



山东大学
SHANDONG UNIVERSITY



Cross-section measurements and search for vector states at cms energies 4-5 GeV

Hang Zhou (Shandong University)

hzhou@sdu.edu.cn

on behalf of the BESIII Collaboration

11th International Workshop on Charm Physics (CHARM 2023)

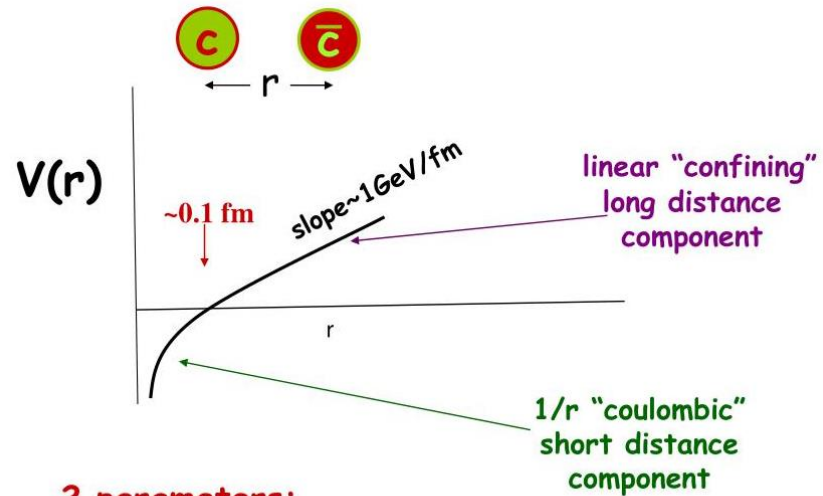
July 18, 2023, Siegen, Germany

Outline

- **Introduction**
- **BESIII experiment and data sets**
- **A selection of recent results**
 - ✓ $e^+e^- \rightarrow KKJ/\psi$
 - ✓ $e^+e^- \rightarrow \phi\chi_{c1,2}$
 - ✓ $e^+e^- \rightarrow D^{*0}D^{*+}\pi^-$
 - ✓ $e^+e^- \rightarrow D_s^{*+}D_s^{*-}$
 - ✓ $e^+e^- \rightarrow \omega\pi^+\pi^-$
- **Summary and prospect**

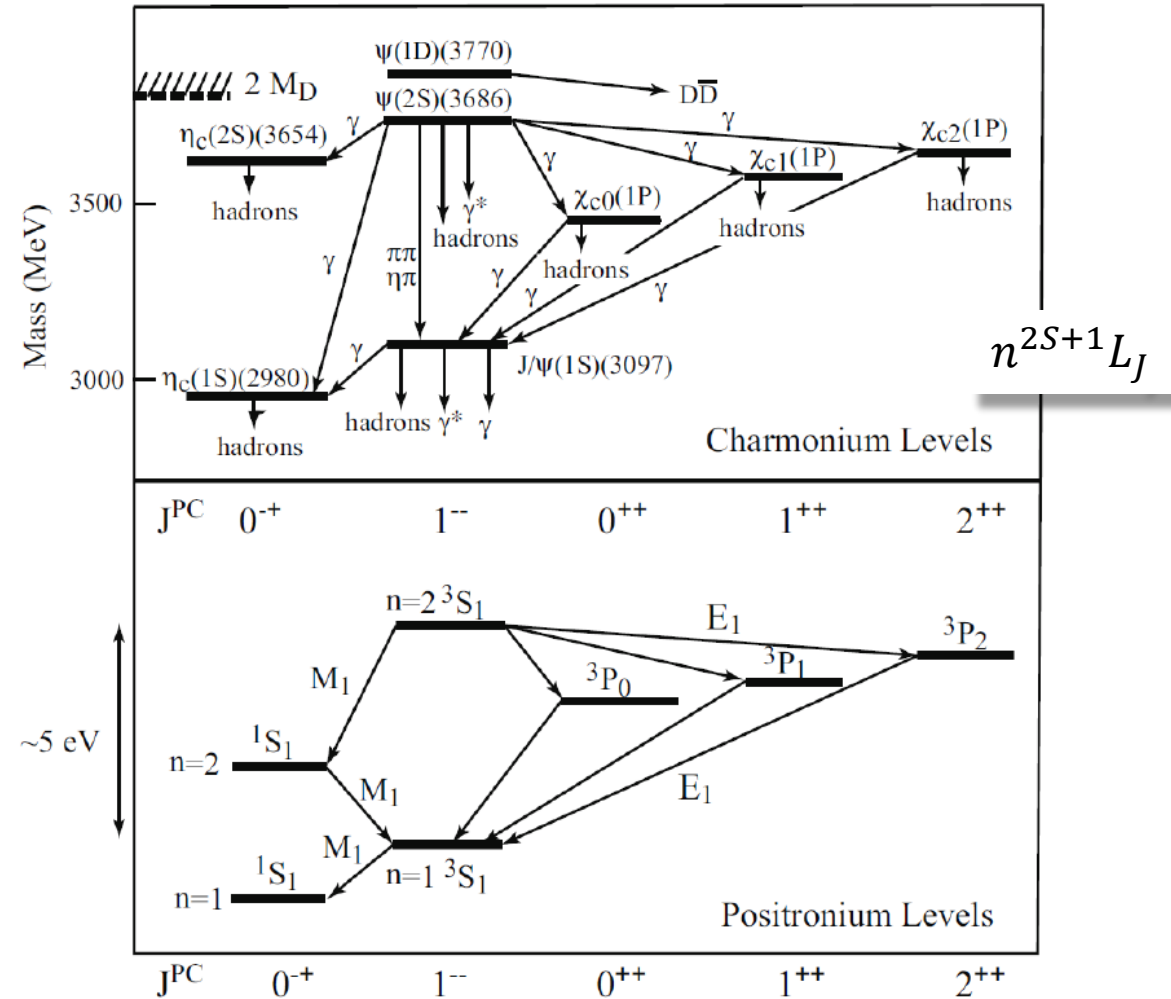
Introduction

“Cornell” potential (Coulomb-like potential)

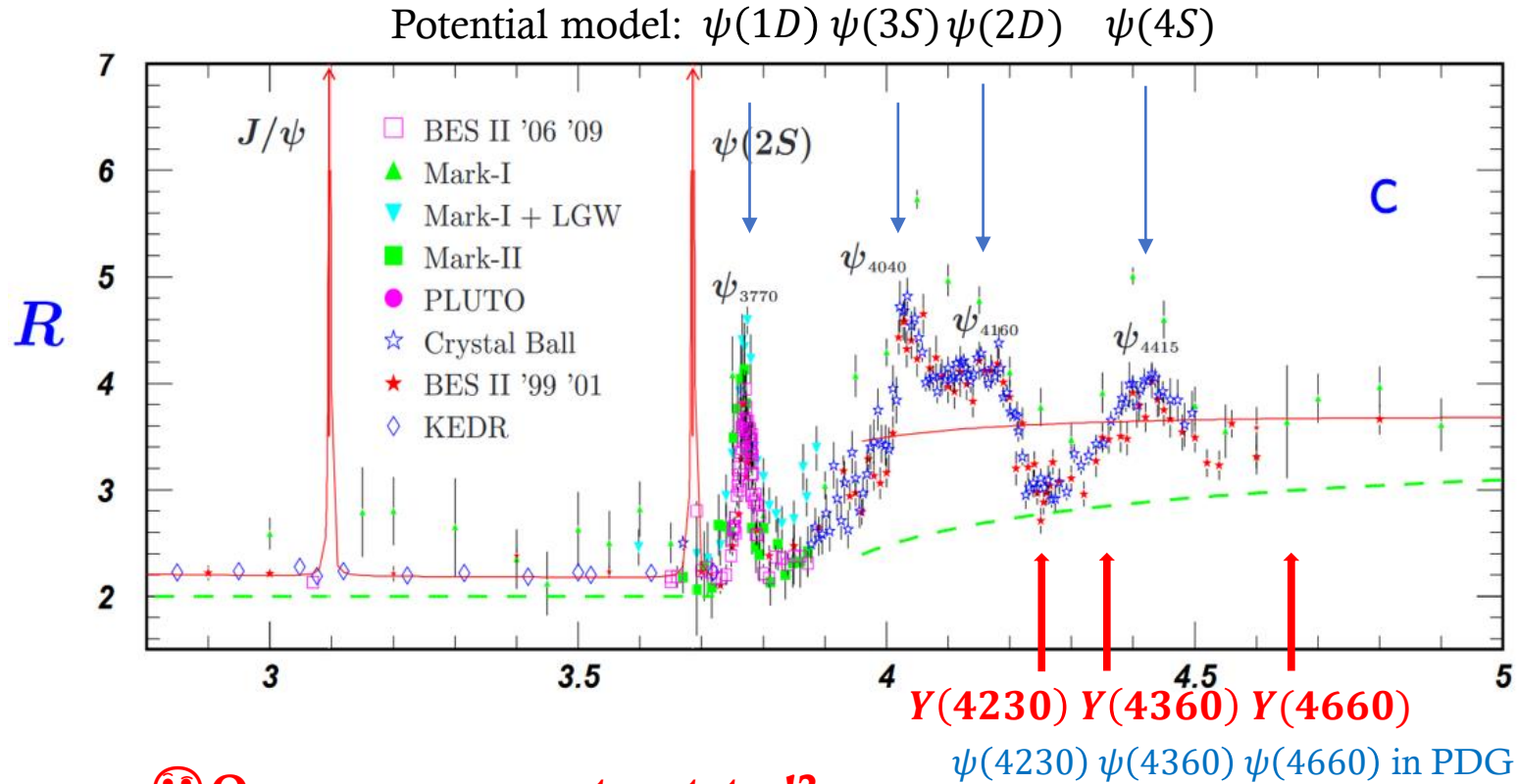
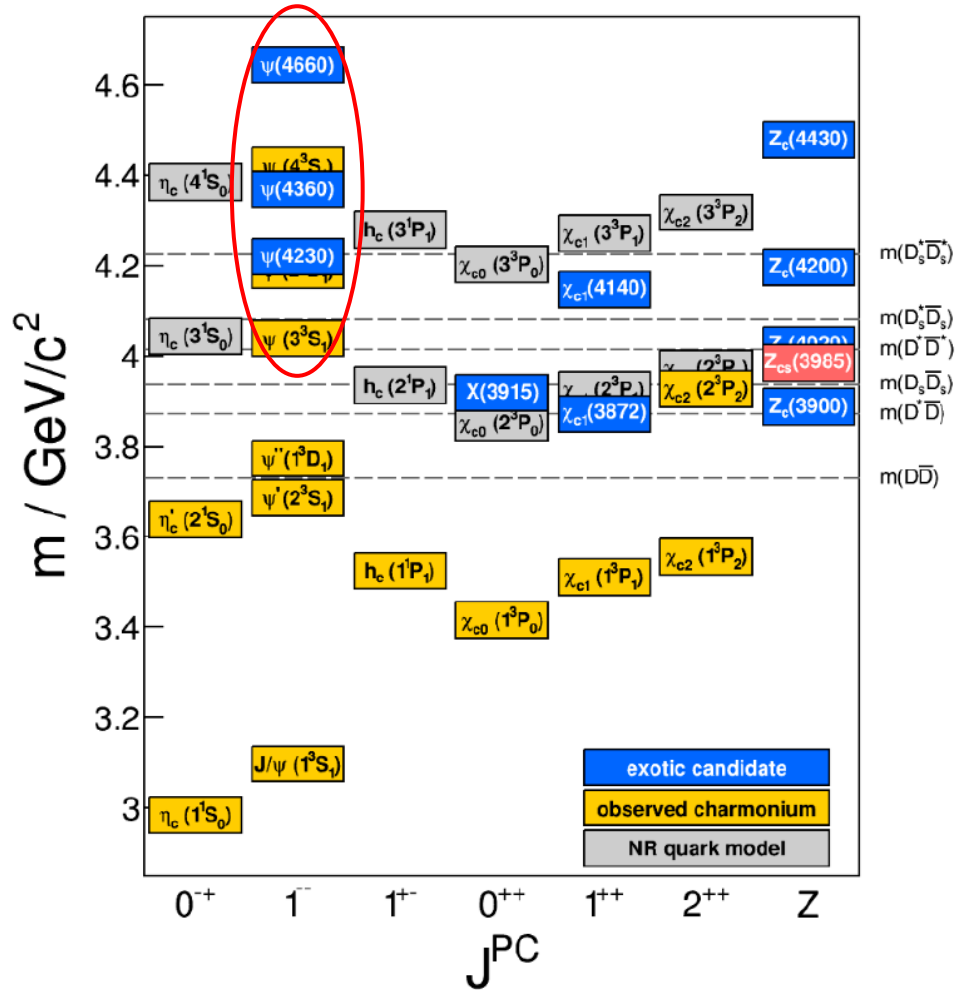


2 parameters:
slope & intercept

$$V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + kr$$



Introduction



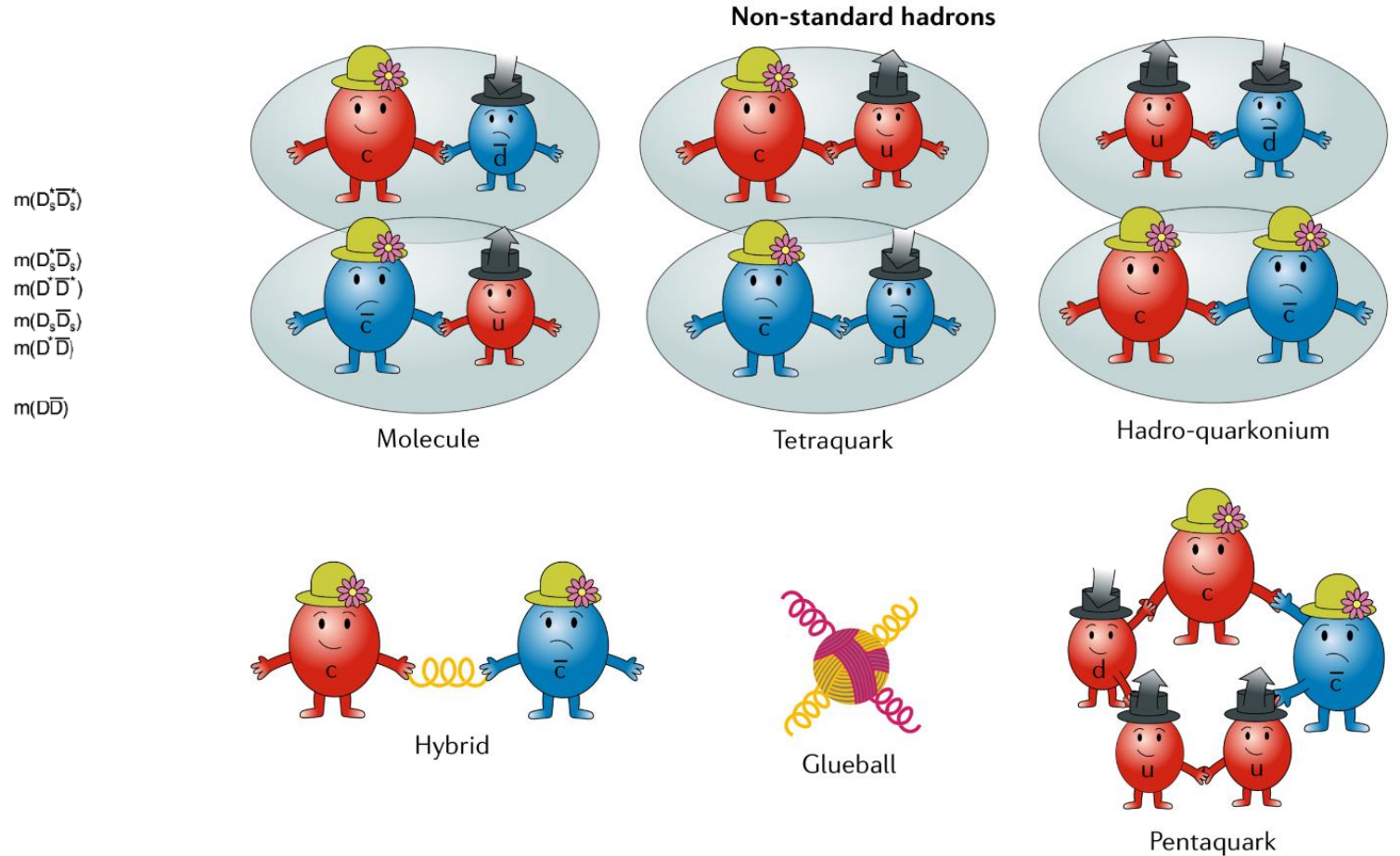
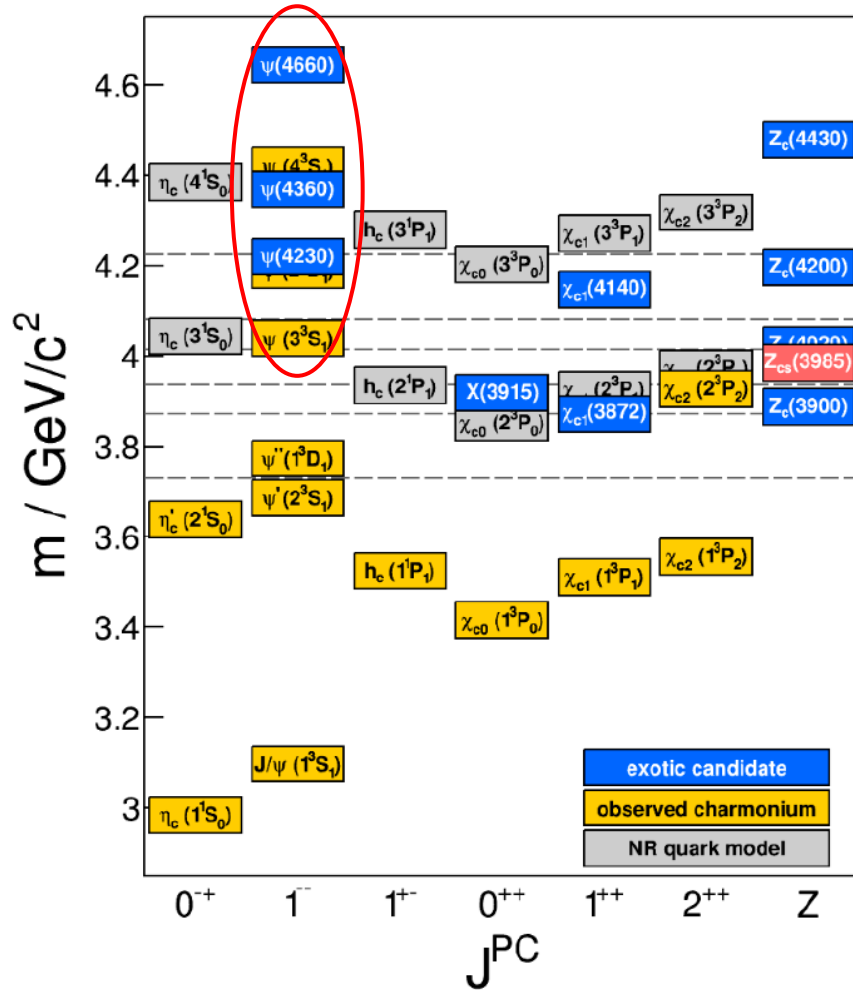
☹️ Overnumerous vector states!?

☹️ $Y \rightarrow$ hidden charm (J/ψ , ψ)!?

☹️ Y puzzle!?

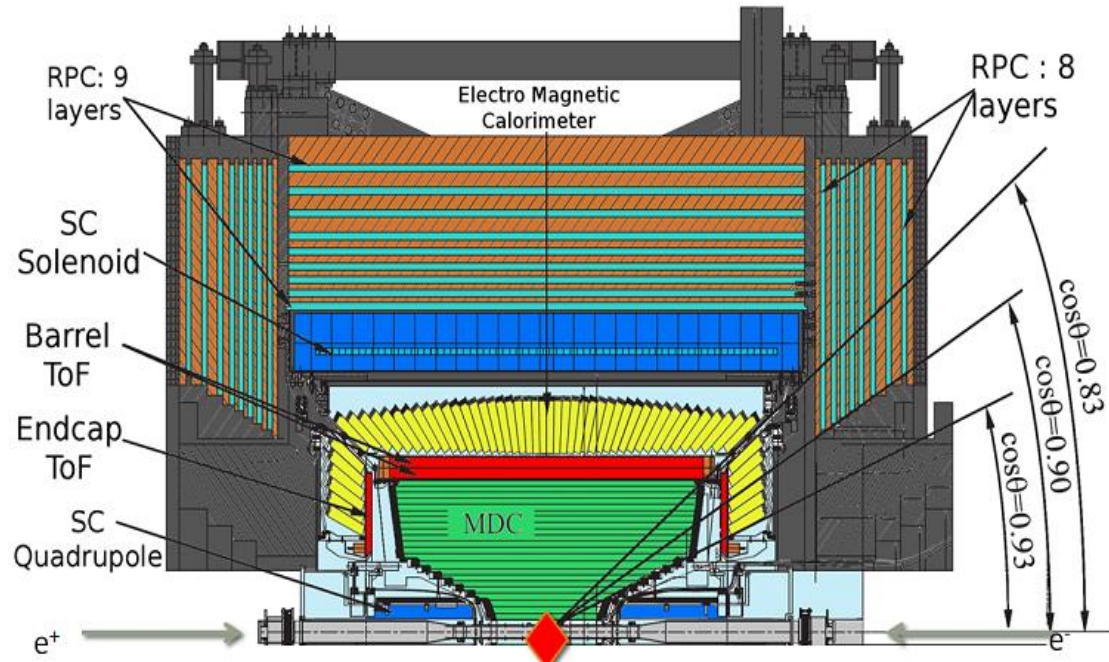
$\psi(4230) \psi(4360) \psi(4660)$ in PDG

Introduction

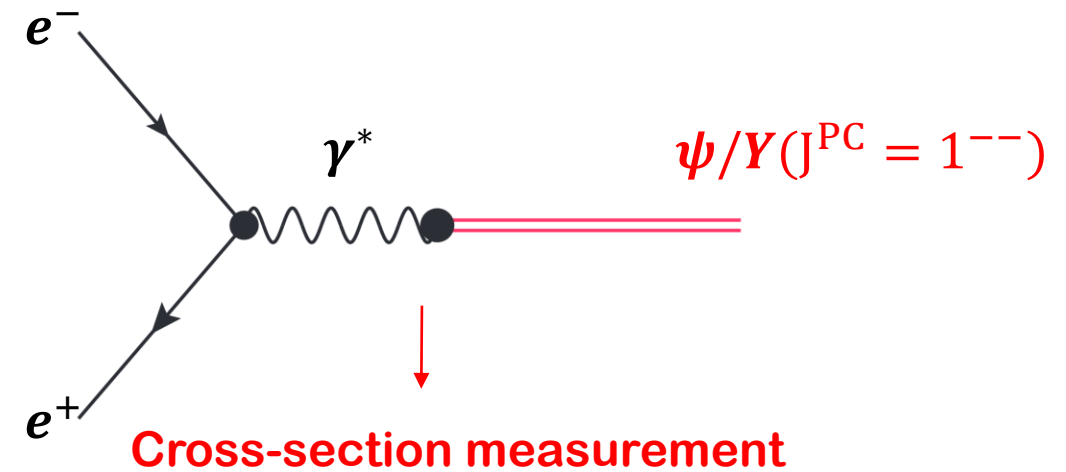


[Nature Rev.Phys. 1, 480-494 \(2019\)](https://doi.org/10.1038/nrnphys.2019.1)

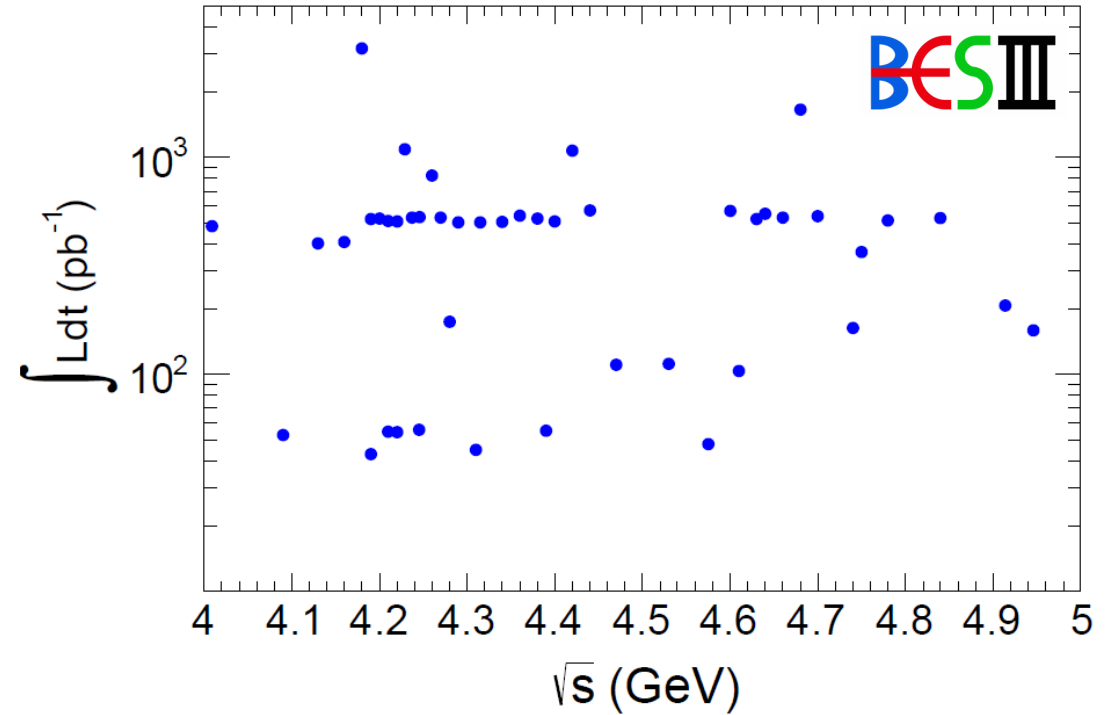
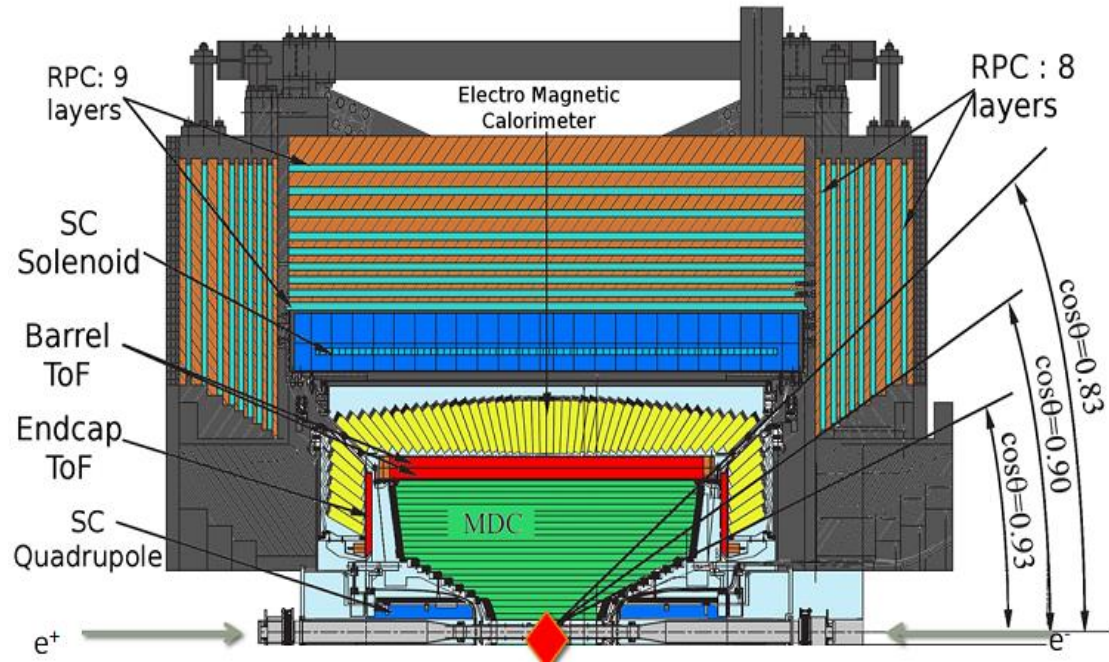
BESIII experiment



- τ - c region $2 < \sqrt{s} < 4.95$ GeV
- Peak luminosity $1.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
@ $\sqrt{s} = 3.77$ GeV
- Clean background environment
- **ψ/Y factory ($\sigma_E < 2$ MeV)**



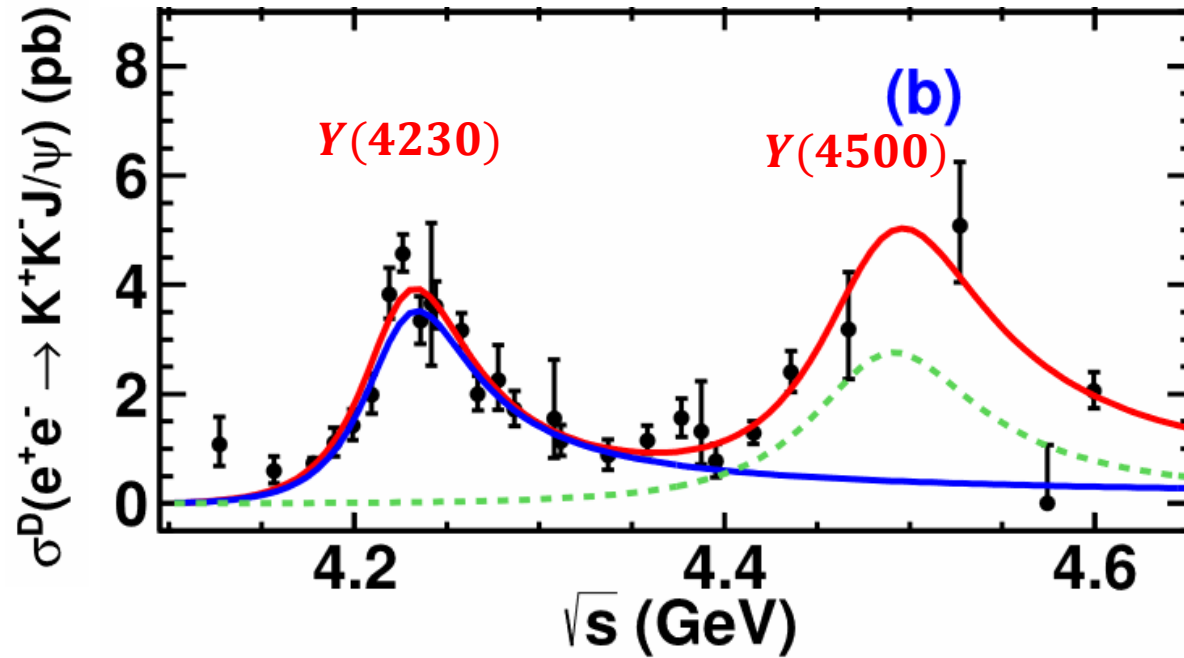
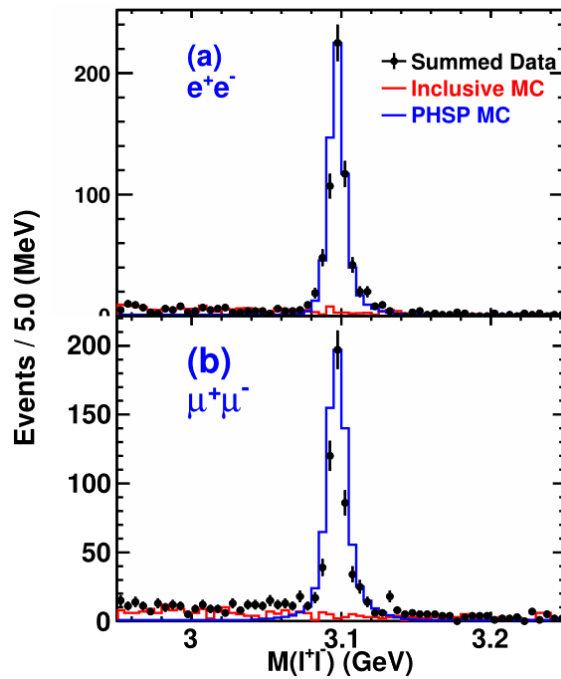
BESIII experiment



- High luminosity scan ($\sim 500 \text{ pb}^{-1}/10 \text{ MeV}$)
- **22 fb^{-1}** ($4 < \sqrt{s} < 5 \text{ GeV}$) for XYZ study

$e^+e^- \rightarrow K^+K^-J/\psi$

CPC 46, 111002 (2022)



Coherent of 2 BW functions:

	Mass (MeV/ c^2)	Width (MeV)
Y(4230) (29σ)	$4225.3 \pm 2.3 \pm 21.5$	$72.9 \pm 6.1 \pm 30.8$
Y(4500) (8σ)	$4484.7 \pm 13.3 \pm 24.1$	$111.1 \pm 30.1 \pm 15.2$

• First observation of $Y(4230) \rightarrow K^+K^-J/\psi$

• 5S-4D mixing (J.Z. Wang et al., PRD 99, 114003 (2019))

• Hadronic molecule (X.K. Dong et al., Prog. Phys. 41, 65 (2021))

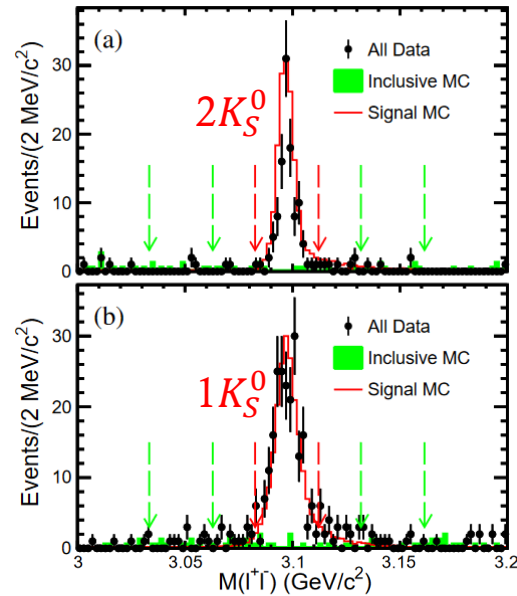
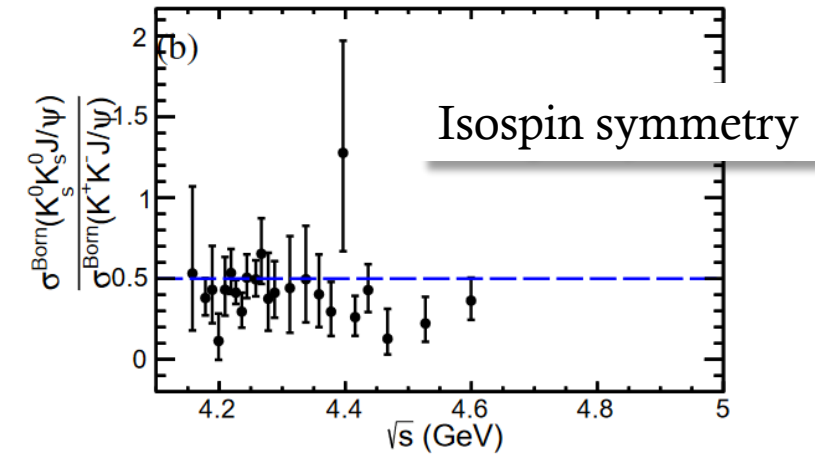
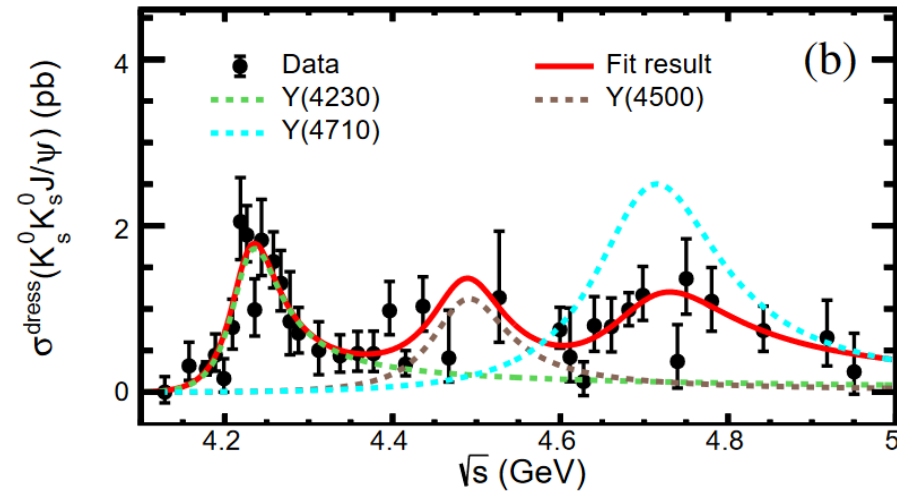
• A ($cs\bar{c}\bar{s}$) state (T.W. Chiu et al., PRD 73, 094510 (2006))

New!

$e^+e^- \rightarrow K_S^0 K_S^0 J/\psi$

PRD 107, 092005 (2023)

K_S^0 decay	Branching fraction
$K_S^0 \rightarrow \pi^+ \pi^-$, $K_S^0 \rightarrow \pi^+ \pi^-$	$\sim 49\%$
$K_S^0 \rightarrow \pi^+ \pi^-$, $K_S^0 \rightarrow \pi^0 \pi^0$	$\sim 42\%$
$K_S^0 \rightarrow \pi^0 \pi^0$, $K_S^0 \rightarrow \pi^0 \pi^0$	$\sim 9\%$



Coherent of 3 BW functions:

	Mass (MeV/c ²)	Width (MeV)
Y(4230) (26σ)	$4226.9 \pm 6.6 \pm 22.0$	$71.7 \pm 16.2 \pm 32.8$
Y(4500) (fixed)	$e^+e^- \rightarrow K^+K^- J/\psi$ (BESIII)	
Y(4710) (4σ)	$4704.0 \pm 52.3 \pm 69.5$	$183.2 \pm 114.0 \pm 96.1$

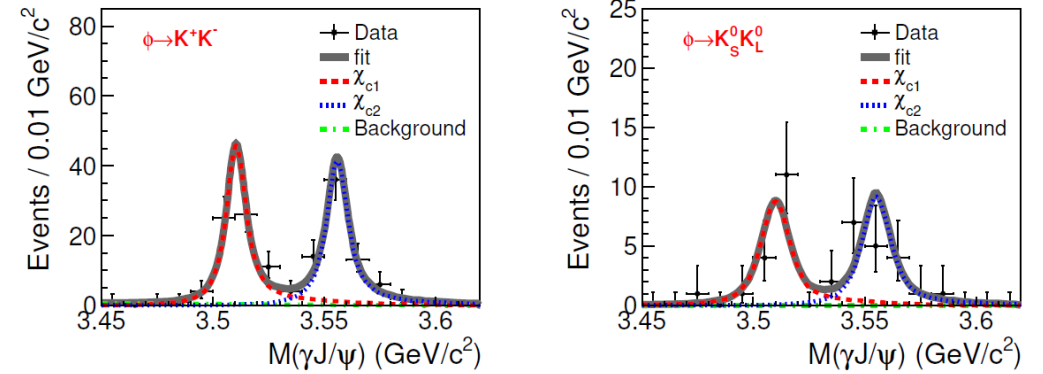
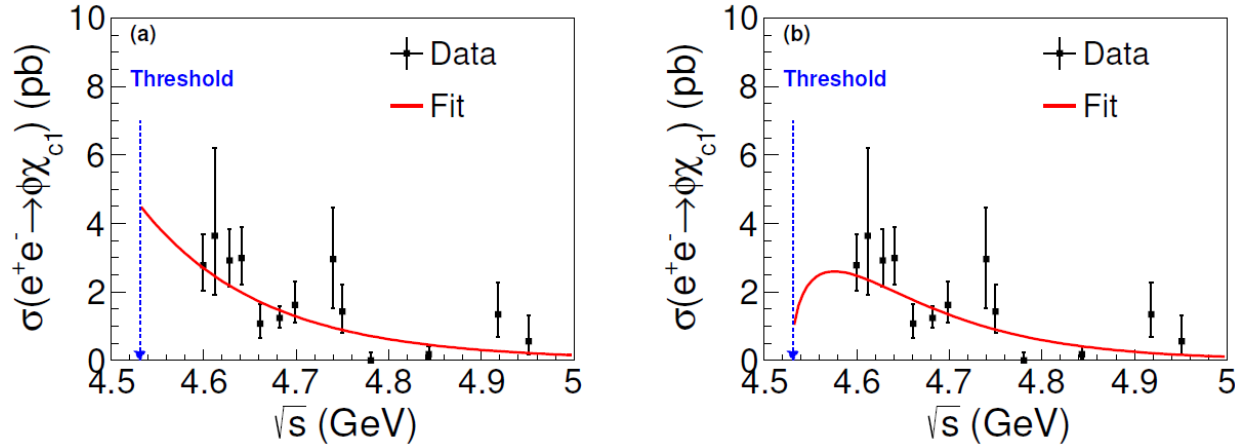
→ First observation

→ $\psi(5S)$?

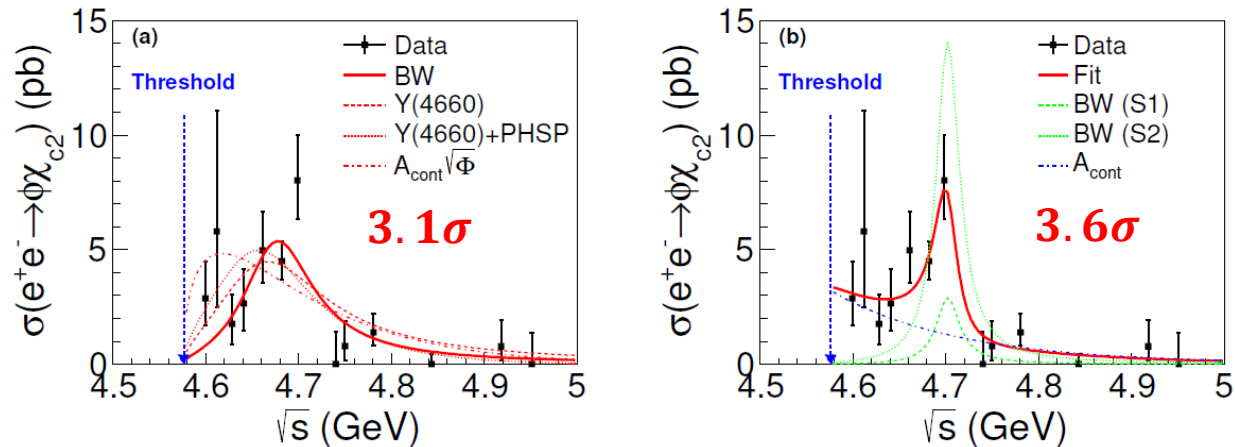
Update on $e^+e^- \rightarrow K^+K^- J/\psi$ is coming soon!!

$e^+e^- \rightarrow \phi\chi_{c1,c2}$

$\phi\chi_{c1}$: A power law (or PHSP corrected) continuum



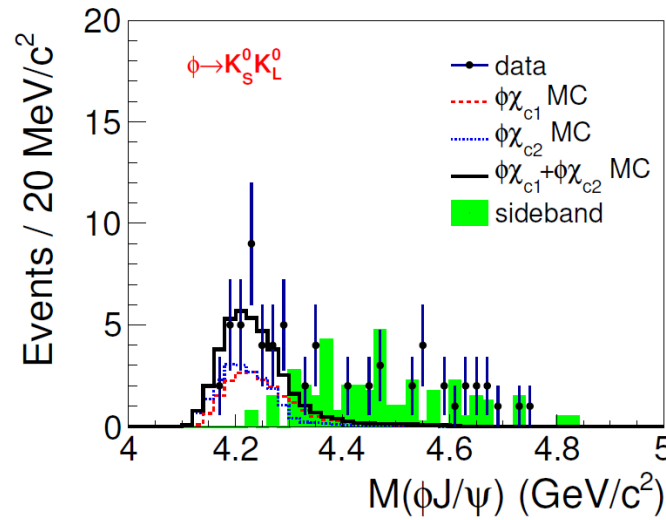
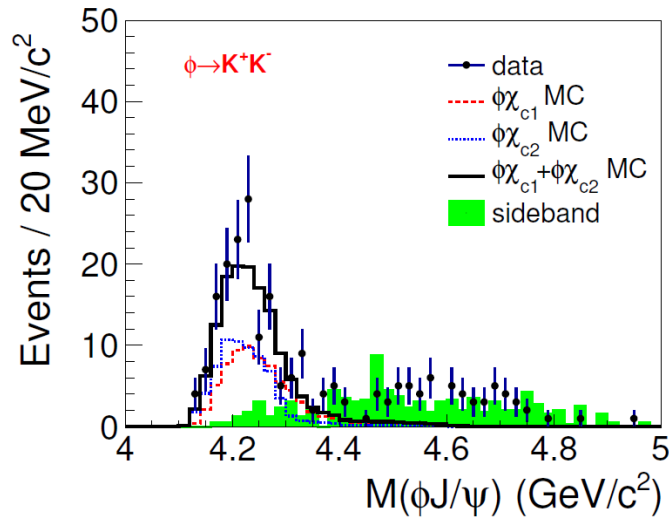
$\phi\chi_{c2}$: BW or BW+Continuum



$ee \rightarrow \phi\chi_{c2}$	Mass (MeV/c ²)	Width (MeV)
<i>BW</i>	$4672.7 \pm 10.8 \pm 3.9$	$93.2 \pm 19.8 \pm 9.4$
<i>BW</i> + A_{cont}	$4701.8 \pm 10.9 \pm 2.7$	$30.5 \pm 22.3 \pm 14.6$

- First evidence of $Y(4660) \rightarrow \phi\chi_{c2}$
- A new structure around 4.7 GeV?

$e^+e^- \rightarrow \gamma(\phi J/\psi)$

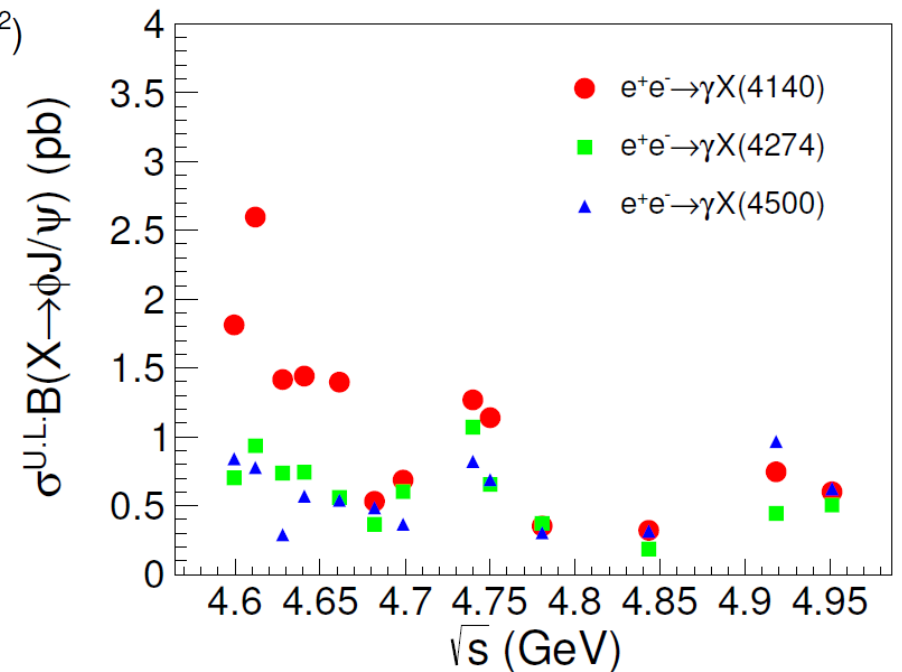


Events are dominated by $\phi\chi_{c1,c2}$

Upper limits for production cross sections of

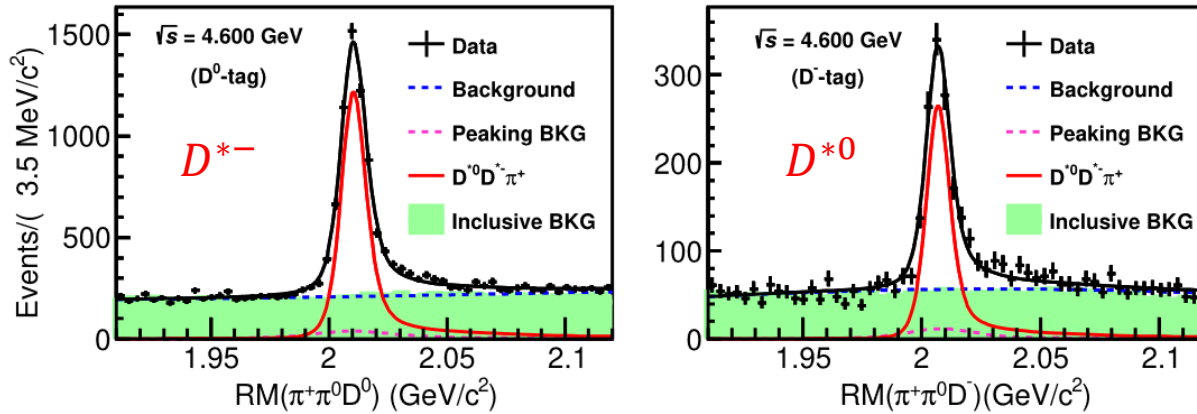
$$e^+e^- \rightarrow \gamma X(4140)/X(4274)/X(4500)$$

[PRL 127, 082001 \(2021\) \[LHCb 9 fb⁻¹\]](#)



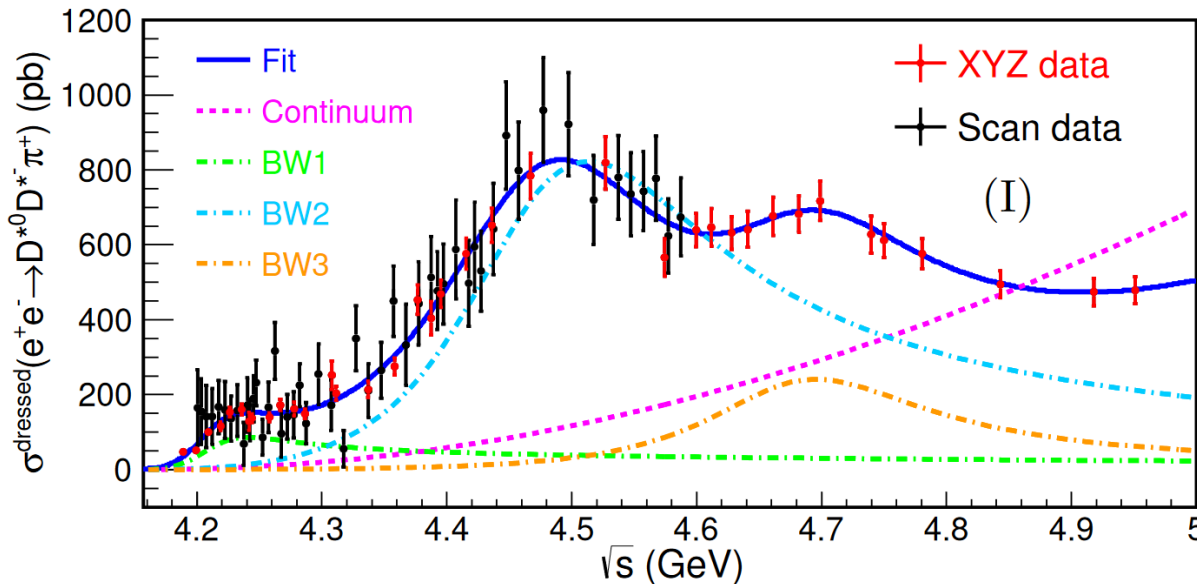
$e^+e^- \rightarrow D^{*0}D^{*-}\pi^+ + c.c.$

PRL 130, 121901 (2023)



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

	Mass (MeV/c ²)	Width (MeV)
BW_1	$4209.6 \pm 4.7 \pm 5.9$	$81.6 \pm 17.8 \pm 9.0$
BW_2	$4469.1 \pm 26.2 \pm 3.6$	$246.3 \pm 36.7 \pm 9.4$
BW_3	$4675.3 \pm 29.5 \pm 3.5$	$218.3 \pm 72.9 \pm 9.3$



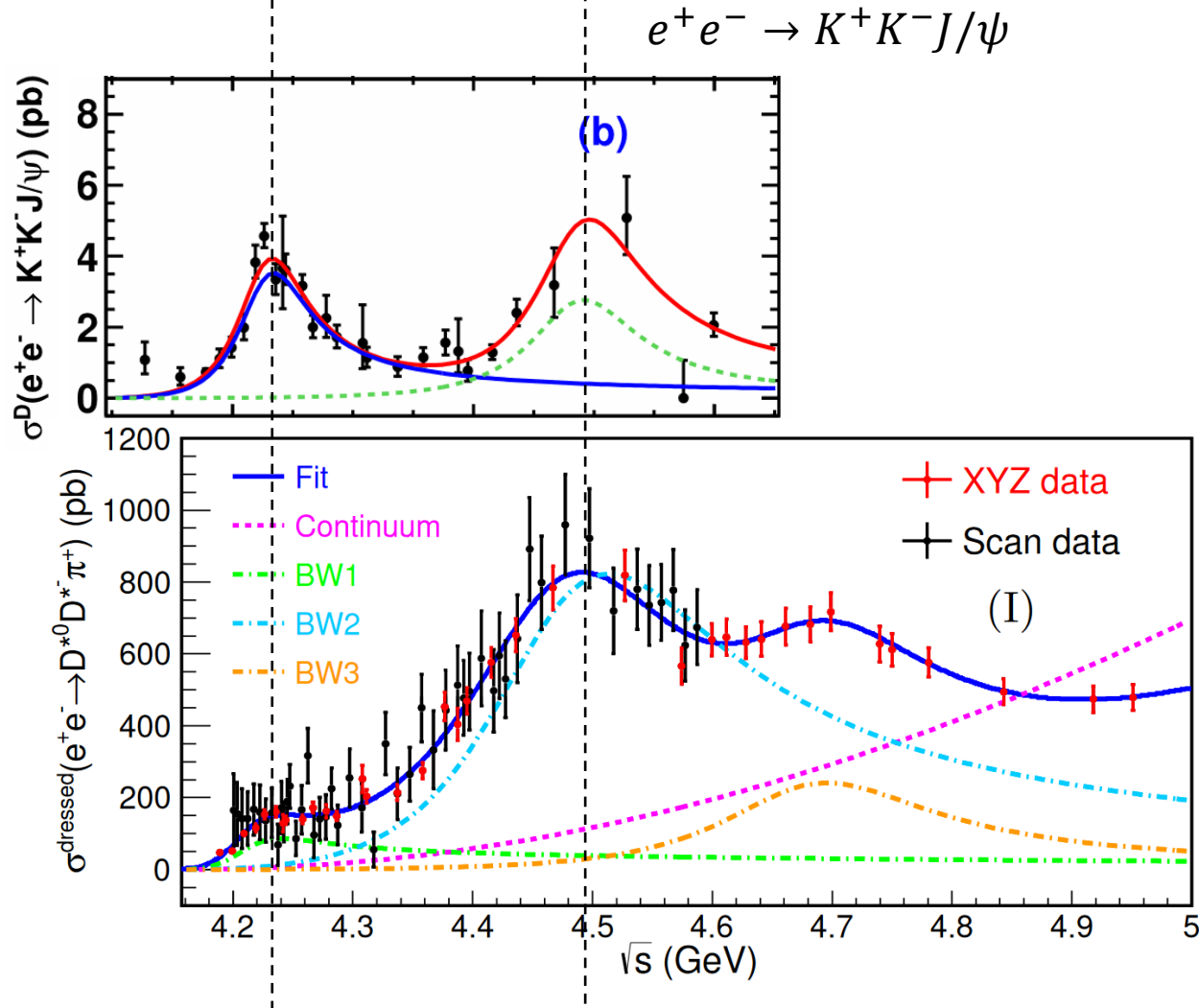
$BW_1 \rightarrow Y(4230)$ strongly couple with open charm

$BW_2 \rightarrow Y(4500)$ in K^+K^-J/ψ

$BW_3 \rightarrow Y(4660)$ first open charm decay

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

PRL 130, 121901 (2023)



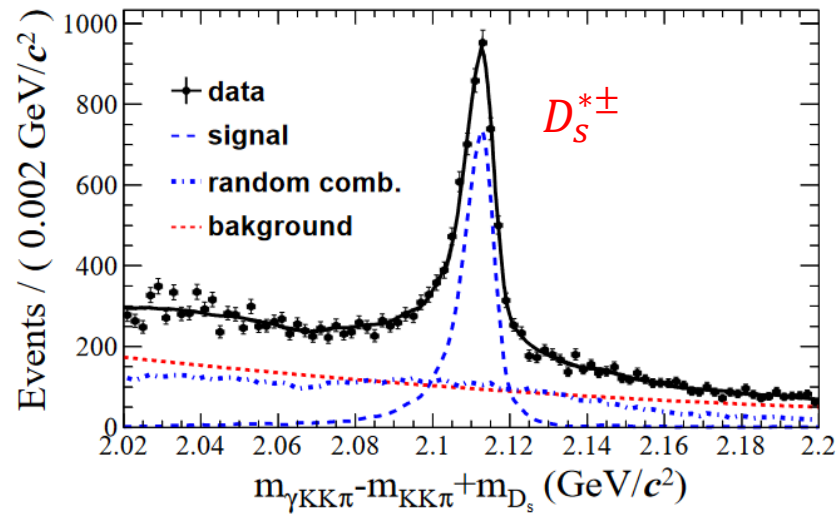
$$\sigma^{\text{dressed}}(\sqrt{s}) = C_0 \left| C_1 \sqrt{\Phi(\sqrt{s})} + \sum_{k=1}^3 \text{BW}_k(\sqrt{s}) e^{i\phi_k} \right|^2$$

	Mass (MeV/ c^2)	Width (MeV)
BW_1	$4209.6 \pm 4.7 \pm 5.9$	$81.6 \pm 17.8 \pm 9.0$
BW_2	$4469.1 \pm 26.2 \pm 3.6$	$246.3 \pm 36.7 \pm 9.4$
BW_3	$4675.3 \pm 29.5 \pm 3.5$	$218.3 \pm 72.9 \pm 9.3$

$$BW_2 \rightarrow Y(4500): \frac{\Gamma[Y(4500) \rightarrow D^{*0}D^{*-}\pi^+]}{\Gamma[Y(4500) \rightarrow K\bar{K}J/\psi]} > 100$$

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

arXiv: 2305.10789 (submitted to PRL)



New!

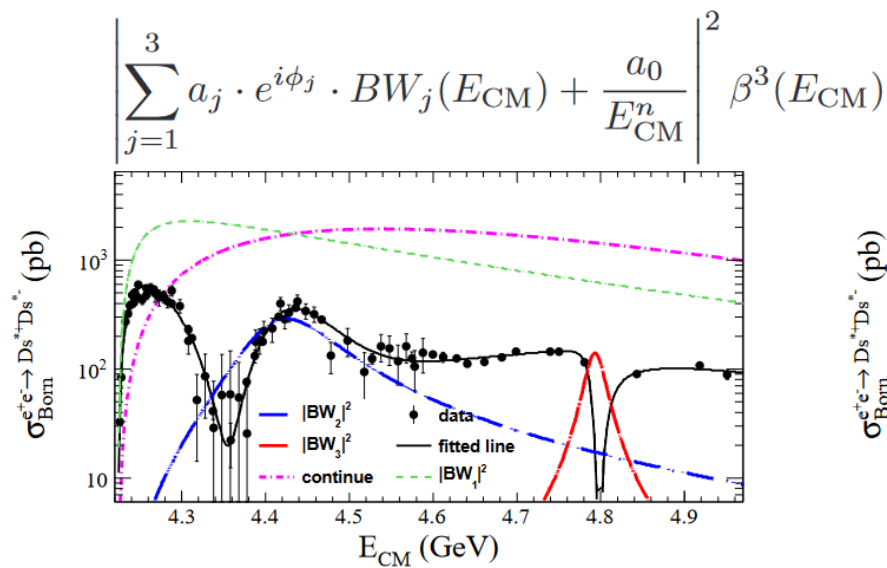
	Result 1	Result 2	Result 3
M_1 (MeV/ c^2)	4186.5 ± 9.0	4193.8 ± 7.5	4195.3 ± 7.5
Γ_1 (MeV)	55 ± 17	61.2 ± 9.0	61.8 ± 9.0
M_2 (MeV/ c^2)	4414.5 ± 3.2	4412.8 ± 3.2	4411.0 ± 3.2
Γ_2 (MeV)	122.6 ± 7.0	120.3 ± 7.0	120.0 ± 7.0
M_3 (MeV/ c^2)	4793.3 ± 7.5	4789.8 ± 9.0	4786 ± 10
Γ_3 (MeV)	27.1 ± 7.0	41 ± 39	60 ± 35

most massive charmoniumlike

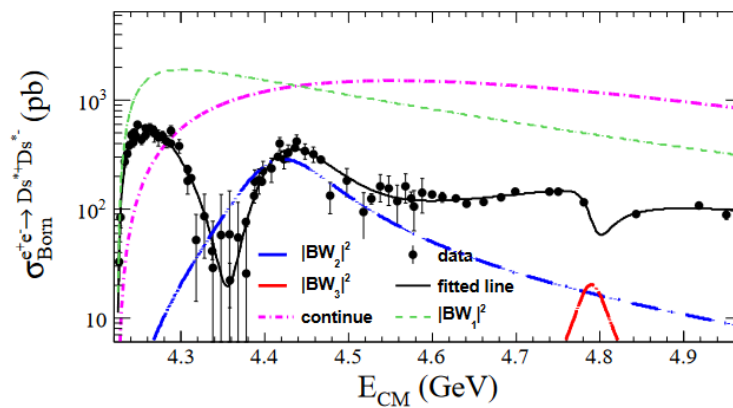
BW_1 : near $D_s^{*+} D_s^{*-}$ threshold $\rightarrow [Y(4230)/\psi(4160)?]$

BW_2 : consistent with $\psi(4415)$, but larger width

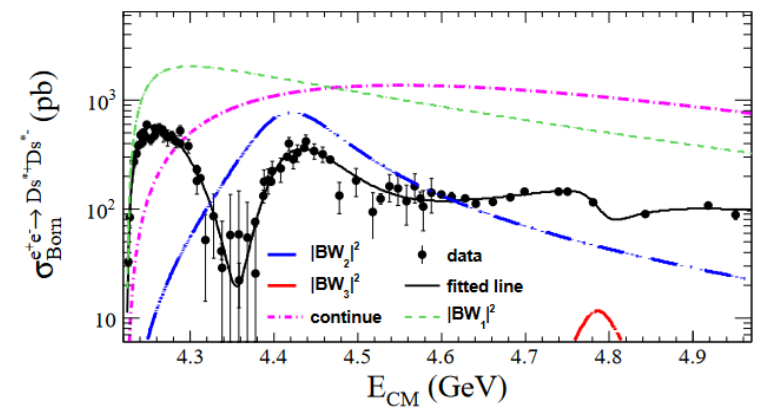
BW_3 : $Y(4790) > 6.1\sigma$ (model dependent, data @ 4.8 GeV)



Hang Zhou (SDU)



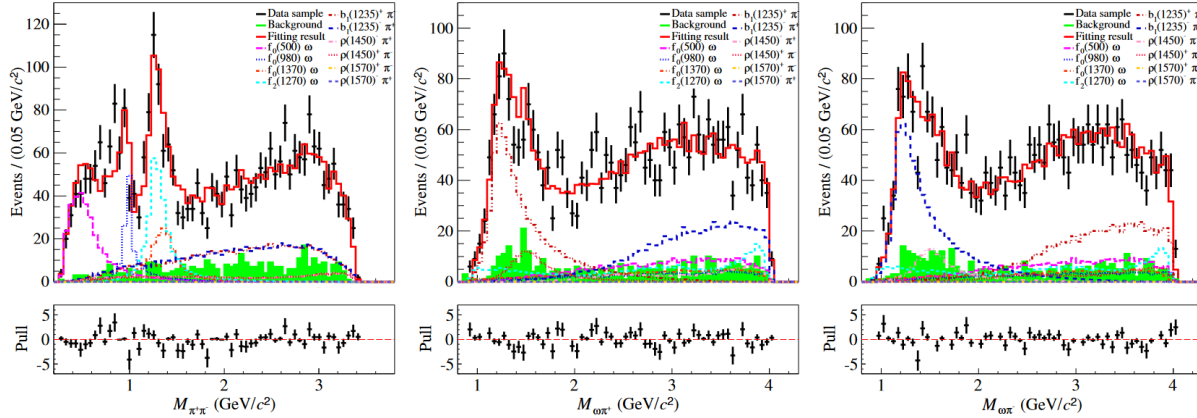
CHARM 2023, Siegen, Germany



14

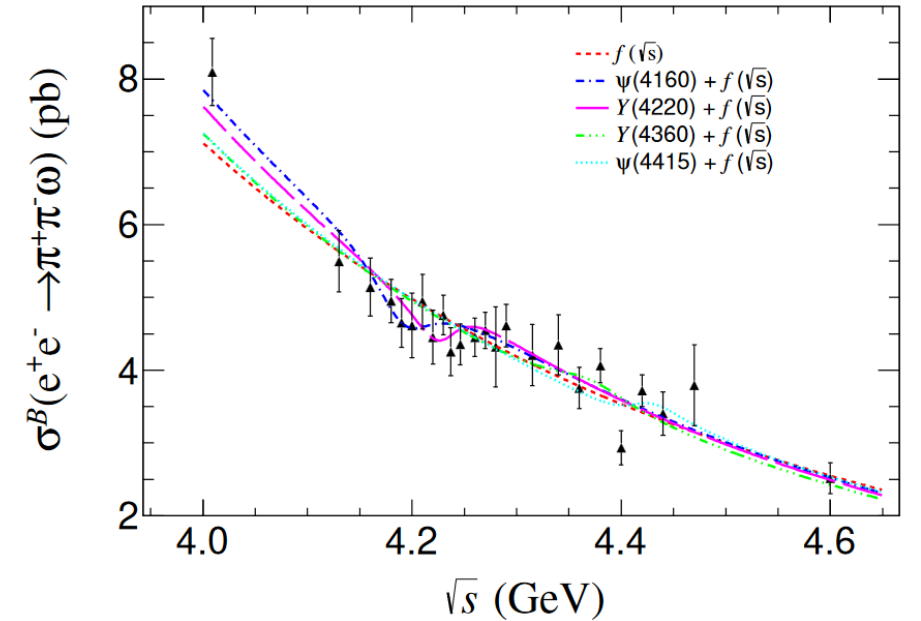
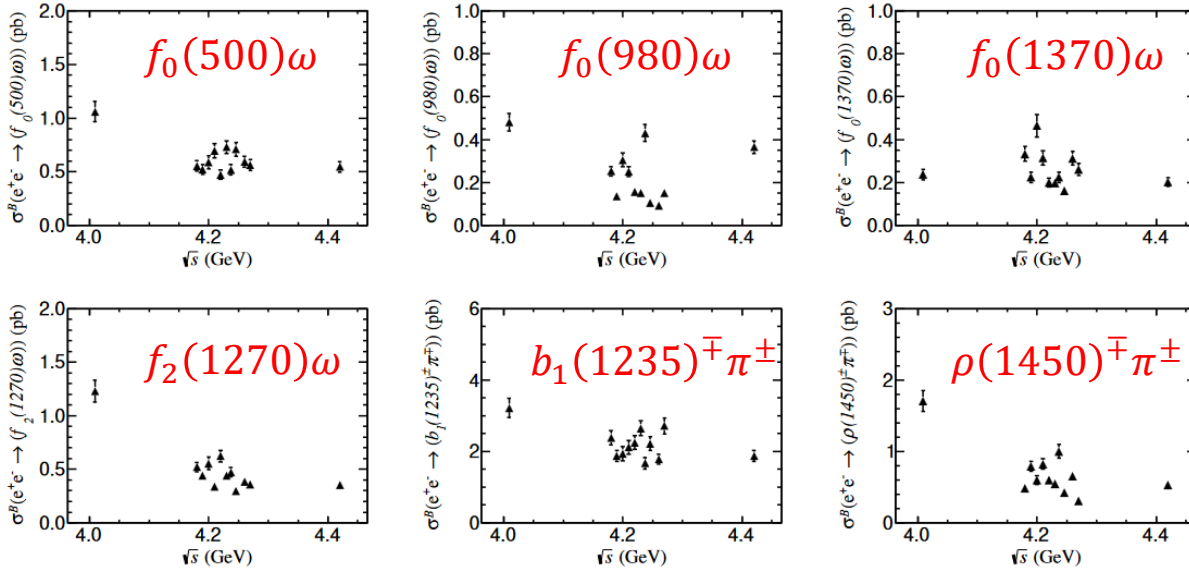
$$e^+ e^- \rightarrow \omega \pi^+ \pi^-$$

Amplitude analysis at $\sqrt{s} = 4.18$ GeV



$$\sigma^{\text{Born}}(\sqrt{s}) = |BW(\sqrt{s})e^{i\phi} + \sqrt{f(\sqrt{s})}|^2 \quad (\text{fixed } M \text{ \& } \Gamma)$$

Cross sections for the components with $>5\sigma$

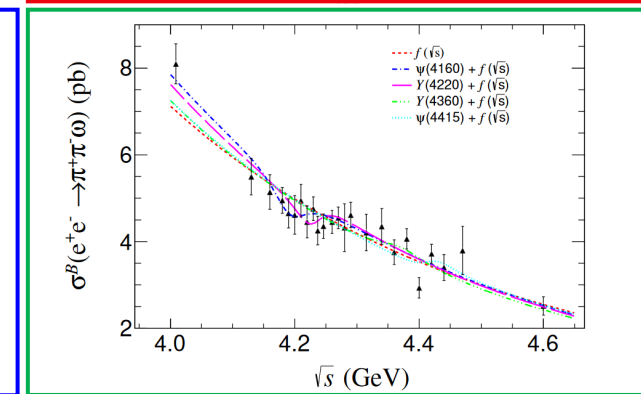
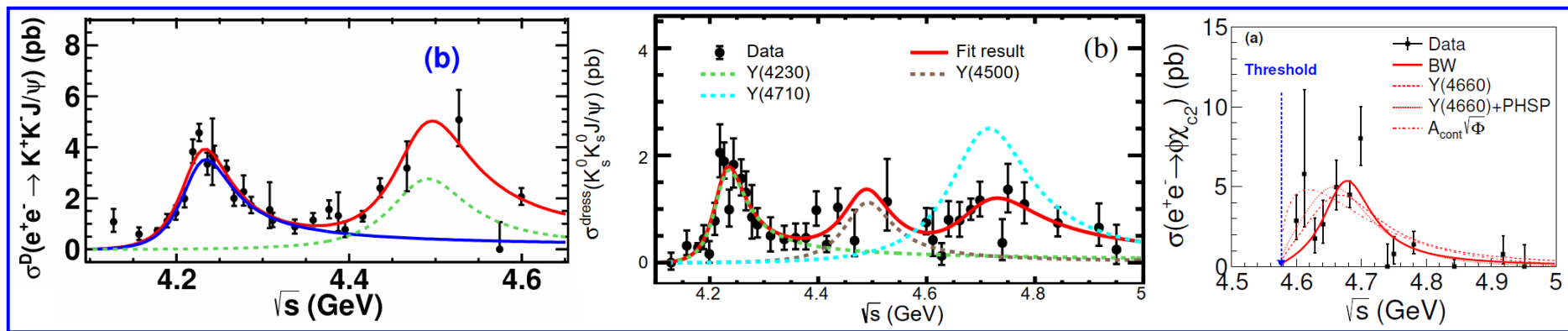
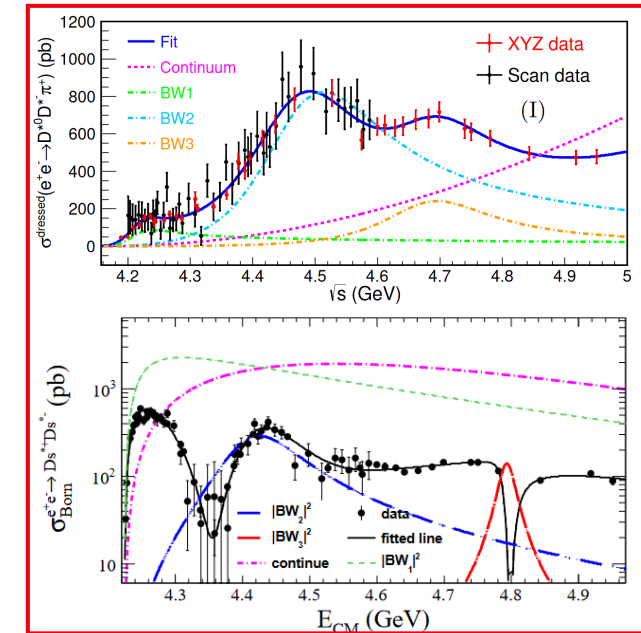


3.6 σ 3.1 σ

- Evidence of $\psi(4160)/Y(4220) \rightarrow$ light hadron
- $Y(4360)$ and $\psi(4415)$ are not significant

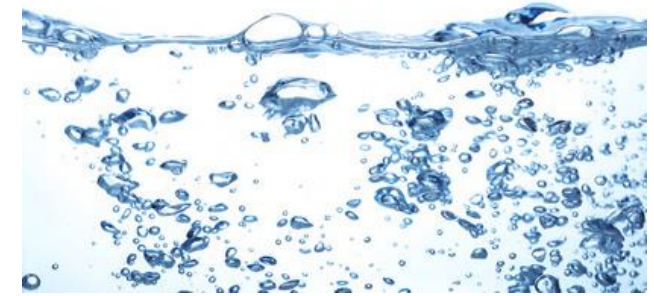
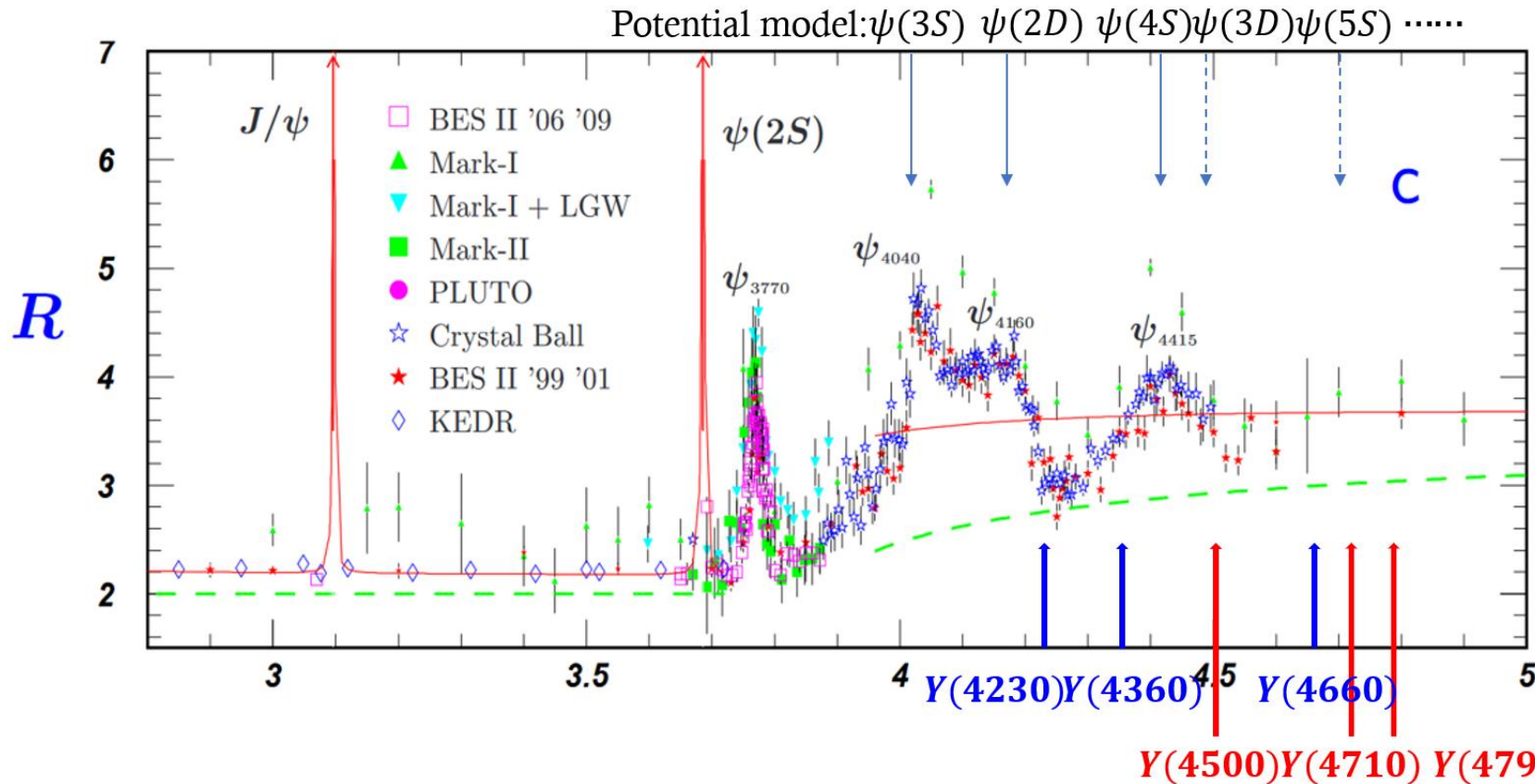
Summary & Prospect

- BESIII has achieved significant progress in the study of **vector states (Y/ψ)**
 - $Y(4230)$ and $Y(4500)$ in $e^+e^- \rightarrow K^+K^-J/\psi$
 - $Y(4230)$ and $Y(4710)$ (4σ) in $e^+e^- \rightarrow K_S^0 K_S^0 J/\psi$
 - Evidence of $Y(4660) \rightarrow \phi\chi_{c2}$, or a structure around 4.7 GeV
 - $Y(4230)$, $Y(4500)$ and $Y(4660)$ in $e^+e^- \rightarrow D^{*0}D^{*-}\pi^+$
 - $Y(4230)$, $\psi(4415)$ and $Y(4790)$ in $e^+e^- \rightarrow D_s^{*+}D_s^{*-}$
 - Evidence of $\psi(4160)/Y(4220) \rightarrow \omega\pi^+\pi^-$



Summary & Prospect

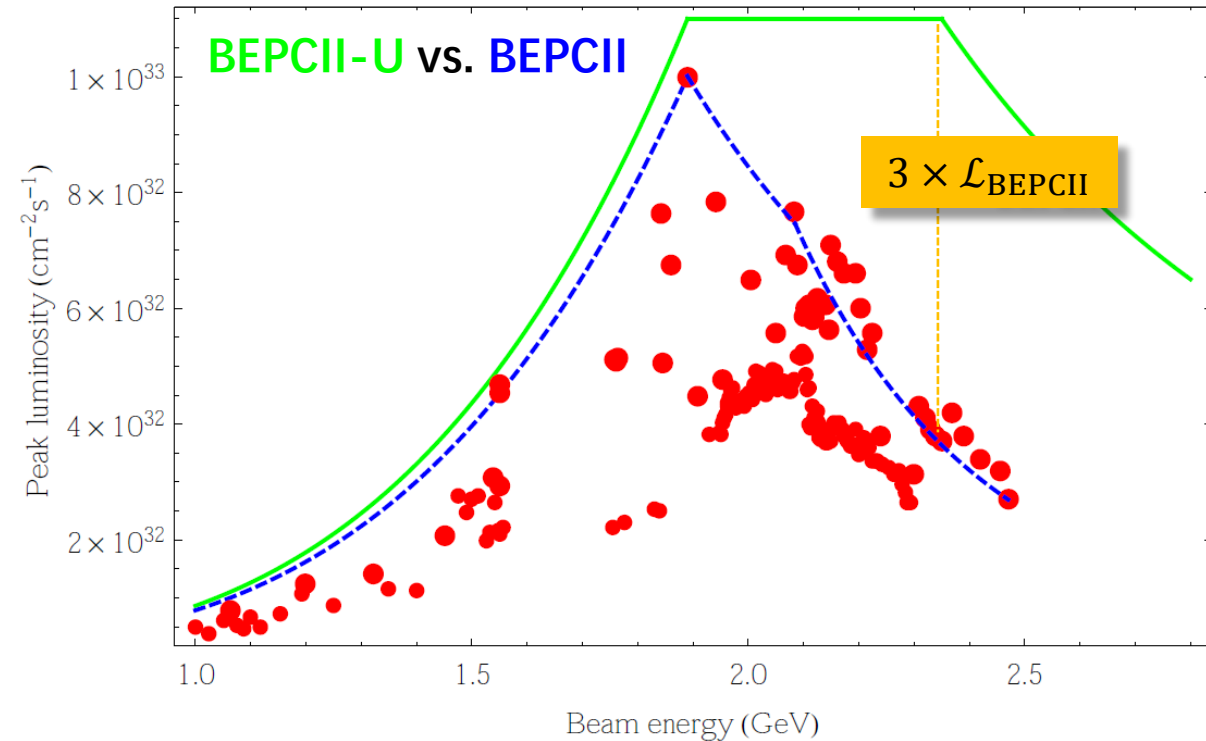
M.A. Sultan et al., PRD 90, 054001 (2014)
S. Kanwal et al., EPJA 58, 219 (2022)



How many vector charmonia ($c\bar{c}$) between 4-5 GeV? Exotics (e.g. $c\bar{c}q\bar{q}$, $c\bar{c}g$...) are also expected. Have they already been observed?

More theoretical/experimental efforts necessary!!

Summary & Prospect



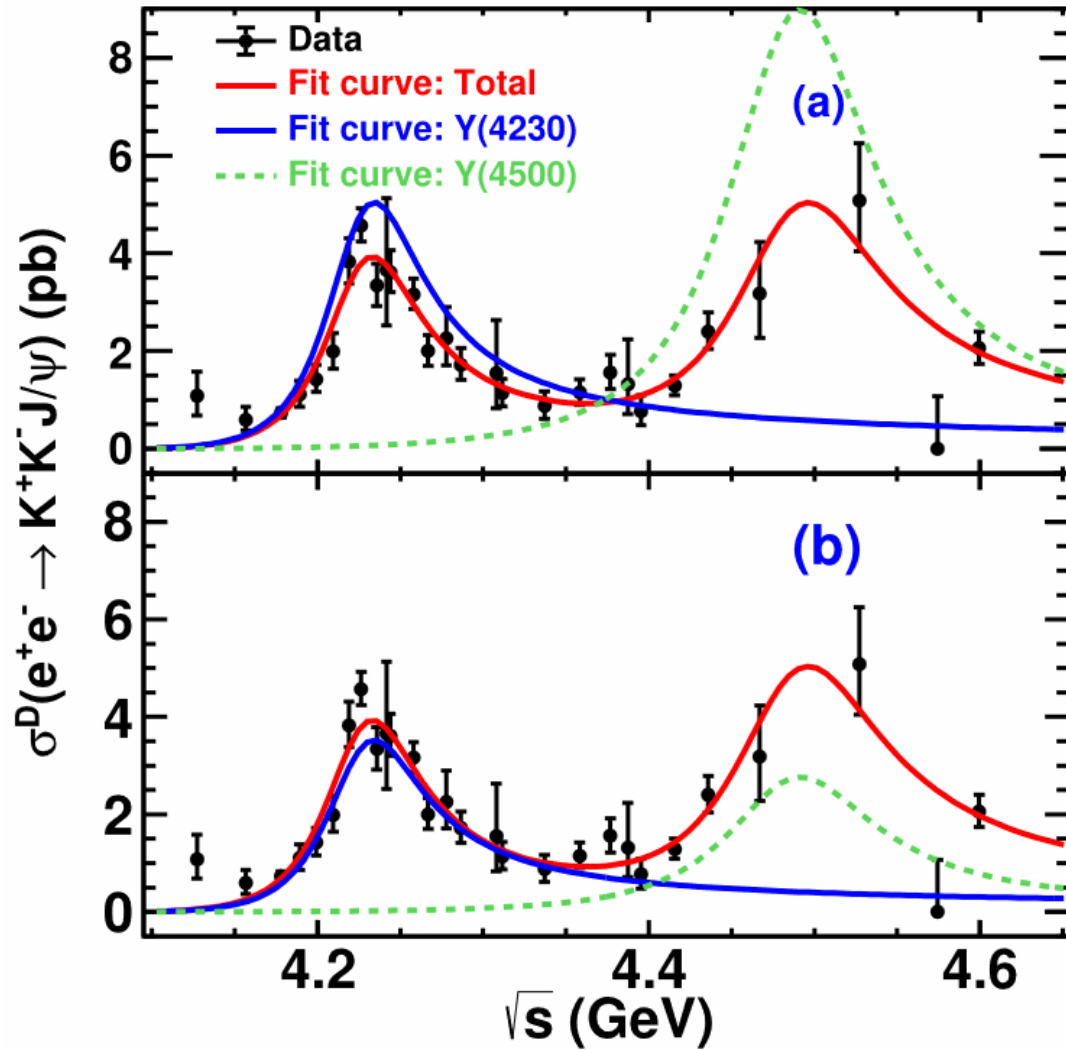
- The BEPCII-U scheduled in the summer 2024
- Luminosity of BEPCII-U increased by a factor of **3 @ $\sqrt{s} = 4.7 \text{ GeV}$** enabling efficient collection of XYZ data; \sqrt{s} extends to **5.6 GeV**; Commissioning in **2025**
- Stay tuned for more exciting results from BESIII! BESIII is still Charming :)

Thanks for your attention!



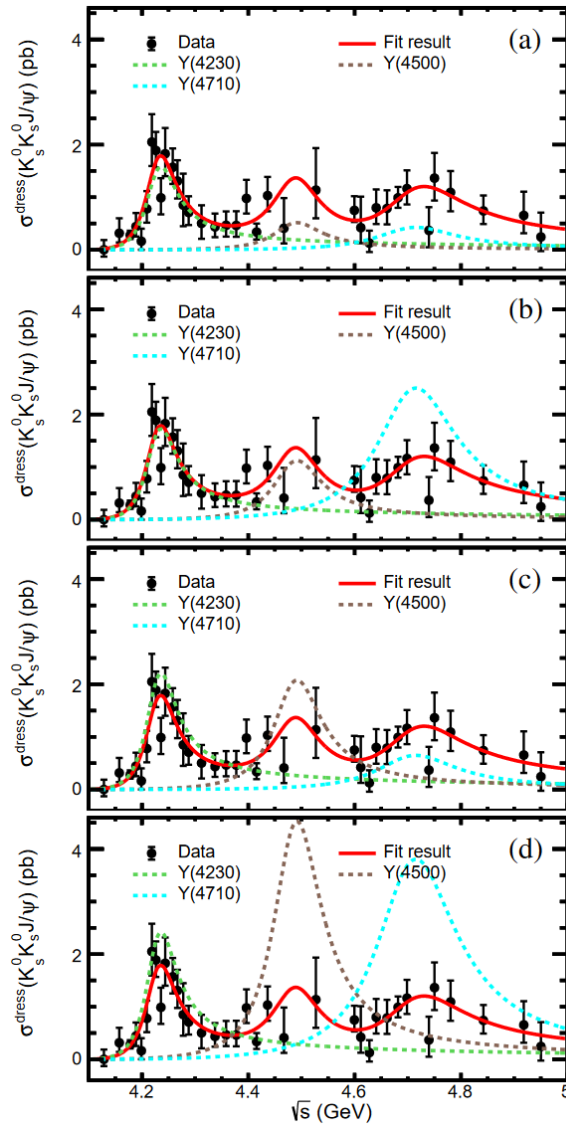
Back up

$e^+e^- \rightarrow K^+K^-J/\psi$



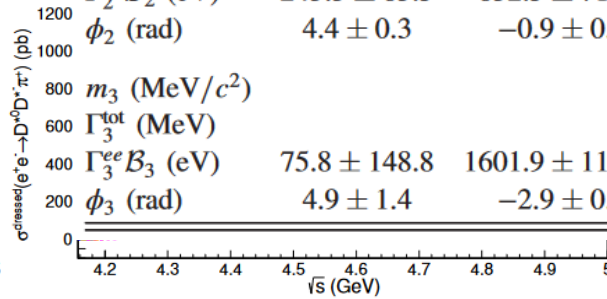
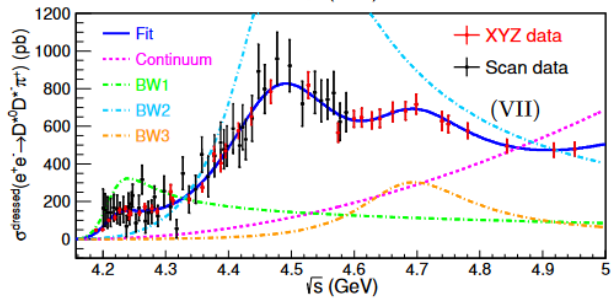
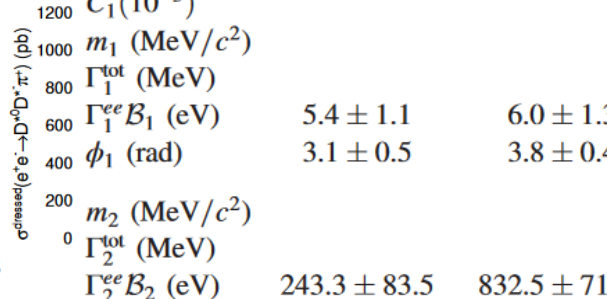
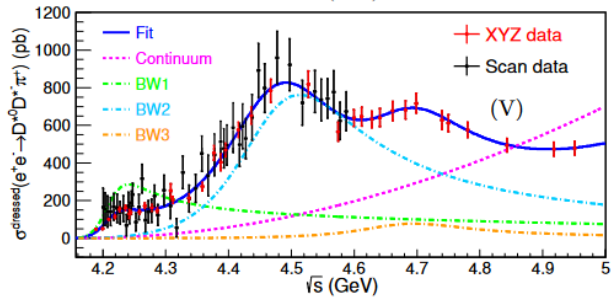
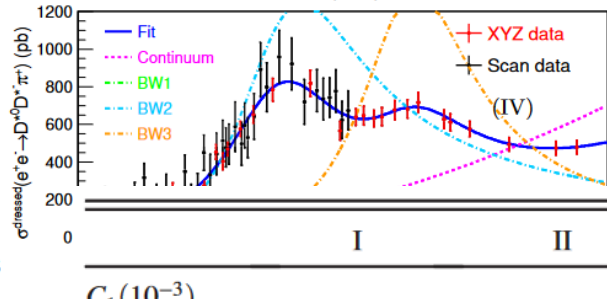
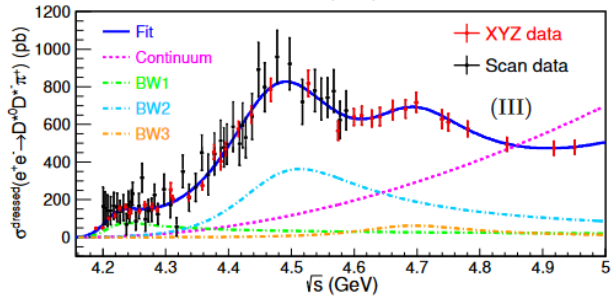
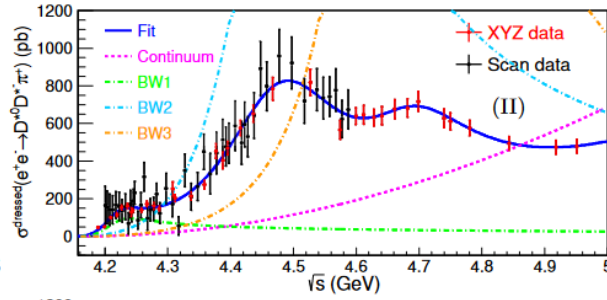
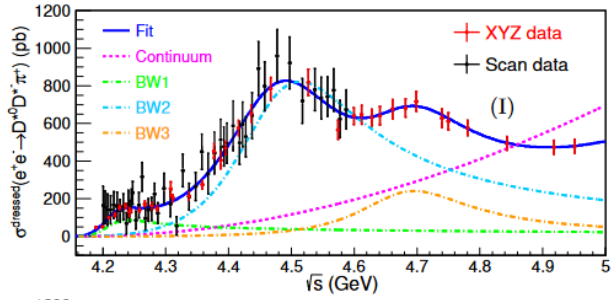
	Parameters	Solution I	Solution II
Y(4230)	M/MeV	$4225.3 \pm 2.3 \pm 21.5$	
	$\Gamma_{\text{tot}}/\text{MeV}$	$72.9 \pm 6.1 \pm 30.8$	
	$\Gamma_{ee}\mathcal{B}/\text{eV}$	$0.42 \pm 0.04 \pm 0.15$	$0.29 \pm 0.02 \pm 0.10$
Y(4500)	M/MeV	$4484.7 \pm 13.3 \pm 24.1$	
	$\Gamma_{\text{tot}}/\text{MeV}$	$111.1 \pm 30.1 \pm 15.2$	
	$\Gamma_{ee}\mathcal{B}/\text{eV}$	$1.35 \pm 0.14 \pm 0.07$	$0.41 \pm 0.08 \pm 0.13$
Phase angle	φ/rad	$1.72 \pm 0.09 \pm 0.52$	$5.49 \pm 0.35 \pm 0.58$

$$e^+ e^- \rightarrow K_S^0 K_S^0 J/\psi$$



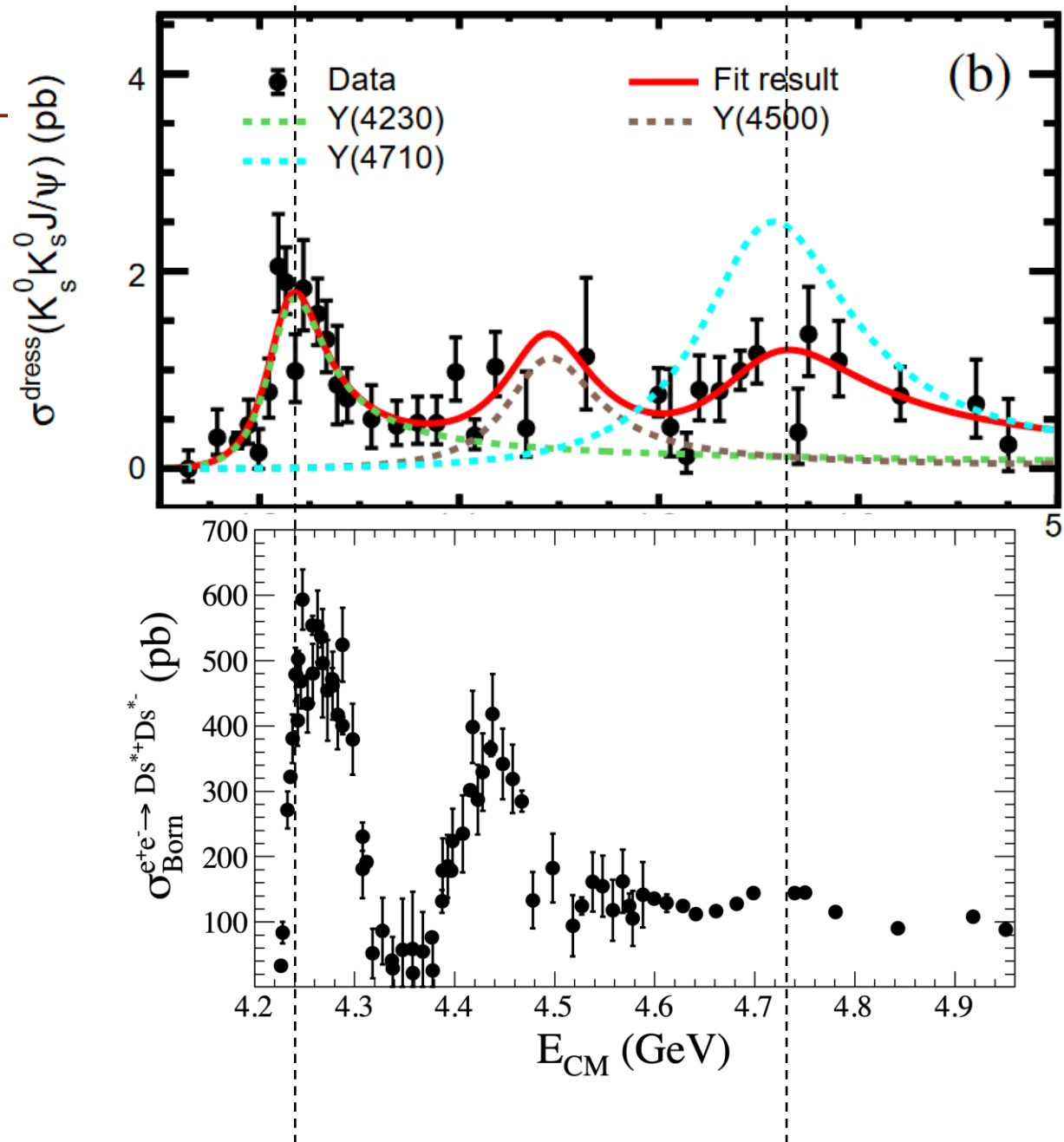
Parameter	Solution I	Solution II	Solution III	Solution IV
M_{4230} (MeV/ c^2)		$4226.9 \pm 6.6 \pm 22.0$		
Γ_{4230} (MeV)		$71.7 \pm 16.2 \pm 32.8$		
$(\Gamma_{ee}\mathcal{B})_{4230}$ (eV)	$0.13 \pm 0.02 \pm 0.05$	$0.14 \pm 0.03 \pm 0.06$	$0.18 \pm 0.05 \pm 0.07$	$0.20 \pm 0.04 \pm 0.07$
M_{4500} (MeV/ c^2)		$4484.7 \pm 13.3 \pm 24.1$ [Ref. [31]]		
(fixed)	1.4σ			
Γ_{4500} (MeV) (fixed)		$111.1 \pm 30.1 \pm 15.2$ [Ref. [31]]		
$(\Gamma_{ee}\mathcal{B})_{4500}$ (eV)	$0.08 \pm 0.09 \pm 0.04$	$0.17 \pm 0.14 \pm 0.05$	$0.31 \pm 0.26 \pm 0.11$	$0.68 \pm 0.24 \pm 0.18$
ϕ_{4500} (rad)	$1.02 \pm 0.57 \pm 0.56$	$1.74 \pm 1.11 \pm 0.46$	$4.26 \pm 0.76 \pm 0.91$	$4.98 \pm 0.31 \pm 0.74$
M_{4710} (MeV/ c^2)		$4704.0 \pm 52.3 \pm 69.5$		
Γ_{4710} (MeV)		$183.2 \pm 114.0 \pm 96.1$		
$(\Gamma_{ee}\mathcal{B})_{4710}$ (eV)	$0.12 \pm 0.09 \pm 0.11$	$0.68 \pm 0.26 \pm 0.21$	$0.18 \pm 0.20 \pm 0.10$	$1.04 \pm 0.60 \pm 0.35$
ϕ_{4710} (rad)	$0.92 \pm 0.99 \pm 0.84$	$5.37 \pm 0.46 \pm 0.95$	$5.38 \pm 1.02 \pm 0.80$	$3.55 \pm 0.27 \pm 1.03$

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

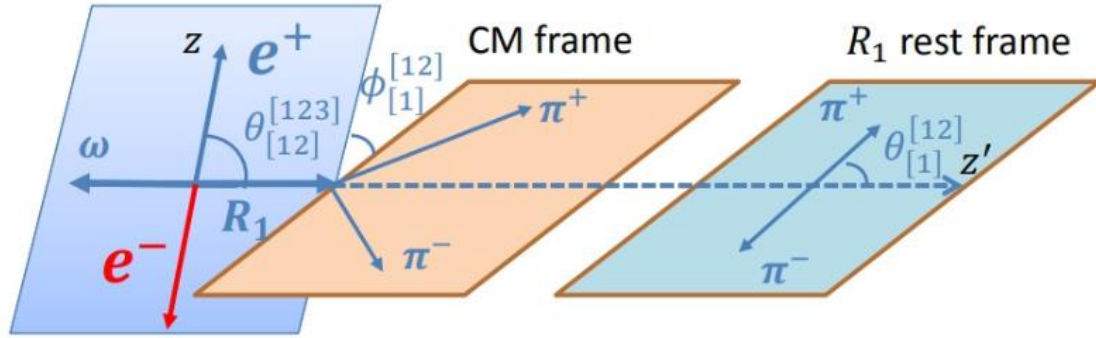


	I	II	III	IV	V	VI	VII	VIII
$C_1 (10^{-3})$					4.2 ± 1.5			
$m_1 (\text{MeV}/c^2)$					4209.6 ± 4.7			
$\Gamma_1^{\text{tot}} (\text{MeV})$					81.6 ± 17.8			
$\Gamma_1^{ee} \mathcal{B}_1 (\text{eV})$	5.4 ± 1.1	6.0 ± 1.3	4.8 ± 0.9	5.3 ± 1.1	17.9 ± 7.2	19.8 ± 6.6	20.2 ± 7.4	22.4 ± 9.0
$\phi_1 (\text{rad})$	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
$m_2 (\text{MeV}/c^2)$					4469.1 ± 26.2			
$\Gamma_2^{\text{tot}} (\text{MeV})$					246.3 ± 36.7			
$\Gamma_2^{ee} \mathcal{B}_2 (\text{eV})$	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
$\phi_2 (\text{rad})$	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
$m_3 (\text{MeV}/c^2)$					4675.3 ± 29.5			
$\Gamma_3^{\text{tot}} (\text{MeV})$					218.3 ± 72.9			
$\Gamma_3^{ee} \mathcal{B}_3 (\text{eV})$	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
$\phi_3 (\text{rad})$	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

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



$$e^+ e^- \rightarrow \omega \pi^+ \pi^-$$



Resonance	Mass (MeV/ c^2)	Width (MeV)	Group A	Group B
$f_0(500)$	507 (400~550)	475 (400~700)	27.8σ	22.8σ
$f_0(980)$	990 ± 20	—	10.9σ	6.4σ
$f_0(1370)$	1350 ± 150	200 ± 50	6.2σ	3.4σ
$f_2(1270)$	1275.5 ± 0.8	186.7 ± 2.2	9.3σ	5.4σ
$b_1(1235)^\pm$	1179.0 ± 9.0	255.8 ± 16.4	31.8σ	25.7σ
$\rho(1450)^\pm$	1465.0 ± 25	400 ± 60	4.7σ	6.9σ
$\rho(1570)^\pm$	1570 ± 70	144 ± 90	4.3σ	2.4σ
$\pi^+ \pi^1 \omega$	—	—	6.5σ	3.0σ

$$BW_1(s) = \frac{1}{s - M^2 + i(g_1 \rho_{\pi\pi}(s) + g_2 \rho_{K\bar{K}}(s))},$$

$f_0(980)$

$$BW_2(s) = \frac{1}{s - m_0^2 + i\sqrt{s}\Gamma}, \text{ with } \Gamma = \sqrt{1 - \frac{4m_\pi^2}{s}}\Gamma_0,$$

$f_0(500)$

$$BW_3(s) = \frac{1}{s - m_0^2 + i\sqrt{s}\Gamma},$$

$b_1(1235)^\pm, f_0(1370), f_2(1270), \rho(1450)^\pm, \rho(1570)^\pm$