The Vector Charmoniumlike Spectrum at BESIII (Open Charm Decays)

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On behalf of the BESIII collaboration

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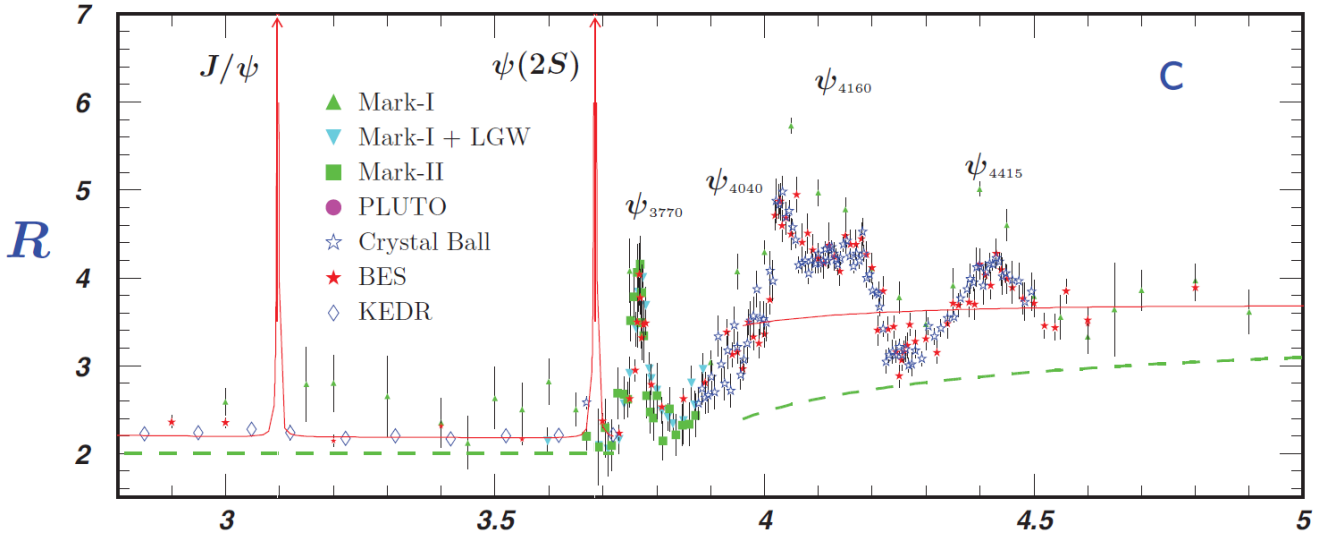
Outline

- Introduction
- Three recent results at BESIII: precision measurements of the cross-sections of
  1. $e^+e^- \to D^0\overline{D}^0$ and D^+D^-
  2. $e^+e^- \to D_s^{*+}D_s^{*-}$
  3. $e^+e^- \to D^{*0}D^{*-}\pi^+ + c.c.$
- Summary and outlook

Introductions

- Potential model predicts only three vector charmonium states (3S, 1D, 4S) from CM energy 4.0 to 4.6 GeV
- Combining with the R-value measurement, they are likely the $\psi(4040)[3S]$, $\psi(4160)[1D]$, $\psi(4415)[4S]$

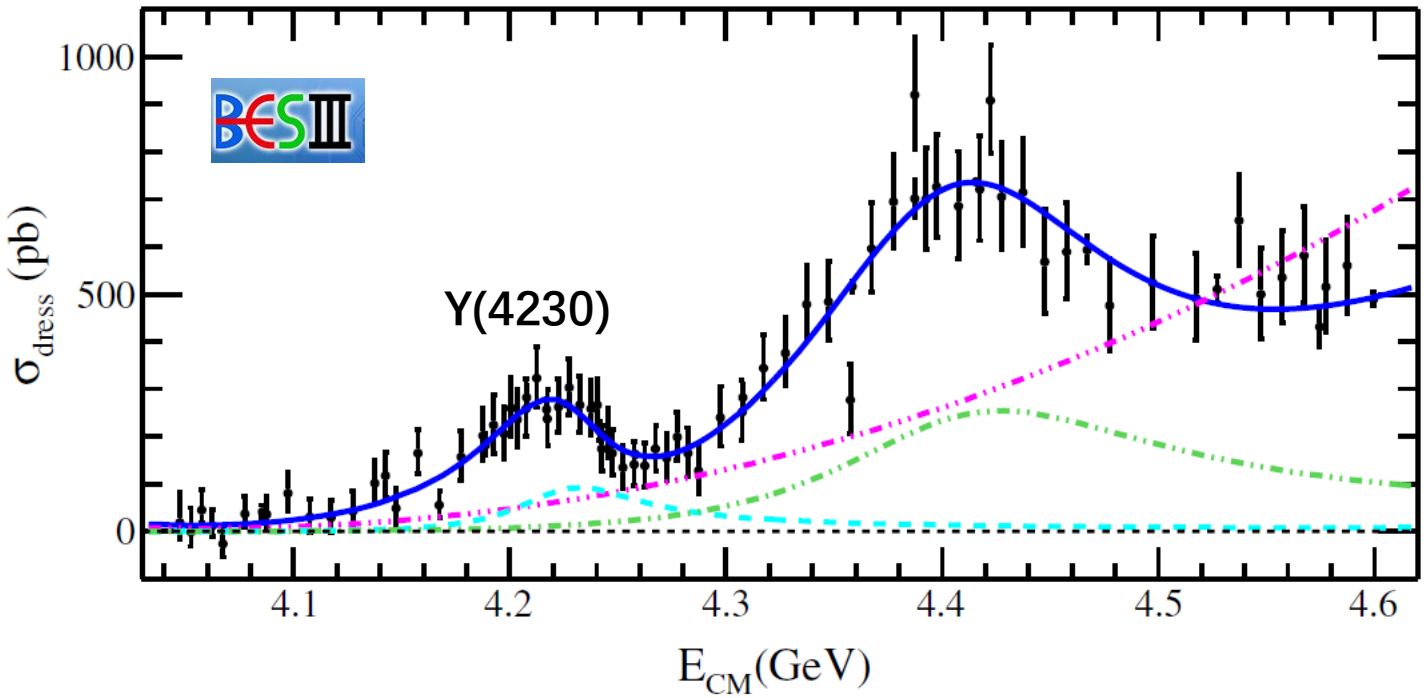


PRD 98, 030001 (2018)

- The overpopulated states, traditionally only observed in hidden-charm final states, are assigned as exotic charmoniumlike states

  Y(4220), Y(4360), Y(4500), Y(4660), etc. [see Aiqiang's talk for details]

Question I: Do the vector charmoniumlike states only couple to hidden charm states?



$e^+e^- \to \pi^+ D^0 D^{*-}$

PRL 122, 102002 (2019)

Question II: Do they couple to other open charm states?

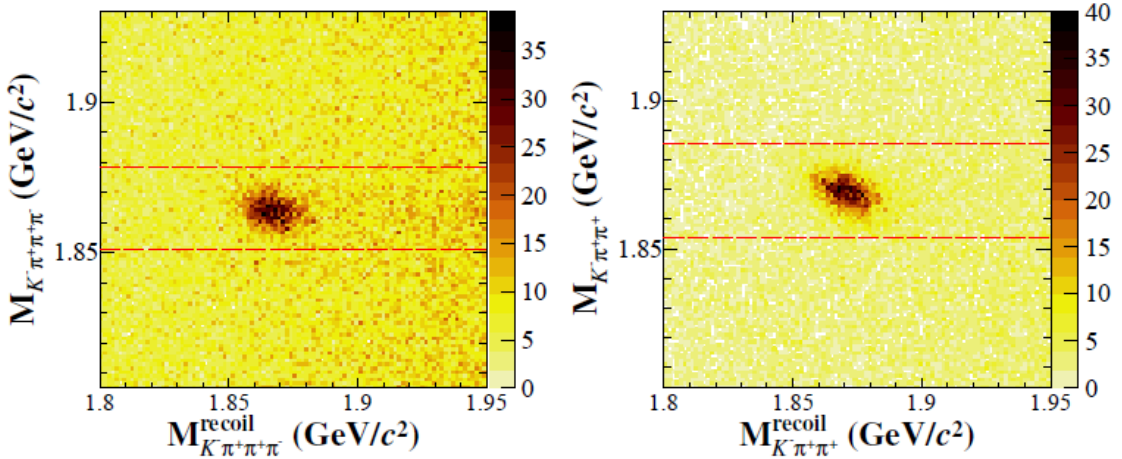
$e^+e^- \to D^0\bar{D}^0$ and D^+D^-

Brand New

BESIII arXiv:2402.03829

- $\sqrt{s}$ from 3.80 to 4.95 GeV
- Integrated luminosity $20\ fb^{-1}$
- Single tag technique is employed
  - $D^0(D^+)$ is reconstructed via $K^-\pi^+\pi^+\pi^-(K^-\pi^+\pi^+)$ mode

$D^0\bar{D}^0$

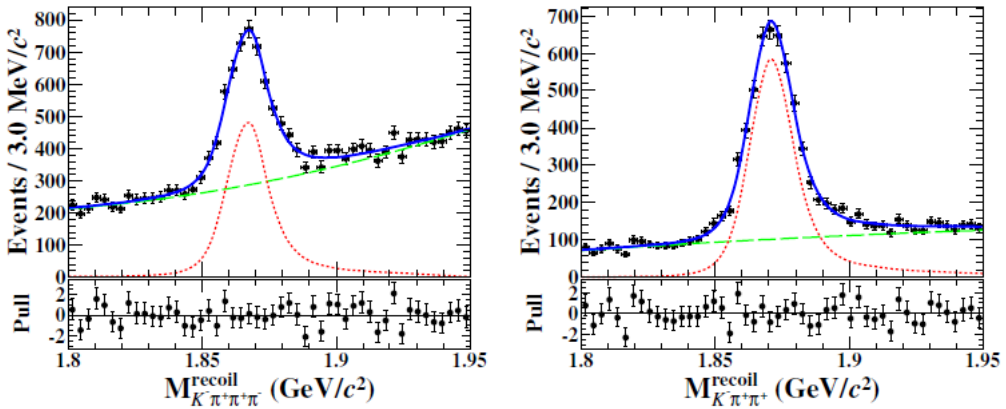


D^+D^-

$e^+e^- \to D^0\bar{D}^0$ and D^+D^-

arXiv:2402.03829

4.2 GeV

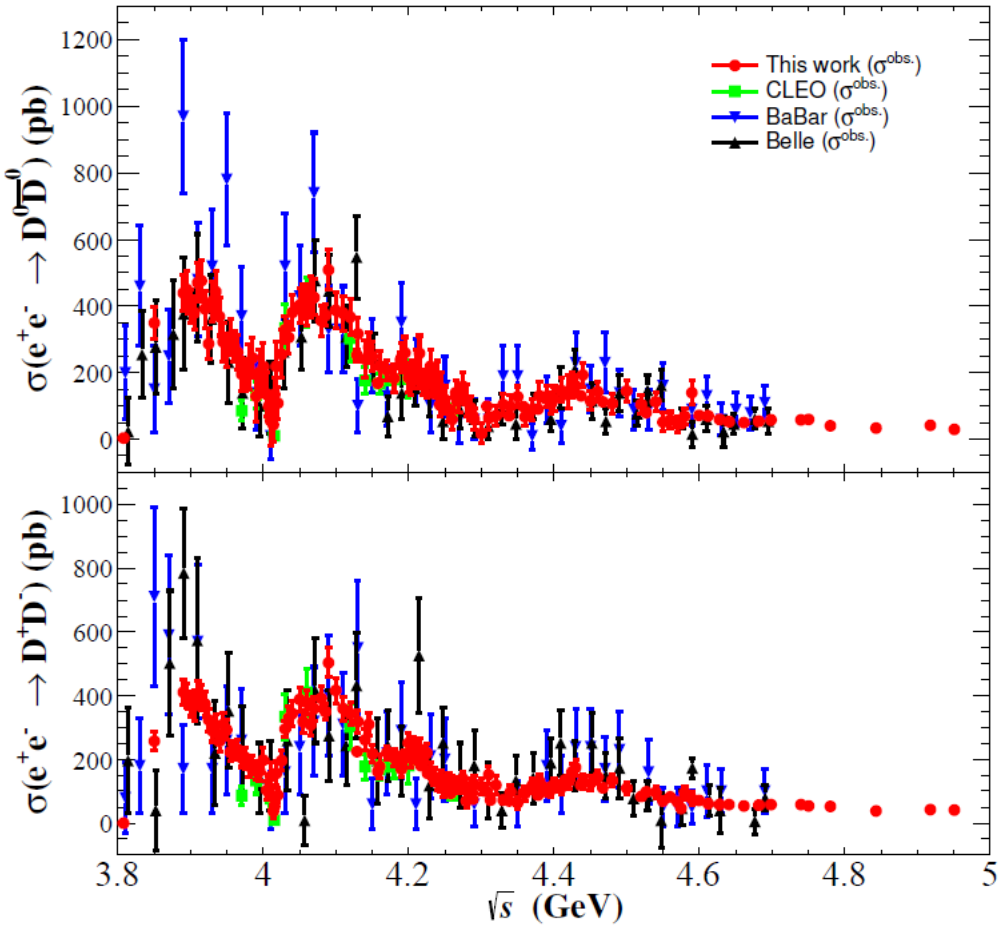


$D^0\bar{D}^0$ D^+D^-

- Signal: MC convoluted with Gaussian
- Background: 2nd order poly nominal

$$\sigma^B(s) = \frac{N_{\rm obs}}{2\mathcal{L}(1+\delta)\frac{1}{|1-\Pi|^2}\epsilon\mathcal{B}}$$

The systematics is 7.0%(6.5%) for $D^0(D^+)$ mode



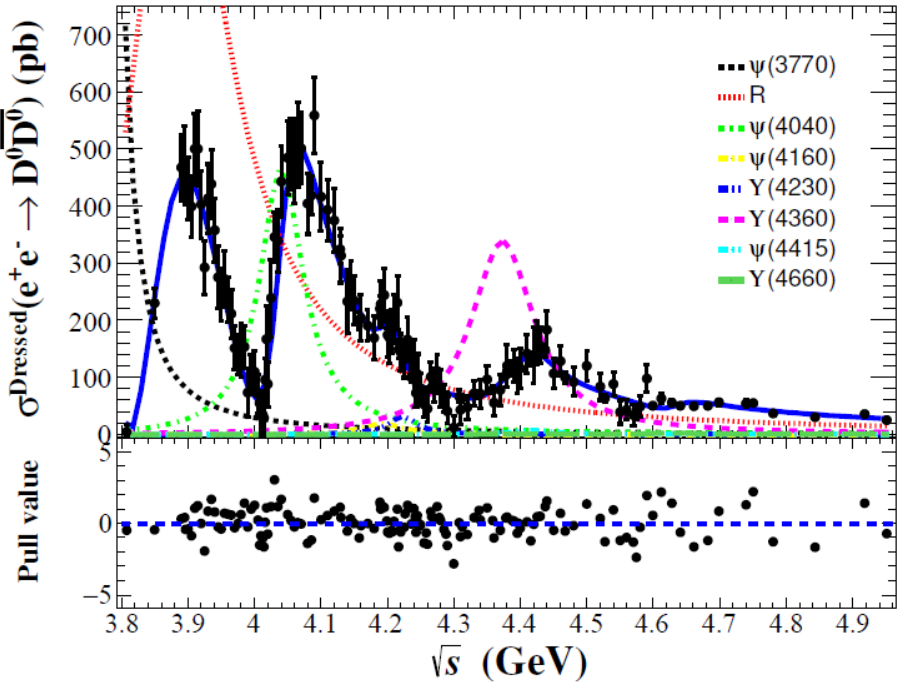
Consistent with previous measurements

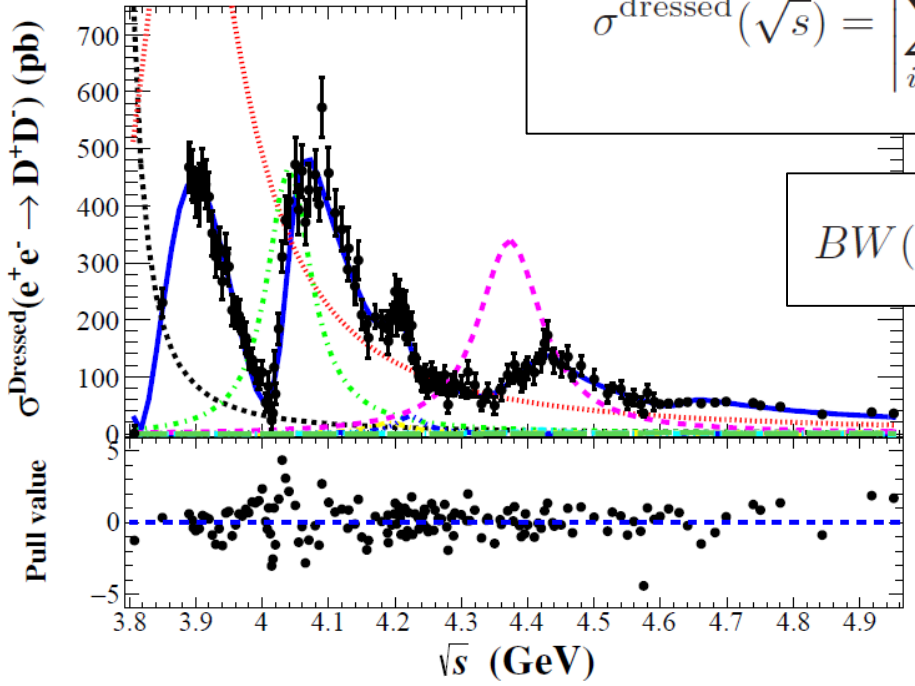
$e^+e^- \to D^0\bar{D}^0$ and D^+D^-

arXiv:2402.03829

$$\sigma^{\text{dressed}}(\sqrt{s}) = \left| \sum_{i=1} e^{i\phi} BW_i(\sqrt{s}) \sqrt{\frac{P(\sqrt{s})}{P(M)}} \right|^2$$

$$BW(\sqrt{s}) = \frac{\sqrt{12\pi\Gamma_{ee}\mathcal{B}\Gamma}}{s - M^2 + iM\Gamma}$$





coupled channel effect?

	$e^+e^- \to D\bar{D}$							
	$\psi(3770)$	R	$\psi(4040)$	$\psi(4160)$	$Y(4230)$	$Y(4360)$	$\psi(4415)$	$Y(4660)$
Mass (MeV/c^2)	3773.7 (fixed)	3872.5±14.2±3.0	4039 (fixed)	4191 (fixed)	4222.5 (fixed)	4374 (fixed)	4421 (fixed)	4630 (fixed)
Width (MeV/c^2)	87.6 (fixed)	179.7±14.1±7.0	80 (fixed)	70 (fixed)	48 (fixed)	118 (fixed)	62 (fixed)	72 (fixed)
$\Gamma_{ee}\mathcal{B}$ (eV)	95-106	202-292	41-44	1-2	1-2	50-144	0-2	0-1
S(σ)	10	> 20	13	7	11	11	4	8
χ^2/d.o.f = 346/275	p-value = 0.002							

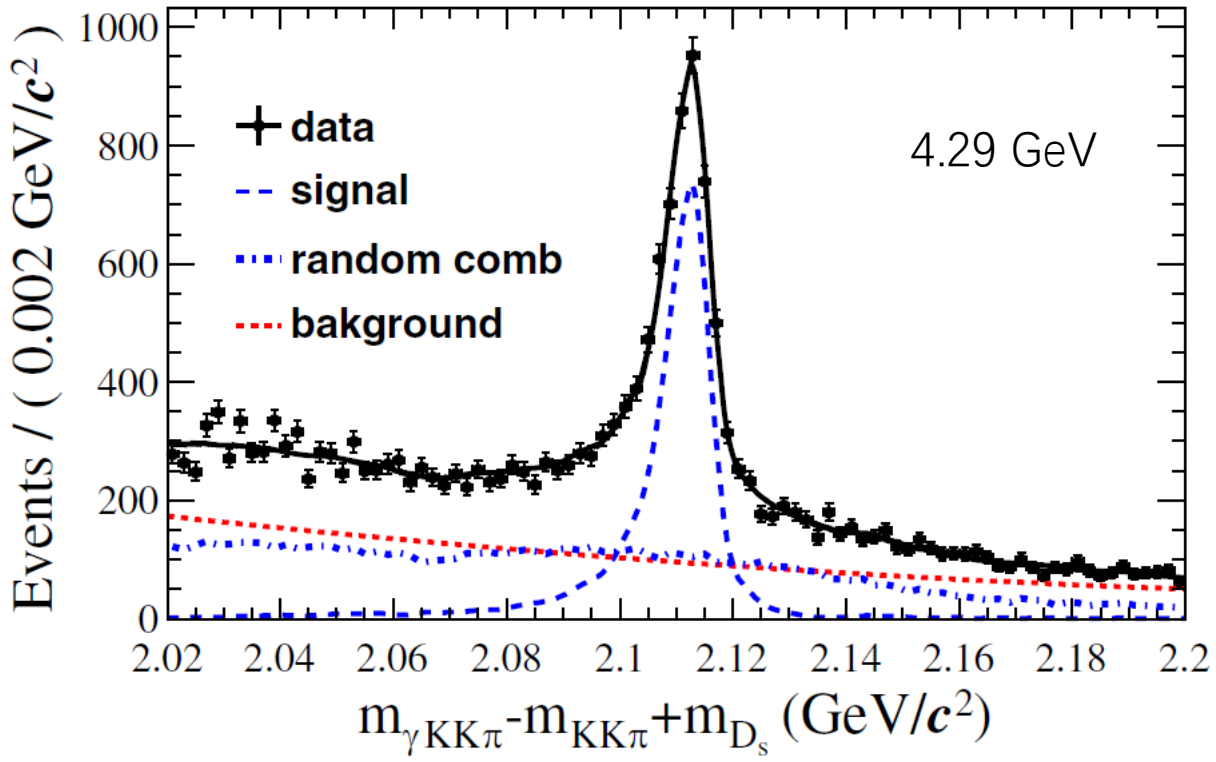
$e^+e^- \to D_s^{*+}D_s^{*-}$

PRL 131, 151903 (2023)

- $\sqrt{s}$ from 4.226 to 4.95 GeV
- Integrated luminosity: $15.67\ fb^{-1}$
- Semi-inclusive method: only reconstruct D_s^{*+} or D_s^{*-} with $D_s^{*\pm} \to \gamma D_s^{\pm} \to \gamma K^+K^-\pi^{\pm}$
  - After select $D_s^{\pm}$, keep all $\gamma D_s^{\pm}$ combinations
  - And require $|M_{miss} - m_{D_s^*}| < 5\sigma_{M_{miss}}^{MC}(\mathrm{E_{cm}})$

$e^+e^- \to D_s^{*+}D_s^{*-}$

PRL 131, 151903 (2023)



- Signal: MC shape convoluted Gaussian
- Backgrounds:
  1. Random combinations
  2. 2nd Chebyshev function

$$\sigma_{\rm Born} = \sigma_{\rm dressed}|1+\Pi|^2 = \frac{N^{\rm fit}_{D_s^*} - N_{D_s^\pm D_s^{*\mp}}}{2\mathcal{B}(D_s^\pm \to K^+K^-\pi^\pm)\epsilon(1+\delta)\frac{1}{|1+\Pi|^2}\mathcal{L}_{\rm int}}$$

Possible peaking background $e^+e^- \to \gamma_{ISR}D_s^\pm D_s^{*\mp}$ is subtracted

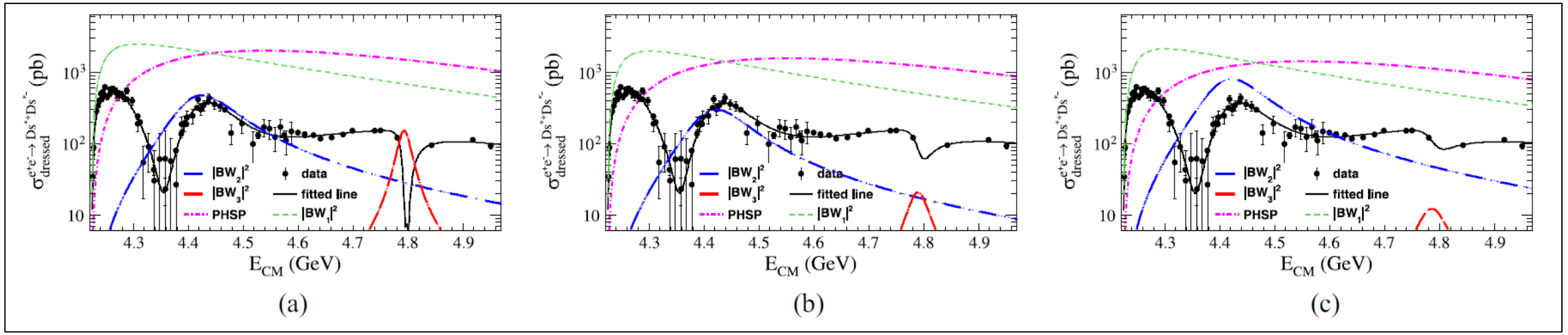
Systematic uncertainties of the cross-sections vary from 26% to 6% from low to high energies

The large uncertainty at lower region due to the calibration of energy

$e^+e^- \to D_s^{*+}D_s^{*-}$

$$\sigma_{\text{dressed}} = \left| BW_1(E_{\text{c.m.}}) + \sum_{j=2}^{3} BW_j(E_{\text{c.m.}}) e^{i\phi_j} + \frac{a_0\sqrt{\beta^3(E_{\text{c.m.}})}}{E^n_{\text{c.m.}}} e^{i\phi_0} \right|^2$$

- The significances of third structure exceed 5.9σ in all three results.
- The width of the it varies a lot due to limited statistics.



	Result 1	Result 2	Result 3
M_1 (MeV/c^2)	4186.8 ± 8.7	4194.1 ± 6.8	4195.6 ± 6.5
Γ_1 (MeV)	55 ± 15	61.1 ± 8.5	61.7 ± 7.7
M_2 (MeV/c^2)	4414.6 ± 3.4	4411.9 ± 3.2	4411.1 ± 3.2
Γ_2 (MeV)	122.5 ± 7.5	120.2 ± 7.4	119.9 ± 7.3
M_3 (MeV/c^2)	4793.3 ± 6.7	4789.7 ± 8.7	4786.0 ± 9.4
Γ_3 (MeV)	27.1 ± 6.5	42 ± 75	60 ± 34

In the nominal fit, only statistics are considered.

Systematics of resonance parameters are large

Sources	Fitting	R	$E_{\text{c.m.}}$	σ_{dressed}	Total
M_1 (MeV/c^2)	8.8	2.9	28.3	5.1	30
Γ_1 (MeV)	6.7	1.9	51	11.8	53
M_2 (MeV/c^2)	3.5	0.6	4.0	3.0	6.1
Γ_2 (MeV)	2.6	0.2	7.6	1.0	8.1
M_3 (MeV/c^2)	7.3	1.0	2.4	5.1	9.3
Γ_3 (MeV)	32.9	1.1	5.3	3.4	34

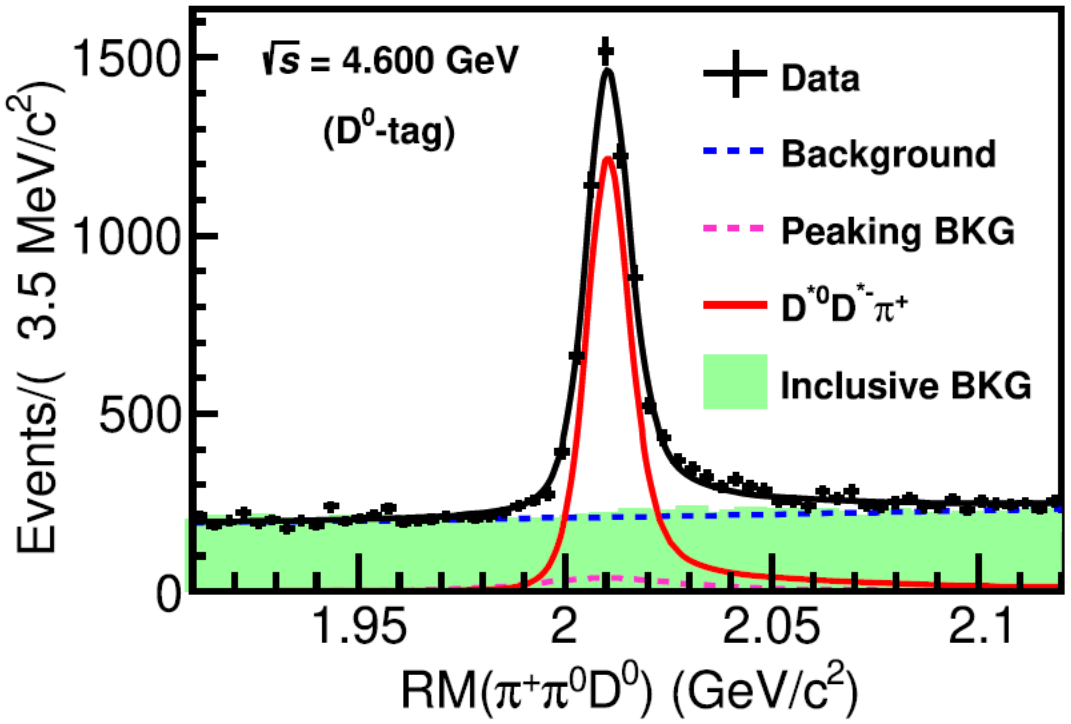
$e^+e^- \to D^{*0}D^{*-}\pi^+ + c.c.$

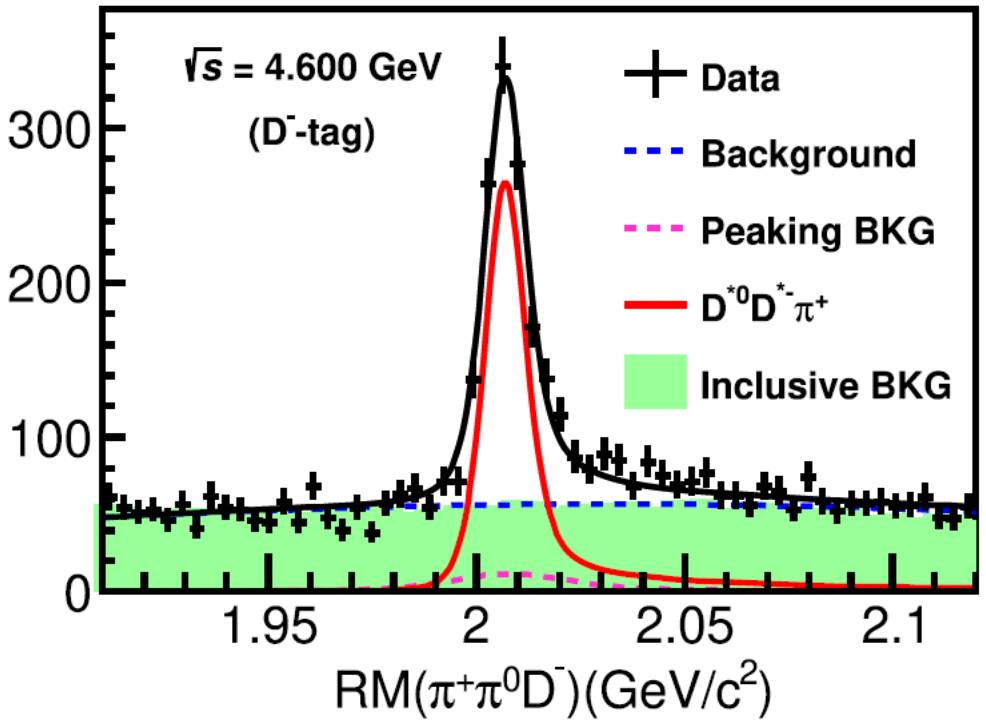
PRL 130, 121901 (2023)

- $\sqrt{s}$ from 4.189 to 4.951 GeV
- Integrated luminosity: $17.9\ fb^{-1}$
- The cross sections are measured for the first time
- Partial reconstruction technique: D^0 tag (D^- tag)
  1. Bachelor charged π
  2. $D^0(D^-)$ meson
  3. At least one soft π^0 from $D^{*0}(D^{*-}) \to D^0(D^-)\pi^0$
  4. Only decays $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$ and $D^- \to K^+\pi^-\pi^-$ are reconstructed
  5. 3C kinematic fit is performed constraining on π^0, D, D^*, and $\chi^2_{3C} < 50$

$e^+e^- \to D^{*0}D^{*-}\pi^+ + c.c.$

PRL 130, 121901 (2023)





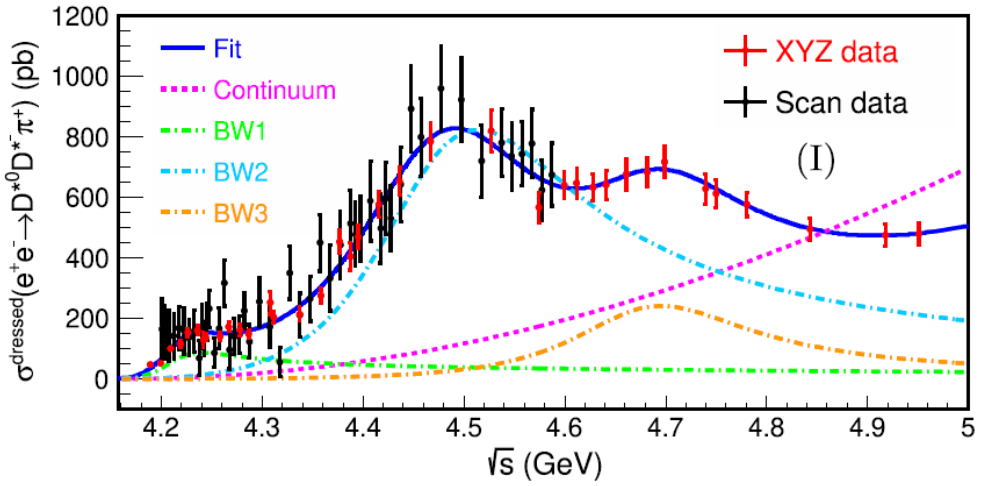
- Signal: MC shape convoluted with Gaussian
- Backgrounds:
  1. Unmatched MC samples (ratio fixed)
  2. 2nd order Chebyshev function

$$\sigma^{\rm Born} = \frac{\sigma^{\rm dressed}}{\frac{1}{|1-\Pi|^2}} = \frac{N^{\rm obs}_{D^{0(-)}\text{-tag}}}{\mathcal{L}_{\rm int}\,\epsilon_{D^{0(-)}\text{-tag}}\,\hat{\mathcal{B}}_{D^{0(-)}\text{-tag}}\,(1+\delta^{\rm ISR})\,\frac{1}{|1-\Pi|^2}}$$

Systematics: 6.7~9.6%

$e^+e^- \to D^{*0}D^{*-}\pi^+ + c.c.$

PRL 130, 121901 (2023)



eight solutions

	I	II	III	IV	V	VI	VII	VIII
$C_1(10^{-3})$				4.2 ± 1.5				
m_1 (MeV/c^2)				4209.6 ± 4.7				
Γ_1^{tot} (MeV)				81.6 ± 17.8				
$\Gamma_1^{ee}\mathcal{B}_1$ (eV)	5.4 ± 1.1	6.0 ± 1.3	4.8 ± 0.9	5.3 ± 1.1	17.9 ± 7.2	19.8 ± 6.6	20.2 ± 7.4	22.4 ± 9.0
ϕ_1 (rad)	3.1 ± 0.5	3.8 ± 0.4	1.9 ± 0.7	2.6 ± 0.6	4.2 ± 0.3	4.8 ± 0.2	5.4 ± 0.3	6.0 ± 0.3
m_2 (MeV/c^2)				4469.1 ± 26.2				
Γ_2^{tot} (MeV)				246.3 ± 36.7				
$\Gamma_2^{ee}\mathcal{B}_2$ (eV)	243.3 ± 83.5	832.5 ± 716.5	107.4 ± 50.6	367.4 ± 370.8	225.5 ± 94.9	770.8 ± 383.8	510.1 ± 202.3	1744.3 ± 926.9
ϕ_2 (rad)	4.4 ± 0.3	-0.9 ± 0.3	2.6 ± 0.6	3.7 ± 0.8	1.9 ± 0.8	3.0 ± 0.4	3.7 ± 0.3	-1.5 ± 0.3
m_3 (MeV/c^2)				4675.3 ± 29.5				
Γ_3^{tot} (MeV)				218.3 ± 72.9				
$\Gamma_3^{ee}\mathcal{B}_3$ (eV)	75.8 ± 148.8	1601.9 ± 1152.6	19.4 ± 27.1	411.6 ± 230.5	24.4 ± 34.5	515.6 ± 244.6	95.1 ± 173.1	2005.3 ± 1166.1
ϕ_3 (rad)	4.9 ± 1.4	-2.9 ± 0.4	2.1 ± 0.4	0.6 ± 1.1	1.7 ± 0.5	6.5 ± 0.5	4.5 ± 1.3	-3.3 ± 0.3

Y(4500) ?

Y(4660) ?

$$\sigma^{\text{dressed}}(\sqrt{s}) = C_0 \left| C_1 \sqrt{\Phi(\sqrt{s})} + \sum_{k=1}^{3} \text{BW}_k(\sqrt{s}) e^{i\phi_k} \right|^2$$

$$\text{BW}_k(\sqrt{s}) = \frac{m_k}{\sqrt{s}} \frac{\sqrt{12\pi\,\Gamma_k^{ee}\,\mathcal{B}_k\,\Gamma_k^{\text{tot}}}}{s - m_k^2 + i m_k \Gamma_k^{\text{tot}}} \sqrt{\frac{\Phi(\sqrt{s})}{\Phi(m_k)}}$$

Systematics of parameters

Source	Energy	Beam spread	Fit model	Total
m_1 (MeV/c^2)	0.8	5.5	2.0	5.9
Γ_1^{tot} (MeV)	···	1.7	8.8	9.0
m_2 (MeV/c^2)	0.8	3.5	0.7	3.6
Γ_2^{tot} (MeV)	···	6.9	6.4	9.4
m_3 (MeV/c^2)	0.8	1.5	3.1	3.5
Γ_3^{tot} (MeV)	···	7.4	5.7	9.3

The significance of the three-resonance hypothesis over the two-resonance hypothesis as 10.8σ

Summary and outlook

- Three precision measurements of the cross-sections of $e^+e^- \to D\overline{D}, D_s^{*+}D_s^{*-}, D^{*0}D^{*-}\pi^+ + c.c.$ are presented
- Abundant structures are observed
  - Some comparable to known charmoniumlike states observed in hidden charm processes: Y(4230), Y(4360), Y(4660)
  - **Vector charmoniumlike states couple strongly to the open charm states!**
  - Some novel structures
  - It's complex to describe the cross-sections (imperfect model: sum of BWs)
- In the future, coupled channels analysis are desired to including open and hidden charm, as well as charmonium and charmoniumlike resonances. Of course, more measurements (some will be released by BESIII soon) are important. $e^+e^- \to DD^*, D_sD_s, D_sD_s^*$ are on the road.

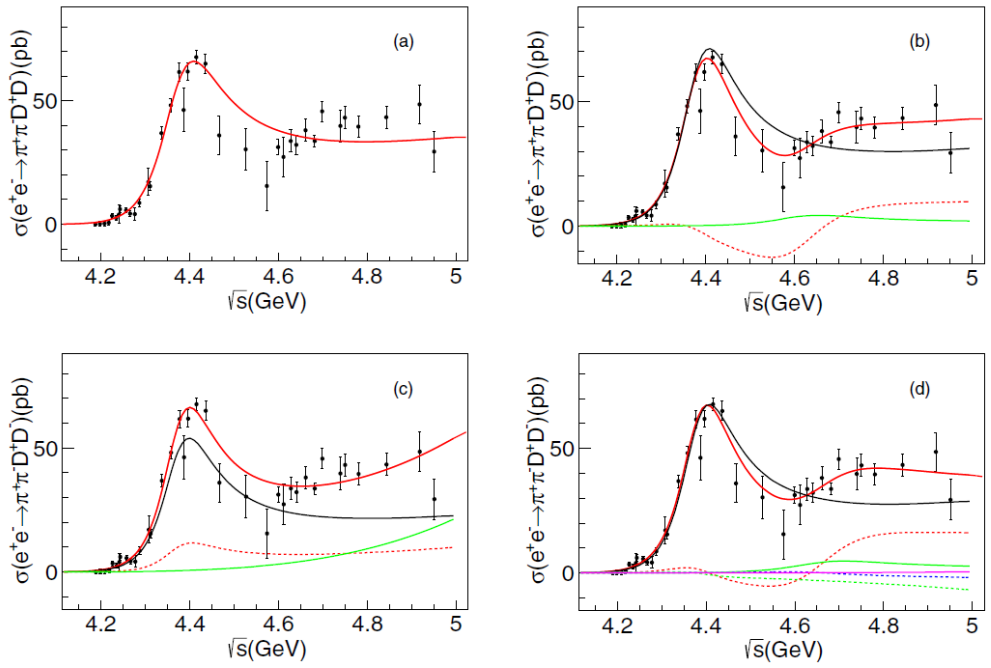
Thanks!

backup

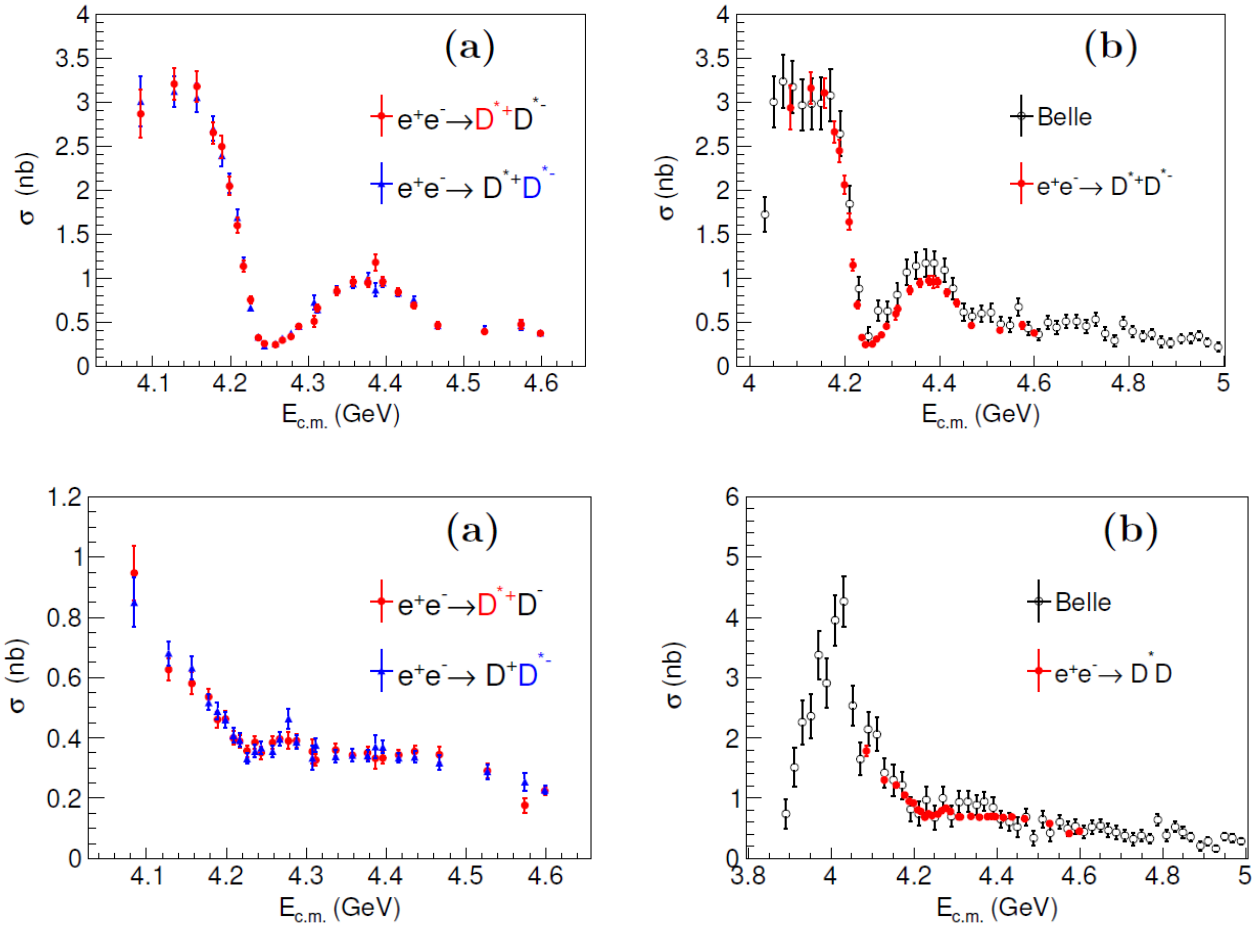
BESIII previous measurements

- Measurement of $e^+e^- \to \pi^+\pi^- D^+ D^-$ cross sections at center-of-mass energies from 4.190 to 4.946 GeV, arXiv:2208.00099, published in Phys. Rev. D 106, 052012 (2022)
- Cross section measurements of the $e^+e^- \to D^{*+}D^{*-}$ and $e^+e^- \to D^{*+}D^-$ processes at center-of-mass energies from 4.085 to 4.600 GeV, arXiv:2112.06477, published in JHEP 05, 155, (2022)
- Measurements of Born Cross Sections of $e^+e^- \to D^{*+}_s D^-_{sJ}$+c.c., arXiv:2106.02298, published in Phys. Rev. D 104, 032012 (2021)
- Evidence of a resonant structure in the $e^+e^- \to \pi^+ D^0 D^{*-}$ cross section between 4.05 and 4.60 GeV arXiv:1808.02847, published in Phys. Rev. Lett. 122, 102002 (2019)

Phys. Rev. D 106, 052012 (2022)



JHEP 05, 155, (2022)



Main contents

- Precise Measurement of Born Cross Sections for $e^+e^- \to$ D anti-D and Observation of One Structure between $\sqrt{s}$=3.80−4.95 GeV, arXiv:2402.03829, submitted to Phys. Rev. Lett.
- Precise measurement of the $e^+e^- \to D^{*+}_s D^{*-}_s$ cross sections at center-of-mass energies from threshold to 4.95 GeV, arXiv:2305.10789, published in Phys. Rev. Lett. 131, 151903 (2023)
- Observation of Three Charmonium-like States with $J^{PC}=1^{--}$ in $e^+ e^- \to D^{*0}D^{*-}\pi^+$ + c.c. process, arXiv:2301.07321, published in Phys. Rev. Lett. 130, 121901 (2023)
- Measurement of the Energy-Dependent Electromagnetic Form Factors of a Charmed Baryon, arXiv:2307.07316, published in Phys. Rev. Lett. 131, 191901 (2023)