



復旦大學
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The cross-section measurements of electron-positron annihilation above 4 GeV

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Outline

1. $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$

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

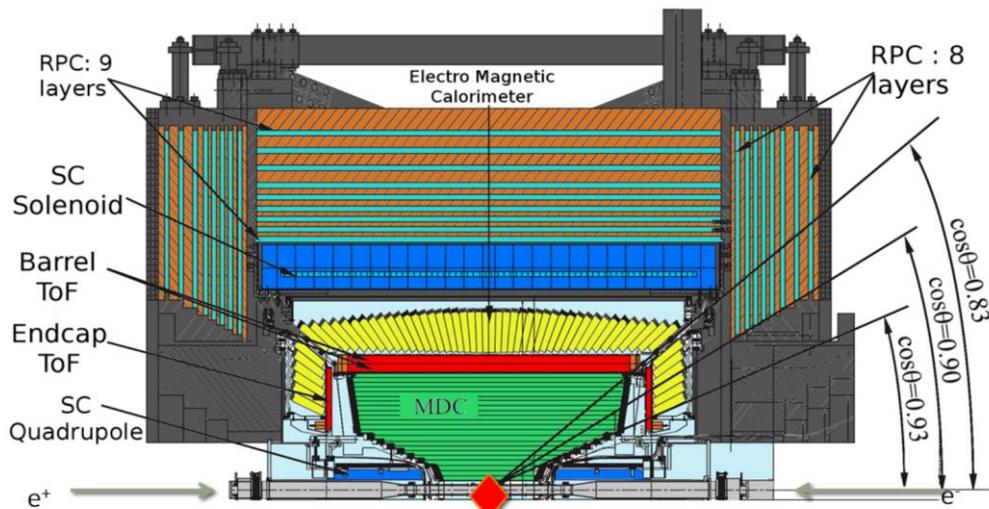
3. $e^+e^- \rightarrow \pi^+\pi^-J/\psi$

4. $e^+e^- \rightarrow D^{*+}D^{*-}$ and $D^{*+}D^- + c.c.$

Motivation

- ✓ Many Exotic Charmonium-like(XYZ) states have been discovered in the quarkonium spectrum.
- ✓ The XYZ states show properties inconsistent with expectations from established quark models
- ✓ Search for more decay modes will be helpful to understand their properties;
- ✓ BESIII experiment shows its advantages on Charmonium(-like) states studies.

北京谱仪 (BESIII)



■ 子系统

束流管、主漂移室、飞行时间计数器、电磁量能器、超导、缪子计数器

- 100亿 J/ψ 事例
- 27亿 $\psi(2S)$ 事例
- 3fb^{-1} $\psi(3770)$ 数据
- 25fb^{-1} 能量高于 $\psi(3770)$ 的数据

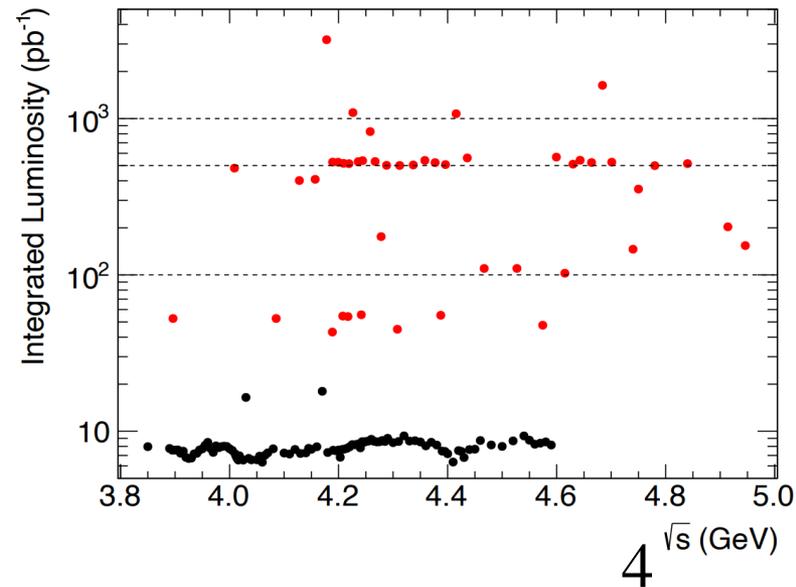
Data for XYZ study

XYZ ($> 50\text{fb}^{-1}$):

- $\sqrt{s} > 3.8\text{ GeV}$: 22 fb^{-1}
- $3.8 < \sqrt{s} \leq 4.6\text{ GeV}$: 16 fb^{-1}
- $4.6 < \sqrt{s} \leq 4.7\text{ GeV}$: 3.8 fb^{-1}
- $\sqrt{s} > 4.7\text{ GeV}$: 1.9 fb^{-1}

R scan:

- 104 energy points
- $7\sim 9\text{ pb}^{-1}$ each energy
- $3.8 < \sqrt{s} < 4.6\text{ GeV}$

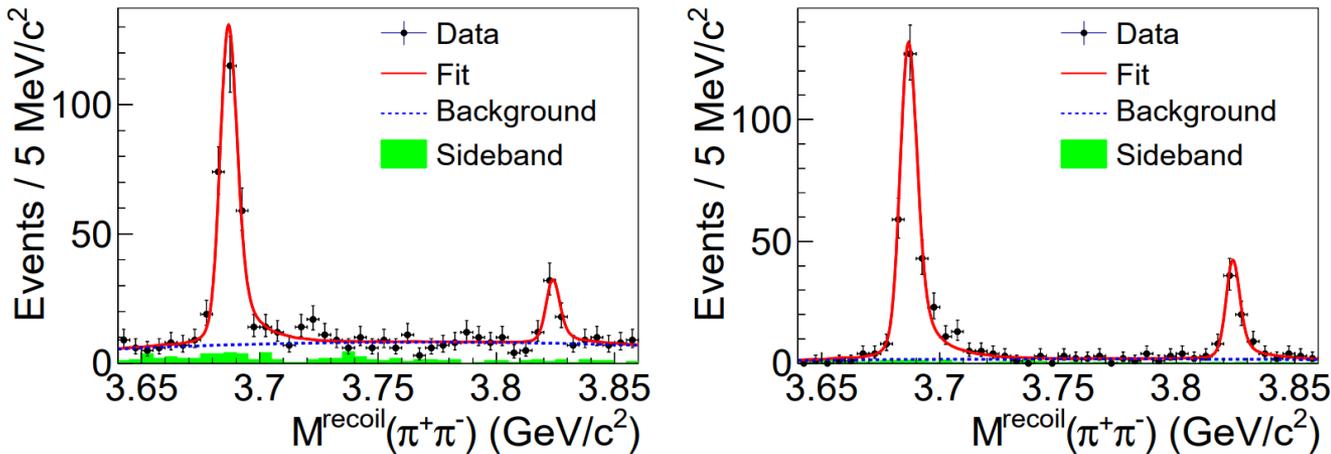


Cross section measurement of $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$

arXiv:2203.05815

- $\sqrt{s} = 4.23 \sim 4.70 \text{ GeV}$ $L_{int} = 11.3 \text{ fb}^{-1}$
- $\psi_2(3823) \rightarrow \gamma\chi_{c1}/\chi_{c2}, \chi_{c1}/\chi_{c2} \rightarrow \gamma J/\psi, J/\psi \rightarrow l^+l^- (l = e, \mu)$

Simultaneous fit to recoil mass of $\pi^+\pi^-$ from data



Mode1: missing one photon Mode2: full reconstruction

- According to the mass scale calibration of $\psi(2S)$ signal, the mass of $\psi_2(3823)$ is
 $M[\psi_2(3823)] = 3823.12 \pm 0.43 \pm 0.13 \text{ MeV}/c^2$.
- It is the most precise measurement of the $\psi_2(3823)$ mass.
- The width of $\psi_2(3823)$ is
 $\Gamma[\psi_2(3823)] < 2.9 \text{ MeV}$ at 90% C.L.,
- which is the most stringent constraint on its width

Cross section measurement of $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$

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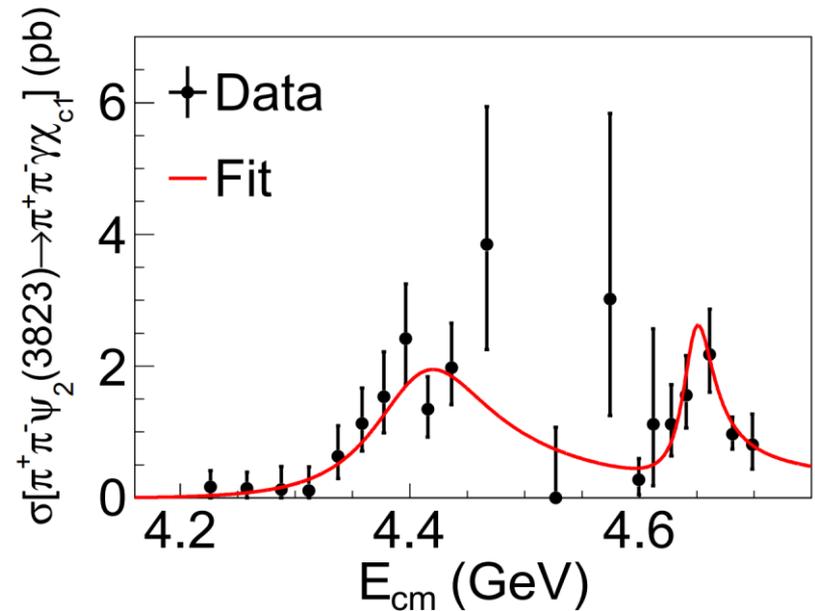
- Two resonance structures are observed in line-shape of $\sigma[e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823) \rightarrow \pi^+\pi^-\gamma\chi_{c1}]$:

$$M[R_1] = 4406.9 \pm 17.2 \pm 4.5 \text{ MeV}/c^2$$

$$\Gamma[R_1] = 128.1 \pm 37.2 \pm 2.3 \text{ MeV}$$

$$M[R_2] = 4647.9 \pm 8.6 \pm 0.8 \text{ MeV}/c^2$$

$$\Gamma[R_2] = 33.1 \pm 18.6 \pm 4.1 \text{ MeV}$$

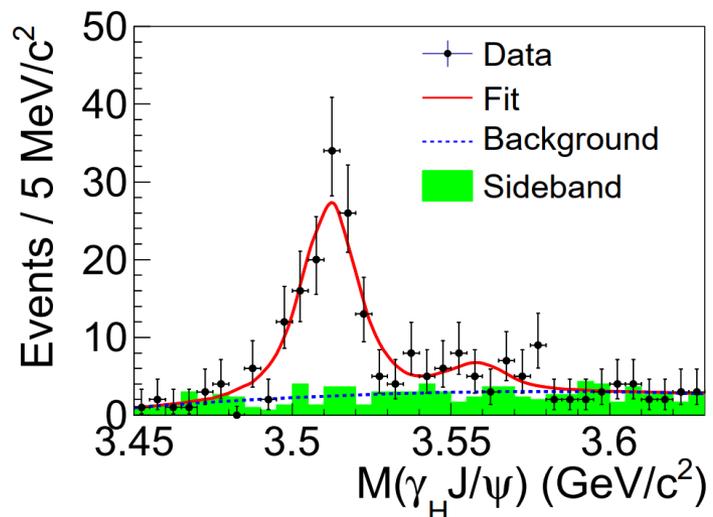


They are consistent with $Y(4360)$ and $Y(4660)$

It is the first observation of Y -states decaying to D wave charmonium state.

Cross section measurement of $e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$

arXiv:2203.05815



- The signal significance of $\psi_2(3823) \rightarrow \gamma\chi_{c2}$ is less than 3σ , the relative branching ratio is

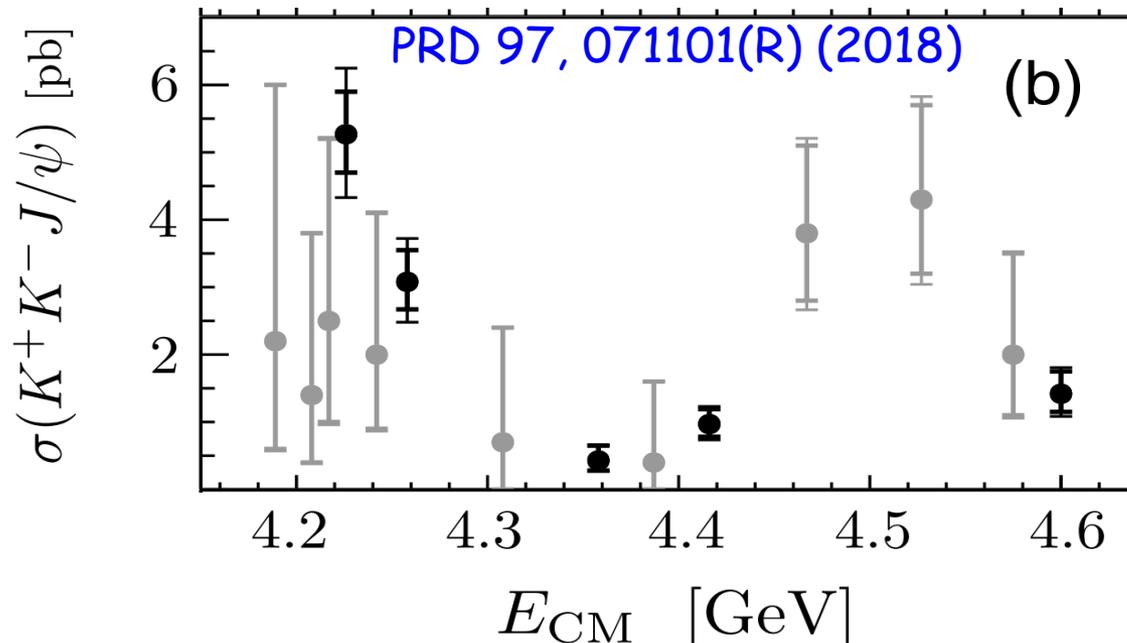
$$\frac{B[\psi_2(3823) \rightarrow \gamma\chi_{c2}]}{B[\psi_2(3823) \rightarrow \gamma\chi_{c1}]} < 0.51 \text{ at } 90\% \text{ C.L.},$$

which agrees with the recent measurement [Phys. Rev. D 103, L091102 (2021)]

Cross section measurement of $e^+e^- \rightarrow K^+K^-J/\psi$

arXiv:2204.07800

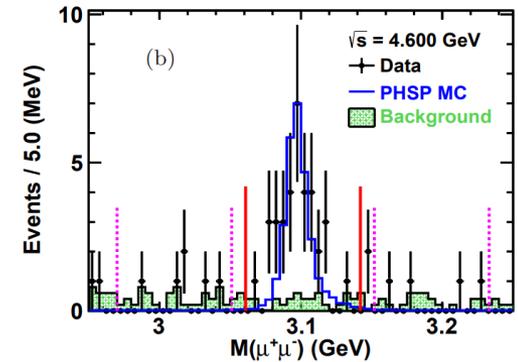
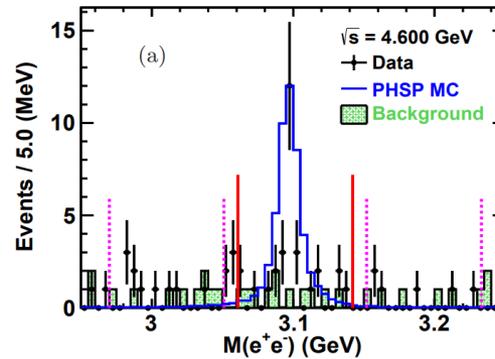
- Compared to the popular decay $e^+e^- \rightarrow \pi^+\pi^-J/\psi$, K^+K^-J/ψ is an important channel to clarify the puzzle of Y states.
- $e^+e^- \rightarrow K^+K^-J/\psi$ has been measured by CLEO, Belle, and BESIII experiments, no significant signals of Y(4230). [PRL 96, 162003 (2006); PRD 77, 011105 (2008); PRD 89, 072015 (2014); PRD 97, 071101(R) (2018)]



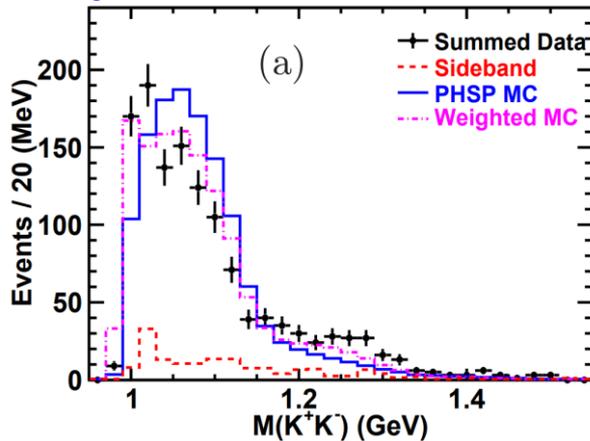
Cross section measurement of $e^+e^- \rightarrow K^+K^-J/\psi$

arXiv:2204.07800

- $\sqrt{s} = 4.127 \sim 4.600 \text{ GeV}$ $L_{int} = 15.6 \text{ fb}^{-1}$
- A partial reconstruction with missing a K, is applied to improve efficiency.
- No peaking background, then the signal yields are obtained from background subtraction and the uncertainties are estimated by TRolke method.



$f_0(980)$ and $f_2(1270)$



$$e^+e^- \rightarrow K^+K^-J/\psi, f_0(980)J/\psi, f_2(1270)J/\psi$$
$$f_0(980)/f_2(1270) \rightarrow K^+K^-,$$
$$J/\psi \rightarrow l^+l^- (l = e, \mu)$$

Cross section measurement of $e^+e^- \rightarrow K^+K^-J/\psi$

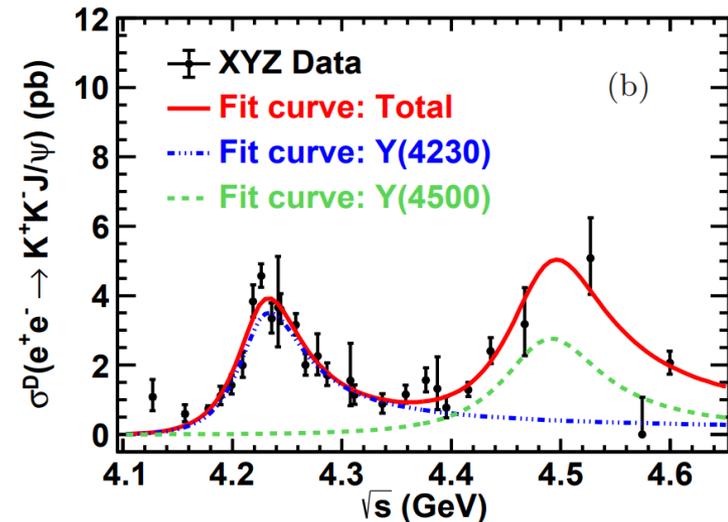
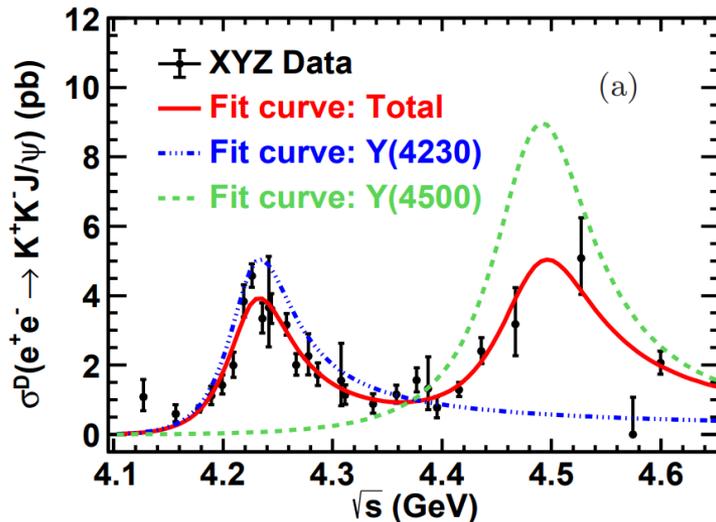
arXiv:2204.07800

- Two structures are observed in the Born cross sections of $e^+e^- \rightarrow K^+K^-J/\psi$ for the first time.

$$M[Y(4500)] = 4484.7 \pm 13.3 \pm 24.1 \text{ MeV}/c^2$$

$$\Gamma[Y(4500)] = 111.1 \pm 30.1 \pm 15.2 \text{ MeV}$$

- $Y(4500)$ is observed for the first time, with the significance of 8σ , and its mass is consistent with some theoretical predictions:
 - 5S-4D mixing scheme [PRD99, 114003 (2019)]
 - heavy-antiheavy hadronic molecules model [ProgrPhys41, 65(2021)]
 - Lattice QCD result for a $(c\bar{s}\bar{c}\bar{s})$ state [PRD73, 094510 (2006)]



Cross section measurement of $e^+e^- \rightarrow K^+K^-J/\psi$

arXiv:2204.07800

- Two structures are observed in the born cross sections of $e^+e^- \rightarrow K^+K^-J/\psi$ for the first time.

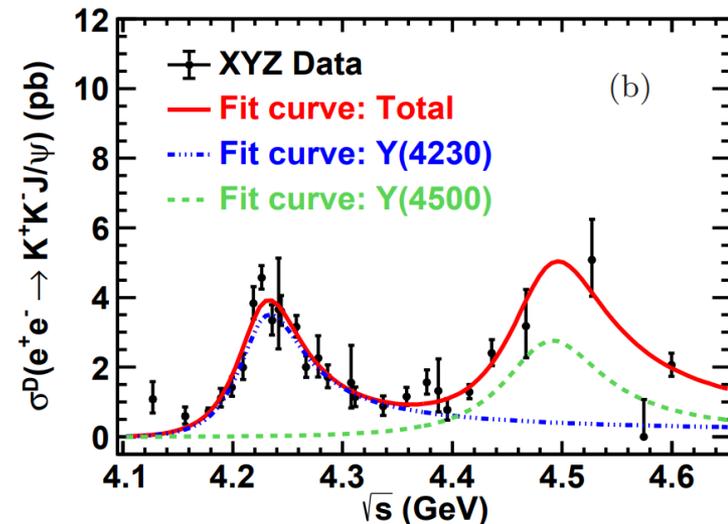
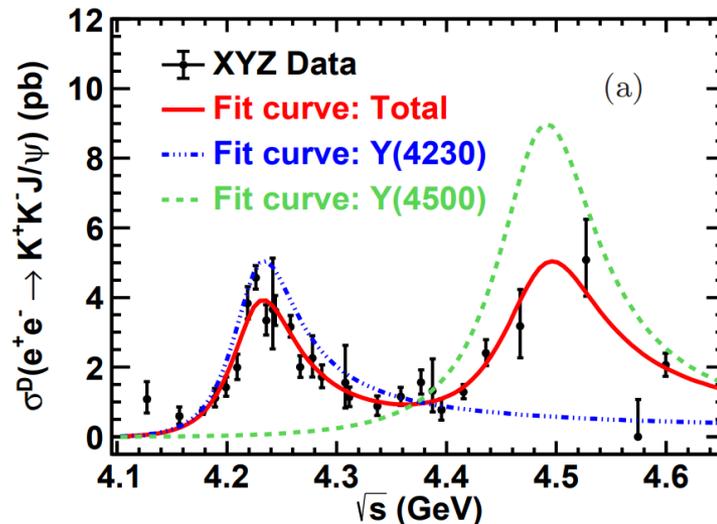
$$4222.7 \pm 2.6 \text{ MeV } (S = 1.7)$$

$$M[Y(4230)] = 4225.3 \pm 2.3 \pm 21.5 \text{ MeV}/c^2$$

$$\Gamma[Y(4230)] = 72.9 \pm 6.1 \pm 30.8 \text{ MeV}$$

$$49 \pm 8 \text{ MeV } (S = 3.5) \text{ PDG}$$

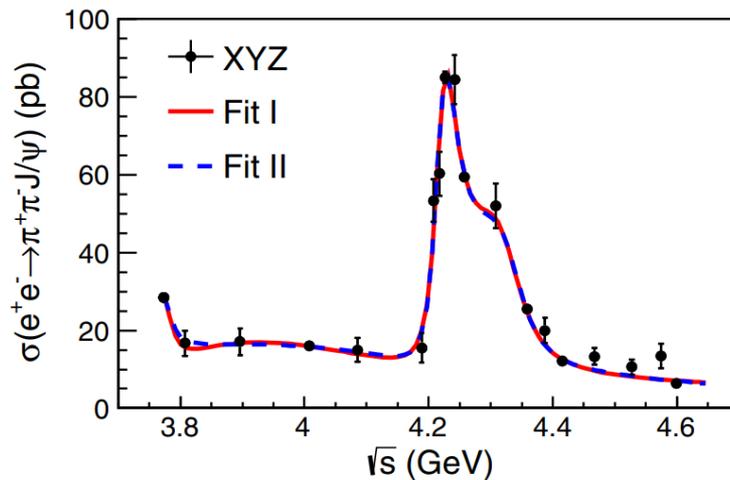
- $Y(4230)$ is observed in $e^+e^- \rightarrow K^+K^-J/\psi$ cross-sectional line shape for the first time, with the significance of 29σ .
- $0.02 < \frac{B[Y(4230) \rightarrow K^+K^-J/\psi]}{B[Y(4230) \rightarrow \pi^+\pi^-J/\psi]} < 0.26$ [reference: PRL 118, 092001 (2017)]



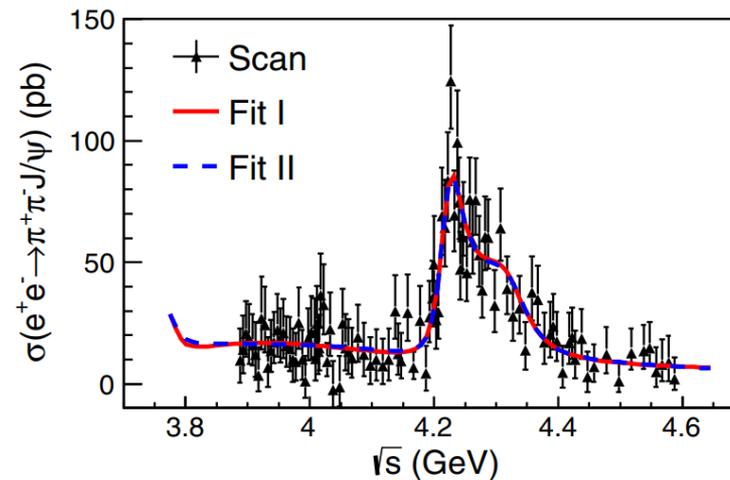
Cross section measurement of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$

arXiv:2206.08554

- 2017年, BESIII实验在 $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ 截面谱上发现Y(4260)质量更偏向于4.23 GeV
- Y(4230) (或Y(4220)) 是Y(4260)结构的主要成分。
- BESIII在 $e^+e^- \rightarrow \pi^0\pi^0J/\psi$ 、 $\pi^+\pi^-h_c$ 、 $\omega\chi_{c0}$ 、 $\mu^+\mu^-$ 、 $\eta J/\psi$ 、 $\gamma X(3872)$ 、 $\pi^+\pi^-\psi(2S)$ 和 $\pi^+D^0D^{*-}$ 中也发现了Y(4230)



9 fb^{-1} BESIII data



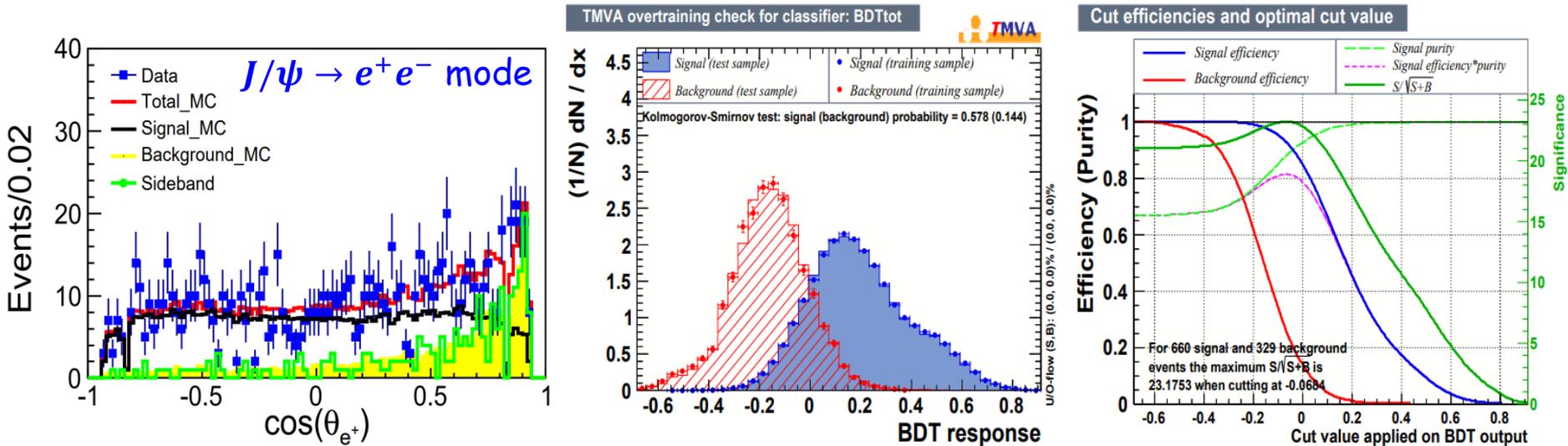
PRL 118, 092001 (2017)

Cross section measurement of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$

arXiv:2206.08554

- $\sqrt{s} = 3.773 \sim 4.700 \text{ GeV}$ $L_{int} = 23 \text{ fb}^{-1}$
- $J/\psi \rightarrow l^+l^- (l = e, \mu)$

Boost Decision Tree(BDT) method is used to the background suppression for $e^+e^- \rightarrow \pi^+\pi^-\mu^+\mu^-$ (with $\gamma^*\gamma^* \rightarrow \mu^+\mu^-$)



The response of the BDT is required to maximize the $S/\sqrt{S+B}$

Cross section measurement of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$

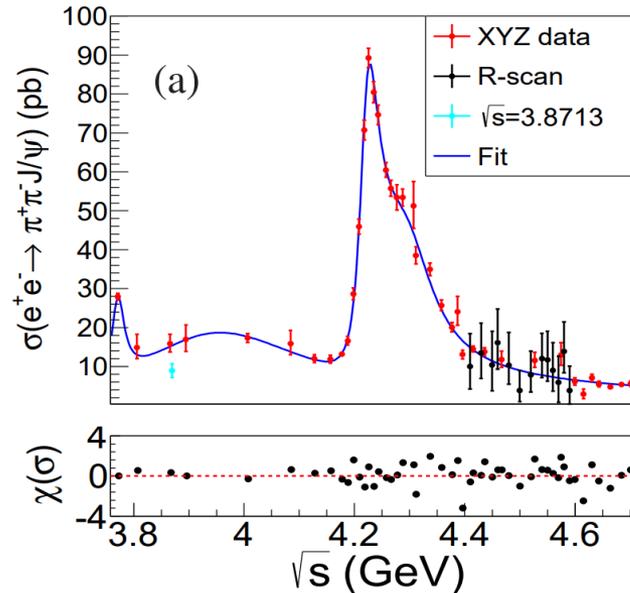
arXiv:2206.08554

- Fit to cross section of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$

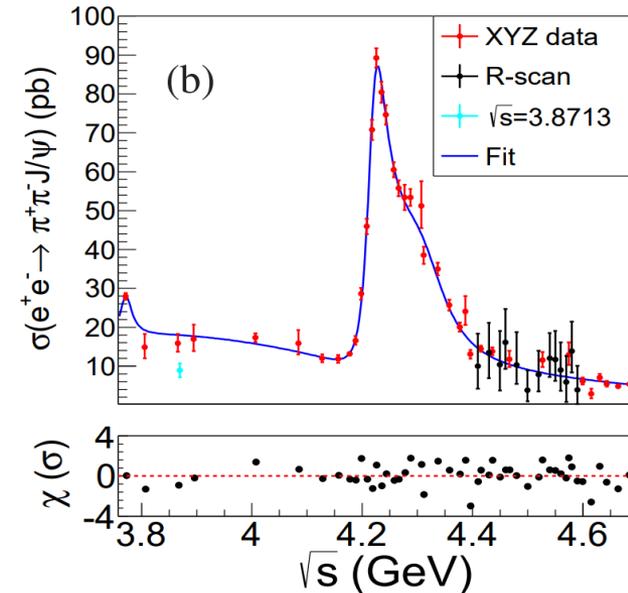
exp:exponential function

Model 1: $\psi(3770)_{Fix} + BW_0 + Y(4220) + Y(4320)$

Model 2: $\psi(3770)_{Fix} + BW_0 * exp + Y(4220) + Y(4320)$



$\chi^2/ndf=54.0/40$



$\chi^2/ndf=57.3/41$

- This measurement improves upon the precision about 60% than before (@4.226 and 4.258 GeV).
- The significances of $Y(4220)$ and $Y(4320)$ are larger than 10σ
- Parameters of the $Y(4220)$ state are stable.

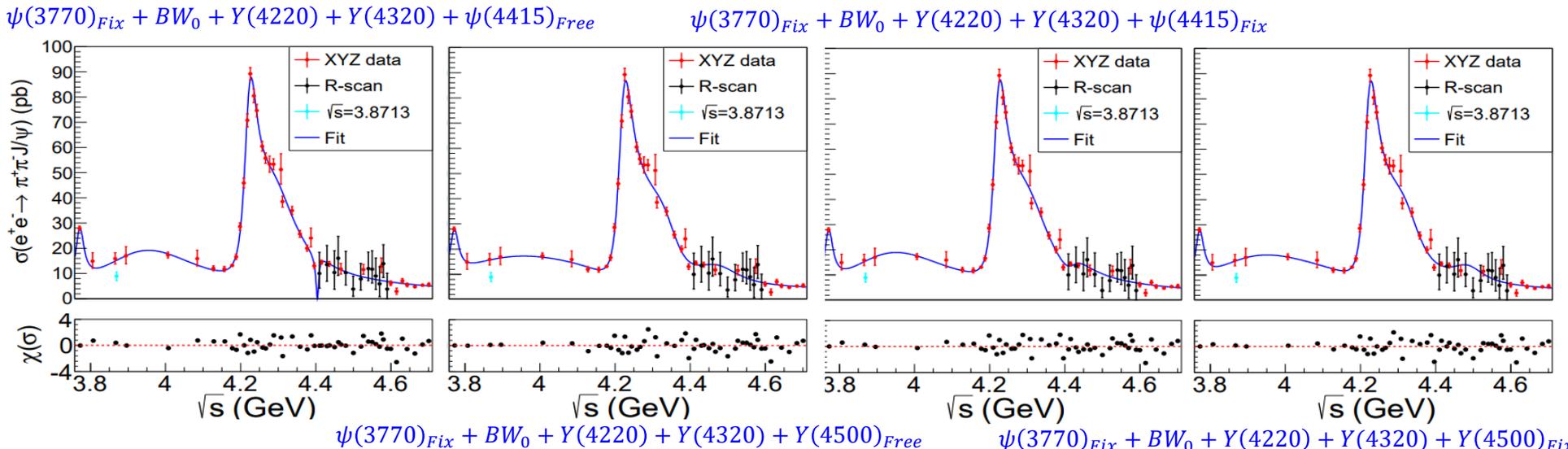
$$M[Y(4220)] = 4221.4 \pm 1.5 \pm 2.0 \text{ MeV}/c^2$$

$$\Gamma[Y(4220)] = 41.8 \pm 2.9 \pm 2.7 \text{ MeV}$$

Cross section measurement of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$

arXiv:2206.08554

- Fit to cross section of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$



Model 1(Model 2):

χ^2/ndf	40.1/36 (44.8/37)	47.6/36 (48.7/37)	45.4/38 (48.7/39)	48.1/38 (51.3/39)
Significance	4.0 σ (3.6 σ)	2.1 σ (2.7 σ)	3.3 σ (3.3 σ)	2.6 σ (3.1 σ)
	✘	✘	✘	✘

- Parameters of the $Y(4320)$ state depend on the presence of an additional structure close to 4.5 GeV (possibly $\psi(4415)$).

$$M[Y(4320)] = 4298 \pm 12 \pm 26 \text{ MeV}/c^2$$

$$\Gamma[Y(4320)] = 127 \pm 17 \pm 10 \text{ MeV}$$

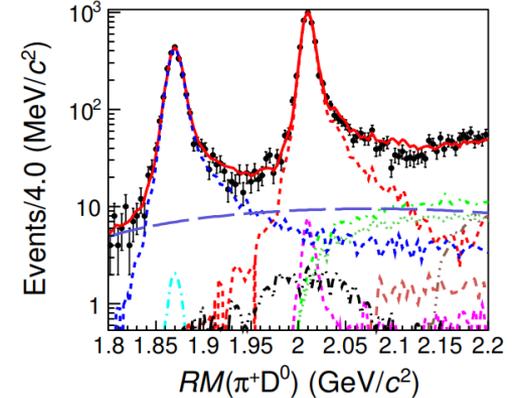
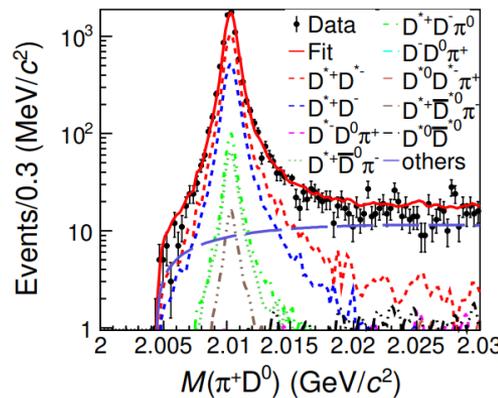
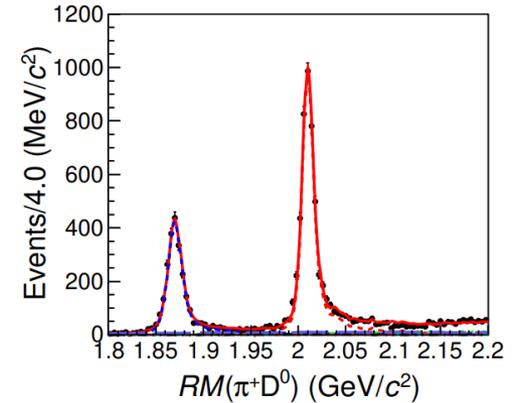
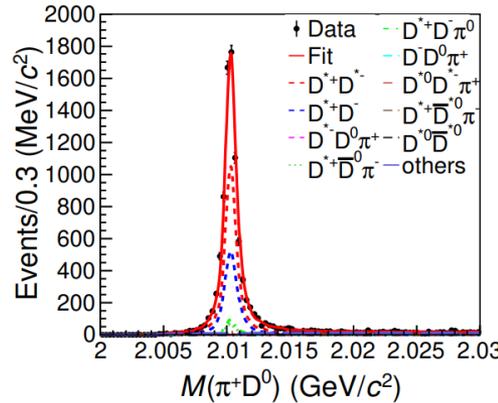
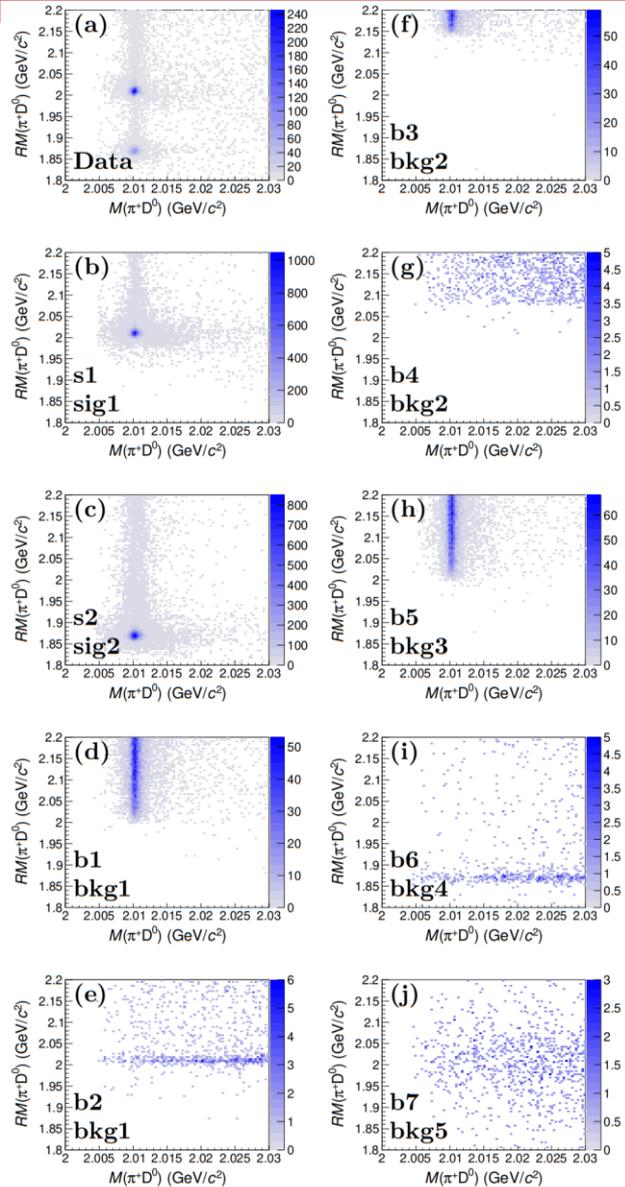
Cross section measurement of $e^+e^- \rightarrow D^{*+}D^{*-}$

and $D^{*+}D^- + c.c.$

JHEP05(2022)155

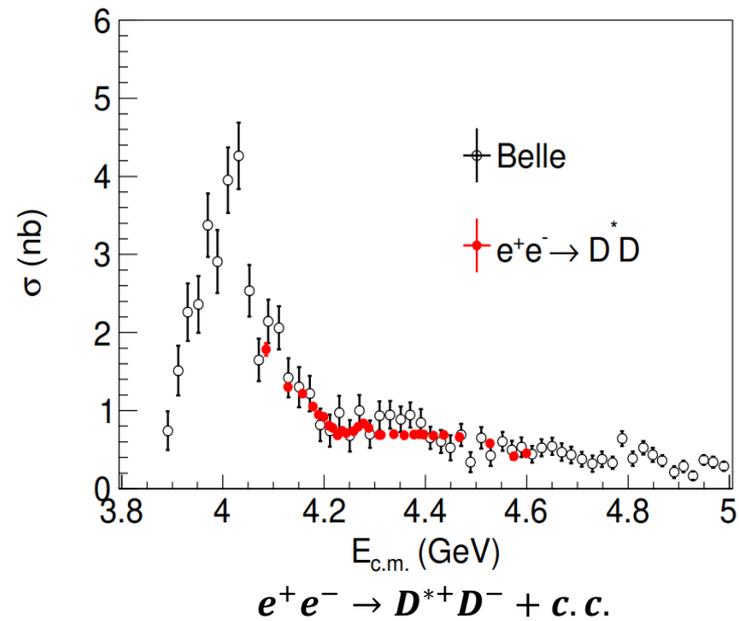
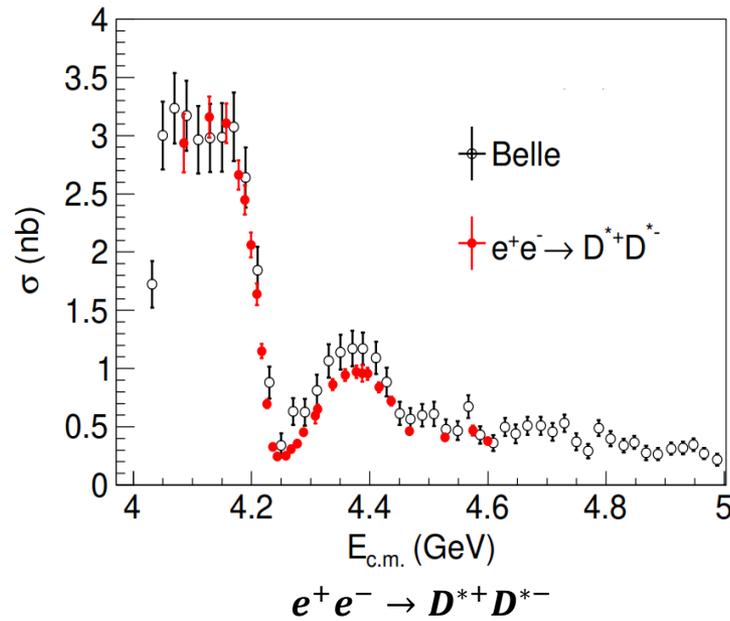
- $\sqrt{s} = 4.085 \sim 4.600 \text{ GeV}$ $L_{int} = 15.7 \text{ fb}^{-1}$
- Partial reconstruction: $D^{*+} \rightarrow \pi^+ D^0, D^0 \rightarrow K^- \pi^+$

2D Fit to invariant mass and recoil mass distributions of $\pi^+ D^0$ from data



Cross section measurement of $e^+e^- \rightarrow D^{*+}D^{*-}$ and $D^{*+}D^- + c.c.$

JHEP05(2022)155



- The cross sections are consistent with and more precise than those of the Belle, BaBar, and CLEO experiments.
- The structures in the cross sections measured by the previous experiments are confirmed.
- More measurements on other two-body open-charm modes such as $D\bar{D}$, $D_S^+D_S^-$, $D_S^{*+}D_S^- + c.c.$, $D_S^{*+}D_S^{*-}$, and multi-body modes such as $\pi D\bar{D}$, $\pi D^*\bar{D} + c.c.$, $\pi\pi D\bar{D}$ are necessary to finally reveal the nature of vector charmonium(-like) states.

Summary

The observed structures coupled to decay channels

Ecm/GeV	Structures	$\pi^+\pi^-\psi_2(3823)$	K^+K^-J/ψ	$\pi^+\pi^-J/\psi$	$D^{*+}D^{*-}$	$D^{*+}D^-$
4.23	Y(4230)		✓	✓		
4.32	Y(4320)			✓		
4.4	$\psi(4415)^+$ Y(4360)?	✓			✓	
4.5	Y(4500)		✓			
4.66	Y(4660)	✓				
<4.2	$\psi(4040)/$ $\psi(4160)$				✓	✓

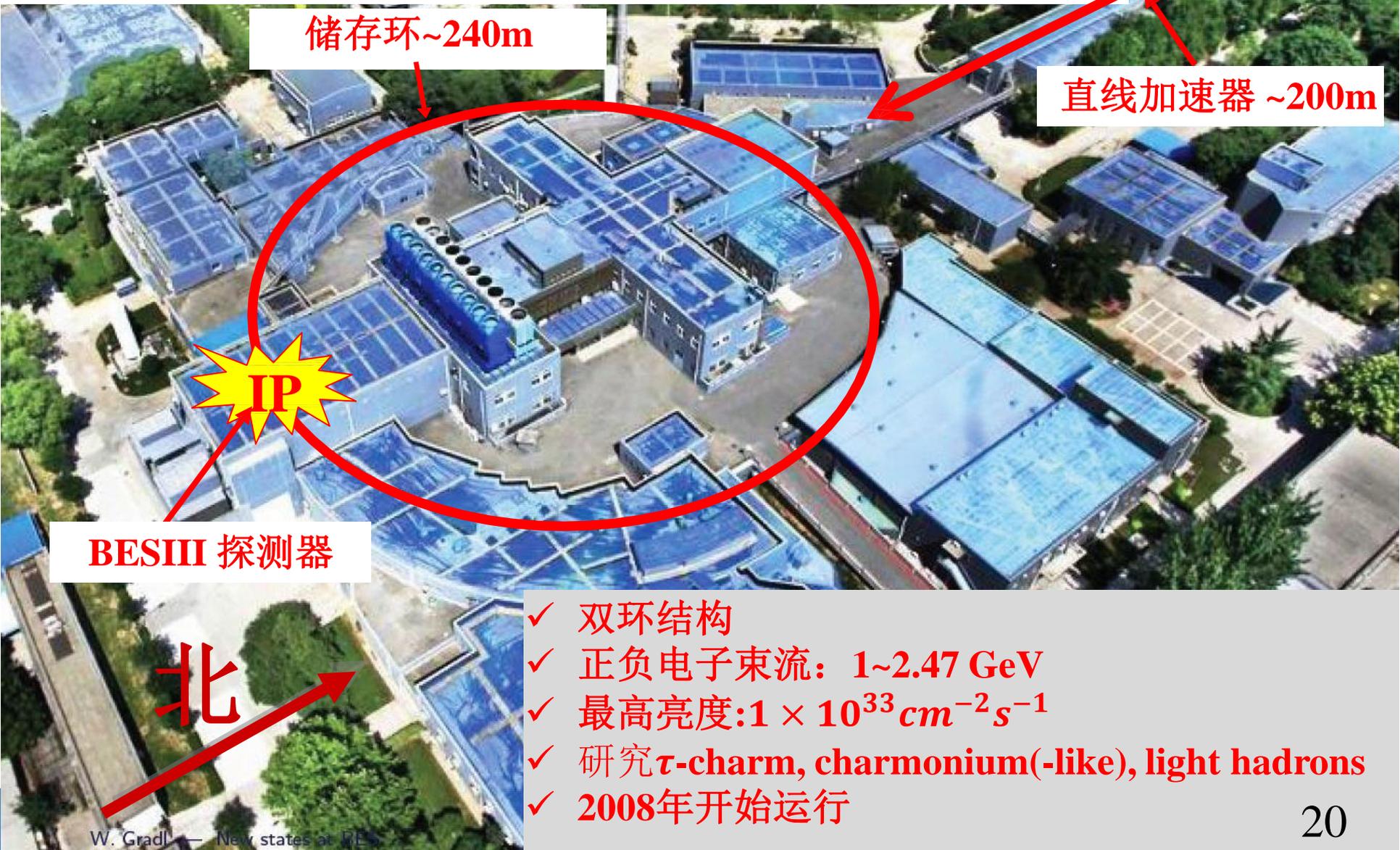
- An abundance of vector charmonium and charmonium-like states are observed in e^+e^- decaying into hidden/open charm final states.
- More measurements or researches are necessary to finally reveal the nature of vector charmonium(-like) states

谢谢！

Back up

北京正负电子对撞机

Beijing Electron Positron Collider II (BEPC II)



储存环~240m

直线加速器 ~200m

IP

BESIII 探测器

北

- ✓ 双环结构
- ✓ 正负电子束流: 1~2.47 GeV
- ✓ 最高亮度: $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- ✓ 研究 τ -charm, charmonium(-like), light hadrons
- ✓ 2008年开始运行