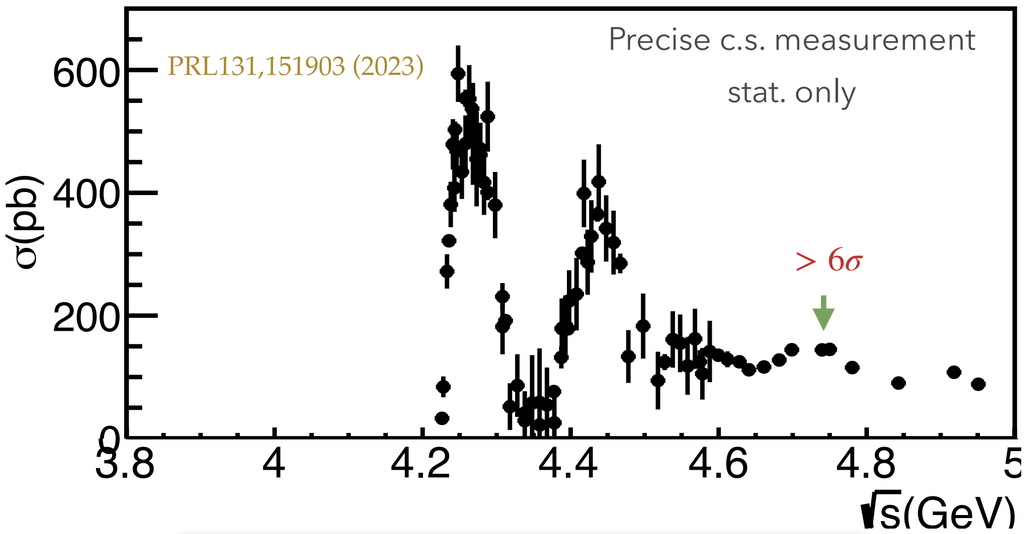



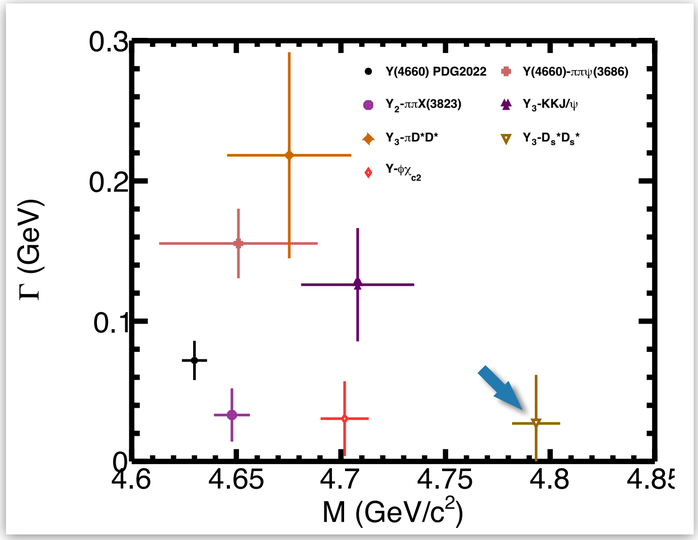

- $M = 4544.2 \pm 18.7 \pm 1.7$ MeV/$c^2$
  $\Gamma = 116.1 \pm 33.5 \pm 1.7$ MeV
- Significance over PHSP: $5.8\sigma$
- Mass higher than structure seen in $KKJ/\psi$ and $\pi D^*D^*$

- $M = 4413.6 \pm 9.0 \pm 0.8$ MeV/$c^2$
  $\Gamma = 110.5 \pm 15.0 \pm 2.9$ MeV
- Significance over PHSP: $10.7\sigma$
- Parameters consistent with $\psi(4415)$

arXiv:2401.14720, accepted by PRL

# Precise CS Measurement of Open Charm Processes



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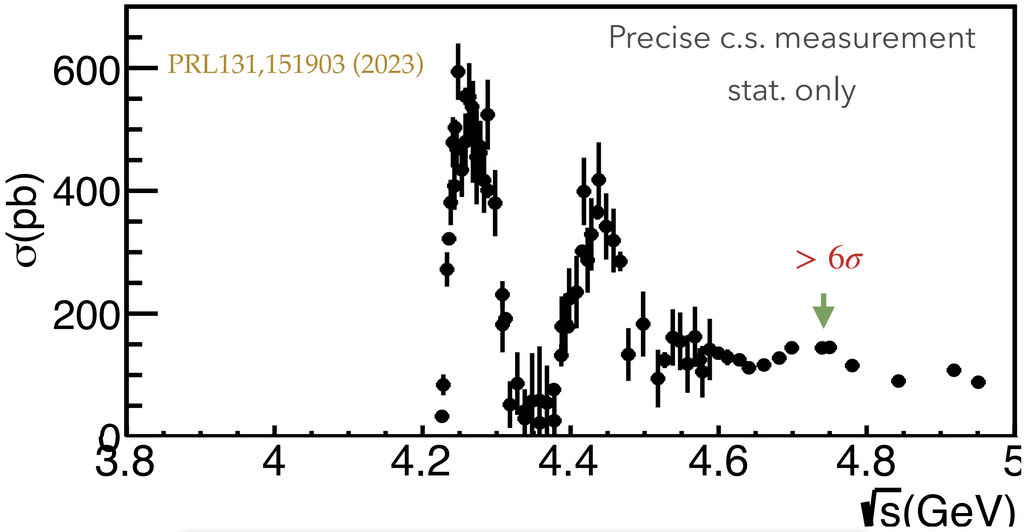
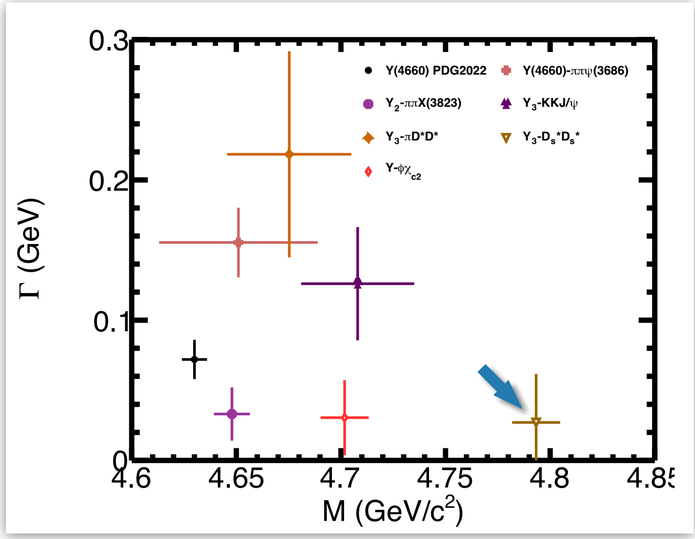
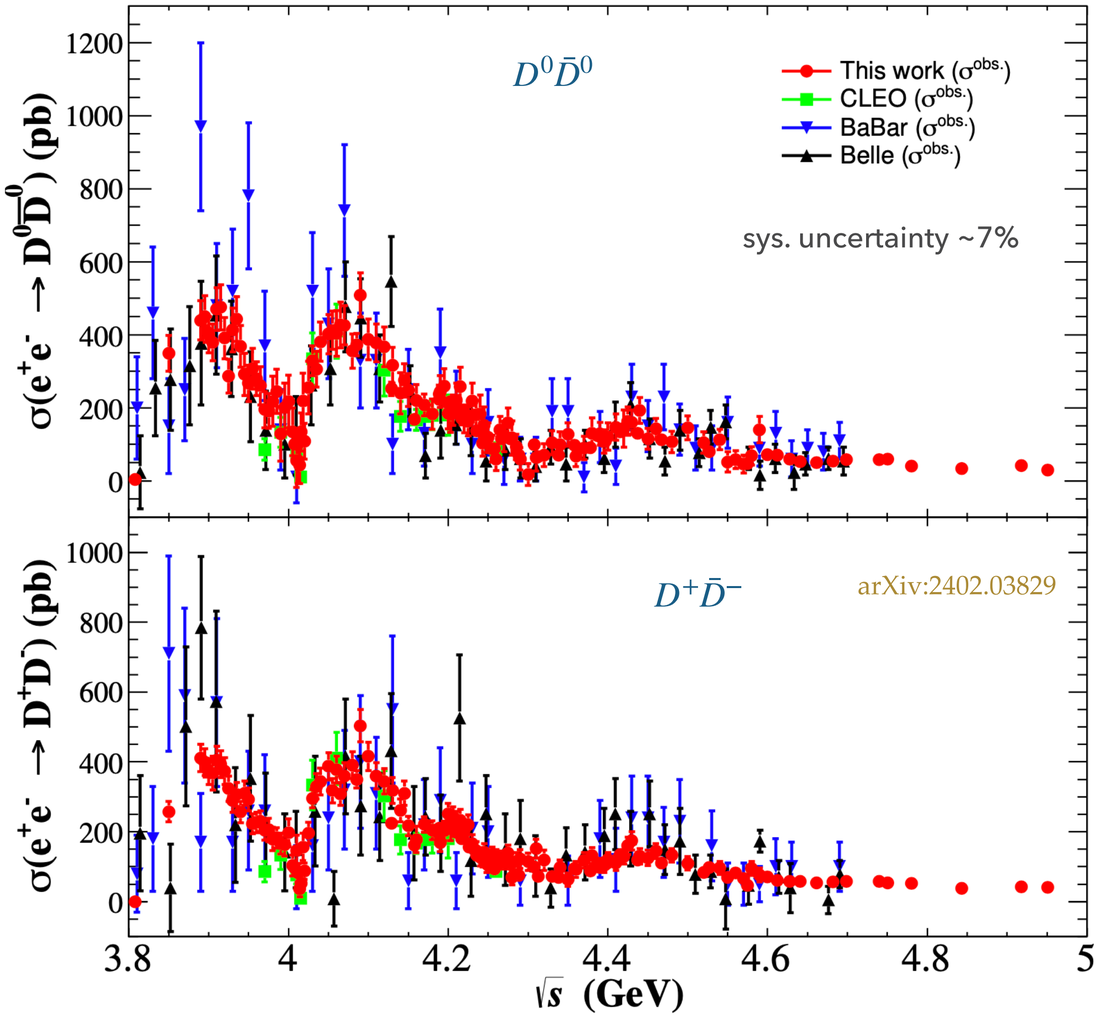
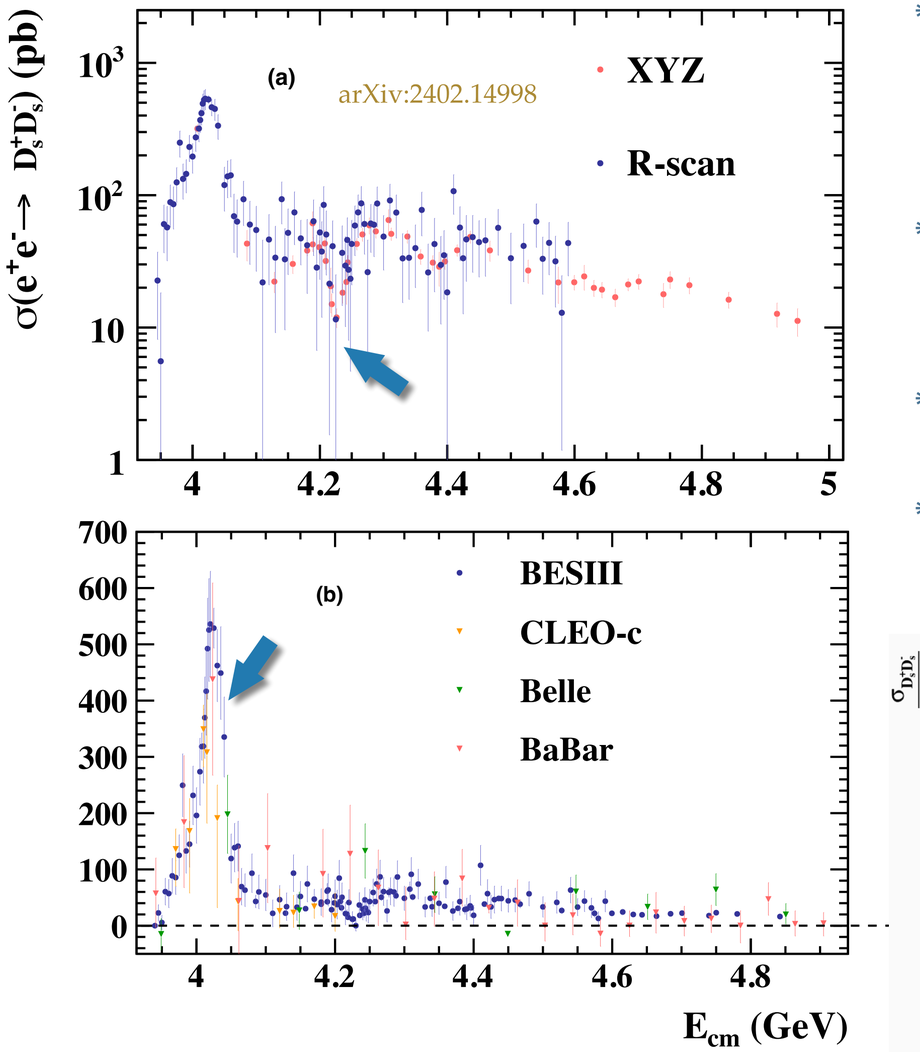


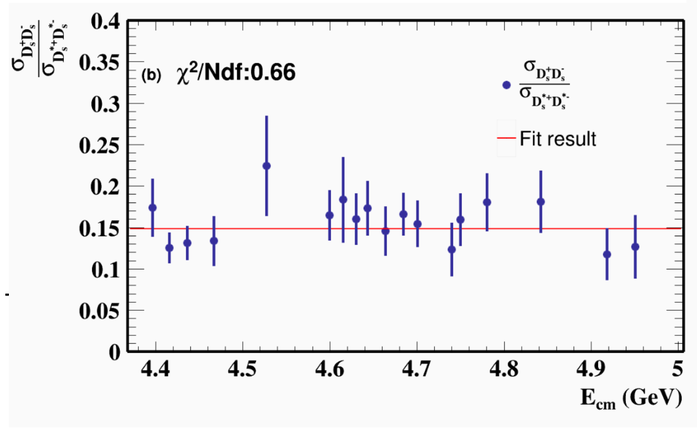



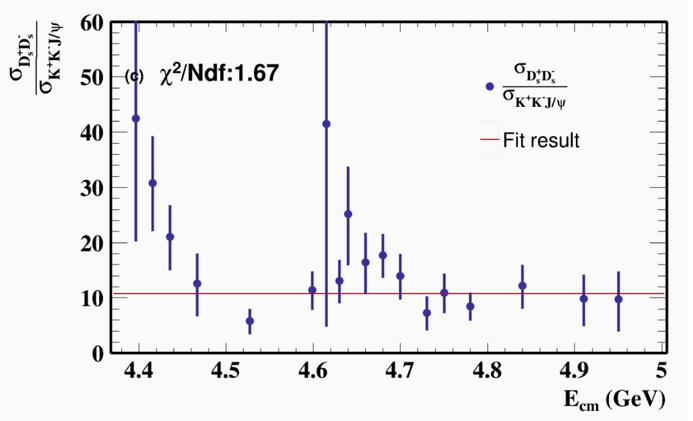



# Precise CS Measurement of Open Charm Processes

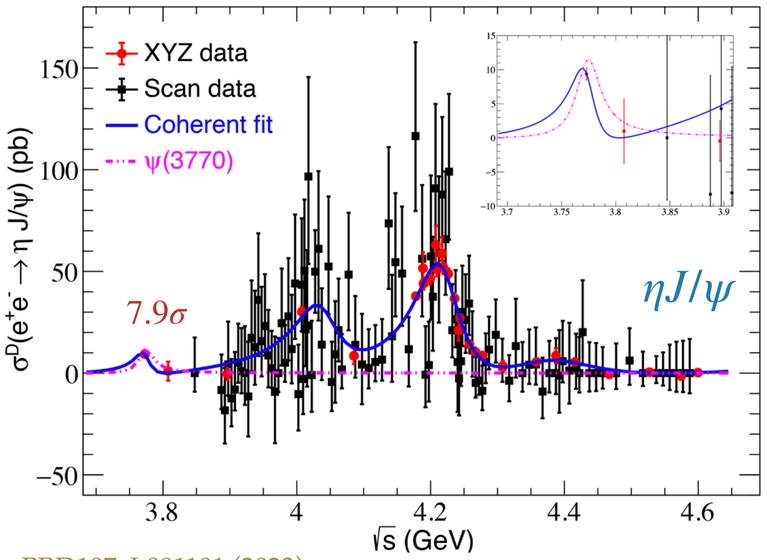


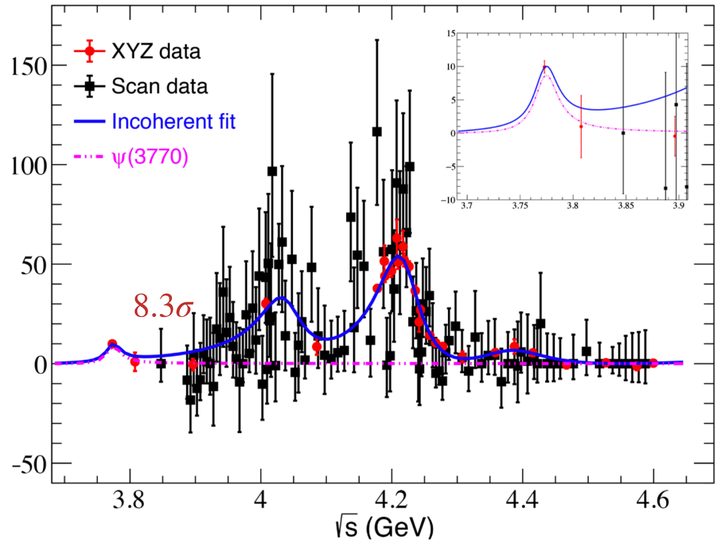

- Cross section peaks above the threshold, implies the presence of a strong coupled channel effect (E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, T. M. Yan, PRD21, 203 (1980))
- Maximum cross section around 4.02 GeV higher than previous studies using ISR method
- A narrow dip around 4.23 GeV, close to $D_s^{*+}D_s^{*-}$ threshold
- Constant ratio to $D_s^{*+}D_s^{*-}$, where a structure around 4.78 GeV is observed



# Non-DD Decay of ψ(3770)




PRD107, L091101 (2023)

$\sigma^B = (8.88 \pm 0.87 \pm 0.42)$ pb

| Parameters | Coherent fit | | | | Incoherent fit |
|---|---|---|---|---|---|
| | Solution1 | Solution2 | Solution3 | Solution4 | |
| $M_1$(MeV/$c^2$) | 3773.7 (fixed) | | | | 3773.7 (fixed) |
| $\Gamma_1$(MeV) | 27.2 (fixed) | | | | 27.2 (fixed) |
| $C_0$ | $13.3 \pm 1.9$ | | | | $11.0 \pm 1.6$ |
| $\mathcal{B}r_1(\times 10^{-4})$ | $11.3 \pm 5.9 \pm 1.1$ | $11.6 \pm 6.0 \pm 1.1$ | $11.2 \pm 5.8 \pm 1.1$ | $11.5 \pm 6.0 \pm 1.1$ | $8.7 \pm 1.0 \pm 0.8$ |
| $\phi_1$(rad) | $3.9 \pm 0.6 \pm 0.07$ | $4.2 \pm 0.6 \pm 0.09$ | $3.7 \pm 0.6 \pm 0.05$ | $4.1 \pm 0.6 \pm 0.08$ | |

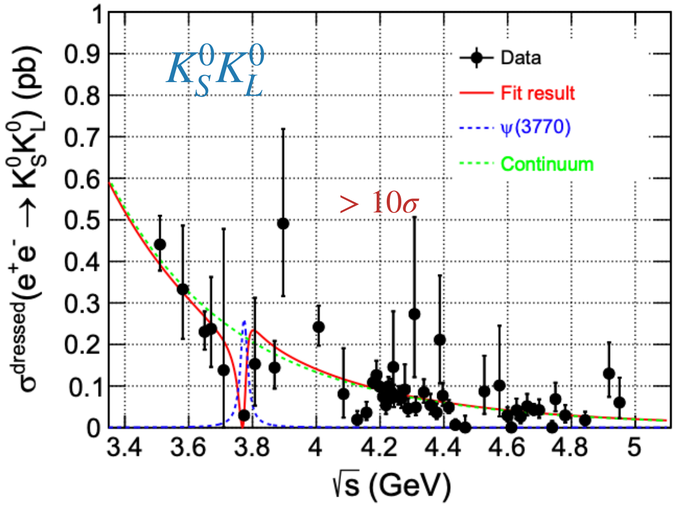
CLEO result: $3.5\sigma$

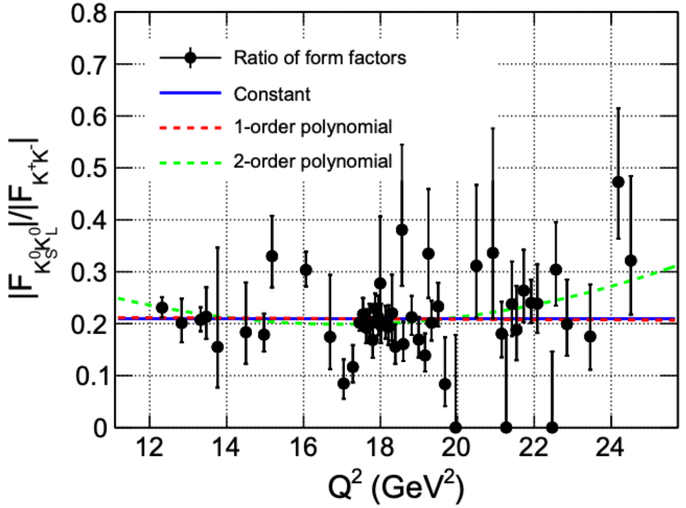
$(8.7 \pm 3.3 \pm 2.2) \times 10^{-4}$

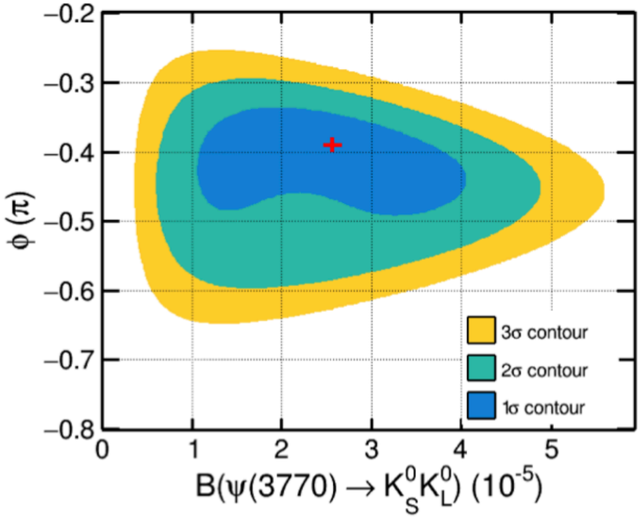
interference between $\psi(3770)$, continuum, and Y states

# Non-DD Decay of ψ(3770)

PRL132, 131901 (2024)



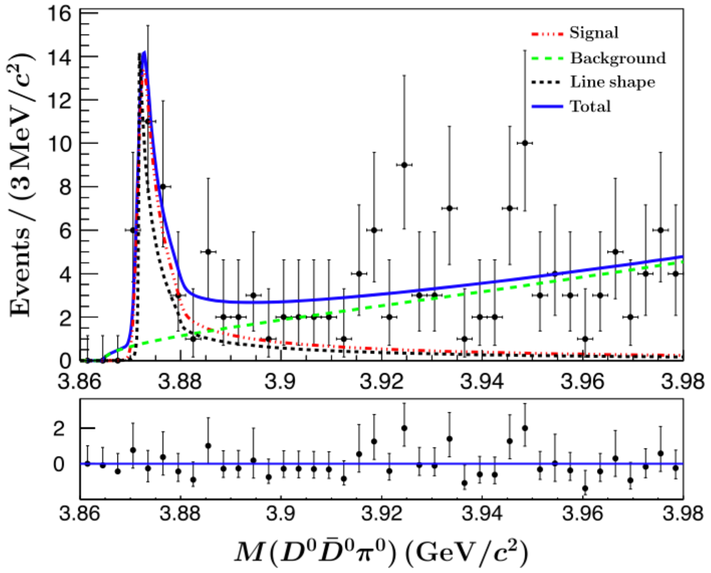



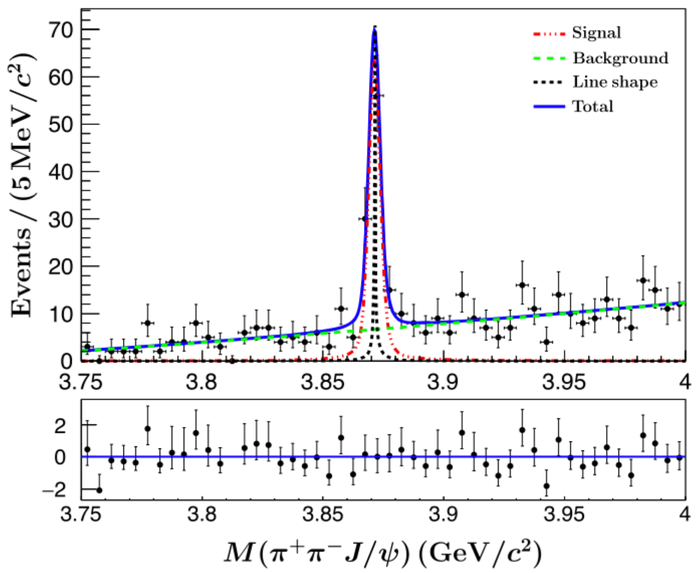



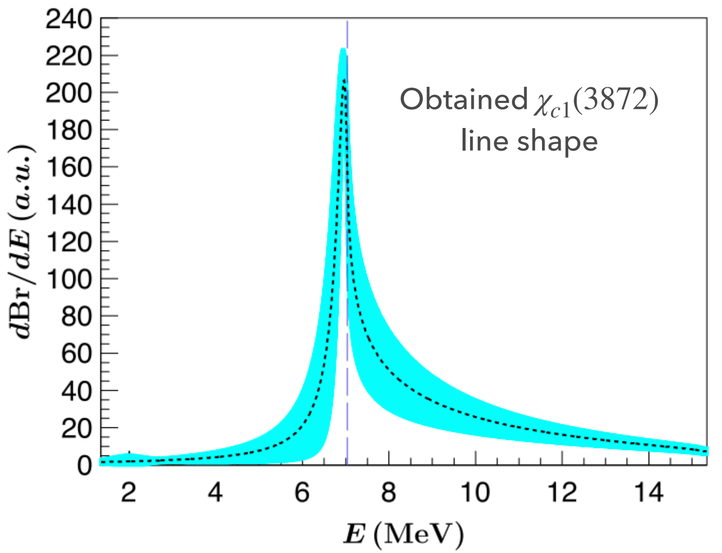

- $\mathcal{B} = (2.63^{+1.40}_{-1.59}) \times 10^{-5}, \phi = (-0.39^{+0.05}_{-0.10})\pi$
- Branching fraction in good agreement with the prediction of the S- and D-wave charmonium mixing model (J. L. Rosner, PRD 64, 094002 (2001), P. Wang, X. H. Mo, C. Z. Yuan, PRD 70, 077505 (2004)))
- $|F_{K^0_S K^0_L}|/|F_{K^+K^-}| = 0.21 \pm 0.01$, indicates a small but significant effect of flavor-SU(3) breaking in the kaon wave function, excludes the possibility that flavor-SU(3) breaking is the primary reason for the strong experimental violation of the pQCD production of $|F(\pi^\pm)|/|F(K^\pm)| = f_\pi^2/f_K^2$

Evidence also seen in baryon pair processes

# Line Shape of X(3872)



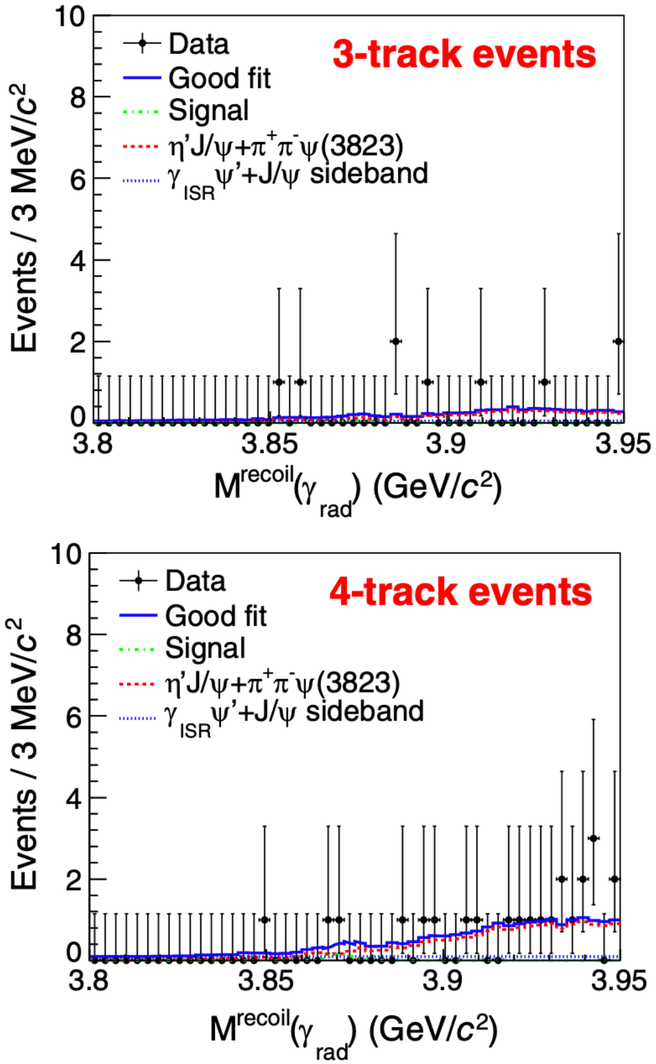




- Effects of the couple-channels and the off-shell $D^{*0}$ are included in the parameterization
- Line share mass:
  $M_X = (3871.63 \pm 0.13^{+0.06}_{-0.05})$ MeV
- Weinberg's compositeness: Z=1 - pure elemental state; Z=0 -pure bound state

| Parameters | BESIII | LHCb |
|---|---|---|
| g | $0.16 \pm 0.010^{+1.12}_{-0.11}$ | $0.108 \pm 0.003^{+0.005}_{-0.006}$ |
| Re[EI] (MeV) | $7.04 \pm 0.15^{+0.07}_{-0.08}$ | 7.10 |
| Im[EI] (MeV) | $-0.19 \pm 0.08^{+0.14}_{-0.19}$ | -0.13 |
| $\Gamma[\pi^+\pi^- J/\psi]/\Gamma[D^0\bar{D}^{*0}]$ | $0.05 \pm 0.01^{+0.01}_{-0.02}$ | $0.11 \pm 0.03$ |
| FWHM (MeV) | $0.44^{+0.13+0.38}_{-0.35-0.25}$ | $0.22^{+0.06+0.25}_{-0.08-0.17}$ |
| Z | 0.18 | 0.15 (0.33) |

# Decays of X(3872)

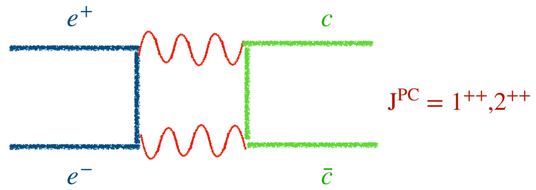


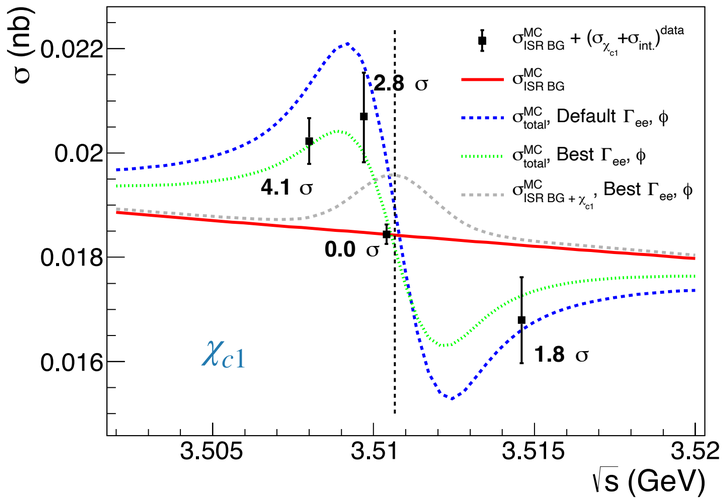

- 10.9 fb$^{-1}$ data samples from 4.16 to 4.34 GeV
- Decay ratio of $X(3872) \to \pi^0\chi_{c1}$ and $X(3872) \to \pi^+\pi^-\chi_{c1}$ can be used to discriminate theoretical interpretations for the nature of $X(3872)$
  - $\approx 0.04$ for $\chi_{c1}(2P)$
  - Enhanced if it is a shallow bound state of a $\bar{D}^0 D^{*0}$ pair
- No obvious signal is found in data,
  $$R = \frac{B[\chi_{c1} \to \pi^+\pi^-\chi_{c1}]}{B[\chi_{c1} \to \pi^+\pi^- J/\psi]} < 0.18 \text{ at } 90\% \text{ C. L.}$$
- $\frac{\Gamma[\chi_{c1}(3872) \to \chi_{c1}\pi^0]}{\Gamma[\chi_{c1}(3872) \to \chi_{c1}\pi^+\pi^-]} > 5$, two orders of magnitude greater than expectation for $\chi_{c1}(2P)$

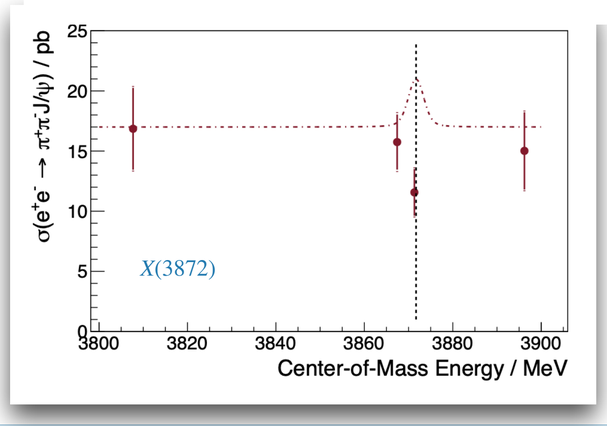
PRD09, L071101 (2024)

# New Production Mechanism of C-even States

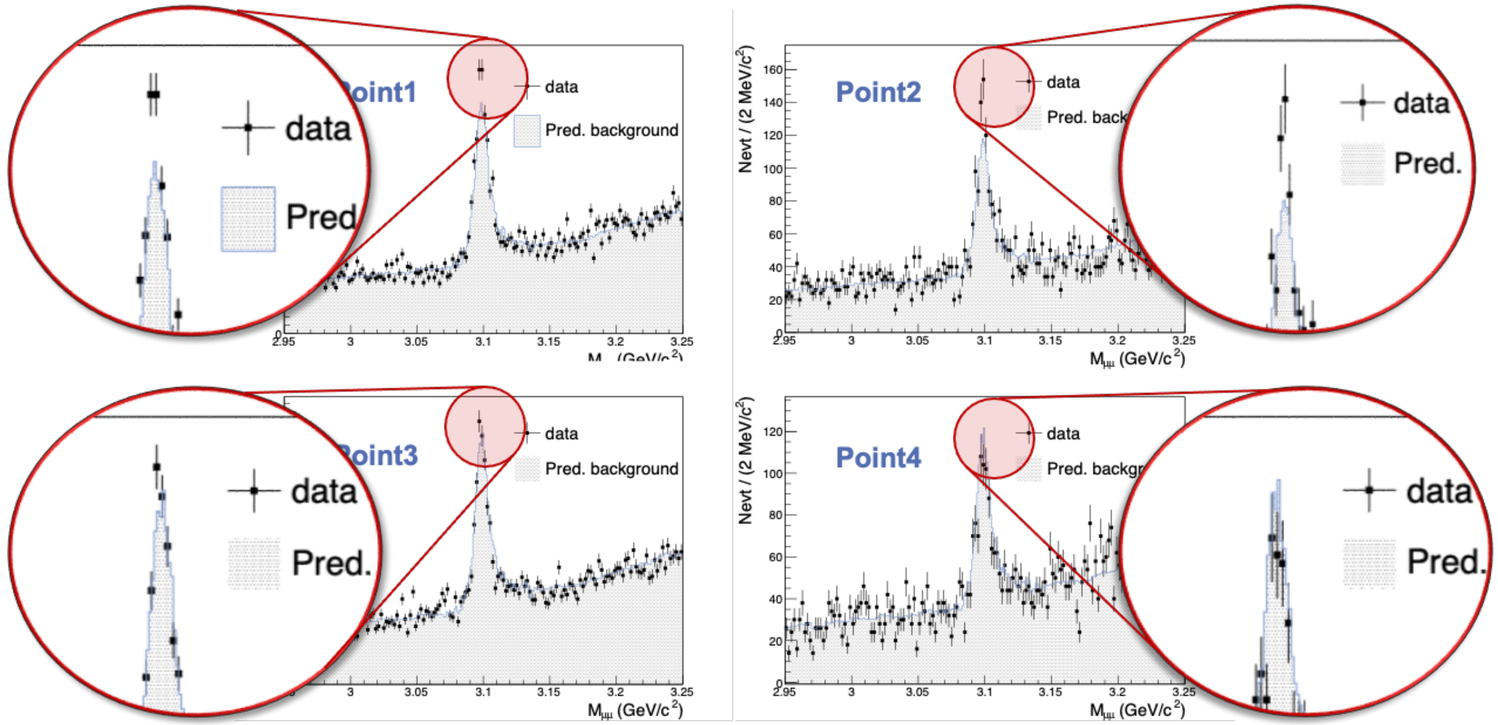
- Dedicated scan sample around the resonance
- Careful study of background process and interference effect!



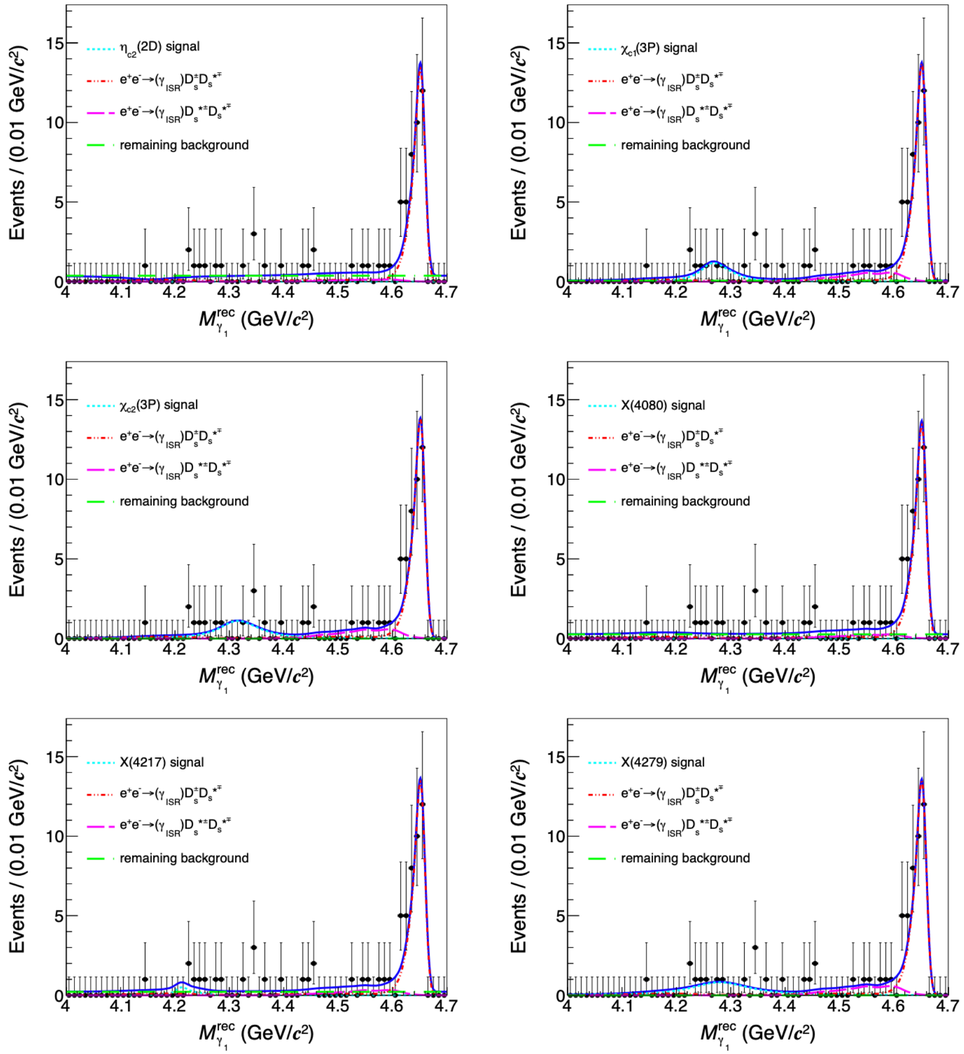




PRD 107 (2023) 032007




PRL 129 (2022), 122001

# C-even States in Radiative Transition Process




hybrid

| State | $M$ (MeV/$c^2$) | $\Gamma$ (MeV) | $\Gamma_{D_s^\pm D_s^{*\mp}}$ (MeV) | $J^{PC}$ |
|---|---|---|---|---|
| $\eta_{c2}(2D)$ [4] | 4158 | 111 | 18 | $2^{-+}$ |
| $\chi_{c1}(3P)$ [4] | 4271 | 39 | 9.7 | $1^{++}$ |
| $\chi_{c2}(3P)$ [4] | 4317 | 66 | 11 | $2^{++}$ |
| $X(4080)$ [20] | 4082.55 | 5 | - | $1^{++}$ |
| $X(4217)$ [9–11] | 4217 | 6 | 6 | $1^{-+}$ |
| $X(4279)$ [9–11] | 4279 | 110 | 34 | $0^{-+}$ |

Molecula: X, K, Dong, F. K. Guo, B. S. Zou, Progr. Phys. 41, 65 (2021)
hybrid states: G.K.Cheung. (Hadron Spectrum Collaboration) JHEP 12, 089 (2016)
C. Farina, H. Garcia Tecocoatzi, A. Giachino, E. Santopinto, E. S. Swanson, PRD102, 014023 (2020)

| | $\eta_{c2}(2D)$ | $\chi_{c1}(3P)$ | $\chi_{c2}(3P)$ | $X(4080)$ | $X(4217)$ | $X(4279)$ |
|---|---|---|---|---|---|---|
| $f^r$ | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 |
| $f^v$ | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 |
| $N_{\rm sig}^{\rm UL}$ | 6.7 | 16.3 | 18.7 | 2.4 | 7.6 | 19.6 |
| $N_{\rm sig}$ | $-5.6^{+4.2}_{-3.2}$ | $9.8^{+5.2}_{-4.4}$ | $13.0^{+4.5}_{-3.9}$ | $-0.9^{+0.3}_{-0.2}$ | $2.3^{+3.0}_{-2.4}$ | $13.8^{+4.5}_{-3.8}$ |
| Significance ($\sigma$) | 1.3 | 2.6 | 3.1 | – | 0.9 | 3.3 |
| $\bar{\epsilon}$ ($10^{-4}$) | 3.73 | 3.48 | 3.26 | 4.21 | 3.50 | 3.11 |
| $\sigma^{\rm UL}\cdot\mathcal{B}$ with sys. (pb) | 13.3 | 36.3 | 45.5 | 4.1 | 15.7 | 51.7 |

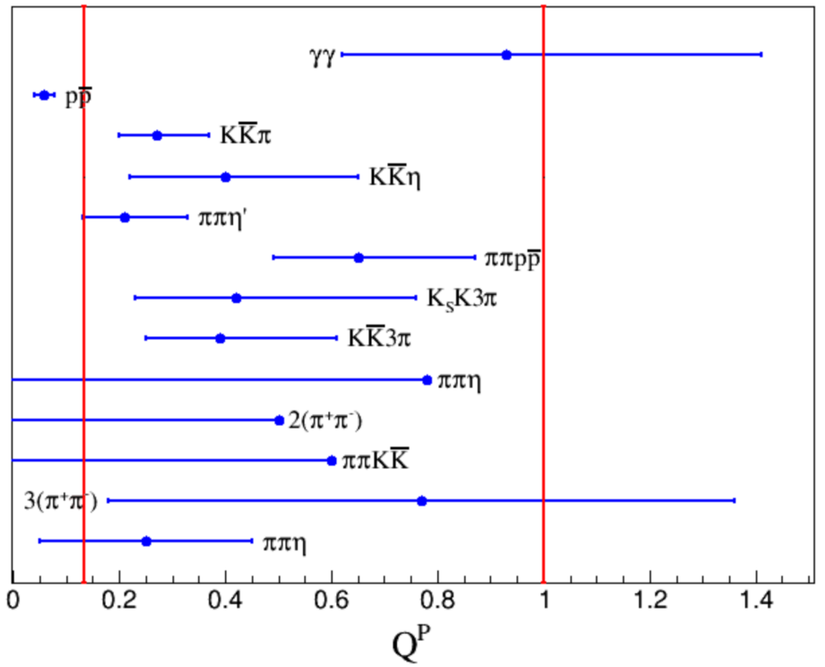
arXiv:2404.02033

# Hadronic Decay of $\eta_c(2S)$

- $Q = \dfrac{\eta_c(2S) \to h}{\eta_c(1S) \to h} \approx 12\%$[M. Anselmino, M. Genovese, E. Predazzi, PRD44, 1597 (1991)] or 100% [K. T. Chao, Y. F. Gu, S. F. Tuan, Commun. Theor. Phys. 25, 471 (1996)]

- Analyzing existing data, the ratios of the branching fractions of $\eta_c(2S)$ and $\eta_c(1S)$ decays into 10 different final states are obtained by H. P. Wang and C. Z Yuan [CPC46, 071001 (2022)]

- Using large $\psi(3686)$ data sample, several hadronic decays of $\eta_c(2S)$ are measured
  - $3(\pi^+\pi^-)$[PRD 106, 032014 (2022)], $\pi^+\pi^-\eta$ [PRD107, 052007 (2023)]
  - $K\bar{K}\eta$, $K\bar{K}\eta'$, $2(\pi^+\pi^-)\eta$, ...



# Summary

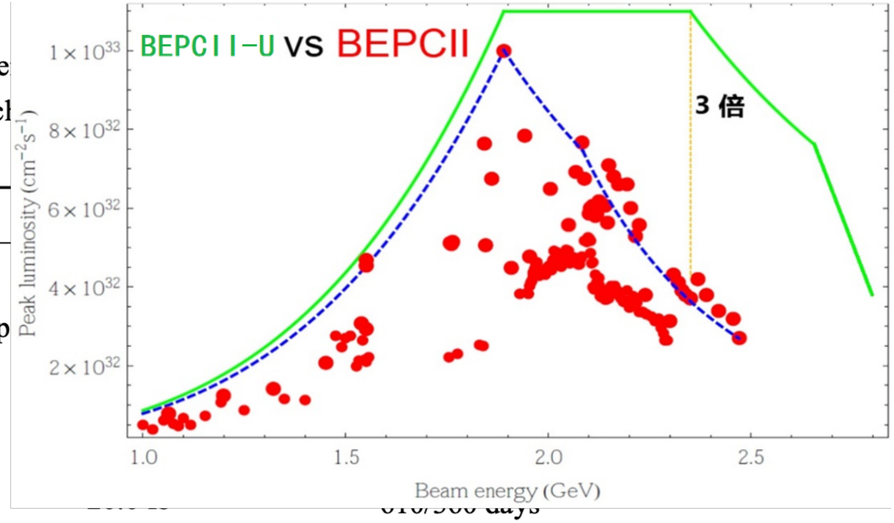
- Properties of vector states have been investigated using various processes, including open charm, hidden charm, and light hadronic final states
  - Y(4230) is seen in 10 decay modes; rich structures in the cross section line shapes above 4.3 GeV, more data samples are needed around 4.5 GeV and 4.7 GeV
  - No evident structure is seen in light hadron process
  - Hard to get a unified picture with current used strategy [use simply formula to fit cross section], require joint effort/better modeling ⇒ combined fit with K-matrix?
  - Interference effect need to be considered properly
- Line shape and new decays of $X(3872)$ investigated ⇒ study in direct electron-positron annihilation process in the future?
- Decay properties studies for lower charmonium states, e.g. hadronic transition, hadronic decays, need refined theoretical predictions

**Thank You!**

# Future Data Samples

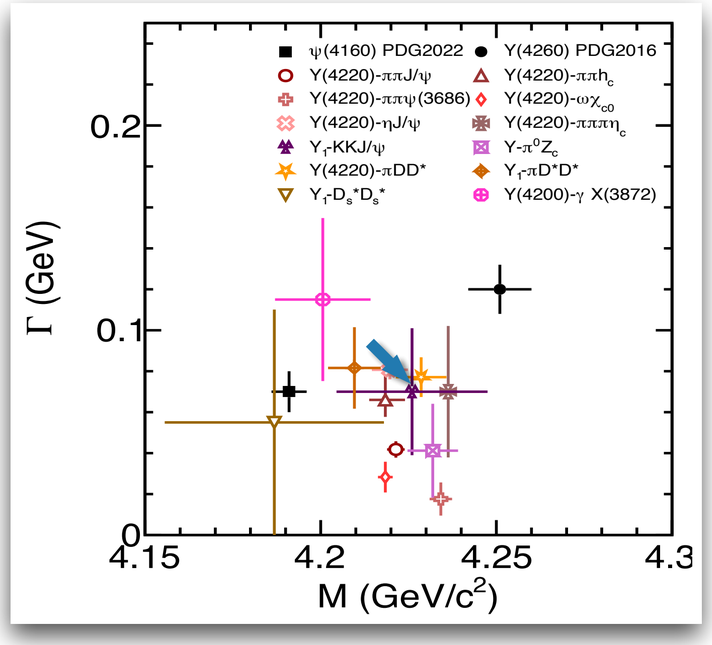
Table 7.1. List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the re
most column shows the number of required data taking days with the current ($T_C$) and upgraded ($T_U$) macl
implementation and beam current increase.

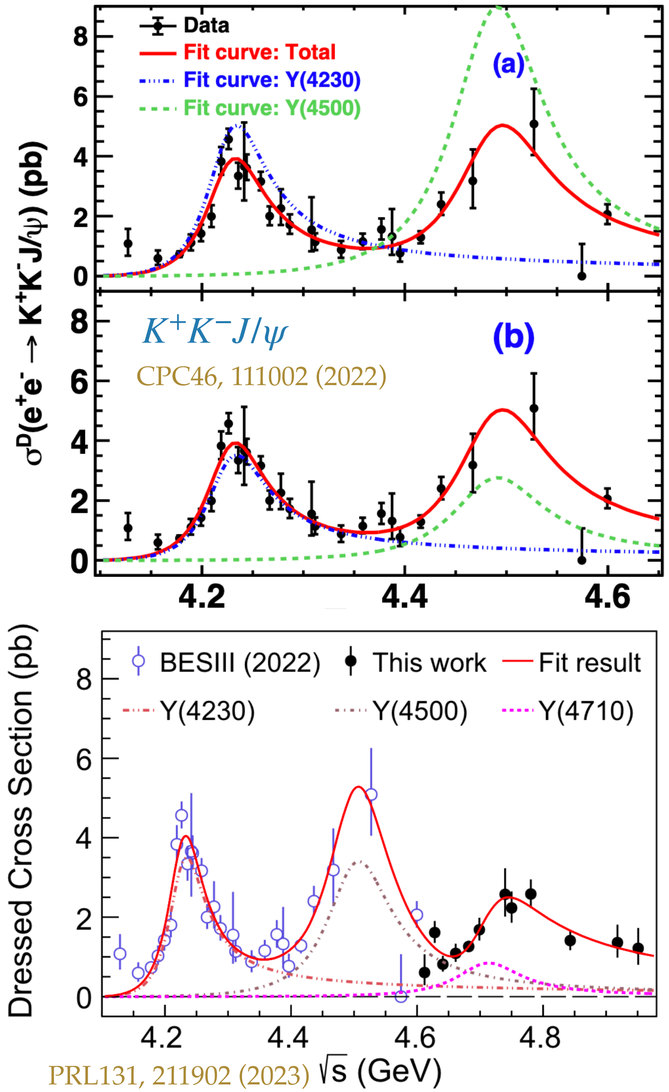
| Energy | Physics motivations | Current data | Comp | | |
|---|---|---|---|---|---|
| 1.8 - 2.0 GeV | $R$ values Nucleon cross-sections | N/A | | | |
| 2.0 - 3.1 GeV | $R$ values Cross-sections | Fine scan (20 energy points) | | | |
| $J/\psi$ peak | Light hadron & Glueball $J/\psi$ decays | 3.2 fb$^{-1}$ (10 billion) | | | |
| $\psi(3686)$ peak | Light hadron & Glueball Charmonium decays | 0.67 fb$^{-1}$ (0.45 billion) | | | |
| $\psi(3770)$ peak | $D^0/D^\pm$ decays | 2.9 fb$^{-1}$ | | | |
| 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 | $\Xi_c$ 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

# Update of $K^+K^-J/\psi$ Cross Section



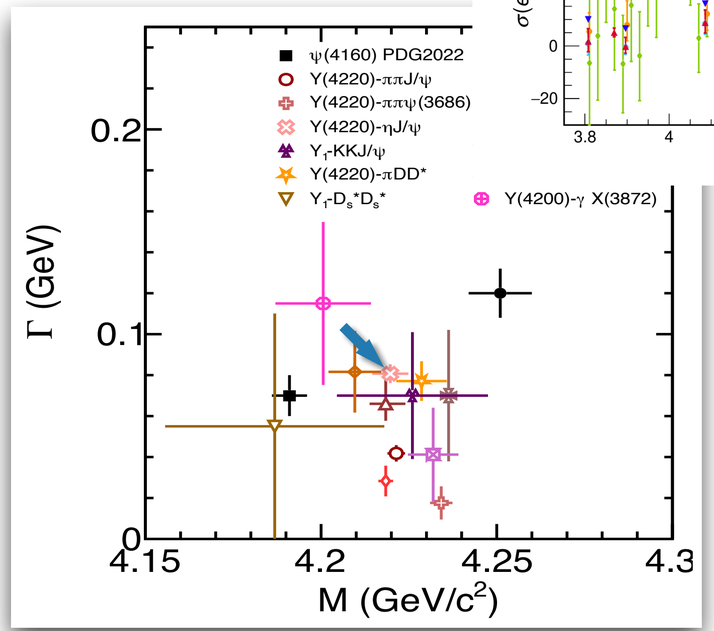

PRL131, 211902 (2023)

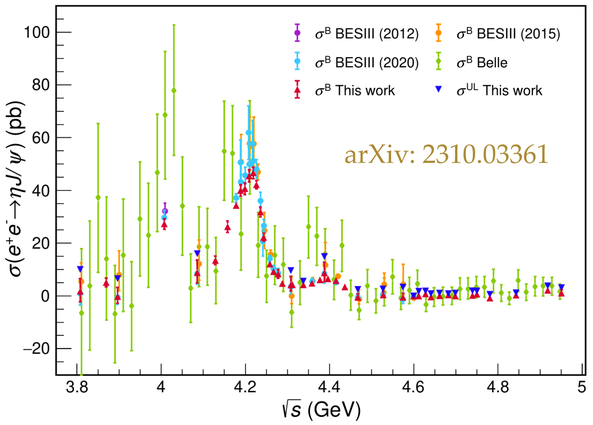
- ML fit with coherent sum of two BWs
- Mass: $4225.3 \pm 2.3 \pm 21.5$ MeV
- Width: $72.9 \pm 6.1 \pm 30.8$ MeV
- Significance $> 5\sigma$

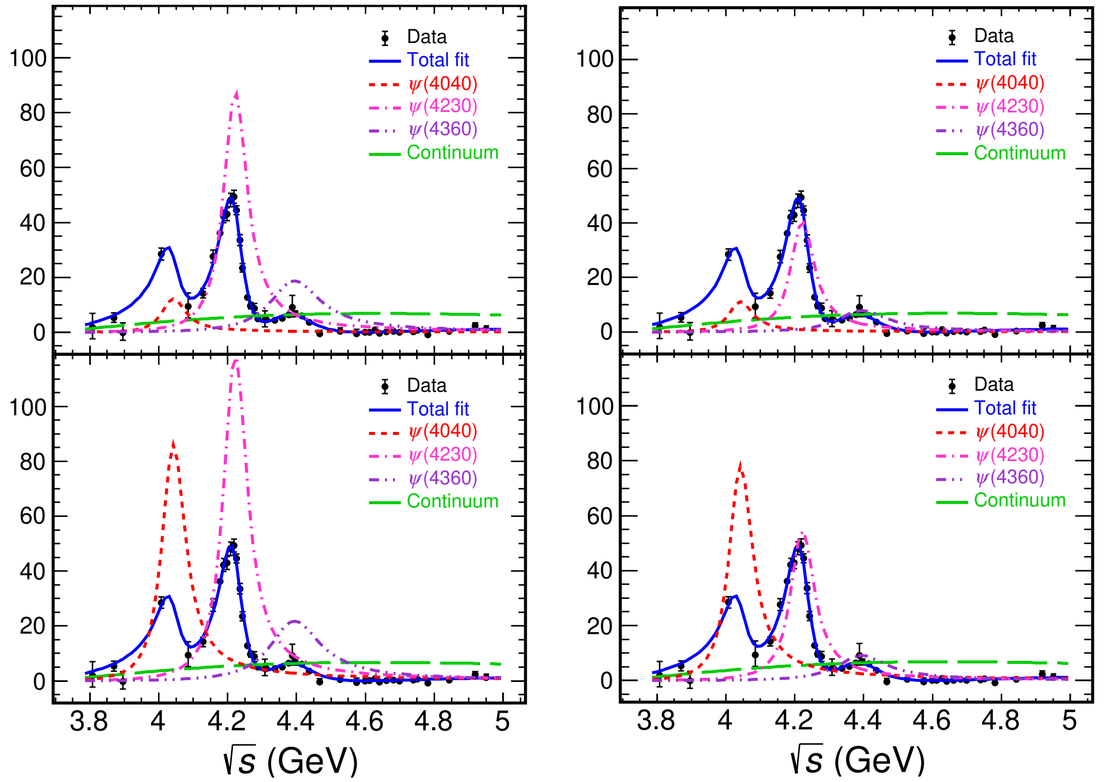
| Ratio to $\pi\pi J/\psi$ | $K\bar{K}J/\psi$ Sol. I | $K\bar{K}J/\psi$ Sol. II |
|---|---|---|
| $\pi\pi J/\psi$ Sol. I | $0.17 \pm 0.02$ | $0.25 \pm 0.04$ |
| $\pi\pi J/\psi$ Sol. II | $0.097 \pm 0.017$ | $0.14 \pm 0.03$ |
| $\pi\pi J/\psi$ Sol. III | $0.035 \pm 0.004$ | $0.051 \pm 0.007$ |
| $\pi\pi J/\psi$ Sol. IV | $0.020 \pm 0.002$ | $0.028 \pm 0.004$ |

- ML fit with coherent sum of three BWs
- Mass: $4226.0 \pm 1.4$ MeV
- Width: $70.0^{+3.9}_{-3.6}$ MeV

# Update of ηJ/ψ Cross Section




- 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 $\Gamma_{ee}$ to be ~0.63-0.66 keV, $\mathcal{B}[\psi(4230) \to \eta J/\psi) =$ $(6.06 \pm 0.76 \pm 0.17) \times 10^{-3}$ or $(18.89 \pm 1.75 \pm 0.90) \times 10^{-3}$