Recent Charmonium and Exotics Study at BESIII

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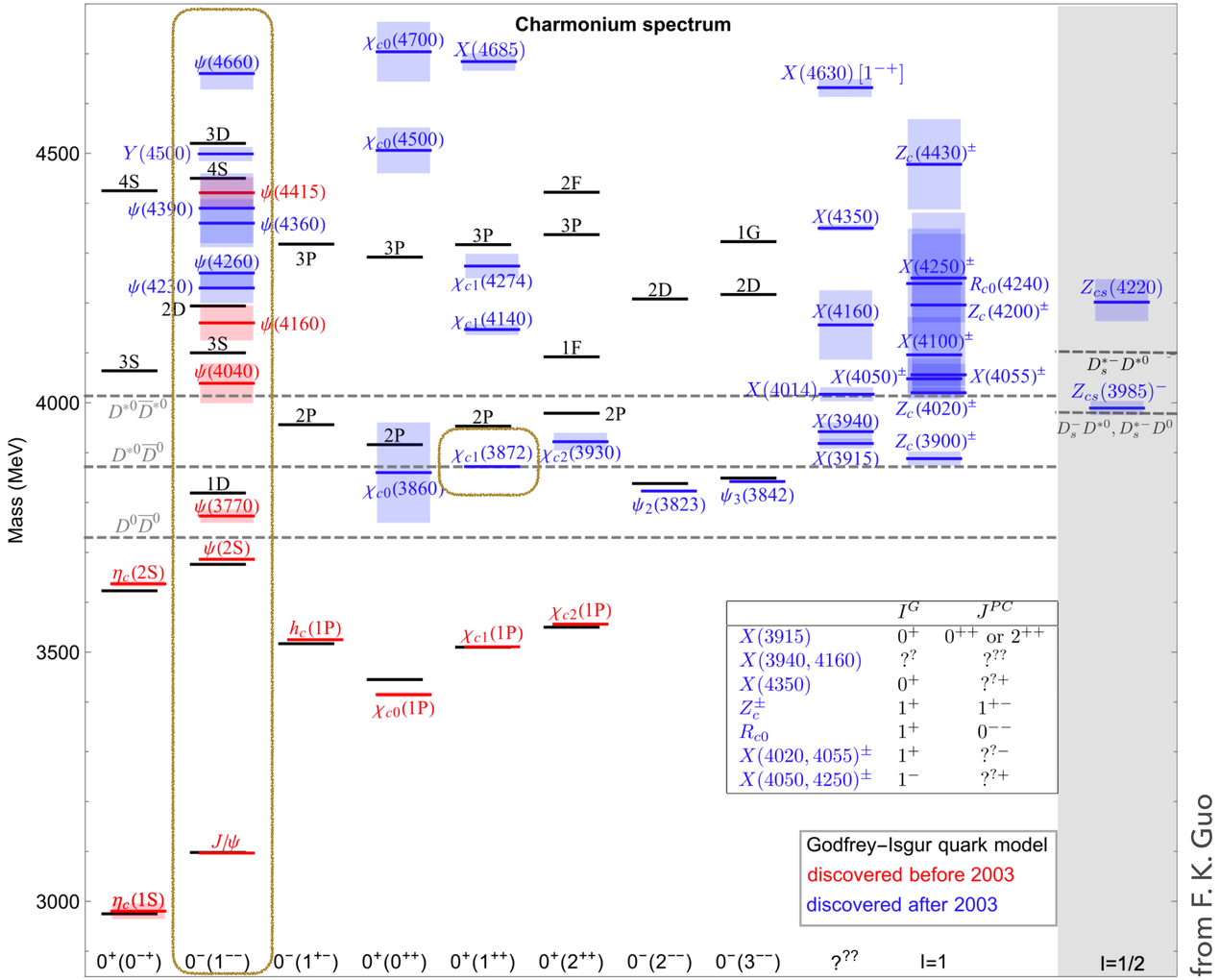
On behalf of BESIII Collaboration

FPCP2024, Thailand

2024.05.27-05.31

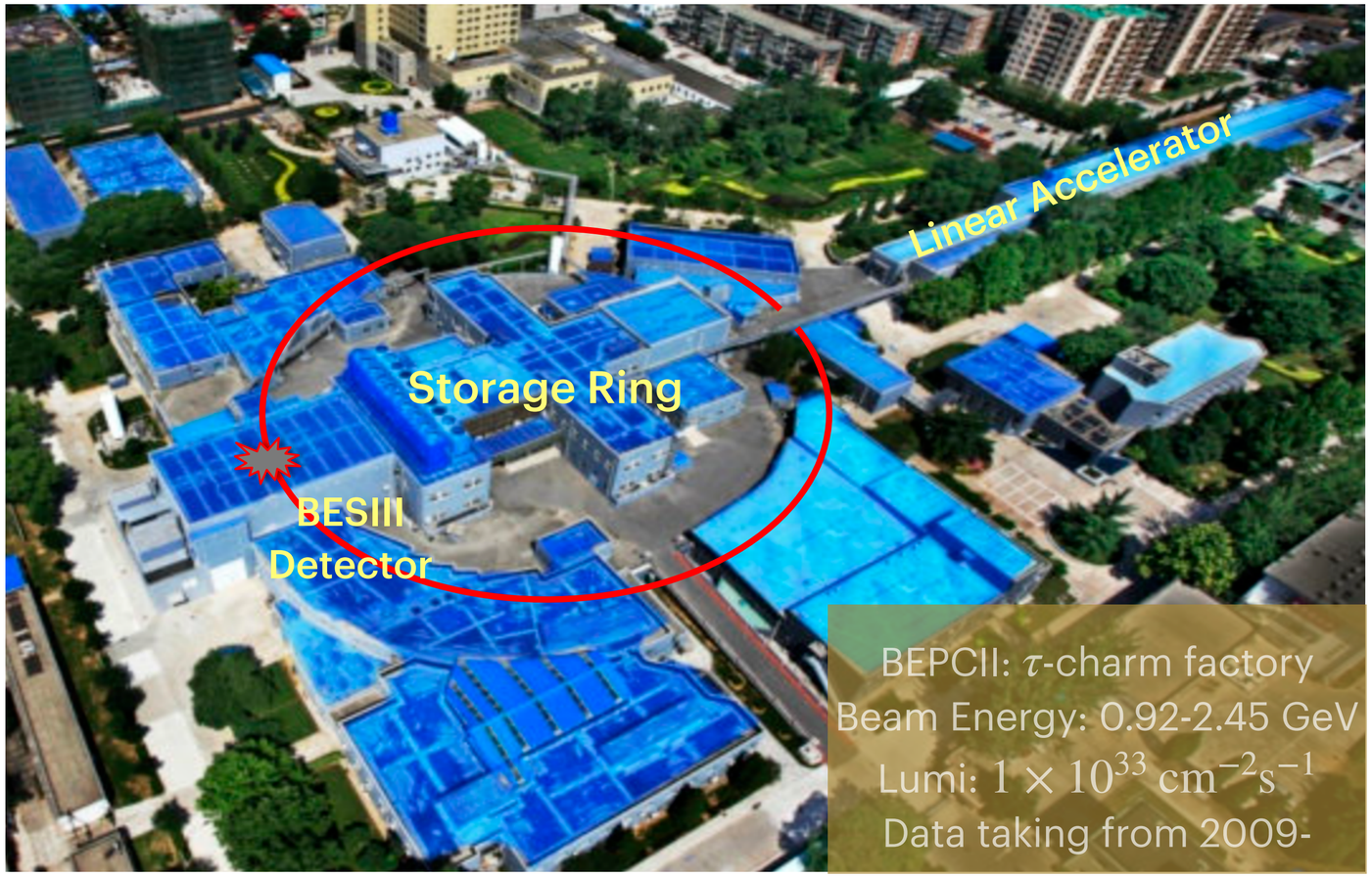
Charmonium Spectroscopy



from F. K. Guo

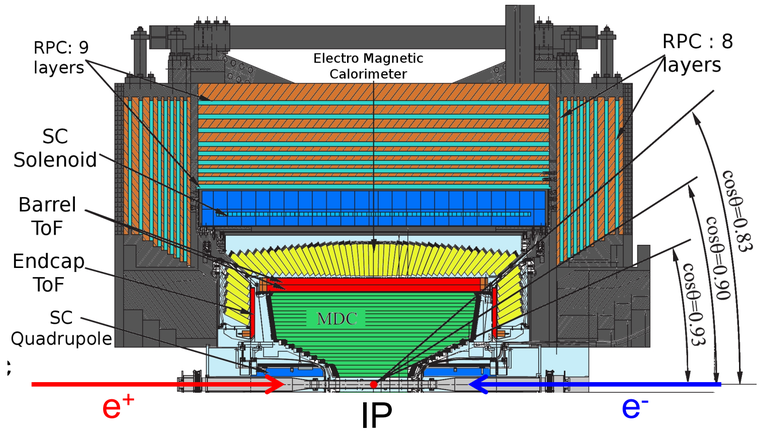
- Selected topics in this talk:
  - Vector charmonium(-like) states
    - Hadronic transitions
    - Precise measurement of the open charm processes
  - New measurements of $X(3872)$
  - Radiative transition in search for C-even states

Beijing Electron Positron Collider II and BESIII



BEPCII: τ-charm factory
Beam Energy: 0.92-2.45 GeV
Lumi: $1 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$
Data taking from 2009-

Solenoid Magnet: 0.9/1.0 T



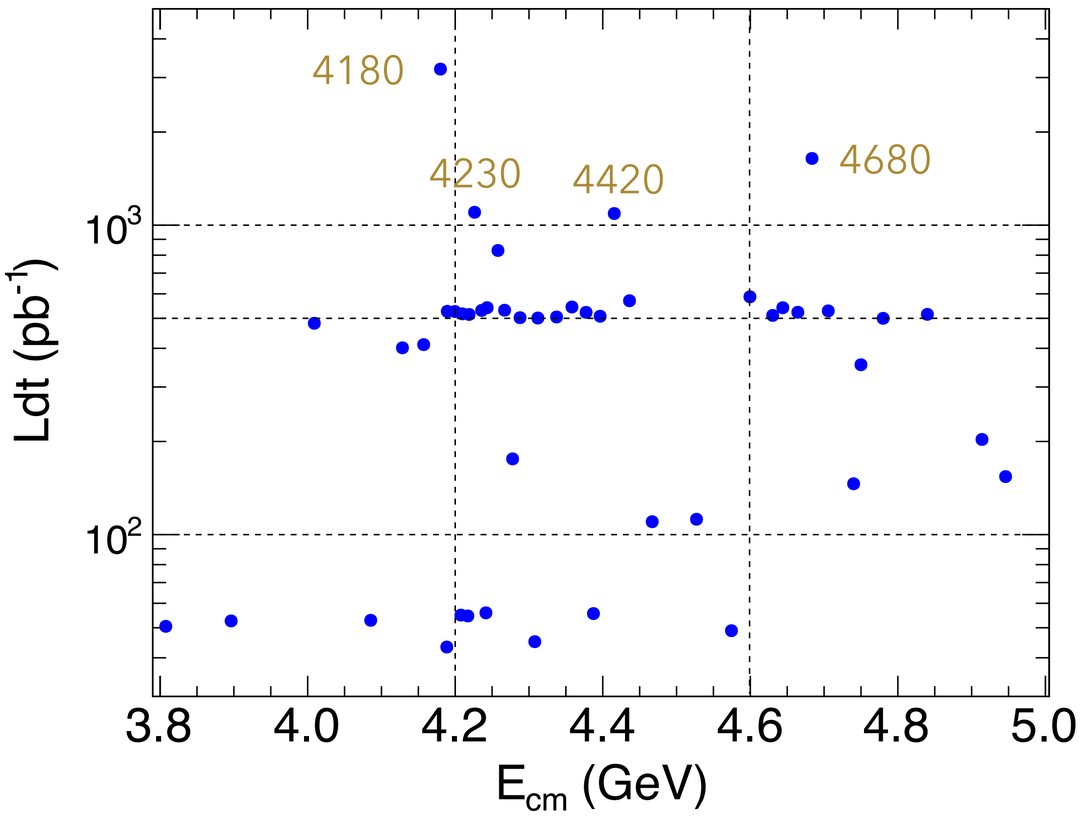
MUC $\sigma_{R\Phi}$: 2 cm

TOF
σ_T :80 ps
110 ps (60 ps)

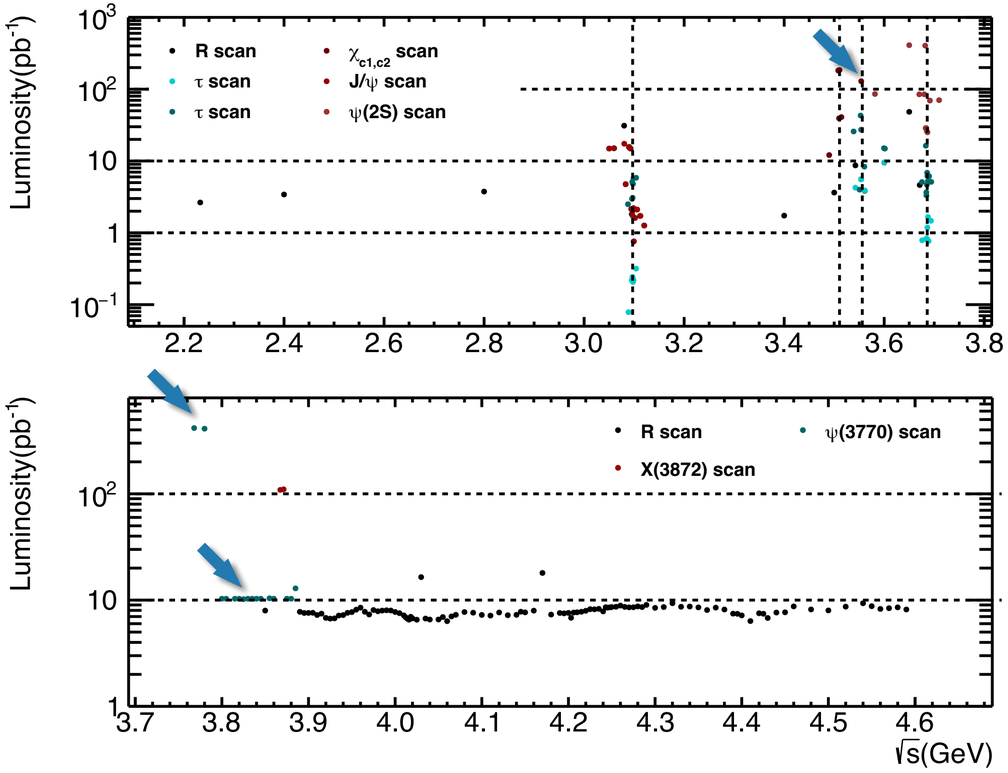
MDC
dE/dx: 6%
σ_p/p: 0.5% at 1GeV/c

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

BESIII Data Samples



46 sample, ~22 fb^{-1}

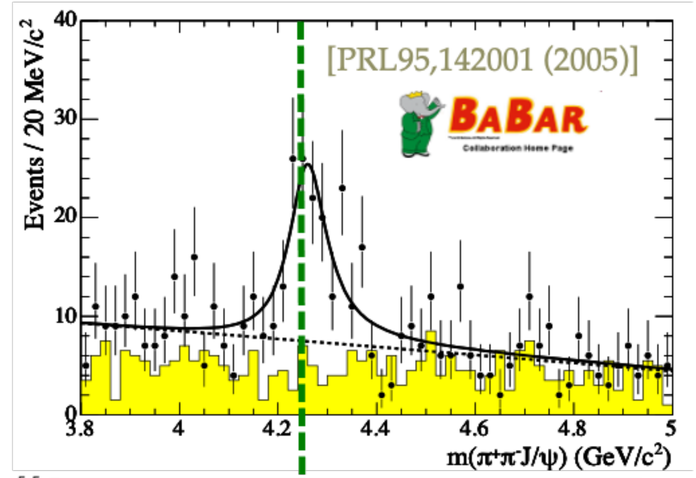


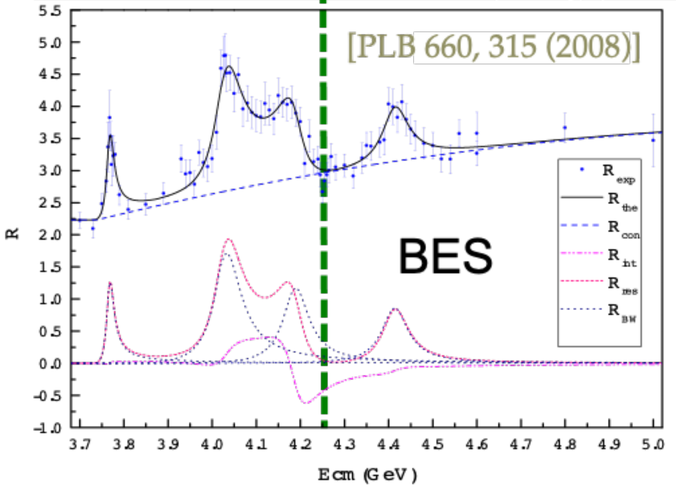
+ Small scan sample, ~3.5 fb^{-1}

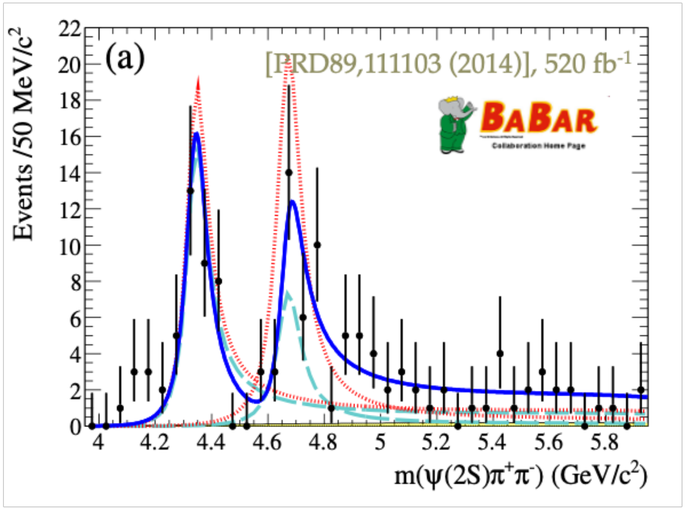
+ 10 Billion J/ψ, 2.7 Billion $\psi(3686)$, 20 fb^{-1} $\psi(3770)$

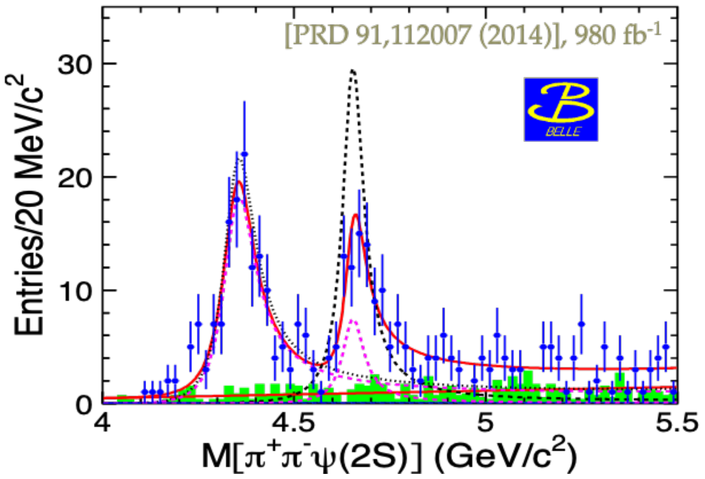
Discovery of Y States

- 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

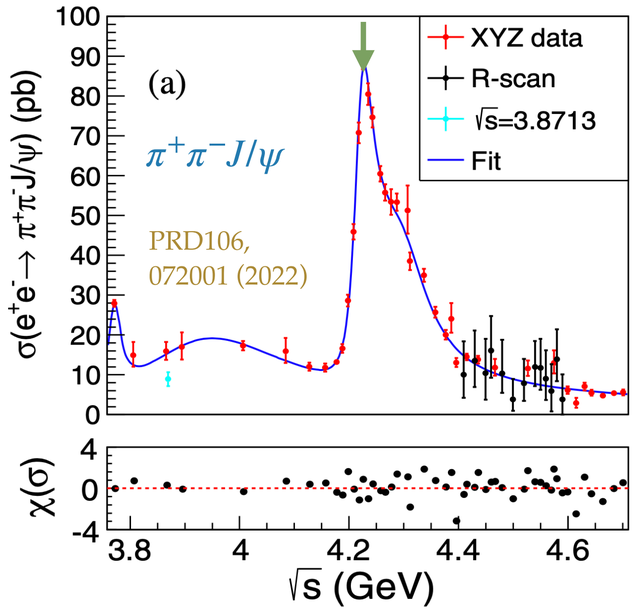


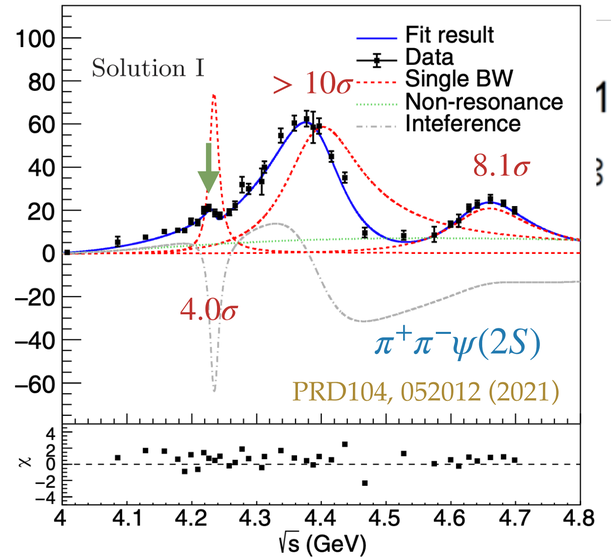


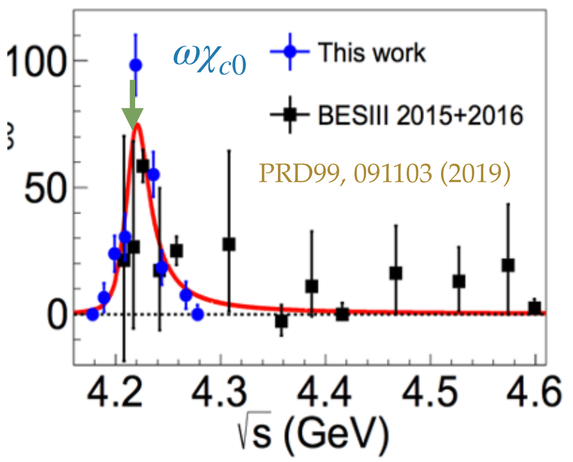




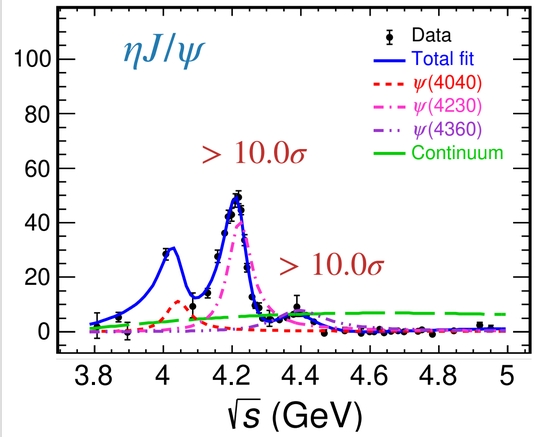
Y(4260) ⇒ Y(4230)

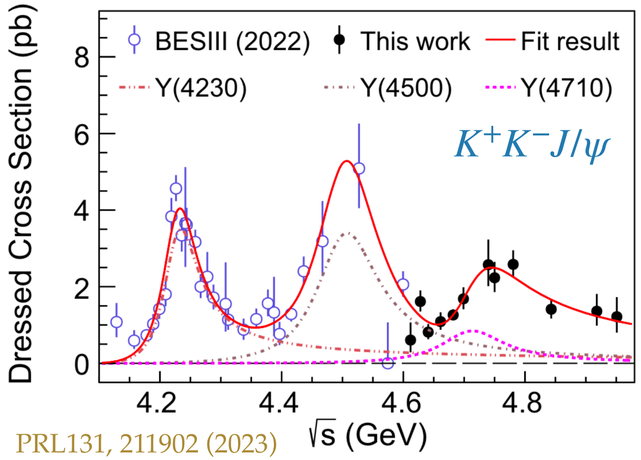




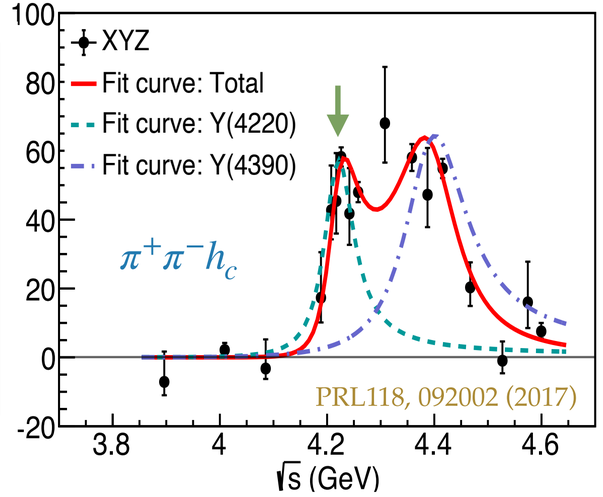


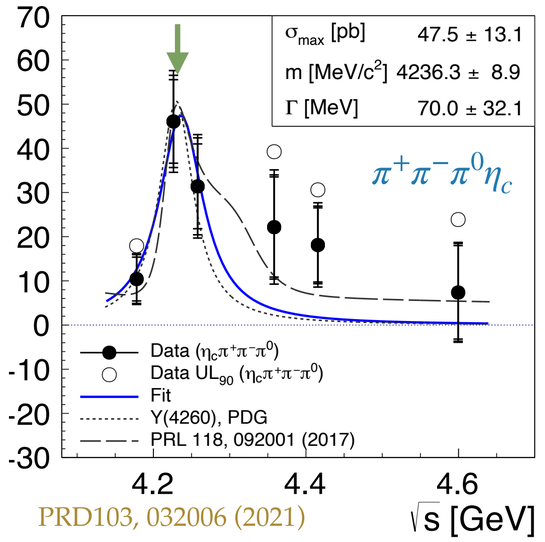
arXiv: 2310.03361



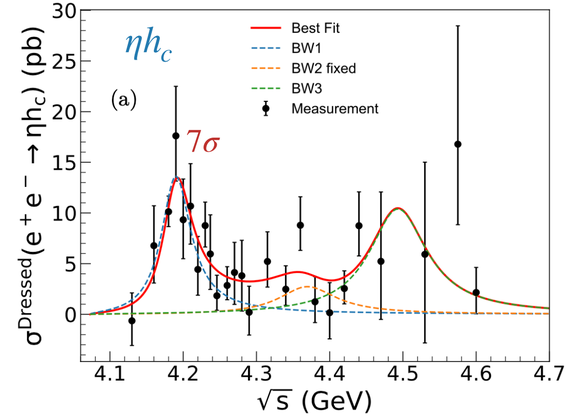


PRL131, 211902 (2023)



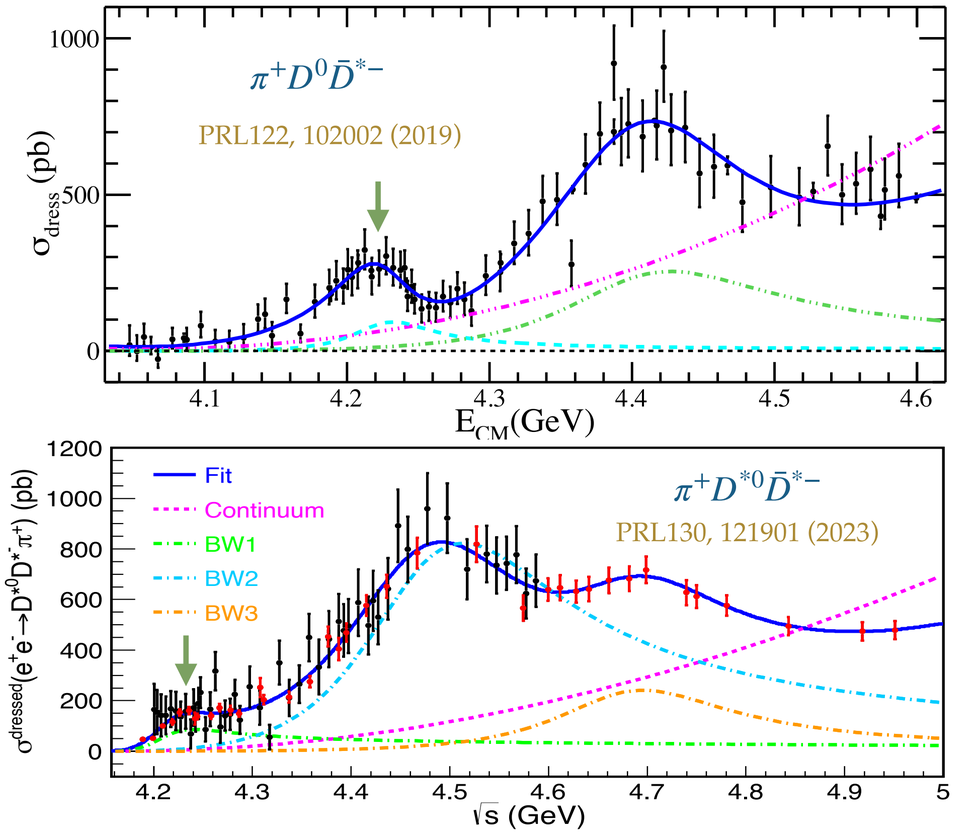


PRD103, 032006 (2021)

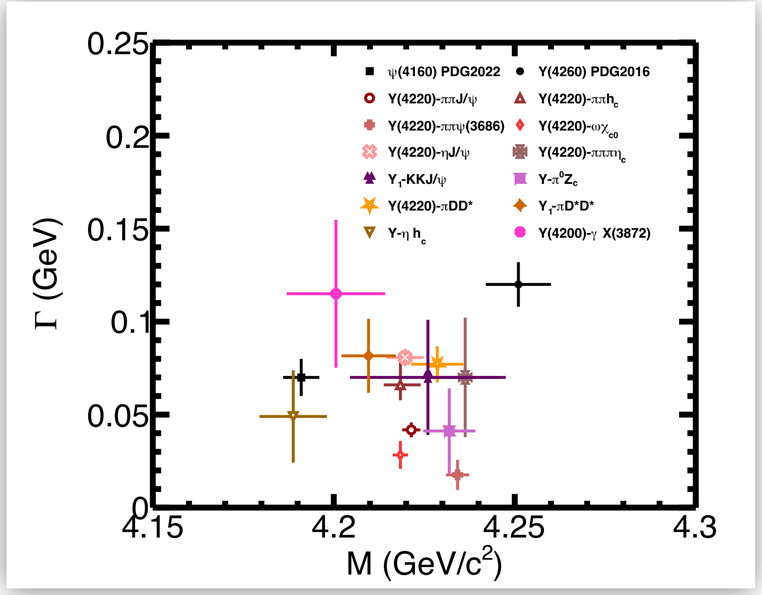


arXiv:2404.06718

Y(4230) in Open Charm Process



Mass and width from different process



⇑

determined with BW parameterization

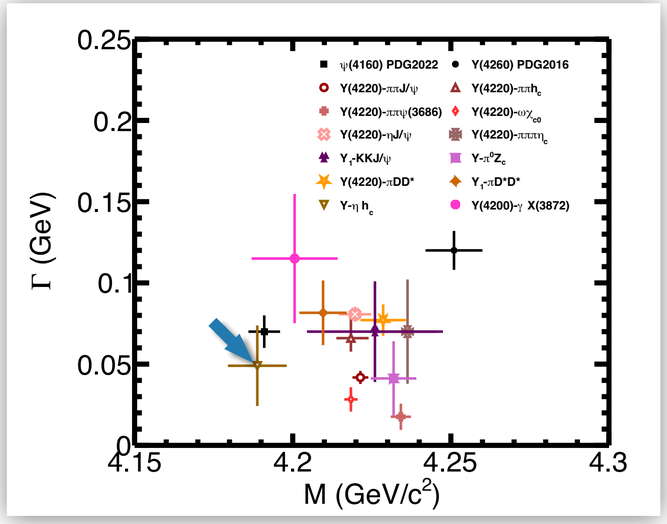
consider possible interference

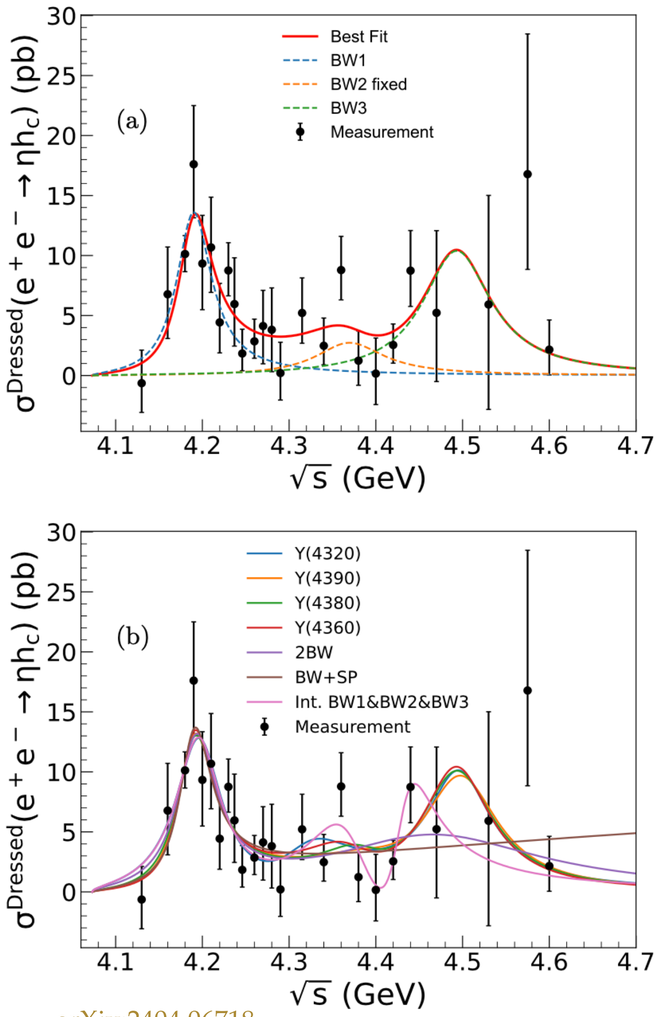
⇓

$\Gamma_{ee}B$(eV)	$\pi^+\pi^-J/\psi$	$\pi^+\pi^-h_c$	$\omega\chi_{c0}$	$\pi^+\pi^-\psi(2S)$	$\eta J/\psi$	K^+K^-J/ψ	$\pi^+\pi^-J/\psi$	$\pi^\pm(D\bar{D}^*)^\mp$	$\pi^\pm(D^*\bar{D}^*)^\mp$
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 ηh_c Cross Section



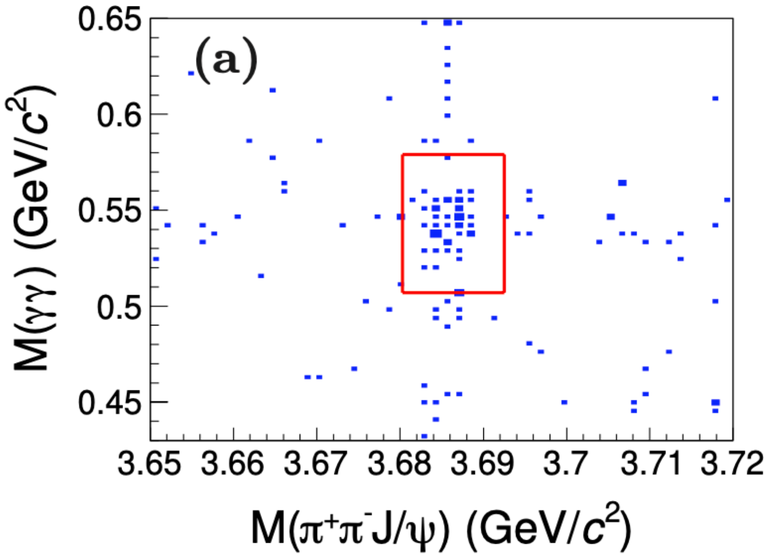


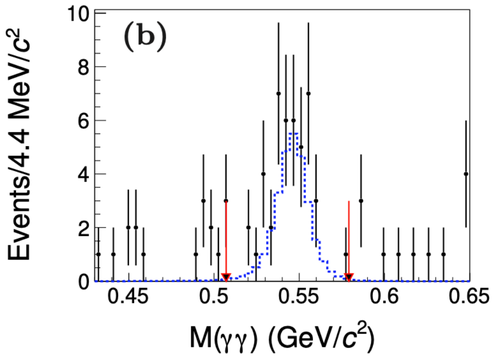
arXiv:2404.06718

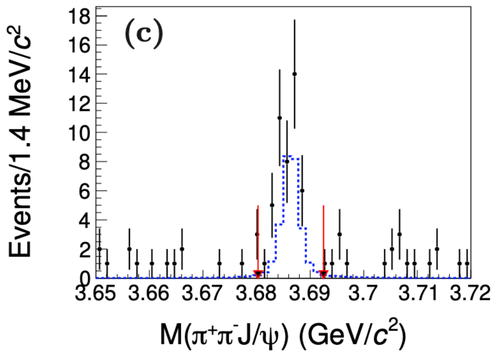
- 15 fb^{-1} data sample from 4.129 to 4.600 GeV
- $\sigma^{\text{dressed}} = |BW_1 + BW_2 e^{i\phi}|^2 + |BW_3|^2$
  - Mass and Width of BW_2 fixed to Y(4360)
  - $M_1 = 4188.8 \pm 4.7 \pm 8.0$ MeV/c^2
    $\Gamma_1 = 49 \pm 16 \pm 19$ MeV
    $\Gamma_{ee}\mathcal{B} = 0.80 \pm 0.19 \pm 0.45$ eV
- Alternative 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 BWs
  - statistical significance of BW_1 in all cases > 7σ

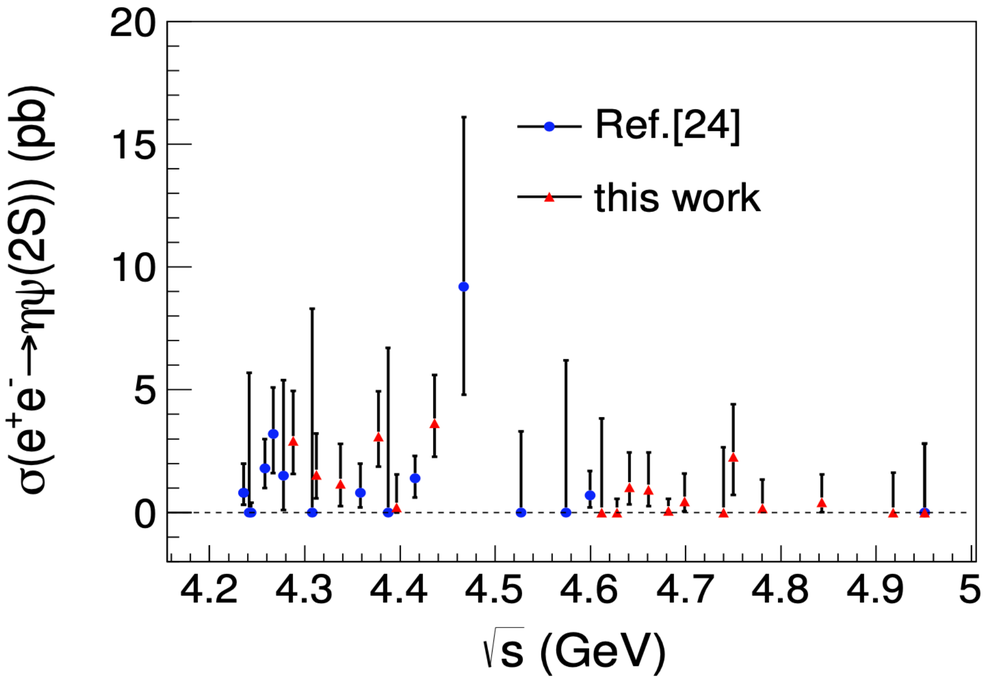
Update of ηψ(2S) and Search for $\tilde{X}(3872)$

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









significance > 5σ

combing previous data samples

Update of ηψ(2S) and Search for $\tilde{X}(3872)$

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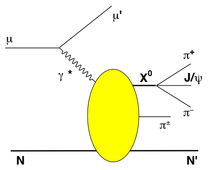
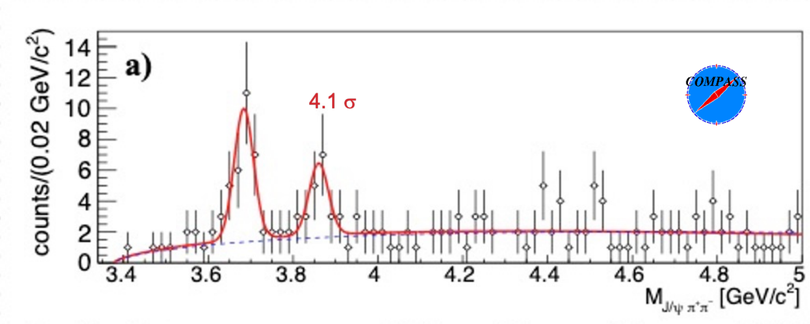


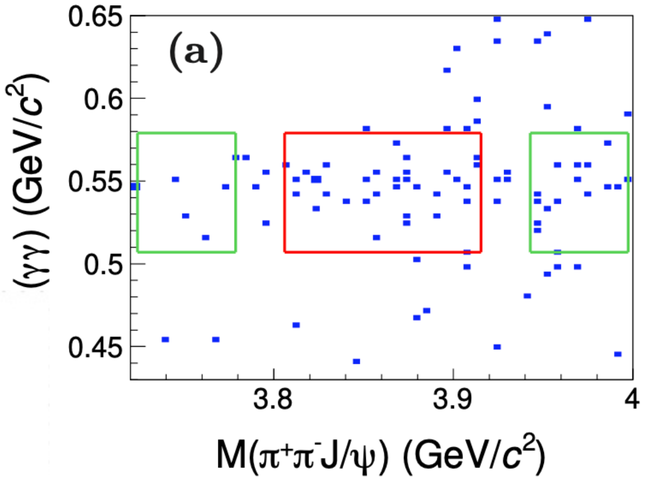
$$\gamma^* N \to X[\to \pi^+\pi^- J/\psi]\pi^\pm N'$$

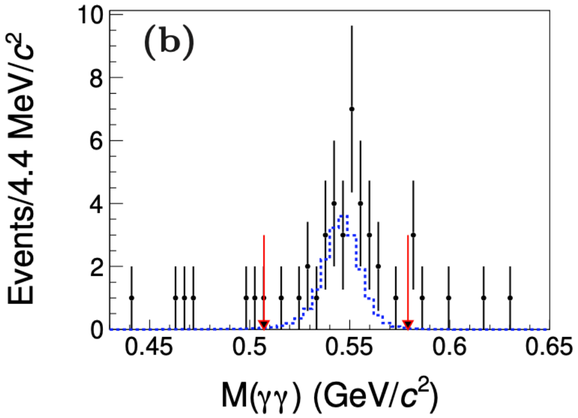
PLB 783, 334-340 (2018)

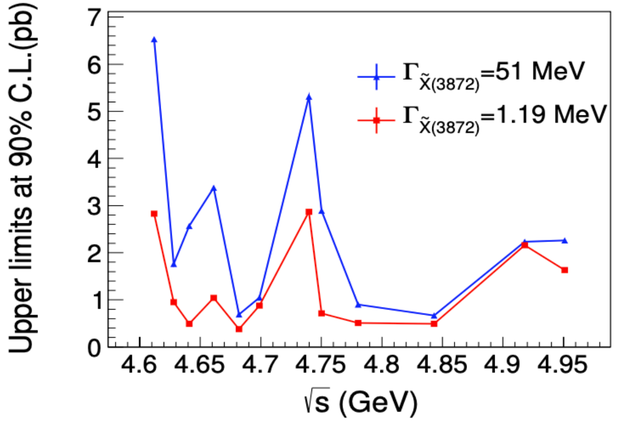


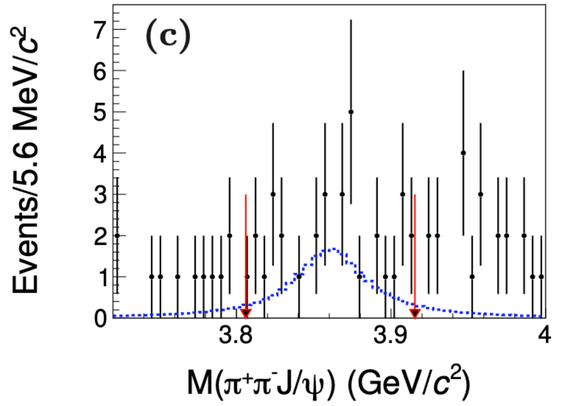
$$[(3860.0 \pm 10.4)\ \mathrm{MeV}/c^2,\ \ < 51\ \mathrm{MeV}]$$

arXiv:2403.16811





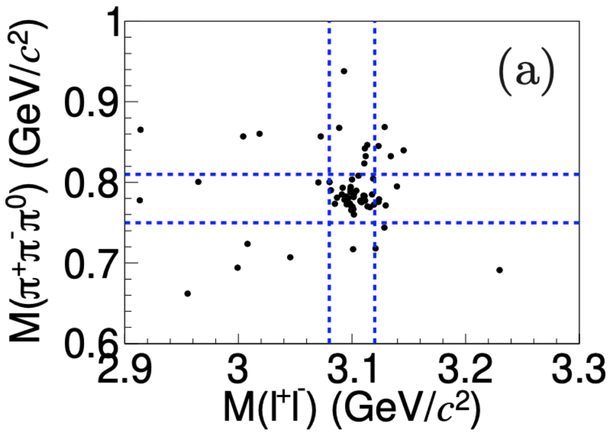


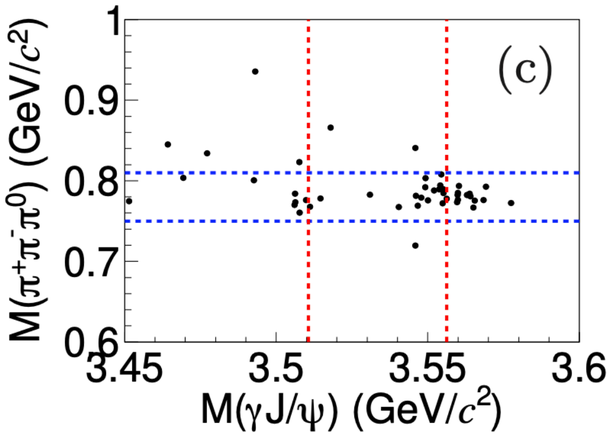


Observations in $\omega\chi_{c1}$ and $\omega\chi_{c2}$

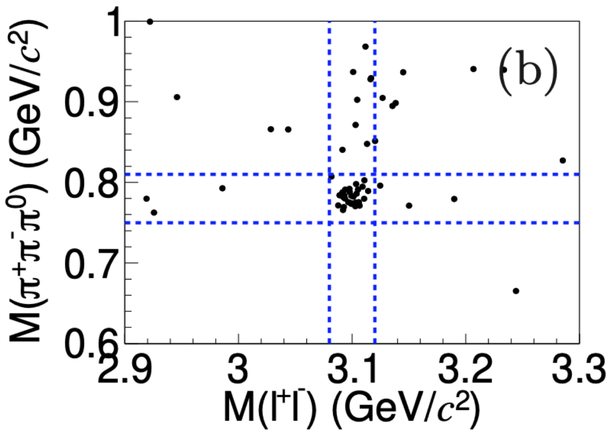
- 11.0 fb^{-1} data sample from 4.308 to 4.951 GeV

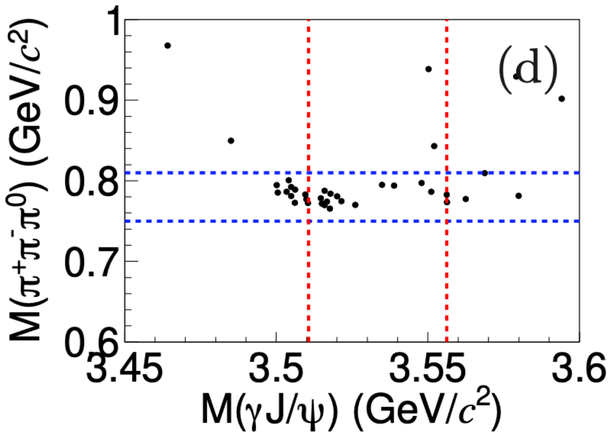
4436 sample

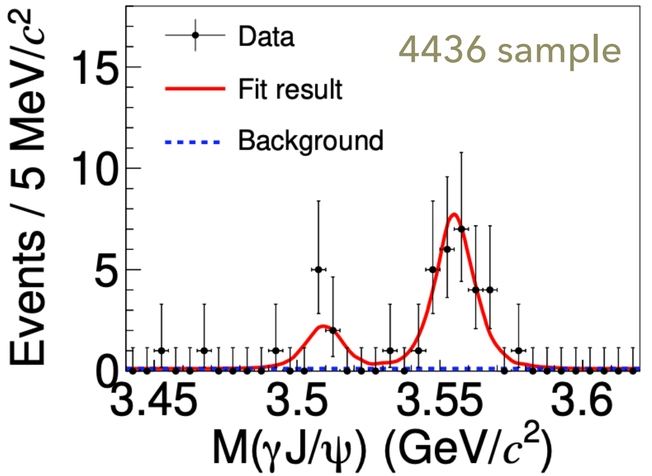


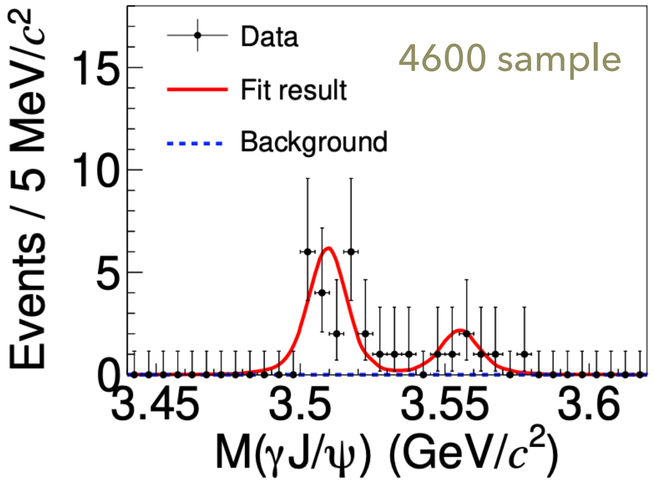


4600 sample









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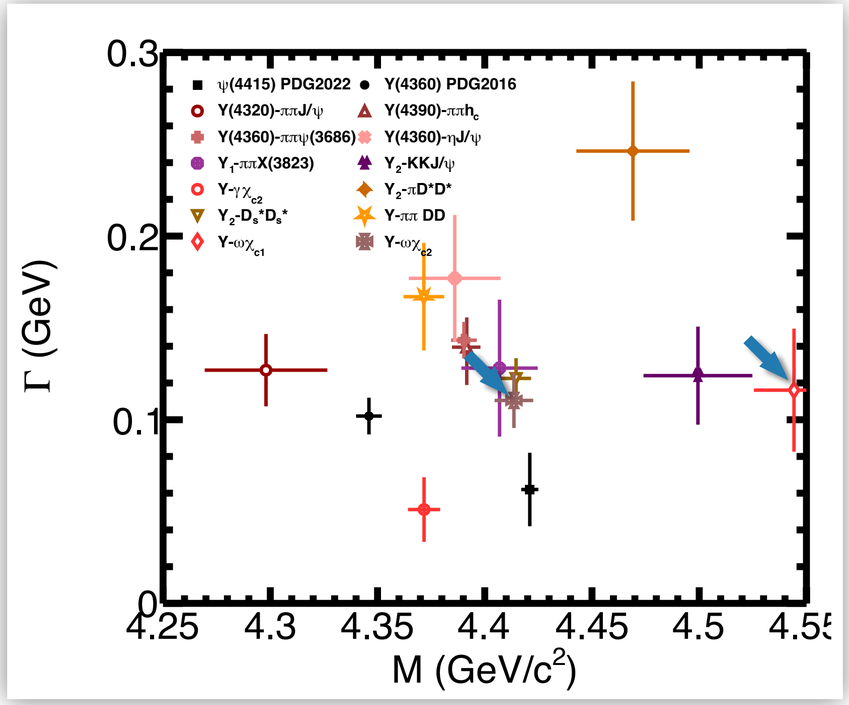
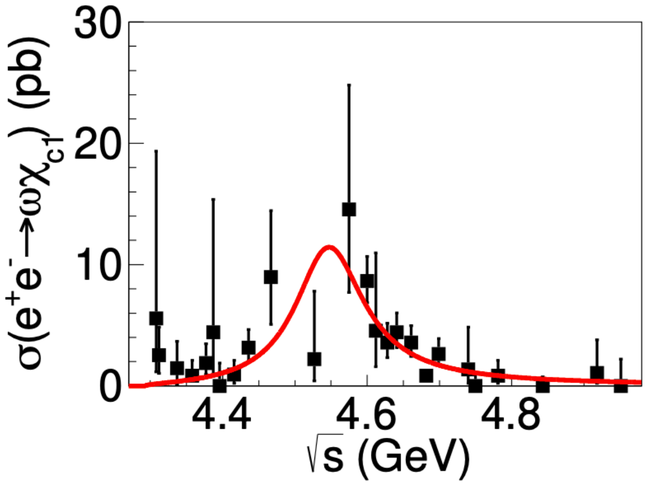
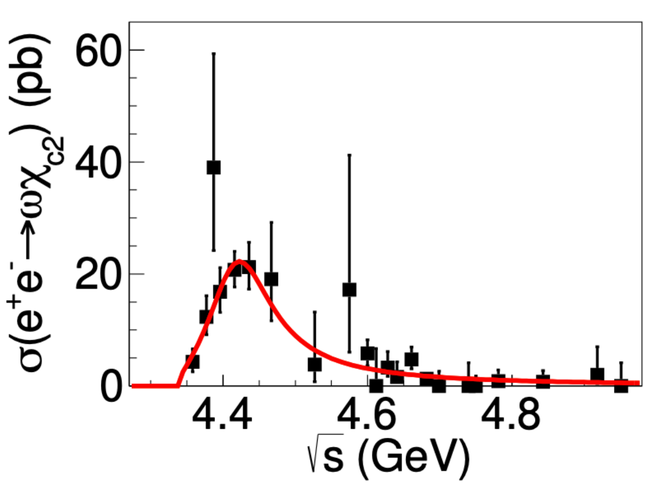
- 11.0 fb^{-1} data sample from 4.308 to 4.951 GeV



PRL,132, 161901 (2024)

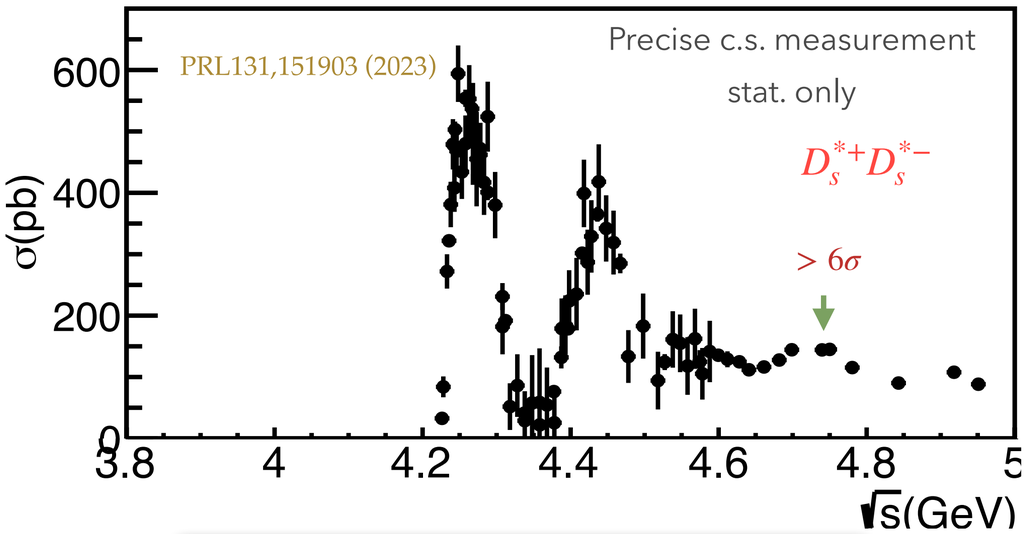


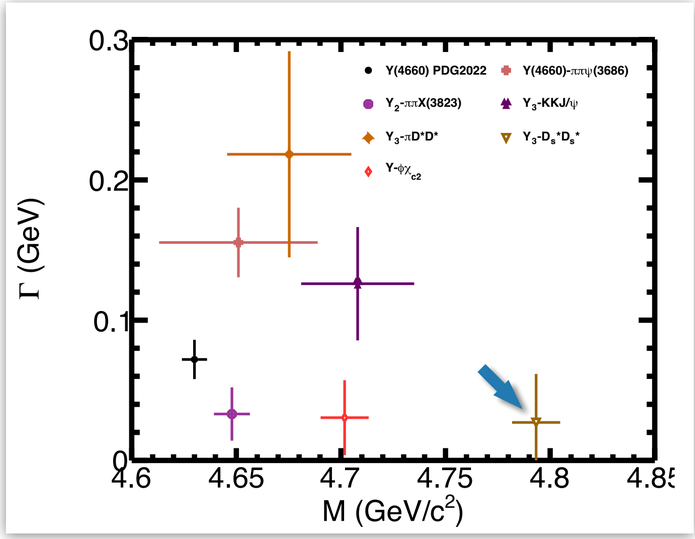
- $M = 4544.2 \pm 18.7 \pm 1.7$ MeV/c^2
  $\Gamma = 116.1 \pm 33.5 \pm 1.7$ MeV
- Significance over PHSP: 5.8σ
- Mass higher than structure seen in KKJ/ψ and πD^*D^*



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

Precise CS Measurement of Open Charm Processes





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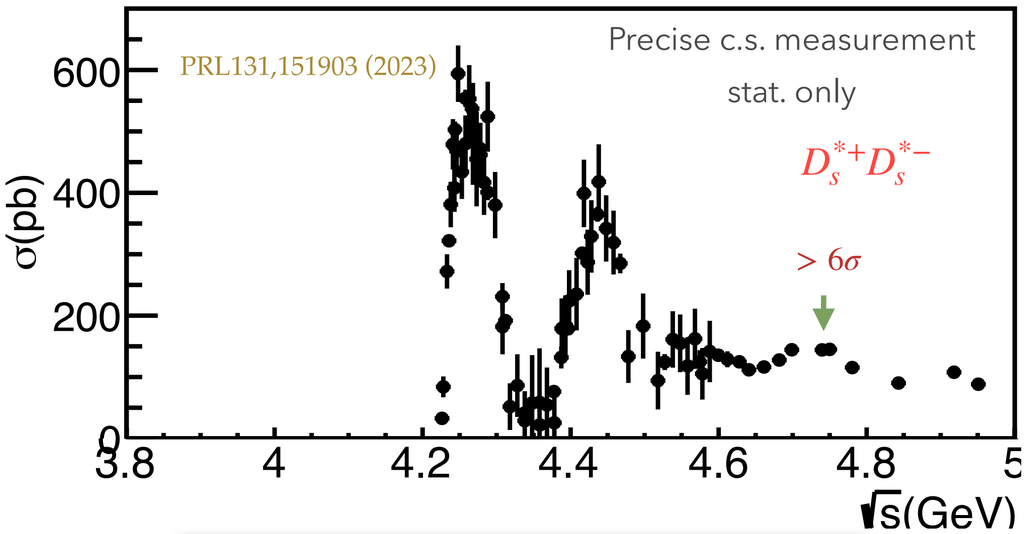
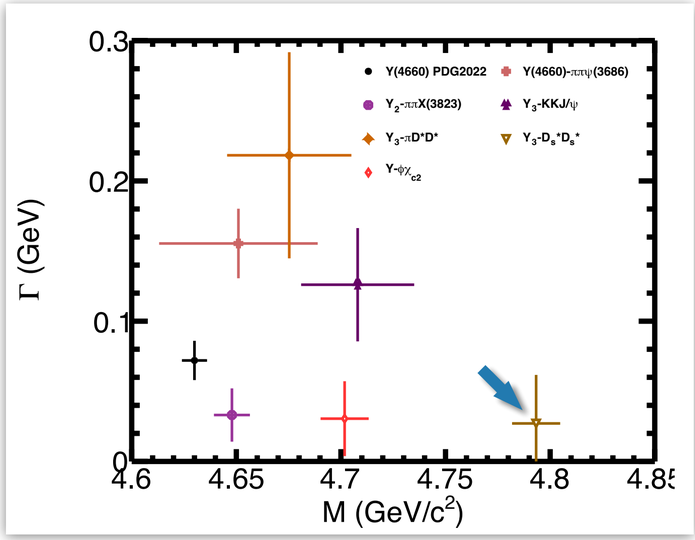
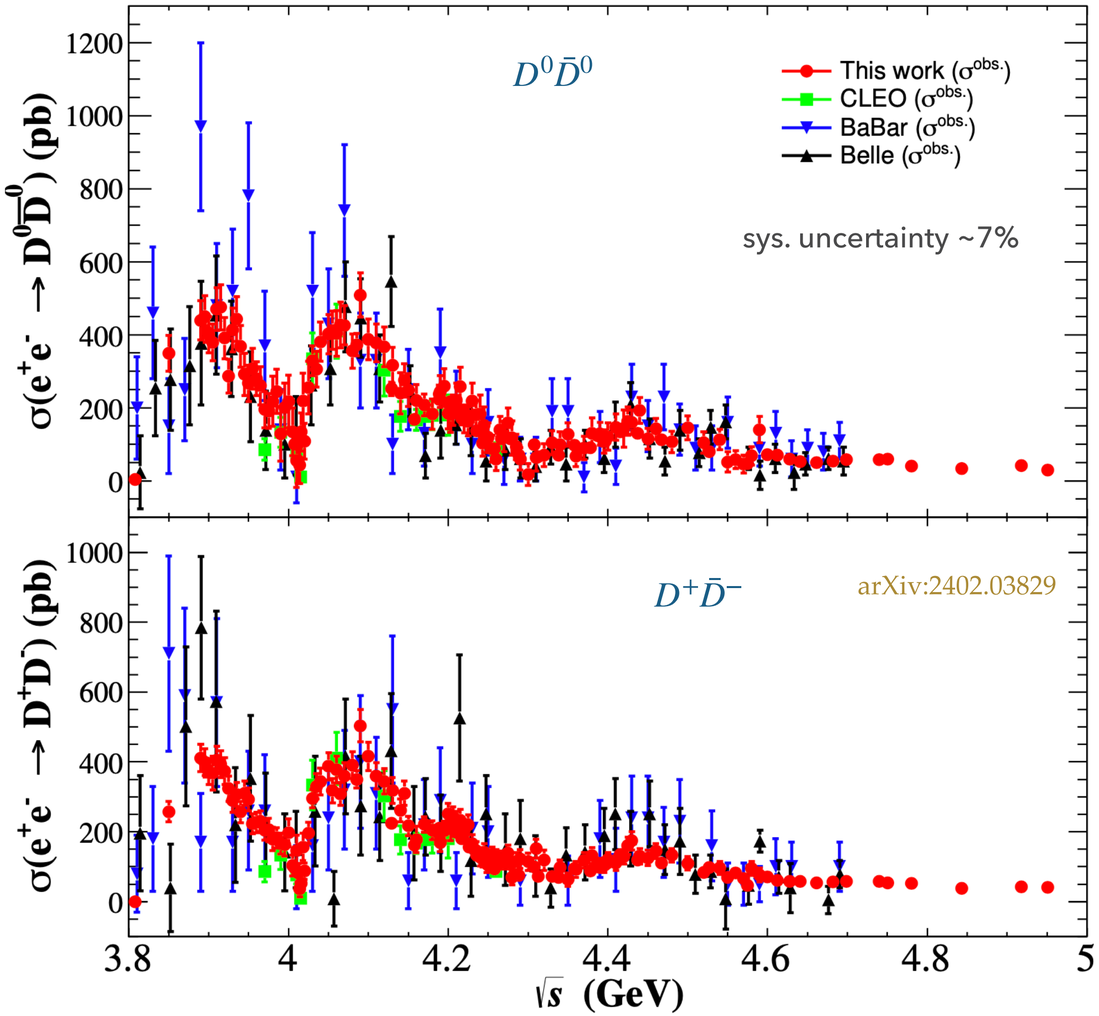
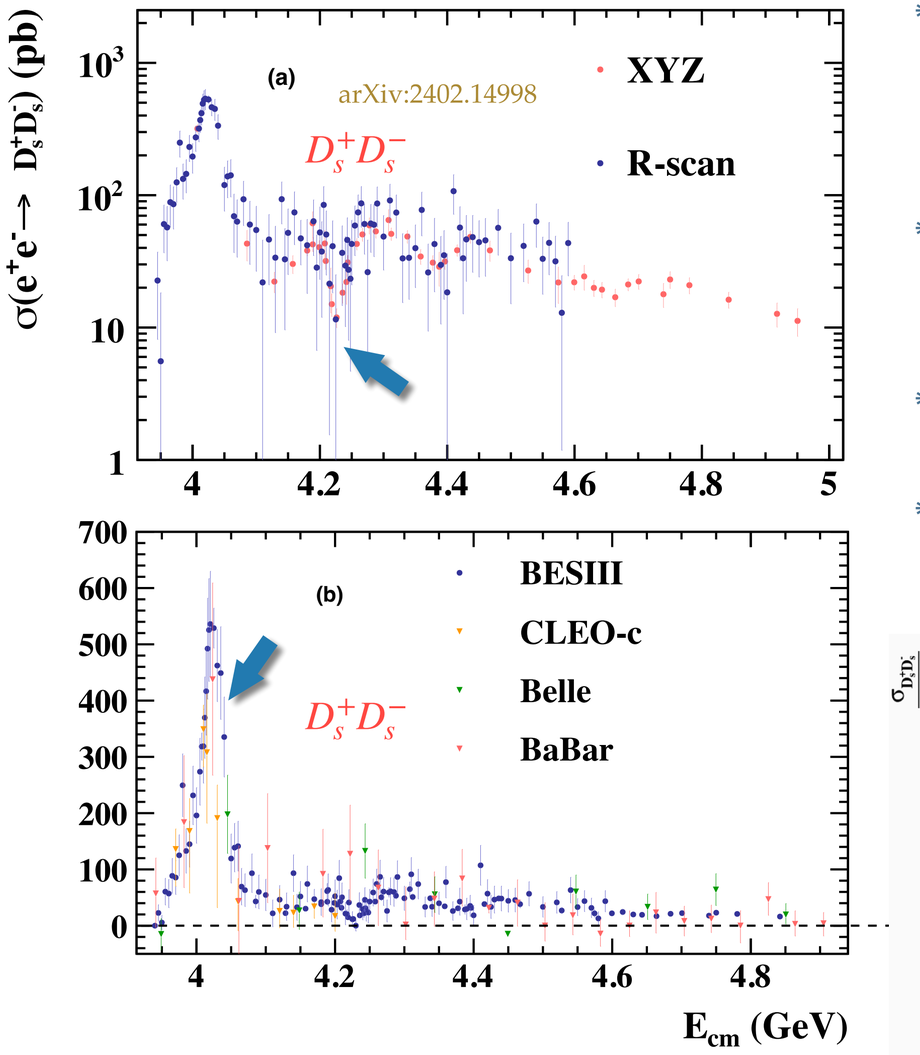


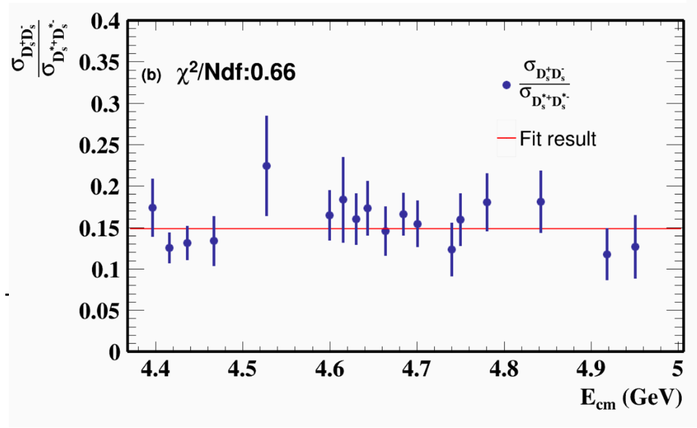


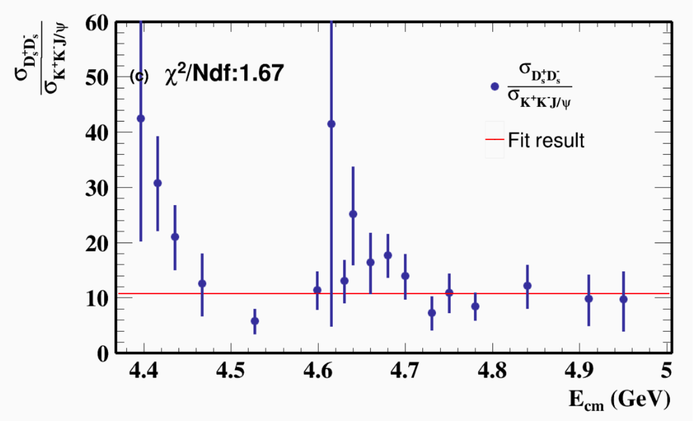


Precise CS Measurement of Open Charm Processes

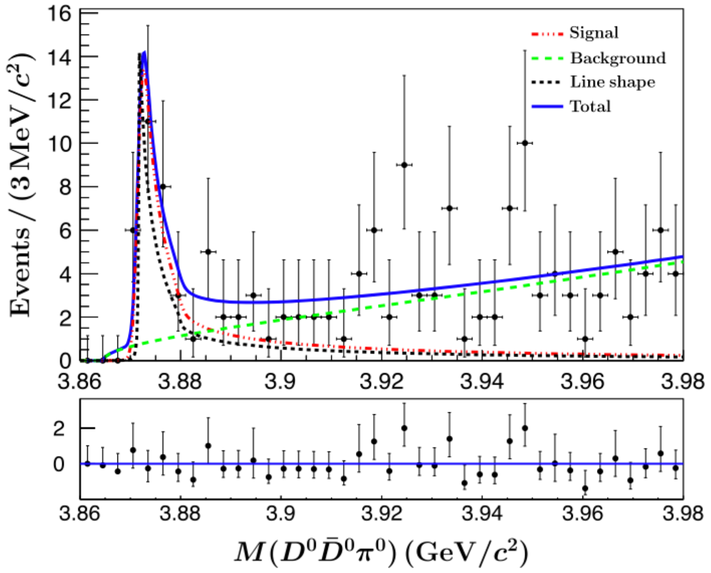


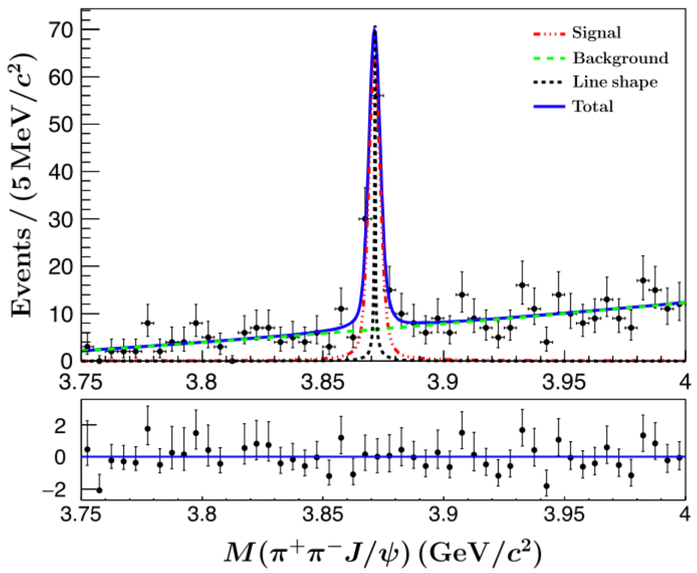
- Cross section peaks above the threshold, implies the presence of a strong coupled channel effect (E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, T. M. Yan, PRD21, 203 (1980))
- Maximum cross section around 4.02 GeV higher than previous studies using ISR method
- A narrow dip around 4.23 GeV, close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

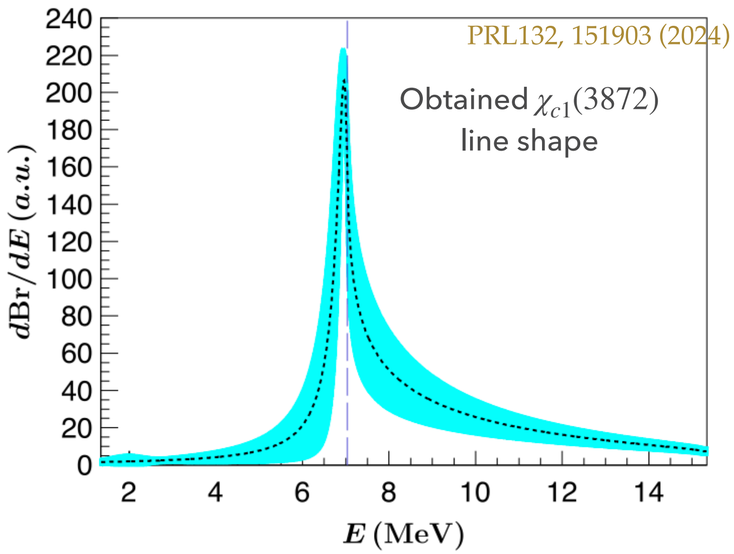




Line Shape of X(3872)



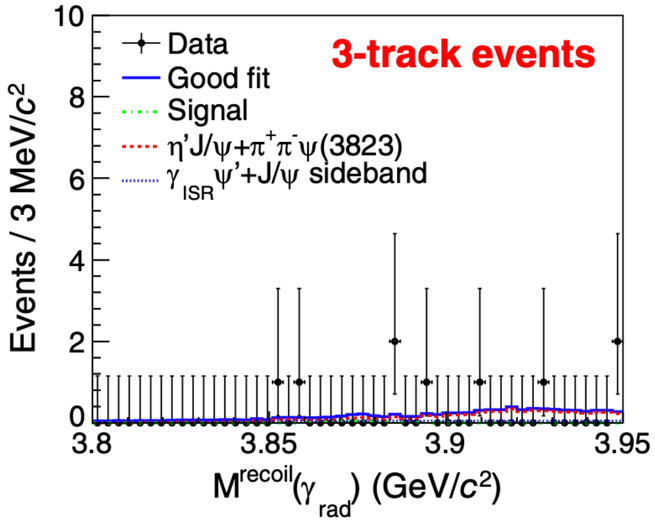


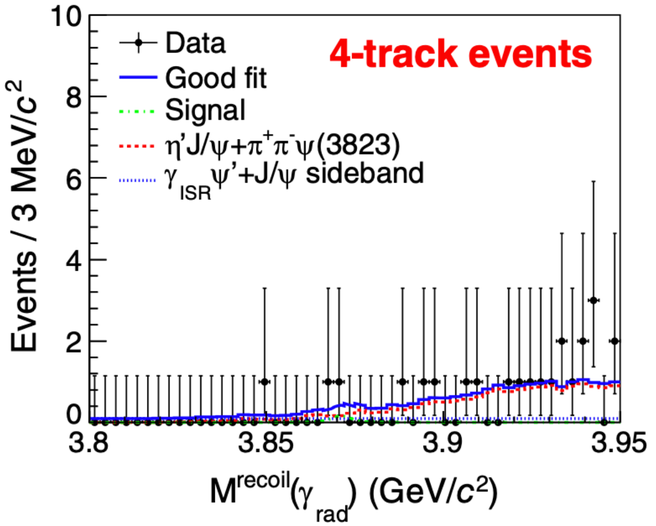


- Effects of the couple-channels and the off-shell D^{*0} are included in the parameterization
- Line share mass:
  $M_X = (3871.63 \pm 0.13^{+0.06}_{-0.05})$ MeV
- Weinberg's compositeness: Z=1 - pure elemental state; Z=0 -pure bound state

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 ± 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) (I)

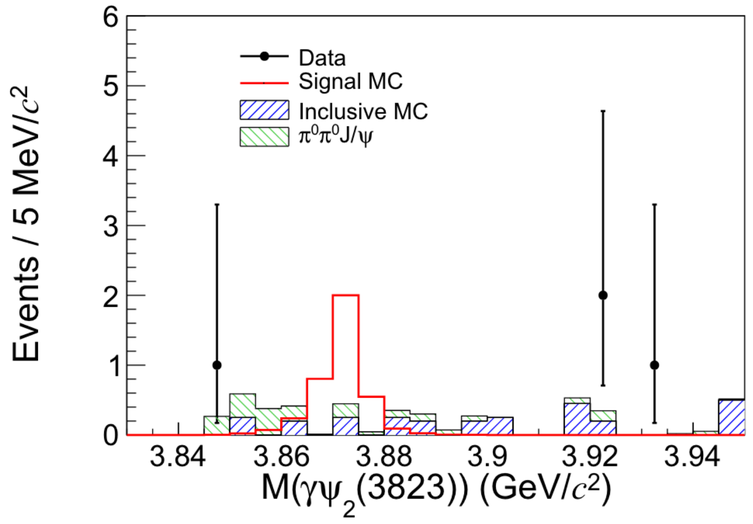




- 10.9 fb^{-1} data samples from 4.16 to 4.34 GeV
- Decay ratio of $X(3872) \to \pi^0\chi_{c1}$ and $X(3872) \to \pi^+\pi^-\chi_{c1}$ can be used to discriminate theoretical interpretations for the nature of $X(3872)$
  - ≈ 0.04 for $\chi_{c1}(2P)$
  - Enhanced if it is a shallow bound state of a $\bar{D}^0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

PRD09, L071101 (2024)

Decays of X(3872) (II)



$\Gamma_{\chi_{c1}(3872)} = 1190 \pm 210$ keV [2]

$\Gamma_{\psi_2(3823)} = 520 \pm 100$ keV [23]

$\mathcal{B}(\chi_{c1}(3872) \to \pi^+\pi^- J/\psi) = (3.8 \pm 1.2) \times 10^{-2}$ [2]

	NR [20]	GI [20]	LQCD [23]
$\Gamma_{\chi_{c1}(2P)\to\gamma\psi(1^3D_2)}$ (keV)	35	18	–
$\Gamma_{\psi(1^3D_2)\to\gamma\chi_{c1}(1P)}$ (keV)	307	268	337 ± 27
$\mathcal{R}_{\chi_{c1}(2P)}$	0.46 ± 0.19	0.21 ± 0.09	0.50 ± 0.21, 0.26 ± 0.11

- 9.0 fb^{-1} data samples from 4.178 to 4.278 GeV
- The radiative transition $X(3872) \to \gamma\psi_2(3823)$ has been searched for the first time.

  No obvious signal is found in the data,

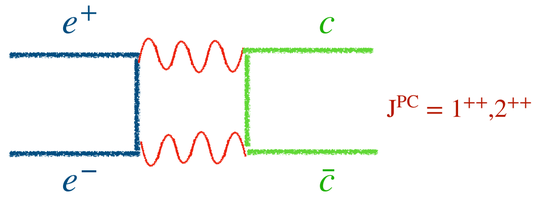
$$R = \frac{\mathcal{B}(\chi_{c1}(3872) \to \gamma\psi_2(3823), \psi_2(3823) \to \gamma\chi_{c1})}{\mathcal{B}(\chi_{c1}(3872) \to \pi^+\pi^- J/\psi)} < 0.075$$

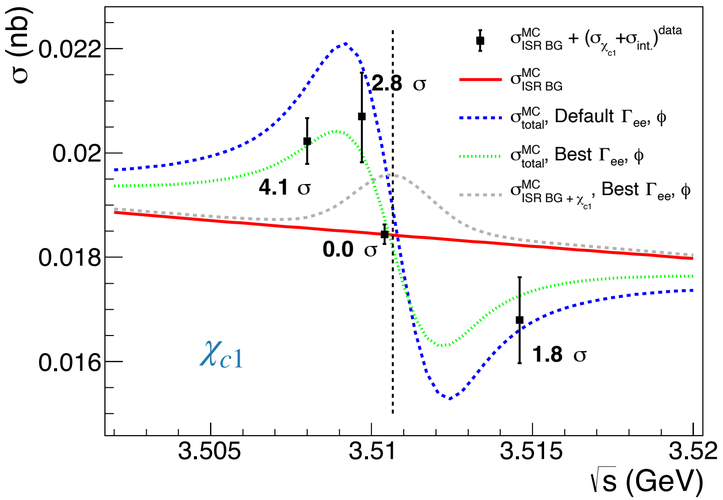
  at 90% C. L.
- This upper limit is more than 1σ below the theoretical calculation of R under the assumption the $\chi_{c1}(3872)$ is the pure charmonium state $\chi_{c1}(2P)$.

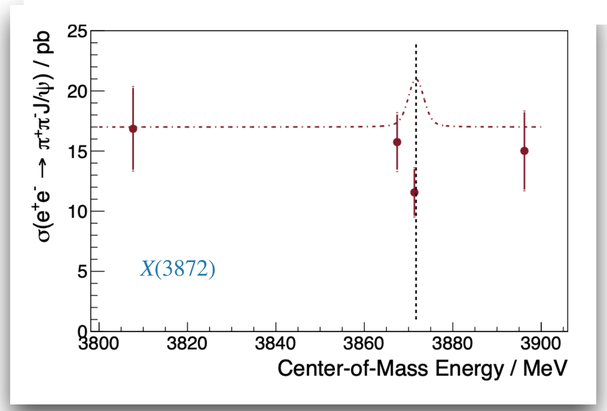
arXiv:2405.07741

New Production Mechanism of C-even States

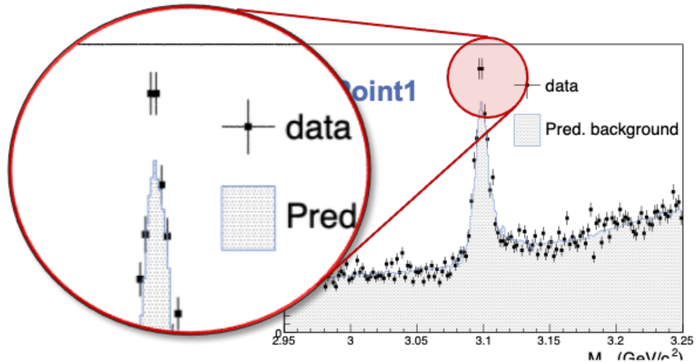
- Dedicated scan sample around the resonance
- Careful study of background process and interference effect!

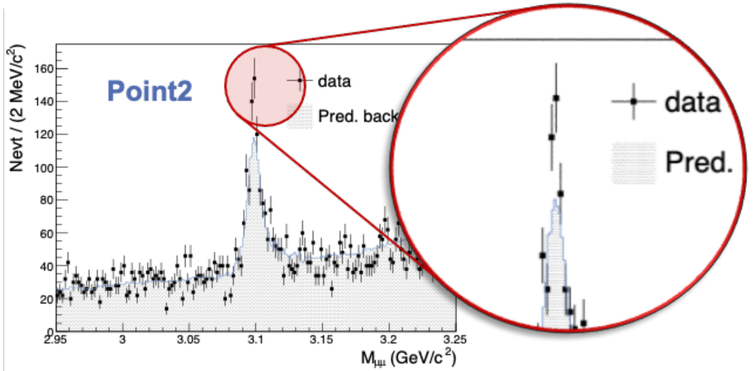


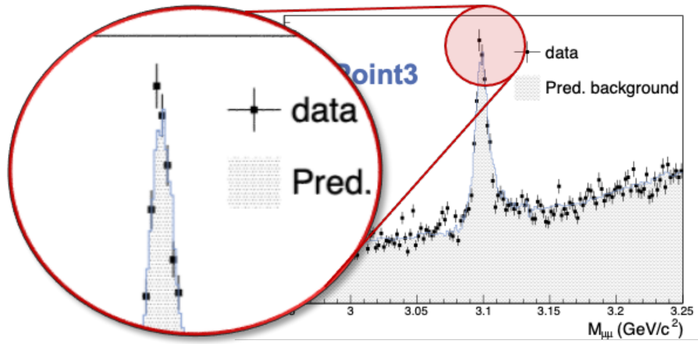


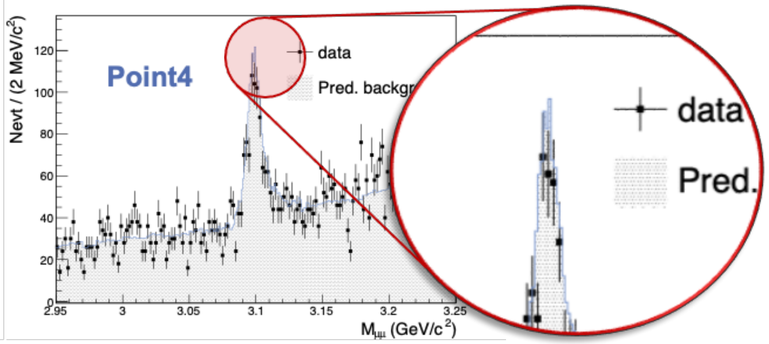


PRD 107 (2023) 032007



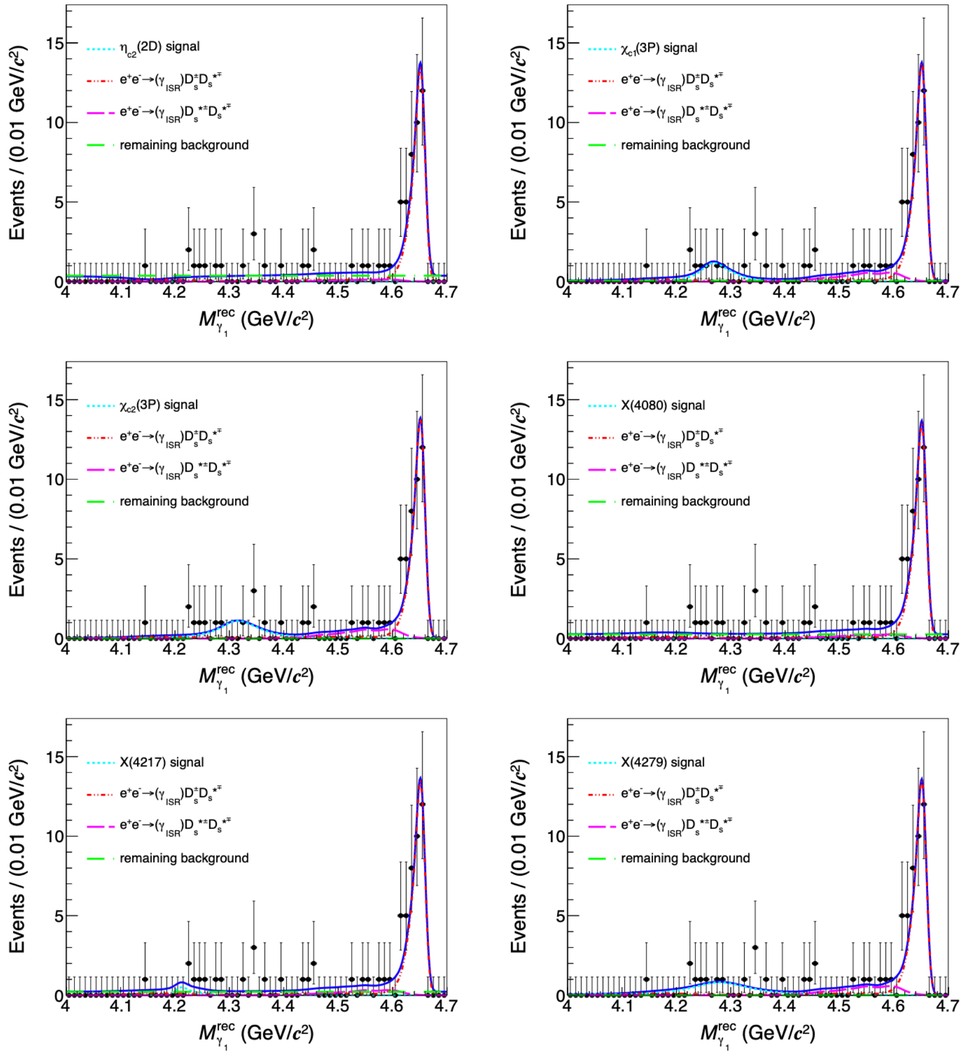






PRL 129 (2022), 122001

C-even States in Radiative Transition Process



$$e^+e^- \to \gamma D_s D_s^*$$

State	M (MeV/c^2)	Γ (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^{++}
hybrid $X(4217)$ [9–11]	4217	6	6	1^{-+}
$X(4279)$ [9–11]	4279	110	34	0^{-+}

Molecular states: 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 (σ)	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

Summary

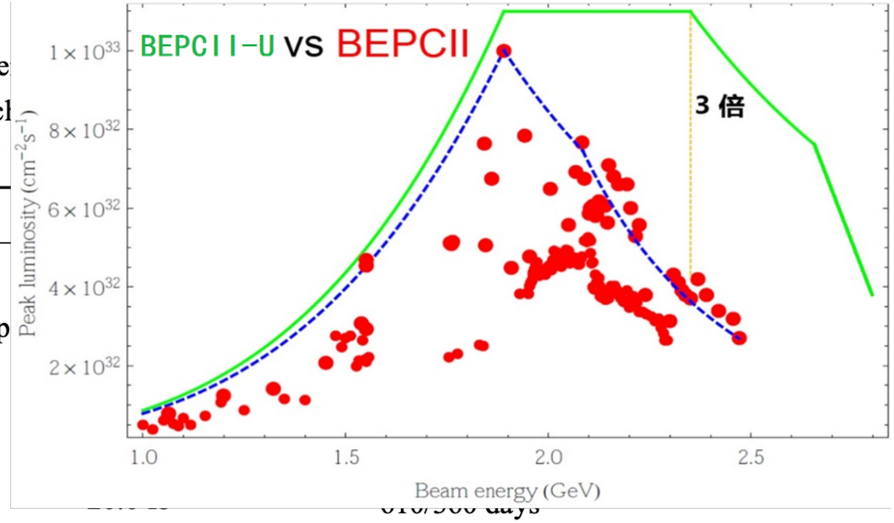
- Properties of vector states have been investigated using various processes, including open charm, hidden charm, and light hadronic final states
  I. Y(4230) is seen in 10 decay modes; rich structures in the cross section line shapes above 4.3 GeV, more data samples are needed around 4.5 GeV and 4.7 GeV
  II. No evident structure is seen in light hadron process
  III. 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?
  IV. 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?

Thank You!

Future Data Samples

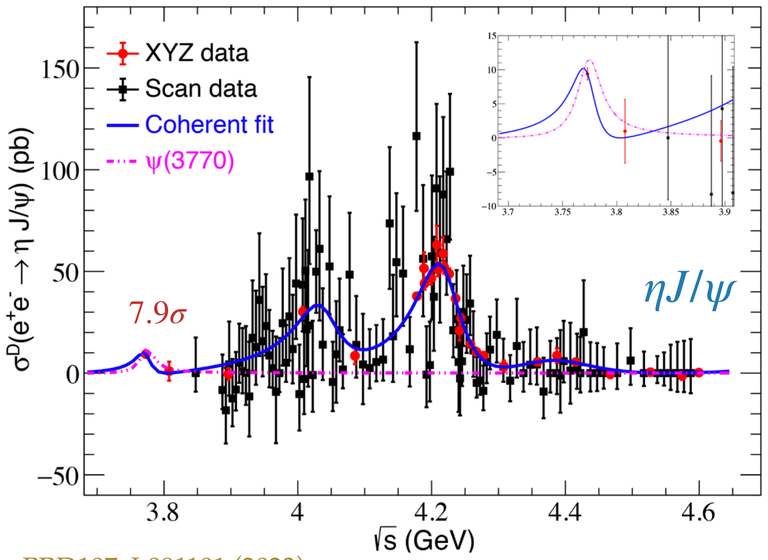
Table 7.1. List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the re
most column shows the number of required data taking days with the current (T_C) and upgraded (T_U) macl
implementation and beam current increase.

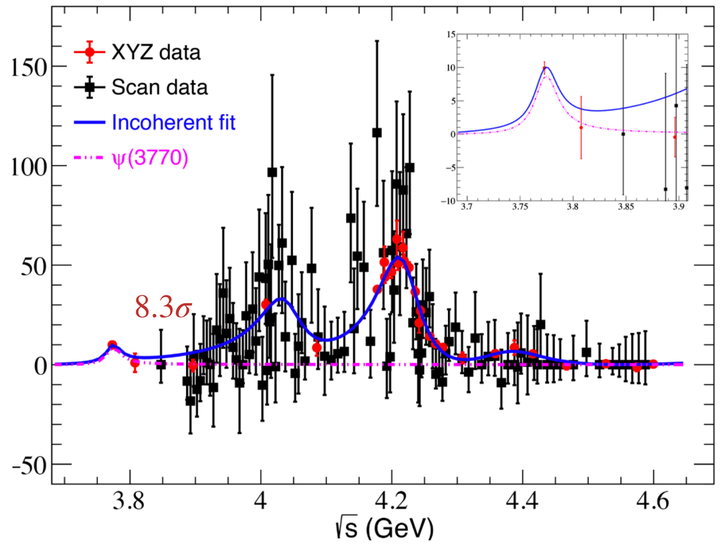
Energy	Physics motivations	Current data	Comp		
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A			
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)			
J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)			
$\psi(3686)$ peak	Light hadron & Glueball Charmonium decays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

Non-DD Decay of ψ(3770)





PRD107, L091101 (2023)

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

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

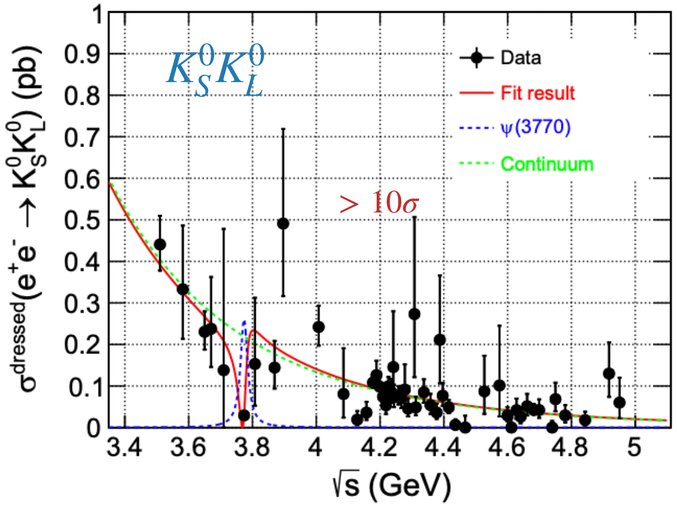
CLEO result: 3.5σ

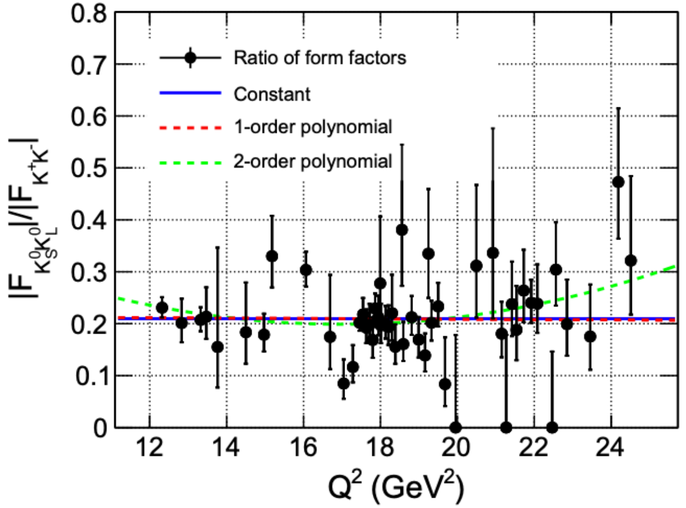
$(8.7 \pm 3.3 \pm 2.2) \times 10^{-4}$

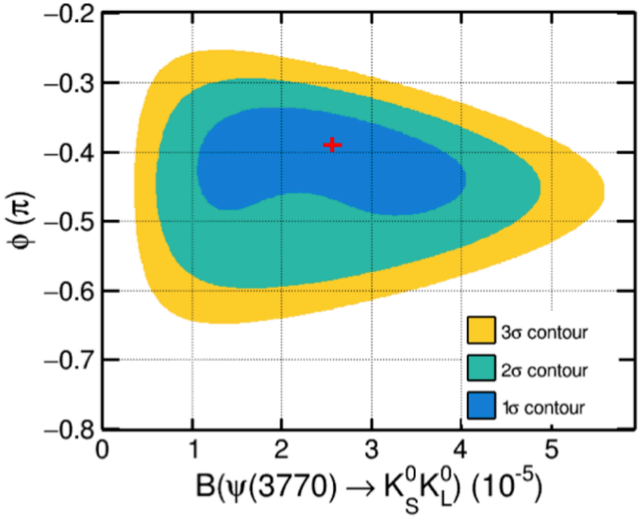
interference between $\psi(3770)$, continuum, and Y states

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)))
- $|F_{K_S^0K_L^0}|/|F_{K^+K^-}| = 0.21 \pm 0.01$, 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