XYZ production with BESIII

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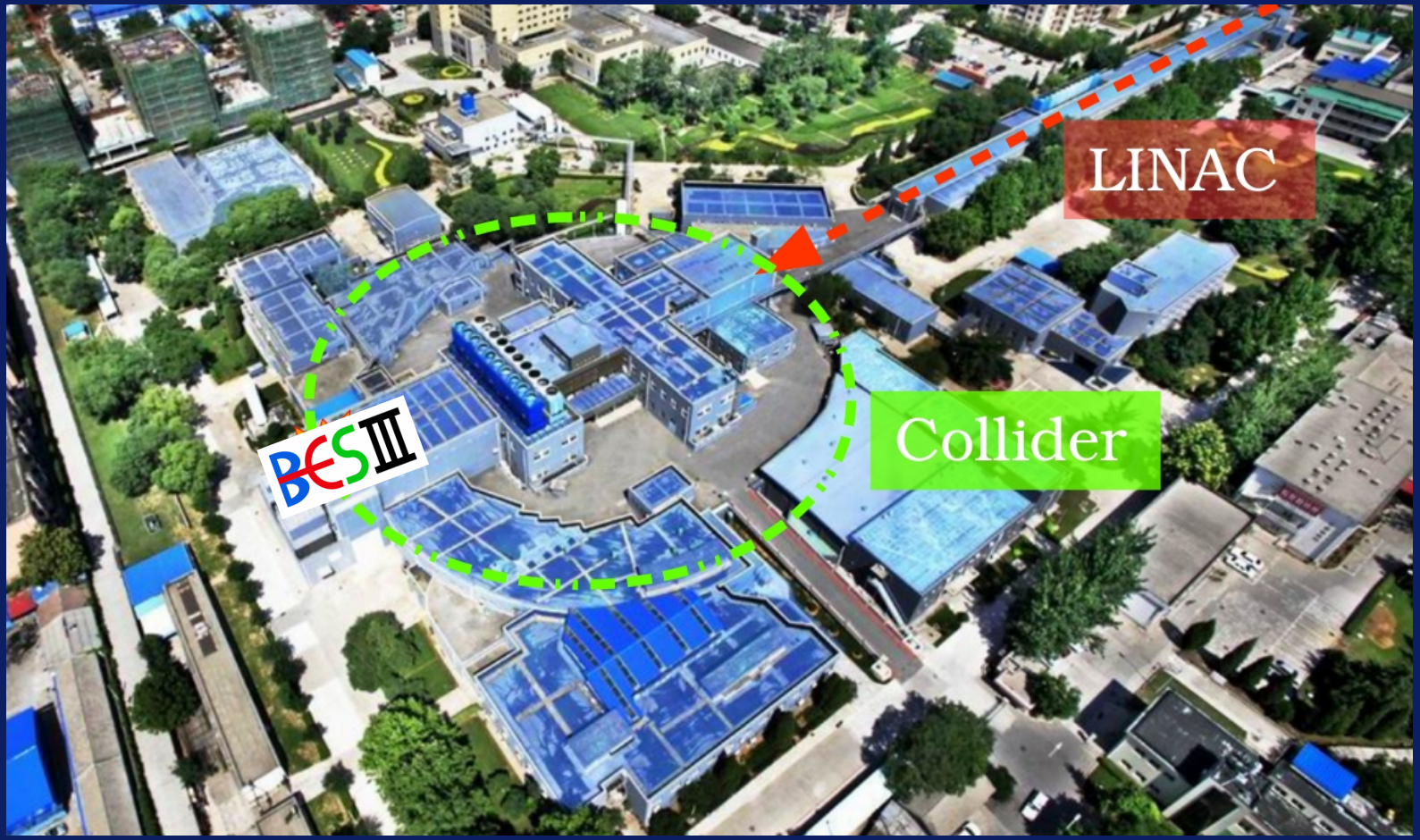
On behalf of the BESIII Collaboration

Exotic Heavy Meson Spectroscopy and Strucutre with EIC – August 15, 2022 – Stony Brook



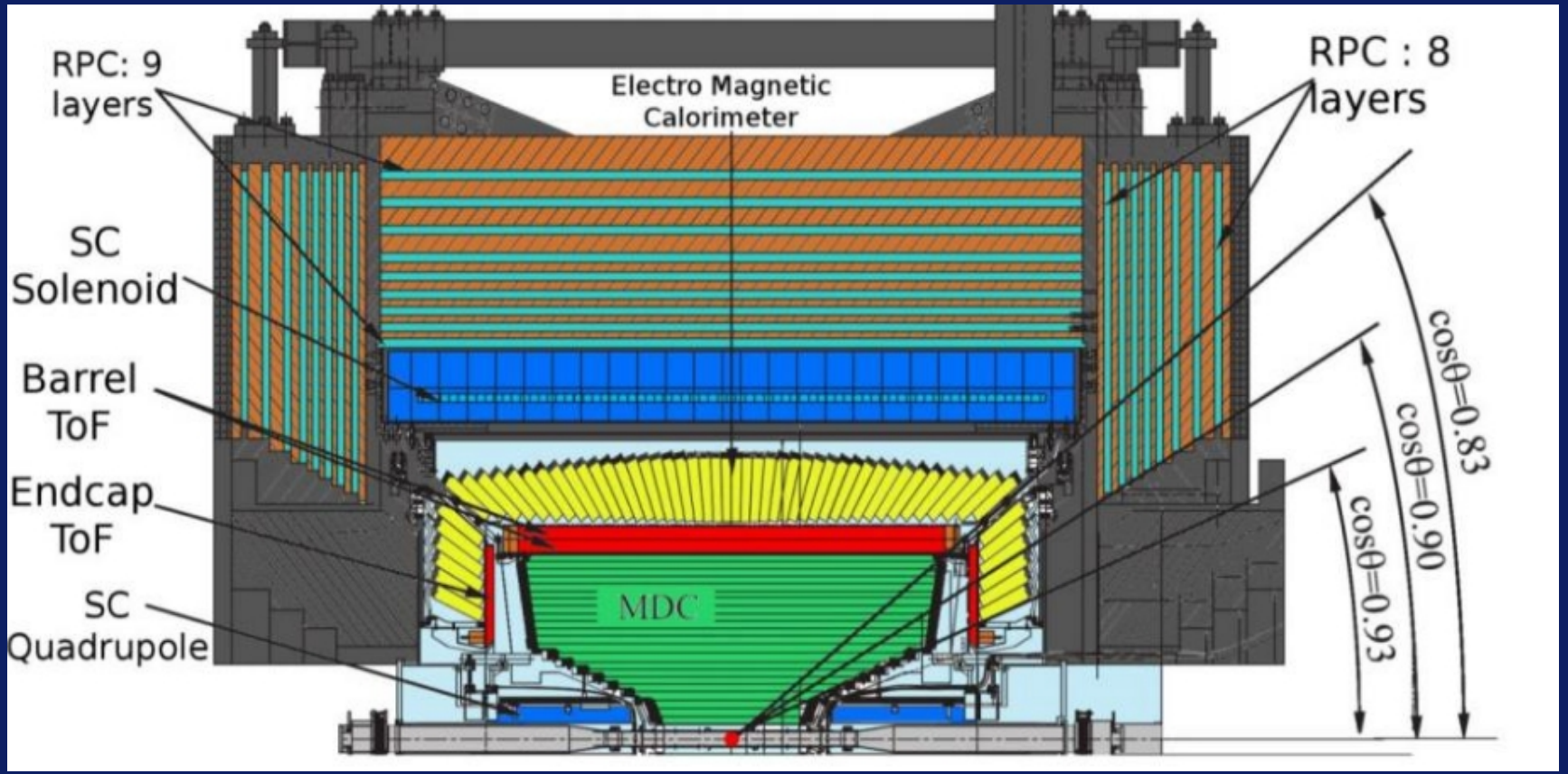
BEPCII @ IHEP

electron-positron collider

E_{cm} = 2 – 4.95 GeV

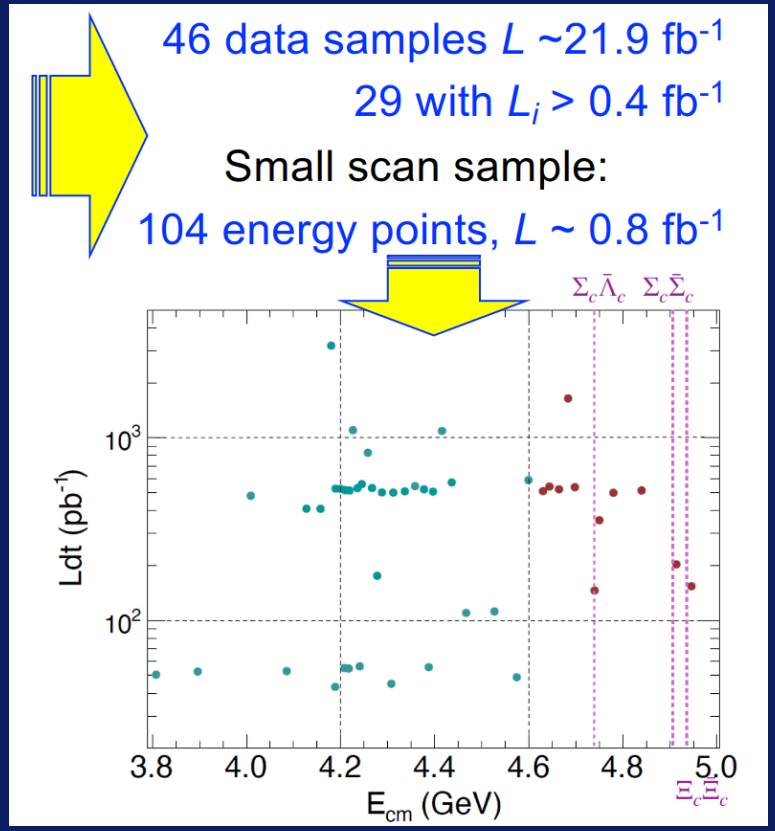
Luminosity = 10^{33} $cm^{-2}s^{-1}$

BESIII @ BEPCII



BESIII Datasets

BESIII full datasets



XYZ-focused datasets

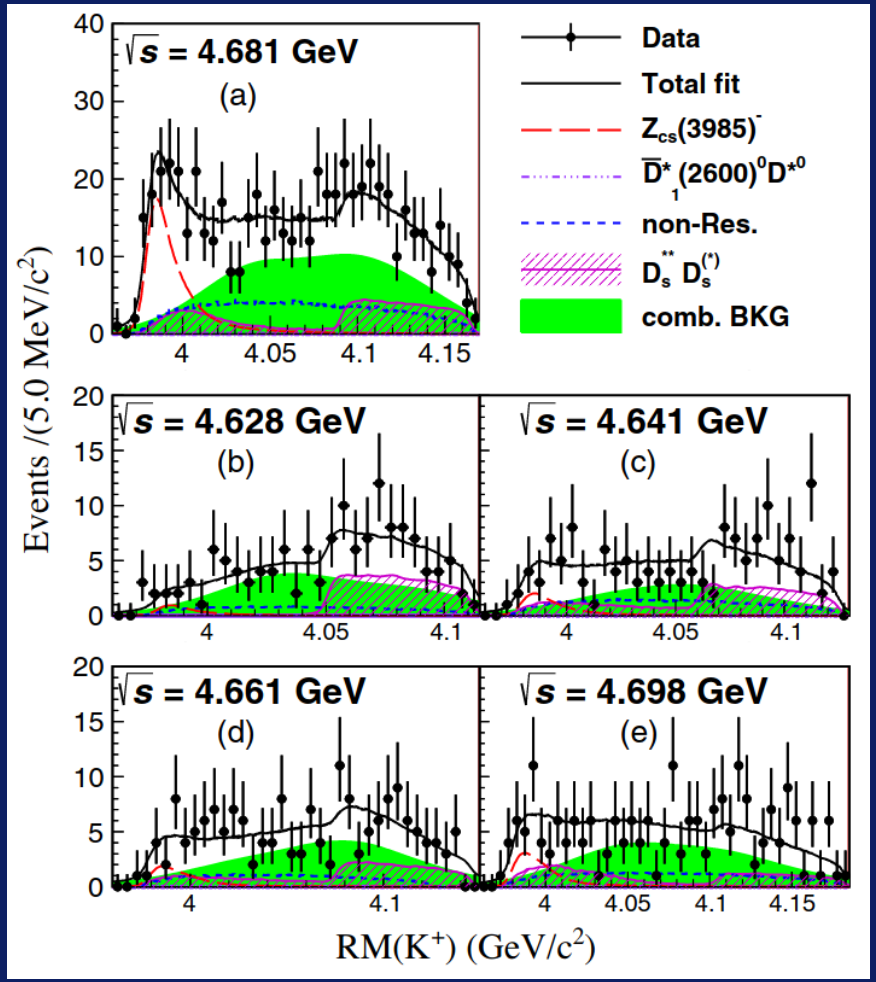
Outline of the results

- Z states:
  - Charged Z_{cs}
  - Neutral Z_{cs}
- X states:
  - Search for $X(3872) \rightarrow \pi^0\chi_{c0}$
  - χ_{c1} direct production
- Y states:
  - $\psi(3823)$
  - $\pi^+\pi^- D\overline{D}$ and $\psi(3843)$ new
  - $\pi^+\pi^-\psi(2S)$
  - $K^+K^- J/\psi$
  - $\pi^+\pi^- J/\psi$
  - Open charm final states
  - Light hadron final states

And one search on the connection among these states

$Z_{cs}(3985)^{\pm}$ @ BESIII

PRL 126, 102001 (2021)



Search for "strange" partner of the $Z_c(3900)$

Discovered in the process $e^+e^- \rightarrow K^+(D_sD^* + D^*_sD)$ by studying the K^+ recoil mass

$$\mathcal{F}_j(M) \propto \left| \frac{\sqrt{q \cdot p_j}}{M^2 - m_0^2 + im_0(f\Gamma_1(M) + (1-f)\Gamma_2(M))} \right|^2$$

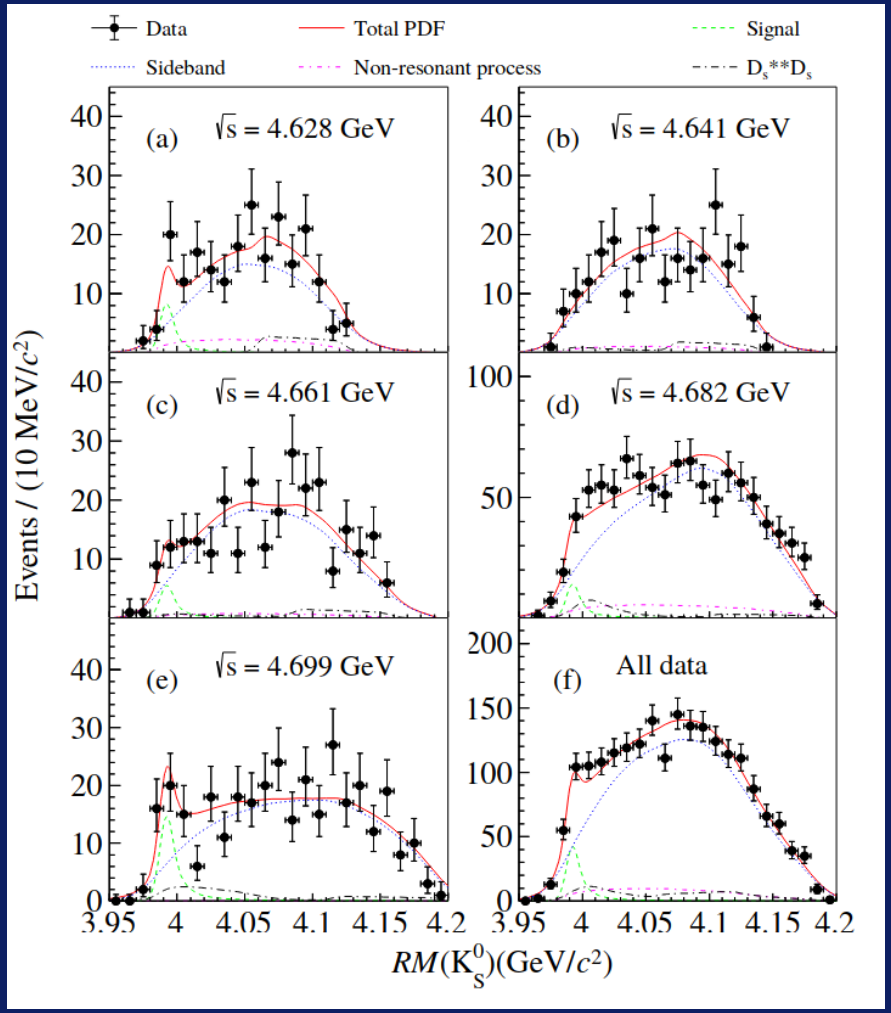
$j = 1 \rightarrow Z_{cs} \rightarrow D_sD^*$; $j = 2 \rightarrow Z_{cs} \rightarrow D^*_sD$

$$m_{\text{pole}}[Z_{cs}(3985)^-] = (3982.5^{+1.8}_{-2.6} \pm 2.1)\ \text{MeV}/c^2,$$
$$\Gamma_{\text{pole}}[Z_{cs}(3985)^-] = (12.8^{+5.3}_{-4.4} \pm 3.0)\ \text{MeV}.$$

(one of the) First candidate of open strangeness charged exotic

$Z_{cs}(3985)^0$ @ BESIII

ArXiv: 2204.13703



Neutral partner of $Z_{cs}(3985)$ useful to assess their nature

Studied with partial reconstruction method in K_s recoil mass

$$R = \left| \frac{1}{M^2 - m_0^2 + im_0(f \cdot \Gamma_1(M) + (1-f) \cdot \Gamma_2(M))} \right|^2$$

$$R_1 = R \cdot q \cdot p_1,$$

$$R_2 = R \cdot q \cdot p_2,$$

$$\Gamma_1(M) = \Gamma_0 \cdot \frac{p_1}{p_1^*} \cdot \frac{m_0}{M},$$

$$\Gamma_2(M) = \Gamma_0 \cdot \frac{p_2}{p_2^*} \cdot \frac{m_0}{M},$$

Evidence at 4.6σ level. Compatible with isospin predictions

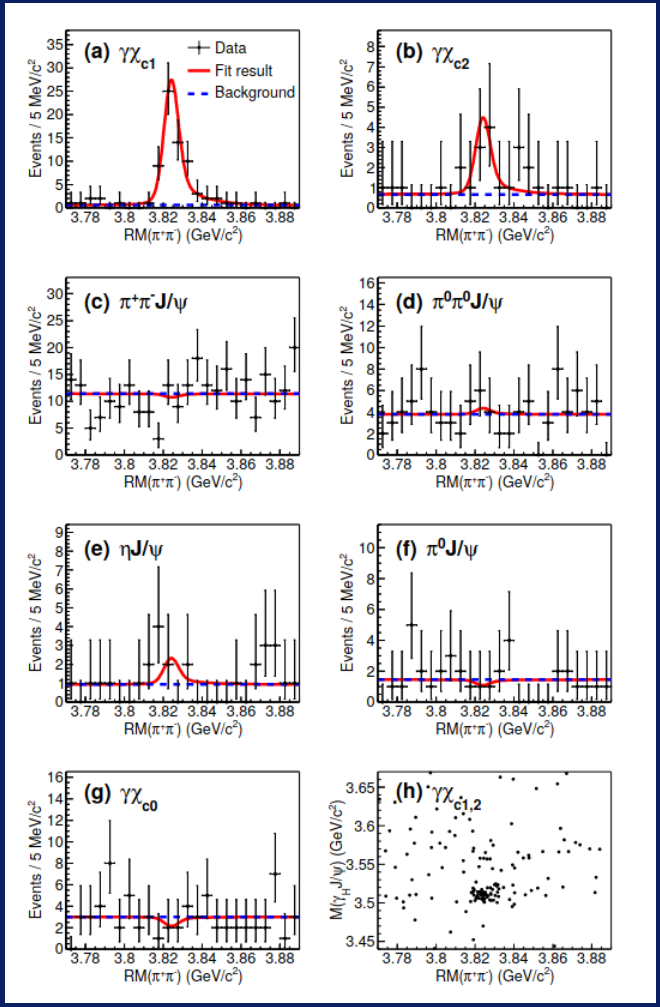
	Mass (MeV/c^2)	Width (MeV)
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$

$\sqrt{s}$ (MeV)	$\sigma^{\rm Born} \times \mathcal{B}$ (pb) $\bar{K}^0 Z_{cs}(3985)^0$	$K^- Z_{cs}(3985)^+$	χ^2	$\chi^2_{\rm total}$/ndf
4628	$4.4^{+2.6}_{-2.2} \pm 2.0$	$0.8^{+1.2}_{-0.8} \pm 0.6$	1.2	
4641	$0.0^{+1.6}_{-0.0} \pm 0.2$	$1.6^{+1.2}_{-1.1} \pm 1.3$	0.5	
4661	$2.8^{+1.8}_{-1.6} \pm 0.6$	$1.6^{+1.3}_{-1.1} \pm 0.8$	0.3	5.1/5
4682	$2.2^{+1.2}_{-1.0} \pm 0.8$	$4.4^{+0.9}_{-0.8} \pm 1.4$	1.0	
4699	$7.0^{+2.2}_{-2.0} \pm 1.8$	$2.4^{+1.1}_{-1.0} \pm 1.2$	2.1	

New $\psi_2(3823)$ decay mode

PRD 103 (2021) 9, L091102

11.8σ



3.2σ

Search for additional experimental evidence of $\psi_2(3823)$ to confirm its status of $\psi_2(1^3D_2)$ in $e^+e^- \to \pi^+\pi^-\psi_2(3823)$

Based on 19 fb^{-1} between 4.1 and 4.7 GeV

Channel	$N^{\psi_2(3823)}$	$\frac{\mathcal{B}(\psi_2(3823)\to\ldots)}{\mathcal{B}(\psi_2(3823)\to\gamma\chi_{c1})}$
$\gamma\chi_{c1}$	63.1 ± 8.5	–
$\gamma\chi_{c2}$	$8.8^{+4.3}_{-3.4}$	$0.28^{+0.14}_{-0.11} \pm 0.02$
$\pi^+\pi^- J/\psi$	< 21.0	< 0.06
$\pi^0\pi^0 J/\psi$	< 10.0	< 0.11
$\eta J/\psi$	< 9.8	< 0.14
$\pi^0 J/\psi$	< 5.6	< 0.03
$\gamma\chi_{c0}$	< 6.3	< 0.24

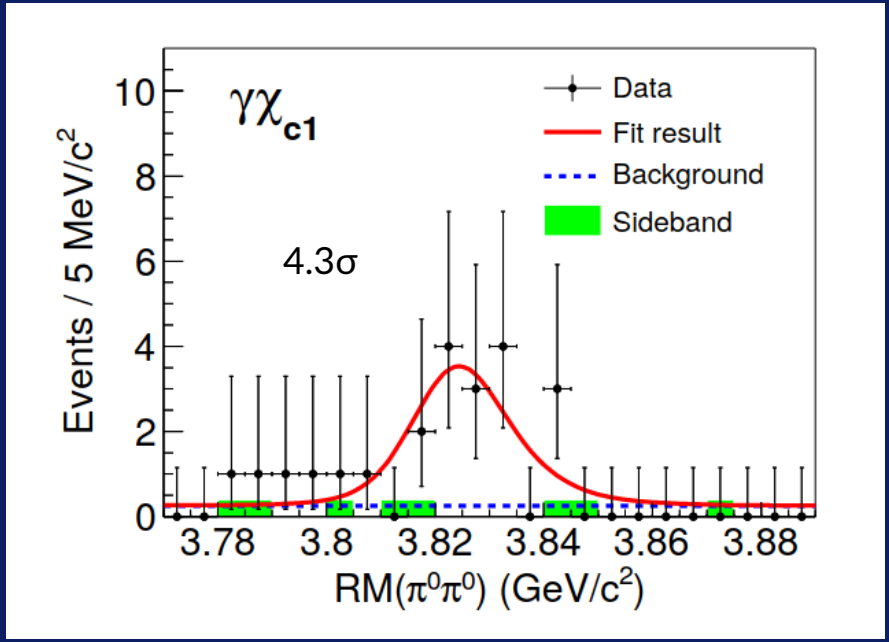
Consistent with theoretical prediction

Lower than theoretical prediction

PRD 55, 4001 (1997), PRL 89, 162002 (2002), PRD 67, 014027 (2003), PRD 69, 054008 (2004), PRD 72, 054026 (2005), PRD 79, 094004 (2009), Front. Phys. 11, 111402 (2016), PRD 95, 034026 (2017), Int. J. Mod. Phys. A 32, 1750035 (2017)

Search for $\psi_2(3823)$ and $\psi_3(3842)$ production mode

PRD 103 (2021) 9, L091102



Search for new production mode of ψ_2 and ψ_3 can help to establish their nature

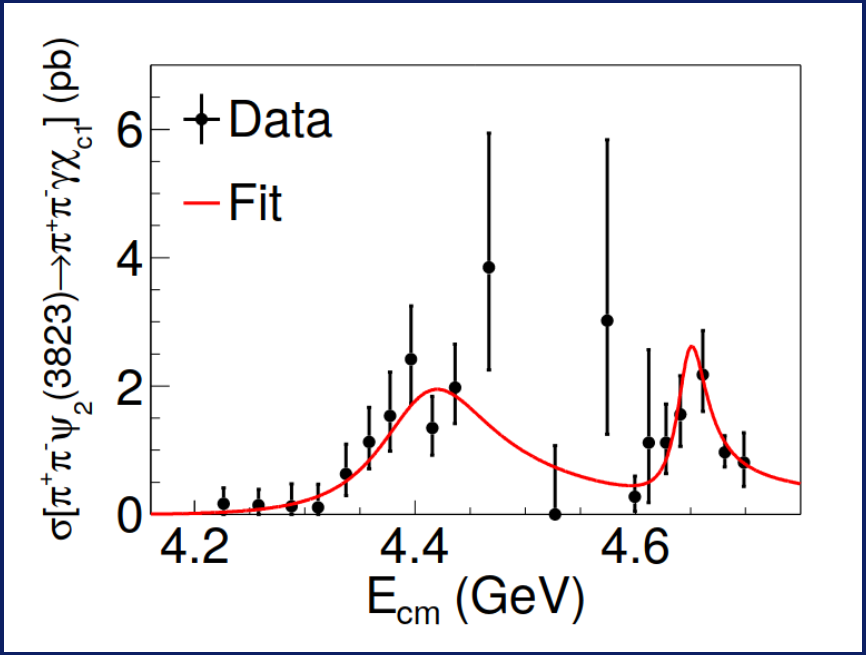
Evidence of $\pi^0\pi^0\psi_2(3823)$, $\psi_2(3823)\to\gamma\chi_{c1}$.
Ratio with charged pions mode confirms isospin simmetry.

$$\frac{\sigma(e^+e^- \to \pi^0\pi^0\psi_2(3823))}{\sigma(e^+e^- \to \pi^+\pi^-\psi_2(3823))} = (0.64^{+0.22}_{-0.20} \pm 0.05)$$

No signal of $\pi^+\pi^-\psi_3(3842)$

$\pi\pi\psi_2(3823)$ lineshape and $\psi_2(3823)$ mass

ArXiv: 2203.05815



$$M[\psi_2(3823)] = 3823.12 \pm 0.43 \pm 0.13\ \mathrm{MeV}/c^2$$

U.L. width (< 2.9 MeV) will help constrains potential models

Study the internal structure of Y states by measuring their coupling with D-wave charmonia

$\psi_2(3823)$ candidates reconstructed in $\gamma\chi_{c1,2}$

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	$267.1 \pm 16.2 \pm 3.2$	$-324.8 \pm 43.0 \pm 5.7$

Two resonances hypothesis favored:
- to single resonance by 2.6σ
- to only continuum one by more than 5σ

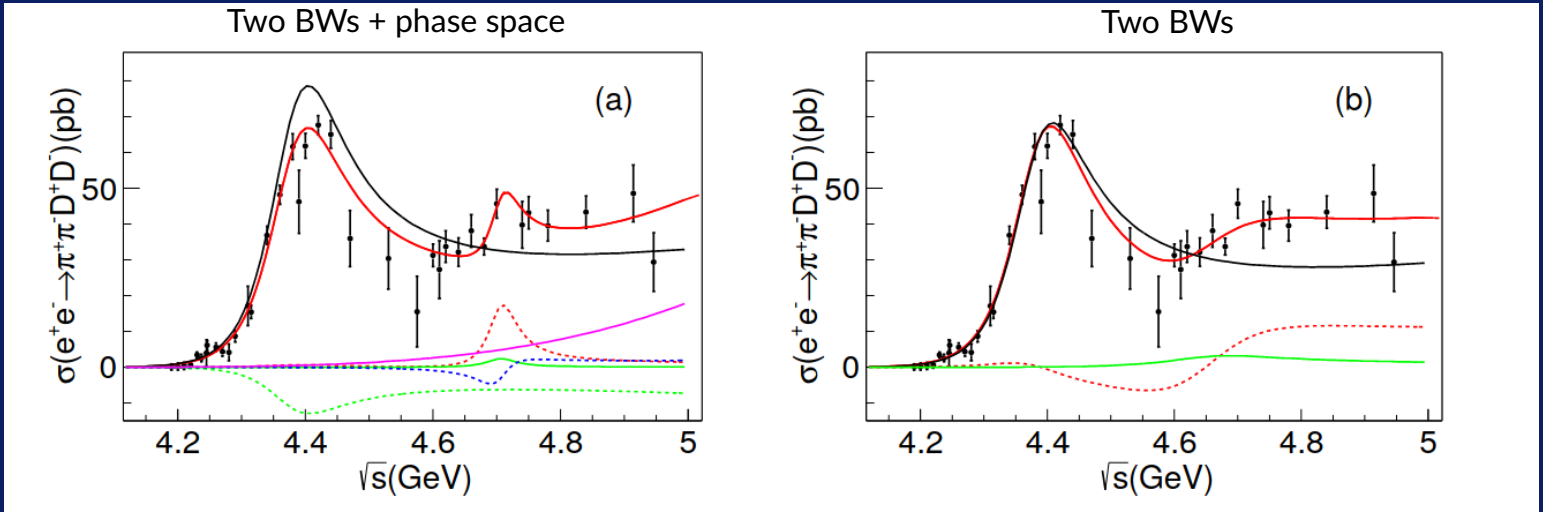
Second largest BF of Y(4660)

ππDD lineshape

ArXiv: 2203.05815

Study the 4-body final state to search for clues about vector resonance in the region 4-4.7 GeV.
3 subprocesses (PHSP, ππψ(3770), $D_1(2420)D$)

Fit to 37 energy values. Partial reconstruction method (one D→ Kππ, one in recoil mass).



Y(4390) / 4.1σ

m_0 (MeV/c^2)	$4373.1 \pm 4.0 \pm 1.0$
Γ_0 (MeV)	$146.5 \pm 7.4 \pm 1.1$
m_1 (MeV/c^2)	$4706 \pm 11 \pm 4$
Γ_1 (MeV)	$45 \pm 28 \pm 9$

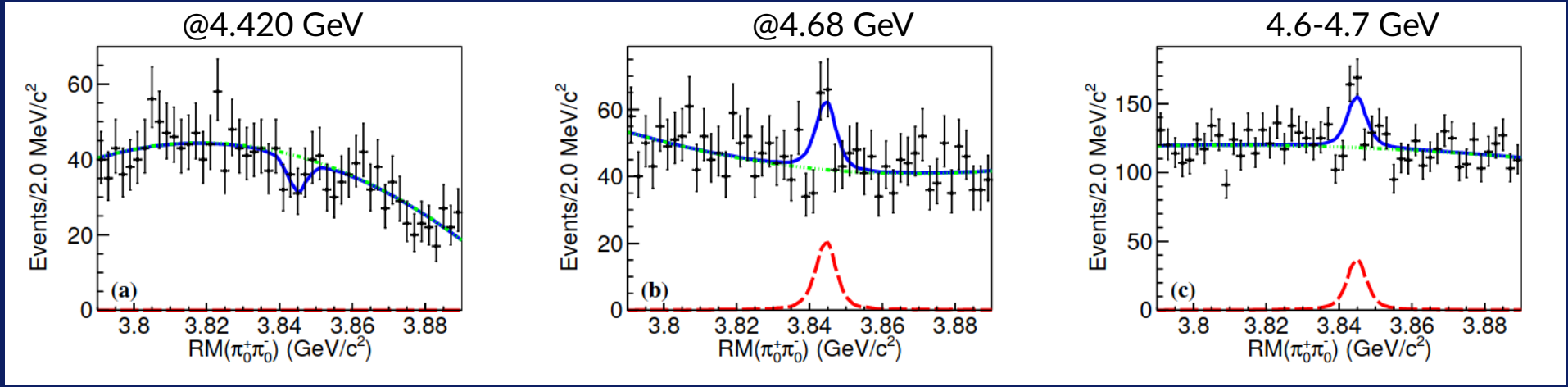
m_0 (MeV/c^2)	4378.0 ± 8.5
Γ_0 (MeV)	152 ± 14
m_1 (MeV/c^2)	4605 ± 90
Γ_1 (MeV)	245 ± 67

Y(4390) / 7σ

Evidence of $\pi\pi\psi_3(3843)$

ArXiv: 2203.05815

Search for spin-3 partner of ψ(3770) and ψ(3823) in its $D\overline{D}$ decay. More stringent requirements on the selection criteria

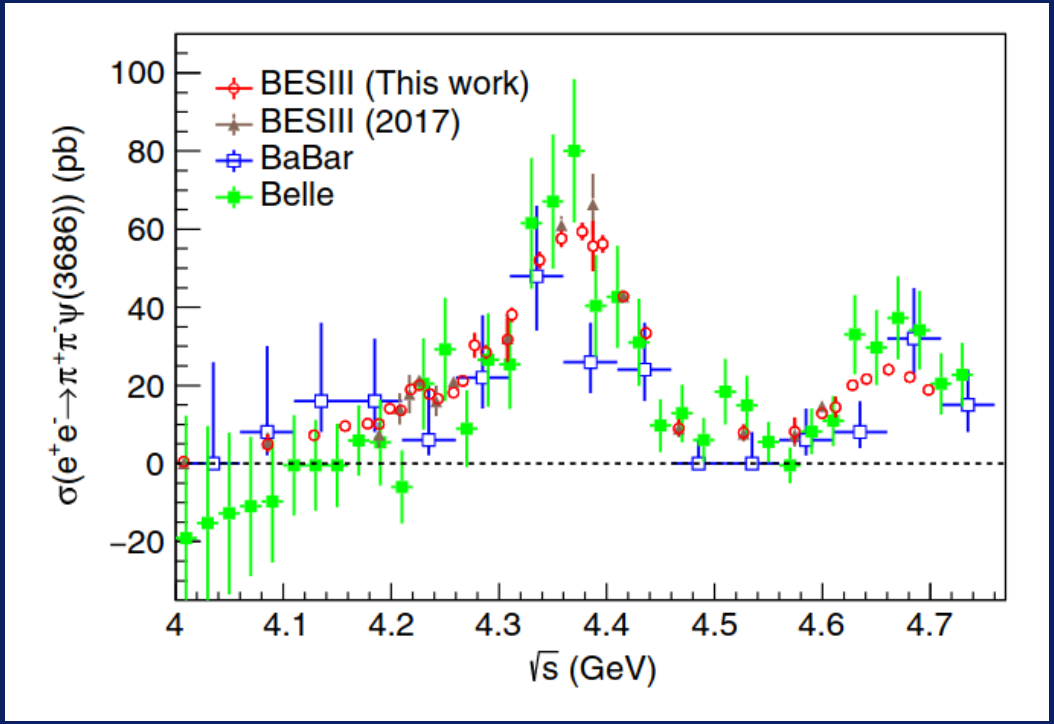


Signal shape extracted using $e^+e^- \rightarrow f_0(500)\psi(3843)$ MC

Combining all dataset in 4.6-4.7 GeV evidence of $\pi\pi\psi(3843)$ at 4.2σ level

$e^+e^- \to \pi\pi\psi(2S)$

PRD 104 (2021) 5, 052012



Extension of a previous work (PRD 96, 032004 (2017))

New measurement up to 4.7 GeV, with addition of new final state.

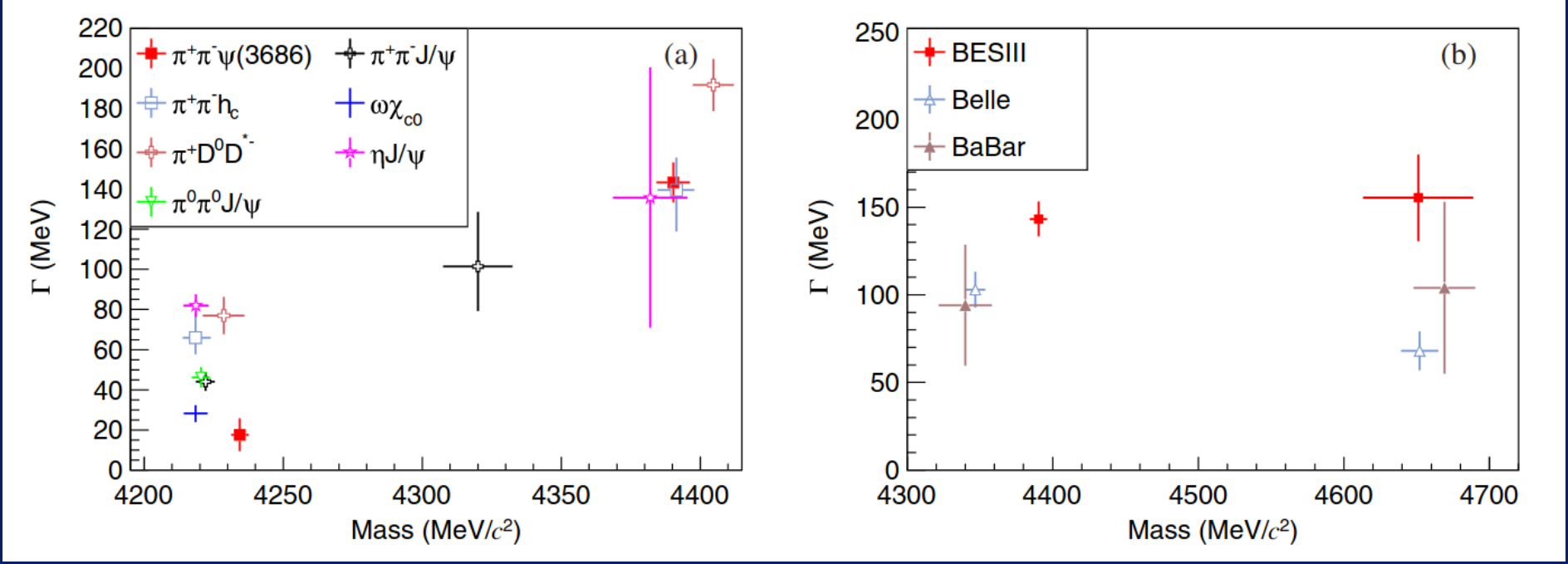
Confirmed both Y(4220) and Y(4390) contribution

First observation of Y(4660) at BESIII thanks to the center of mass upgrade!

BaBar: PRD 89, 111103 (2014)
Belle: PRD 91, 112007 (2015)

Y(4220) – Y(43xx) – Y(4660)

PRD 104 (2021) 5, 052012

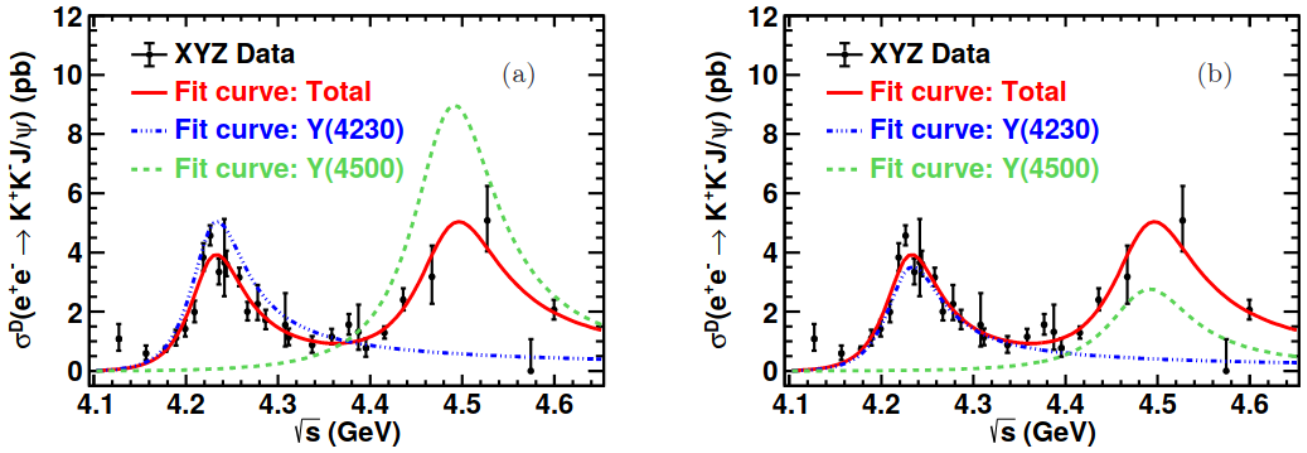


Status of the Y(4220)/Y(43xx) measurements

As observed in ππψ(2S)
Belle: PRD 91, 142002 (2007)
BaBar: PRD 89, 111103 (2014)

New structures in $e^+e^- \to KKJ/\psi$ cross section

ArXiv: 2204.07800



First observation of Y(4230) in KKJ/ψ

$$0.02 < \frac{\mathcal{B}(Y(4230) \to K^+K^-J/\psi)}{\mathcal{B}(Y(4230) \to \pi^+\pi^-J/\psi)} < 0.26$$

New structure Y(4500) observed for first time!

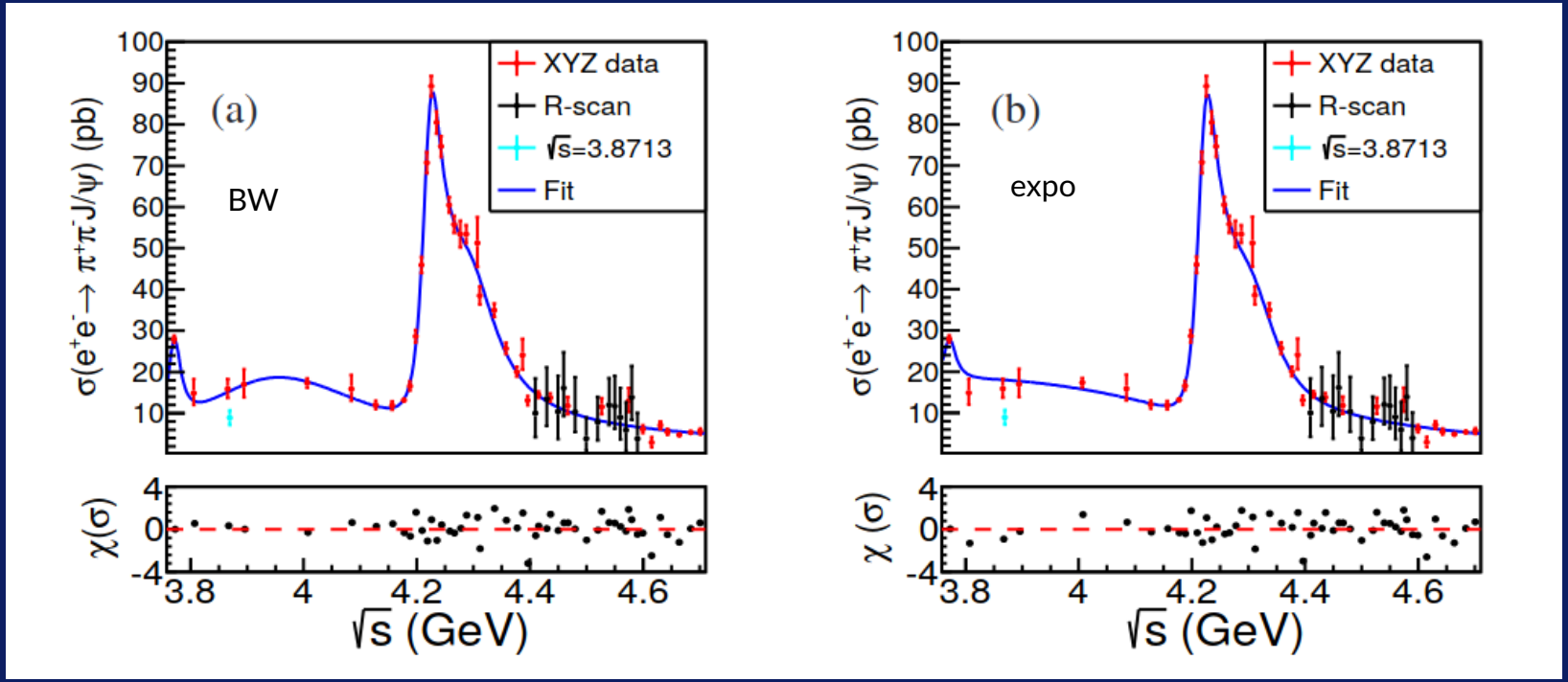
	Parameters	Solution I	Solution II
$Y(4230)$	M(MeV)	$4225.3 \pm 2.3 \pm 21.5$	
	Γ_{tot}(MeV)	$72.9 \pm 6.1 \pm 30.8$	
	$\Gamma_{ee}\mathcal{B}$(eV)	$0.42 \pm 0.04 \pm 0.15$	$0.29 \pm 0.02 \pm 0.10$
$Y(4500)$	M(MeV)	$4484.7 \pm 13.3 \pm 24.1$	
	Γ_{tot}(MeV)	$111.1 \pm 30.1 \pm 15.2$	
	$\Gamma_{ee}\mathcal{B}$(eV)	$1.35 \pm 0.14 \pm 0.06$	$0.41 \pm 0.08 \pm 0.13$
phase angle	φ(rad)	$1.72 \pm 0.09 \pm 0.52$	$5.49 \pm 0.35 \pm 0.58$

Y(4500) compatible with:
- 5S/4D mixing
- $D_s\bar{D}_{s1}$ hadronic molecule
- lattice $c\bar{c}s\bar{s}$ structure

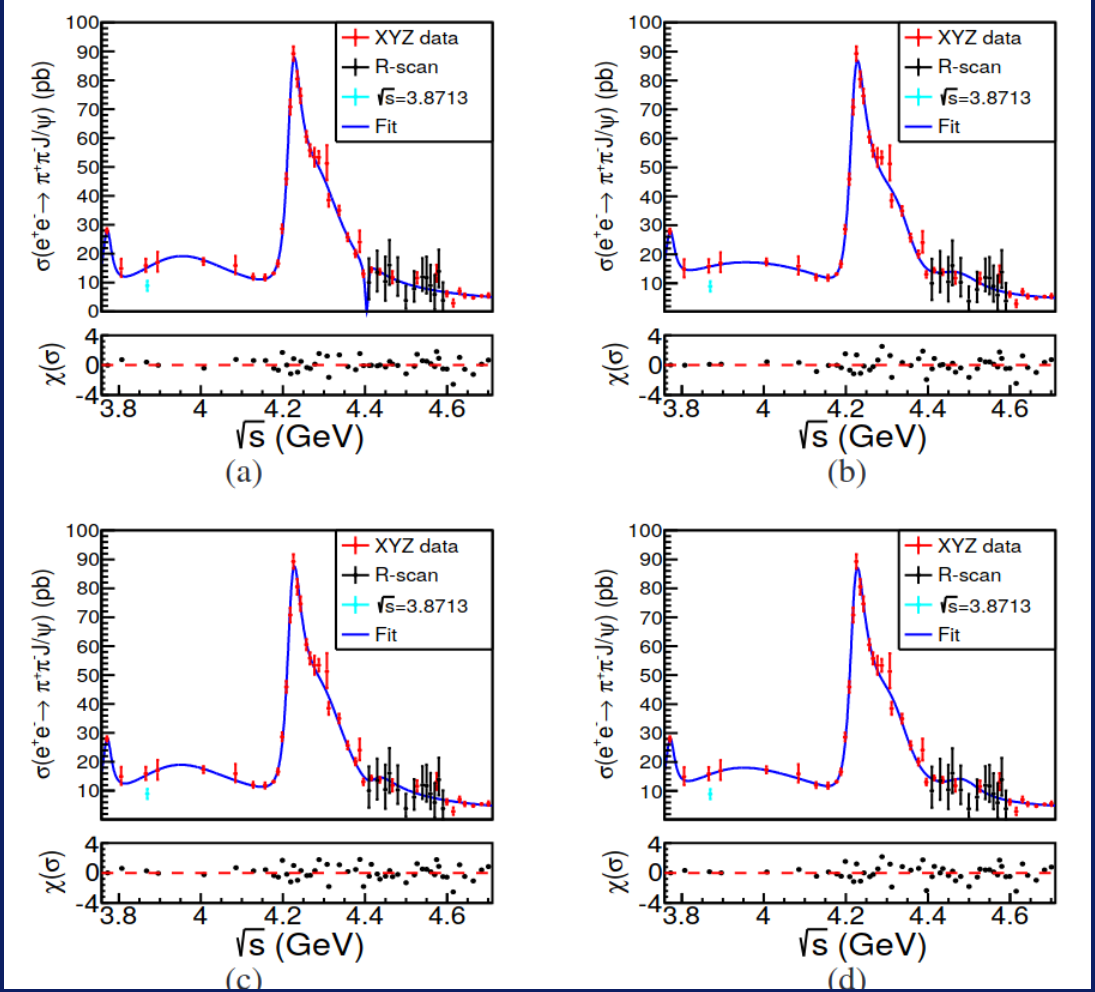
Update of $e^+e^- \to \pi\pi J/\psi$

arXiv:2206.08554

Update of previous measurements with a total of 23/fb between 3.77 and 4.70 GeV



Clear observation of two resonances. Data around 4. GeV favor BW rather than exponential parametrization. Large flactuation at 3.8713 - X(3872)



Update of

$e^+e^- \to \pi\pi J/\psi$ - II

arXiv:2206.08554

Fit with a third resonance yields to a better description of the data.

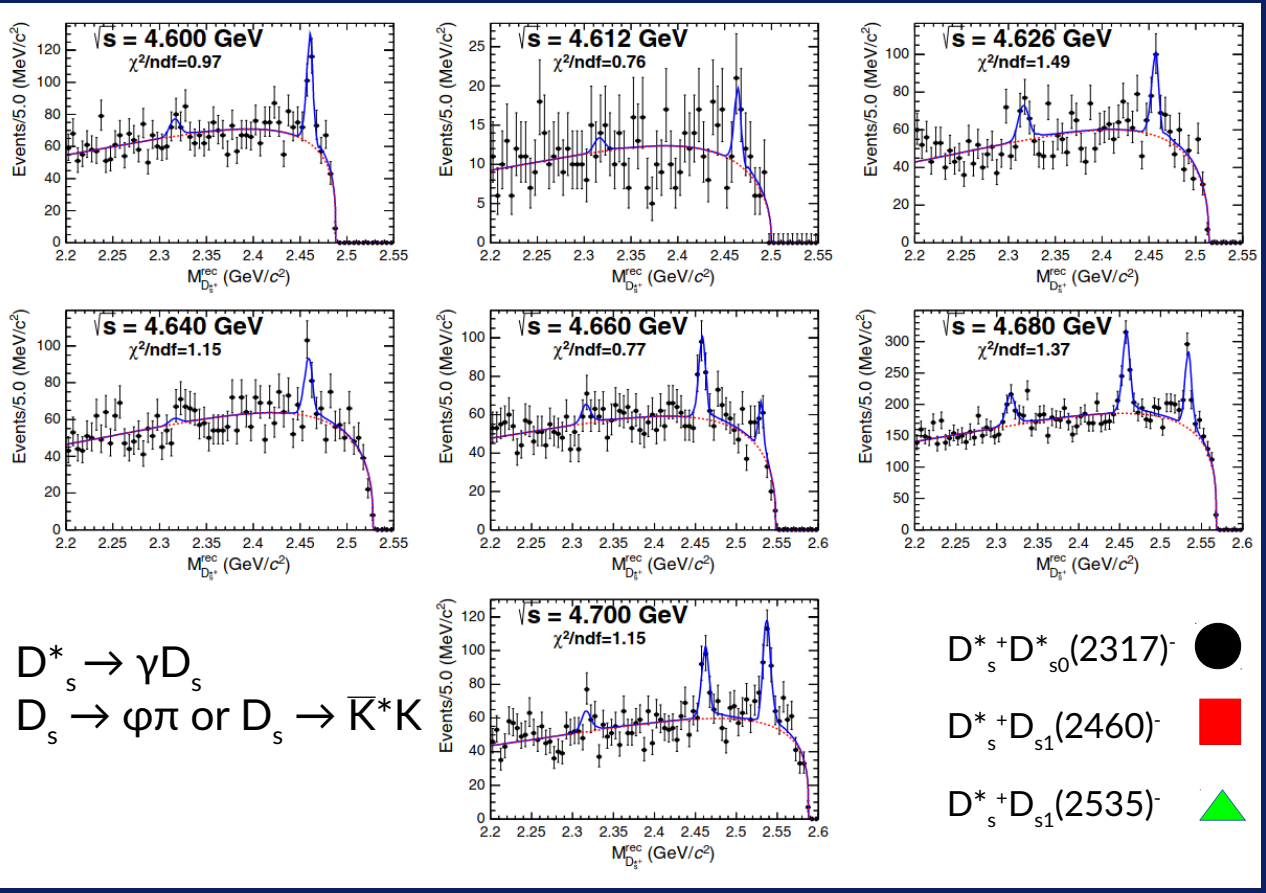
Tested four models:
(a) free → solution compatible with ψ(4415)
(b) free → solution compatible with Y(4500)
(c) fixed to ψ(4415)
(d) fixed to Y(4500)

Impact on "known" resonances:
- Stable results for Y(4220)
- Large differences for Y(4320)

More data are needed in the 4.4 – 4.6 GeV region

PRD 104 (2021) 032012

$e^+e^- \to D^*_s D_{sJ} + c.c.$



$D^*_s \to \gamma D_s$

$D_s \to \varphi\pi$ or $D_s \to \bar{K}^*K$

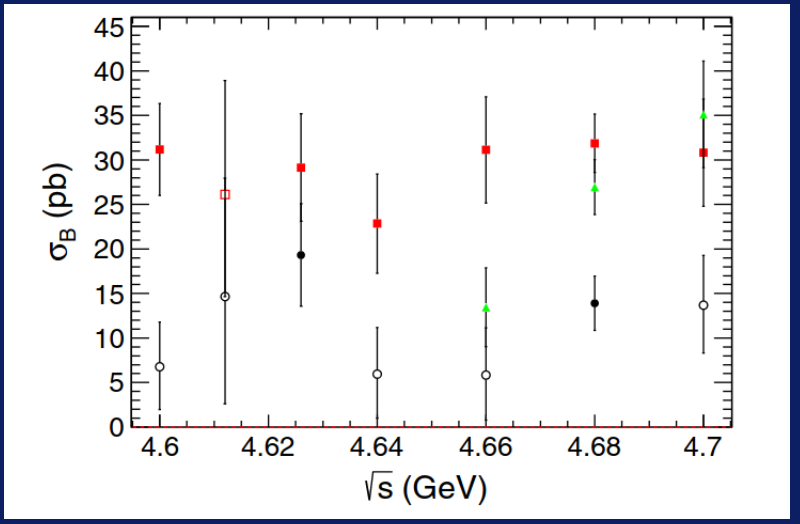
$D^*_s{}^+ D^*_{s0}(2317)^-$

$D^*_s{}^+ D_{s1}(2460)^-$

$D^*_s{}^+ D_{s1}(2535)^-$

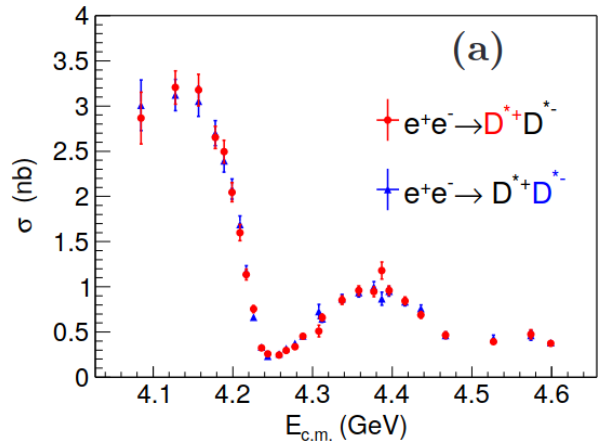
Extension with dataset above 4.6 GeV of previous PRD 101, 112008 (2020)

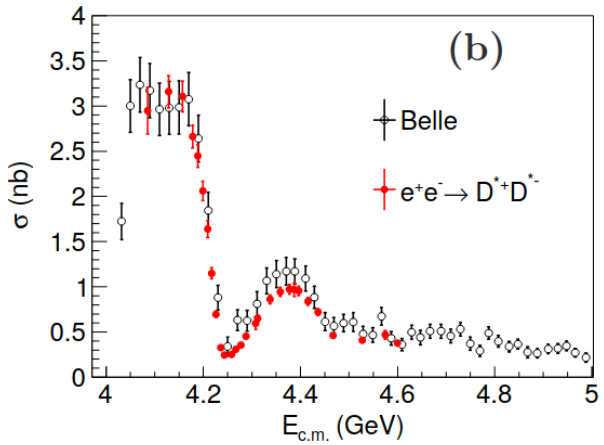
$D^*_{s0}(2317)$ $D_{s1}(2460)$, $D_{s1}(2535)$ identified in D^*_s recoil mass

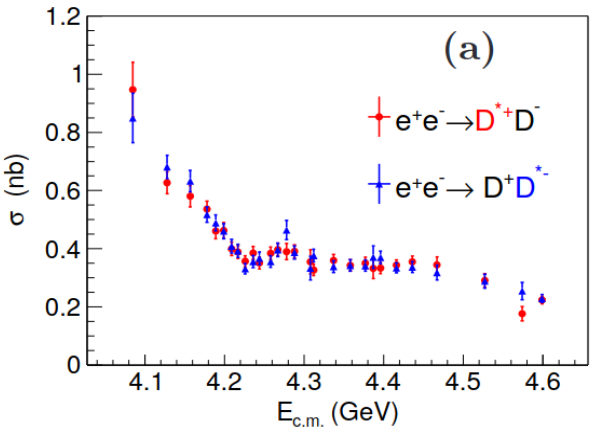


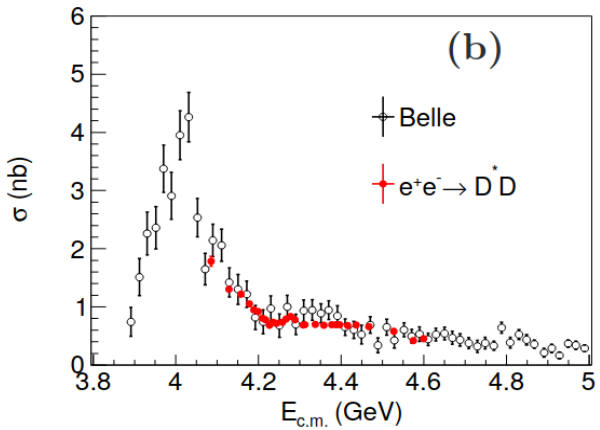
JHEP 2022, 155 (2022)

$e^+e^- \to D^*D^{(*)}$









15.7 fb^{-1} collected between 4.085 and 4.6 GeV

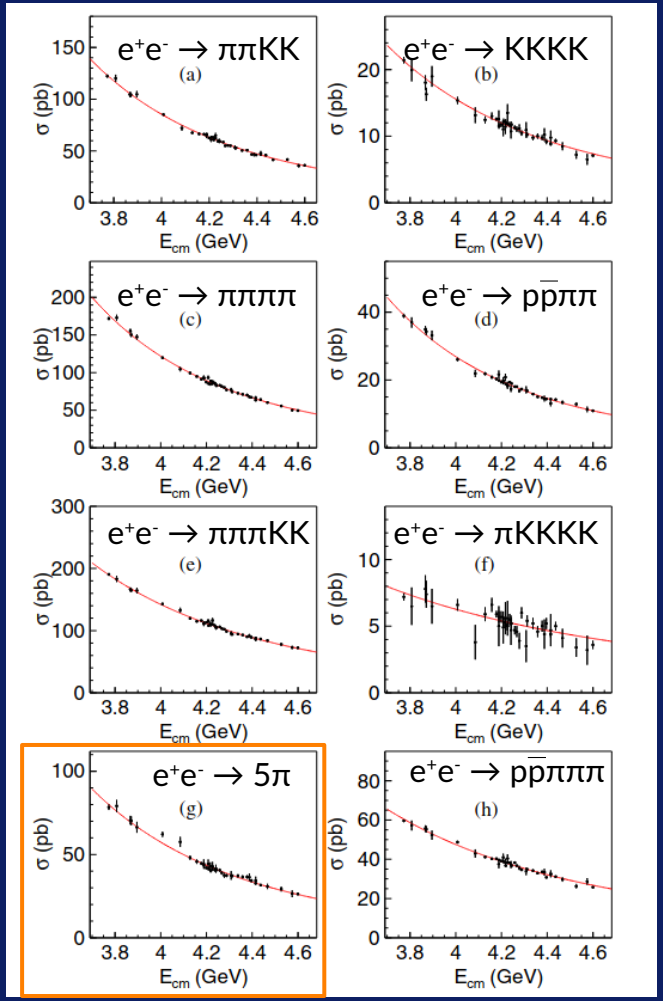
Reconstructed $D^{*+} \to \pi^+D^0$ and $D^0 \to K^-\pi+$.

$D^{(*)-}$ inferred kinematically

Good agreement with existing measurements

Confirmed structure at 4.39 GeV in D*D*

Results can provide information to improve Eur. Phys. J. C81 (2021) 83

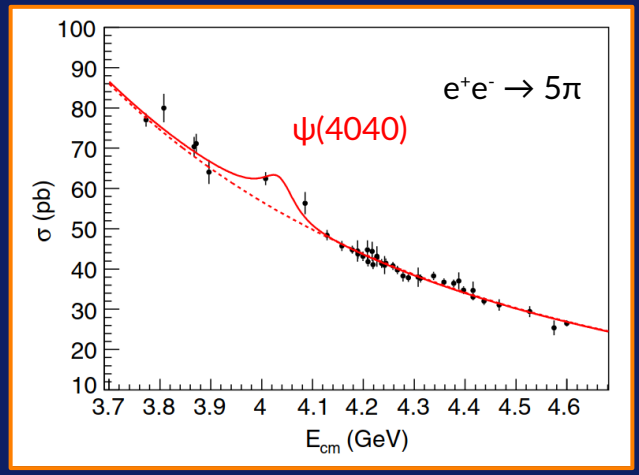


XYZ to light hadrons: $e^+e^- \to$ hadrons

PRD 104 (2021) 11, 112009

At present, charmonium(-like) states above 4 GeV has not been observed decaying into light hadrons.

BESIII reports a list of additional final state useful to add information

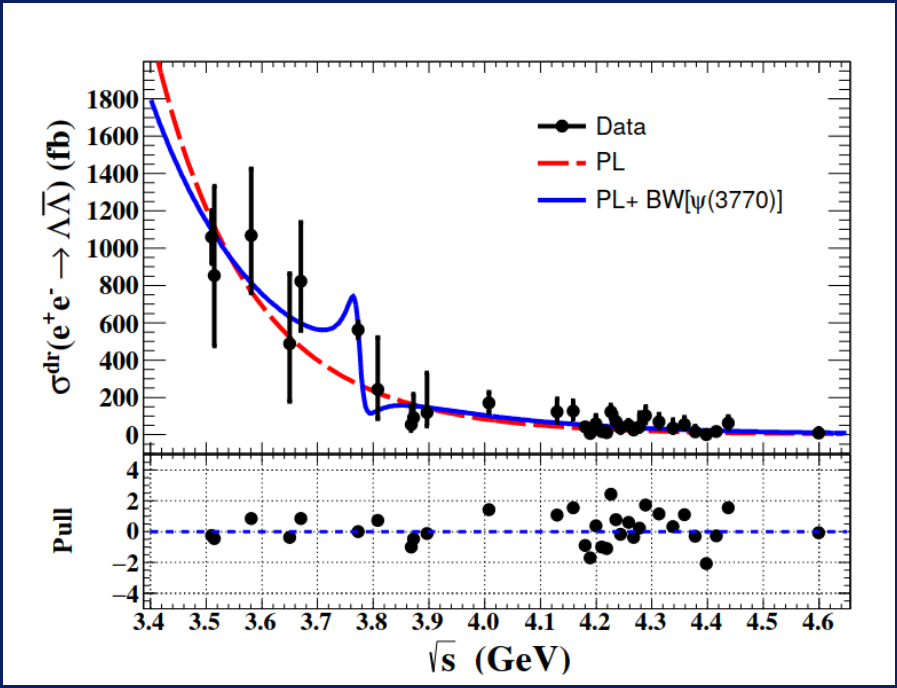


Mass and width fixed to PDG

Evidence of ψ(4040) → 5π at 3.6σ significance
Presented also upper limits for Y(4220)

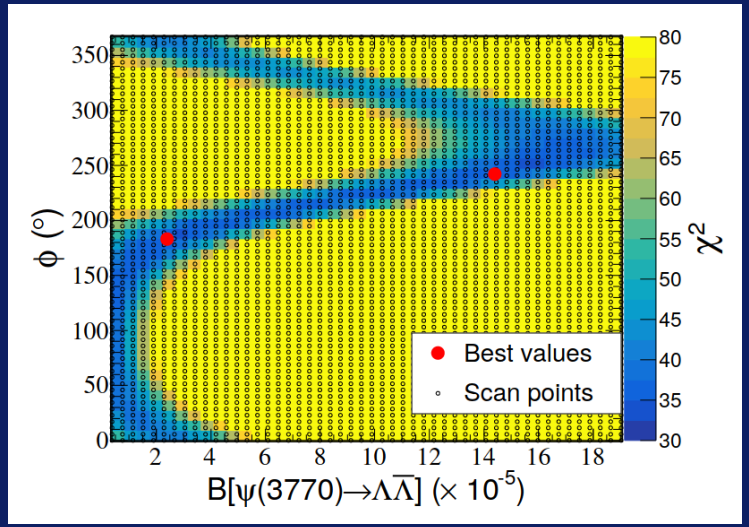
PRD 104, L091104 (2021)

XYZ to light hadrons: $e^+e^- \to \Lambda\bar{\Lambda}$



Study of charmonium-like decay to baryons provide insight:
- on the resonances nature
- on the electromagnetic structure of the baryons

Predictions based on scaling as electronic coupling gives B~5x10^{-7} at ψ(3770)



First evidence of ψ(3770) → $\Lambda\bar{\Lambda}$ decay, BF at least one order of magnitude larger than predicted.

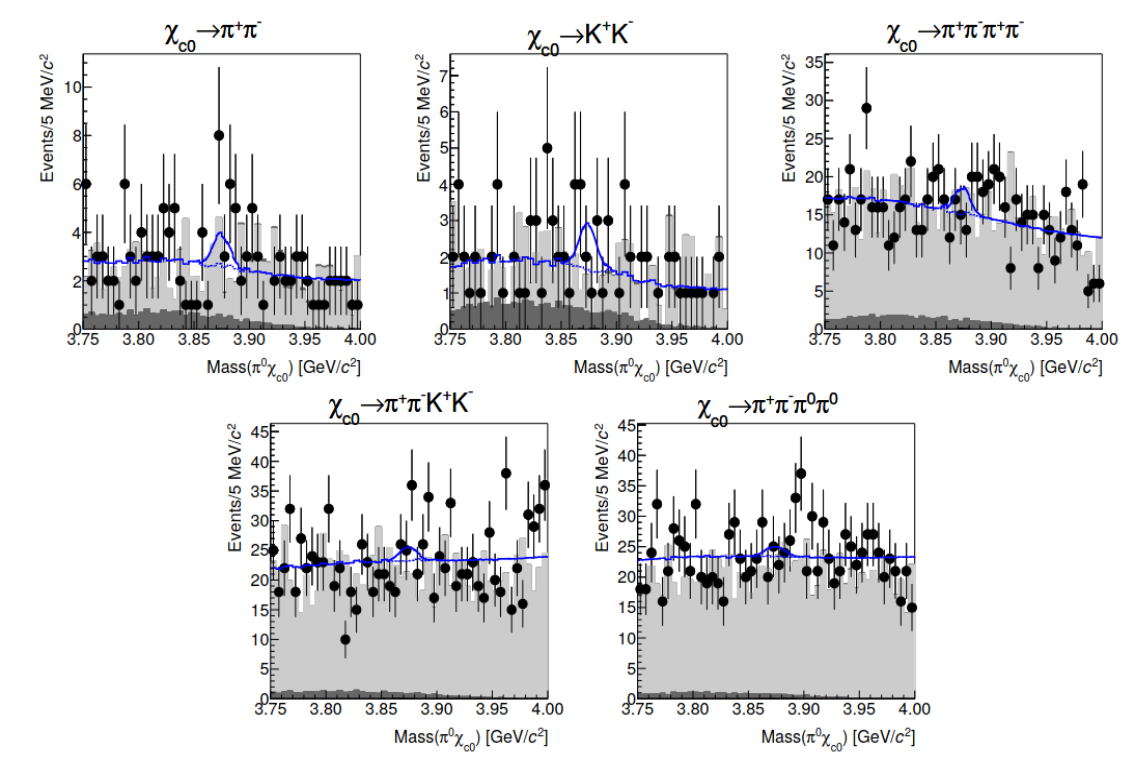
Only U.L. for other charmonium-like states

PRD 105 (2022) 7, 072009

Search for X(3872) → $\pi^0\chi_{c0}$ and X(3872) → $\pi\pi\chi_{c0}$

To understand the nature of X(3872), verify prediction to test the *charmonium-ness* of the state

Ratio	Central Value (Upper Limit)
$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$1.70^{+0.55}_{-0.75} \pm 0.40$ (3.6)
$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}$	$1.9^{+1.2}_{-0.7} \pm 0.5$ (4.4)
$\frac{\mathcal{B}(X(3872)\to\pi^+\pi^-\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$0.06^{+0.24}_{-0.23} \pm 0.12$ (0.68)
$\frac{\mathcal{B}(X(3872)\to\pi^0\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$-0.55^{+0.53}_{-0.42} \pm 0.33$ (1.7)

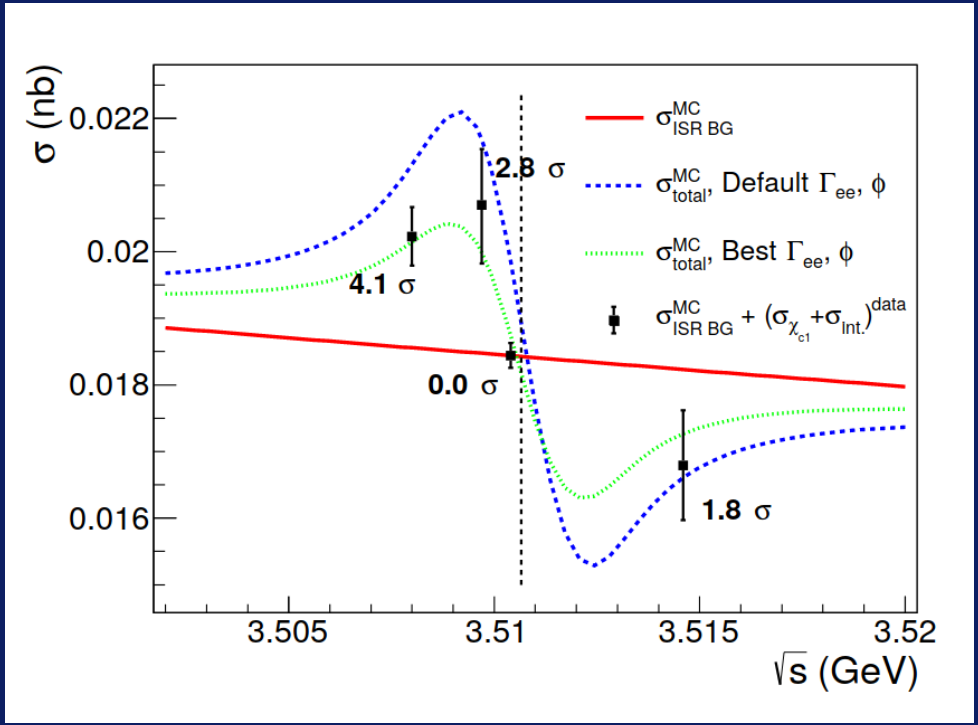


Using also PRL122 202001 (2019)

Upper limits (90% C.L.) still not conclusive.
New statistics will be collected with BEPCII-U

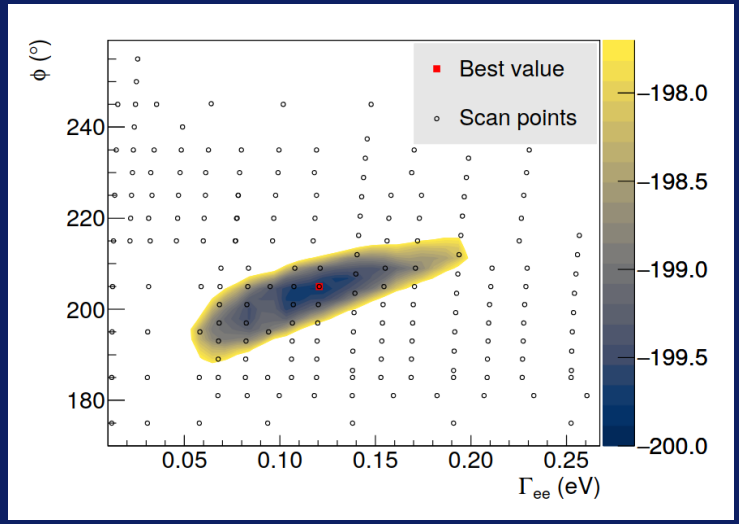
$\chi_{c1}(1P)$ direct production

ArXiv: 2203.13782



Study of $e^+e^- \rightarrow \gamma J/\psi$ to extract interference pattern

First observation (5σ) of χ_{c1} direct production at e^+e^- collider



Similar approach for X(3872).
Paper in preparation!

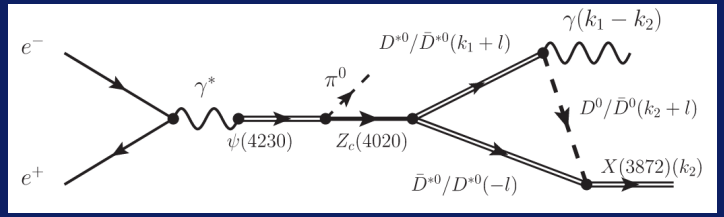
Electronic width same order of magnitude with theoretical calculation

PRD 104, 012001 (2021)

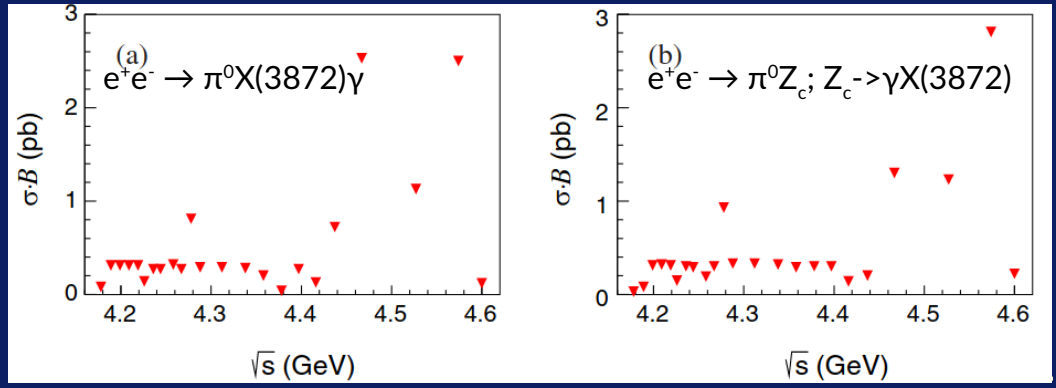
Connections

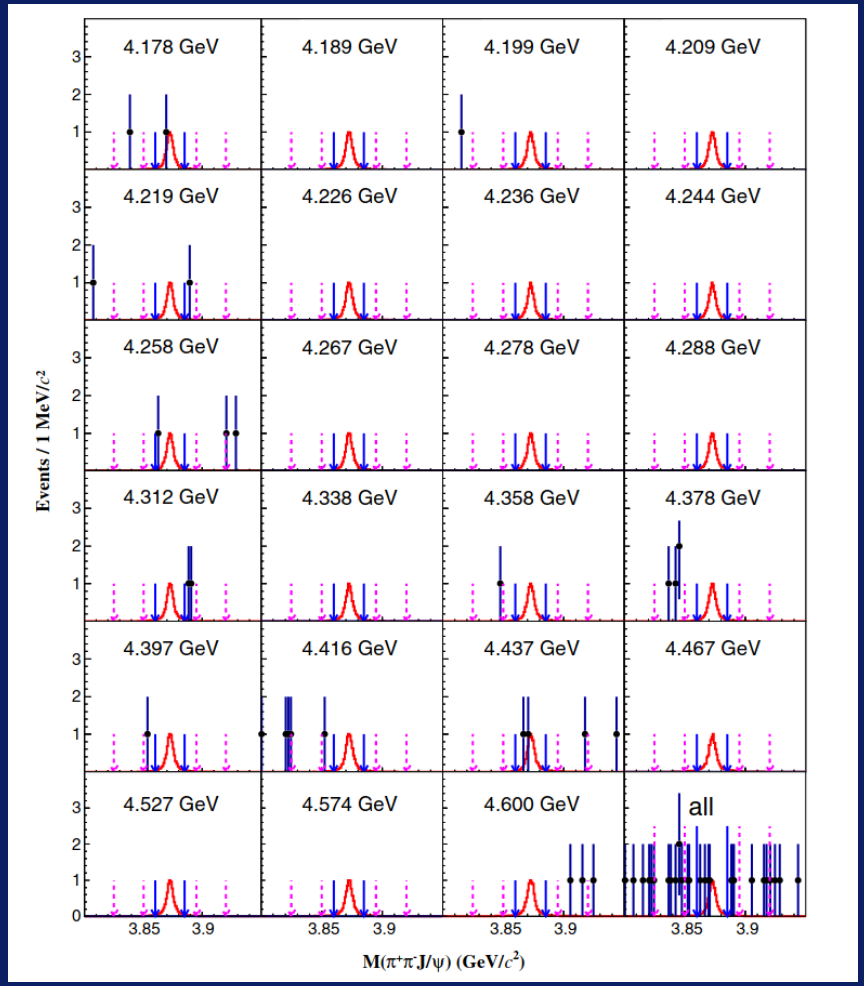
The process $e^+e^- \to \pi^0 Z_c$; $Z_c \to \gamma X(3872)$ can be useful:

- Study connections among the XYZ states
- Improve the measurement of the X(3872) mass, as proposed in PRD 102, 114041 (2020)



No signal found. Defined UL (90% CL)





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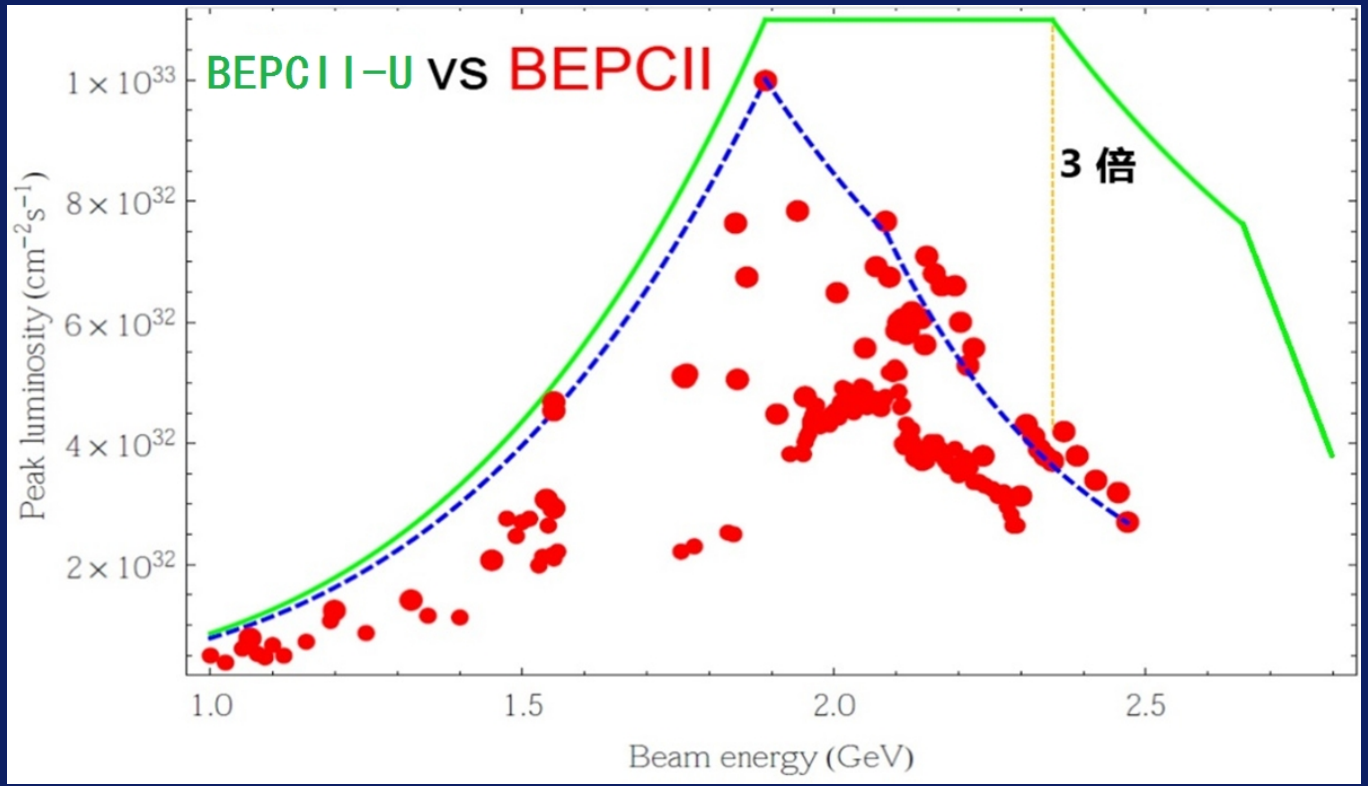


Accelerator upgrade:

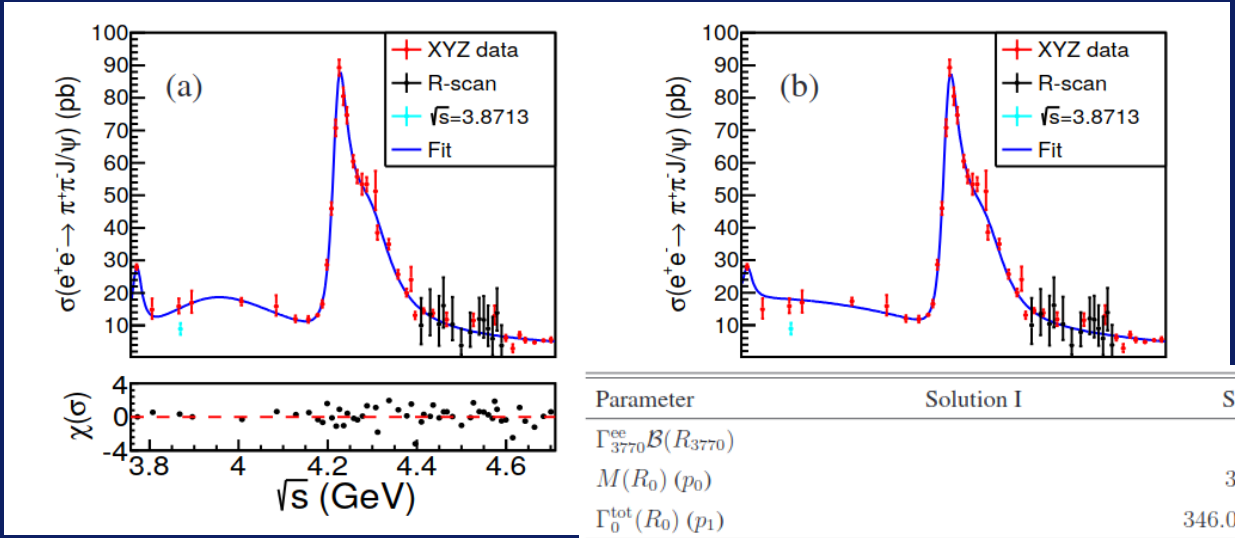
- center of mass maximum energy up to 5.6 GeV
- 3 times the present luminosity in XYZ region

Planned in 2024 with also new inner tracker based on cylindrical GEM


Thanks!

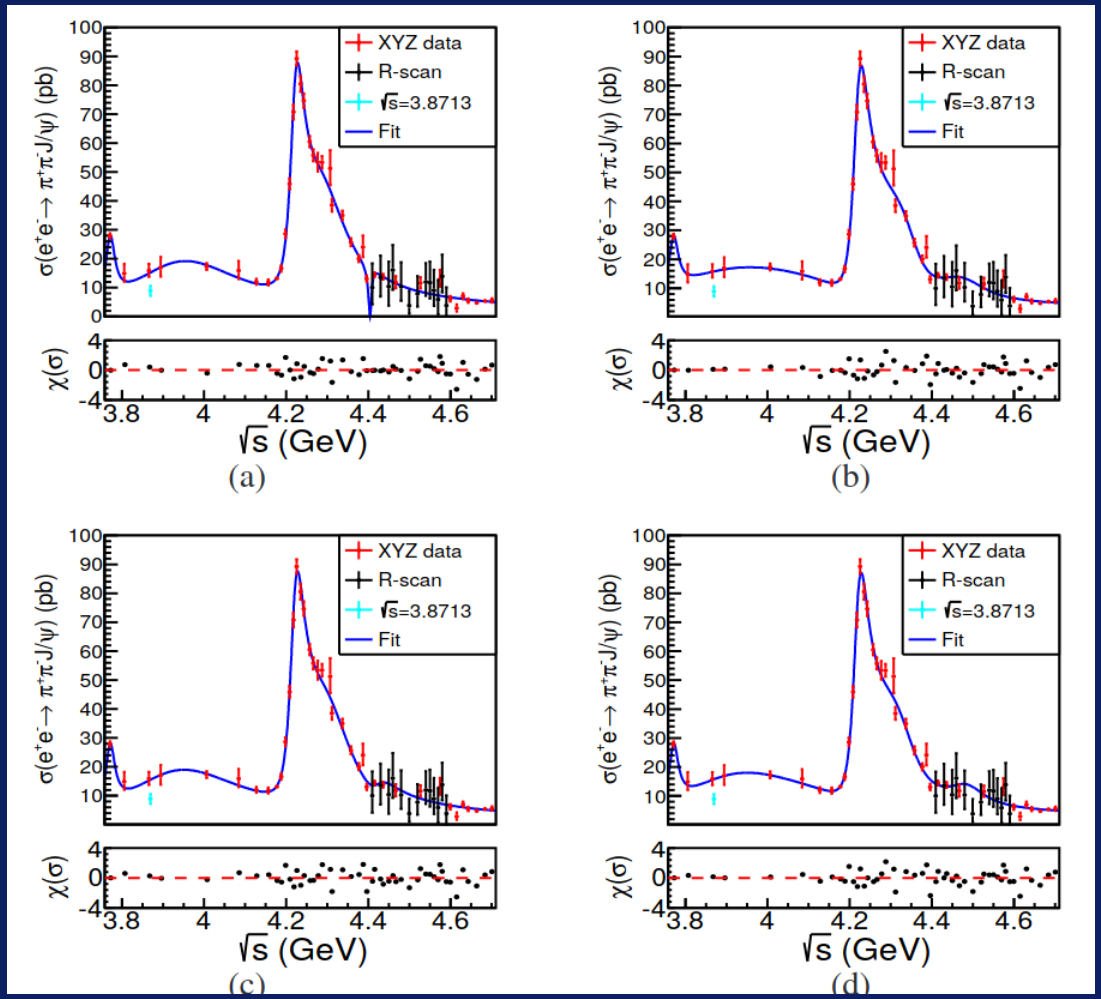
Additional Materials

Update of $e^+e^- \to \pi\pi J/psi$



Parameter	Solution I	Solution II	Solution III	Solution IV
$\Gamma^{ee}_{3770}\mathcal{B}(R_{3770})$		0.6 ± 0.1 (0.3 ± 0.1)		
$M(R_0)$ (p_0)		3905.5 ± 30.1 (4.4 ± 0.3)		
$\Gamma^{tot}_0(R_0)$ (p_1)		346.0 ± 48.5 $((2.7 \pm 0.6) \times 10^{-3})$		
$\Gamma^{ee}_0\mathcal{B}(R_0)$	5.5 ± 0.5 (...)	6.9 ± 0.7 (...)	8.3 ± 0.6 (...)	10.5 ± 0.9 (...)
$M(R_1)$		4221.4 ± 1.5 (4220.1 ± 1.2)		
$\Gamma^{tot}_1(R_1)$		41.8 ± 2.9 (43.6 ± 2.6)		
$\Gamma^{ee}_1\mathcal{B}(R_1)$	1.7 ± 0.2 (1.7 ± 0.2)	8.2 ± 0.9 (8.6 ± 0.5)	3.0 ± 0.5 (2.5 ± 0.3)	14.6 ± 1.2 (12.7 ± 0.8)
$M(R_2)$		4297.5 ± 12.1 (4316.2 ± 12.4)		
$\Gamma^{tot}_2(R_2)$		126.6 ± 16.7 (124.3 ± 18.0)		
$\Gamma^{ee}_2\mathcal{B}(R_2)$	1.2 ± 0.3 (0.7 ± 0.2)	2.3 ± 0.8 (1.1 ± 0.3)	15.6 ± 2.1 (15.0 ± 1.2)	30.2 ± 3.3 (23.6 ± 2.9)
ϕ_1	-3.7 ± 5.4 (-24.3 ± 3.0)	-124.6 ± 11.7 (78.8 ± 5.1)	87.7 ± 21.9 (-88.0 ± 12.1)	-33.5 ± 11.2 (15.1 ± 7.8)
ϕ_2	79.6 ± 18.5 (106.4 ± 16.5)	35.8 ± 27.2 (-184.6 ± 15.1)	-104.7 ± 26.9 (179.5 ± 9.1)	-148.7 ± 4.5 (-112.5 ± 6.2)
χ^2/ndf		54.0/40 (57.3/41)		

Update of $e^+e^- \to \pi\pi J/psi$ - II



Parameter	Result I	Result II
$M(R_1)$	4221.0 ± 1.6 (4220.3 ± 1.6)	4219.8 ± 1.3 (4219.1 ± 1.2)
$\Gamma_1^{\rm tot}(R_1)$	41.0 ± 3.0 (42.3 ± 3.0)	45.4 ± 2.8 (46.3 ± 2.5)
$M(R_2)$	4293.7 ± 13.1 (4304.8 ± 18.8)	4345.8 ± 28.4 (4357.9 ± 20.2)
$\Gamma_2^{\rm tot}(R_2)$	152.4 ± 23.9 (144.3 ± 31.5)	130.1 ± 20.7 (107.9 ± 25.6)
$M(R_2)$	4405.6 ± 4.5 (4405.0 ± 6.7)	4471.1 ± 36.2 (4550.9 ± 16.9)
$\Gamma_3^{\rm tot}(R_3)$	9.1 ± 2.5 (8.7 ± 4.9)	159.7 ± 97.0 (211.8 ± 132.8)
χ^2/ndf	40.1/36 (44.8/37)	47.6/36 (48.7/37)
Significance	4.0σ (3.6σ)	2.1σ (2.7σ)

Parameter	Result III	Result IV
$M(R_1)$	4223.9 ± 1.4 (4219.6 ± 1.3)	4220.2 ± 1.3 (4219.4 ± 1.1)
$\Gamma_1^{\rm tot}(R_1)$	42.2 ± 3.2 (44.3 ± 2.7)	44.5 ± 2.9 (45.3 ± 2.5)
$M(R_2)$	4308.5 ± 17.6 (4333.2 ± 23.2)	4328.58 ± 18.9 (4347.1 ± 14.5)
$\Gamma_2^{\rm tot}(R_2)$	161.4 ± 24.6 (153.2 ± 26.2)	133.8 ± 20.2 (127.5 ± 22.2)
$M(R_2)$	4421 (fixed)	4485 (fixed)
$\Gamma_3^{\rm tot}(R_3)$	62 (fixed)	111 (fixed)
χ^2/ndf	45.4/38 (48.7/39)	48.1/38 (51.3/39)
Significance	3.3σ (3.3σ)	2.6σ (3.1σ)