BESIII上的XYZ研究

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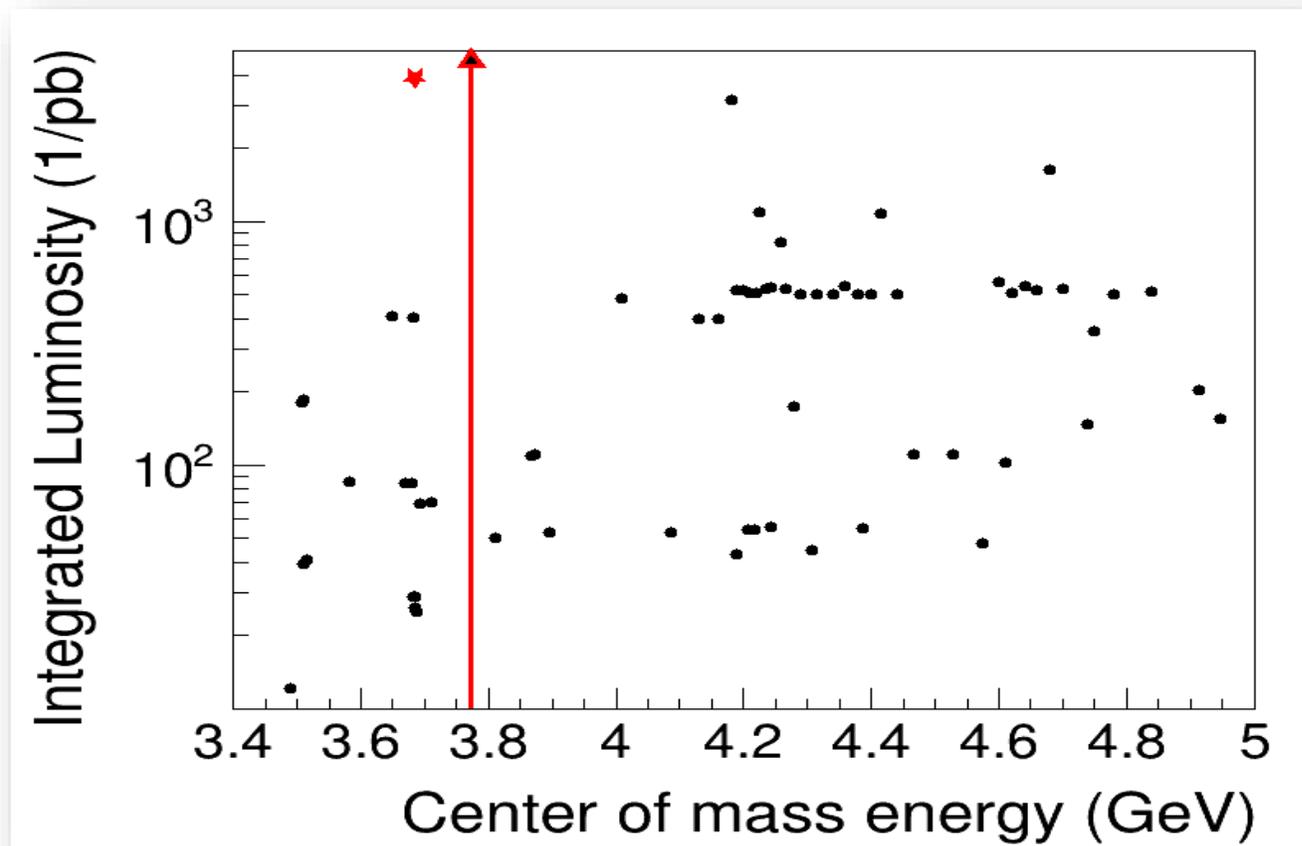
BESIII实验物理研讨会

2026年2月5日-9日，北京昌平（承办：华北电力大学）

大纲

- 引言（~~BESIII实验~~与XYZ简介）
- 成就回顾
- 近期结果
- 挑战与机遇
- 小结

What are charmonium-like (XYZ) states

charmonia: $c\bar{c}$

Exotic states with hidden charm

CZY & S. L. Olsen, *Nature Reviews Physics* **1**, 480 (2019)

Y: vector states

Z: $isospin \neq 0$

X: remained

Primarily studies the properties of charmonium-like states, including but are not limited to
- Searching for new states
- Determining the internal structure
- Measuring masses and widths
- Measuring transitions and decays
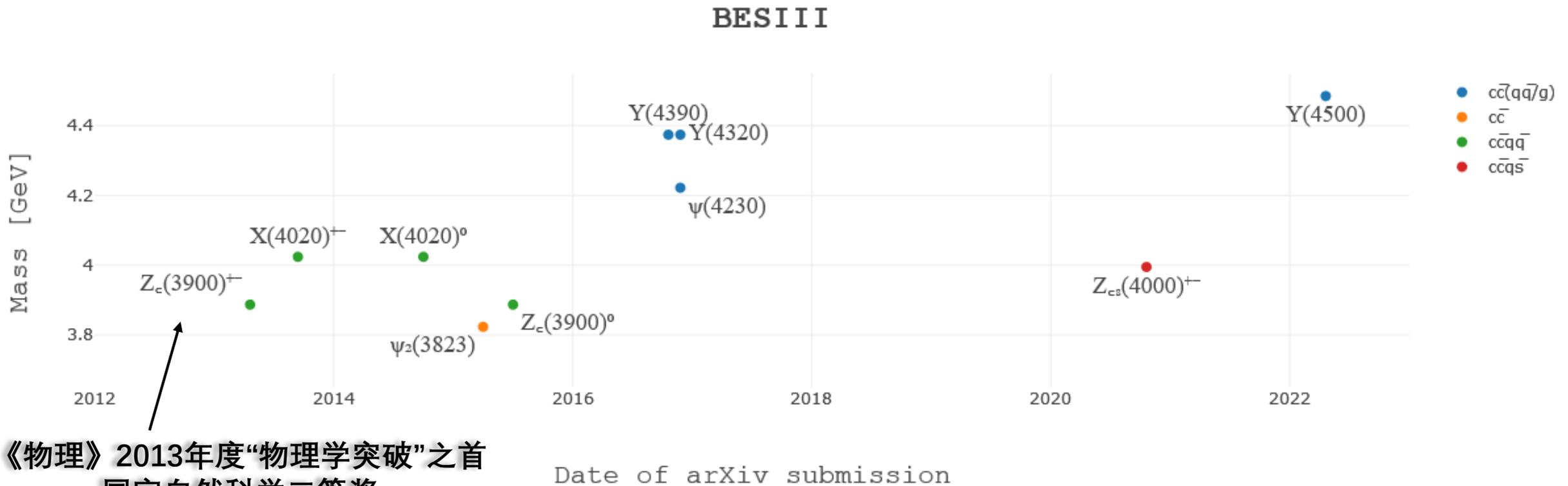- Searching for new decay channels

How to study charmonium-like states at BESIII

Data samples
accumulated at BESIII
among the years

$22fb^{-1}$ above 4 GeV

Line shapes of cross-sections for Y, whose (radiative & hadronic) transitions for X and Z
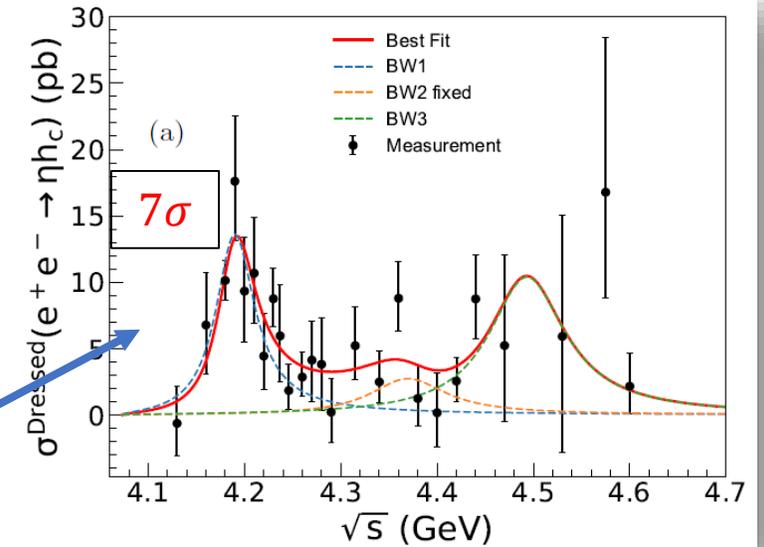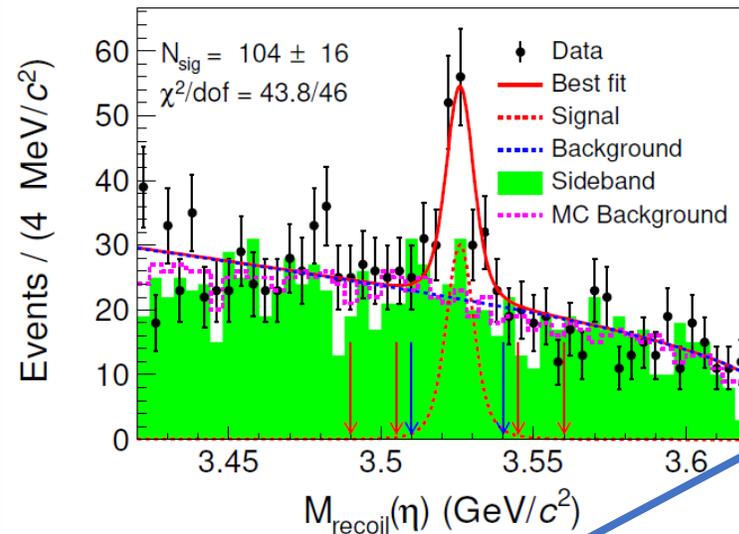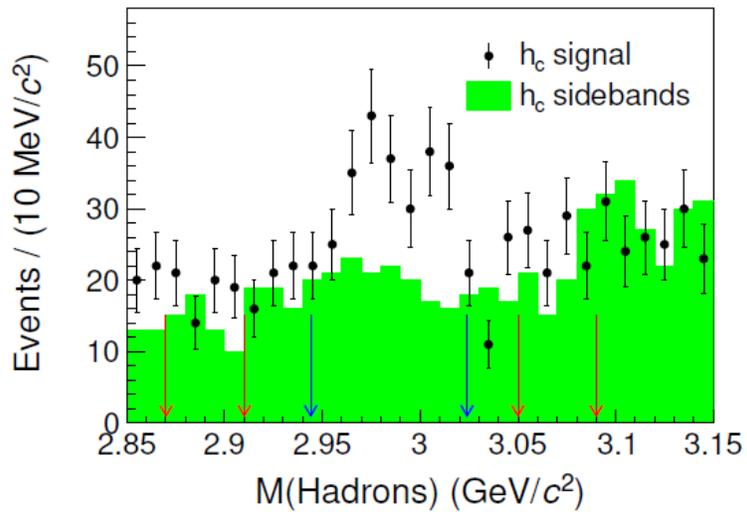
Previous discovered

BESIII

Y(4390)
Y(4320)
ψ(4230)
Y(4500)
X(4020)⁺
X(4020)⁰
$Z_c(3900)^+$
$Z_c(3900)^0$
$Z_{cs}(4000)^+$
ψ₂(3823)

Legend: cc̄(qq̄/g), cc̄, cc̄qq̄, cc̄qs̄

Mass [GeV] axis: 3.8, 4, 4.2, 4.4
Date of arXiv submission axis: 2012, 2014, 2016, 2018, 2020, 2022

《物理》2013年度"物理学突破"之首
国家自然科学二等奖

From QWG ExoticHub

Recent highlights (I): $e^+e^- \to \eta h_c$

16 η_c decay channels

7σ

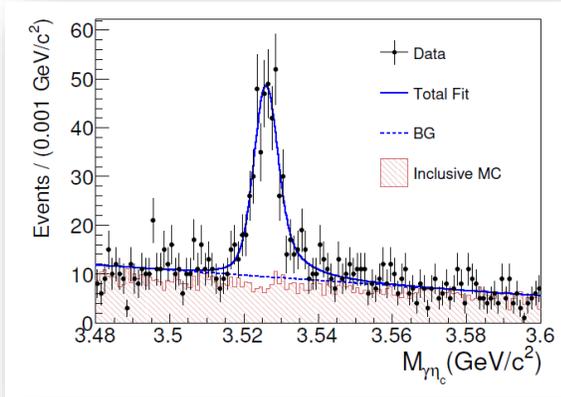| $\Gamma_{ee}\mathcal{B}$ (eV)	M (MeV/c^2)	Γ_{tot} (MeV)
$0.80 \pm 0.19 \pm 0.45$	$4188.8 \pm 4.7 \pm 8.0$	$49 \pm 16 \pm 19$

Recent highlights (II): $e^+e^- \to \pi^+\pi^- h_c$
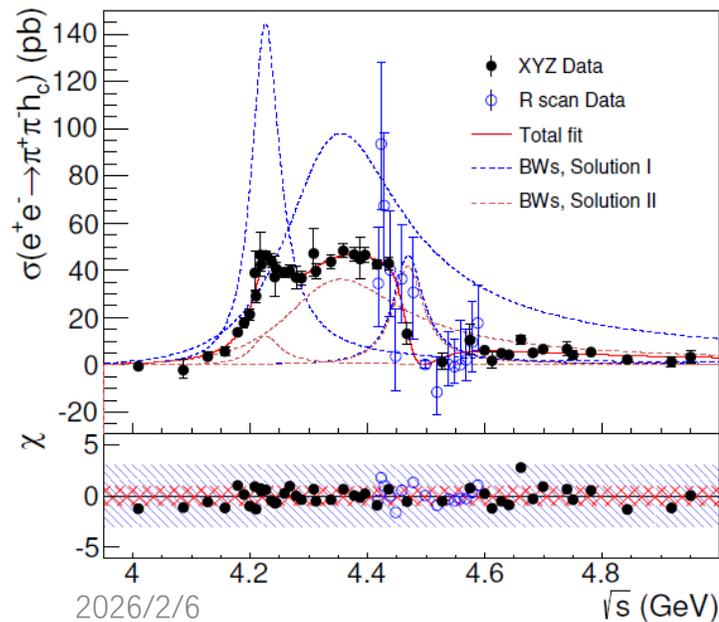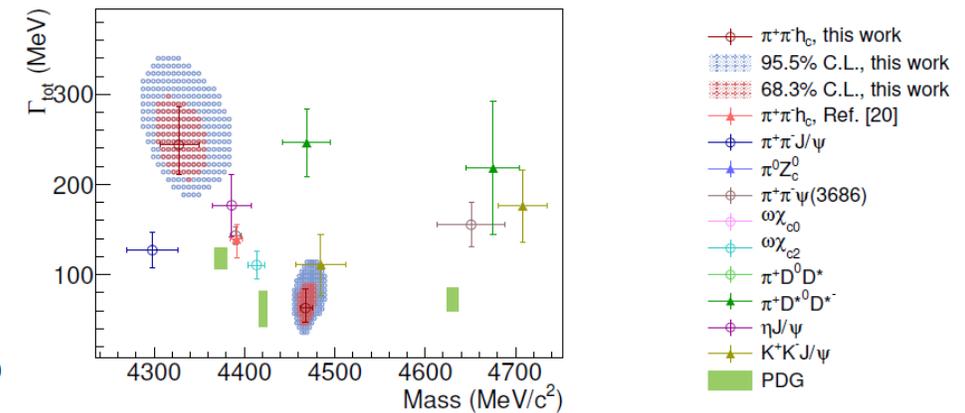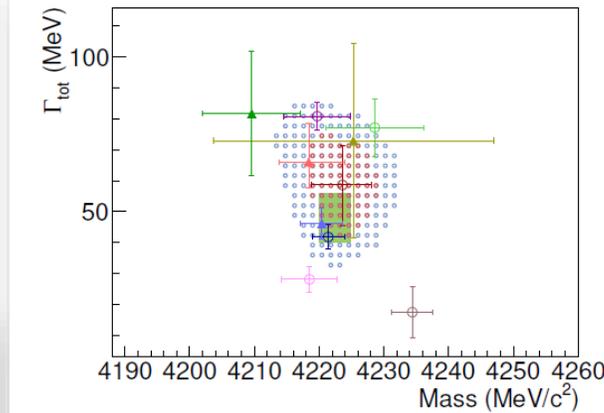
Parameter	R_1	R_2	R_3
M (MeV/c^2)	$4223.6^{+3.6+2.6}_{-3.7-2.9}$	$4327.4^{+20.1+10.7}_{-18.8-9.3}$	$4467.4^{+7.2+3.2}_{-5.4-2.7}$
Γ (MeV)	$58.5^{+10.8+6.7}_{-11.4-6.5}$	$244.1^{+34.0+24.2}_{-27.1-18.3}$	$62.8^{+19.2+9.9}_{-14.4-7.0}$
$\Gamma_{ee}\cdot\mathcal{B}(R \to \pi^+\pi^- h_c)$ (eV)	$10.2^{+1.2+1.4}_{-1.5-1.4}$ $(0.9^{+0.4+0.3}_{-0.4-0.2})$	$29.1^{+5.7+4.4}_{-3.9-3.4}$ $(10.8^{+2.5+1.9}_{-1.8-1.5})$	$3.9^{+3.5+1.7}_{-1.7-0.5}$ $(3.5^{+3.0+1.5}_{-1.6-0.7})$
ϕ (rad)	...	$3.6^{+0.1+0.1}_{-0.1-0.1}$ $(0.7^{+0.3+0.2}_{-0.3-0.2})$	$0.7^{+0.3+0.1}_{-0.3-0.2}$ $(-2.2^{+0.3+0.2}_{-0.3-0.1})$

The third resonance is necessary with statistical significance of 5σ

Recent highlights (III): PWA of $e^+e^- \to \pi^+\pi^- J/\psi$

1 $\pi^\pm Z_c^\mp(3900), f_0(980)J/\psi, (\pi^+\pi^-)_{S-wave}J/\psi$ — dominant

$Z_c(4020)$ is not significant

Sample	M (MeV/c^2)	Γ (MeV)
4.1567 − 4.1989	3883.5 ± 1.6	38.6 ± 3.6
4.2091 − 4.2357	3884.0 ± 1.0	37.8 ± 1.6
4.2438 − 4.2776	3884.9 ± 1.8	34.2 ± 3.3
4.2866 − 4.3583	3890.0 ± 2.3	36.1 ± 4.2
Average	3884.6 ± 0.7 ± 3.3	37.2 ± 1.3 ± 6.6

2 Mass and width are consistent in diff E regions
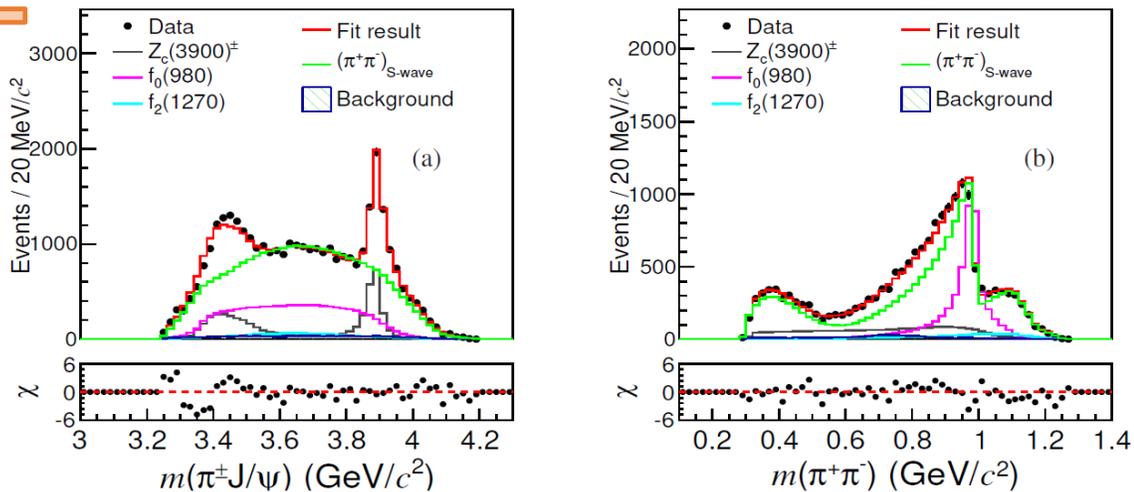
| Process	Y(4220)		Y(4320)
	M (MeV/c^2)	Γ (MeV)	Significance
$\pi^\pm Z_c(3900)^\mp$ (model I)	4225.7 ± 6.8 ± 6.8	66.5 ± 16.1 ± 24.1	2.1σ
$\pi^\pm Z_c(3900)^\mp$ (model II)	4223.1 ± 6.4 ± 0.6	53.8 ± 19.1 ± 0.3	2.0σ
$f_0(980)J/\psi$ (model III)	4225.6 ± 4.5 ± 0.6	48.4 ± 9.8 ± 0.2	0.5σ
$(\pi^+\pi^-)_{S-wave}J/\psi$ (model IV)	4218.8 ± 3.4 ± 3.7	43.5 ± 5.3 ± 5.0	11.7σ
$Y(4220)^{ave}$	4225.7 ± 4.1 ± 3.4	57.5 ± 9.4 ± 12.1	

3
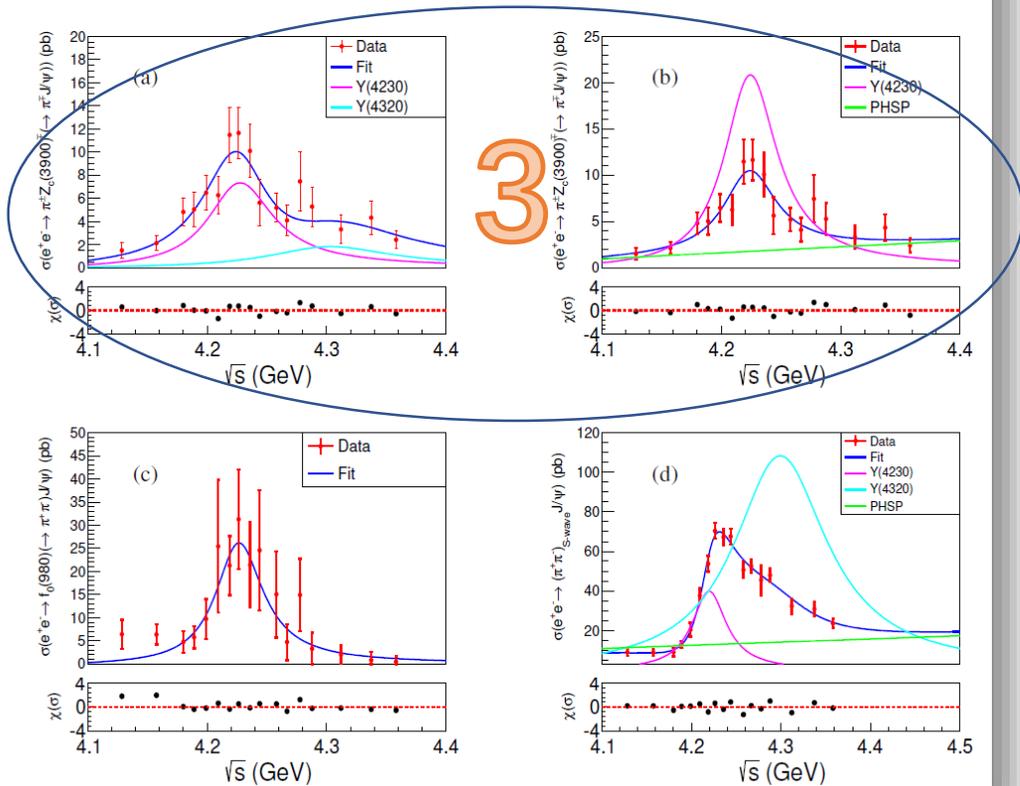
Suffer from multiple solutions and local minimum

Recent highlights (IV): $e^+e^- \to \pi^0\pi^0\psi(3686)$
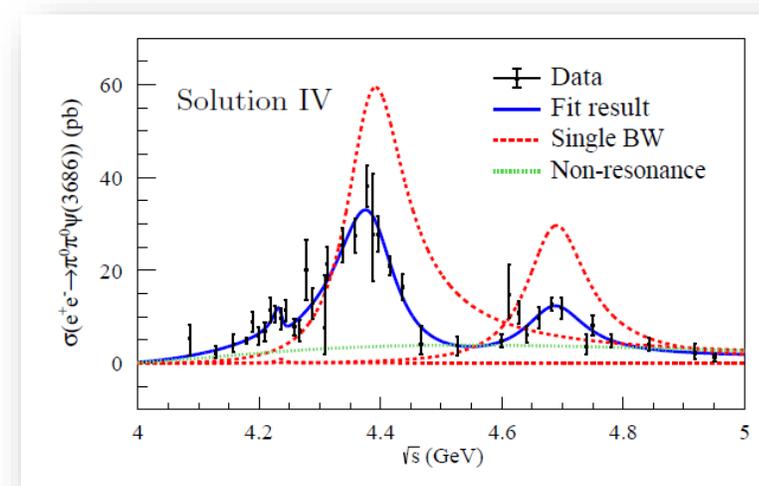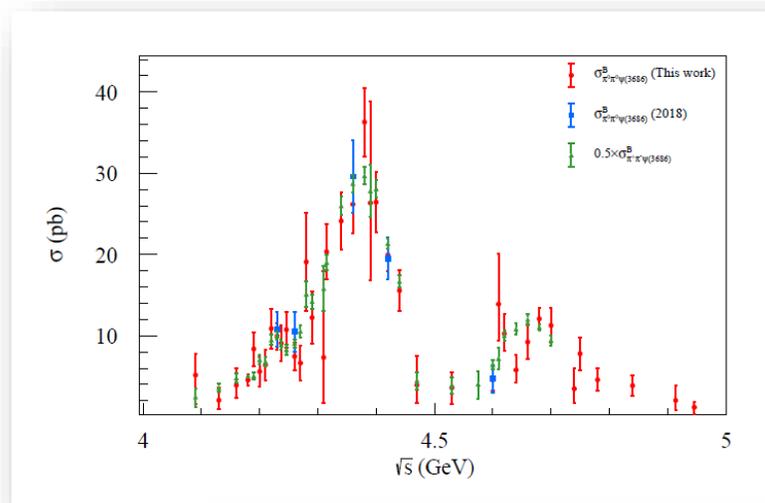
| Parameter	Solution I	Solution II	Solution III	Solution IV
$M(Y4230)$ (MeV/c^2)		4234.4 (fixed)		
$\Gamma^{tot}(Y4230)$ (MeV)		17.6 (fixed)		
$\mathcal{B}\Gamma^{ee}(Y4230)$ (eV)	$0.81 \pm 0.07 \pm 0.37$	$0.02 \pm 0.01 \pm 0.01$	$0.87 \pm 0.08 \pm 0.43$	$0.02 \pm 0.01 \pm 0.01$
$M(Y4390)$ (MeV/c^2)		$4383.0 \pm 8.6 \pm 1.9$		
$\Gamma^{tot}(Y4390)$ (MeV)		$117.4 \pm 20.7 \pm 4.8$		
$\mathcal{B}\Gamma^{ee}(Y4390)$ (eV)	$3.18 \pm 1.21 \pm 0.57$	$2.92 \pm 1.07 \pm 0.36$	$9.90 \pm 1.42 \pm 0.76$	$9.03 \pm 1.22 \pm 0.09$
$M(Y4660)$ (MeV/c^2)		$4684.0 \pm 17.3 \pm 1.9$		
$\Gamma^{tot}(Y4660)$ (MeV)		$119.5 \pm 47.1 \pm 9.1$		
$\mathcal{B}\Gamma^{ee}(Y4660)$ (eV)	$0.80 \pm 0.73 \pm 0.14$	$0.79 \pm 0.70 \pm 0.13$	$5.36 \pm 1.60 \pm 0.39$	$5.31 \pm 1.58 \pm 0.23$
$\phi_{Y(4230)}$ (rad)	2.03 ± 0.25	6.14 ± 0.41	1.23 ± 0.18	5.35 ± 0.52
$\phi_{Y(4660)}$ (rad)	5.99 ± 0.40	5.93 ± 0.40	5.28 ± 0.46	5.22 ± 0.46
ϕ_{cont} (rad)	3.87 ± 0.36	3.69 ± 0.33	2.23 ± 0.27	2.06 ± 0.24
a ($\times 10^5$)	4.2 ± 9.5	3.3 ± 8.0	5.3 ± 22.8	4.9 ± 22.6
n	8.7 ± 1.8	8.6 ± 1.8	8.9 ± 3.6	8.9 ± 3.6

挑战
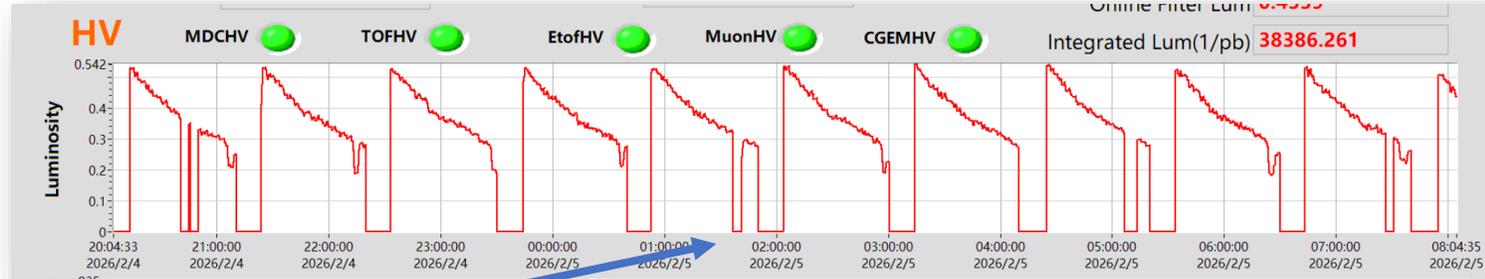
个人观点

- 新探测器CGEM 【从悲观到谨慎乐观】
- 与 Belle-II 与 LHCb 的竞争与互补
  - BESIII优势：高亮度扫描数据，正负电子对撞的纯净环境、良好的光子分辨与探测能力
- 最大化实验测量的效能
  - 如何区别分子态与紧致四夸克态？
  - 如何将隐粲与开粲结果联系起来？
  - 如何将类粲偶素与粲偶素联系与区分？
- 发现的不确定性与外部期待的压力

arXiv:2601.20790 [pdf, other]

Observation of the decay $\chi_{c1}(3872) \to J/\psi \mu^+ \mu^-$

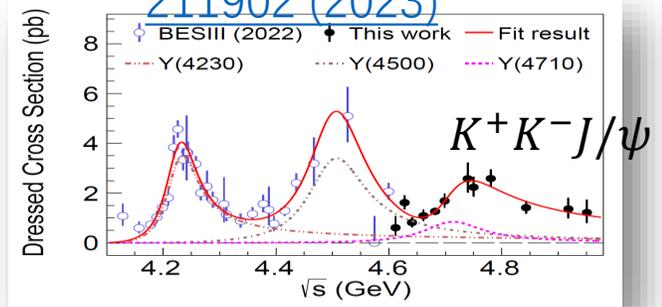LHCb collaboration: R. Aaij, A.S.W. Abdelmotteleb, C. Abellan Bete

yield is 60 ± 11
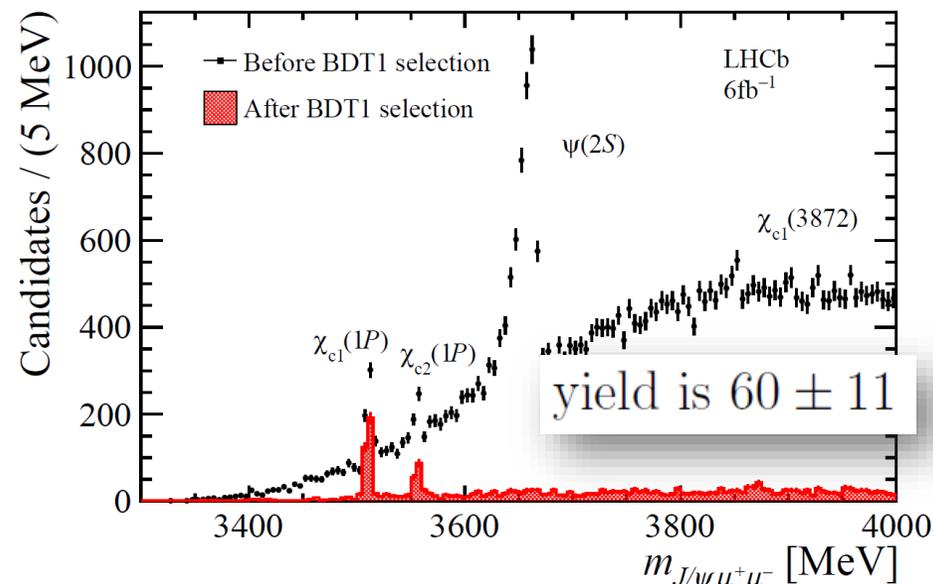
$$\frac{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\mu^+\mu^-)}{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)} = (1.64 \pm 0.32 \pm 0.05) \times 10^{-3}$$

Similar yield of X(3872) $\to \gamma J/\psi$ at BESIII

含奇异夸克的XYZ粒子寻找的阴性结果
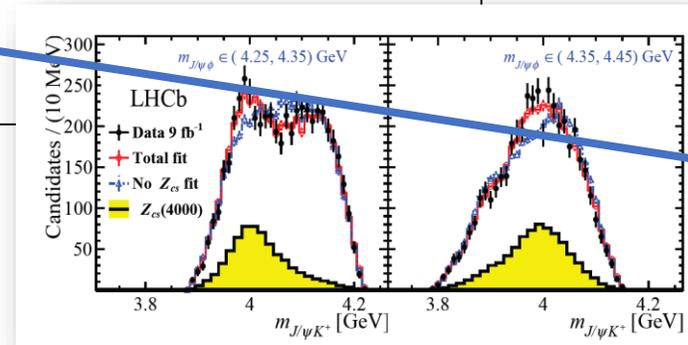
- 除了KKJ/ψ，我们在其他 $e^+e^- \to KK + charmonium\,(\eta_c, \chi_{c0}, \chi_{c1}, \chi_{c2}, h_c, \psi(2S), \psi(3770))$ 等过程中，均未在单个能量点看到显著信号迹象。

- 没有在 $e^+e^- \to \gamma\phi J\psi$ 等过程中看到 C 宇称为正的 X_s 态
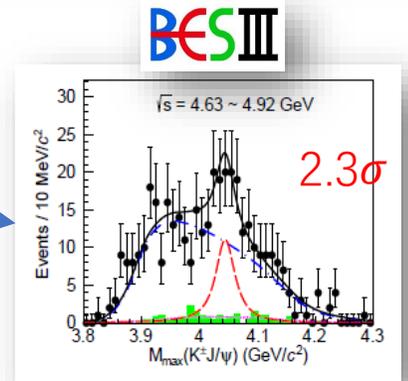
- 没有在 KJ/ψ 系统中看到 Z_{cs} 态

以上，都在我们的预期之外

Phys. Rev. Lett. 131, 211902 (2023)

K^+K^-J/ψ

PRL 127, 082001 (2021)

PRL 131, 211902 (2023)

2.3σ

Ways to beyond the limited statistics (analysis)

- Improved reconstruction methods and more decay channels

Decay channels in $e^+e^- \to \phi\chi_{c0}/\eta_{c2}(1D)$

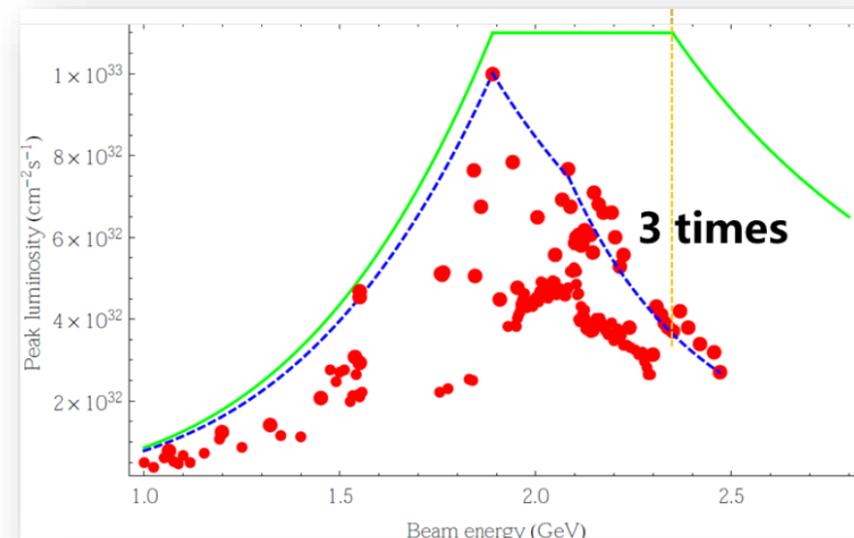| χ_{c0} Decay	Full $K^\pm\pi^\pm\pi^0$			Miss $K^\pm$ $K^\pm\pi^\pm\pi^0$			Miss $\pi^\pm$ $K^\pm\pi^\pm\pi^0$			Miss π^0 $K^\pm\pi^\pm\pi^0$		
$\pi^+\pi^-$	2	2	0	1	2	0	2	1	0	-	-	-
$\pi^+\pi^-\pi^0\pi^0$	2	2	2	1	2	2	2	1	2	2	2	1
$K^+K^-\pi^+\pi^-$	4	2	0	3	2	0	4	1	0	-	-	-
$2(\pi^+\pi^-)$	2	4	0	1	4	0	2	3	0	-	-	-
$3(\pi^+\pi^-)$	2	6	0	1	6	0	2	5	0	-	-	-

Various reconstructions in $e^+e^- \to K^+K^-\psi(2S)$
- Approach (i): tag K^+, K^-, and J/ψ from $\psi(2S) \to X J/\psi$
- Approach (ii): tag K^+ or K^-, and $\psi(2S)$ with $\pi^+\pi^-J/\psi$, 1C
- Approach (iii): tag K^+, K^-, and $\psi(2S)$ with l^+l^-
- Approach (iv): tag K^+ or K^-, and $\psi(2S)$ with l^+l^-, 1C

- (Deep) machine learning and AI assistant?

Ways to beyond the limited statistics (data)

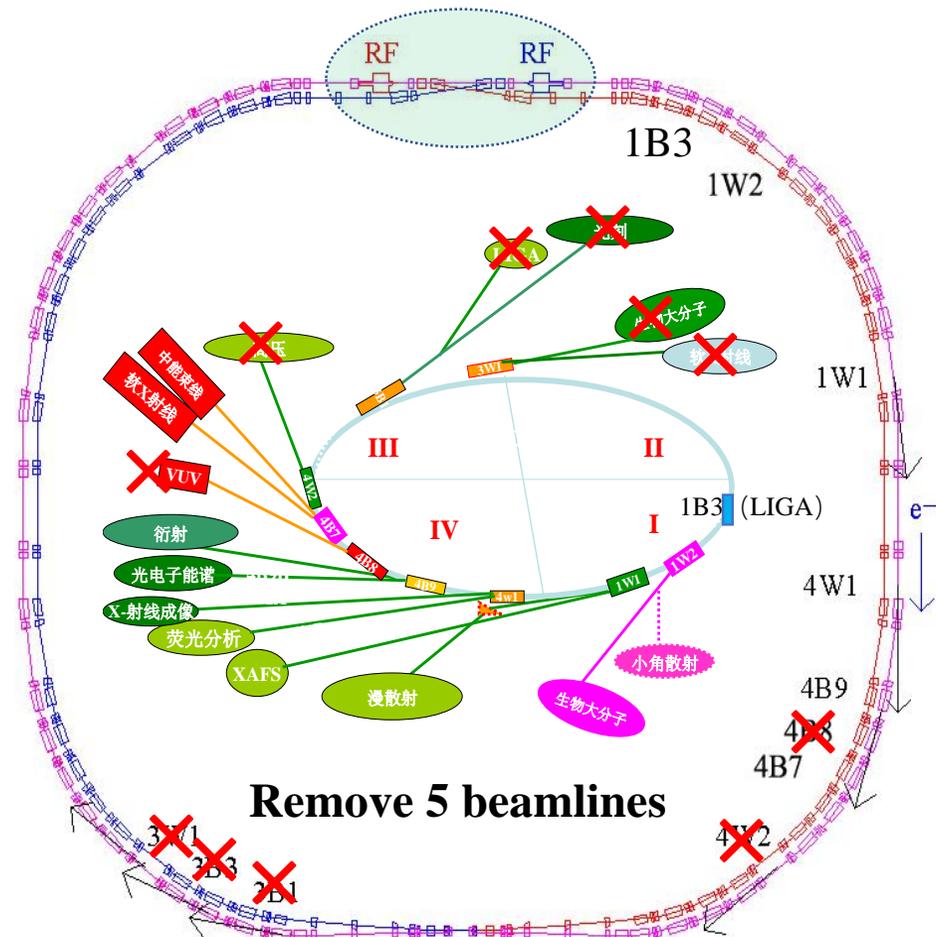BEPCII has upgraded in both Lum. and Max. E

- Luminosity is increased by a factor 3 @ 2.35 GeV
- Maximun beam energy is increased up to 2.8 GeV

Timeline:

2020 White Paper of BESIII	Jun. 2021 Feasibility Study Report	Apr. 2022 Design Finished	Jul. 2024 Shutdown for Installation	Feb. 2026 Taking $\psi(2S)$ data
May. 2020 Internal Review of Accelerator	Jul. 2021 Project Approved	Jun. 2024 Fabrication Finished	Jan. 2025 Commissioning	

BEPCII keep running

Accelerator physics

Key Technologies: Double beam power & Optics upgrade & Higher gradient of magnets

	BEPCII @ 2.35GeV	BEPCII-U @ 2.35GeV	BEPCII-U @ 2.8GeV
L $[10^{32}cm^{-2}s^{-1}]$	**3.5**	**11**	**3.7**
β_y^* [cm]	**1.5**	**1.35**	**3.0**
Beam current [mA]	400	900	450
SR Power [kW]	**110**	**250**	**250**
$\xi_{y,lum}$	0.029	0.033	0.043
Emittance [nmrad]	**147**	**152**	**200**
Couping [%]	**0.53**	**0.35**	**0.5**
Bucket Height	0.0069	0.011	0.009
$\sigma_{z,0}$ [cm]	1.54	1.07	1.4
σ_z [cm]	**1.69**	**1.22**	**1.6**
RF Voltage [MV]	**1.6**	**3.3**	**3.3**

Remove 5 beamlines

No dedicated SR operation, only parasitic SR experiments, 10 months/year BESIII time.

C.H. Yu @ BESIII 2024 autumn workshop

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Status of BEPCII upgrade project

BEPCII Operation plan

- **Sep. 2021 – Jun. 2024**   **Data taking at ψ (3770) for 20fb^{-1}**

- **Jul. 2024 – Dec. 2024**   **Summer shutdown for upgrade**

- **Jan. 2025 – Jul. 2025**   **Data taking at beam energy 1.843GeV ψ (3686)**

- **Aug. 2025 – Sep. 2025**   **2nd SC magnet hor. test & the 4th RF cavity installation**

- **Oct. 2025 – Jul. 2026**   **Data taking around beam energy 2.35GeV (project test)**

- **Aug. 2026 – Sep. 2026**   **2 SC magnets installation & LINAC final upgrade**

- **Oct. 2026 – Sep. 2028**   **Data taking within beam energy 2.1-2.5GeV**

- **Sep. 2028 – Jul. 2030**   **Data taking within beam energy 2.5-2.8GeV**

Institute of High Energy Physics Chinese Academy of Sciences

A short term plan for next two years

- A Short term plan for 2025-2026: [9/fb + 18/fb]

  - 4.61 - 4.75 GeV, 10 points, 7.1/fb in total [114 days] $\Rightarrow Y(4710)$, $Y \to Z_{cs}$

    $Z_{cs}^{()}$ in both open charm and hidden charm processes

    - PlanB: 4.61 - 4.71 GeV first, 3.4/fb in total [55 days]

  - 4.4-4.6 GeV, add 7 points, 20 MeV step, 3.5/fb [56 days] $\Rightarrow Y(4500)$

  - data samples around 4.7 GeV for Zcs, 2-3 points, 2-3/fb each,
    exact enery to be determined from the scan result [96-144 days]

  - 4.76 - 5.0 GeV, 25 points, 18.2/fb in total [319 days]

问题：BESIII未来计划采集大量数据，特别是在4.5 GeV以上能区。在有限的束流时间内，如何确定数据采集能点的优先级？

回答：这是一个动态优化过程。1）**理论指导**：与理论家紧密合作，关注那些对区分四夸克态模型（如紧致四夸克、强子分子态）有关键作用的能量点。2）**实验驱动**：基于现有数据的"异常"或"暗示"（如截面增强、角分布异常）来定位精细扫描的能点。3）**系统性扫描**：在资源允许时，应对所有能区进行系统性扫描，以避免错过意外发现。
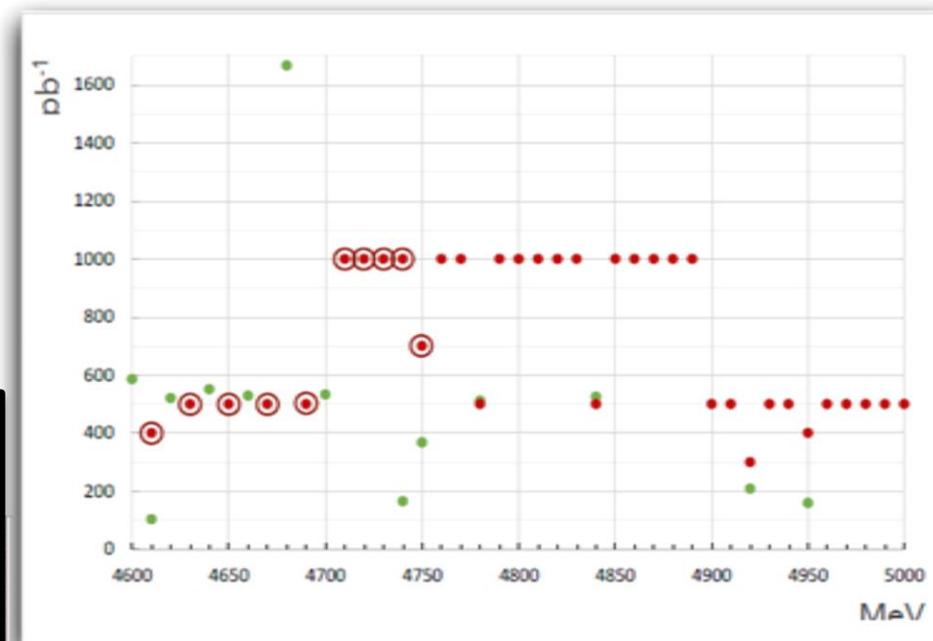
近期可做的测量与寻找

1. 测量带电和中性 $Z_{cs}(3985)$ 共振参数；寻找 $Z_{cs}(3985)$ 新的衰变方式。
2. 以更高精度测量矢量类粲偶素 $Y(4230), Y(4500), Y(4700)$ 的共振参数；对正负电子湮灭成隐粲末态、显粲末态、重子末态和轻强子末态进行截面测量以研究以上Y态的性质。
3. 更高统计量下通过电磁跃迁寻找C宇称为正的X_s粒子
4. 高同位旋Z_c粒子
5. 非零同位旋矢量类粲偶素Y_z
6. 五夸克态P_c
7. 拥有"范外"量子数的粒子态：例如BESIII在$e^+e^- \rightarrow \gamma\eta^{(\prime)}\eta_c$ 与 $\gamma D_s^+ D_{s1}^-(2536)$ 尝试过寻找1^{-+}的类粲偶素态
8. ……

小结

- **挑战与机遇并存，随着新的高能量数据获取，BESIII上的XYZ研究将迎来新一轮快速增长。**

- 在全振幅分析、阈值精密测量等方法学上持续创新，从数据中提取最大信息量。

- 欢迎理论家与实验同仁更多的参加与关注BESIII上的XYZ物理，提出建议与新思路，让我们深化理解非微扰强相互作用。

谢谢！

backup

大概需要多少亮度能在4.68GeV看到显著KK{ccbar}信号？

- 基于一个非常大胆的推测
  - 假设观测事例数满足以下关系(X 表示非 J/ψ 粲偶素）
  - $\dfrac{N(\pi^+\pi^- J/\psi)}{N(\pi^+\pi^- X)}_{@4.23\ GeV} \approx \dfrac{N(K^+K^- J/\psi)}{N(K^+K^- X)}_{@4.68\ GeV}$

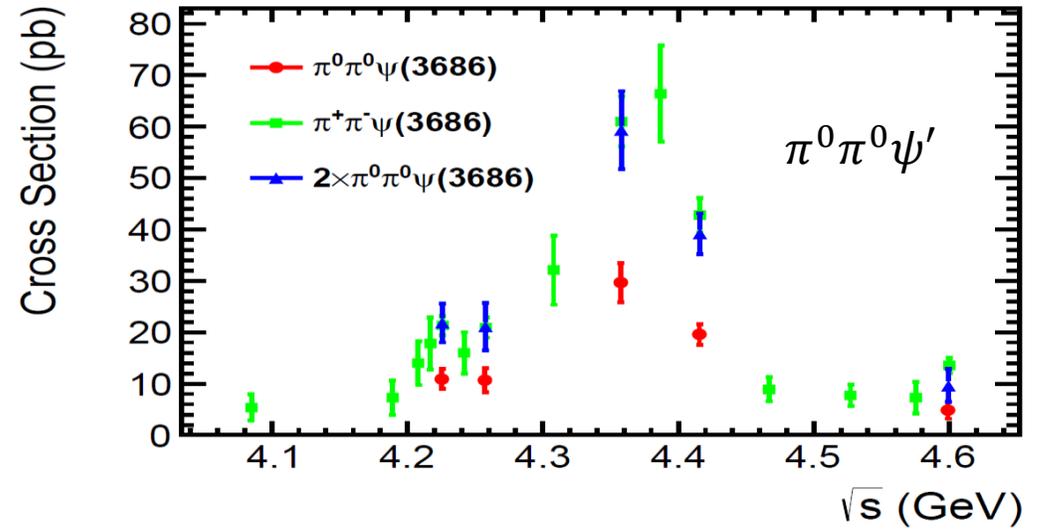- For hc, double current luminosity (1.6/fb) is enough; for psi(2S), triple is enough

Phys. Rev. D 106, 072001 (2022)

$\pi^+\pi^- J/\psi$

Phys. Rev. D 102, 012009 (2020)

$\pi^0\pi^0 J/\psi$

Phys. Rev. D 109, 092012 (2024)

$\eta J/\psi$

Phys. Rev. D 101, 012008 (2020)

$\eta' J/\psi$

Phys. Rev. Lett. 131, 211902 (2023)

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

Phys. Rev. D 107, 092005 (2023)

$K_s^0 K_s^0 J/\psi$

Phys. Rev. D 99, 091103(R) (2019)

$\sigma(e^+e^- \to \omega\chi_{c0})$ (pb)

This work

BESIII 2015+2016

$\omega\chi_{c0}$

$\sqrt{s}$ (GeV)
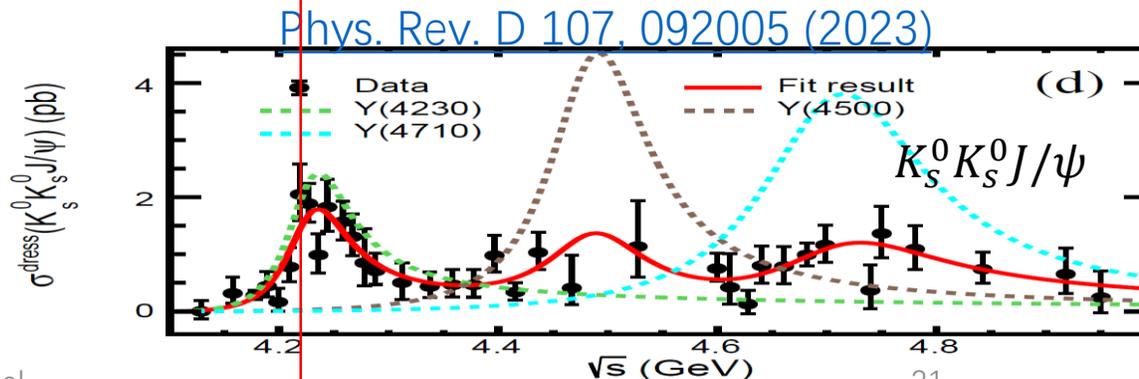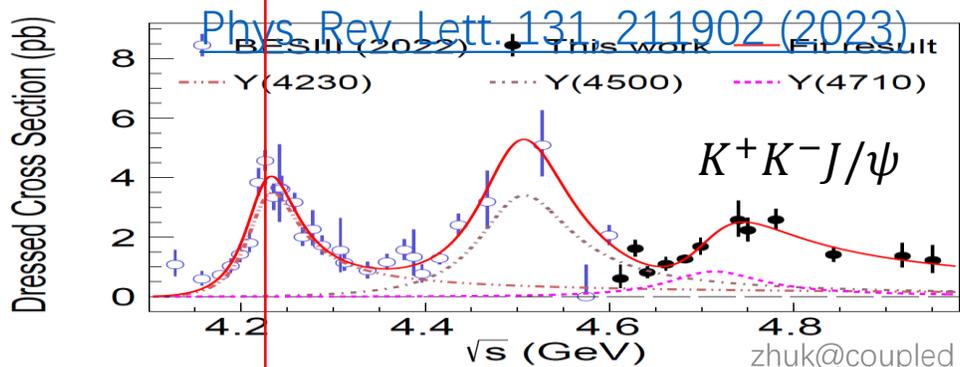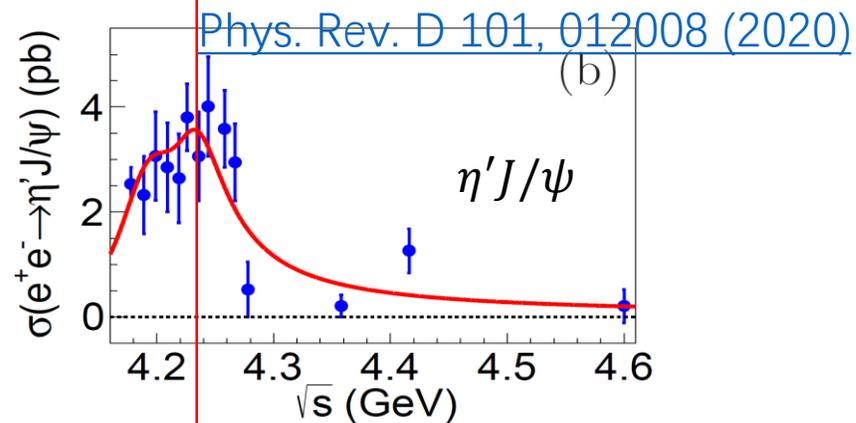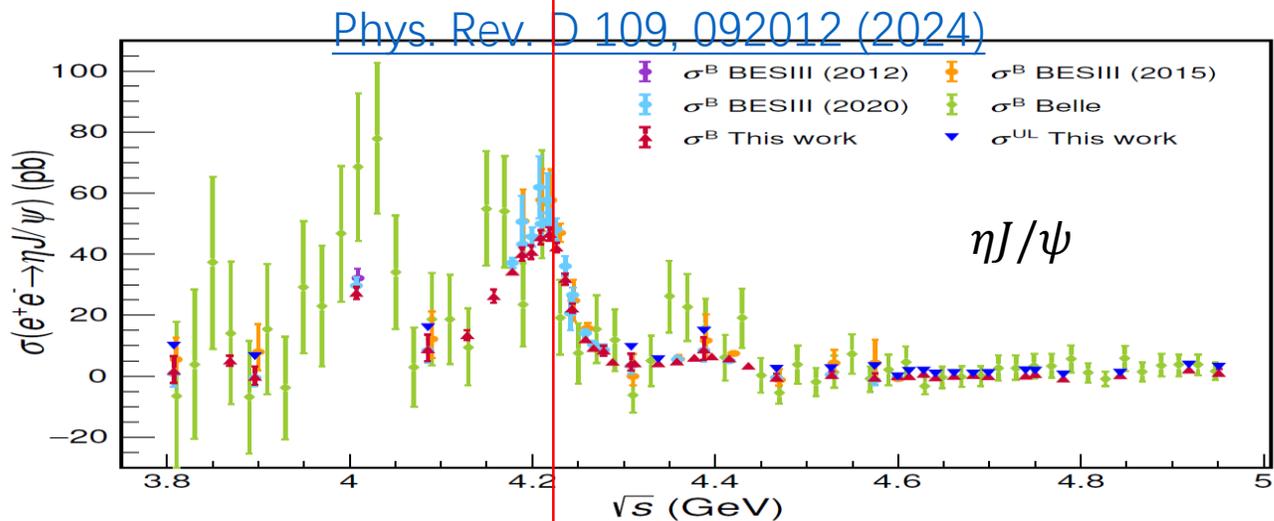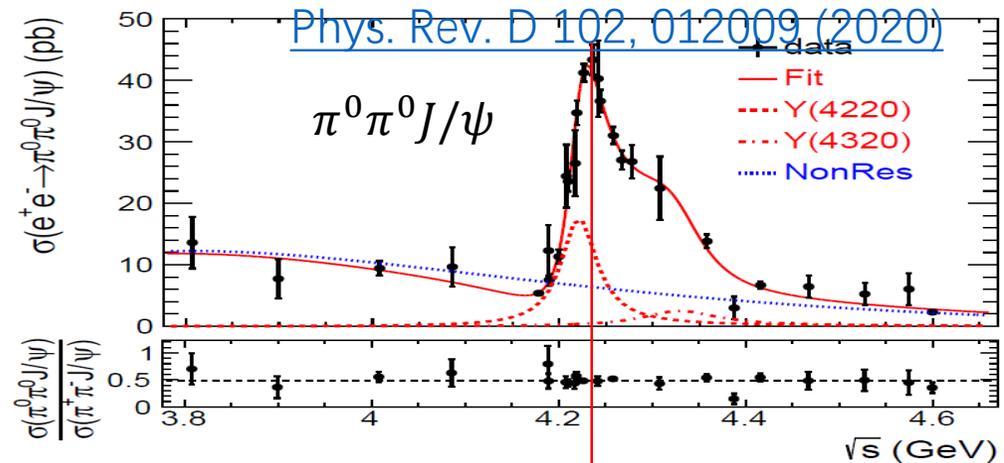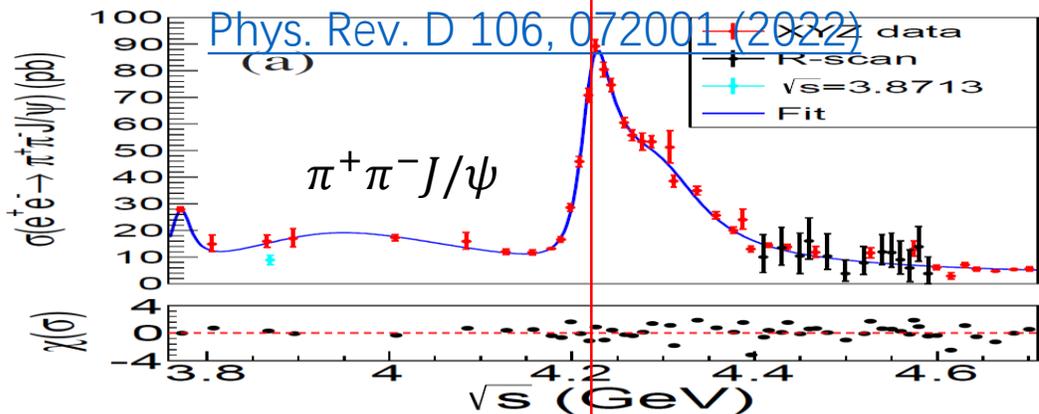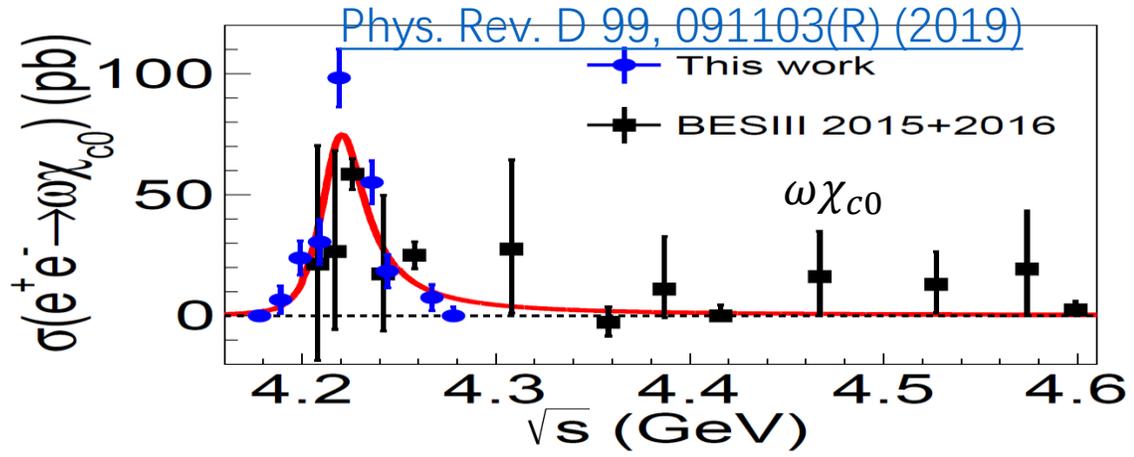
Why the structures order like this?

Phys. Rev. Lett. 132, 161901 (2024)

$\sigma(e^+e^- \to \omega\chi_{c1})$ (pb)

$\omega\chi_{c1}$

$\sqrt{s}$ (GeV)

Phys. Rev. Lett. 132, 161901 (2024)

$\sigma(e^+e^- \to \omega\chi_{c2})$ (pb)

$\omega\chi_{c2}$

$\sqrt{s}$ (GeV)

zhuk@coupled channel
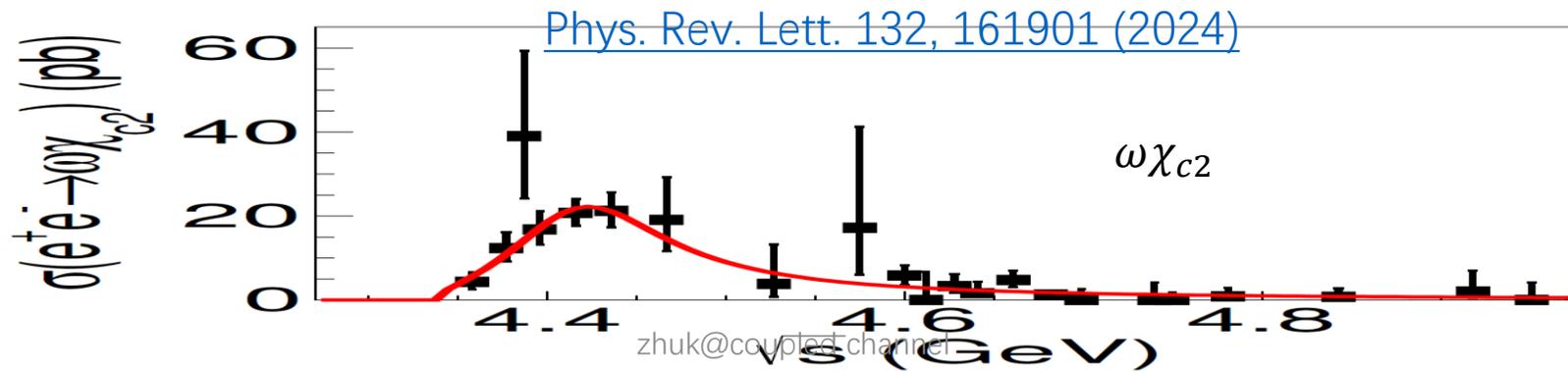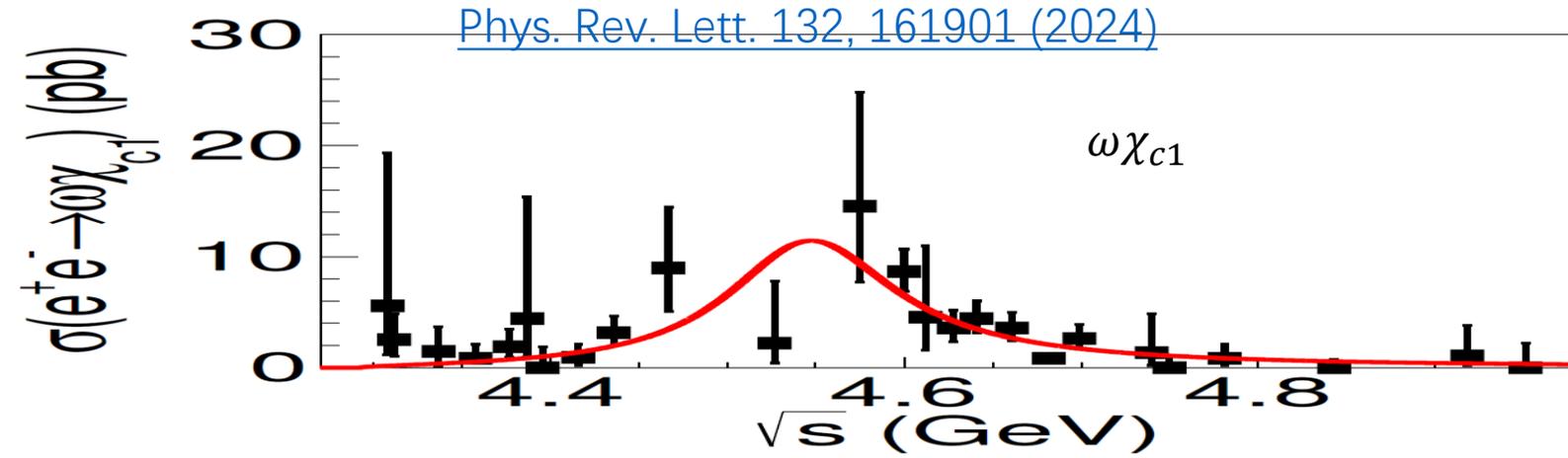
Phys. Rev. D 104, 052012 (2021)

$\pi^+\pi^-\psi'$
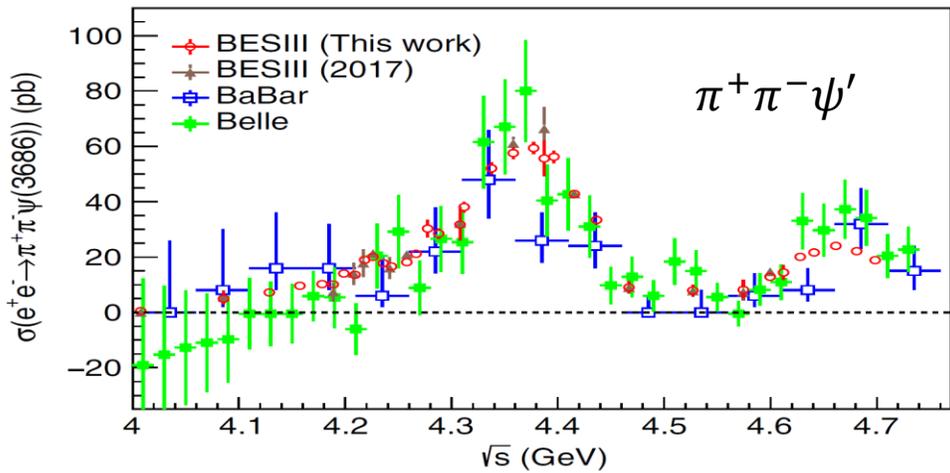
Phys. Rev. D 97, 052001 (2018)

$\pi^0\pi^0\psi'$

Phys. Rev. D 109, 112004 (2024)
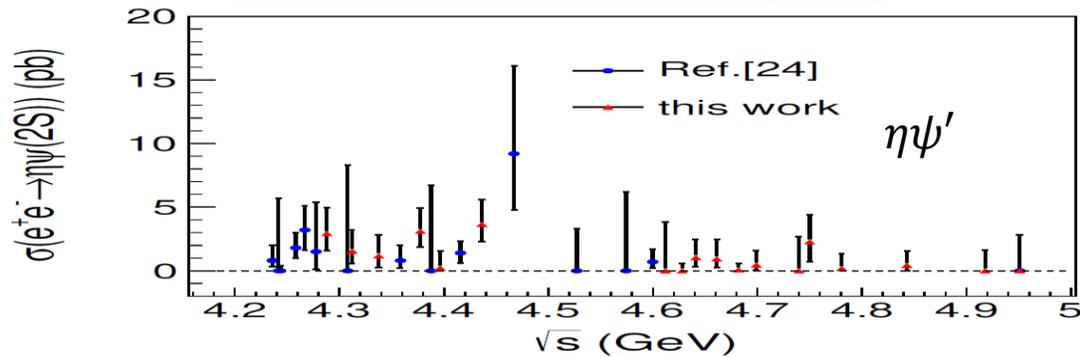
$\eta\psi'$

JHEP 02, 120 (2025)

$K_S^0 K_S^0 \psi'$

arXiv:2407.20009

$K^+K^-\psi'$

Phys. Rev. D 106, 072001 (2022)

$\pi^+\pi^- J/\psi$

Phys. Rev. Lett. 131, 211902 (2023)

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

Phys. Rev. D 104, 052012 (2021)

$\pi^+\pi^- \psi'$

arXiv:2407.20009

$K^+K^- \psi'$
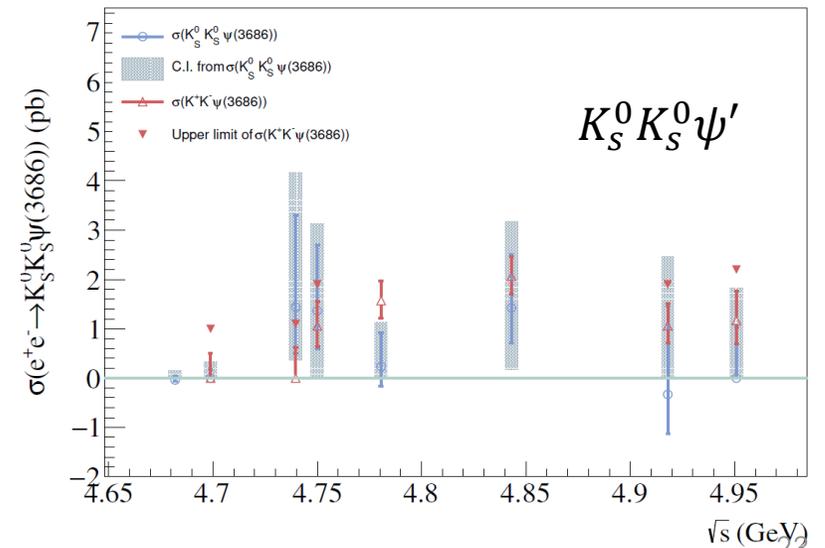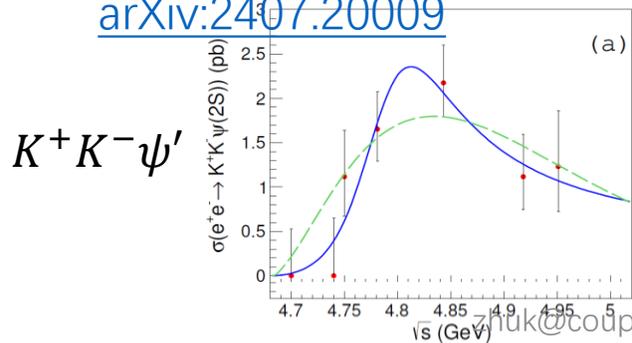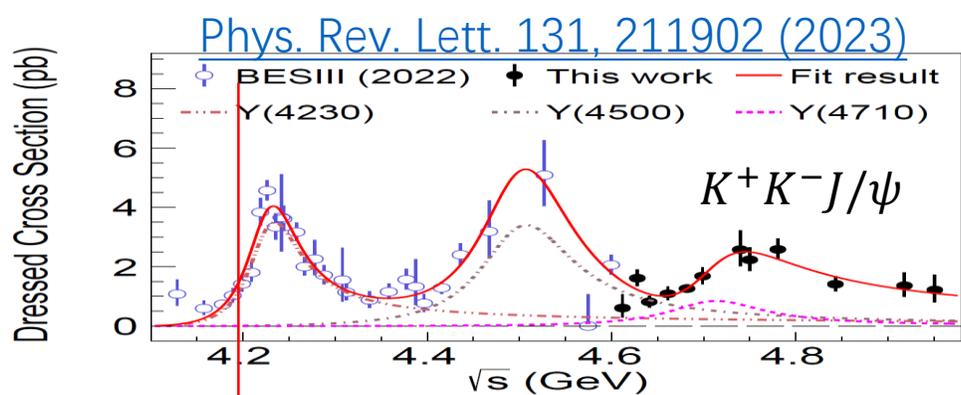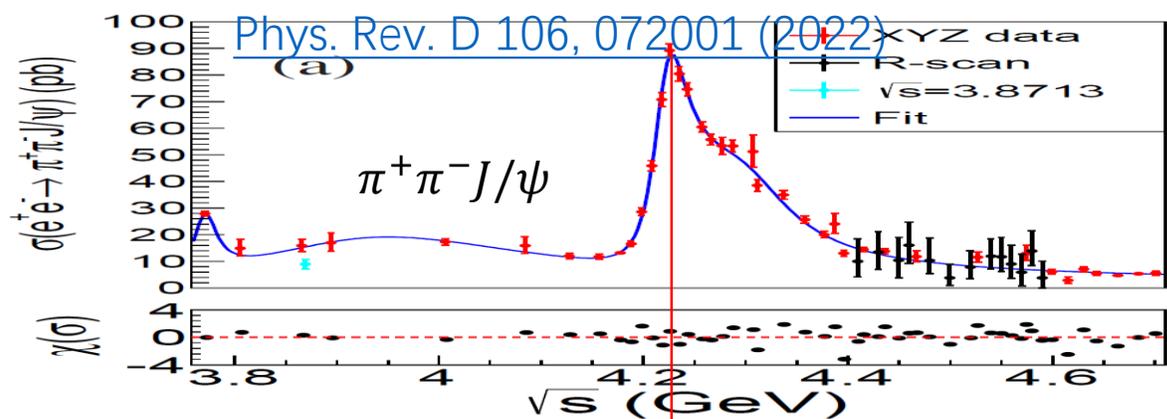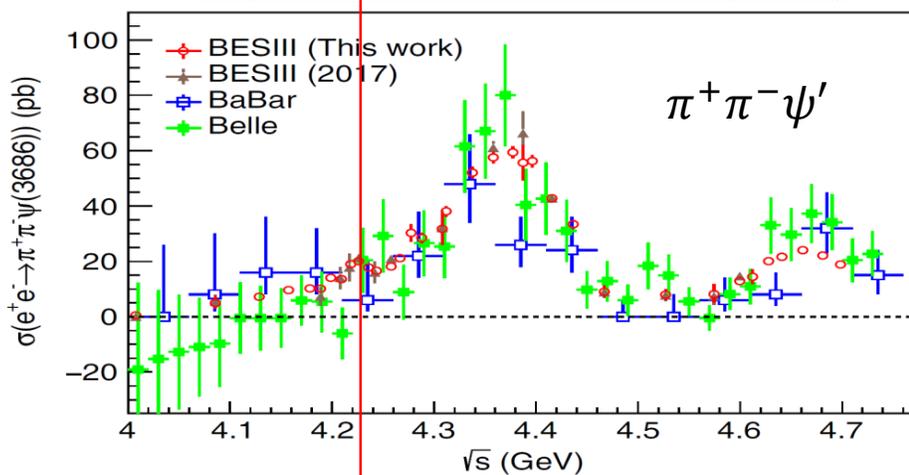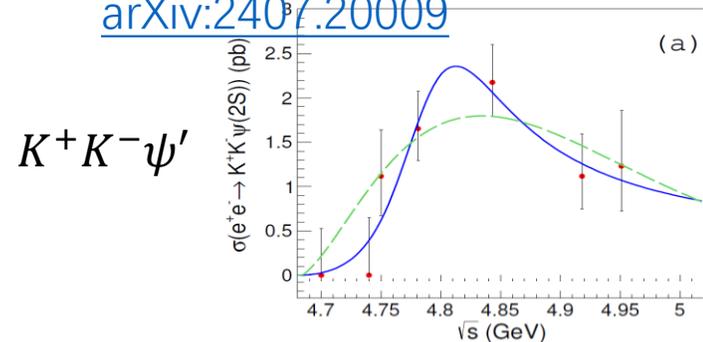
Phys. Rev. Lett. 118, 092002 (2017)

$\pi^+\pi^- h_c$
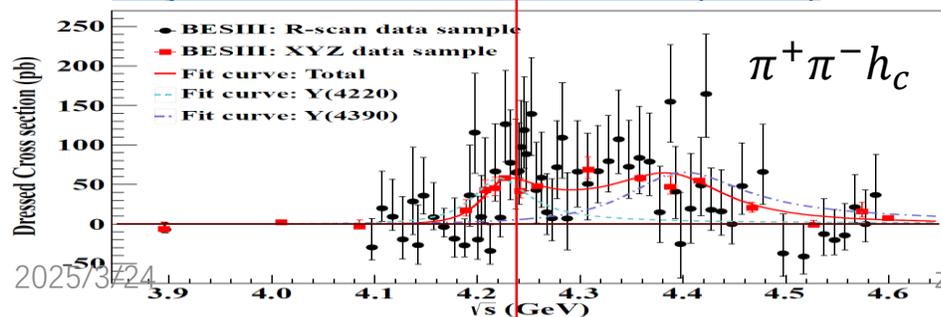
Phys. Rev. D 111, L011101 (2025)
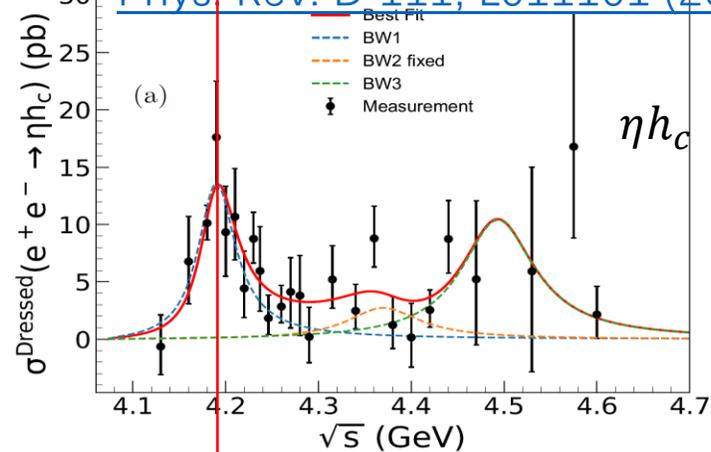
ηh_c

arXiv:2411.19642

(b)

$\sigma_{\text{Inclusive prompt } J/\psi}$

$\sigma_{\text{Total exclusive } J/\psi}$

$J/\psi X$

arXiv:2411.19642

(a)

$\sigma_{\text{Inclusive prompt } \psi(3686)}$

$\sigma_{\text{Total exclusive } \psi(3686)}$

$\psi' X$

Phys. Rev. D 106, 072001 (2022)

$\pi^+\pi^- J/\psi$

Phys. Rev. Lett. 131, 211902 (2023)

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

Phys. Rev. D 104, 052012 (2021)

$\pi^+\pi^- \psi'$

arXiv:2407.20009

$K^+K^- \psi'$

Phys. Rev. Lett. 133, 081901 (2024)

D^+D^-
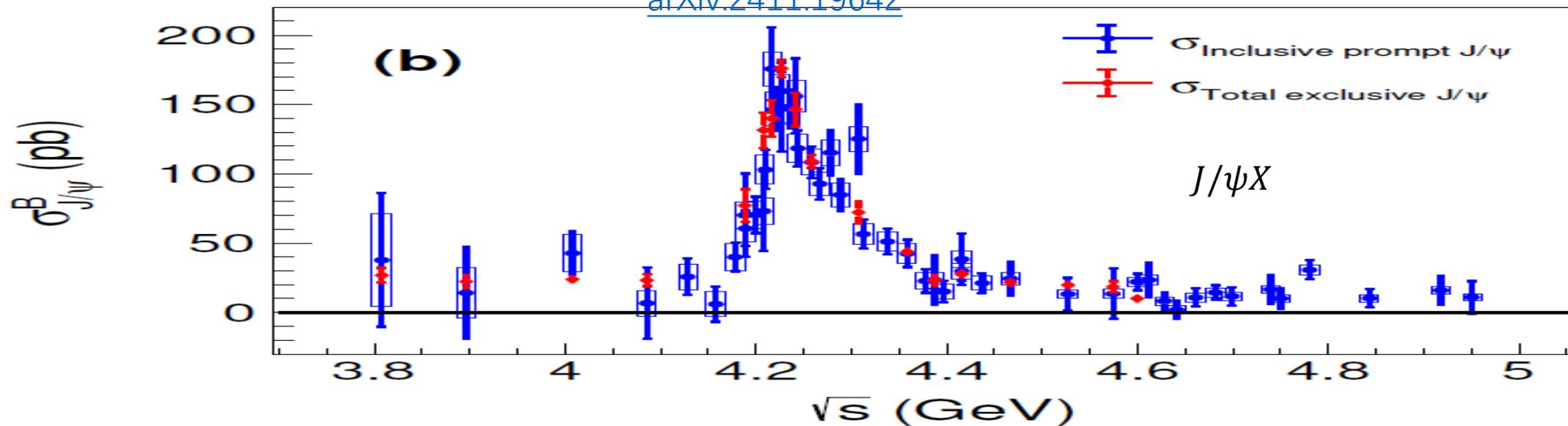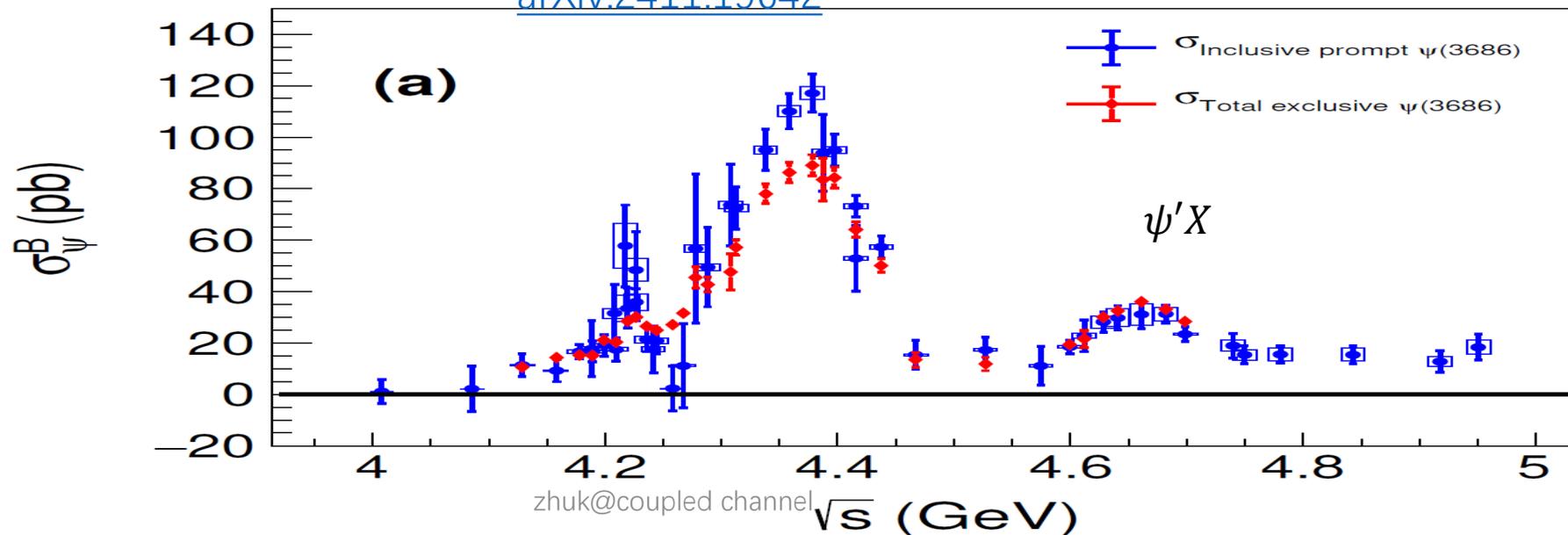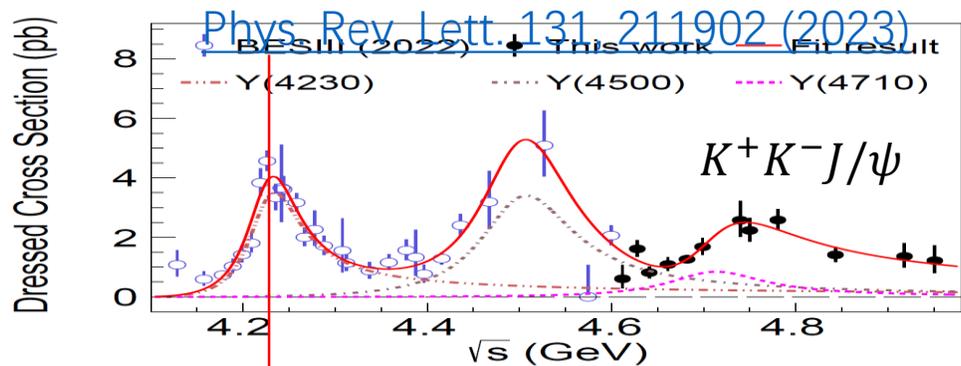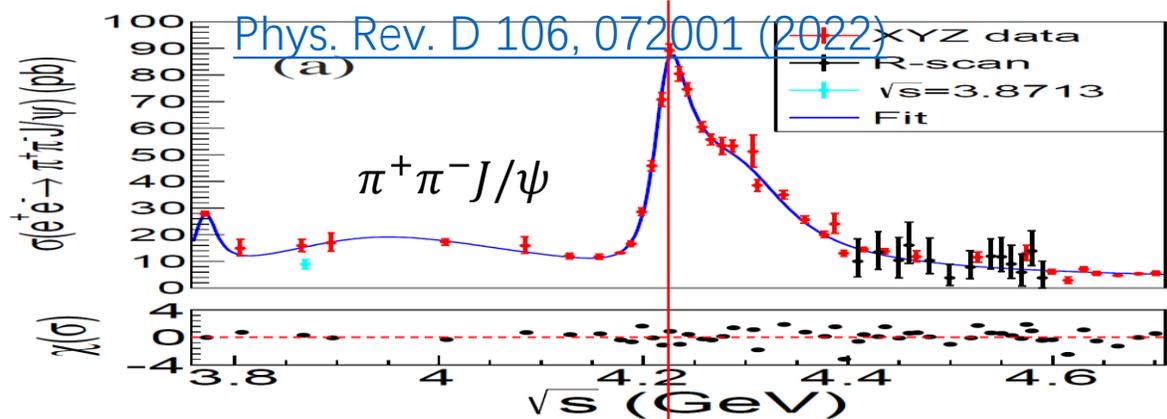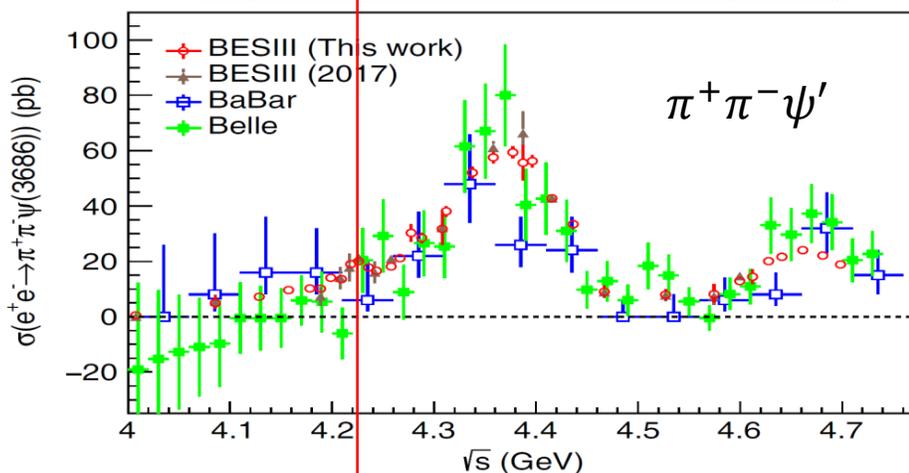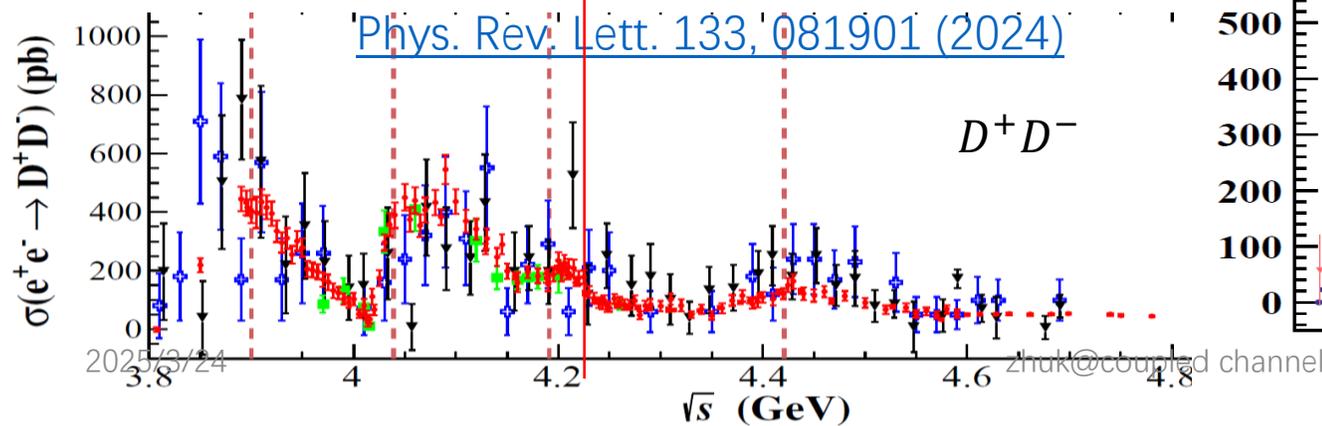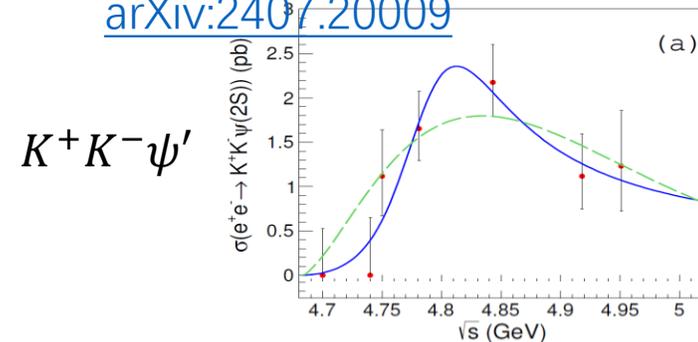
Phys. Rev. Lett. 133, 261902 (2024)

$D_s^+ D_s^-$

2025/3/24

Zhuk@coupled channel

26