Properties of $\psi_2(3823)$

Zhiqing Liu

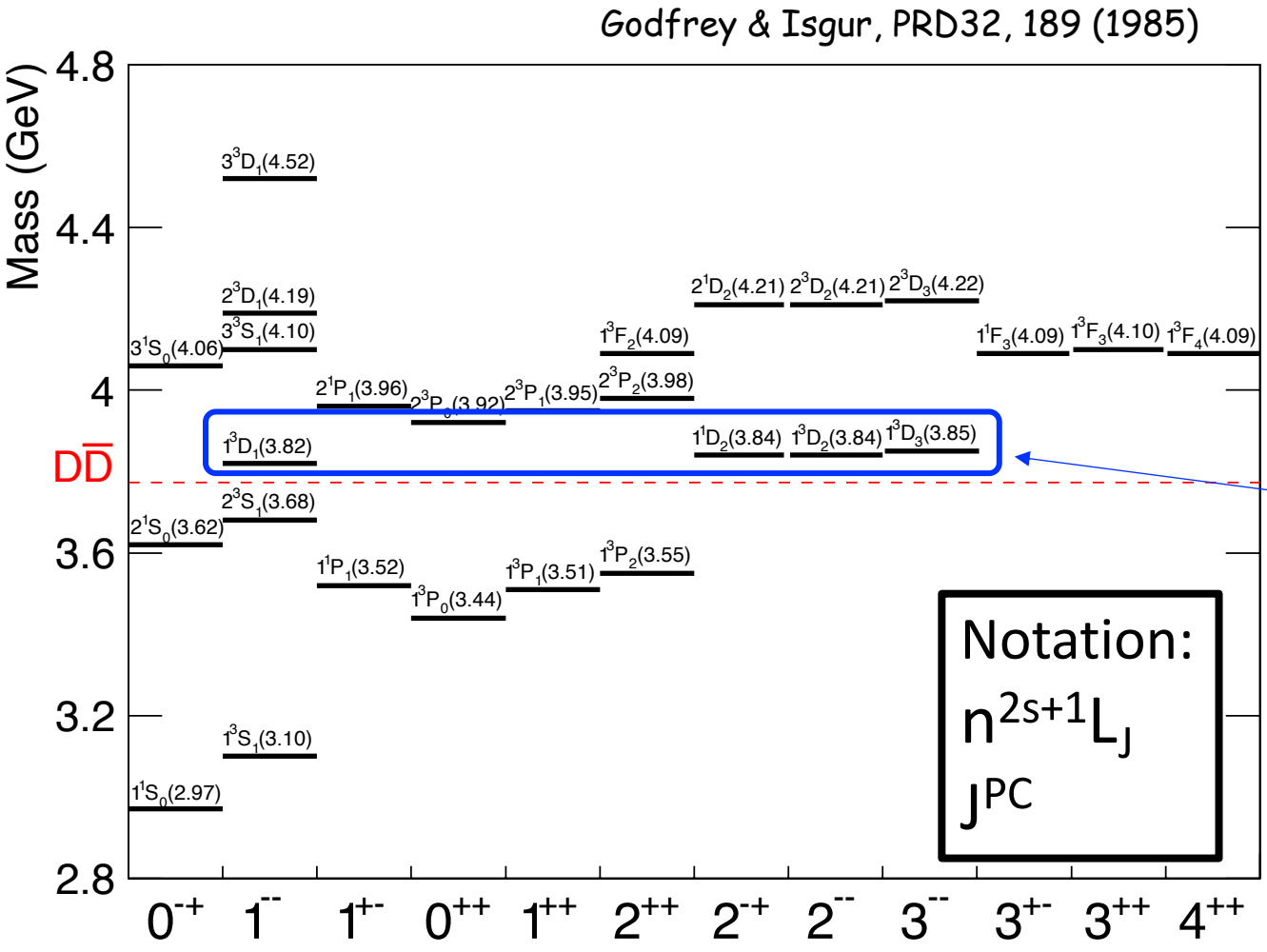
Shandong University

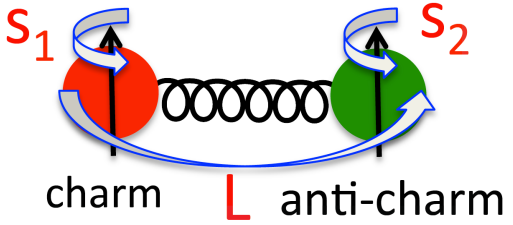
Sep. 30th, GSI/Darmstadt, Germany

Outline

- Introduction
- Discovery of $\psi_2(3823)$
- Properties of $\psi_2(3823)$
- Outlook & Summary

Potential model





- S=1, L=2 (D-wave)

→ J=1, 2, 3 (triplet) [ψ_1, ψ_2, ψ_3]

- S=0, L=2

→ J=2 (singlet) [η_{c2}] (not observed yet)

$\psi(1^3D_2)$

$\psi_2(3823)$!

Predictions of $\psi(1^3D_2)$ state

➢ Mass

$$H = H_0 + V_{q\bar{q}}(\vec{p}, \vec{r}),$$

- 3.84 GeV (Godfrey & Isgur, PRD32, 189)
- 3.80 – 3.83 GeV (NR PRD72, 054026; Ebert PRD67, 014027; Eichten & Quigg PRD69, 094019; Blank PRD84, 096014; …)
- Above (near) the open-charm threshold

➢ Width & Decay

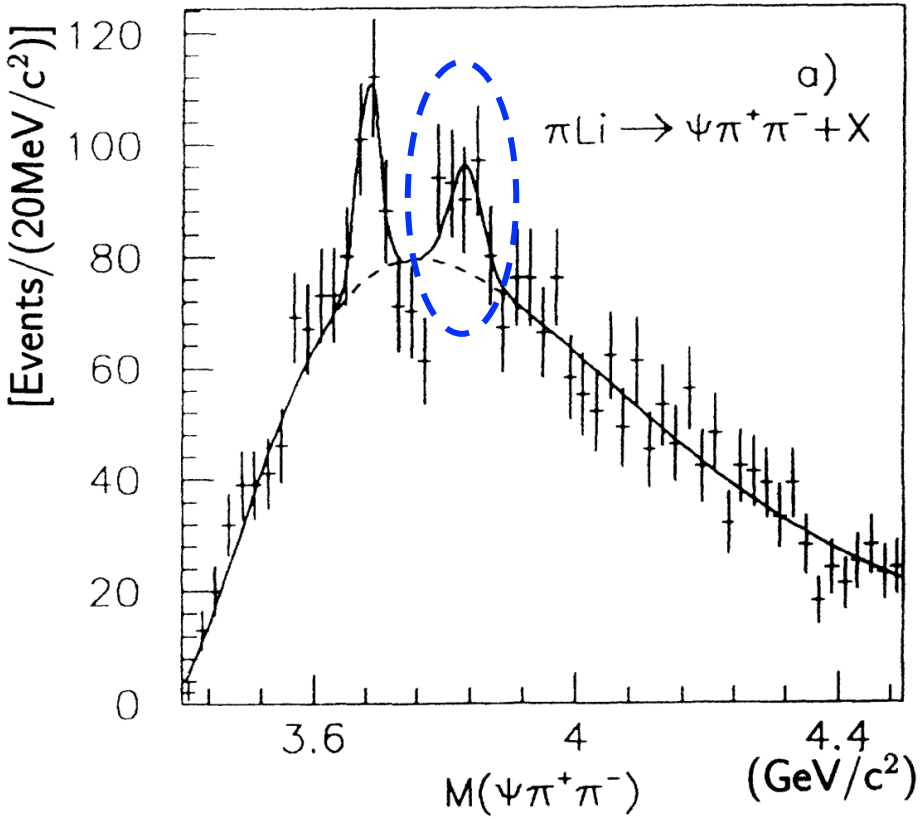
- Below the DD* threshold (~3872 MeV)
- $J^{PC}=2^{--}$, DD decay is forbidden → no open-charm decay width

- Dominant E1 radiative transition width $\Gamma(1^3D_2 \to \gamma\, 1^3P_1)$
- 250/268/265/300 keV (K. T. Chao PRD55, 4001; GI PRD32, 189; Wang arXiv:2208.09667; NR PRD72, 054026…)

- $\Gamma(1^3D_2 \to \gamma\, 1^3P_2)$~60 keV; $\Gamma(1^3D_2 \to \pi^+\pi^- J/\psi)$~46 keV; $\Gamma(1^3D_2 \to ggg)$~12 keV
- Γ(Total)~400 keV → Very narrow & $Br[1^3D_2 \to \gamma\chi_{c1}]$~50%

Experimental search

Phys. Rev. D 50, 4258 (1994)

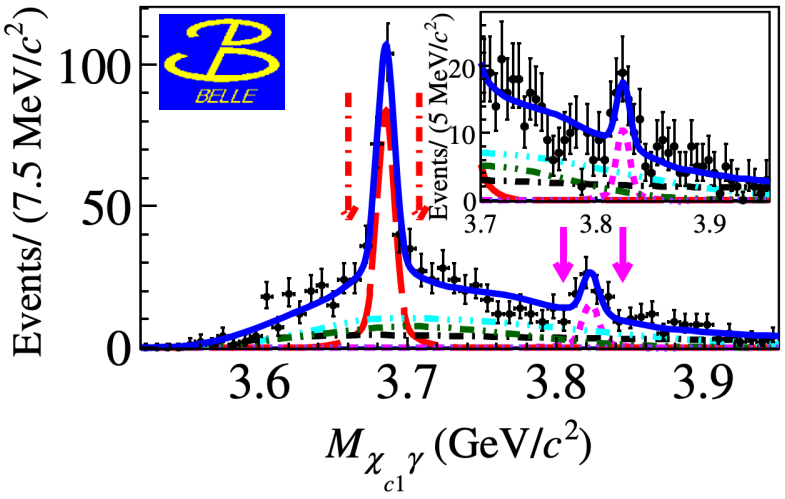


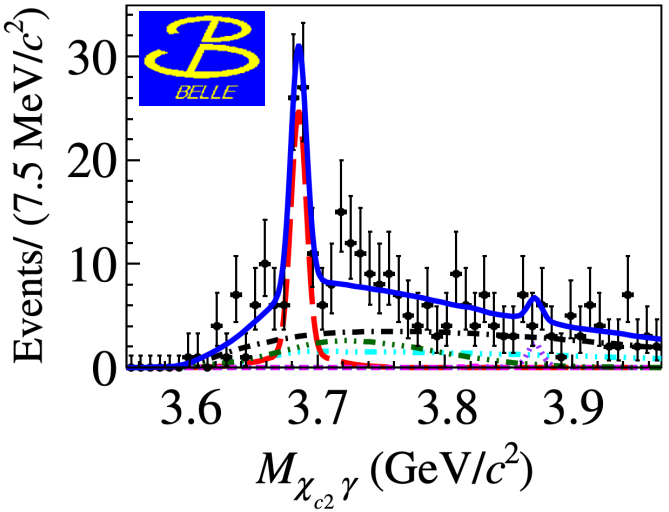
The E705 Collaboration

- 300 GeV/c π beam hit a Lithium target
- Clear $\psi(2S) \rightarrow \pi+\pi-J/\psi$ events (77 signal events)
- Evidence (2.8σ) of structure around (3836 ± 13) MeV (58 events)→ claimed as the 1^3D_2 state

More evidence…

PRL 111, 032001 (2013)





Belle Collaboration

- 772 M BB meson pairs
- $B^{\pm} \rightarrow K^{\pm} X$ with $X \rightarrow \gamma\chi_{c1,c2}$ final state
- Evidence (3.8σ in $B^{\pm}$; 4.0σ including B^0) of X(3823) resonance
- Mass agree with 1^3D_2 predictions, but lower than E705

$$M_{X(3823)} = M^{\text{meas}}_{X(3823)} - M^{\text{meas}}_{\psi'} + M^{\text{PDG}}_{\psi'} = 3823.1 \pm 1.8 \pm 0.7 \text{ MeV}.$$

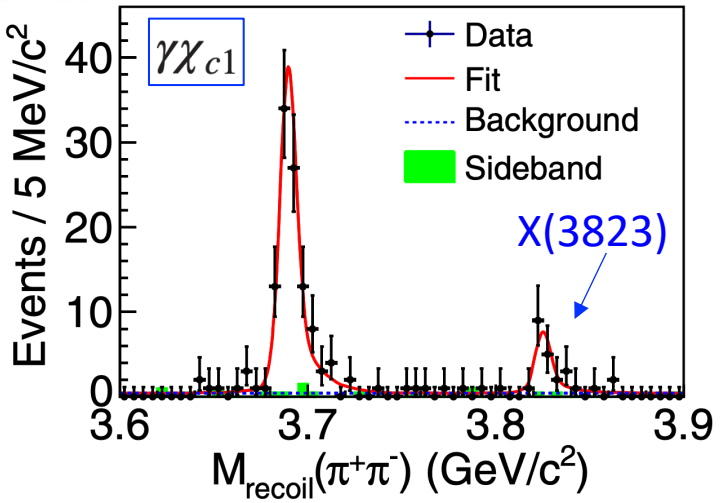
- Decay width to 1^3P_1 is large

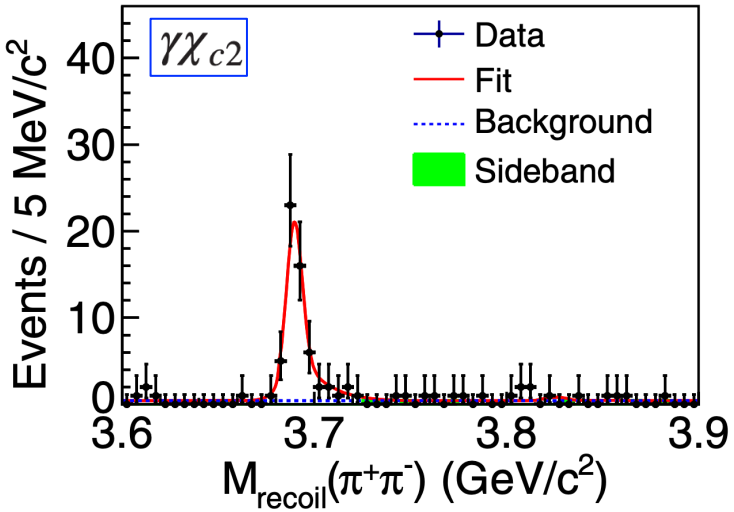
@ 90% C.L.

$$R_B = (\mathcal{B}[X(3823) \rightarrow \chi_{c2}\gamma] / \mathcal{B}[X(3823) \rightarrow \chi_{c1}\gamma]) < 0.41$$

Observation

BESIII 4.6 fb^{-1} , PRL 115, 011803 (2015)





An observation can only be considered as discovery if its significance is over 5σ !

Simon Eidelman
(1948 – 2021)

$\psi_2(3823)$

was $\psi(3823)$, $X(3823)$

- BESIII observed $\psi(1^3D_2)$ with 6.2σ significance !
- 30 years of journey after its birth in theory !

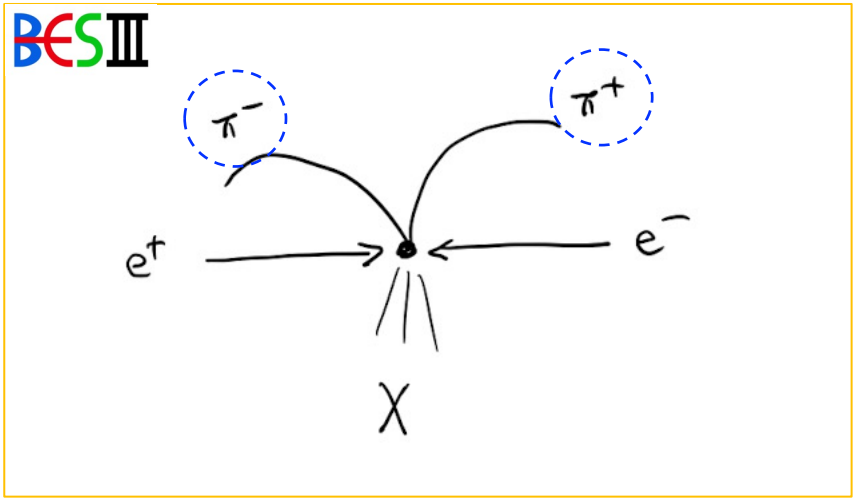
- Study $e^+e^- \to \pi^+\pi^- X$ with $X \to \gamma\chi_{c1,c2}$ using 4.6 fb^{-1} data
- Significant signal (6.2σ) is observed in $X \to \gamma\chi_{c1}$ channel, while lack of signal in $\gamma\chi_{c2}$
- Mass measured to be ($3821.7 \pm 1.3 \pm 0.7$) MeV/c^2, agree with Belle and theoretical predictions
- Decay width agrees with prediction @ 90% C.L.

$$R_B = (\mathcal{B}[X(3823) \to \chi_{c2}\gamma]/\mathcal{B}[X(3823) \to \chi_{c1}\gamma]) < 0.42$$

$\psi_2(3823)$ properties
– A new era of precise studies

Mass & Width

11.3 fb^{-1} , Phys. Rev. Lett. 129, 102003 (2022)

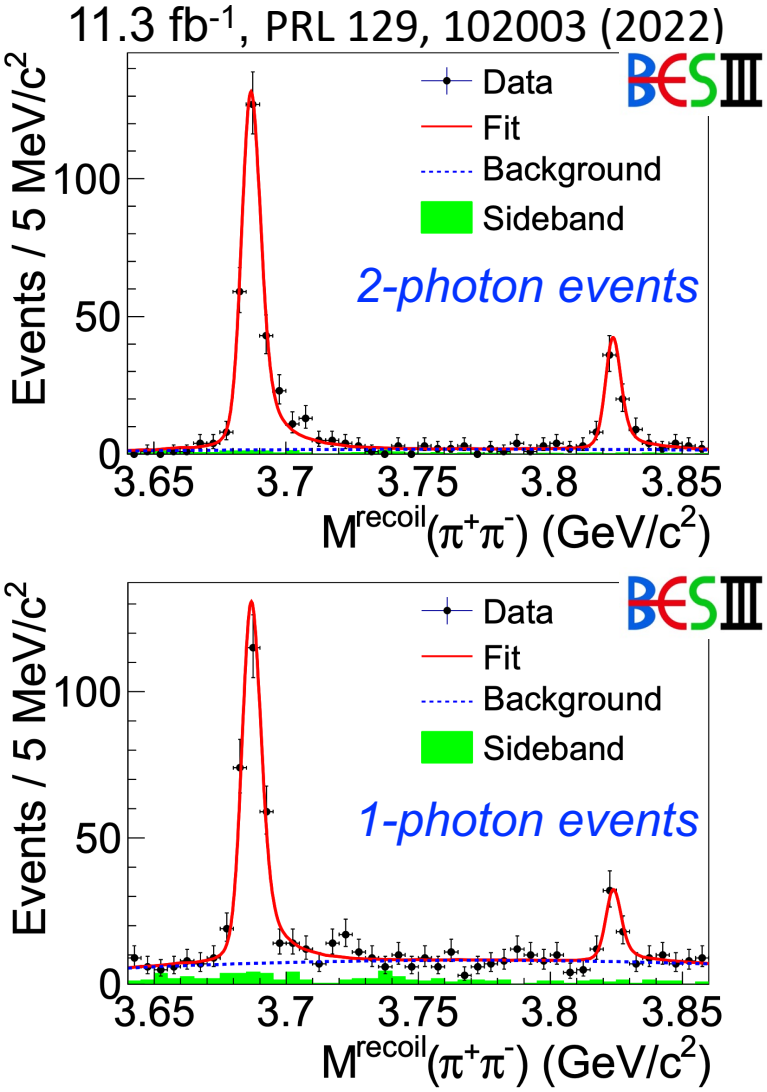


$\psi_2(3823) \rightarrow \gamma_1 \chi_{c1}$ ~ 50%

$\gamma_2 J/\psi$ ~ 34%

- One of the two radiative photons has a chance (45%) to be lost in the detector
- Develop a Partial reconstruction method at BESIII (4-momentum conservation)
- Recoil system of $\pi^+\pi^-$ can keep resolution as good as full reconstruction case!

Mass and Width



- BESIII observed 120 signal events

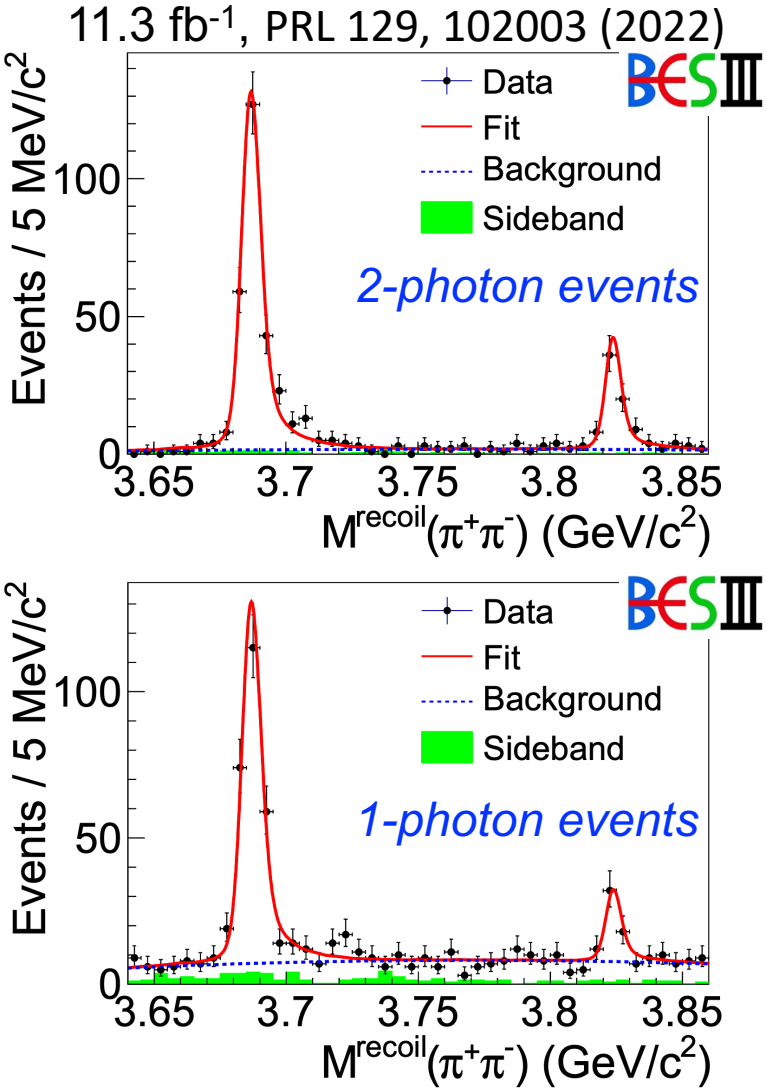
  $m[\psi_2(3823)]=M[\psi_2(3823)]-M[\psi(2S)]+m[\psi(2S)]^{PDG}$

  $=(3823.12\pm0.43\pm0.13)$ MeV/c^2

  $\Gamma[\psi_2(3823)] < 2.9$ MeV @ 90% C.L.

- Most precise measurement to date !

Mass and Width



- BESIII observed 120 signal events

  $m[\psi_2(3823)]=M[\psi_2(3823)]-M[\psi(2S)]+m[\psi(2S)]^{PDG}$

  $=(3823.12\pm0.43\pm0.13)$ MeV/c^2

  $\Gamma[\psi_2(3823)] < 2.9$ MeV @ 90% C.L.

- Most precise measurement to date !

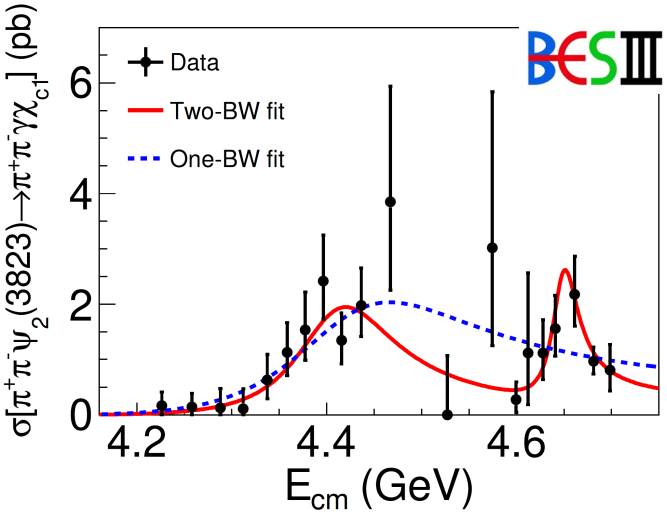
LHCb (137 signal events)

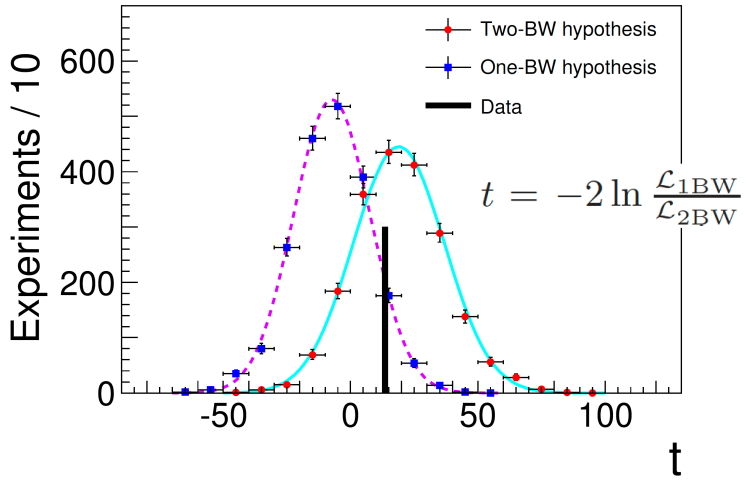
$m=(3824.08\pm0.53\pm0.14)$ MeV/c^2
$\Gamma < 5.2$ MeV @ 90% C.L.

JHEP 08(2020)123

Production via charmonium-like state

11.3 fb^{-1}, PRL 129, 102003 (2022)





- BESIII measure the E_{cm} dependent e+e- $\to\pi^+\pi^-\psi_2(3823)$ cross section
- Resonance structure with >5σ significance
- One single BW resonance

  M=4417.5±26.2±3.5 MeV
  Γ=245±48±13
- Two coherent Y(4360)/Y(4660)

Parameters	Solution I	Solution II
$M[R_1]$	$4406.9 \pm 17.2 \pm 4.5$	
$\Gamma_{\rm tot}[R_1]$	$128.1 \pm 37.2 \pm 2.3$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_1}\mathcal{B}_2$	$0.36 \pm 0.10 \pm 0.03$	$0.30 \pm 0.09 \pm 0.03$
$M[R_2]$	$4647.9 \pm 8.6 \pm 0.8$	
$\Gamma_{\rm tot}[R_2]$	$33.1 \pm 18.6 \pm 4.1$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_2}\mathcal{B}_2$	$0.24 \pm 0.07 \pm 0.02$	$0.06 \pm 0.03 \pm 0.01$
ϕ	$267.1 \pm 16.2 \pm 3.2$	$-324.8 \pm 43.0 \pm 5.7$

$$\frac{\Gamma[\psi(4660)\to\pi^+\pi^-\psi_2(3823)]}{\Gamma[\psi(4660)\to\pi^+\pi^-\psi(2S)]} \sim 20\%$$

$f_0(980)\psi(2S)$ molecule
Y(4260) radial excitation
Baryonium…

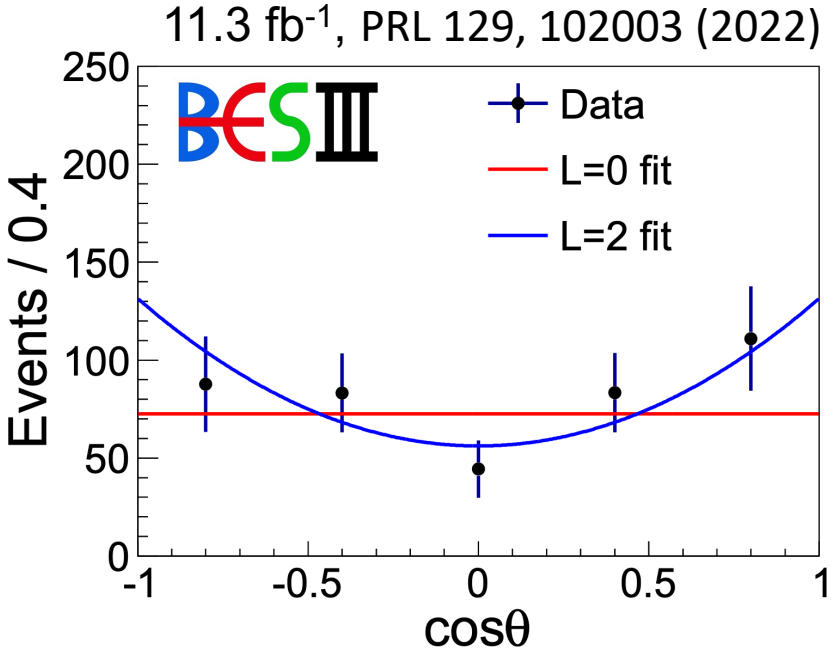
Spin-Parity

$\psi_2(3823)$

was $\psi(3823)$, $X(3823)$

$I^G(J^{PC}) = 0^-(2^{--})$

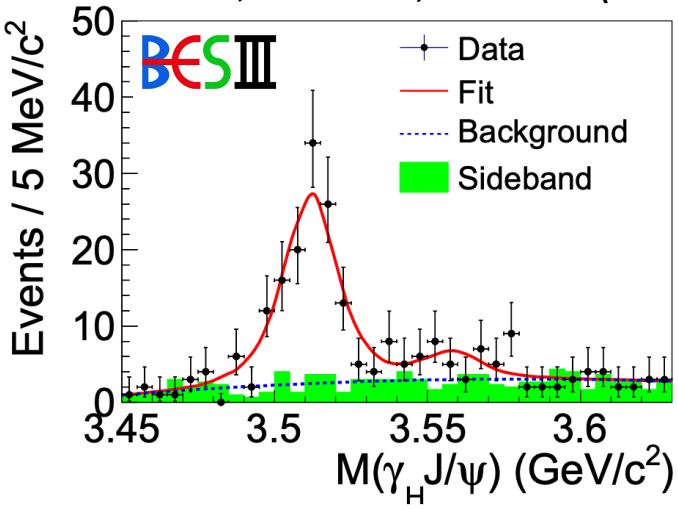
I, J, P need confirmation.



- By assuming $f_0(500)\psi_2(3823)$, BESIII attempt to measure J^P
- Study the scattering angle of $\psi_2(3823)$
- D-wave (2^{--}) → L=2, $(1+\cos^2\theta)$ χ^2/ndf=0.8 (favor)
- S-wave (1^{--}) → L=0, flat χ^2/ndf=1.7 (can not rule out)
- More statistics needed

Decay

11.3 fb^{-1}, PRL 129, 102003 (2022)



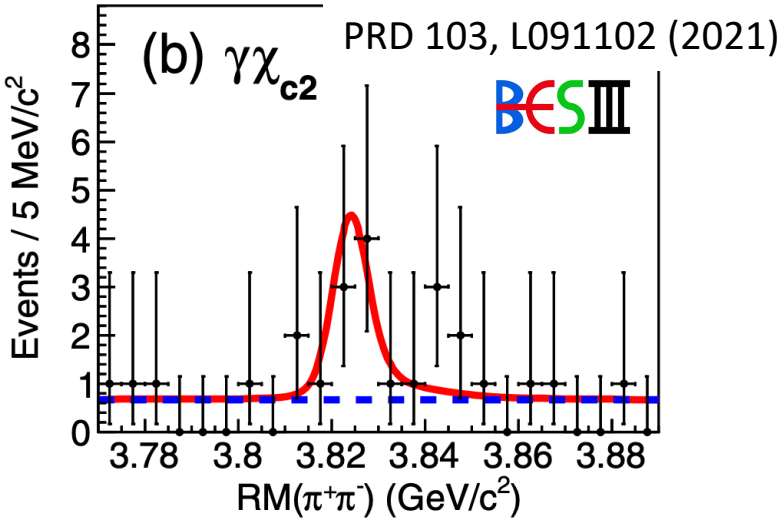
- Evidence of $\psi_2(3823)\to\gamma\chi_{c2}$

$$R = \frac{\mathcal{B}[\psi_2(3823)\to\gamma\chi_{c2}]}{\mathcal{B}[\psi_2(3823)\to\gamma\chi_{c1}]} = 0.33 \pm 0.12$$

$$R < 0.51 \text{ @ 90\% C.L.}$$

Partial reconstruction

PRD 103, L091102 (2021)



$$R = \frac{\mathcal{B}[\psi_2(3823)\to\gamma\chi_{c2}]}{\mathcal{B}[\psi_2(3823)\to\gamma\chi_{c1}]} = 0.28^{+0.14}_{-0.11} \pm 0.02$$

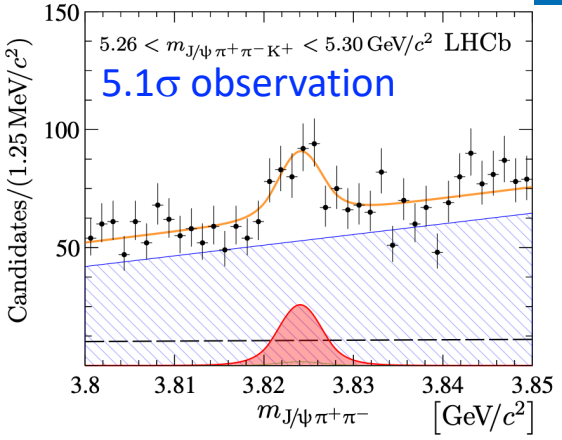
Full reconstruction

Potential model predictions R~0.2

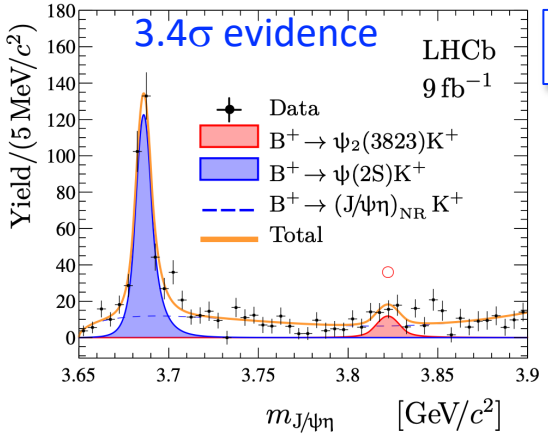
K. T. Chao PRD55, 4001; GI PRD32, 189; Wang arXiv:2208.09667; NR PRD72, 054026…

Decay

JHEP 08(2020)123



JHEP04(2022)046

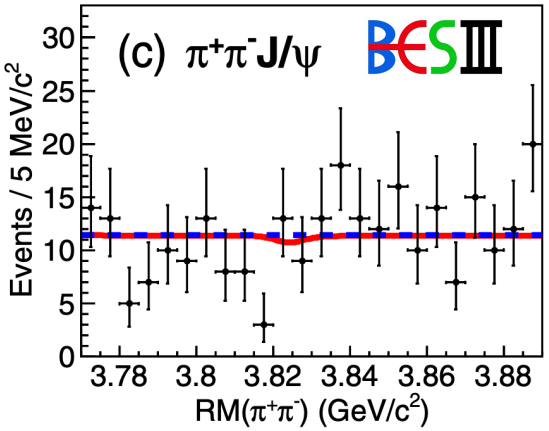


$$\frac{\mathcal{B}_{B^+\to\psi_2(3823)K^+}\times\mathcal{B}_{\psi_2(3823)\to J/\psi\pi^+\pi^-}}{\mathcal{B}_{B^+\to\psi(2S)K^+}\times\mathcal{B}_{\psi(2S)\to J/\psi\pi^+\pi^-}} = (1.31\pm0.25\pm0.04)\times10^{-3}$$

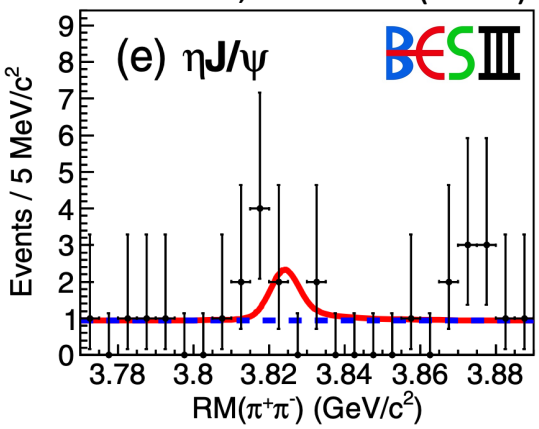
$$\frac{\mathcal{B}(\psi_2(3823)\to J/\psi\eta)}{\mathcal{B}(\psi_2(3823)\to J/\psi\pi^+\pi^-)} = 4.4\,^{+2.5}_{-1.9}\pm0.9$$

$$B_{\psi_2(3823)} = \left(1.25\,^{+0.71}_{-0.53}\pm0.04\right)\times10^{-6}$$

PRD 103, L091102 (2021)



PRD 103, L091102 (2021)

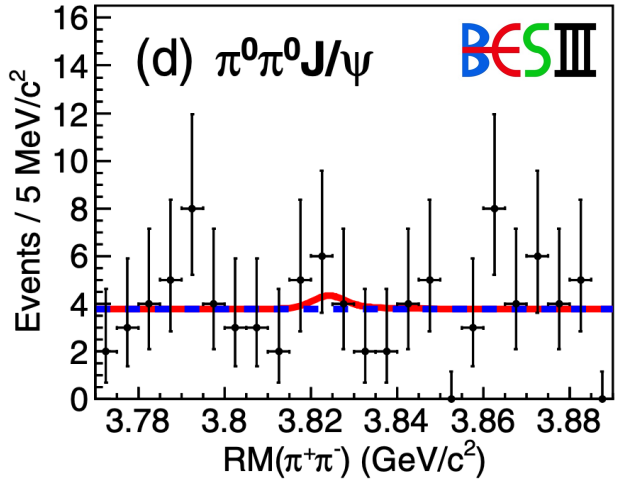


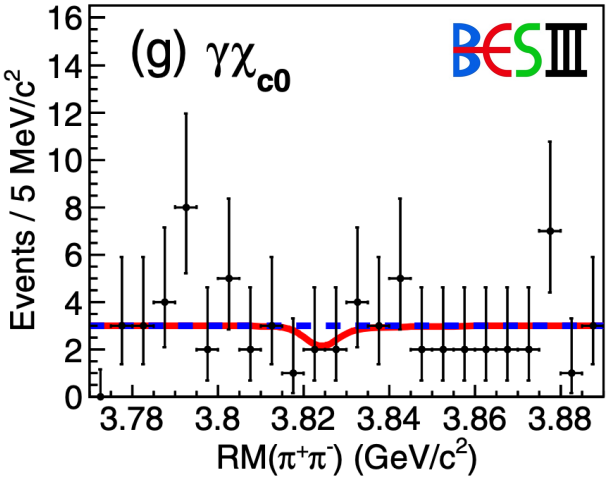
B[$\psi_2\to\pi^+\pi^-J/\psi$]/B[$\to\gamma\chi_{c1}$]<0.06

B[$\psi_2\to\eta J/\psi$]/B[$\to\gamma\chi_{c1}$] < 0.14

Decay

PRD 103, L091102 (2021)

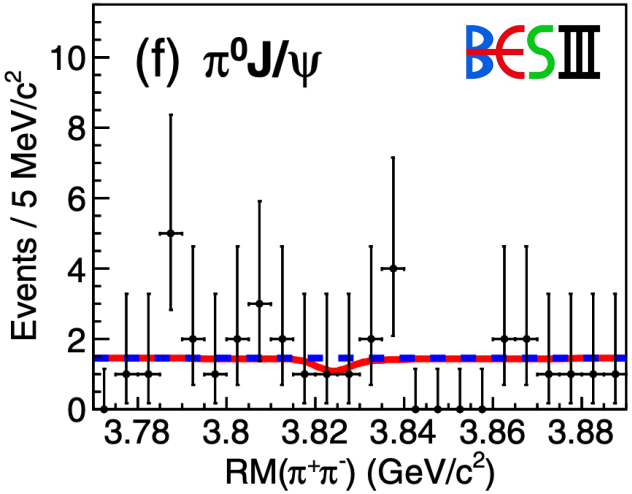


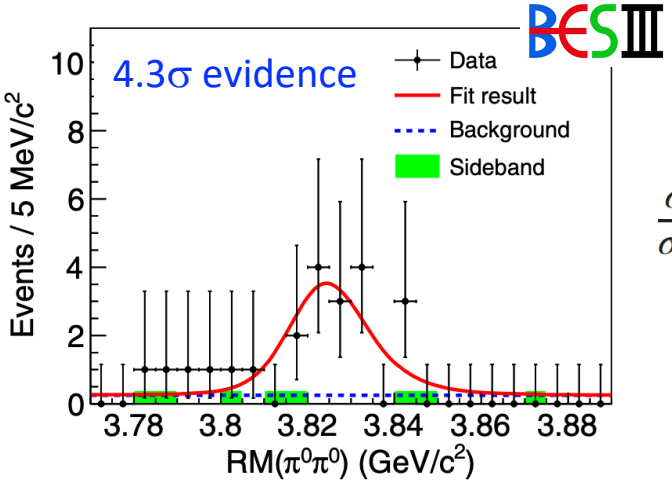


$B[\psi_2 \to \pi^0\pi^0 J/\psi]/B[\to \gamma\chi_{c1}] < 0.11$

$B[\psi_2 \to \gamma\chi_{c0}]/B[\to \gamma\chi_{c1}] < 0.24$

$B[\psi_2 \to \pi^0 J/\psi]/B[\to \gamma\chi_{c1}] < 0.03$

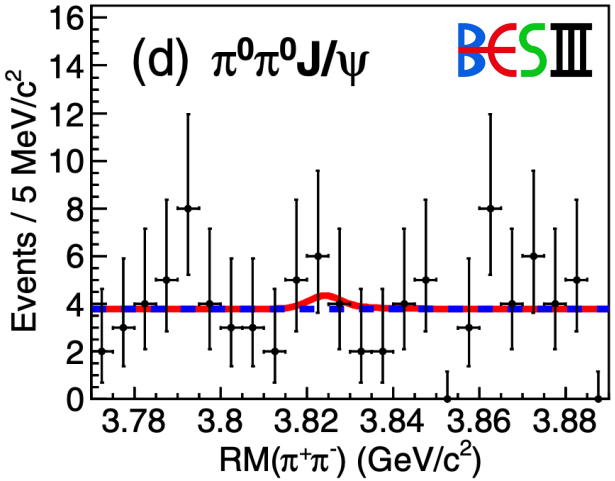


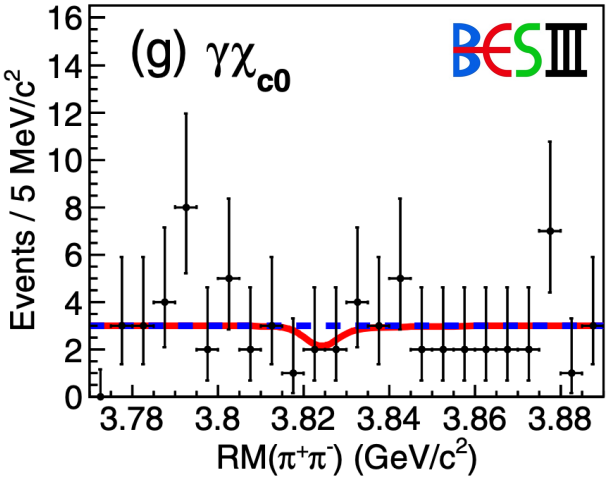


$$\frac{\sigma(e^+e^- \to \pi^0\pi^0\psi_2(3823))}{\sigma(e^+e^- \to \pi^+\pi^-\psi_2(3823))} \sim 0.64 \pm 0.22$$

Decay

PRD 103, L091102 (2021)

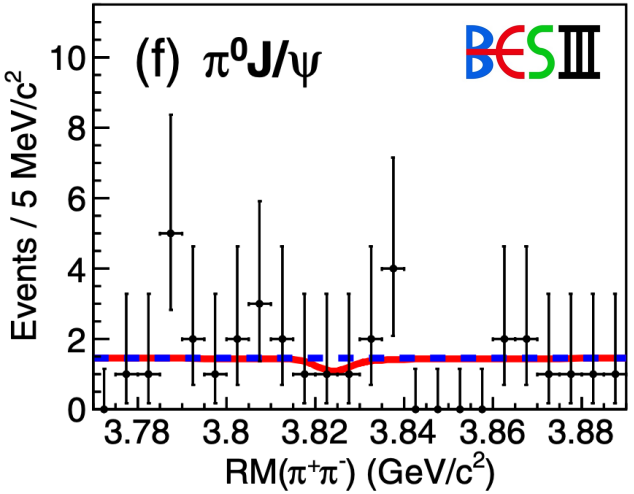


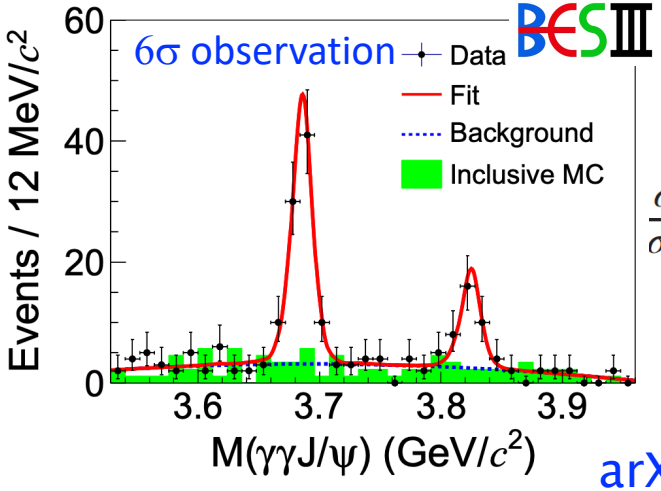


$B[\psi_2 \to \pi^0\pi^0 J/\psi]/B[\to \gamma\chi_{c1}] < 0.11$

$B[\psi_2 \to \gamma\chi_{c0}]/B[\to \gamma\chi_{c1}] < 0.24$

$B[\psi_2 \to \pi^0 J/\psi]/B[\to \gamma\chi_{c1}] < 0.03$





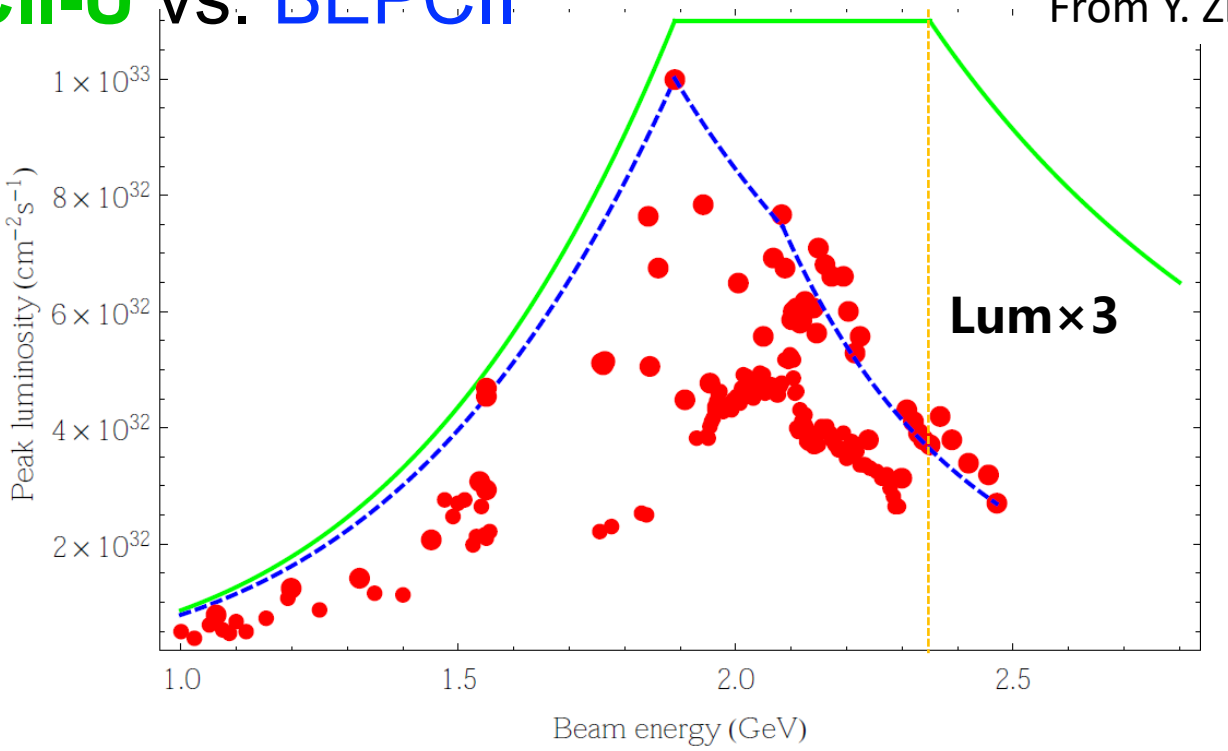
$$\frac{\sigma(e^+e^- \to \pi^0\pi^0\psi_2(3823))}{\sigma(e^+e^- \to \pi^+\pi^-\psi_2(3823))} \sim 0.57 \pm 0.14$$

arXiv:2209.14744

BEPCII-Upgrade

BEPCII-U vs. BEPCII

From Y. Zhang @ FPCP2021



- Luminosity increased by a factor of 3 @ 2.35 GeV
- Beam energy up to 2.8 GeV
- Start running in 2025…

Summary

- The $\psi_2(3823)$ state is well-established with worldwide efforts.
- Lots of progress in studying its properties (mass & width, J^P, and decays).
- BESIII continue to be active in charmonium studies.

Summary

- Outreach activity: What's use of studying $\psi_2(3823)$?

→ A probe to study charmonium-like particles

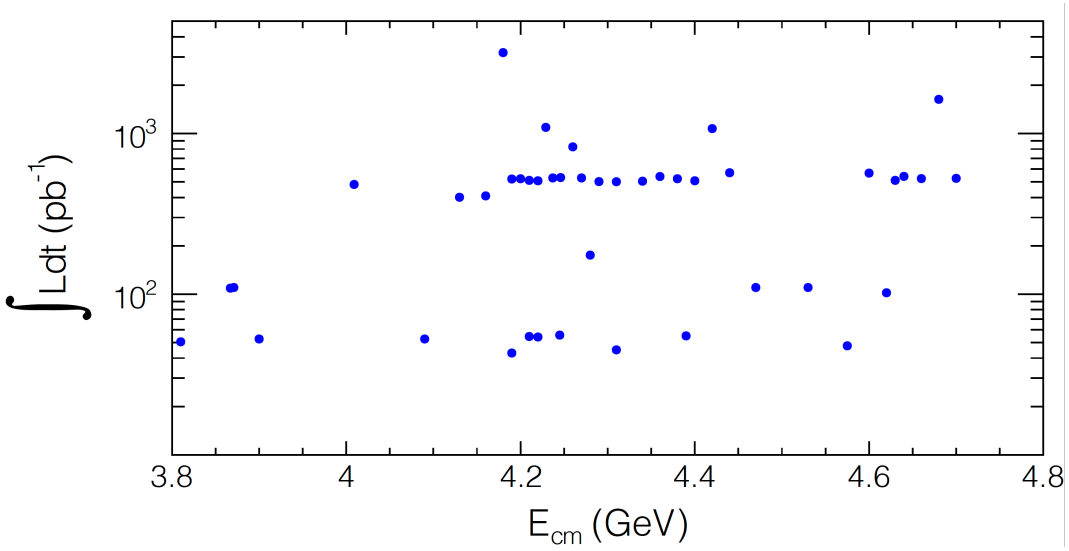
Wissenschaftsmarkt @ Gutenbergplatz

Sep. 15th, 2015

Thanks for your attention !

Backup

BESIII Data Sets (I)



- A scan experiment for vector charmonium-(like) states studies
- Over 23 fb^{-1} data between 3.8 – 4.7 GeV during past 10 years


1988年10月16日
北京正负电子对撞机对撞成功
1988年10月24日，邓小平同志“中国要在高科技领域占有一席之地”

Beijing Electron Positron Collider (BEPCII)

- $\sqrt{s}$ = 2 – 4.946 GeV (τ-charm energy region)
- Design Luminosity 1×10^{33} $cm^{-2}s^{-1}$ (2016 achieved)