

New results on exotic hadrons at BESIII

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(for the BESIII Collaboration)

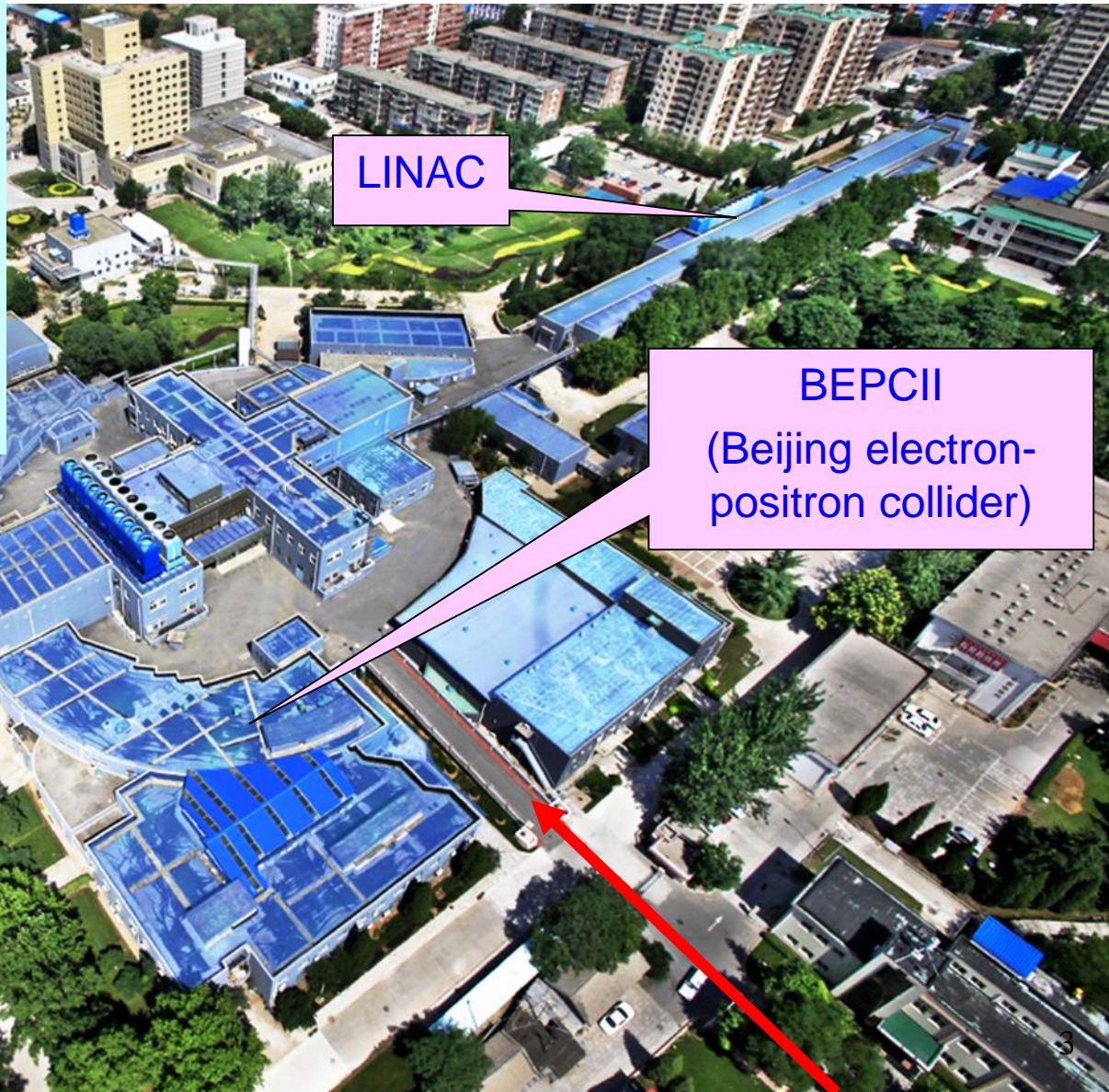
Stony Brook, May 29, 2018

Outline

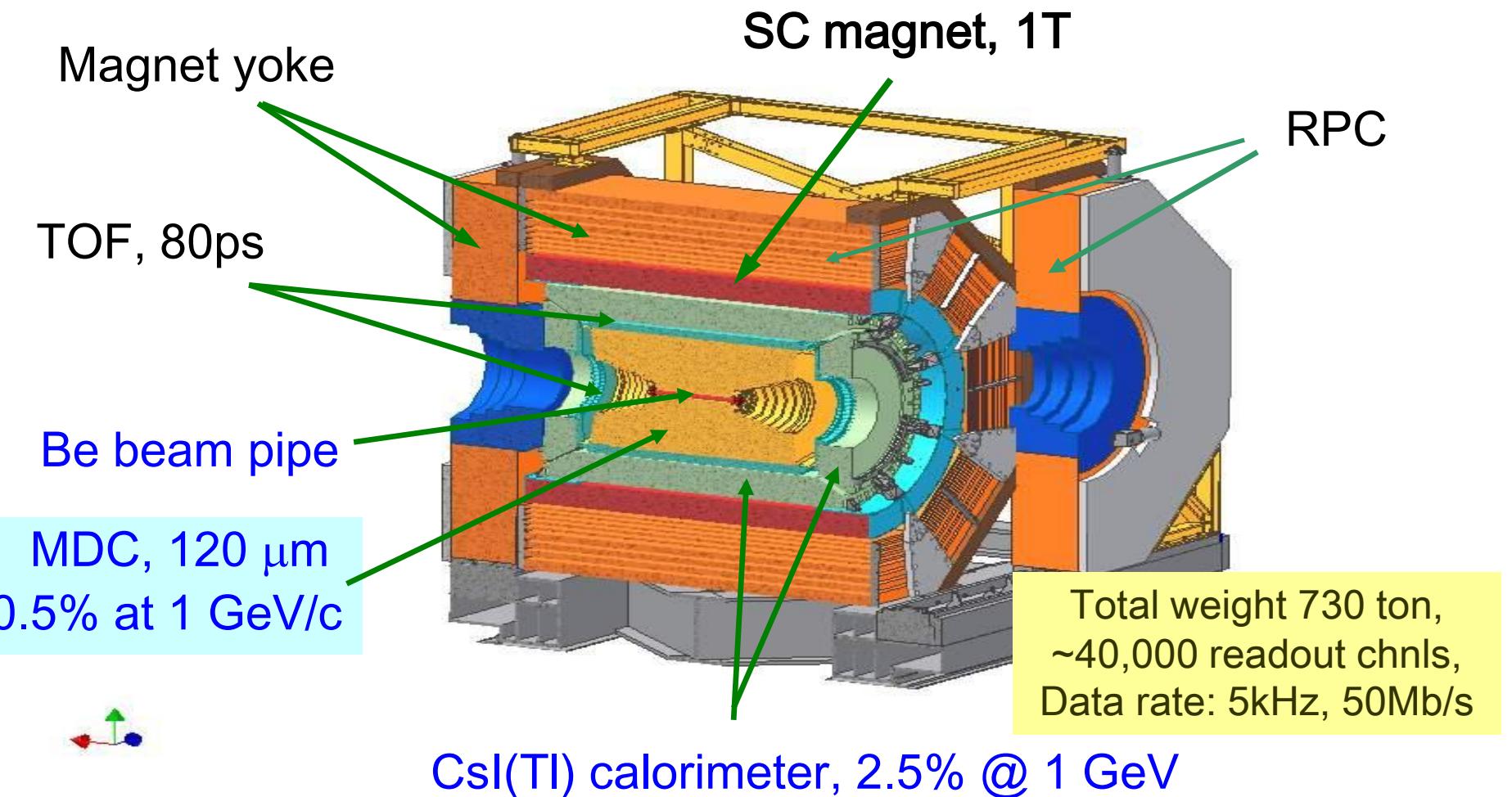
- The BESIII experiment
- charmoniumlike states
 - The Y states — $J^{PC}=1^{--}$
 - The Z_c states — $|=1$ & decays into $\bar{c}c$
- Summary

Beijing Electron Positron Collider (BEPC)

- Founded: 1984
 $E_{cm} = 2.0\text{-}4.6 \text{ GeV}$
- 1989-2005 (BEPC):
 $L_{peak} = 1.0 \times 10^{31} / \text{cm}^2\text{s}$
- 2008-now (BEPCII):
 $L_{peak} = 1.0 \times 10^{33} / \text{cm}^2\text{s}$
(Apr. 5, 2016)

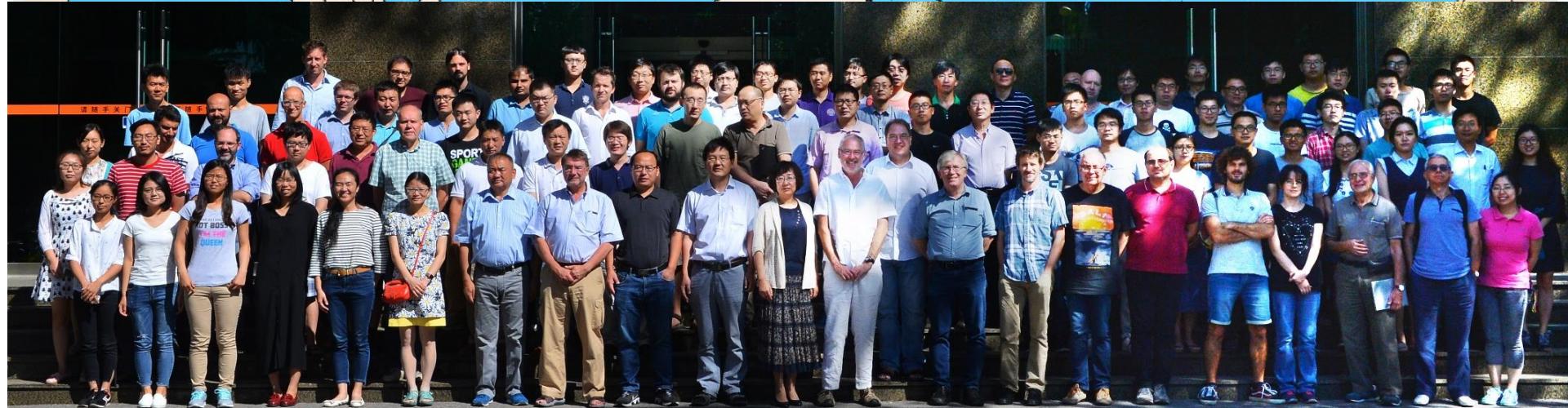
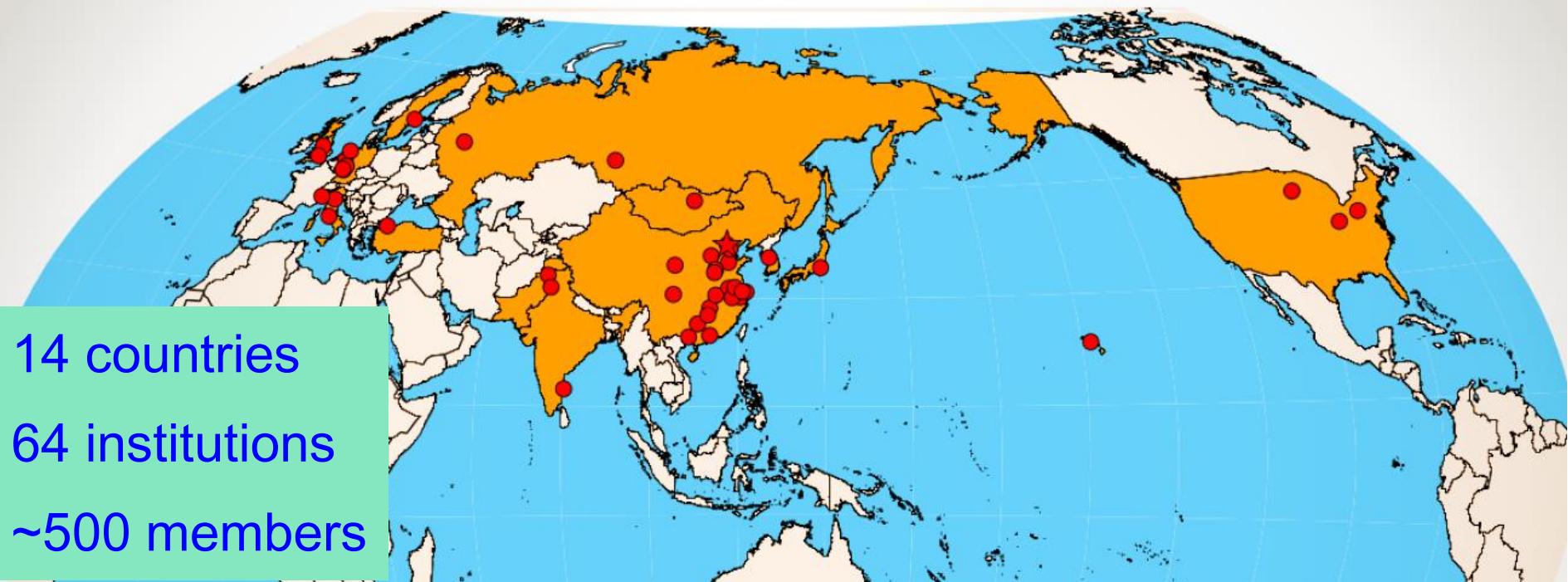


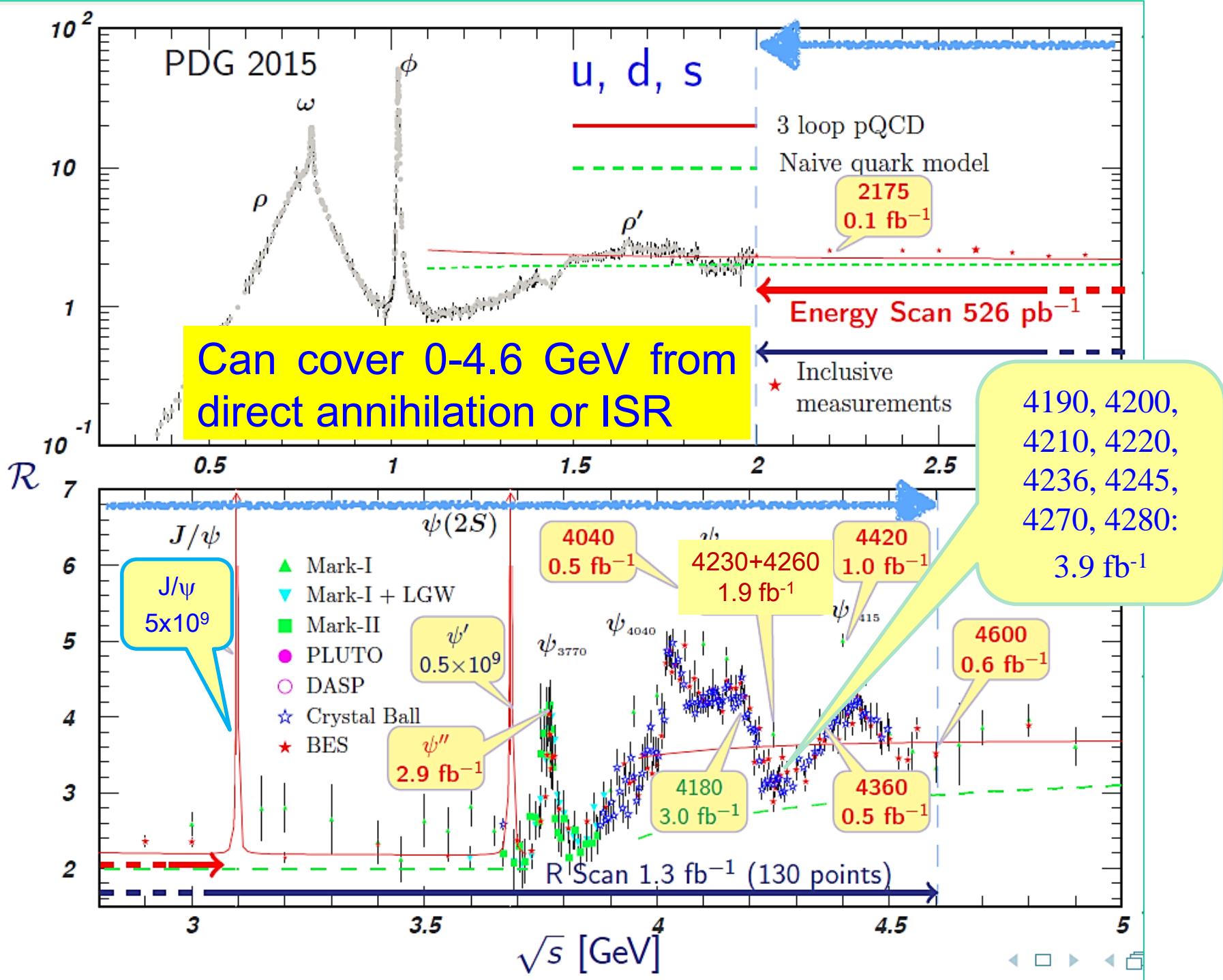
BESIII Detector



Has been in full operation since 2008,
all subdetectors are in very good status!

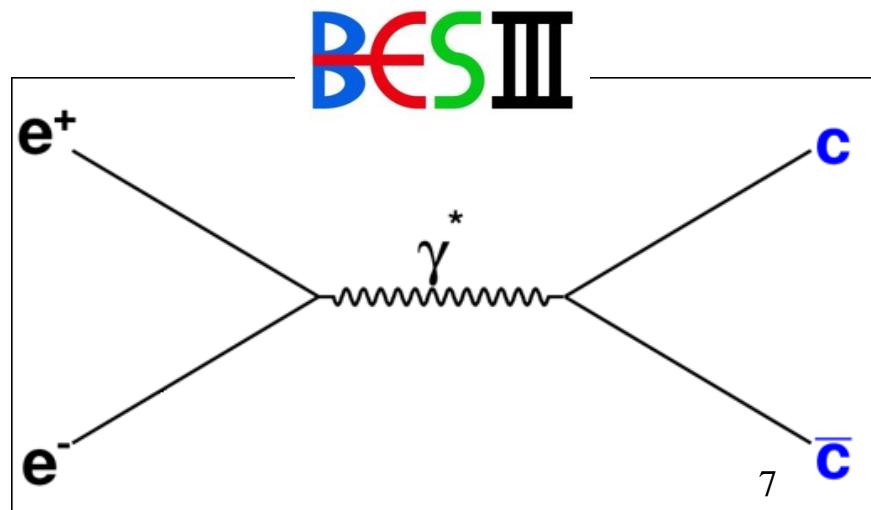
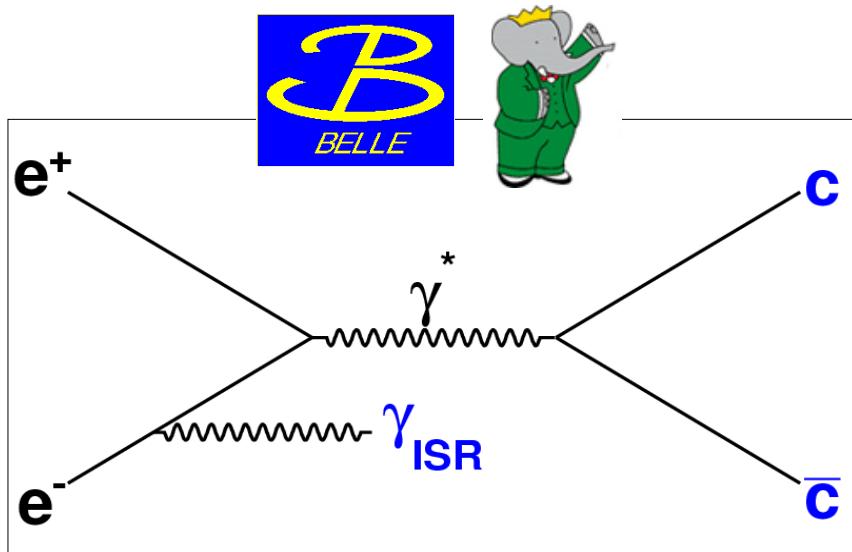
BESIII Collaboration





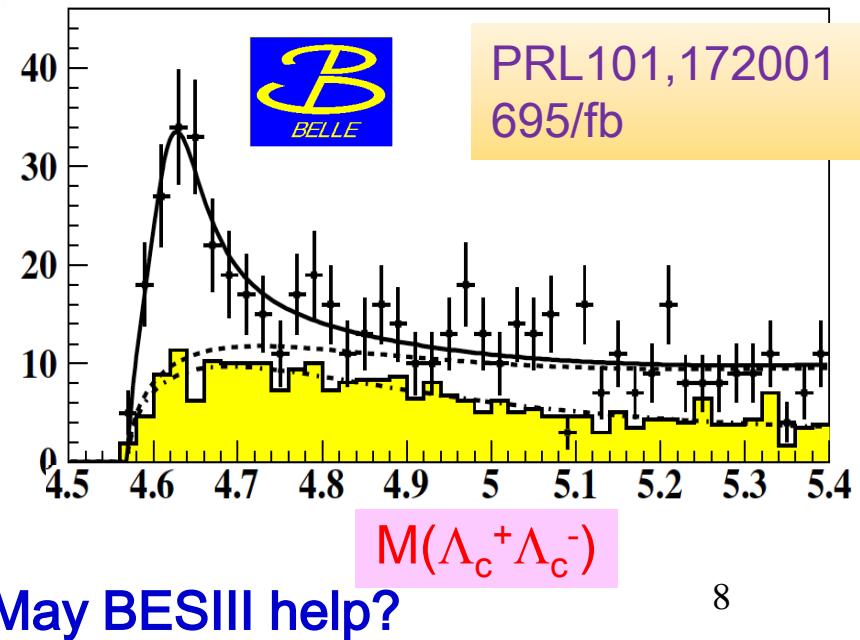
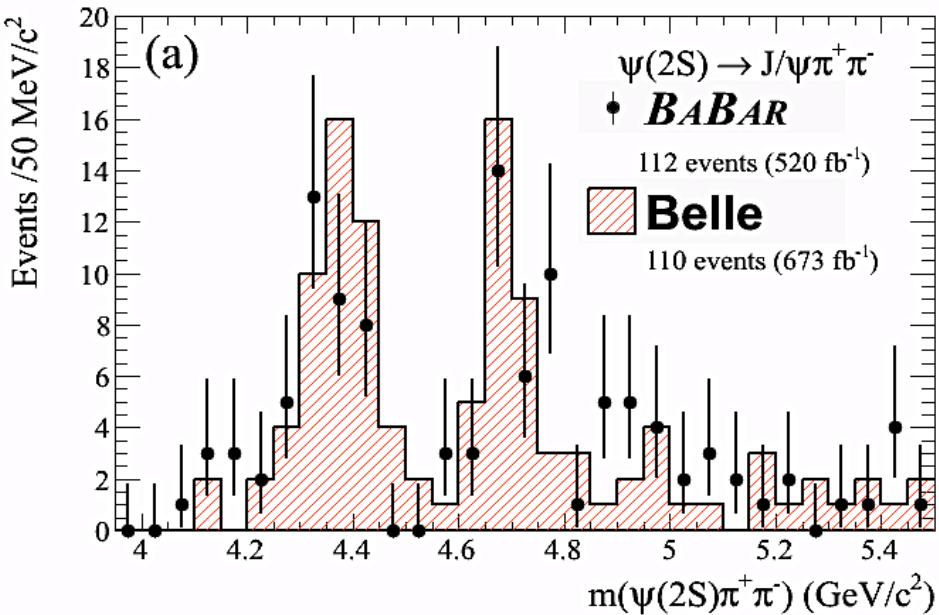
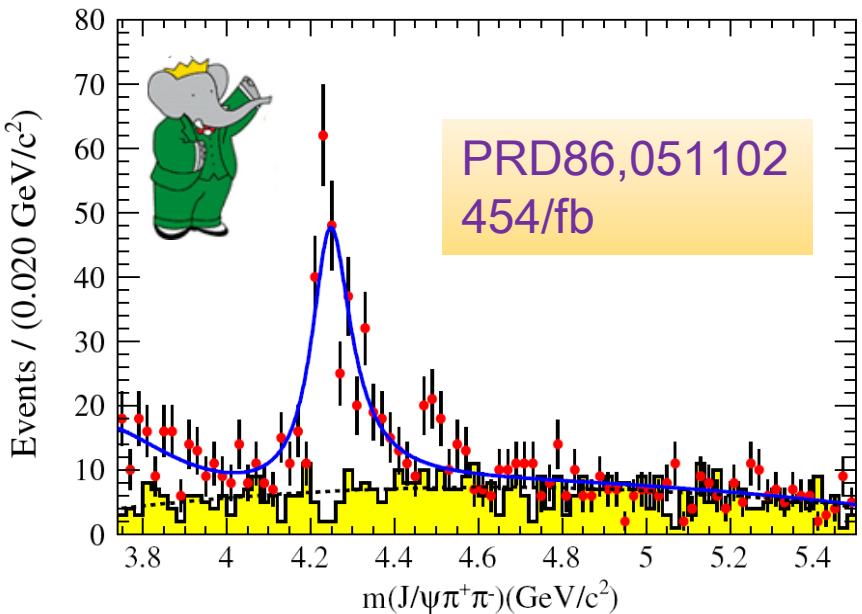
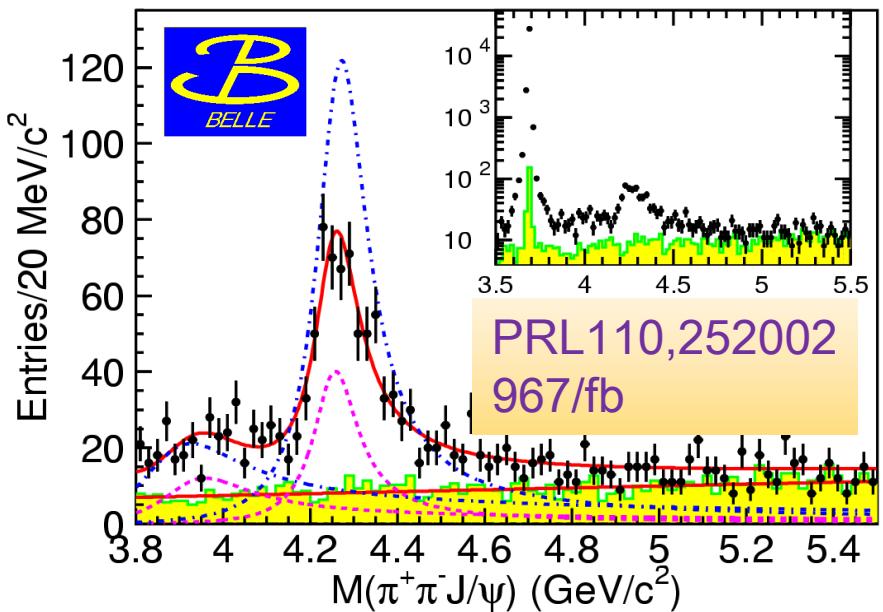
The Y states

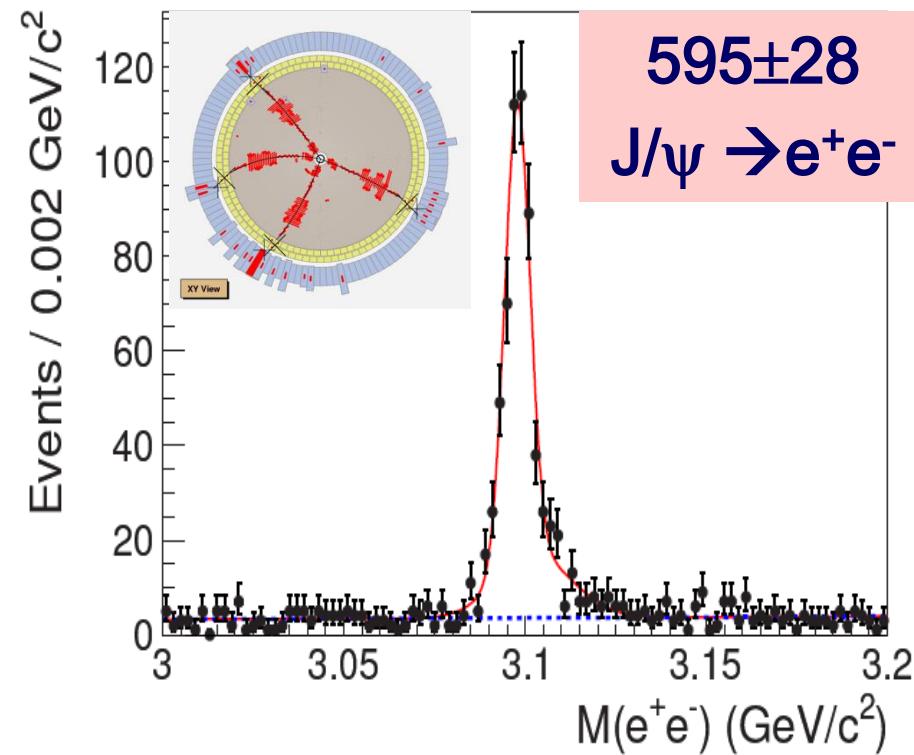
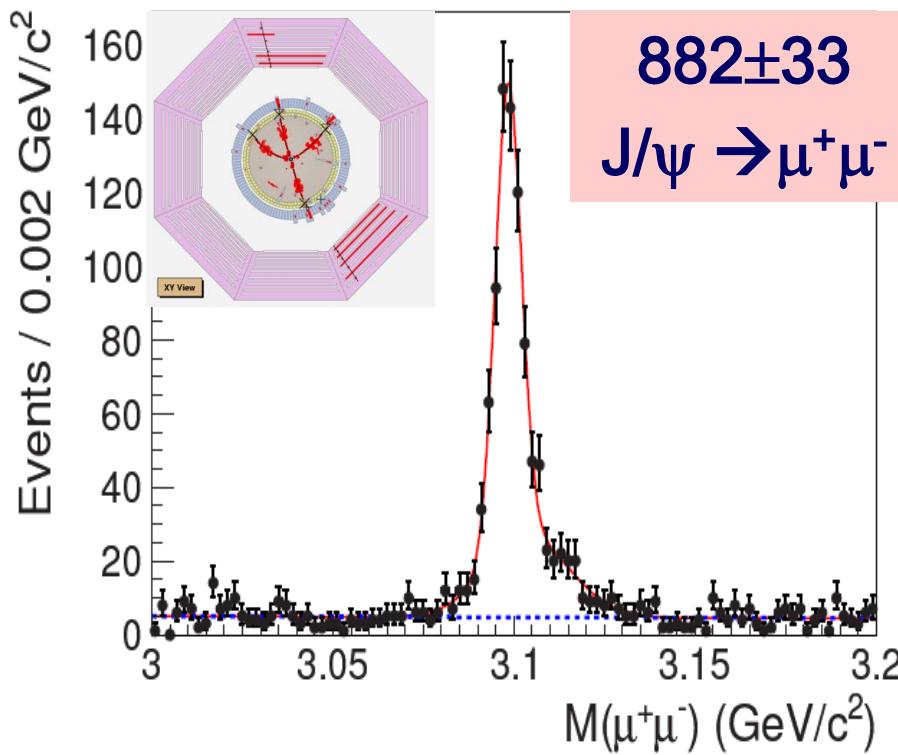
measurements of more final states for the
Y and ψ states



The Y states

Belle: PRL99,142002, 670/fb
 BaBar: PRD89, 111103, 520/fb

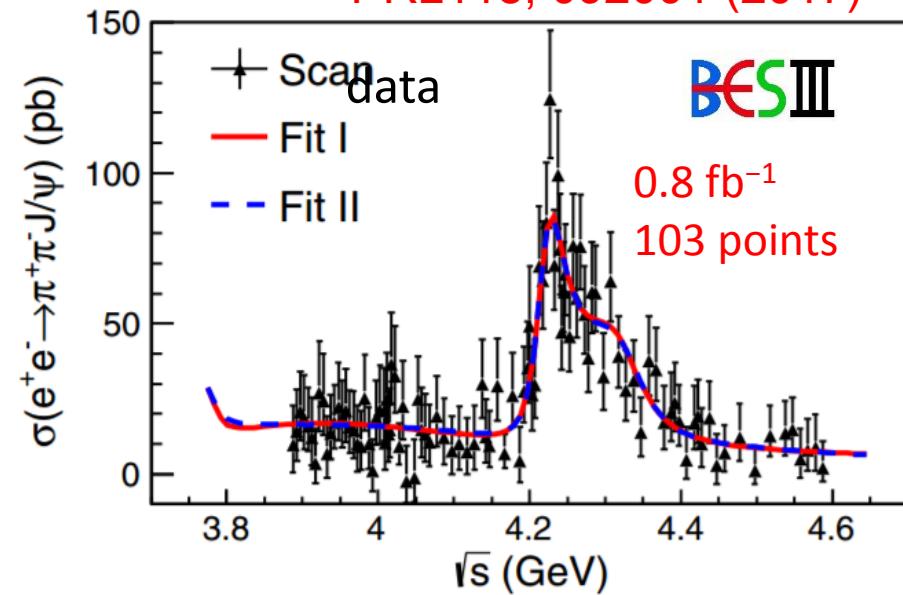
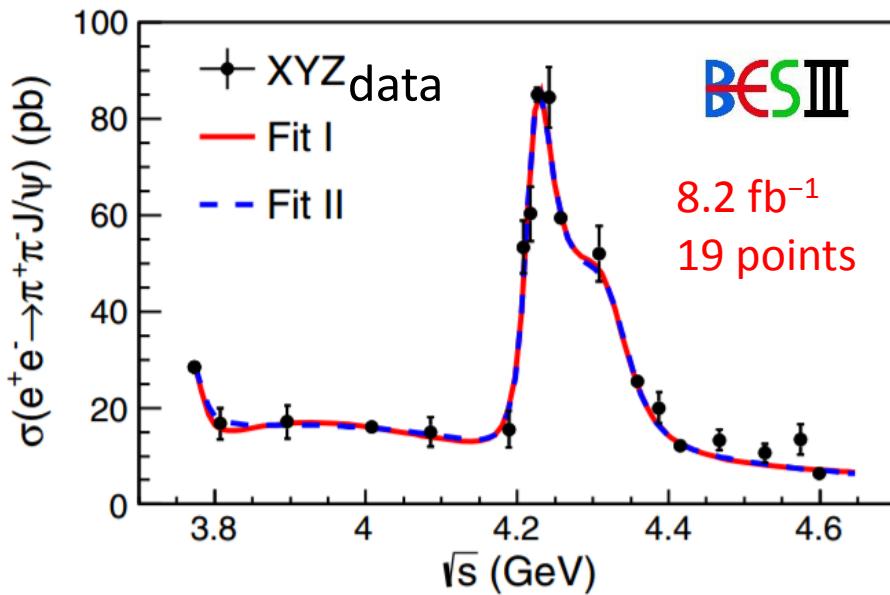


$e^+e^- \rightarrow \pi^+\pi^-J/\psi$ at 4.26 GeV

- Select 4 charged tracks and reconstruct J/ψ with lepton pair.
- Very clean sample, very high efficiency ($\sim 45\%$).
- $\sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi) = (62.9 \pm 1.9 \pm 3.7) \text{ pb}$

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

PRL 118, 092001 (2017)



- Most precise cross section measurement to date from BESIII
- $\text{Fit I} = |\text{BW}_1 + \text{BW}_2 * e^{i\phi_2} + \text{BW}_3 * e^{i\phi_3}|^2$ or $\text{Fit II} = |\exp + \text{BW}_2 * e^{i\phi_2} + \text{BW}_3 * e^{i\phi_3}|^2$ (other fits ruled out)

$$M = 4222.0 \pm 3.1 \pm 1.4 \text{ MeV (lower)}$$

$$\Gamma = 44.1 \pm 4.3 \pm 2.0 \text{ MeV (narrower)}$$

 $X(4260)$ MASS 4251 ± 9

AVERAGE

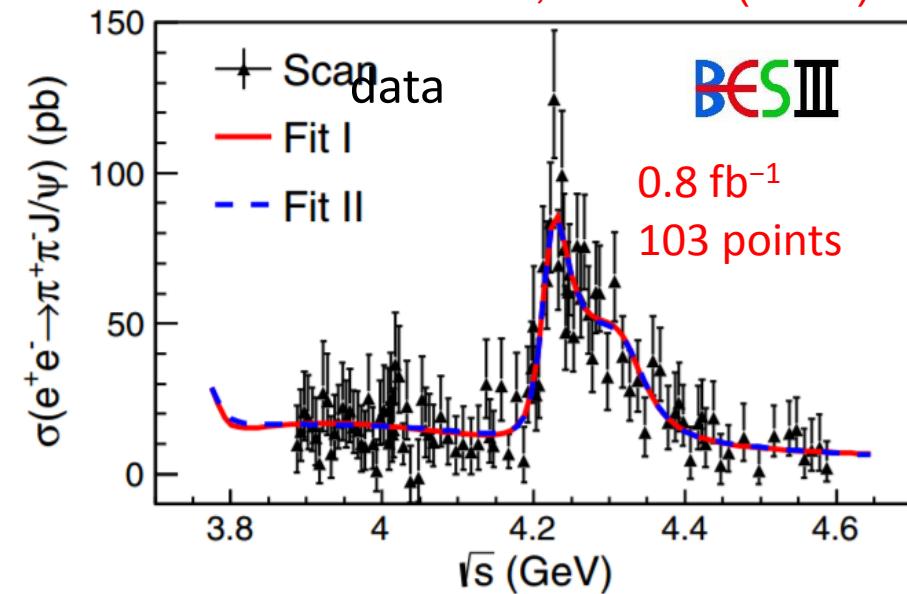
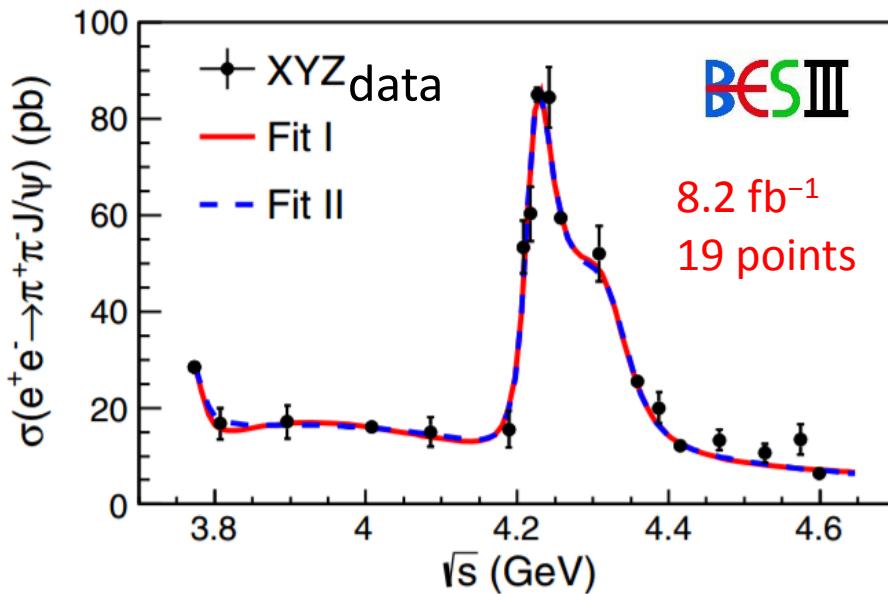
PDG

 $X(4260)$ WIDTH 120 ± 12

AVERAGE

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

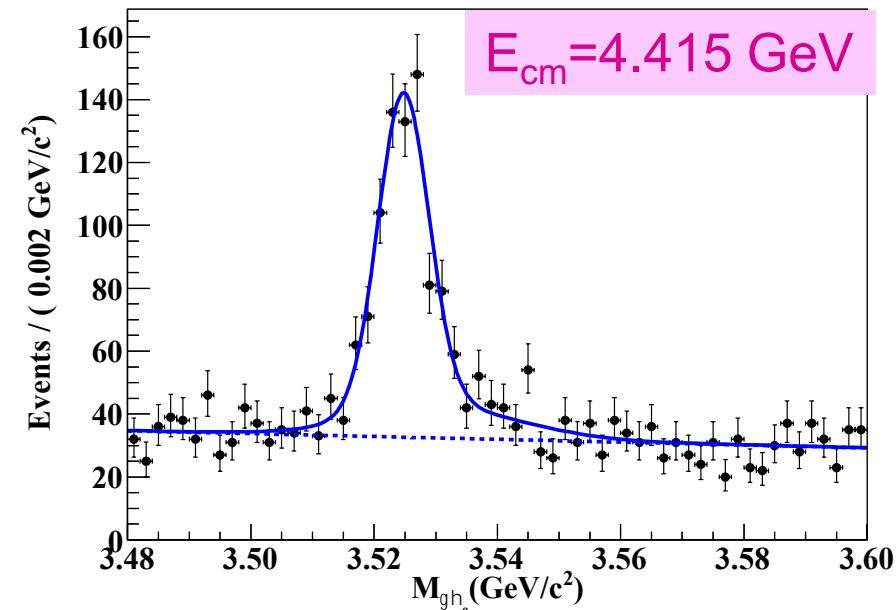
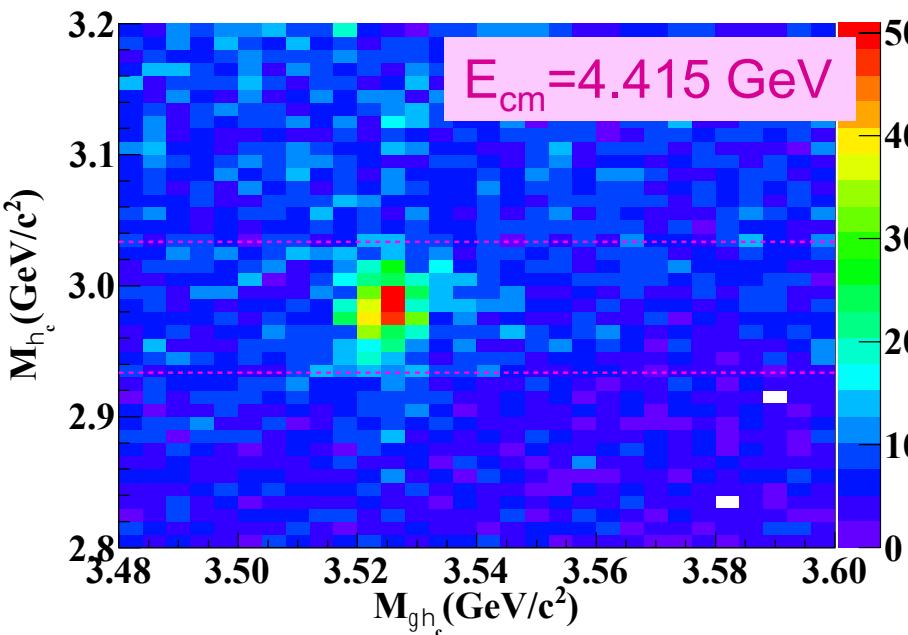
PRL118, 092001 (2017)



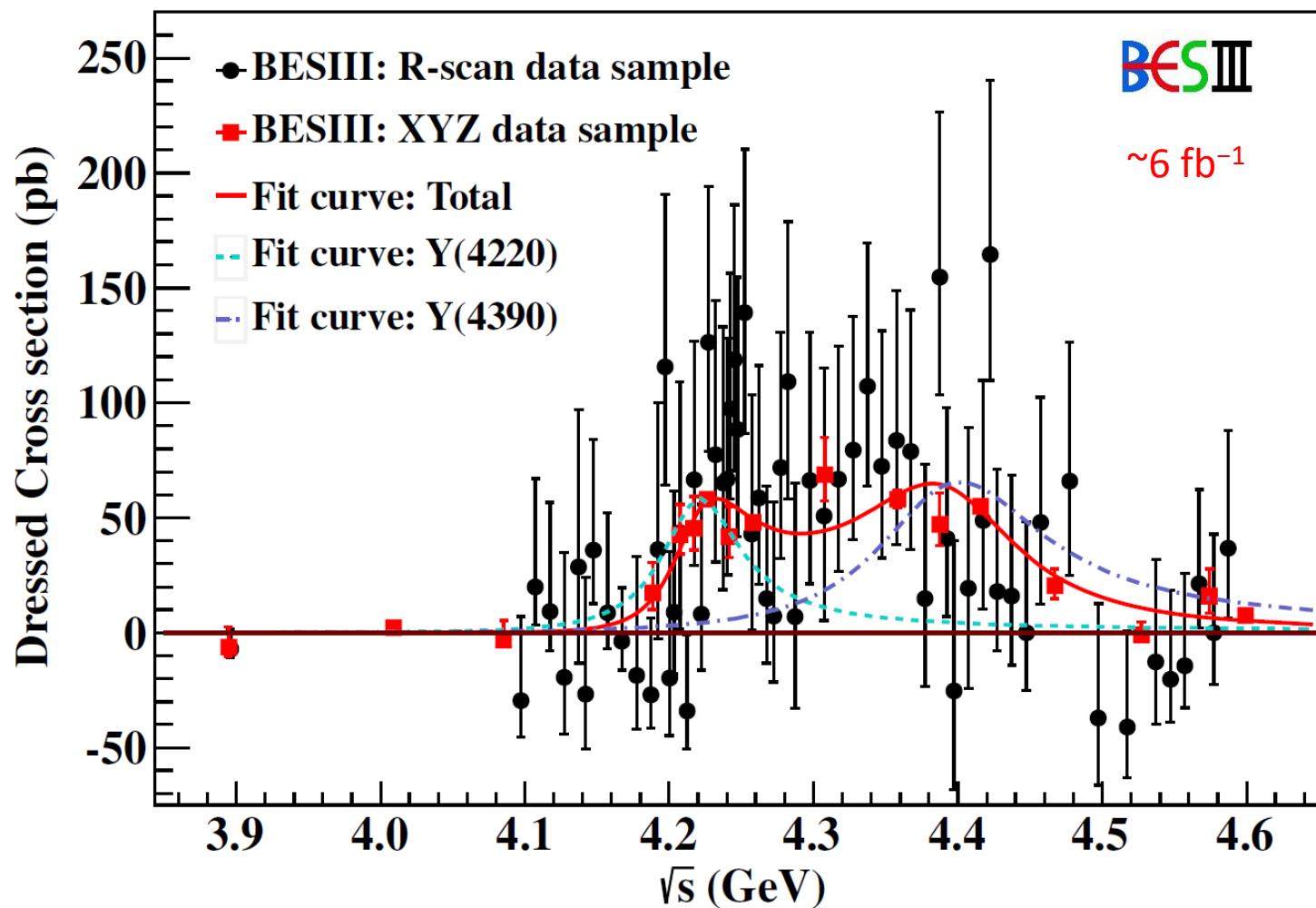
- Most precise cross section measurement to date from BESIII
- $\text{Fit I} = |\text{BW}_1 + \text{BW}_2 * e^{i\phi_2} + \text{BW}_3 * e^{i\phi_3}|^2$ or $\text{Fit II} = |\exp + \text{BW}_2 * e^{i\phi_2} + \text{BW}_3 * e^{i\phi_3}|^2$ (other fits ruled out)
- $M = 4222.0 \pm 3.1 \pm 1.4 \text{ MeV}$ (lower)
- $\Gamma = 44.1 \pm 4.3 \pm 2.0 \text{ MeV}$ (narrower)
- A 2nd resonance Y_2 with $M=4320.0 \pm 10.4 \pm 7.0 \text{ MeV}/c^2$
 $\Gamma=101.4^{+25.3}_{-19.7} \pm 10.2 \text{ MeV}$
- Observed for the first time, significance $> 7.6\sigma$

$e^+e^- \rightarrow \pi^+\pi^- h_c(1P)$

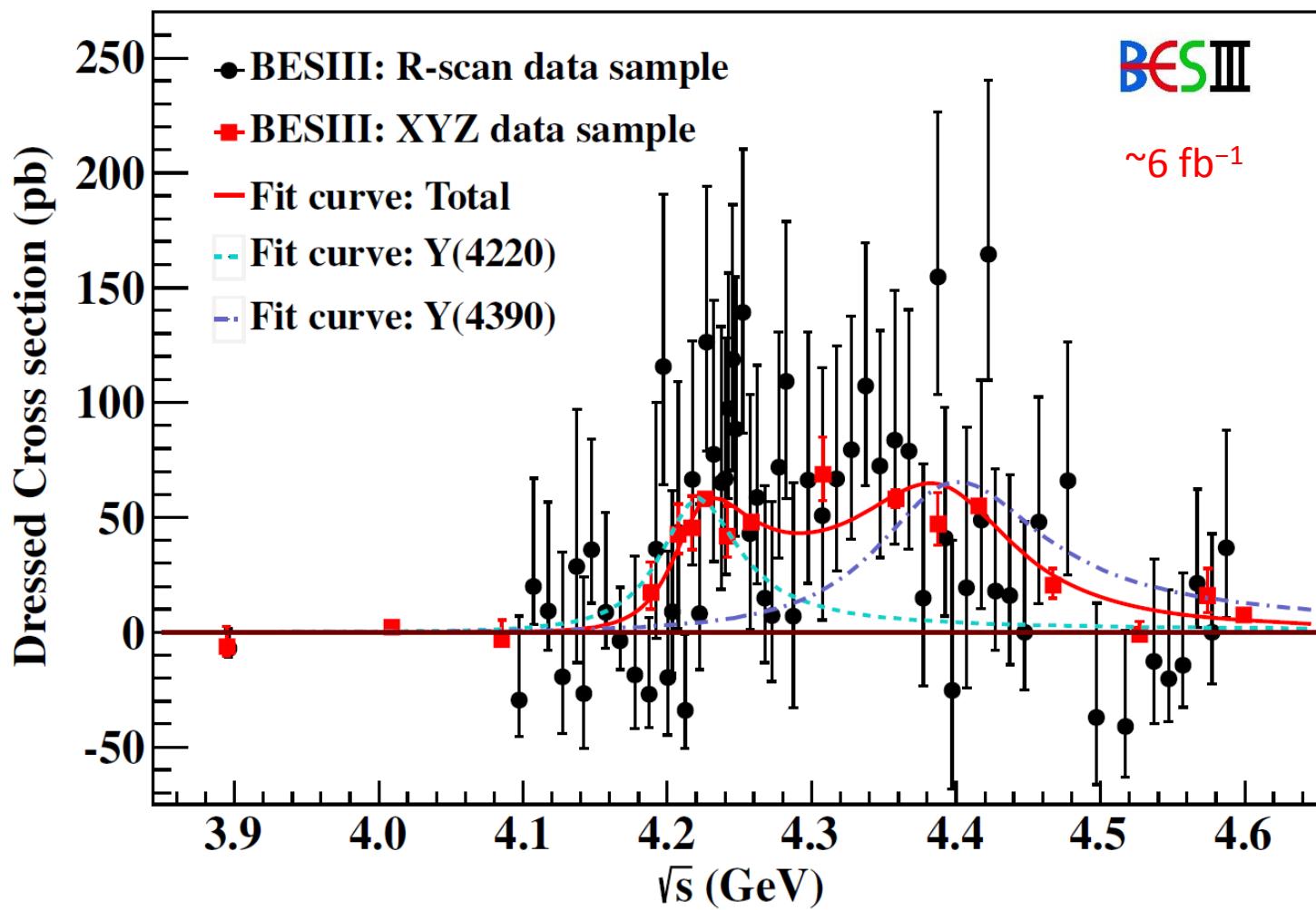
- $h_c \rightarrow \gamma\eta_c, \eta_c \rightarrow \text{hadrons}$ [16 exclusive decay modes]
 - pp, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-pp$, 2(K^+K^-), 2($\pi^+\pi^-$), 3($\pi^+\pi^-$)
 - 2($\pi^+\pi^-$) K^+K^- , $K_S^0 K^+\pi^- + \text{c.c.}$, $K_S^0 K^+\pi^-\pi^+\pi^- + \text{c.c.}$, $K^+K^-\pi^0$
 - $pp\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\pi^0$, 2($\pi^+\pi^-$) η , 2($\pi^+\pi^-$) π^0



Method same as in PRL111, 242001 (2013)



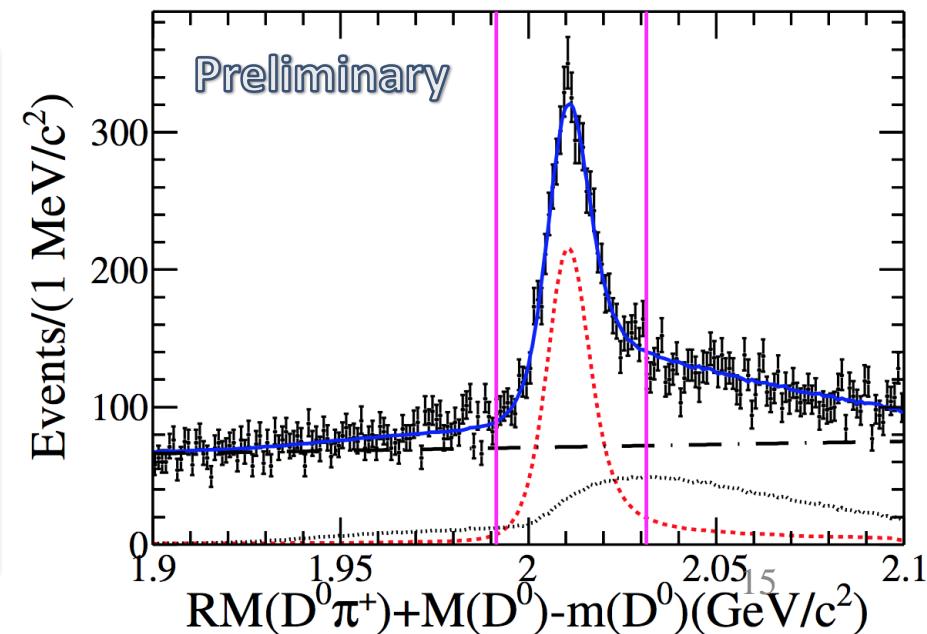
- First precise cross section measurement from threshold to 4.6 GeV
- Fit with $|BW_1 + BW_2 * e^{i\phi_2}|^2$, two resonant structures are evident



- $\triangleright M_1 = 4218.4^{+5.5}_{-4.5} \pm 0.9 \text{ MeV}/c^2, \Gamma_1 = 66.0^{+12.3}_{-8.3} \pm 0.4 \text{ MeV} \rightarrow Y(4220)$
- $\triangleright M_2 = 4391.5^{+6.3}_{-6.8} \pm 1.0 \text{ MeV}/c^2, \Gamma_2 = 139.5^{+16.2}_{-20.6} \pm 0.6 \text{ MeV} \rightarrow Y(4390)$

- Reconstruct $D^0 \rightarrow K^-\pi^+$
- Select the combination closest to D^0 mass ($m(D^0)$)
- Find an additional π^+ ;
- $1.9 < M(D^{*-}) (RM(D^0\pi^+) + M(D^0) - m(D^0)) < 2.1 \text{ GeV}/c^2$
- select the candidate closest to D^{*-} mass

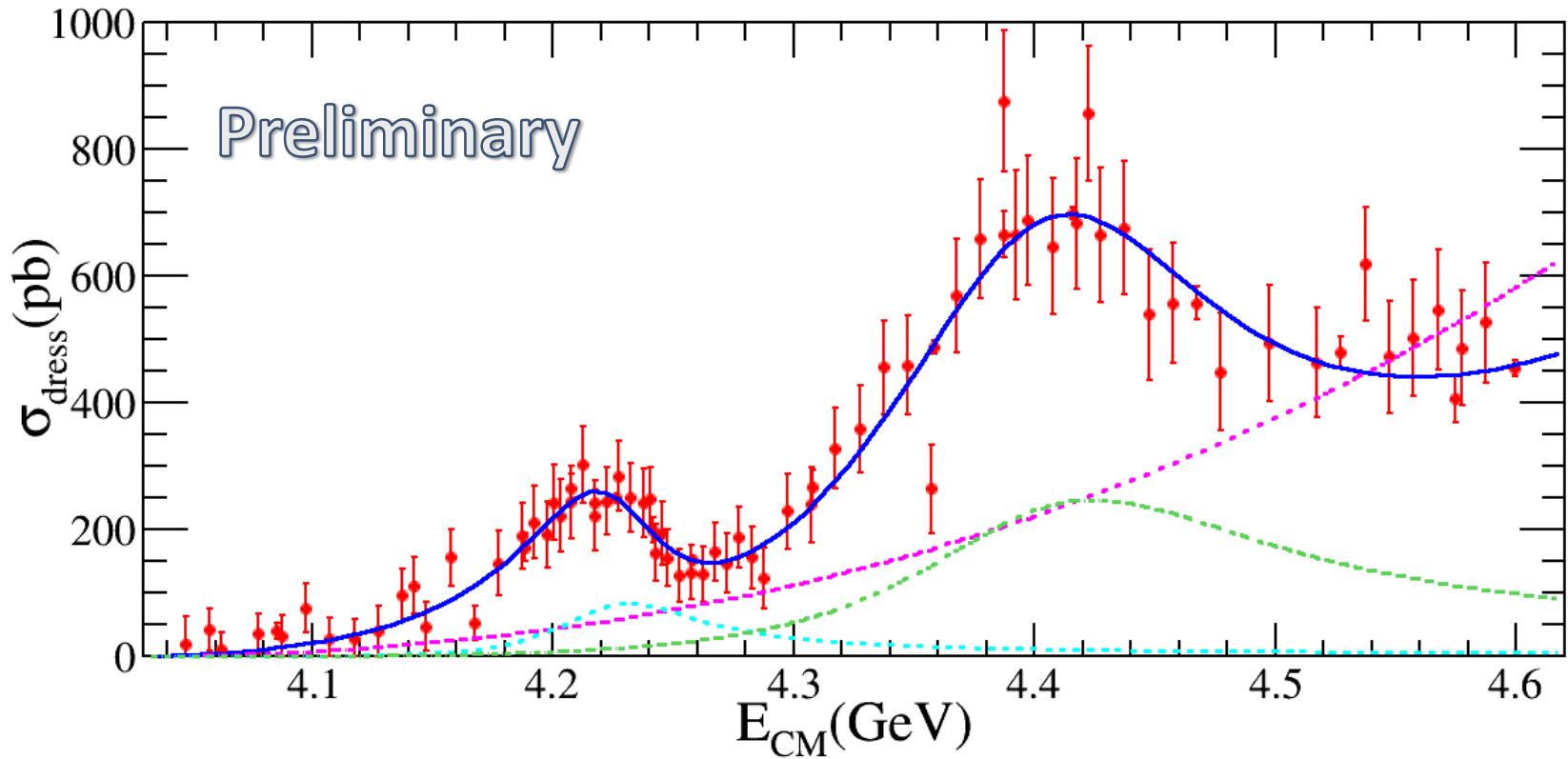
- An un-binned maximum likelihood fit
- Signal shape: MC convolved with a Gaussian;
- The isospin partner background (dotted line) is parameterized with MC;
- A linear function for other bkg



Fit to the dressed Xsection of $e^+e^- \rightarrow \pi^+ D^0 D^{*-} + c.c.$

$$\sigma_{dress} = \frac{N^{obs}}{\mathcal{L}(1 + \delta r)B(D^0 \rightarrow K^-\pi^+)\varepsilon}$$

$$\sigma_{dress}(m) = |c \cdot \sqrt{P(m)} + e^{i\phi_1} B_1(m) \sqrt{\frac{P(m)}{P(M_1)}} + e^{i\phi_2} B_2(m) \sqrt{\frac{P(m)}{P(M_2)}}|^2$$



Fit with a constant (pink dashed triple-dot line) and two constant width relativistic BW functions (green dashed double-dot line and aqua dashed line).

Resonant parameters

Parameters	SolutionI	SolutionII	SolutionIII	SolutionIV
c (10^{-4})		5.5 ± 0.6		
M_1 (MeV/c^2)		4224.8 ± 5.6		The error are statistical only.
Γ_1 (MeV)		72.3 ± 9.1		Preliminary
M_2 (MeV/c^2)		4400.1 ± 9.3		
Γ_2 (MeV)		181.7 ± 16.9		
Γ_1^{el} (eV)	62.9 ± 11.5	7.2 ± 1.8	81.6 ± 15.9	9.3 ± 2.7
Γ_2^{el} (eV)	88.5 ± 15.8	55.3 ± 8.7	551.9 ± 85.3	344.9 ± 70.6
ϕ_1	-2.1 ± 0.1	2.8 ± 0.3	-0.9 ± 0.1	-2.3 ± 0.2
ϕ_2	1.9 ± 0.3	2.3 ± 0.2	2.3 ± 0.1	-1.9 ± 0.1

- Statistical significance is greater than 10σ .
- Consistent with those of Y(4220) and Y(4390) in $e^+e^- \rightarrow \pi^+\pi^- h_c$.

PRD 96, 032004 (2017)

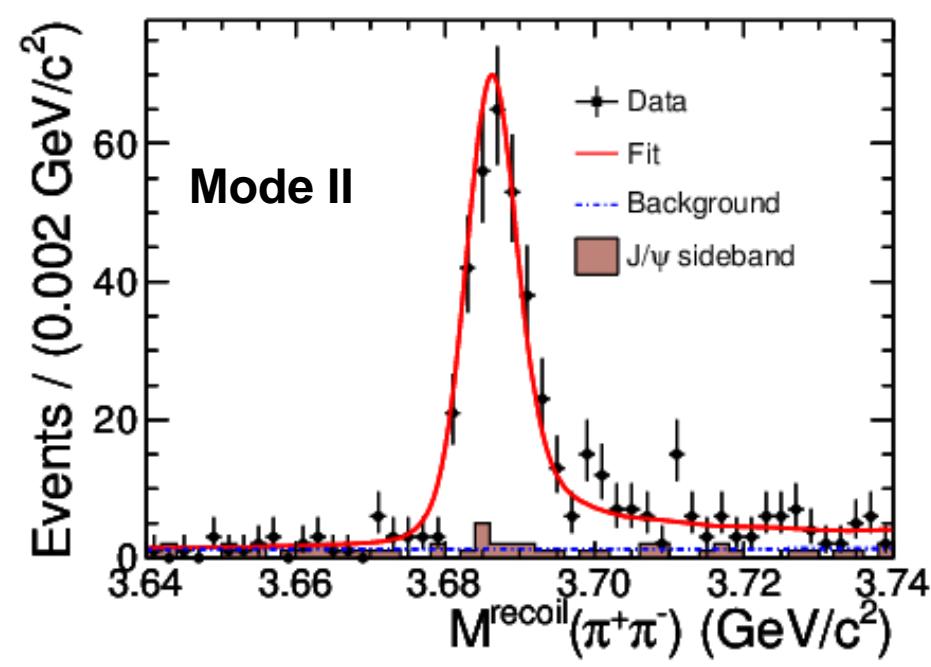
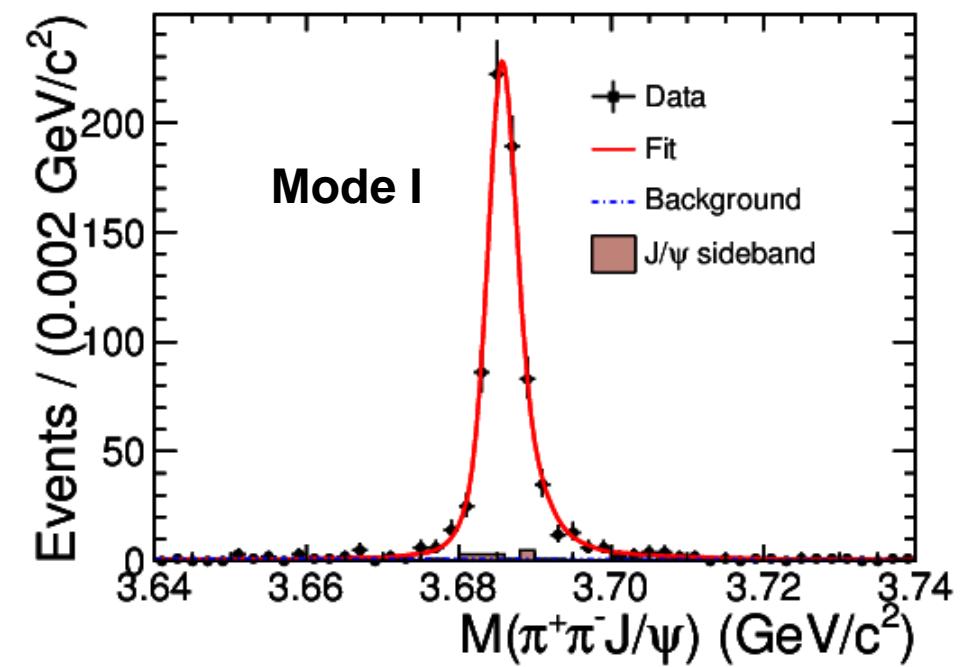
- **Data samples:**
 - 16 energy points from $\sqrt{s}=4.008$ to 4.600 GeV.
 - The total integrated luminosity (L_{int}) is 5.1 fb^{-1} .
- **Reconstructed modes:**

Mode I: $\Psi(3686) \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow l^+l^-$ ($l=e/\mu$)

Mode II: $\Psi(3686) \rightarrow neutrals + J/\psi$,
 $neutrals = (\pi^0\pi^0, \pi^0, \eta \text{ and } \gamma\gamma)$ $J/\psi \rightarrow l^+l^-$ ($l=e/\mu$)

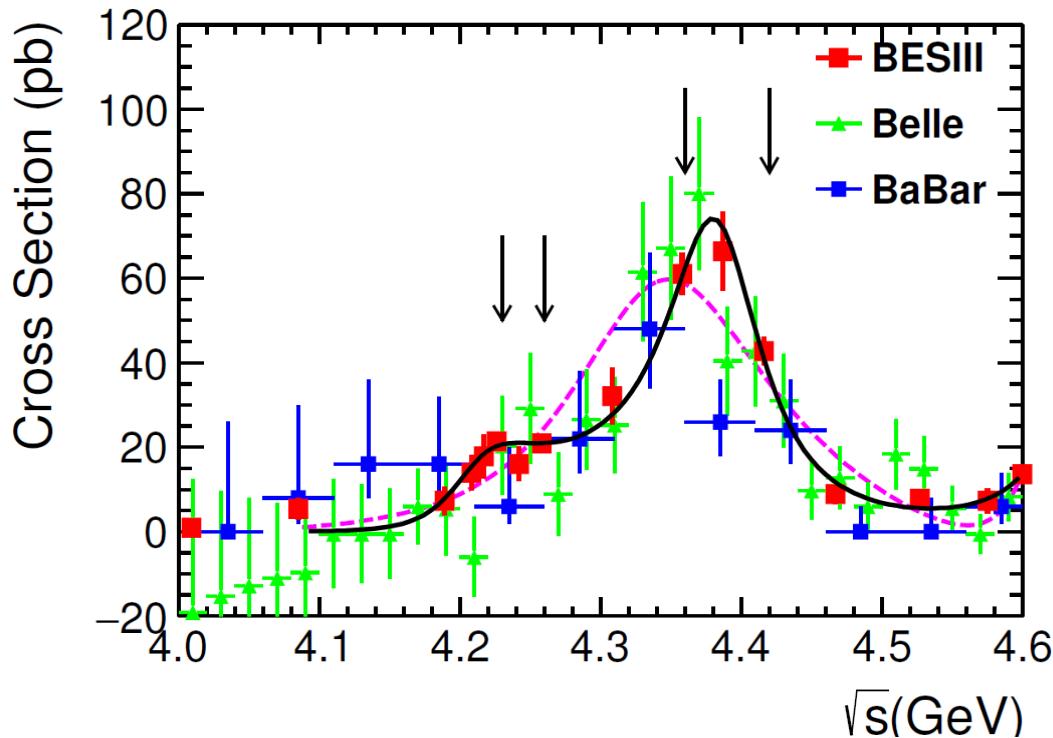
Signals at Ecm=4.416 GeV

PRD 96, 032004 (2017)



- Number of signals are extracted from $\pi^+\pi^-J/\psi$ invariant mass (mode I) and $\pi^+\pi^-$ recoiled mass spectrum (mode II).
- Signals are described with MC simulated shape convolved with a Gaussian function.

The Ys in $e^+e^- \rightarrow \pi^+\pi^-\psi'$

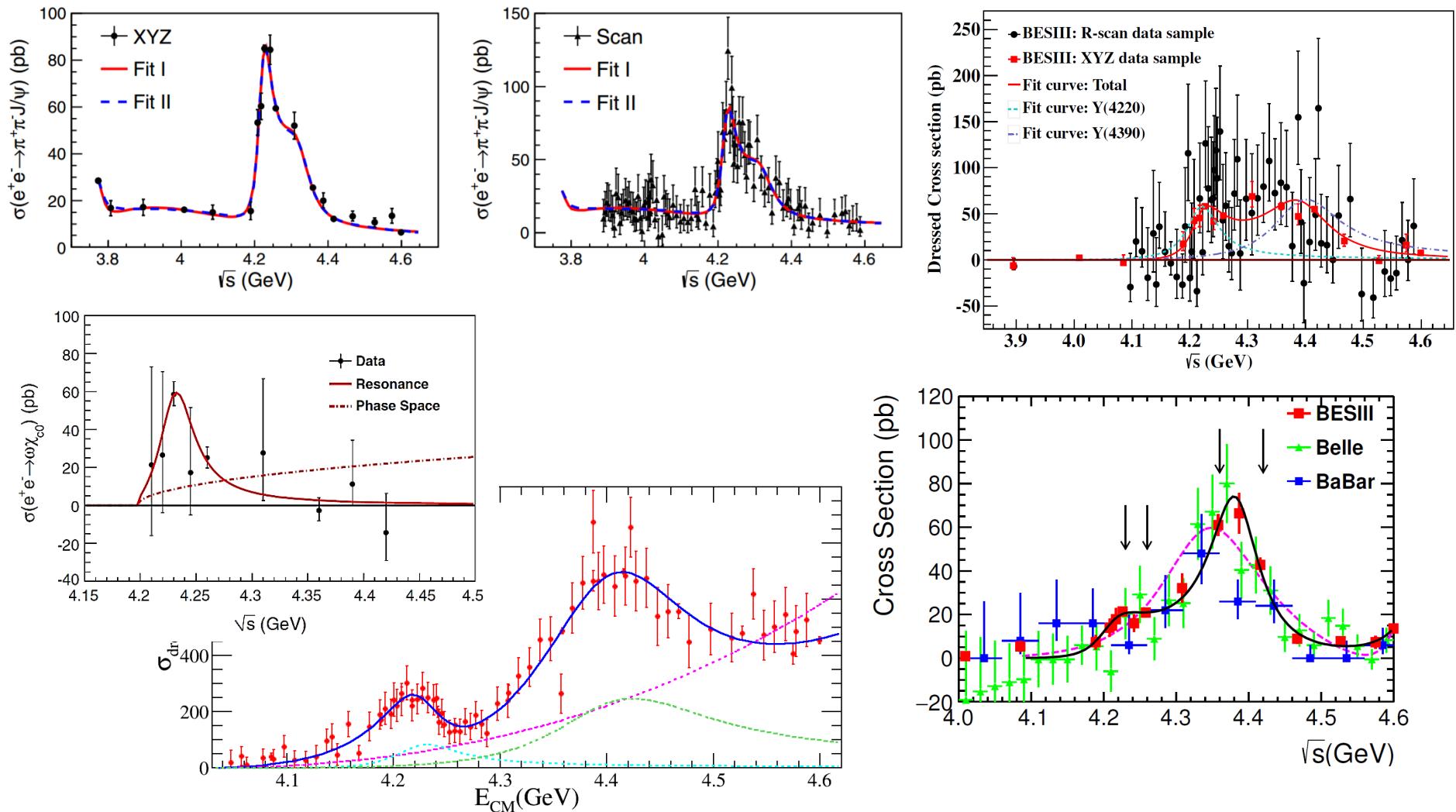


arXiv:1703.08787,
PRD 96, 032004 (2017)

The $Y(4220)$ is necessary
(significance = 5.8σ)
Fix parameters of the
 $Y(4660)$ to Belle results

Parameters	Solution I	Solution II
$M(Y4220)$ (MeV/ c^2)	4209.5 ± 7.4	
$\Gamma(Y(4220))$ (MeV)	80.1 ± 24.6	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4220))$ (eV)	0.8 ± 0.7	0.4 ± 0.3
$M(Y4390)$ (MeV/ c^2)	4383.8 ± 4.2	
$\Gamma(Y(4390))$ (MeV)	84.2 ± 12.5	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4390))$ (eV)	3.6 ± 1.5	2.7 ± 1.0
ϕ_1 (rad)	3.3 ± 1.0	2.8 ± 0.4
ϕ_2 (rad)	0.8 ± 0.9	4.7 ± 0.1

$\Upsilon(4260) \rightarrow \Upsilon(4220)$: what is it?



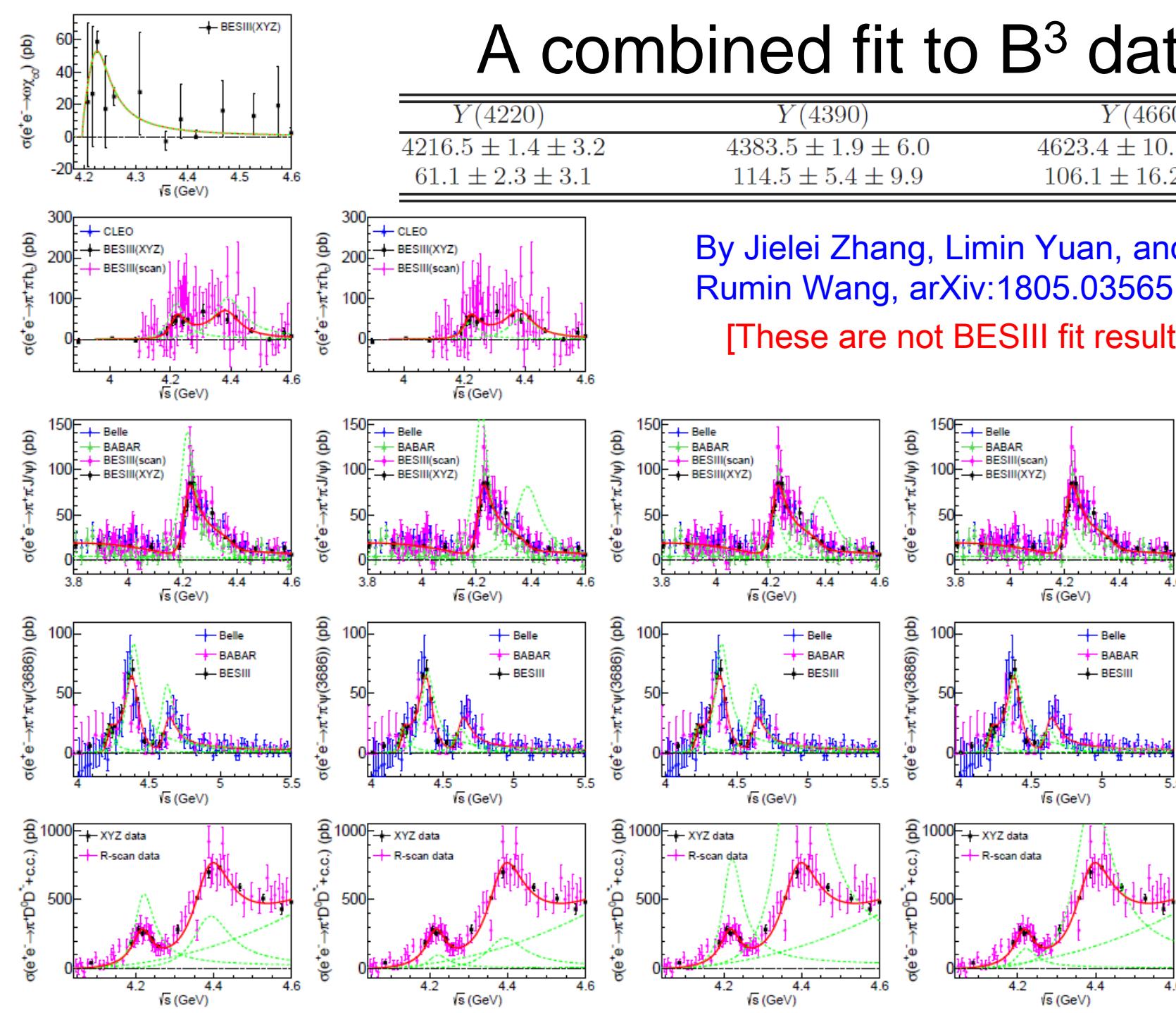
$\Upsilon(4220)$ appeared in $\omega\chi_{c0}$, $\pi^+\pi^-J/\psi$, $\pi^+\pi^-\psi'$, $\pi^+\pi^-h_c$, $D^0D^{*-}\pi^+$
Mass~4220 MeV, Width~ 60 MeV!

A combined fit to B^3 data

	$Y(4220)$	$Y(4390)$	$Y(4660)$
$4216.5 \pm 1.4 \pm 3.2$	$4383.5 \pm 1.9 \pm 6.0$	$4623.4 \pm 10.5 \pm 16.1$	
$61.1 \pm 2.3 \pm 3.1$	$114.5 \pm 5.4 \pm 9.9$	$106.1 \pm 16.2 \pm 17.5$	

By Jielei Zhang, Limin Yuan, and
Rumin Wang, arXiv:1805.03565

[These are not BESIII fit results!]



Leptonic width of Y(4220)

For an isospin-zero charmoniumlike state, we expect

$$\mathcal{B}(Y \rightarrow \pi\pi h_c) = \frac{3}{2} \times \mathcal{B}(Y \rightarrow \pi^+\pi^- h_c),$$

$$\mathcal{B}(Y \rightarrow \pi\pi J/\psi) = \frac{3}{2} \times \mathcal{B}(Y \rightarrow \pi^+\pi^- J/\psi),$$

$$\mathcal{B}(Y \rightarrow \pi\pi\psi(3686)) = \frac{3}{2} \times \mathcal{B}(Y \rightarrow \pi^+\pi^-\psi(3686)),$$

$$\mathcal{B}(Y \rightarrow \pi D\bar{D}^*) = 3 \times \mathcal{B}(Y \rightarrow \pi^+ D^0 D^{*-} + c.c.),$$

$$\begin{aligned}\Gamma_{e^+e^-} &= \sum_i \mathcal{B}_i \times \Gamma_{e^+e^-} \\ &= \mathcal{B}_{\omega\chi_{c0}} \times \Gamma_{e^+e^-} + \mathcal{B}_{\pi\pi h_c} \times \Gamma_{e^+e^-} + \mathcal{B}_{\pi\pi J/\psi} \times \Gamma_{e^+e^-} + \mathcal{B}_{D\bar{D}^*\pi} \times \Gamma_{e^+e^-} + \dots\end{aligned}$$

Taking Solutions with the smallest $B \times \Gamma_{e^+e^-}$,

$$\Gamma_{e^+e^-} > (36.4 \pm 2.0(stat) \pm 4.2(sys)) \text{ eV}$$

More modes being measured:

- charmed meson pairs, light hadrons + η_c

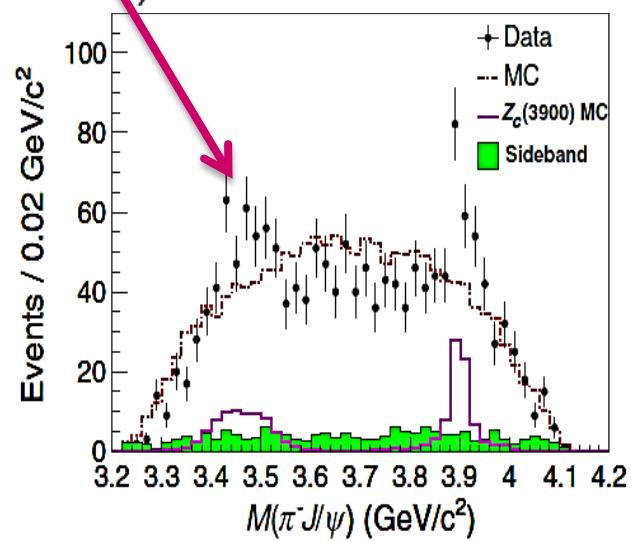
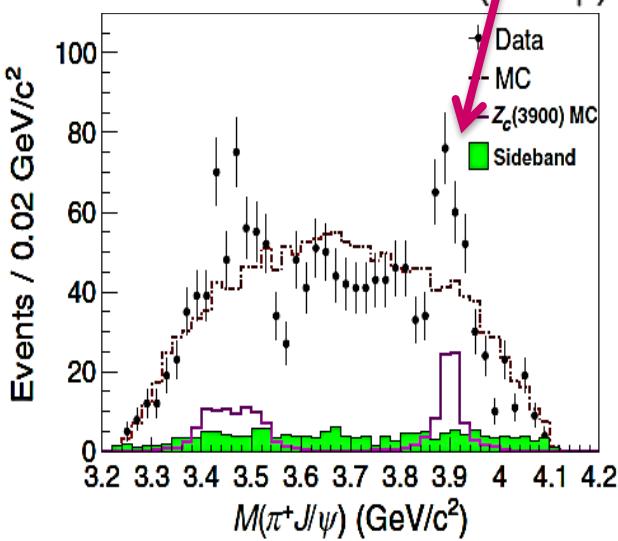
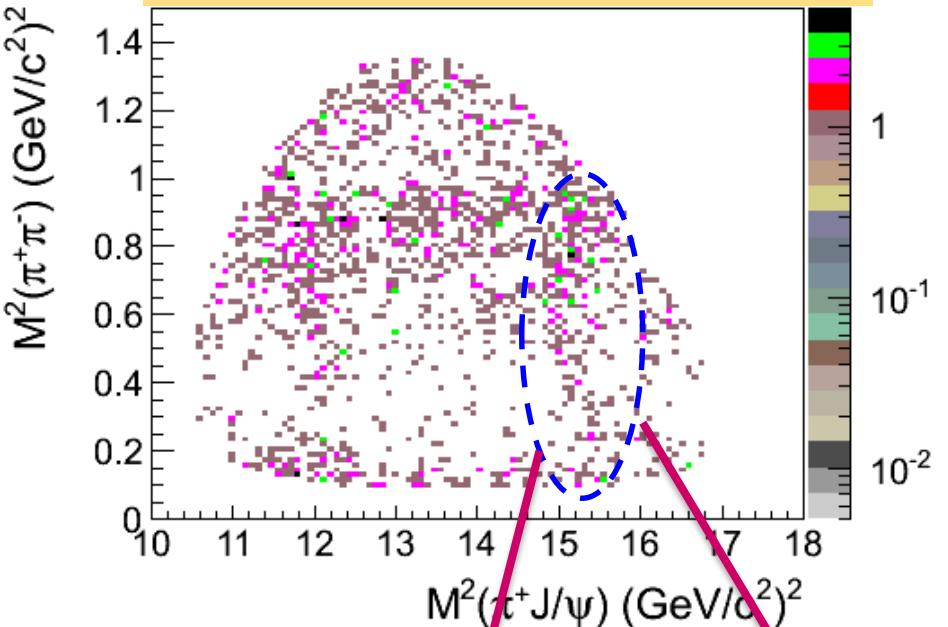
What is $\Upsilon(4220)$?

- Hybrid?
 - Mass agrees with LQCD
 - Couples to e^+e^- weaker than conventional charmonium
 - Couples to spin-singlet strongly
- $\bar{D}_1 D$ molecule? [results come out soon]
 - S-wave open threshold
- $\psi(4S)$ state?
 - Screened potential reduces 4S mass
- $\bar{D}_s^* D_s^*$ molecule?
- $\omega \chi_{c0}$ molecule?
-

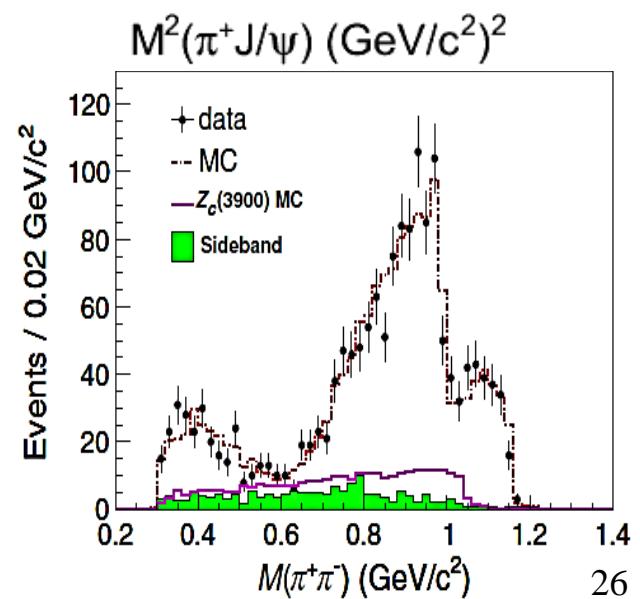
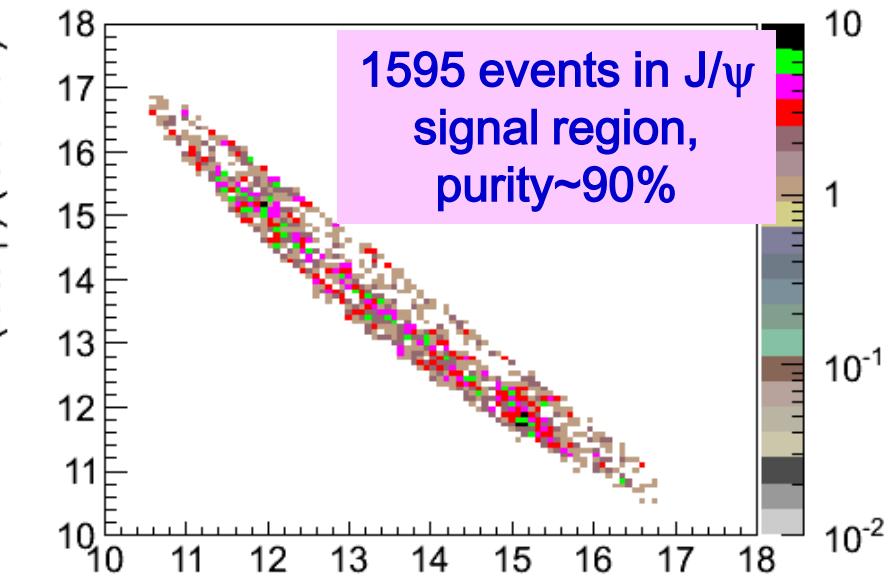
The Z_c states

BESIII $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ at $E_{cm}=4.26$ GeV

PRL 110, 252001 (2013)

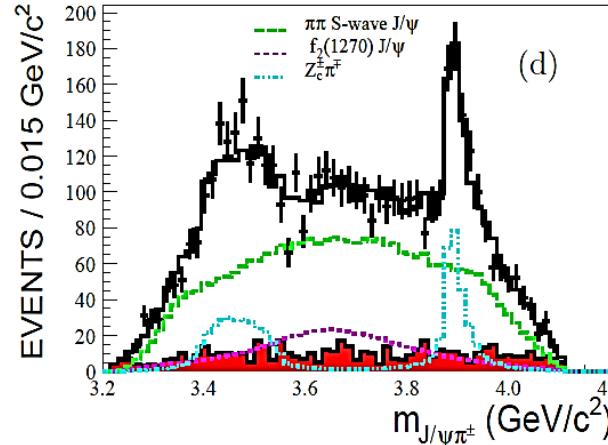
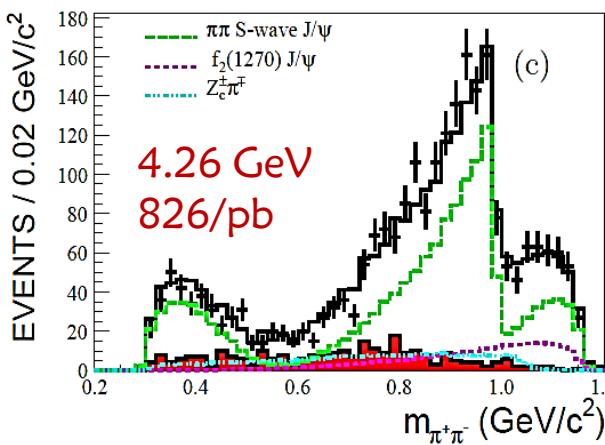
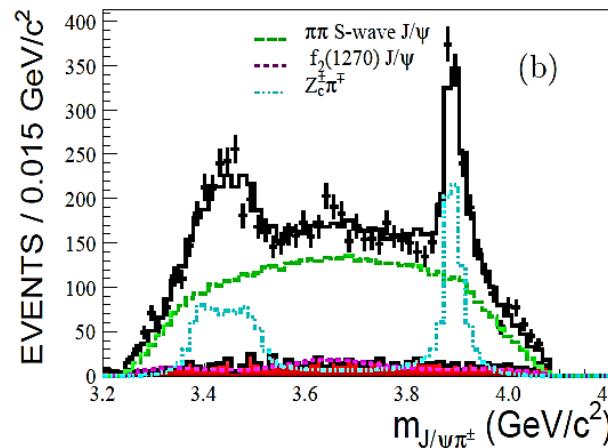
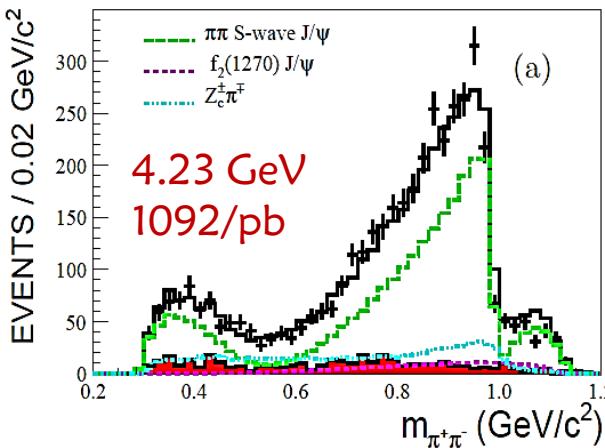


525 pb⁻¹ data at 4.260 GeV



Spin-parity of $Z_c(3900)$

PRL 119, 072001 (2017)



- Asymmetric line shape
- $JP=1+$ preferred over $0-, 1-, 2-, 2+$ by at least 7σ .
- Significant $f_0(980)$ contribution
- $\pi\pi$ D-wave fraction increases as E_{cm} increases

May any model calculate the s-dependent Dalitz plot?

[large data samples at 4.18-4.28 every 0.01 GeV, 4.36, and 4.42 GeV]

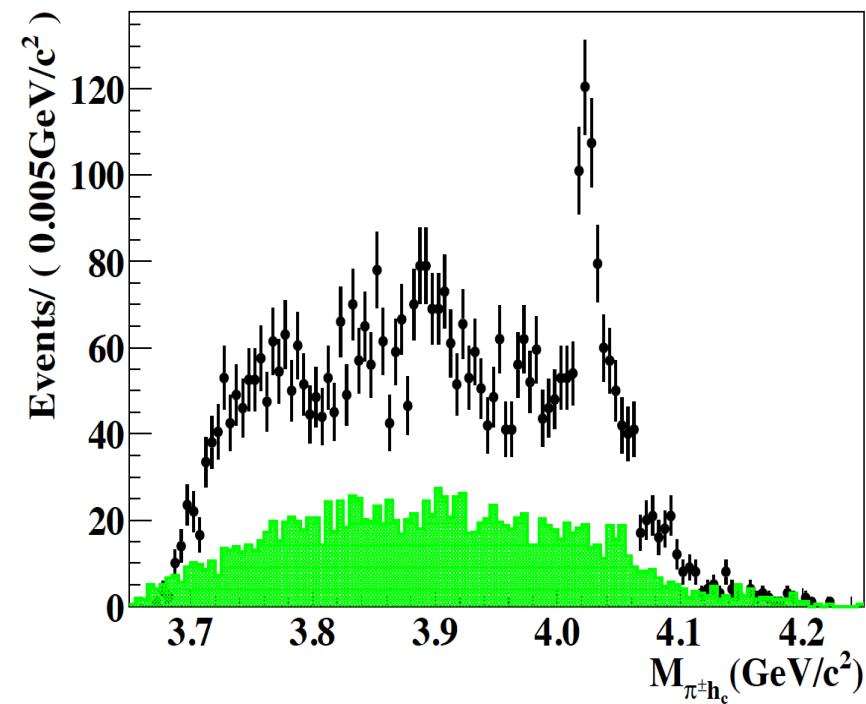
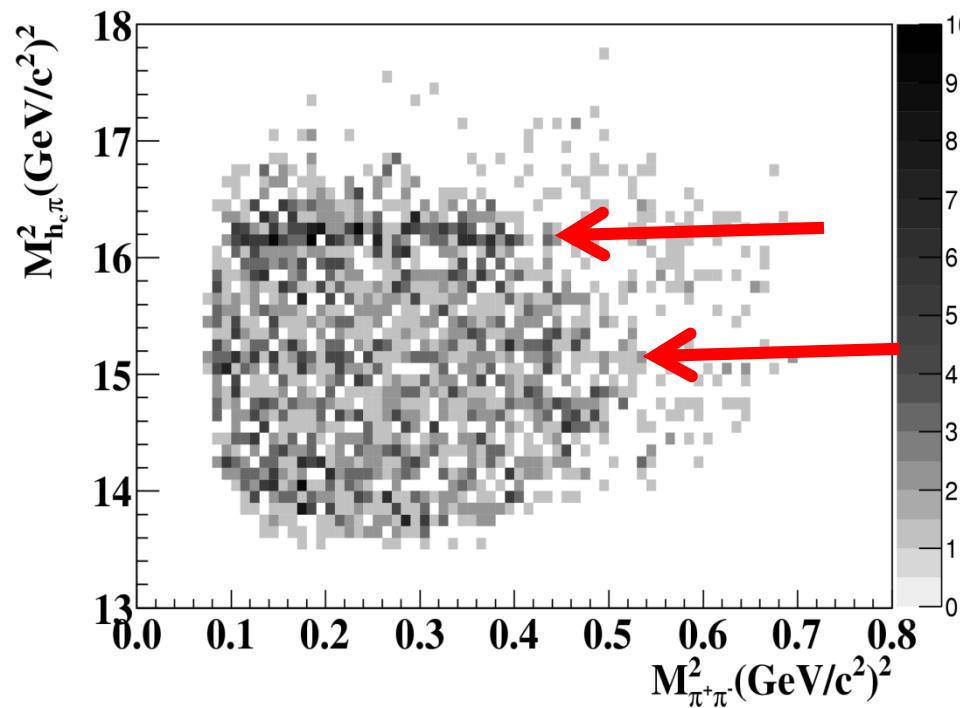
BESIII Improved res. param. of $Z_c(3900)$

$$BW(s, M, g'_1, g'_2) = \frac{1}{s - M^2 + i[g'_1\rho_1(s) + g'_2\rho_2(s)]}$$

parameter	value
Mass	$(3901.5 \pm 2.7 \pm 38.0) \text{ MeV}$
g_1'	$(0.075 \pm 0.006 \pm 0.025) \text{ GeV}^2$
g_2'/g_1'	$27.1 \pm 2.0 \pm 1.9$
M_{pole}	$(3881.2 \pm 4.2 \pm 52.7) \text{ MeV}$
Γ_{pole}	$(51.8 \pm 4.6 \pm 36.0) \text{ MeV}$
Ecm	$\sigma(e^+e^- \rightarrow \pi^+ Z_c + \text{c.c.})$
4.23 GeV	$(21.8 \pm 1.0 \pm 4.4) \text{ pb}$
4.26 GeV	$(11.0 \pm 1.2 \pm 5.4) \text{ pb}$

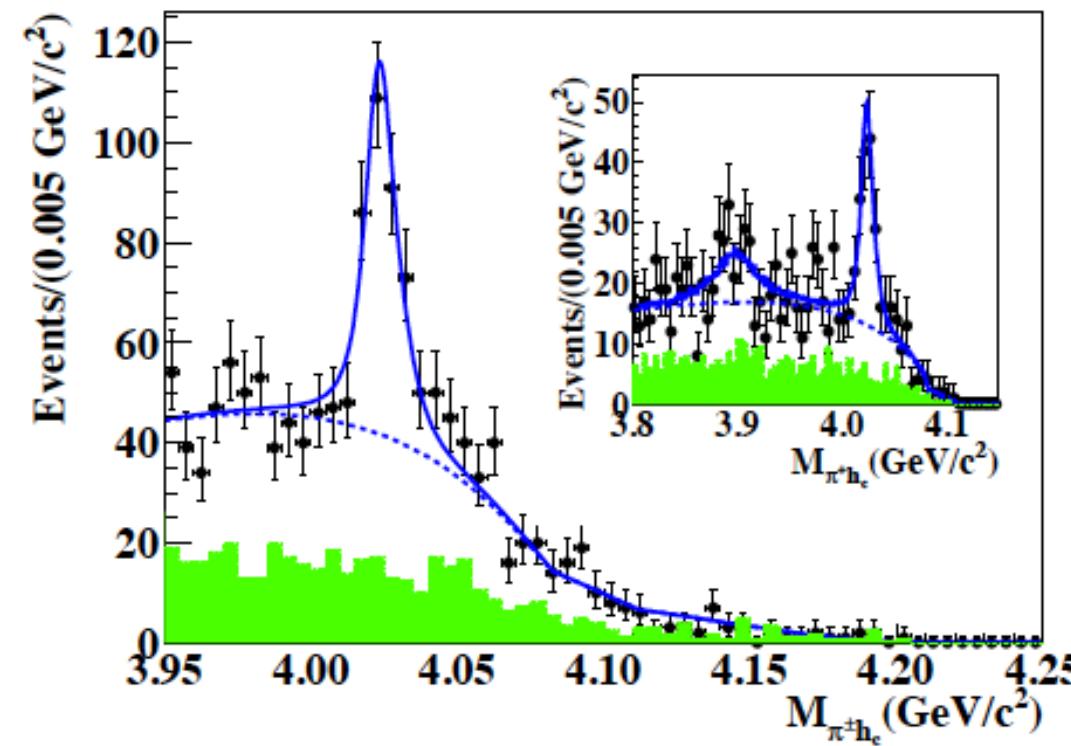
Dalitz plot of $e^+e^- \rightarrow \pi^+\pi^- h_c(1P)$

PRL111, 242001 (2013)



- Obvious structure around 4.02 GeV
- Hints of $Z_c(3900)$
- ~1500 events in h_c signal region at 4.23, 4.26 and 4.36 GeV, purity about 65%

Observation of $Z_c(4020)^+$



BESIII: PRL111, 242001

Simultaneous fit to
4.23/4.26/4.36 GeV data,
16 η_c decay modes. 8.9σ

$M(Z_c(4020)) =$
 $4022.9 \pm 0.8 \pm 2.7 \text{ MeV};$

$\Gamma(Z_c(4020)) =$
 $7.9 \pm 2.7 \pm 2.6 \text{ MeV}$

Close to $\bar{D}^* D^*$ threshold

**Significance: 8.9σ [$Z_c(4020)$]
No significant $Z_c(3900)$ (2.1σ)**

$\sigma(e^+e^- \rightarrow \pi Z_c \rightarrow \pi^+\pi^- h_c)$:

$8.7 \pm 1.9 \pm 2.8 \pm 1.4 \text{ pb}$ @ 4.23 GeV

$7.4 \pm 1.7 \pm 2.1 \pm 1.2 \text{ pb}$ @ 4.26 GeV

$10.3 \pm 2.3 \pm 3.1 \pm 1.6 \text{ pb}$ @ 4.36 GeV

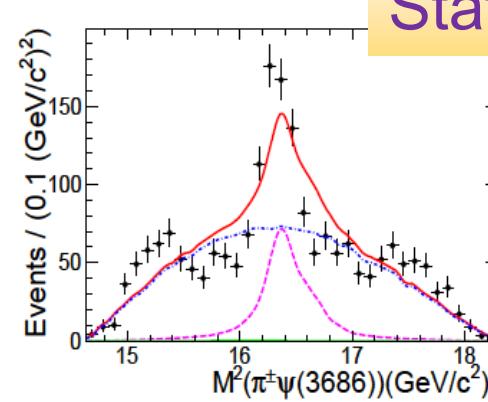
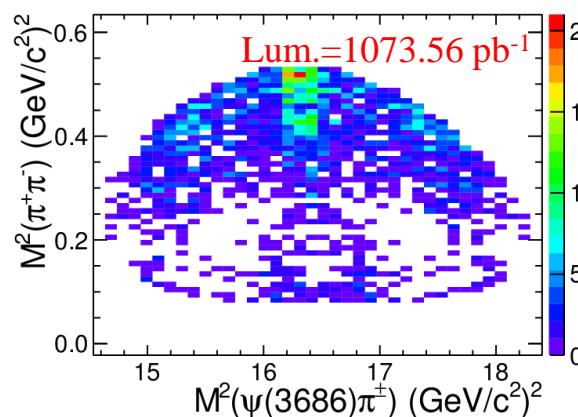
Z_c in $e^+e^- \rightarrow \pi^+\pi^-\psi'$?

PRD 96, 032004 (2017)

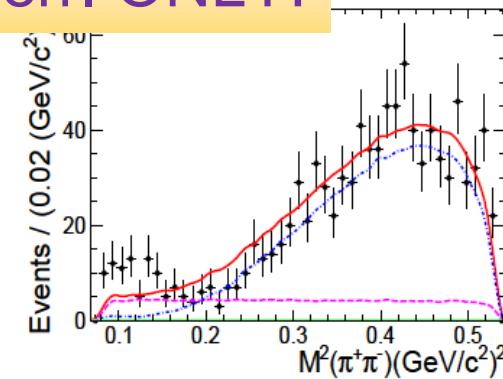
- A prominent narrow structure is observed in $\pi\psi(3686)$ mass spectrum for data at $\sqrt{s} = 4.416$ GeV.
- An S-wave Breit-Wigner fit function is performed on the Dalitz plot of $M^2(\pi^+\psi(3686))$ versus $M^2(\pi^-\psi(3686))$

$$\frac{p \cdot q}{(M_R^2 - x)^2 + M_R^2 \cdot \Gamma^2} + \frac{p \cdot q}{(M_R^2 - y)^2 + M_R^2 \cdot \Gamma^2}$$

- The fit yields a mass of $M=4032.1 \pm 2.4$ MeV/c² and a width of $\Gamma=26.1 \pm 5.3$ MeV, with a significance of 9.2σ

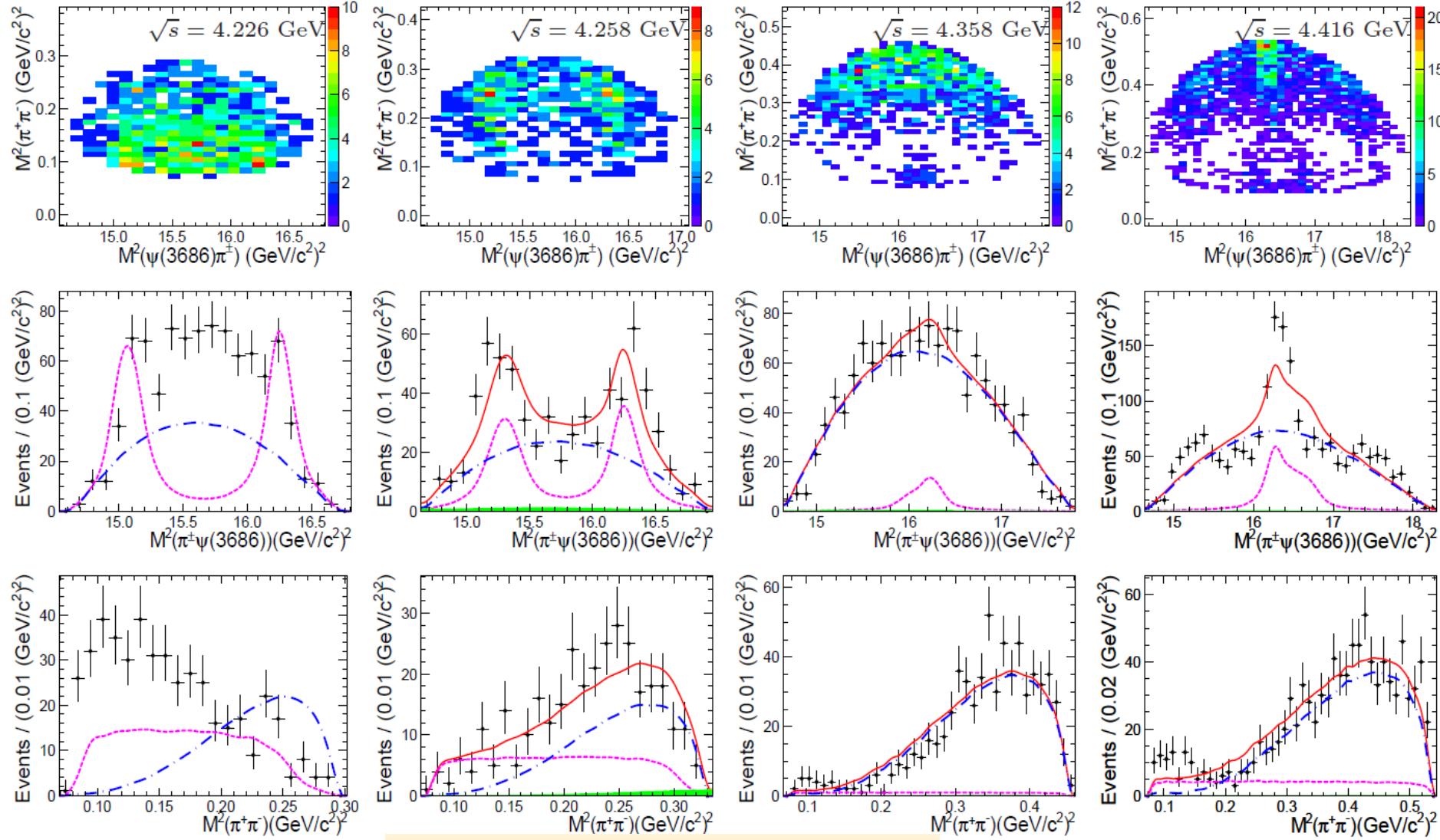


Stat. err. ONLY!

Different behavior between high and low $M^2(\pi^+\pi^-)$!

Fit of intermediate state

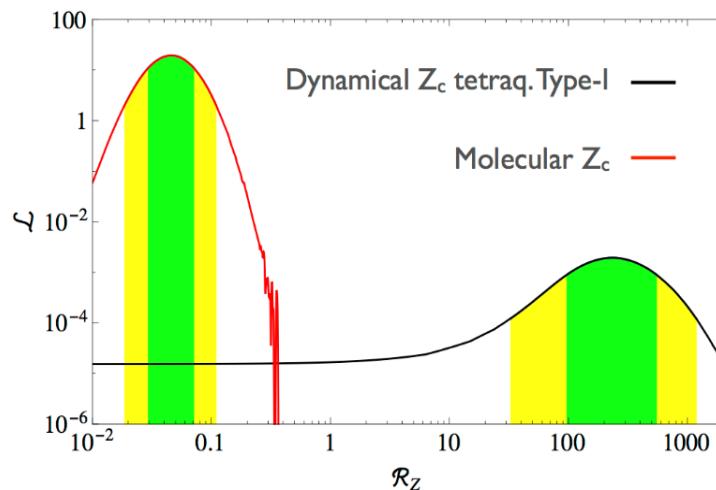
Interference not considered & fits cannot describe data well!



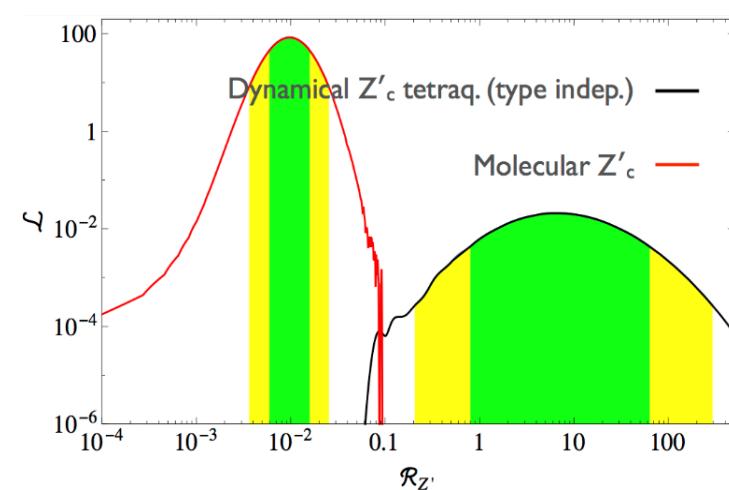
Search for $Z_c \rightarrow \rho\eta_c$



- Search for new decay mode of $Z_c(3900)$ and $Z_c(4020)$
- The ratios of $Z_c^{(\prime)} \rightarrow \rho\eta_c$ to $Z_c^{(\prime)} \rightarrow \pi J/\psi(\pi h_c)$ may discriminate **the tetra-quark** and **molecule** models.



$$R_z = \frac{B(Z_c \rightarrow \rho\eta_c)}{B(Z_c \rightarrow \pi J/\psi)}$$



$$R_{z'} = \frac{B(Z'_c \rightarrow \rho\eta_c)}{B(Z'_c \rightarrow \pi h_c)}$$

A.Esposito, A.L.Guerrieri, A.Pilloni, Phys. Lett. B 746, 194 (2015)

Type II tetraquark model:
neglect the spin-spin interaction outside the diquarks

Evidence for $Z_c \rightarrow \rho \eta_c$



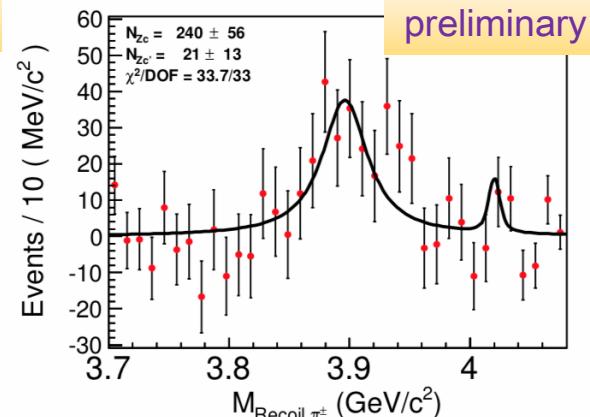
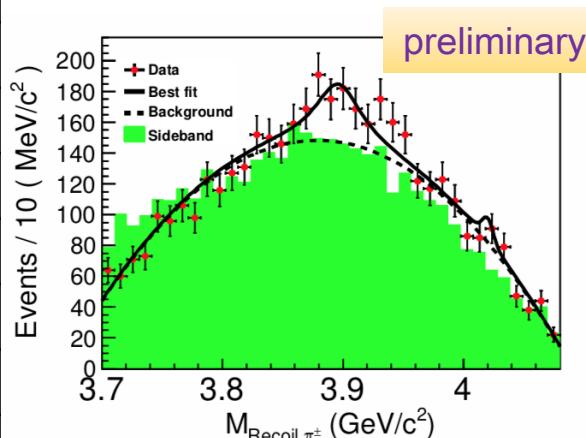
preliminary

- $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0 \eta_c$
- $\eta_c \rightarrow 9$ hadronic decays

Decay mode	BR
$\eta_c \rightarrow p\bar{p}$	$\sim 0.13\%$
$\eta_c \rightarrow 2(K^+ K^-)$	$\sim 0.15\%$
$\eta_c \rightarrow \pi^+ \pi^- K^+ K^-$	$\sim 1.50\%$
$\eta_c \rightarrow K^+ K^- \pi^0$	$\sim 1.20\%$
$\eta_c \rightarrow p\bar{p} \pi^0$	$\sim 0.18\%$
$\eta_c \rightarrow K_S K \pi$	$\sim 1.80\%$
$\eta_c \rightarrow \pi^+ \pi^- \eta$	$\sim 1.60\%$
$\eta_c \rightarrow K^+ K^- \eta$	$\sim 0.57\%$
$\eta_c \rightarrow \pi^+ \pi^- \pi^0 \pi^0$	$\sim 2.40\%$

- Strong evidence of $e^+ e^- \rightarrow \pi Z_c$, $Z_c \rightarrow \rho \eta_c$ at $\sqrt{s} = 4.23$, statistical significance is 4.3σ . (3.9 σ including systematics)

- $e^+ e^- \rightarrow \pi Z'_c, Z'_c \rightarrow \rho \eta_c$ not seen.



$e^+ e^- \rightarrow \pi Z_c, Z_c \rightarrow \rho \eta_c @ 4.23 \text{ GeV}$

Evidence for $Z_c \rightarrow \rho\eta_c$

preliminary

- Measure Born cross section at 4.23 GeV:

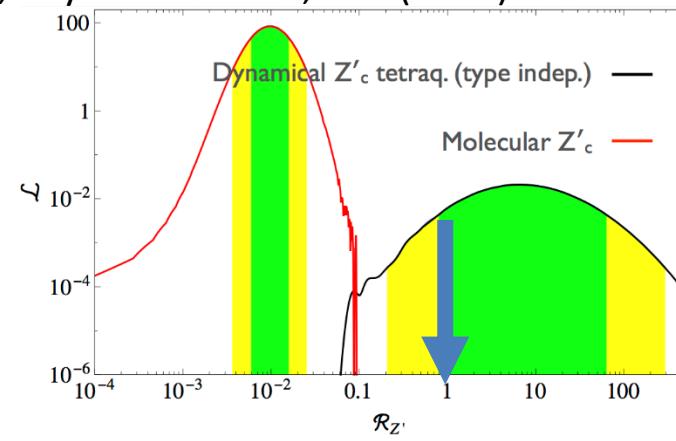
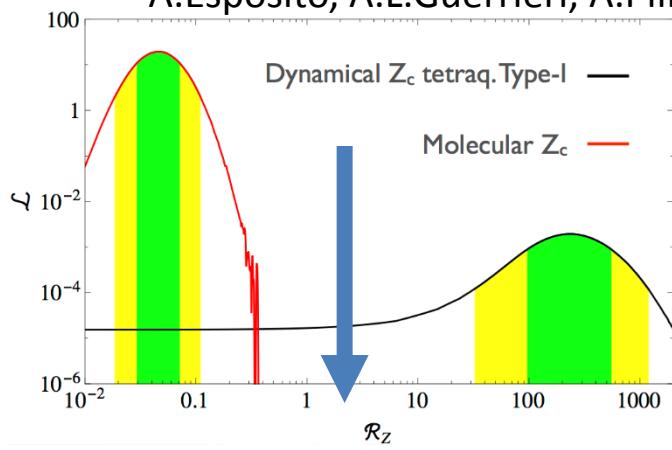
$$\sigma^B(e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta_c) = (46 \pm 12 \pm 10) \text{ pb}$$

$$\sigma^B(e^+e^- \rightarrow \pi Z_c, Z_c \rightarrow \rho \eta_c) = (47 \pm 11 \pm 11) \text{ pb}$$



	$\sqrt{s} = 4.23 \text{ GeV}$	$\sqrt{s} = 4.26 \text{ GeV}$	$\sqrt{s} = 4.36 \text{ GeV}$	Tetra-quarks-I	Tetra-quarks-II	Molecule
$R_{Z_c(3900)}$	2.1 ± 0.8	< 6.4	...	230^{+330}_{-140}	$0.27^{+0.40}_{-0.17}$	$0.046^{+0.025}_{-0.017}$
$R_{Z_c(4020)}$	< 1.9	< 1.2	< 1.0		$6.6^{+56.8}_{-5.8}$	$0.010^{+0.006}_{-0.004}$

A. Esposito, A.L. Guerrieri, A. Pilloni, Phys. Lett. B 746, 194 (2015)



$$R_z = \frac{B(Z_c \rightarrow \rho\eta_c)}{B(Z_c \rightarrow \pi J/\psi)}$$

$$R_{z'} = \frac{B(Z'_c \rightarrow \rho\eta_c)}{B(Z'_c \rightarrow \pi h_c)}$$

Does this suggest Z_c have both tetraquark and molecule components?

Summary of the Z_c states at BESIII

Decay Modes	$Z_c(3900)$	$Z_c(4020)$
$ G(J^{PC})$	$1^+(1^{+-})$	$1^+(??^-)$
$\pi J/\psi$	Discovery mode	No
πh_c	2.1σ	Discovery mode
$\bar{D}^* D$	Yes	No
$\bar{D}^* D^*$	No	Yes
$\pi \psi'$	No	Yes?
$\pi \psi''$?	Yes?
$\rho \eta_c$	4.3σ	No

Summary

- Lots of progress in the study of charmoniumlike states at BESIII
- Measurements of many hidden charm final states, $Y(4260) \rightarrow Y(4220)$ with more decay modes now
- $JP=1+$ for $Z_c(3900)$, evidence for $Z_c(3900) \rightarrow \rho \eta_c$, evidence for a new Z_c structure in $\pi \psi'$ or a new decay mode of the $Z_c(4020)$?
- BESIII will take more data and continue the study.

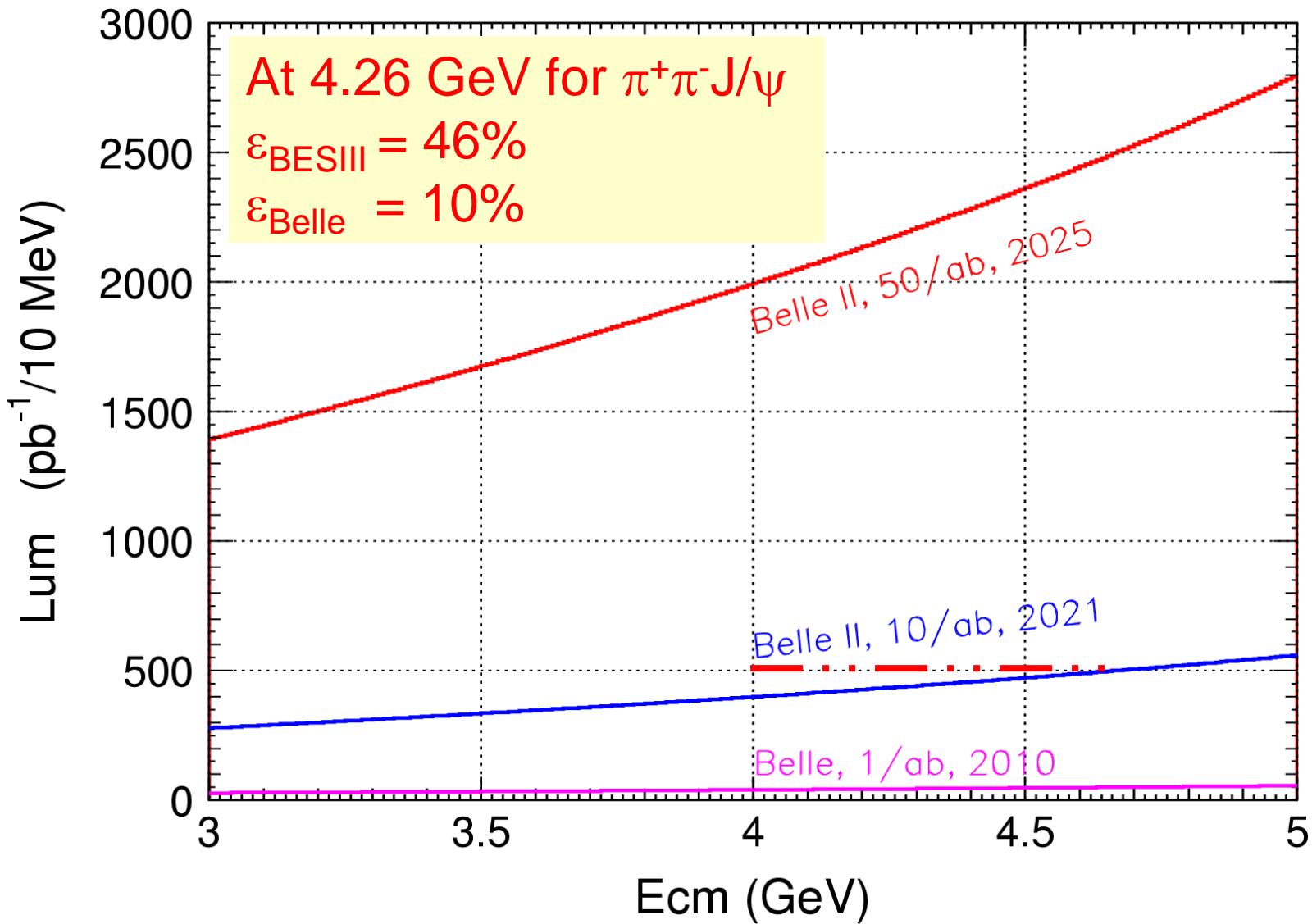
BEPCII Upgrade

- Increase of beam energy
 - Ebeam=2.30→2.35→2.45 GeV
 - Funding approved
 - Plan:
 - get to 2.35 GeV in one year time
 - Another 2 years time to get to 2.45 GeV, change ISPB (Interaction region SePtum Bending) magnet, big challenge
- Top-up injection
 - Data taking efficiency increases by 20~30%
 - Funding approved

Thanks a lot!

Belle II vs. BESIII

ISR produces events at all CM energies BESIII can reach



Charmonium(like) spectroscopy

