$e^+e^- \to D_s D_{s1}(2536), D_s D_{s2}^*(2573)$, Cross Section and Branching Fraction

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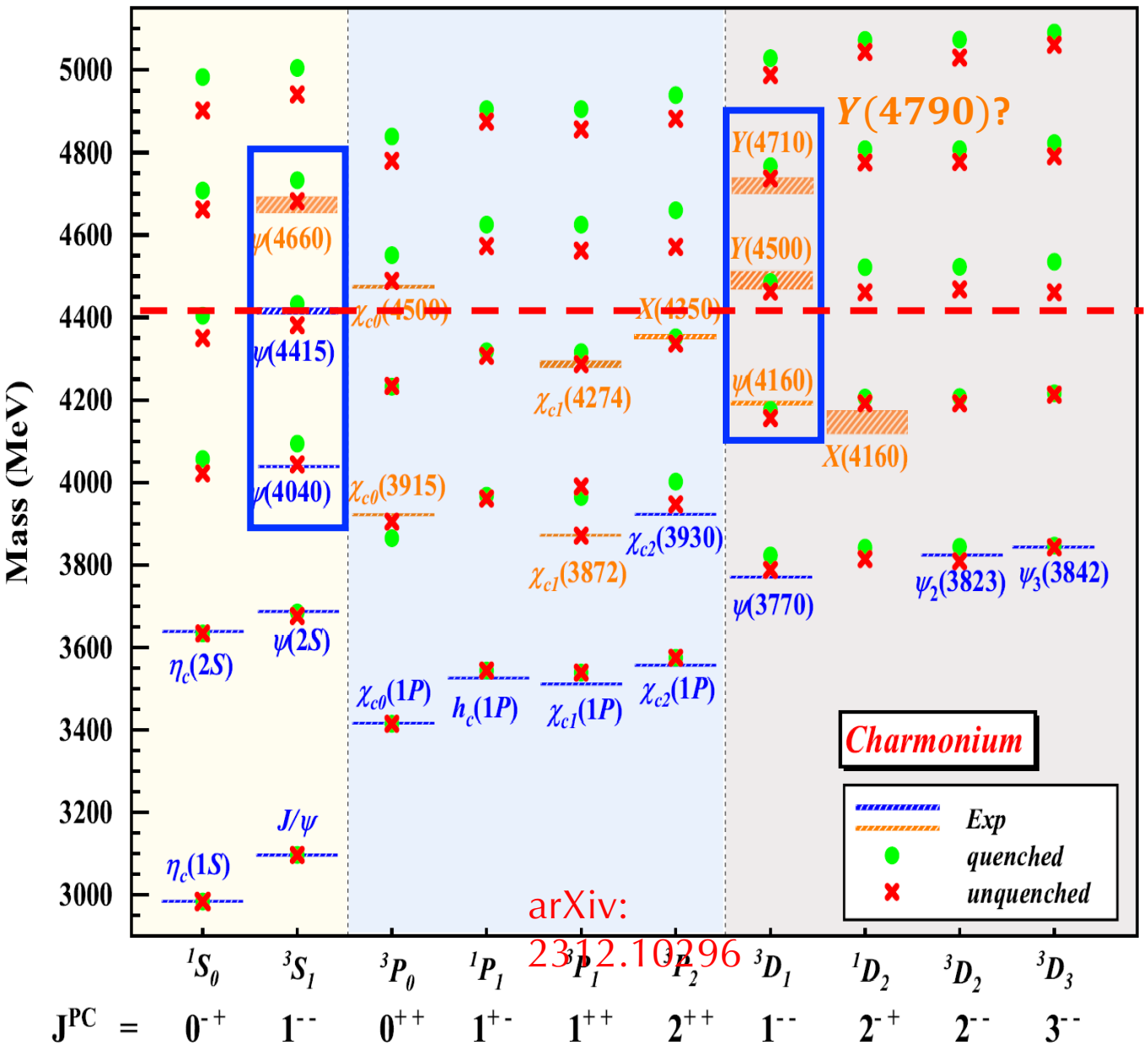


BESIII Charm Hadron Physics Workshop
Chengdu University of Technology

Outline

- Introduction
- Analysis Strategy
- Data Set and MC Sample
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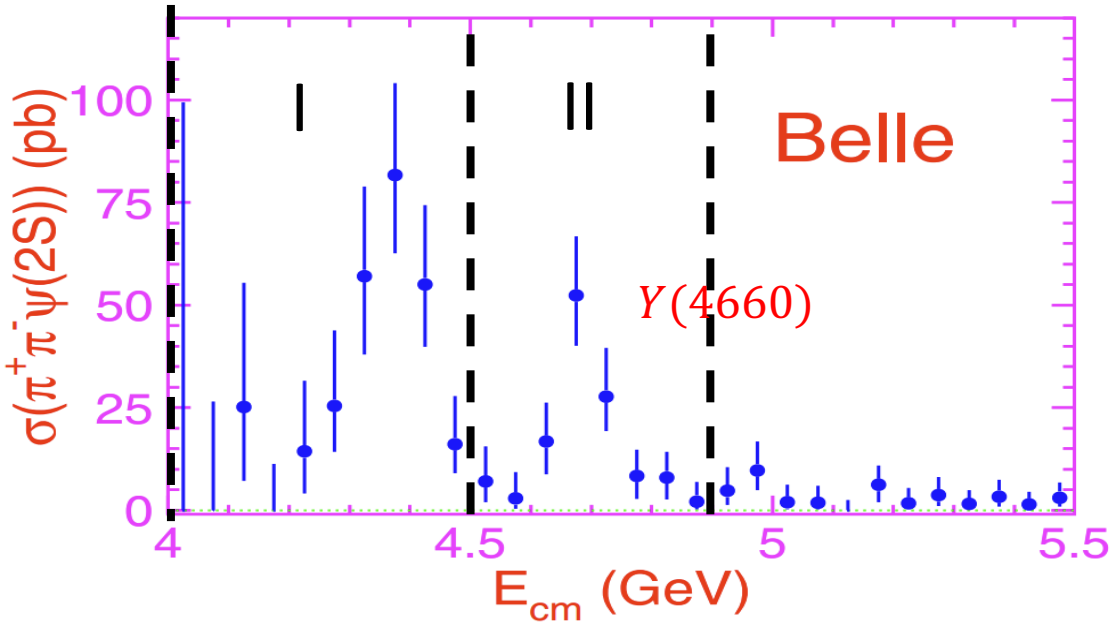
Introduction

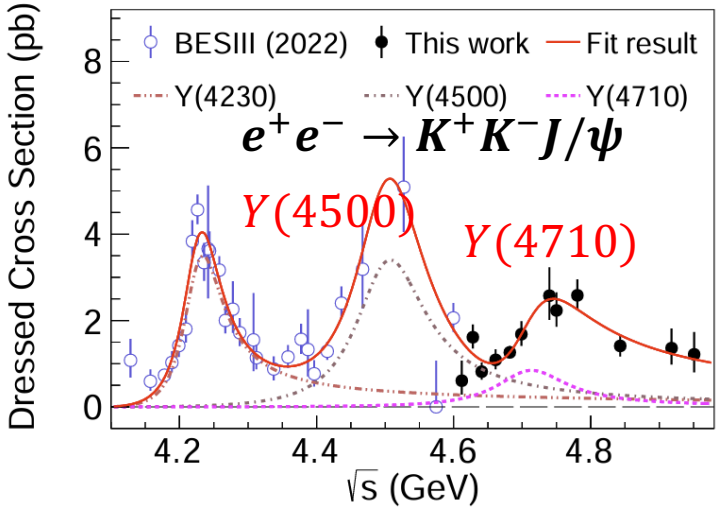


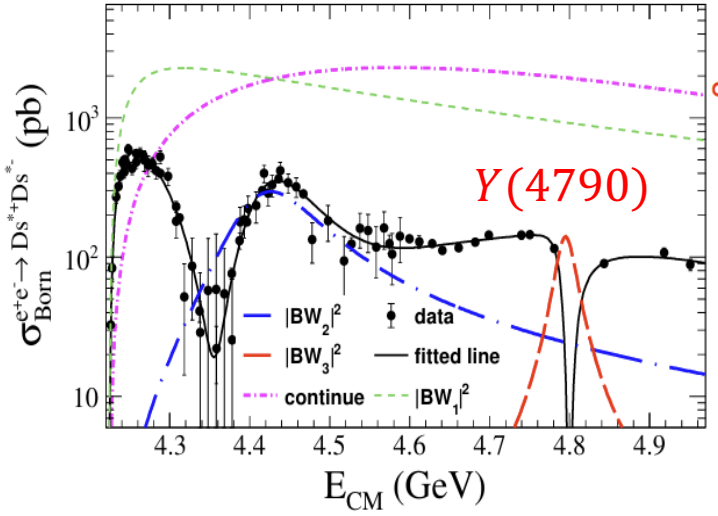
- An unquenched quark model considering coupled channel effects predicts six charmonium states with $J^{PC} = 1^{--}$ between 4.0 and 4.8 GeV/c^2: $\psi(3^3S_1)$, $\psi(2^3D_1)$, $\psi(4^3S_1)$, $\psi(3^3D_1)$, $\psi(5^3S_1)$, and $\psi(4^3D_1)$
- $\psi(3^3S_1)$, $\psi(2^3D_1)$, and $\psi(4^3S_1)$ are usually assigned as $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$, respectively
- $Y(4500)$, $Y(4660)$, $Y(4710)$, and $Y(4790)$ are observed above 4.415 GeV/c^2
- Classification of $\psi(3^3D_1)$, $\psi(5^3S_1)$, and $\psi(4^3D_1)$ is very uncertain

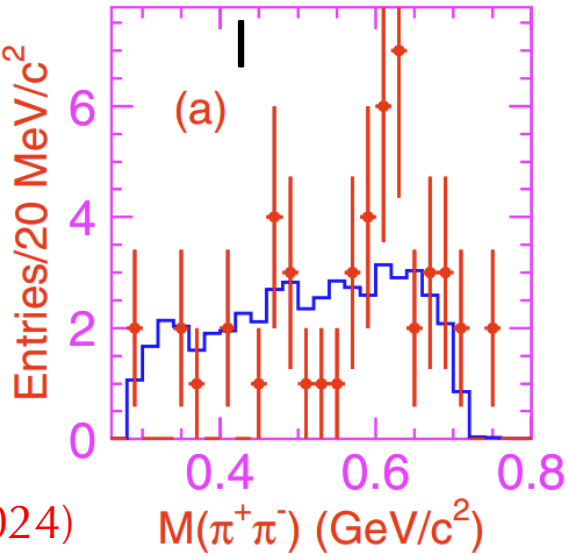
- $Y(4660) \to \pi^+\pi^-\psi(2S)$: $\pi^+\pi^-$ tends to accumulate at $f_0(980)$ → an $s\bar{s}$ component
- $Y(4500)$ and $Y(4710) \to K^+K^-J/\psi$
- $Y(4790) \to D_s^{*+}D_s^{*-}$
- These final states have both $c\bar{c}$ and $s\bar{s}$ components
- Search or study Y states in charm-strange meson pairs?

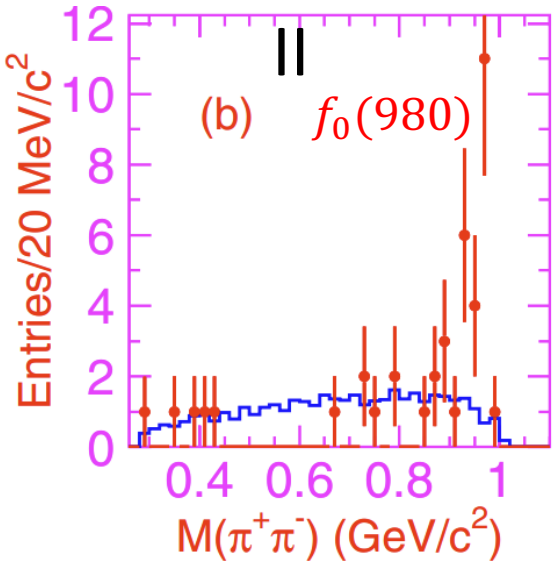
Phys. Rev. Lett. 99, 142002 (2007)











Phys. Rev. Lett. 131, 211902 (2024) Phys. Rev. Lett. 131, 151903 (2024)

■ Belle: $e^+e^- \to D_sD_{s1}(2536), D_sD_{s2}^*(2573)$

$Y(4660)$ M: 4630 ± 6 MeV/c^2 Γ: 72^{+14}_{-12} MeV

$Y(4626)$

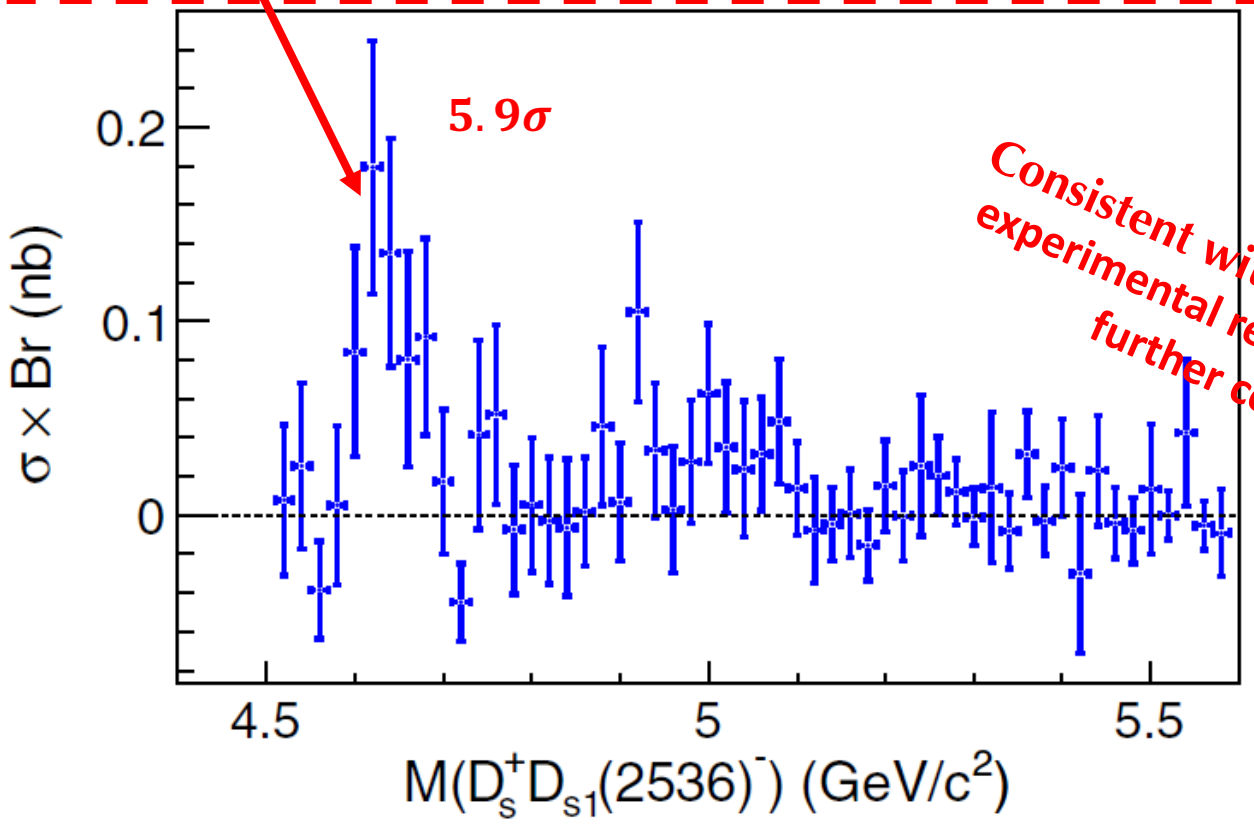
M: $4625.9^{+6.2}_{-6.0}(\text{stat}) \pm 0.4(\text{syst})$ MeV/c^2

Γ: $49.8^{+13.9}_{-11.5}(\text{stat}) \pm 4.0(\text{syst})$ MeV

$Y(4620)$

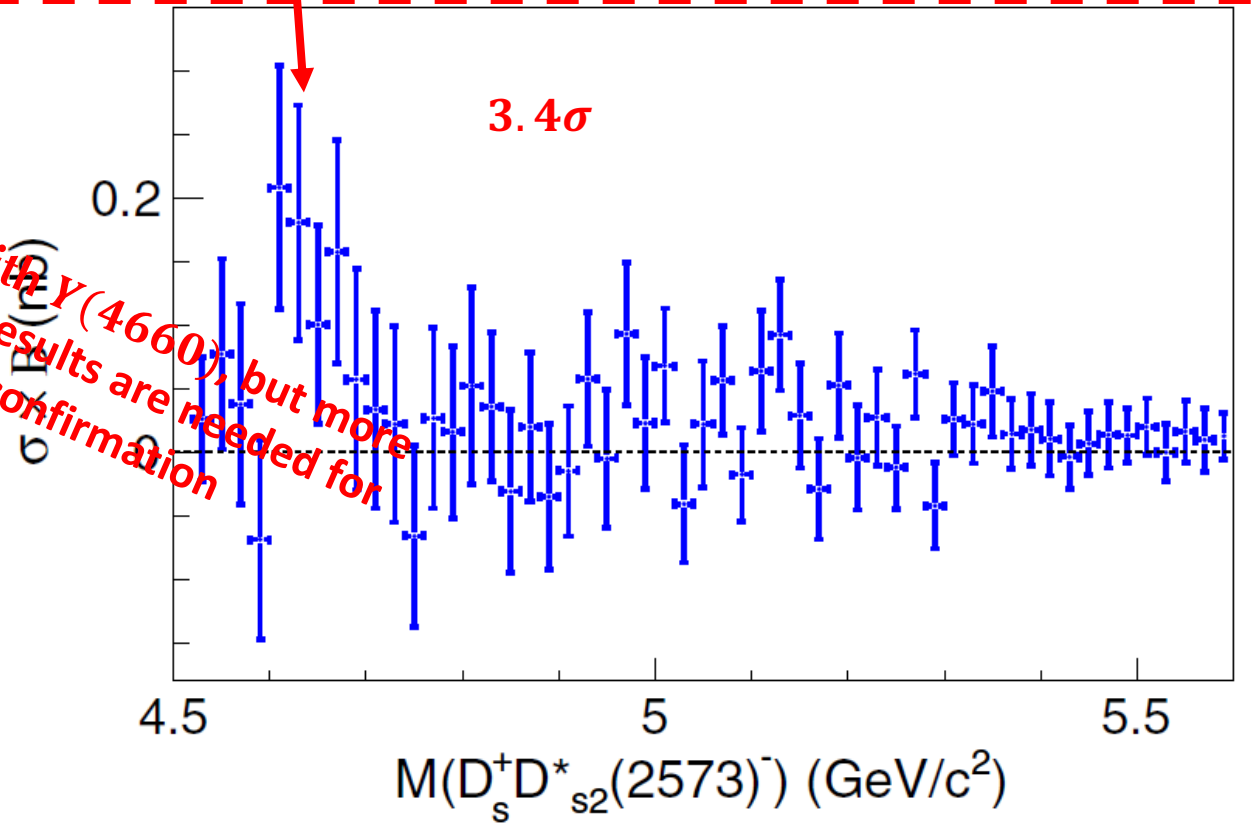
M: $4619.8^{+8.9}_{-8.0}(\text{stat}) \pm 2.3(\text{syst})$ MeV/c^2

Γ: $47.0^{+31.3}_{-14.8}(\text{stat}) \pm 4.6(\text{syst})$ MeV



Phys. Rev. D 100, 111103 (2019)

Consistent with $Y(4660)$, but more experimental results are needed for further confirmation

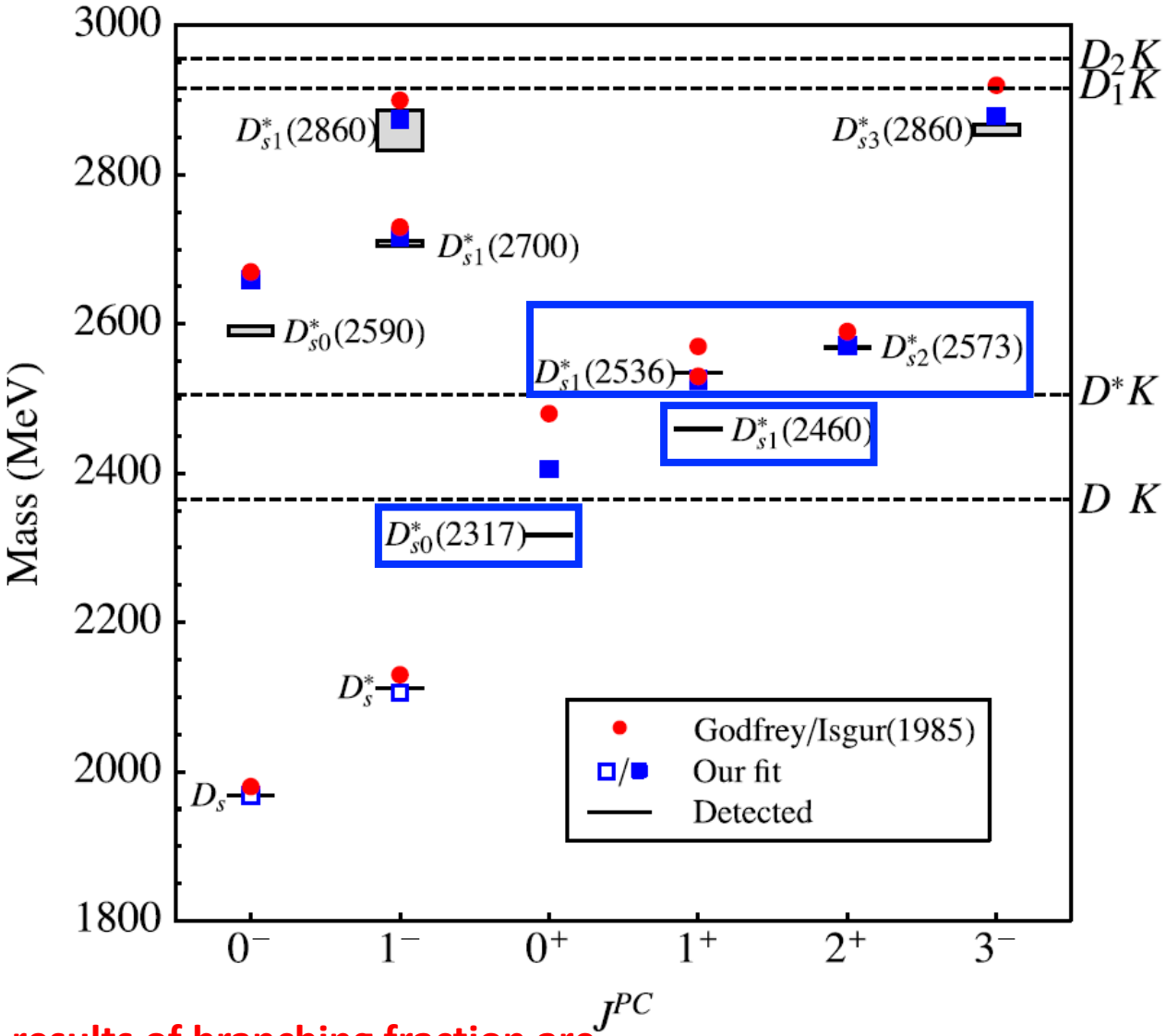


Phys. Rev. D 101, 091101 (2020)

- Four P-wave $c\bar{s}$ states with $J^P = 0^+(D_{s0}^*)$, $1^+(D_{s1})$, $1^+(D_{s1}')$, $2^+(D_{s2}^*)$ are predicted in conventional quark model
- $D_{s0}^*(2317)$ and $D_{s1}(2460)$: are assigned as $0^+(D_{s0}^*)$ and $1^+(D_{s1})$, but are observed with lower mass compared with prediction
- $D_{s1}(2536)$ and $D_{s2}^*(2573)$: are assigned as $1^+(D_{s1}')$ and $2^+(D_{s2}^*)$

- A coupled-channel framework:
  - explain the lower mass of $D_{s0}^*(2317)$ and $D_{s1}(2460)$
  - $D_{s1}(2536)$ and $D_{s2}^*(2573)$ are dominated by bare $c\bar{s}$
- Heavy Quark Limit: arXiv: 2312.04765
  - $D_{s1}(2536) \to D^*K \sim 100\%$
  - $D_{s2}^*(2573) \to DK \sim 90\%$

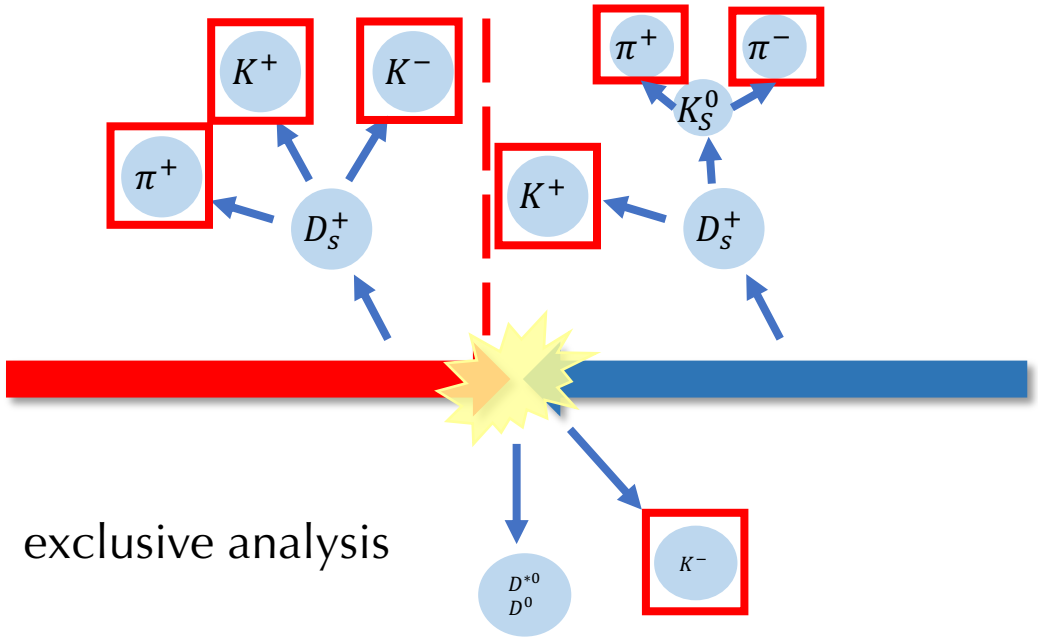
Phys. Rev. Lett. 128, 112001 (2022)



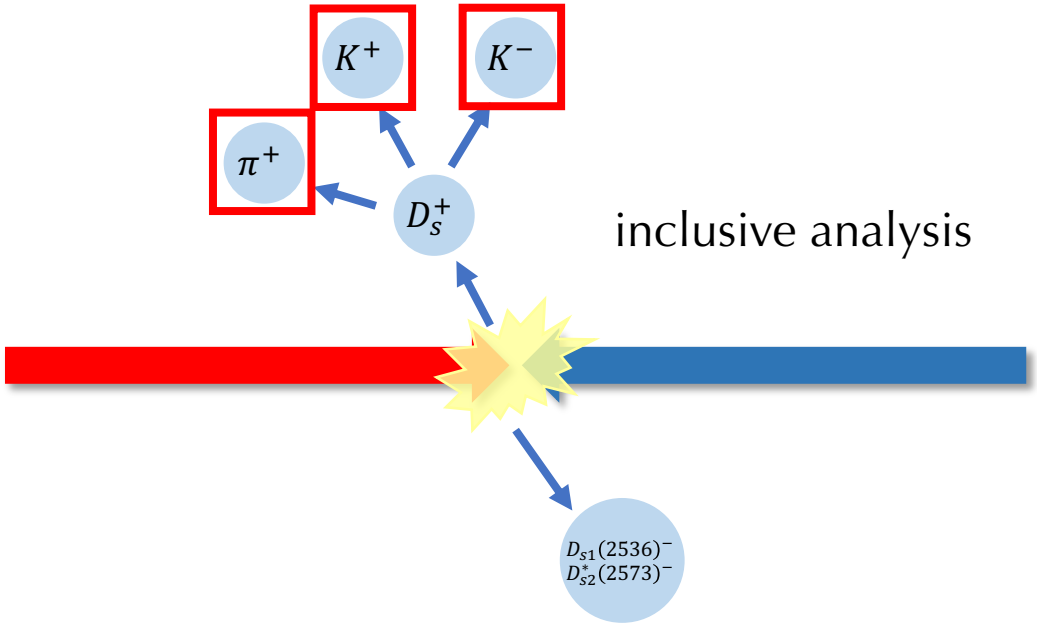
Experimental results of branching fraction are needed for confirmation

Analysis Strategy

- **Possible Y states (exclusive analysis)**:
  - Cross section of $e^+e^- \to D_s^+ D_{s1}(2536)^-$, with $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$
  - Cross section of $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$, with $D_{s2}^*(2573)^- \to \bar{D}^0 K^-$
- **Branching fraction measurement**:
  - Cross section of $e^+e^- \to D_s^+ D_{s1}(2536)^-$, $D_s^+ D_{s2}^*(2573)^-$ (inclusive analysis)
  - $\mathcal{B}$: inclusive analysis + exclusive analysis
- A similar strategy is simultaneously applied on the charge conjugated process, and charge conjugated process or particle is always implied



exclusive analysis



inclusive analysis

Data Set and MC Sample

■ All data samples above the threshold

$\sqrt{s}^{\text{nominal}}$ (GeV)	Measured $\sqrt{s}$ (MeV)	$\mathcal{L}$ (pb^{-1})
4.530	4527.14±0.11±0.72	112.12±0.04±0.73
4.575	4574.50±0.18±0.70	48.93±0.03±0.32
4.600	4599.53±0.07±0.74	586.9±0.1±3.9
4.610	4611.86±0.12±0.32	103.83±0.05±0.55
4.620	4628.00±0.06±0.32	521.52±0.11±2.76
4.640	4640.91±0.06±0.38	552.41±0.12±2.93
4.660	4661.24±0.06±0.29	529.63±0.12±2.81
4.680	4681.92±0.08±0.29	1669.31±0.21±8.85
4.700	4698.82±0.10±0.39	536.45±0.12±2.84
4.740	4739.70±0.20±0.30	164.27±0.07±0.87
4.750	4750.05±0.12±0.29	367.21±0.10±1.95
4.780	4780.54±0.12±0.33	512.78±0.12±2.72
4.840	4843.07±0.20±0.31	527.29±0.12±2.79
4.914	4918.02±0.34±0.35	208.11±0.02±1.10
4.946	4950.93±0.36±0.44	160.37±0.07±0.85

Corresponding to 6.60 pb^{-1}

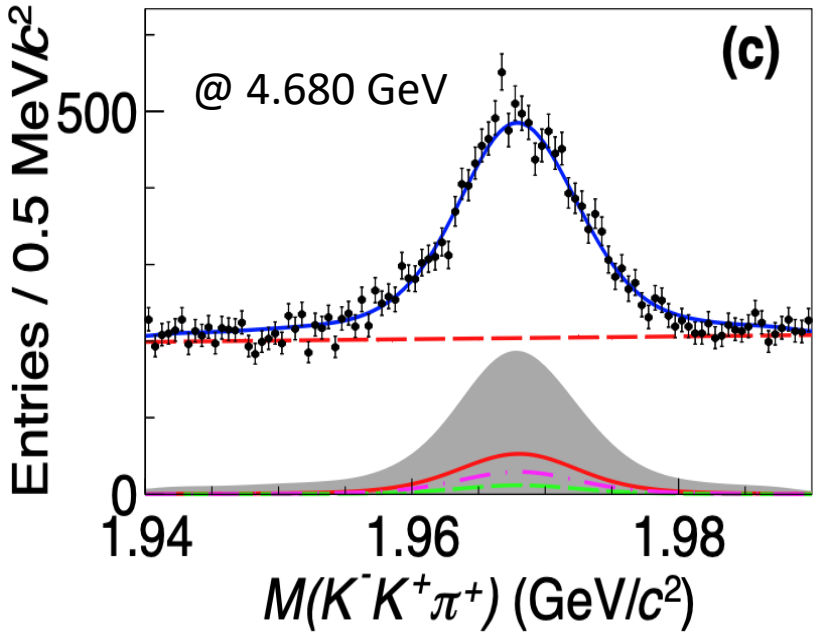
■ Signal MC sample

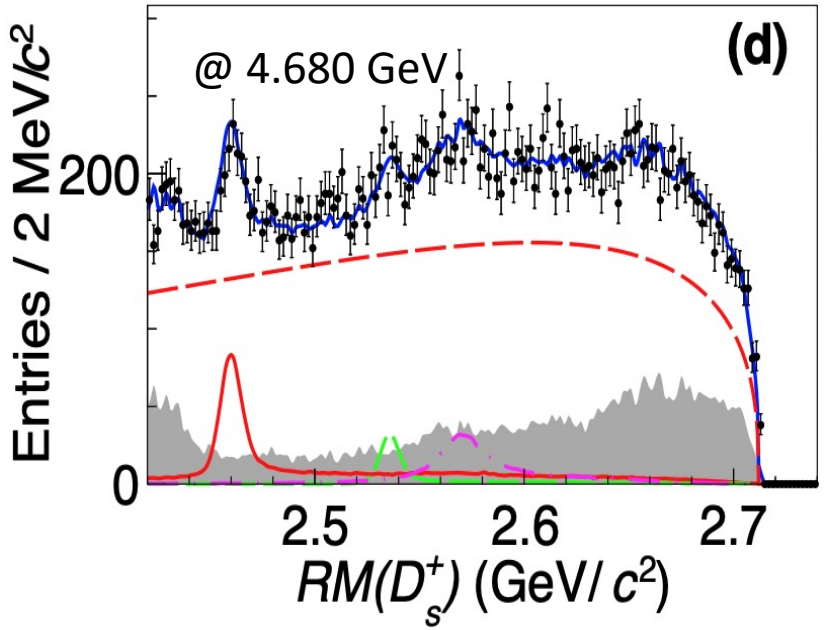
- $e^+e^- \to D_s^+ D_{s1}(2536)^-$:
  S-wave and D-wave$\to 1-\alpha\cos^2\theta$
- $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$:
  D-wave
- $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$:
  S-wave and D-wave→fraction fixed according to Phys. Rev. D 77, 032001 (2008)
- $D_{s2}^*(2573)^- \to \bar{D}^0 K^-$:
  D-wave
- $D_s^+ \to K^-K^+\pi^+$: D_Dalitz
- $D_s^+ \to K_S^0 K^+$: PHSP
- $K_S^0 \to \pi^+\pi^-$: PHSP

Inclusive Analysis

- 2D fit of $M(K^-K^+\pi^+)$ and $RM(D_s^+)$
  - Signal description:
    - ✓ $M(K^-K^+\pi^+)$: MC shape convolving Gaussian function (fixed)
    - ✓ $RM(D_s^+)$:
      - MC shape of $e^+e^- \to D_s^+ D_{s1}(2536)^-$
      - MC shape of $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$
  - Background description:
    - ✓ $M(K^-K^+\pi^+)$: First order Chebychev polynomial function
    - ✓ $RM(D_s^+)$: ARGUS function
    - ✓ Other B.K.G.:
      - Fixed according to previous measurements
      - Fixed according to our measurements
      - Floated in the fit

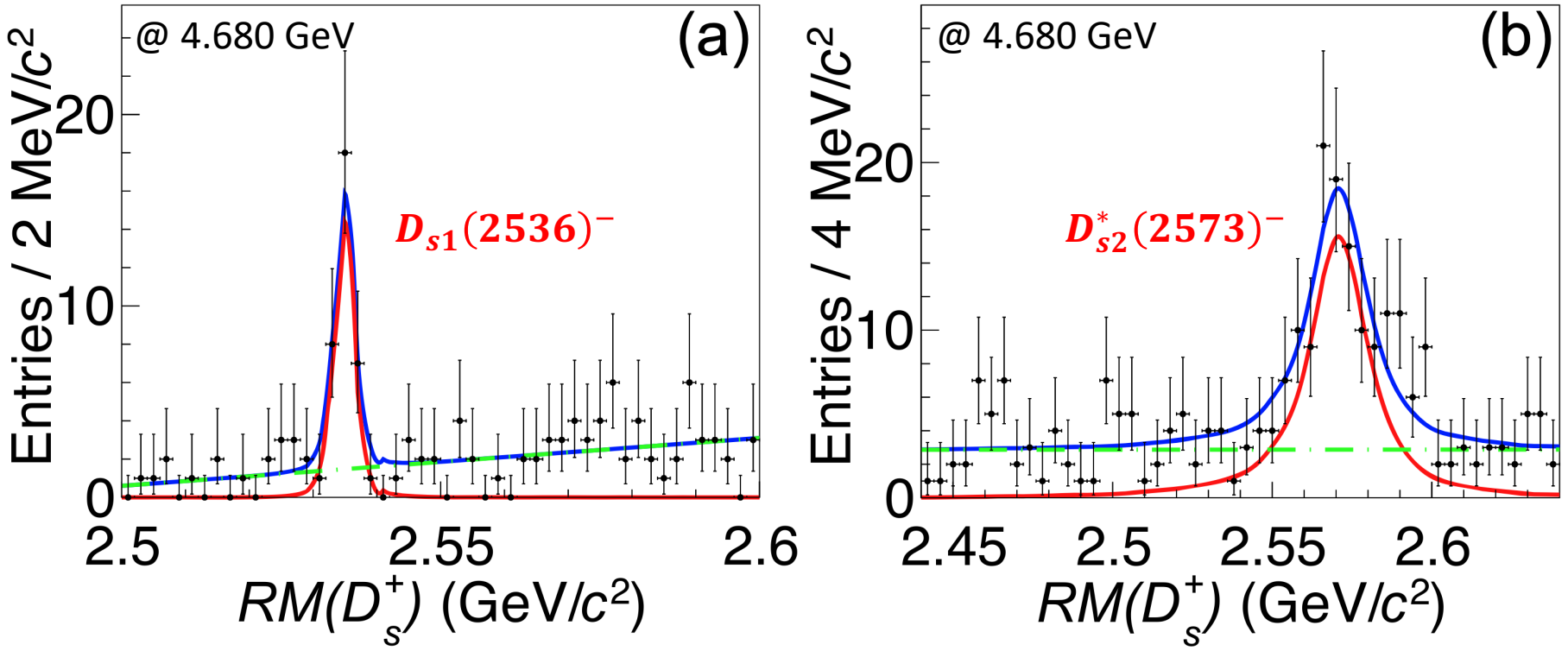
$e^+e^- \to D_s^{*+} D_s^{*-}$
$e^+e^- \to D_s^+ D_{s1}(2460)^-$
$e^+e^- \to D_s^{*+} D_{s0}^*(2317)^-$
$e^+e^- \to D_s^{*+} D_{s1}(2460)^-$
$e^+e^- \to D_s^{*+} D_{s1}(2536)^-$
$e^+e^- \to D_s^+ \bar{D}^0 K^-$
$e^+e^- \to D_s^+ \bar{D}^{*0} K^-$
$e^+e^- \to D_s^{*+} \bar{D}^0 K^-$
$e^+e^- \to D_s^{*+} \bar{D}^{*0} K^-$





Exclusive Analysis

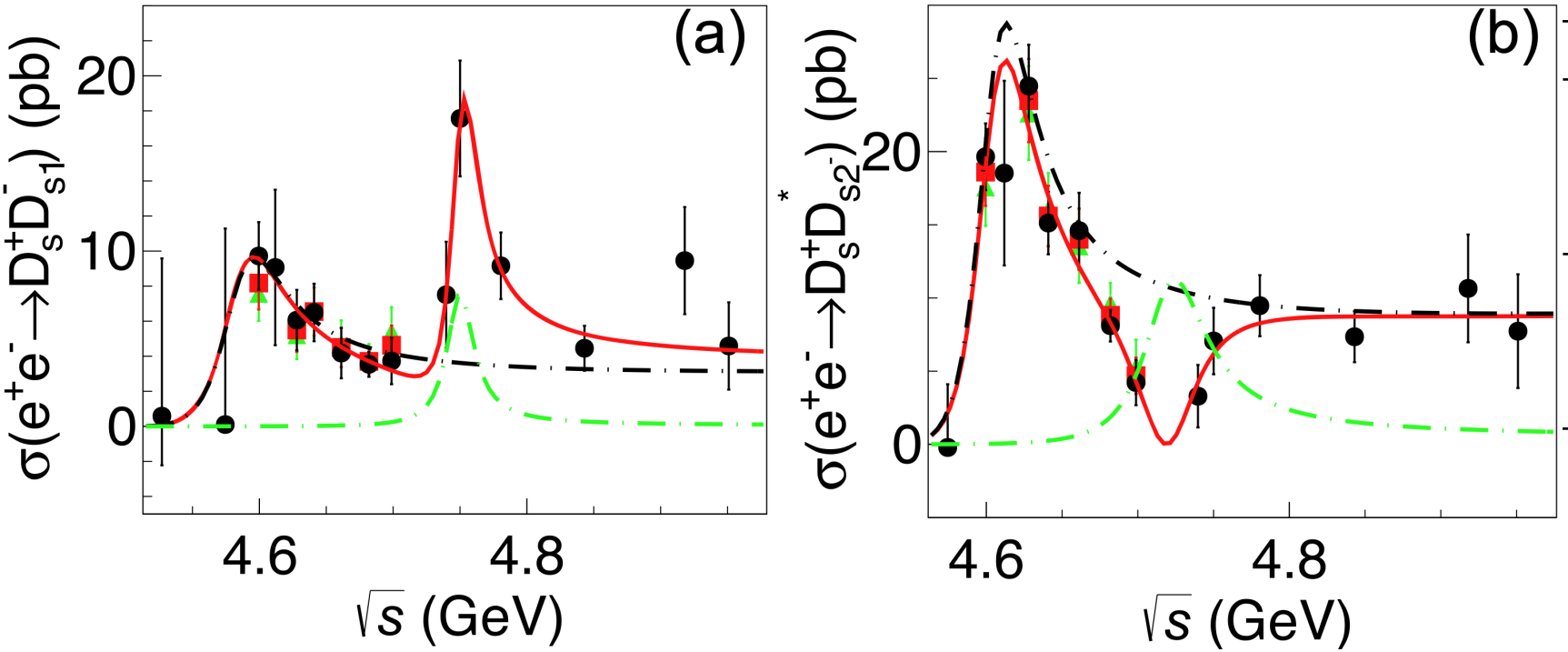
- Fit of $RM(D_s^+)$
  - Signal description:
    - MC shapes of $e^+e^- \to D_s^+ D_{s1}(2536)^-$ and $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$ convolving Gaussian functions
  - Background description:
    - ✓ First order Chebychev polynomial function



Results

Cross Section

$$\sigma^{exc} = \frac{N_{exc}}{\frac{1}{|1-\Pi|^2}(1+\delta)((\epsilon_{exc}(D_s^+ \to K_S^0 K^+)\mathcal{B}(D_s^+ \to K_S^0 K^+)\mathcal{B}(K_S^0 \to \pi^+\pi^-)) + (\epsilon_{exc}(D_s^+ \to K^+K^-\pi^+)\mathcal{B}(D_s^+ \to K^+K^-\pi^+)))\mathcal{L}}$$



Coherent sum of two BW functions

	$D_s^+ D_{s1}(2536)^-$	$D_s^+ D_{s2}^*(2573)^-$
M_0 (MeV/c^2)	4584±14±80	4603.1±3.9±0.8
Γ_0 (MeV)	57±12±219	45.2±5.7
Significance	**7.2σ**	**15σ**
M_1 (MeV/c^2)	4749.9±8.2±5.5	4720±13±2
Γ_1 (MeV)	24.9±8.0±1.0	50±12±1
Significance	4.3σ	2.7σ

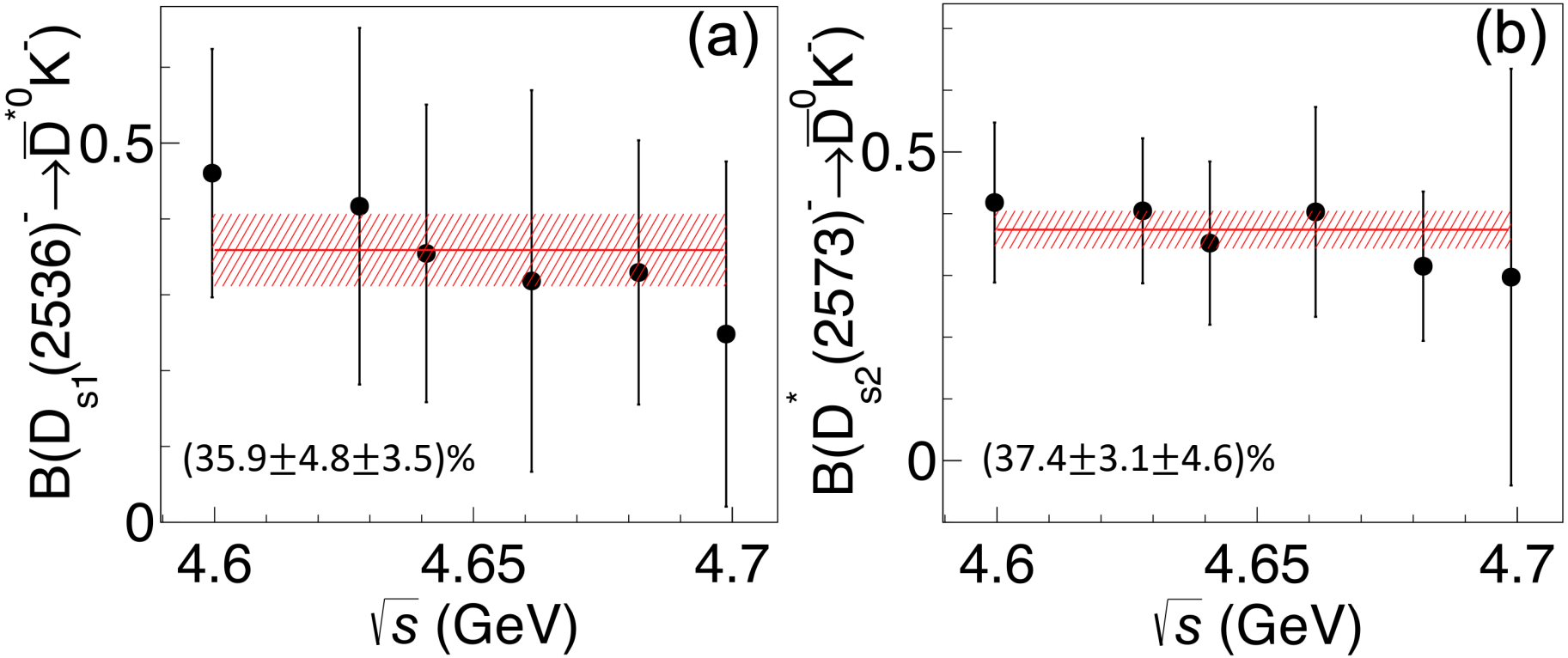
Branching Fraction: Maximum Likelihood Fit

$$\mathcal{L}(\sigma^{inc}, \delta^{inc}, \sigma^{exc}, \delta^{exc}; \sigma_i, \mathcal{B}) = \prod_{i=1}^{6} \mathcal{L}_{inc}(\sigma_i^{inc}, \delta_i^{inc}; \sigma_i)\mathcal{L}_{exc}(\sigma_i^{exc}, \delta_i^{exc}; \sigma_i, \mathcal{B})$$

$$\mathcal{L}_{inc}(\sigma_i^{inc}, \delta_i^{inc}, \sigma_i) = \frac{1}{\sqrt{2\pi}\delta_i^{inc}} e^{-\frac{(\sigma_i^{inc} - \sigma_i)^2}{2(\delta_i^{inc})^2}} \quad \mathcal{L}_{exc}(\sigma_i^{exc}, \delta_i^{exc}, \sigma_i, \mathcal{B}) = \frac{1}{\sqrt{2\pi}\delta_i^{exc}} e^{-\frac{(\sigma_i^{exc} - \sigma_i\mathcal{B})^2}{2(\delta_i^{exc})^2}}$$

$\sigma(e^+e^- \to D_s^+ D_{s1}(2536)^-)$ and $\sigma(e^+e^- \to D_s^+ D_{s2}^*(2573)^-)$

$\mathcal{B}(D_{s1}(2536)^- \to \bar{D}^{*0}K^-)$ and $\mathcal{B}(D_{s2}^*(2573)^- \to \bar{D}^0 K^-)$



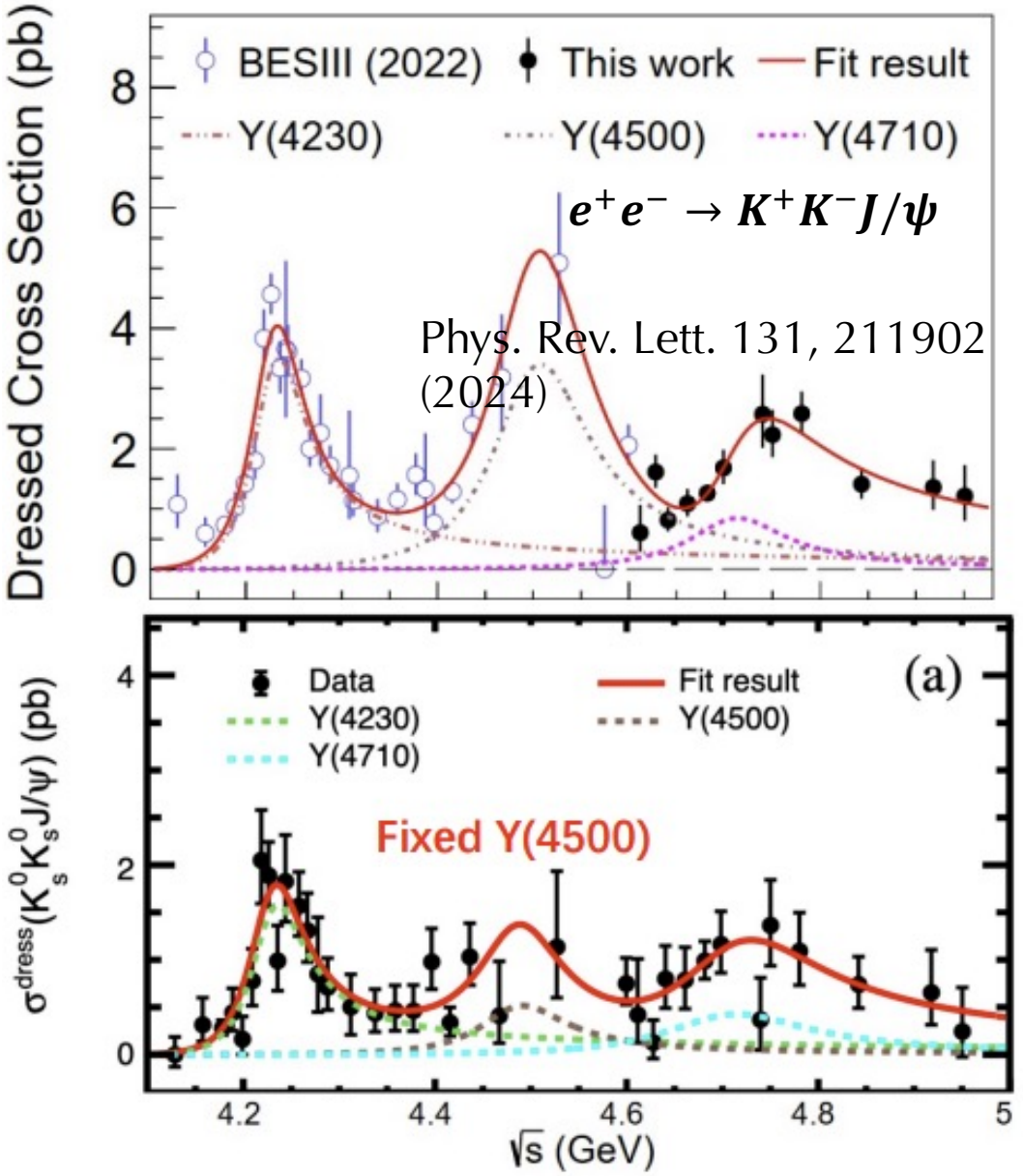
Summary

- Branching fraction measurement
  - $\mathcal{B}(D_{s1}(2536)^- \to \bar{D}^{*0}K^-) = (35.9 \pm 4.8 \pm 3.5)\%$
  - $\mathcal{B}(D_{s2}^*(2573)^- \to \bar{D}^0K^-) = (37.4 \pm 3.1 \pm 4.6)\%$
  - More non-bare $c\bar{s}$ component may exist
- Possible Y states:
  - A resonant structure around 4.6 GeV in $D_s^+D_{s1}(2536)^-$ is observed
    - ✓ Consistent with the $Y(4626)$ reported by Belle
  - A resonant structure around 4.6 GeV in $D_s^+D_{s2}^*(2573)^-$ is observed for the first time
    - ✓ Consistent with the $Y(4620)$ reported by Belle
  - Evidence for a structure at around 4.75 GeV is observed in both processes
    - ✓ May be correlated with $Y(4710)$ and $Y(4790)$ reported by BESIII
- In the future with more data samples above 4.6 GeV @ BESIII:
  - Isospin symmetry test of $D_{s1}(2536) \to D^*K$ and $D_{s2}^*(2573) \to DK$
    - ✓ $\mathcal{B}(\frac{D_{s1}(2536)^- \to D^{*-}\bar{K}^0}{D_{s1}(2536)^- \to \bar{D}^{*0}K^-})$, $\mathcal{B}(\frac{D_{s2}^*(2573)^- \to D^-\bar{K}^0}{D_{s2}^*(2573)^- \to \bar{D}^0\bar{K}^-})$
  - Inclusive analysis of $D_{s1}(2536)/D_{s2}^*(2573) \to D + inclusive$ and $D_{s0}^*(2317)/D_{s1}(2460) \to D_s + inclusive$

Thanks for Your Listening!

BackUp

■ $Y(4500)$ and $Y(4710) \rightarrow K\bar{K}J/\psi$



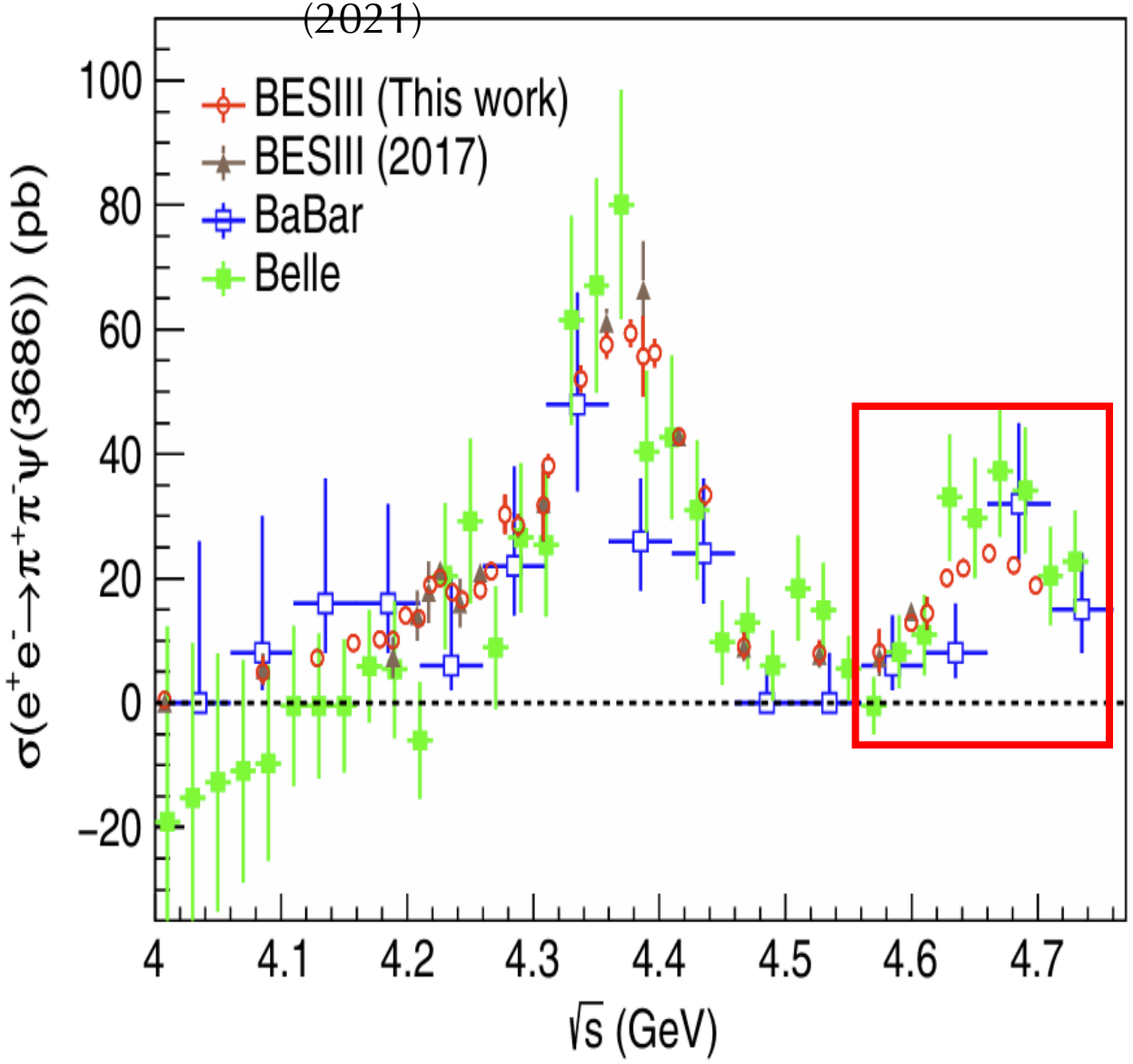
	K^+K^-J/ψ	$K_S^0K_S^0J/\psi$
$M_{Y(4230)}$ (MeV/c^2)	4225.2±2.2	4225.2±2.2
$\Gamma_{Y(4230)}$ (MeV)	70.7±6.1	72±16
$M_{Y(4500)}$ (MeV/c^2)	4499±13	--
$\Gamma_{Y(4500)}$ (MeV)	124±25	--
$M_{Y(4710)}$ (MeV/c^2)	4708±15	4704±52
$\Gamma_{Y(4710)}$ (MeV)	126±31	(18±11)∗ 10

Coherent sum of three BW functions

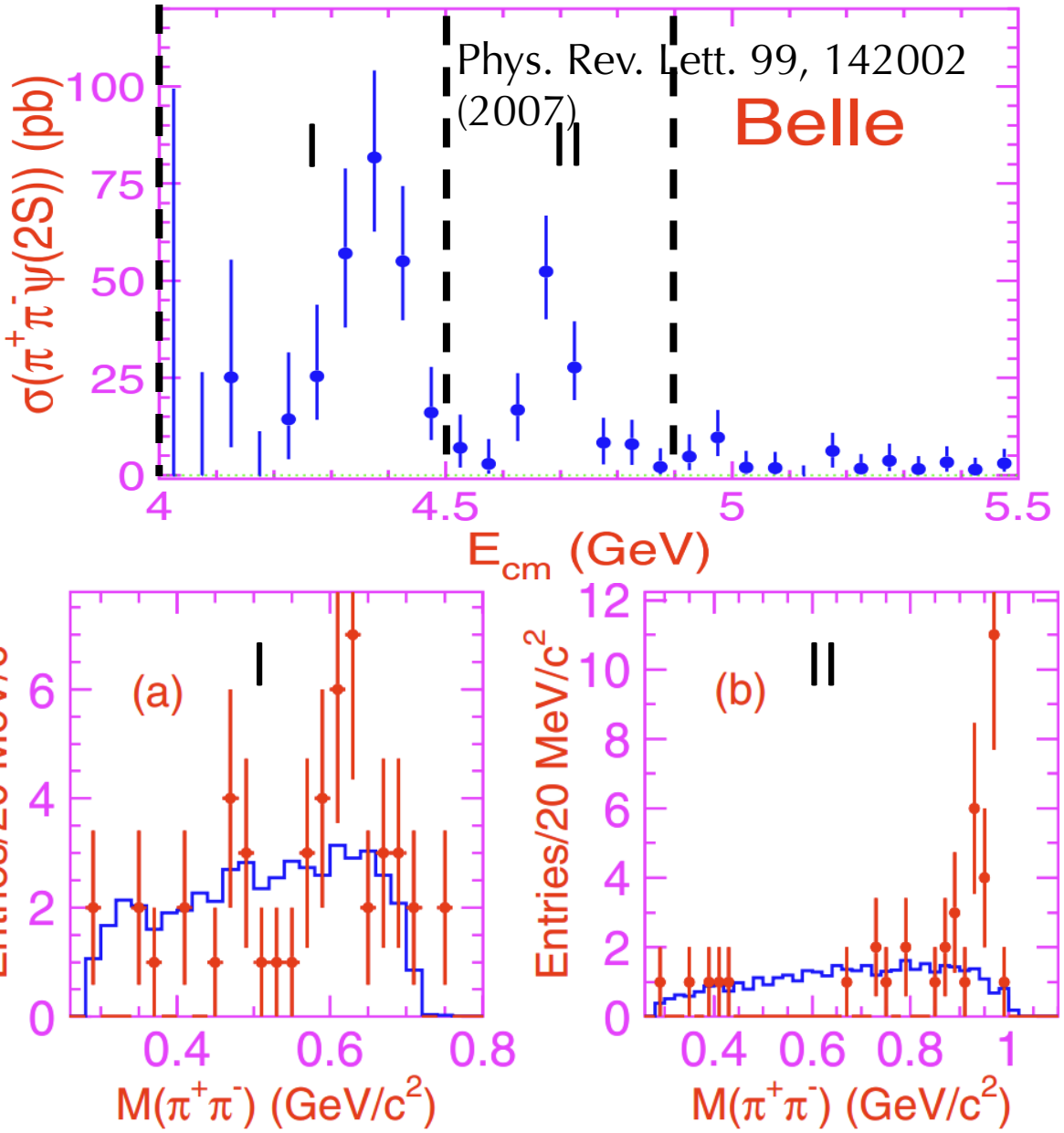
Phys. Rev. D 107, 092005 (2023)

■ $Y(4660) \to \pi^+\pi^-\psi(2S)$: $\pi^+\pi^-$ tends to accumulate at $f_0(980)$ → an $s\bar{s}$ component

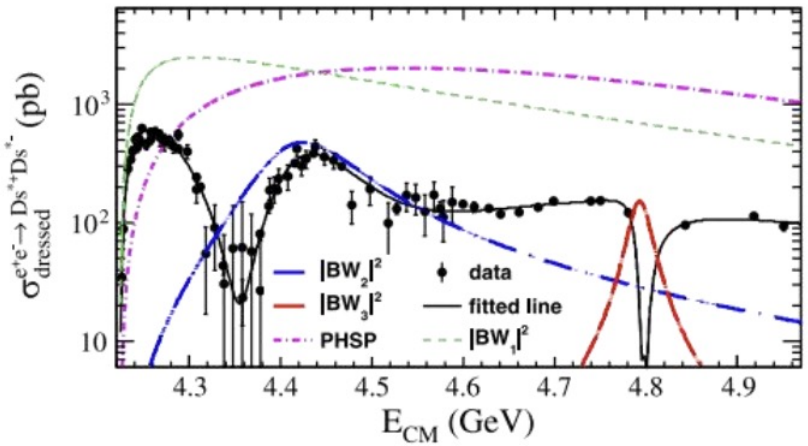
Phys. Rev. D 104, 052012 (2021)



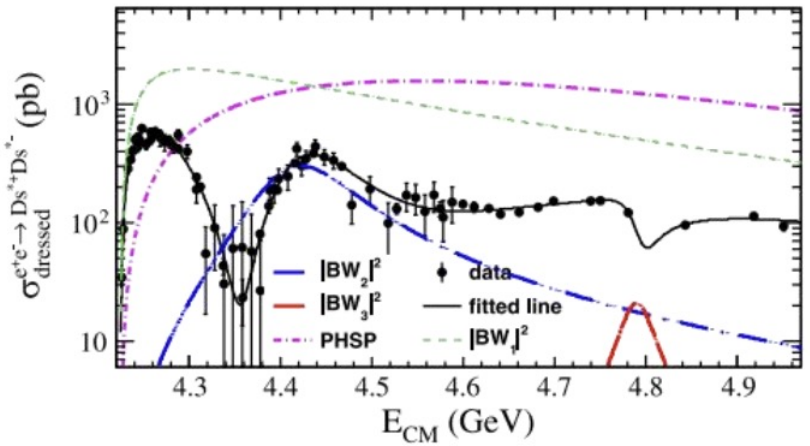
Phys. Rev. Lett. 99, 142002 (2007)



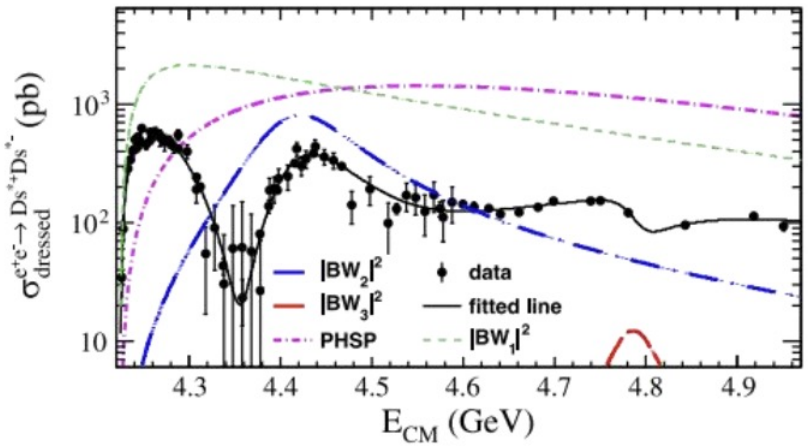
■ $Y(4790) \to D_s^{*+} D_s^{*-}$



(a)



(b)



(c)

Fitting results

	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

The systematic uncertainties

Sources	Fitting	R	$E_{c.m.}$	$\sigma_{dressed}$	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

Different solutions have different parameters: lack of data sample around 4.7 GeV