Exotic hadrons from BESIII

Changzheng Yuan

IHEP, Beijing

(for the BESIII Collaboration)

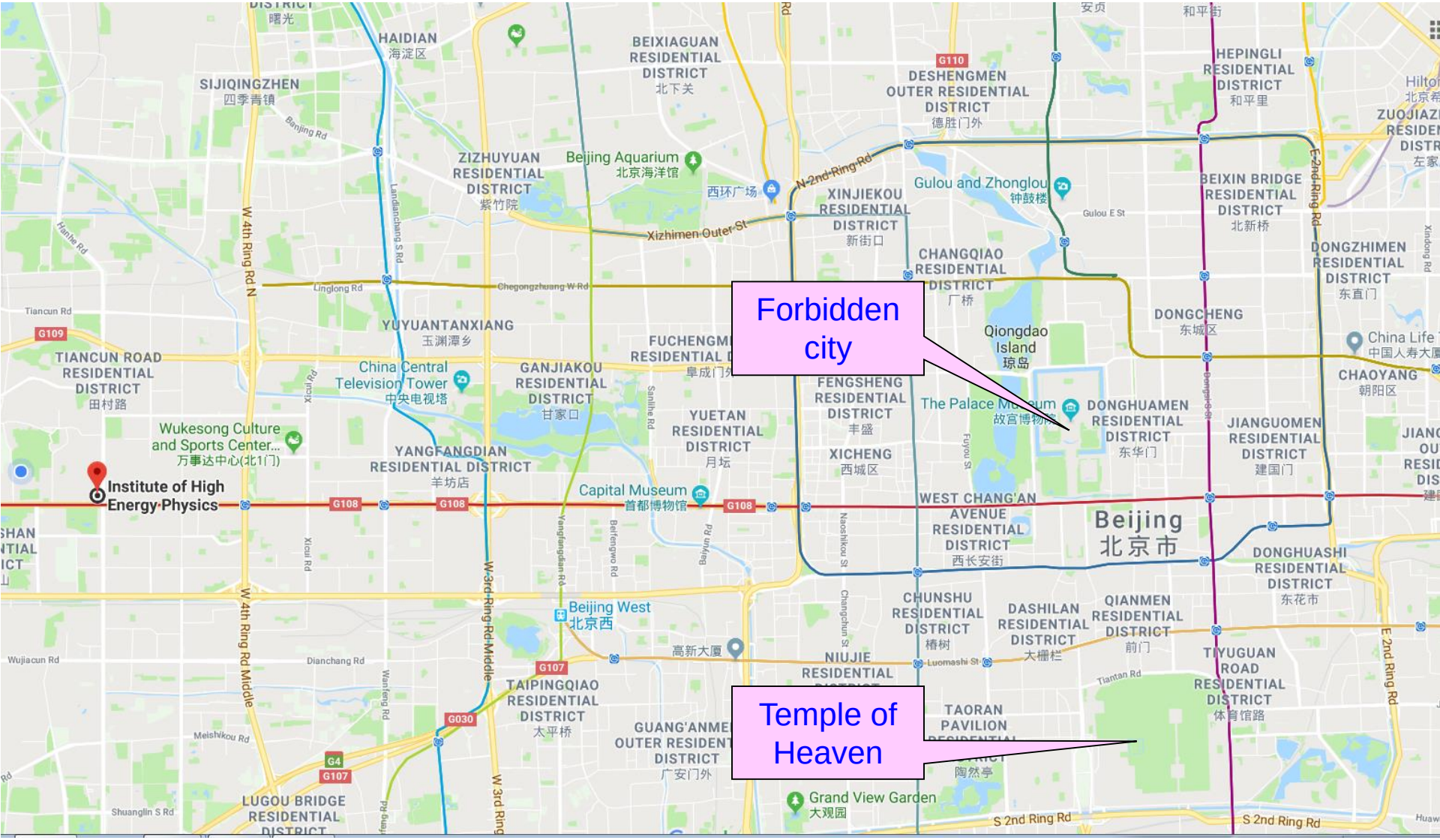
Novosibirsk, May 21, 2018

Outline

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

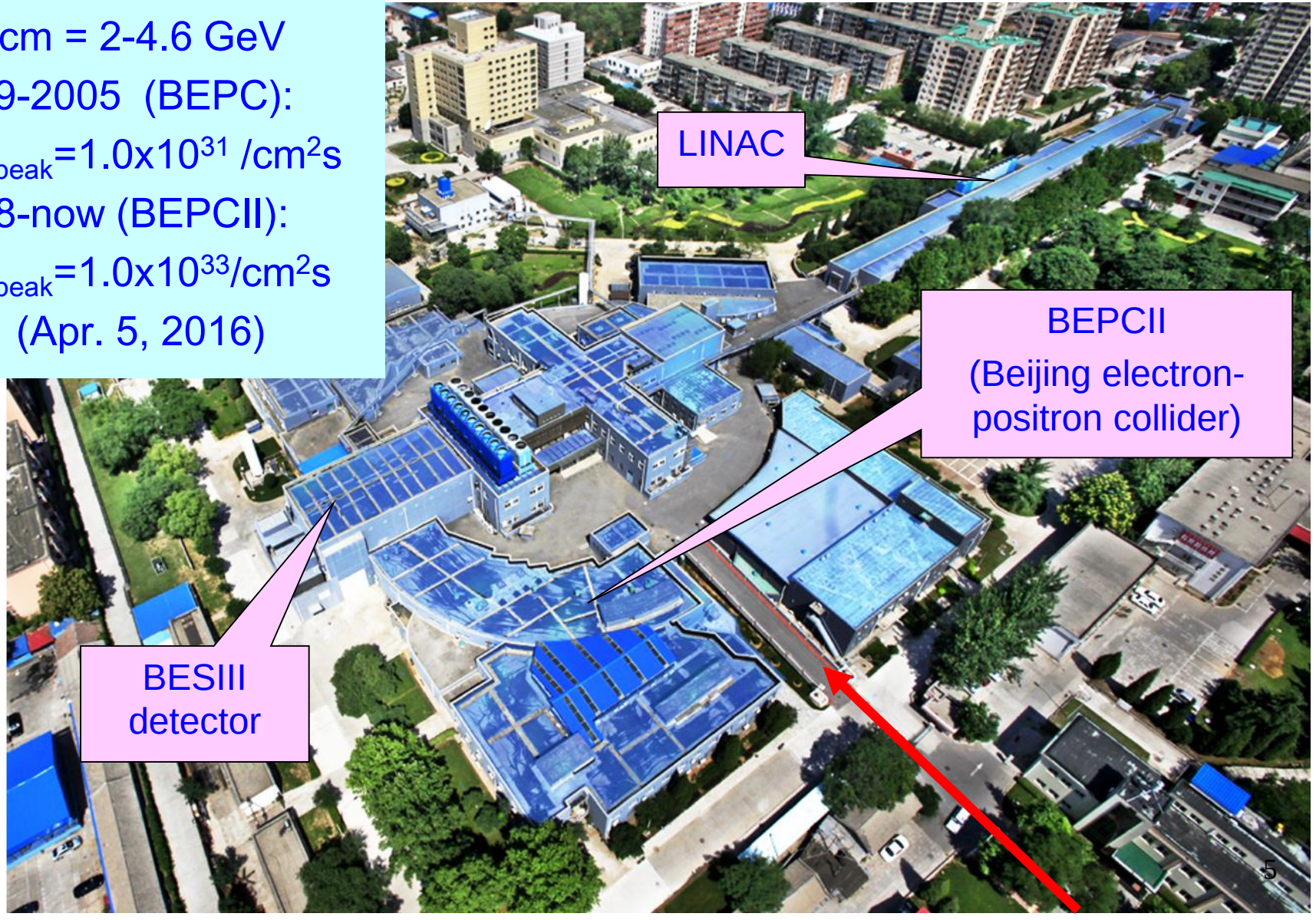
Where is the BESIII experiment

12km west from the Forbidden City

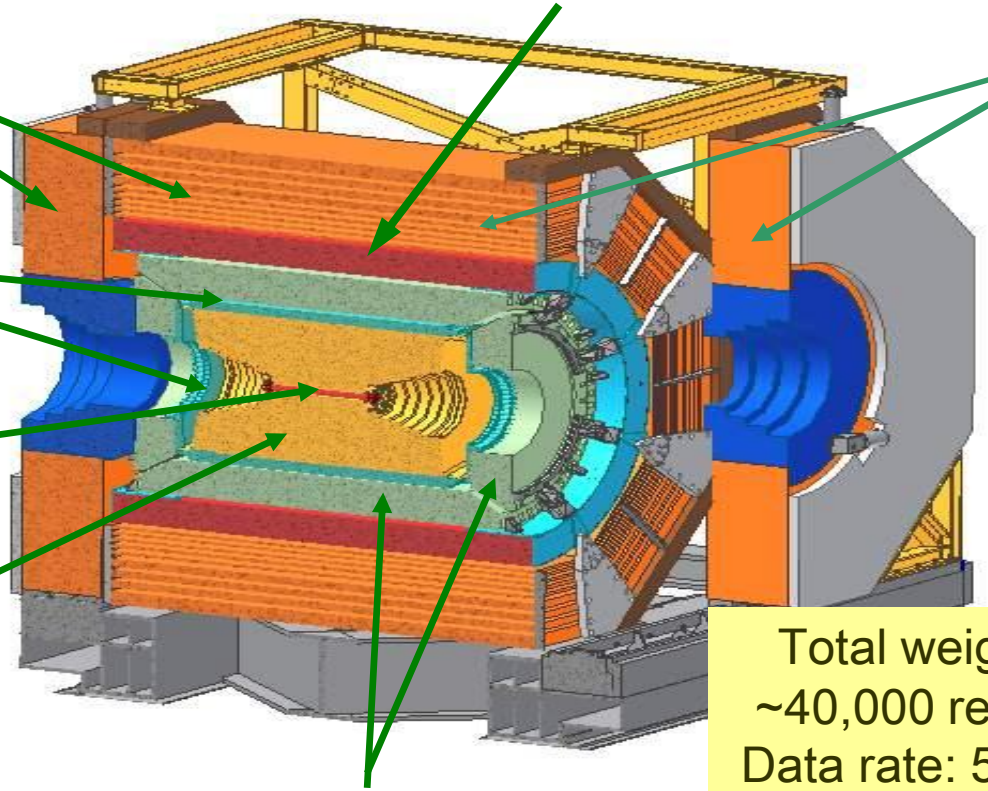


Beijing Electron Positron Collider (BEPC)

- Founded: 1984
  Ecm = 2-4.6 GeV
- 1989-2005 (BEPC):
  L_{peak}=1.0x10^{31} /cm^{2}s
- 2008-now (BEPCII):
  L_{peak}=1.0x10^{33}/cm^{2}s
  (Apr. 5, 2016)



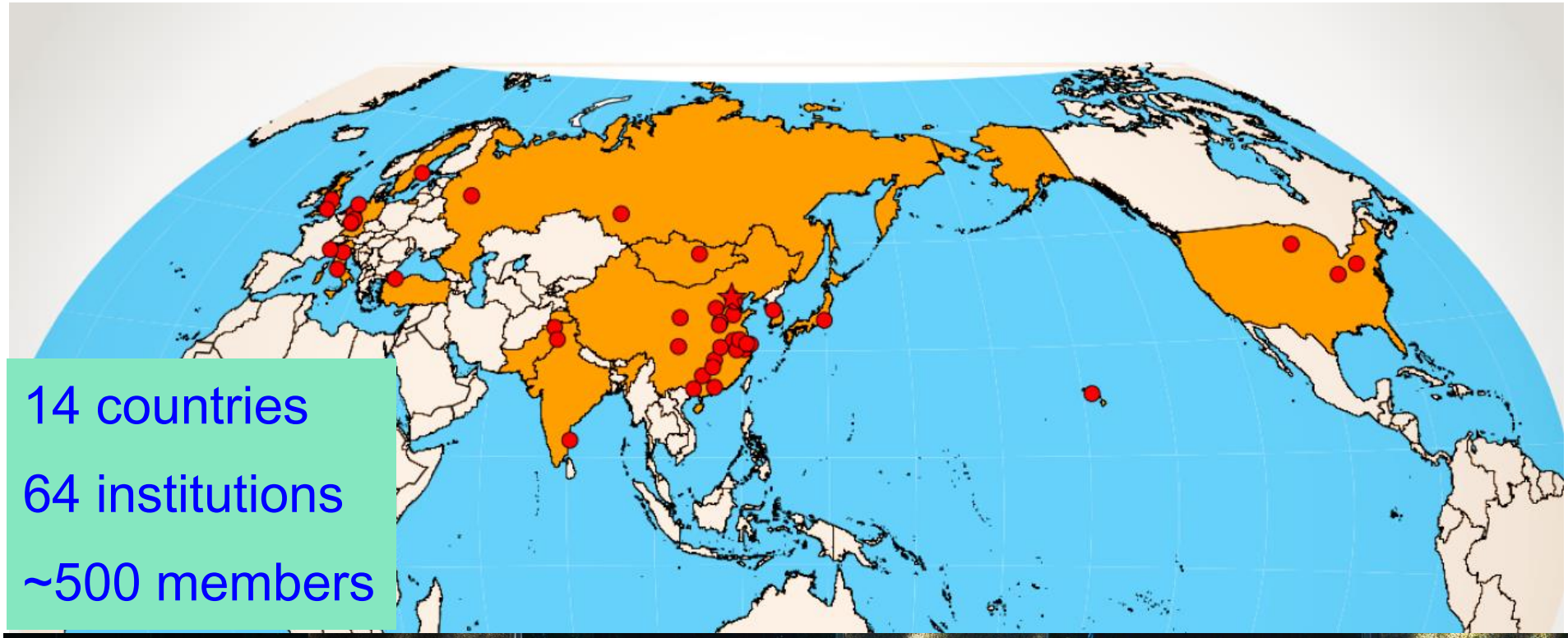
BESIII Detector



Has been in full operation since 2008,

all subdetectors are in very good status!

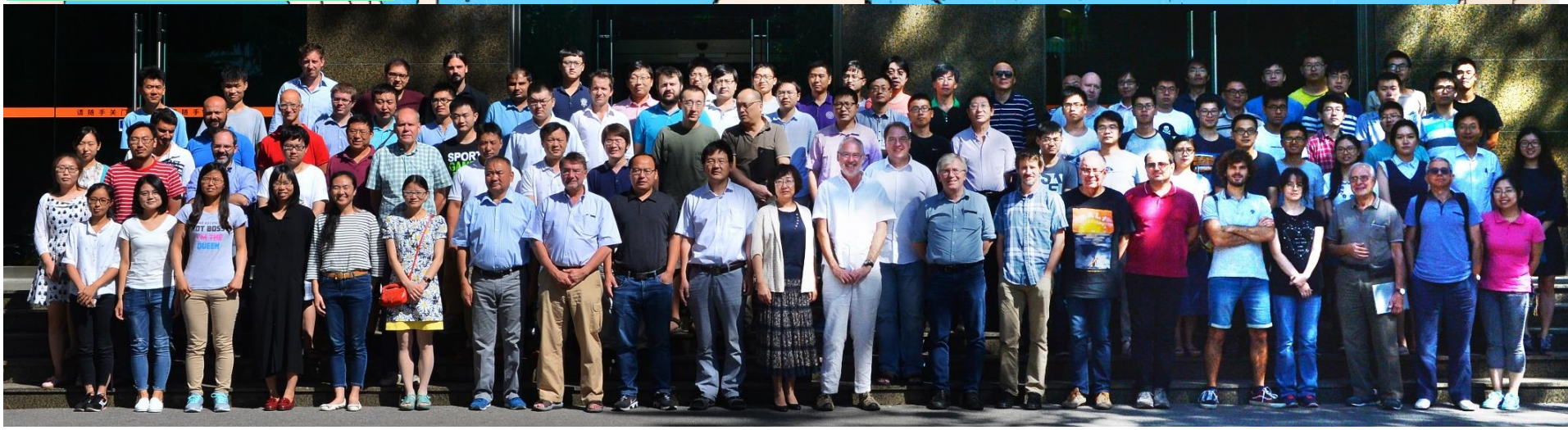
BESIII Collaboration

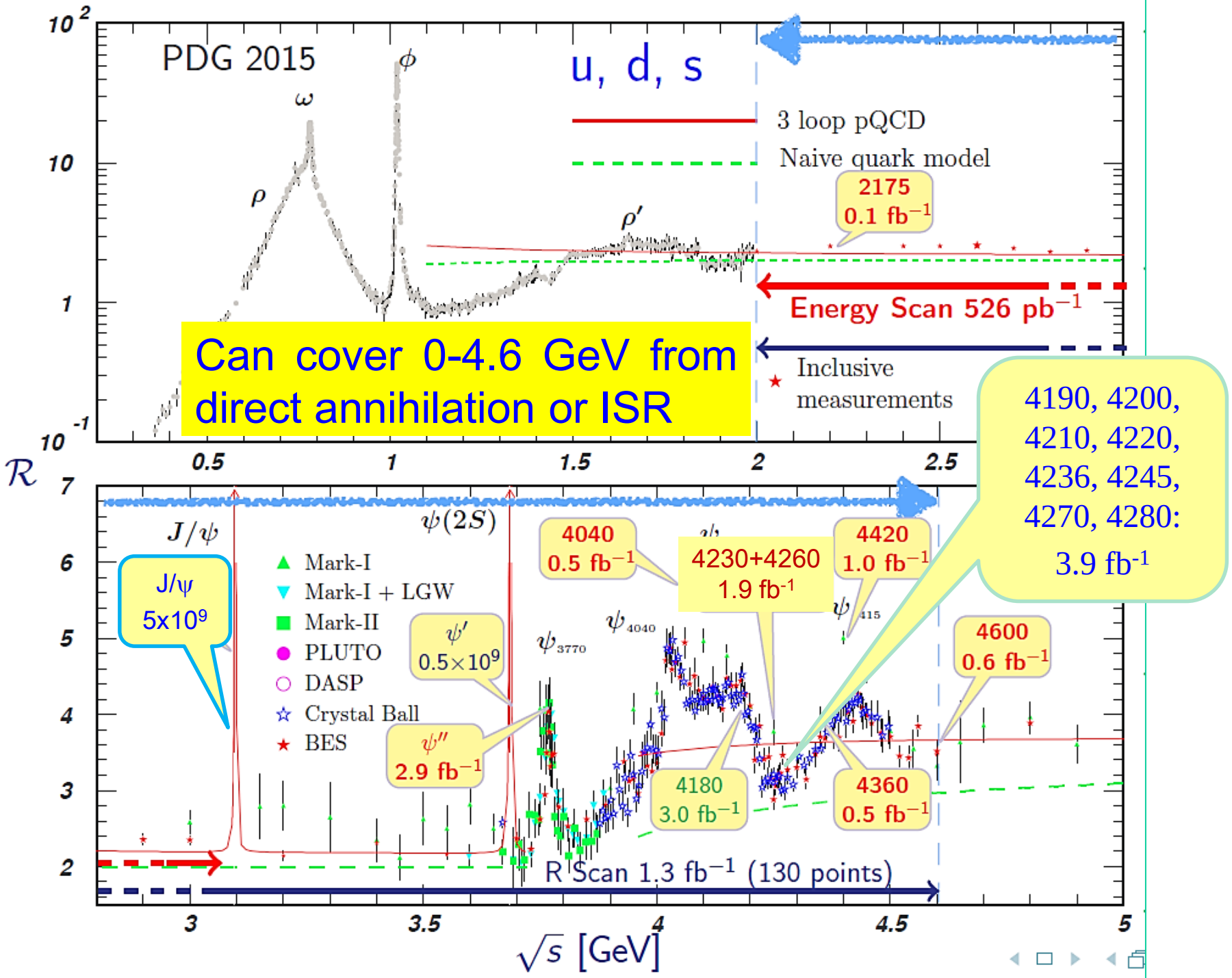


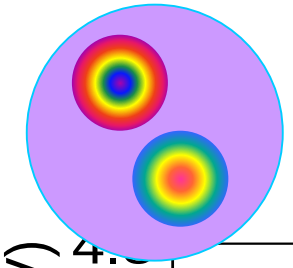
14 countries

64 institutions

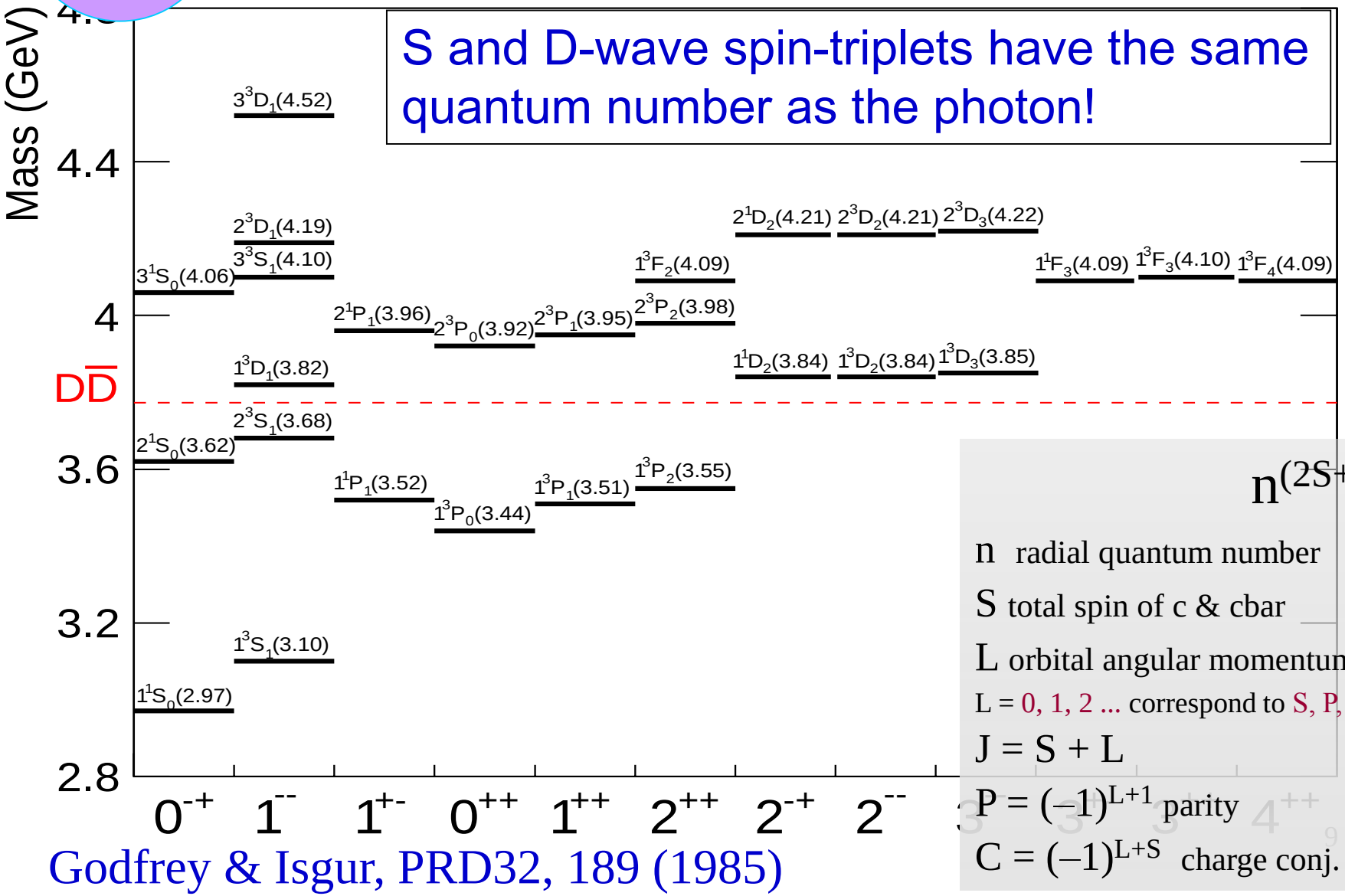
~500 members




PDG 2015
u, d, s
3 loop pQCD
Naive quark model
2175
0.1 fb^{-1}
Energy Scan 526 pb^{-1}
Inclusive measurements
Can cover 0-4.6 GeV from direct annihilation or ISR
4190, 4200, 4210, 4220, 4236, 4245, 4270, 4280: 3.9 fb^{-1}
$\mathcal{R}$
J/ψ
$\psi(2S)$
J/ψ 5x10^9
Mark-I
Mark-I + LGW
Mark-II
PLUTO
DASP
Crystal Ball
BES
ψ' 0.5×10^9
ψ'' 2.9 fb^{-1}
4040 0.5 fb^{-1}
4230+4260 1.9 fb^{-1}
4420 1.0 fb^{-1}
4600 0.6 fb^{-1}
4180 3.0 fb^{-1}
4360 0.5 fb^{-1}
R Scan 1.3 fb^{-1} (130 points)
$\sqrt{s}$ [GeV]



Charmonium spectroscopy



Godfrey & Isgur, PRD32, 189 (1985)

$n^{(2S+1)}L_J$

n radial quantum number

S total spin of c & cbar

L orbital angular momentum

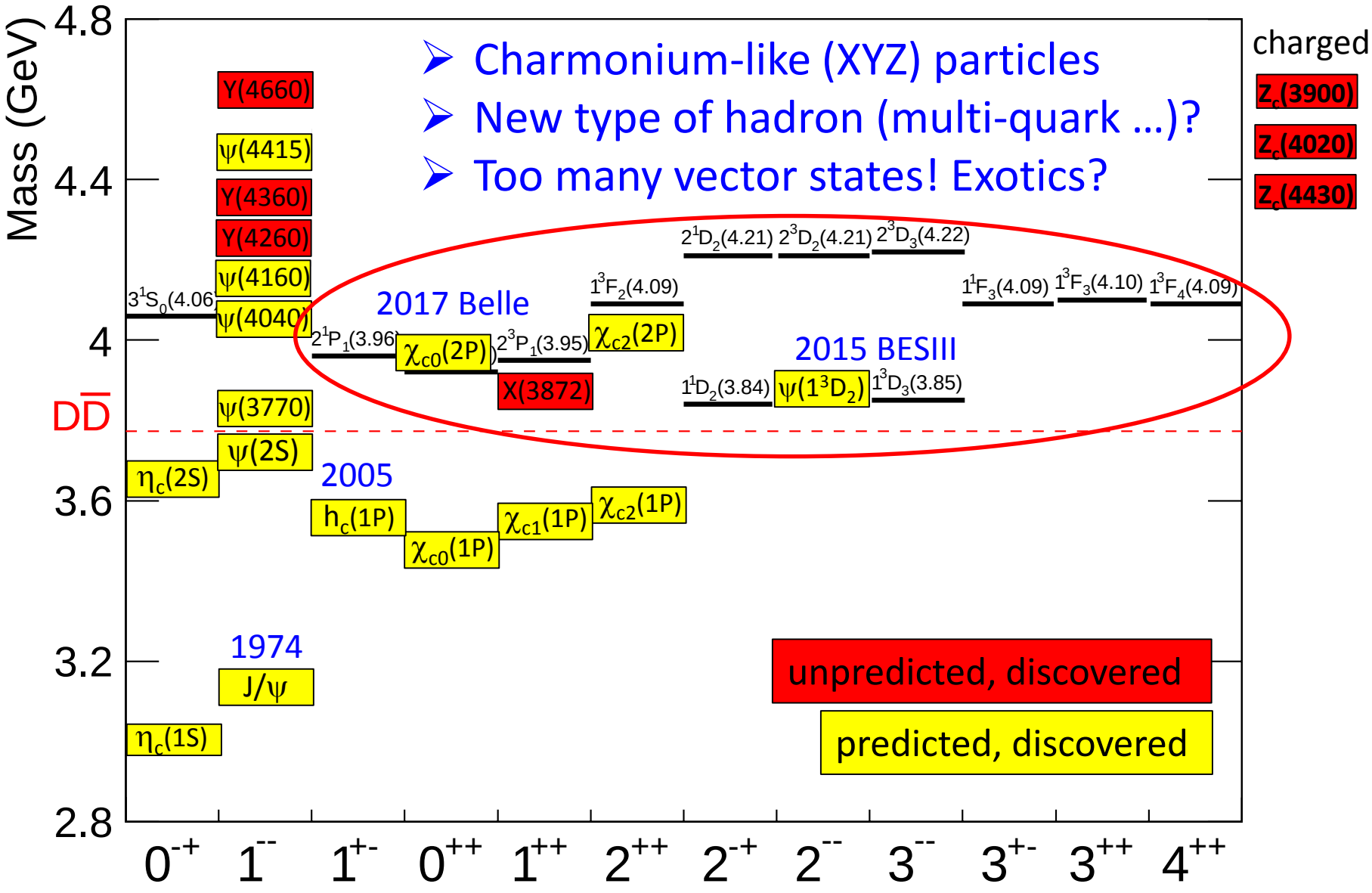
L = 0, 1, 2 ... correspond to S, P, D, …

$J = S + L$

$P = (-1)^{L+1}$ parity

$C = (-1)^{L+S}$ charge conj.

Charmonium(like) spectroscopy

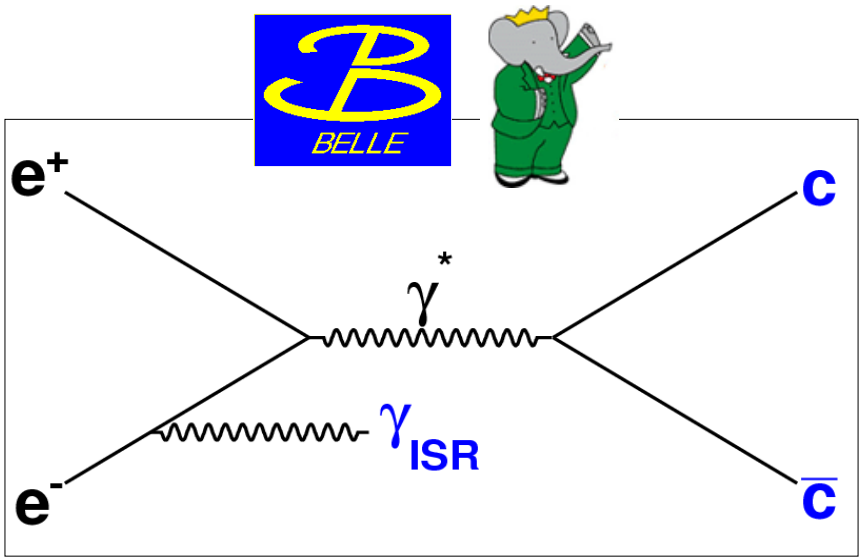


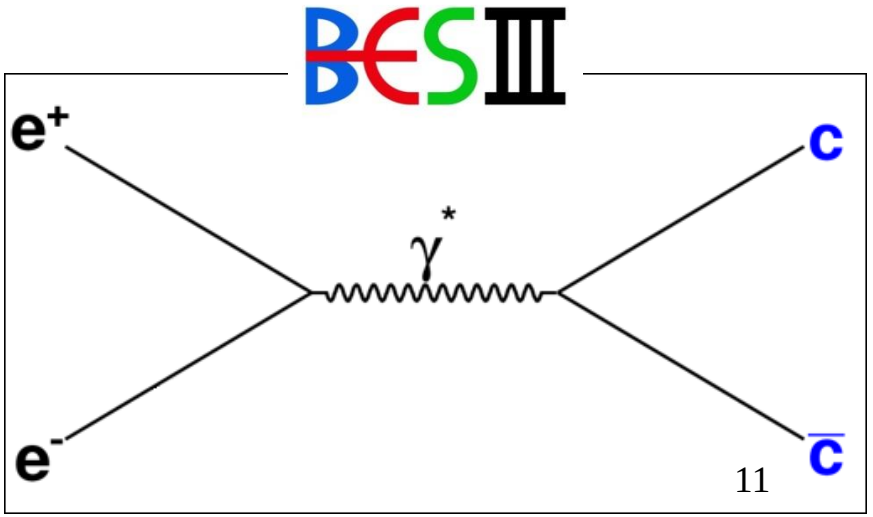
Godfrey & Isgur, PRD32, 189 (1985)

The Y states

measurements of more final states for the

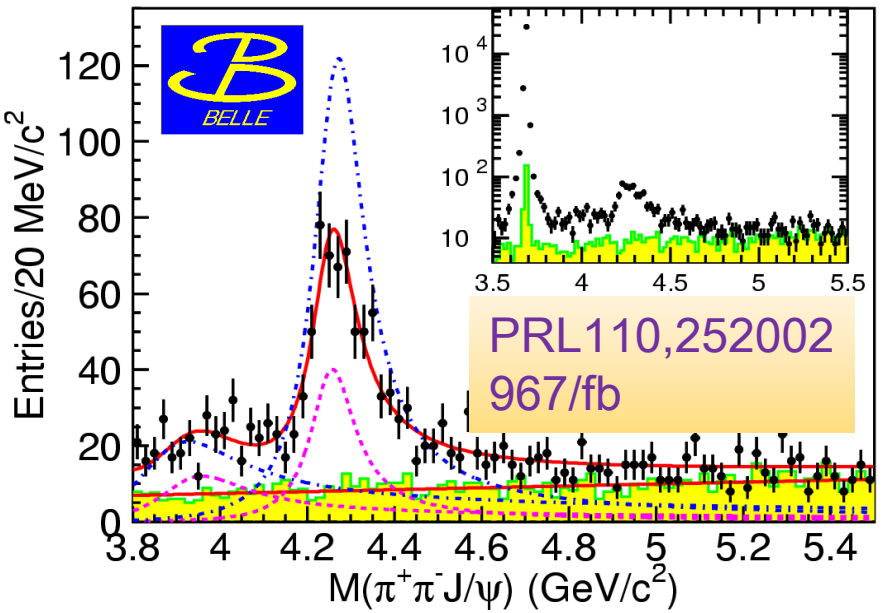
Y and ψ states



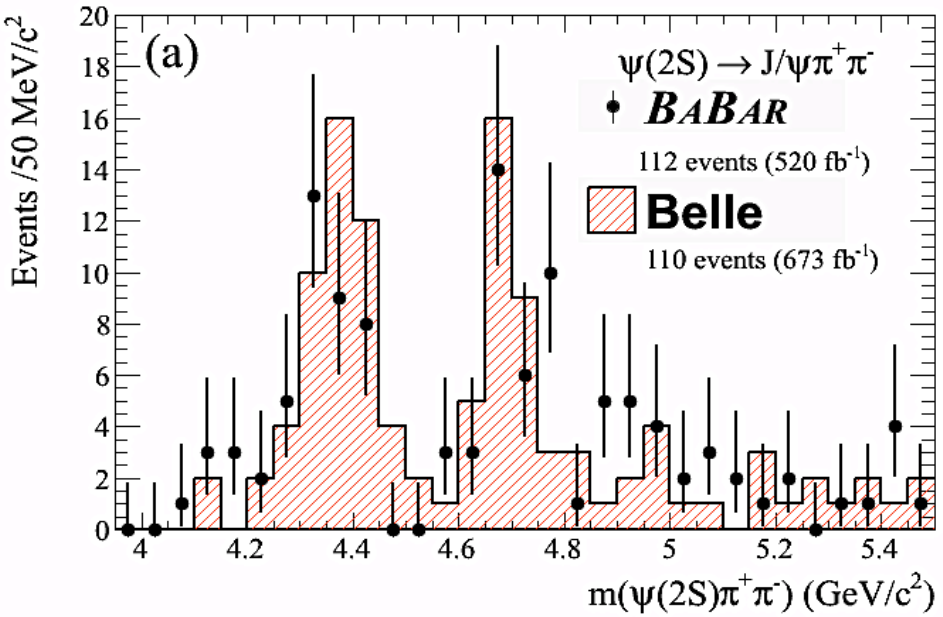


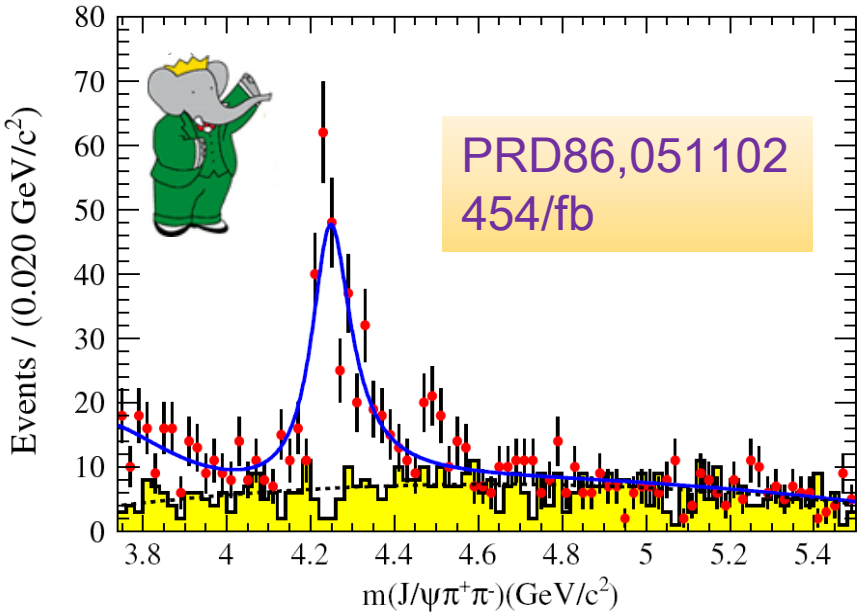
The Y states

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

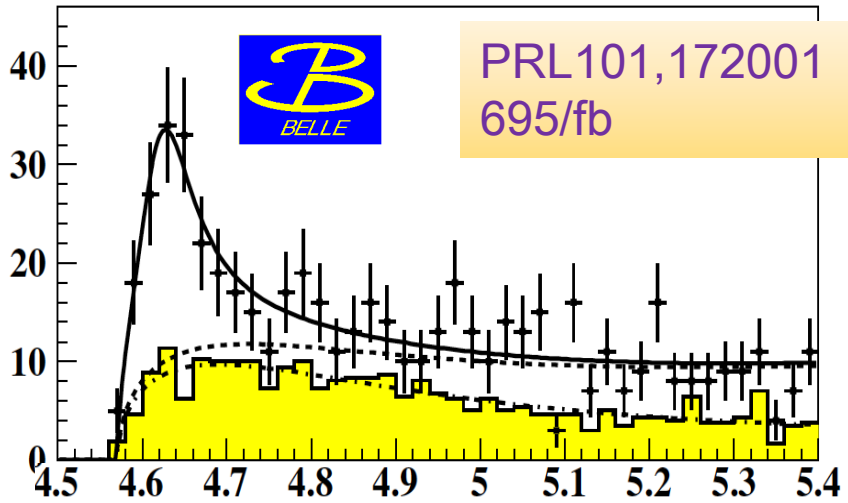


PRL110,252002
967/fb





PRD86,051102
454/fb

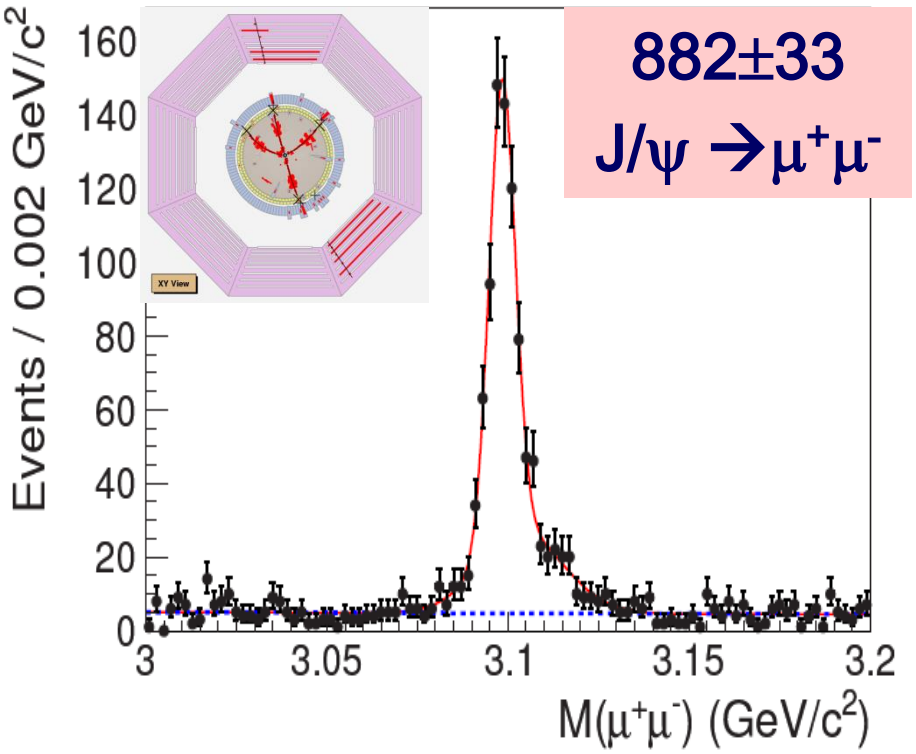


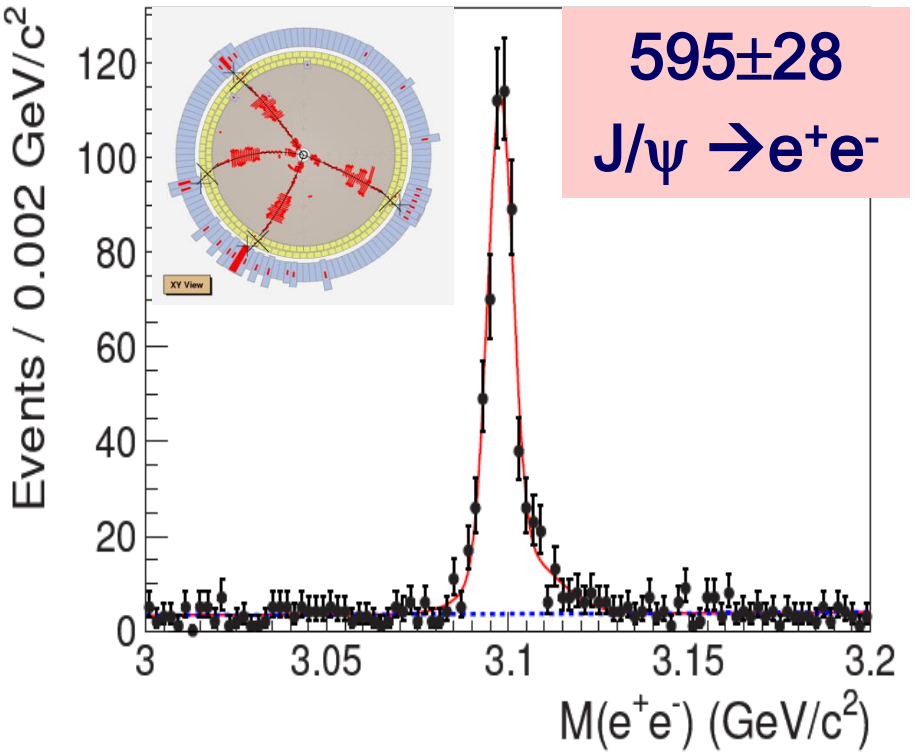
PRL101,172001
695/fb

M($\Lambda_c^+\Lambda_c^-$)

May BESIII help?

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



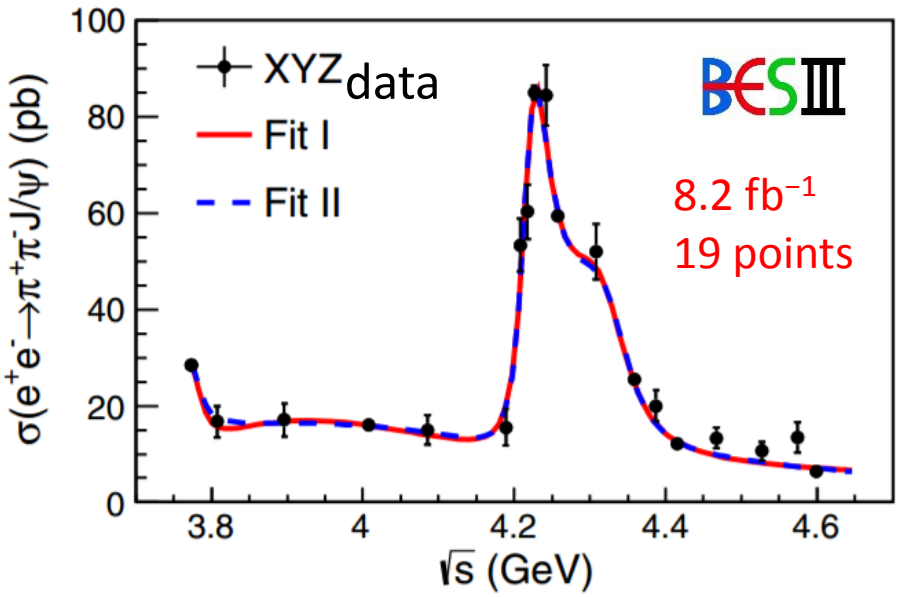


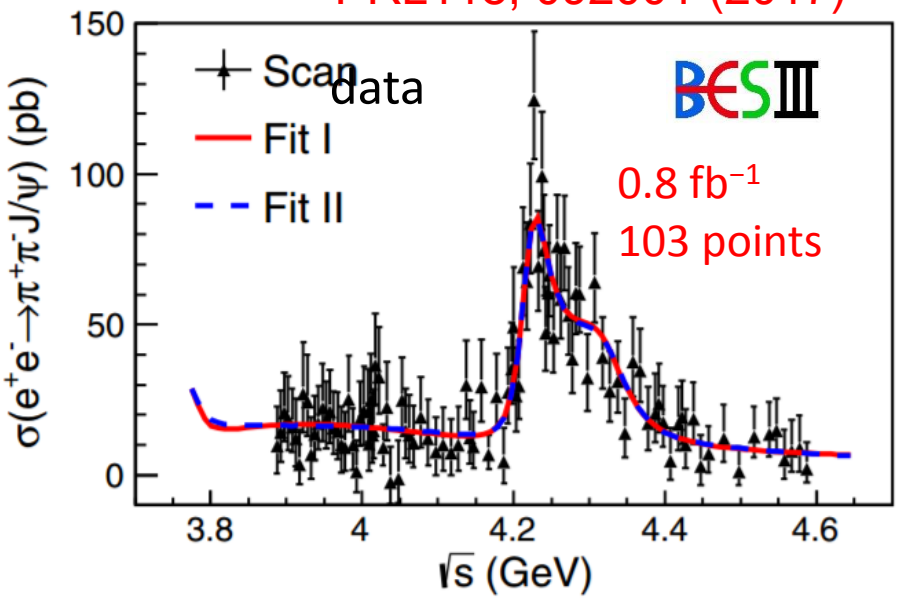
- Select 4 charged tracks and reconstruct J/ψ with lepton pair.
- Very clean sample, very high efficiency (~45%).
- $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$= (62.9±1.9±3.7) pb

PRL110, 252001 (2013)

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

PRL118, 092001 (2017)





- Most precise cross section measurment to date from BESIII
- Fit I = $|BW_1+BW_2*e^{i\phi 2}+BW_3*e^{i\phi 3}|^2$ or Fit II = $|exp+BW_2*e^{i\phi 2}+BW_3*e^{i\phi 3}|^2$ (other fits ruled out)

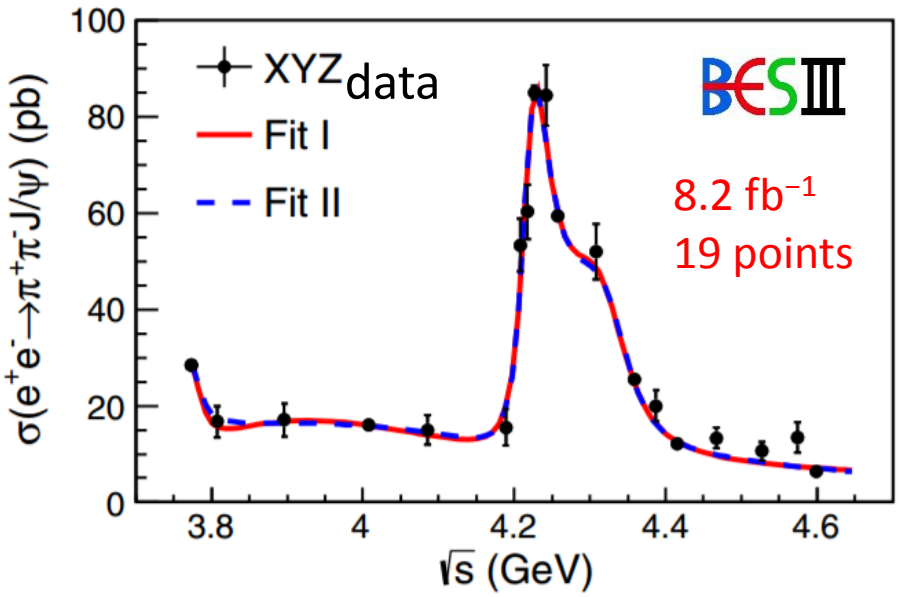
$M = 4222.0 \pm 3.1 \pm 1.4$ MeV (lower)

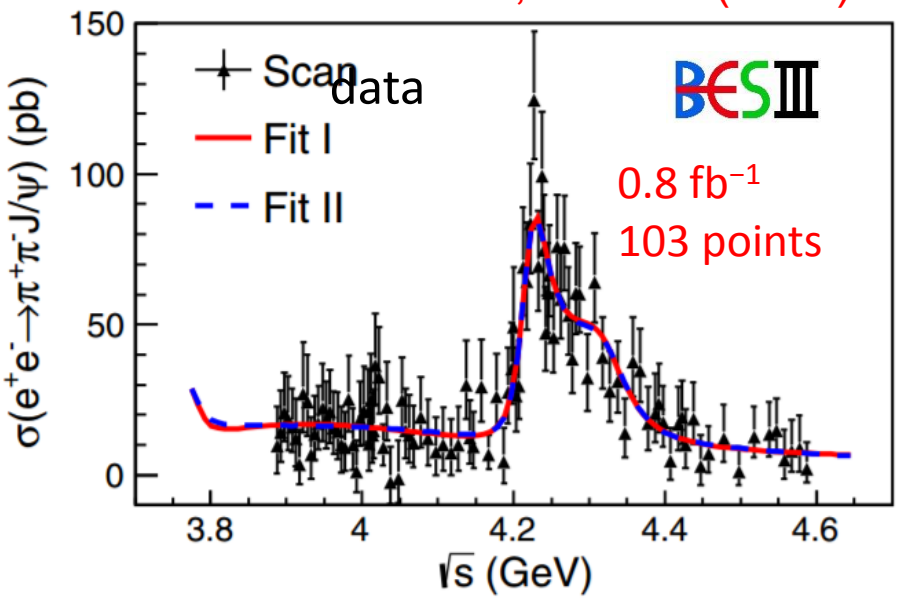
$\Gamma = 44.1 \pm 4.3 \pm 2.0$ MeV (narrower)

$X(4260)$ MASS	4251 ± 9	AVERAGE	PDG
$X(4260)$ WIDTH	120 ±12	AVERAGE	

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

PRL118, 092001 (2017)



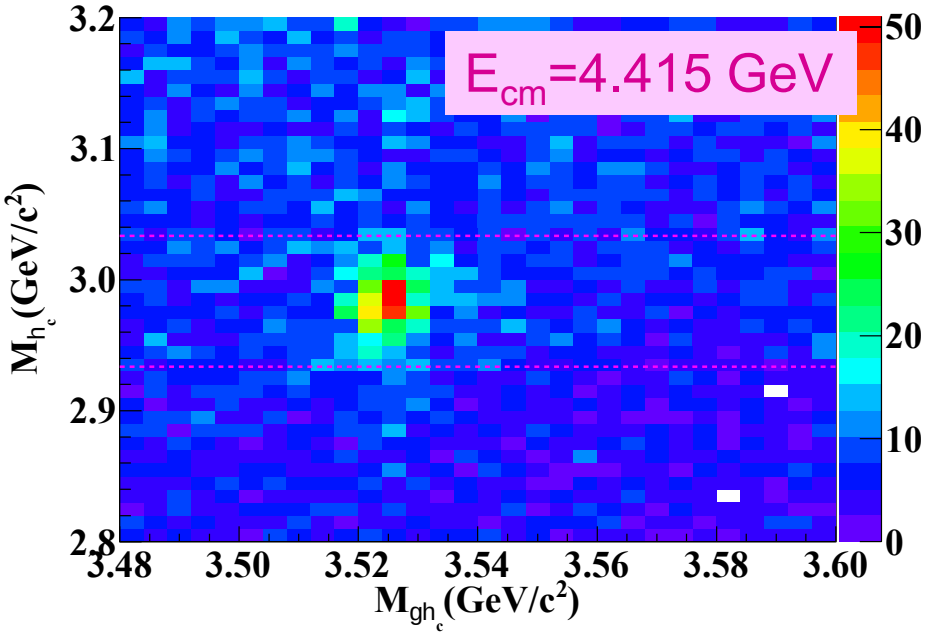


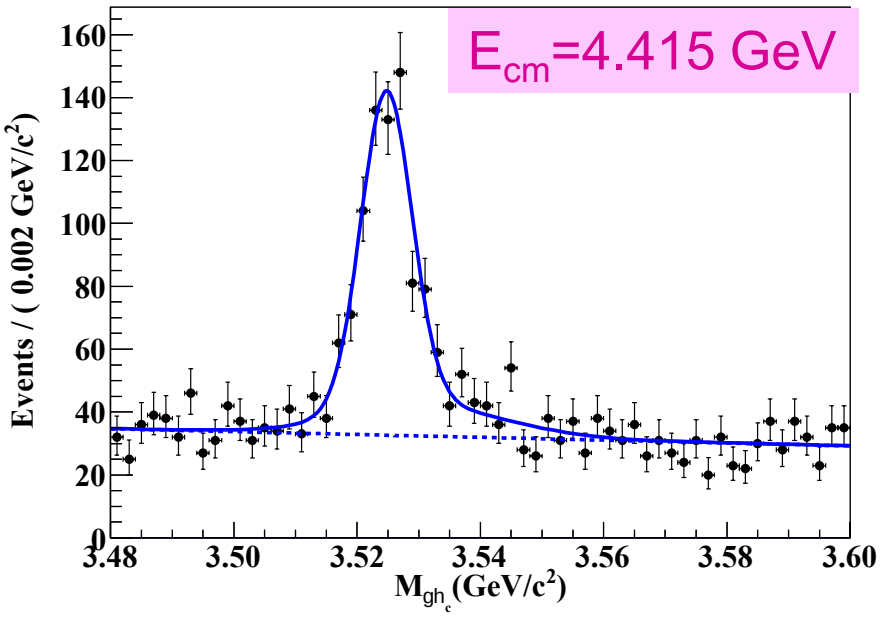
- Most precise cross section measurment to date from BESIII
- Fit I = $|BW_1+BW_2*e^{i\phi 2}+BW_3*e^{i\phi 3}|^2$ or Fit II = $|exp+BW_2*e^{i\phi 2}+BW_3*e^{i\phi 3}|^2$ (other fits ruled out)
- M = $4222.0 \pm 3.1 \pm 1.4$ MeV (lower)
- Γ = $44.1 \pm 4.3 \pm 2.0$ MeV (narrower)

- A 2nd resonance Y_2 with M=$4320.0 \pm 10.4 \pm 7.0$ MeV/c^2
  $\Gamma = 101.4^{+25.3}_{-19.7} \pm 10.2$ MeV
- Observed for the first time, significance > 7.6σ

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

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

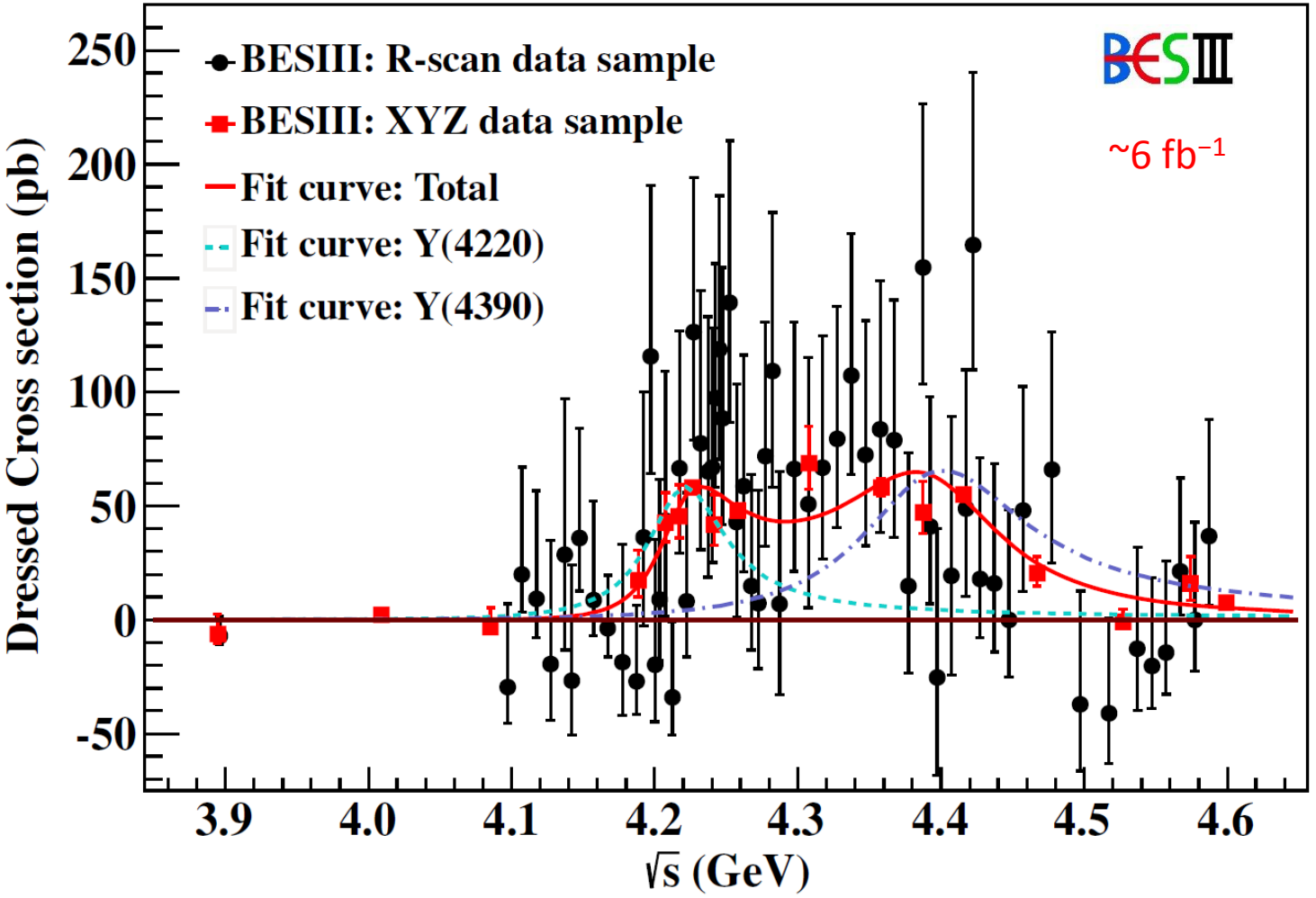




Method same as in PRL111, 242001 (2013)

$e^+e^- \rightarrow \pi^+\pi^- h_c$ cross section

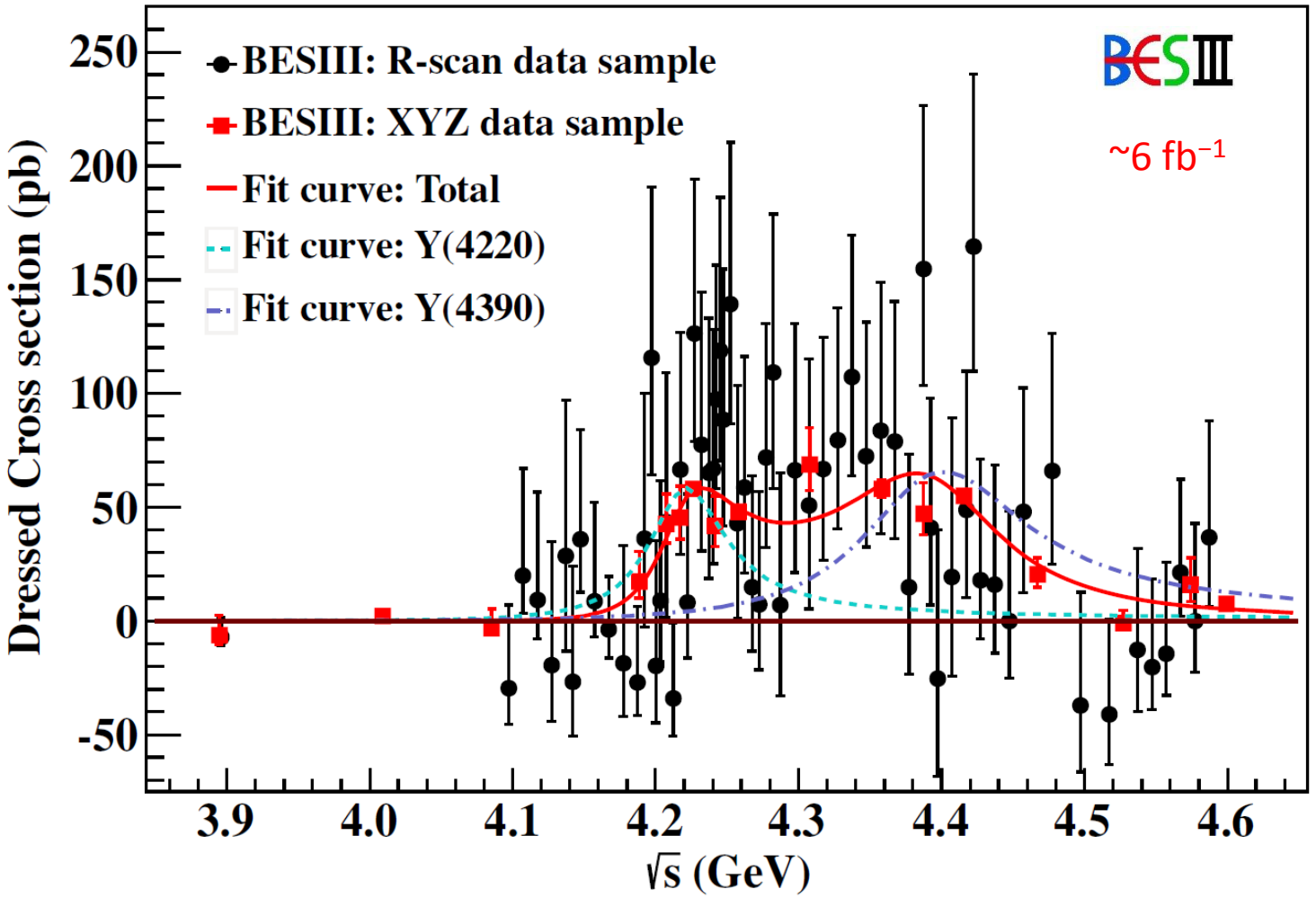
PRL118, 092002 (2017)



- 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

$e^+e^- \to \pi^+\pi^- h_c$ cross section

PRL118, 092002 (2017)

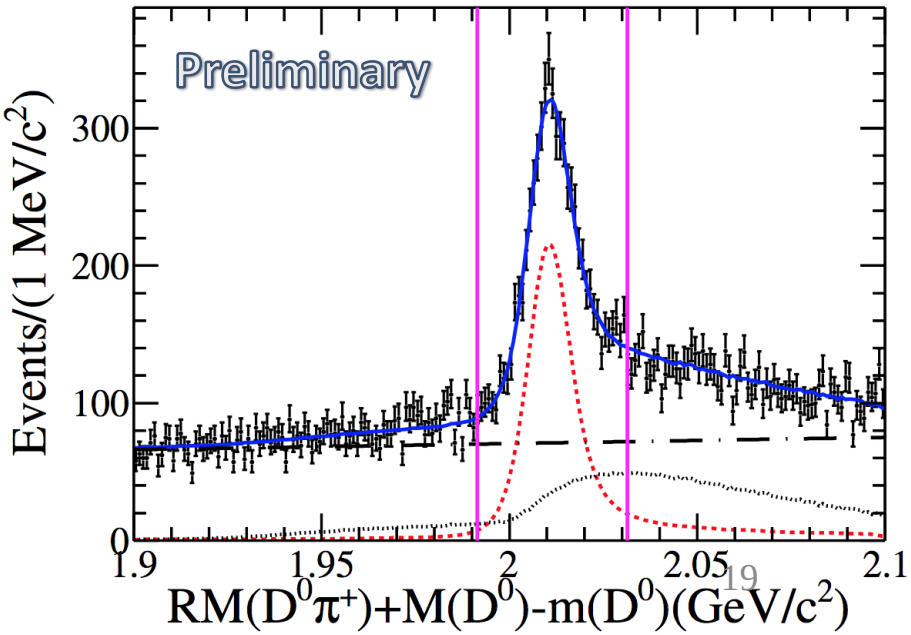


- $M_1 = 4218.4^{+5.5}_{-4.5} \pm 0.9$ MeV/c^2, $\Gamma_1 = 66.0^{+12.3}_{-8.3} \pm 0.4$ MeV → Y(4220)
- $M_2 = 4391.5^{+6.3}_{-6.8} \pm 1.0$ MeV/c^2, $\Gamma_2 = 139.5^{+16.2}_{-20.6} \pm 0.6$ MeV → Y(4390)

$e^+e^- \to \pi^+ D^0 D^{*-} + c.c.$

- Reconstruct $D^0 \to K^-\pi^+$
- 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 GeV/c^2
- select the candidate closest to D^{*-} mass

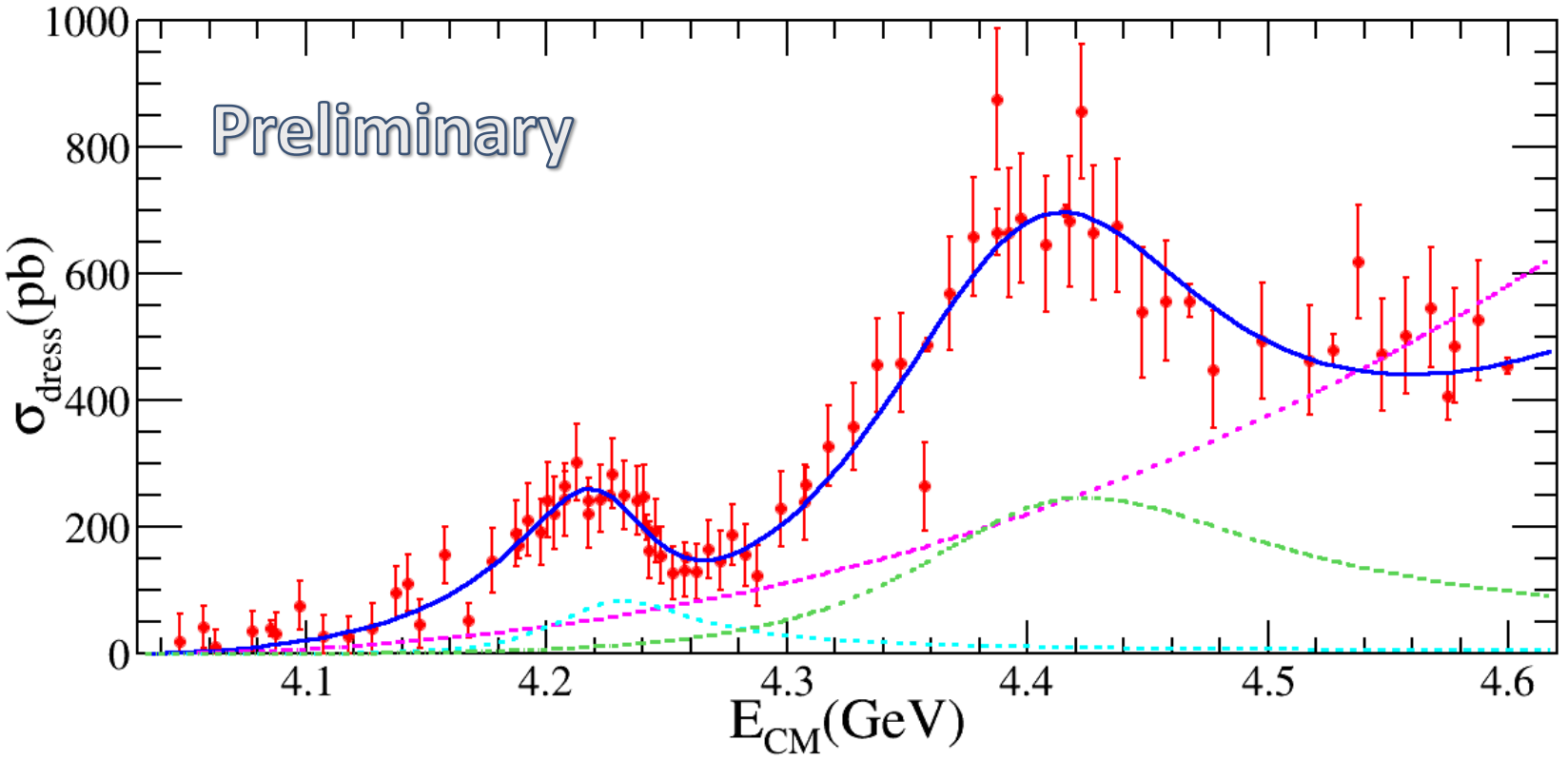
- An un-binned maximum likelihood fit
- Signal shape: MC convolved with a Gaussian;
- The isospin partner background (dotted line) is parameterized with MC;
- A linear function for other bkg



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

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

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



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		
Γ_1 (MeV)		72.3±9.1		
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

The error are statistical only.

Preliminary

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

Improvement of $e^+e^- \to \pi^+\pi^-\psi'$

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:**

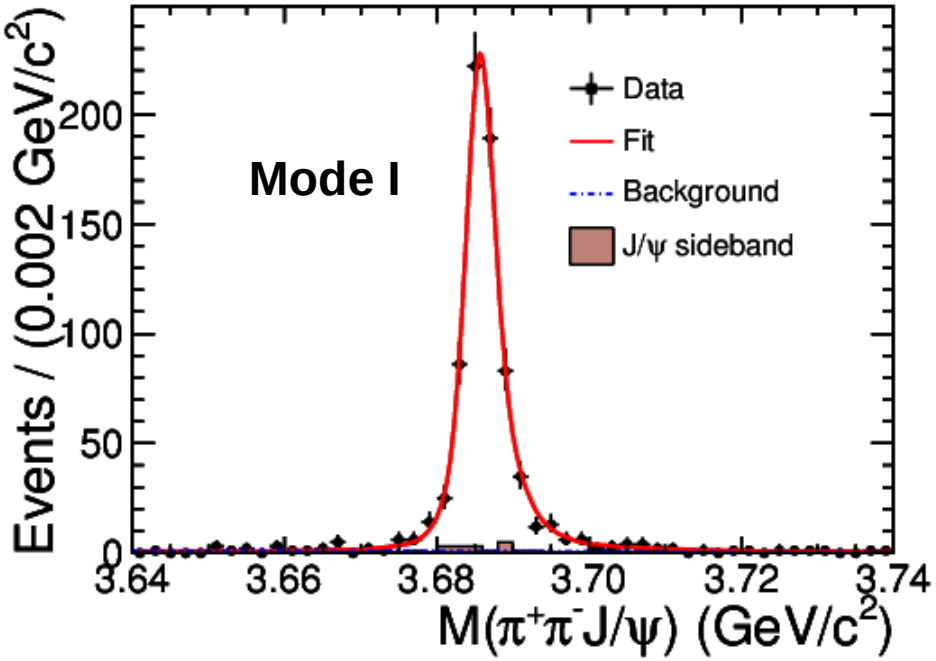
  Mode I: $\Psi(3686) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ (l=e/μ)

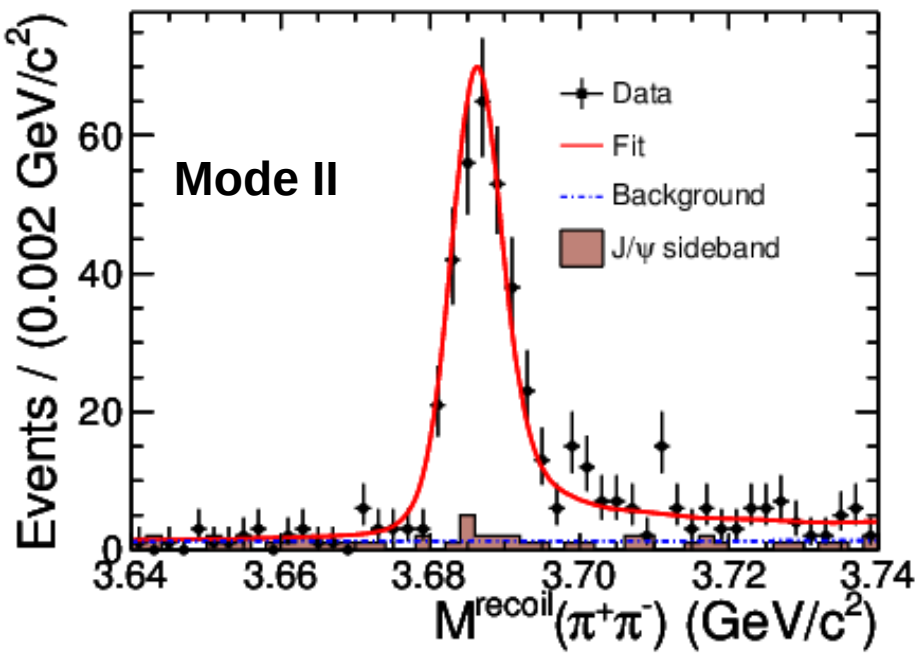
  Mode II: $\Psi(3686) \to$ *neutrals*$+J/\psi$,

  neutrals=($\pi^0\pi^0$, π^0, η and γγ) $J/\psi \to l^+l^-$ (l=e/μ)

Signals at Ecm=4.416 GeV

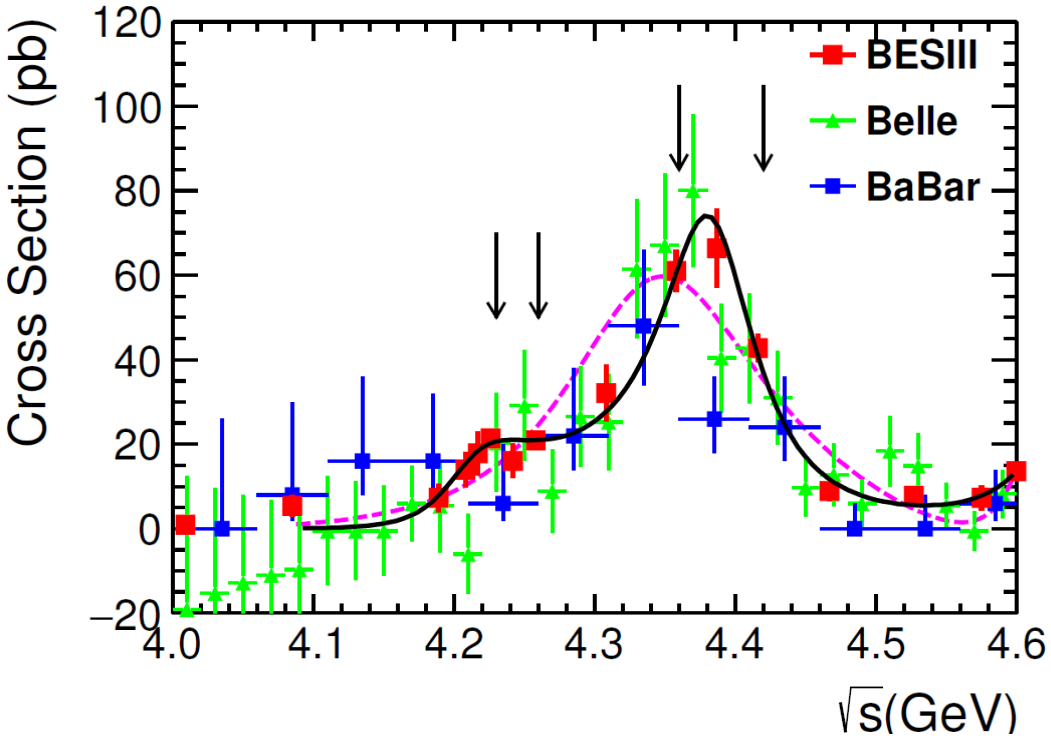
PRD 96, 032004 (2017)





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



arXiv:1703.08787,
PRD 96, 032004 (2017)

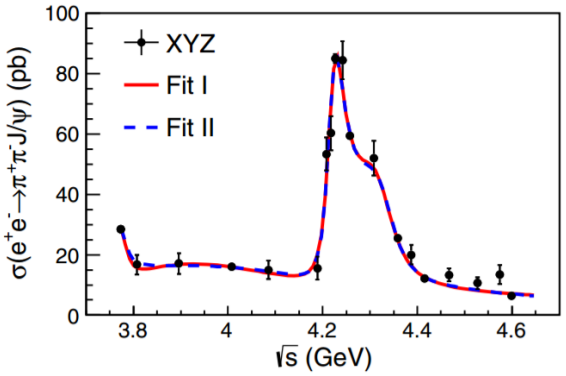
The Y(4220) is necessary

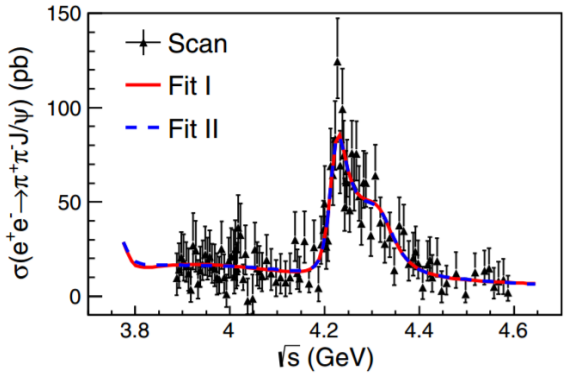
(significance = 5.8σ)

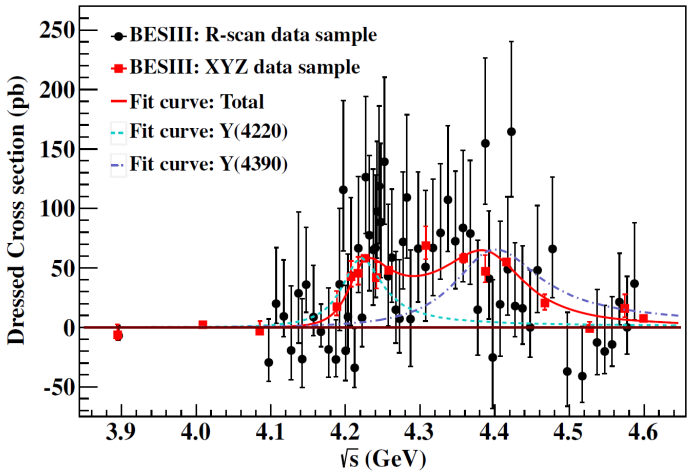
Fix parameters of the Y(4660) to Belle results

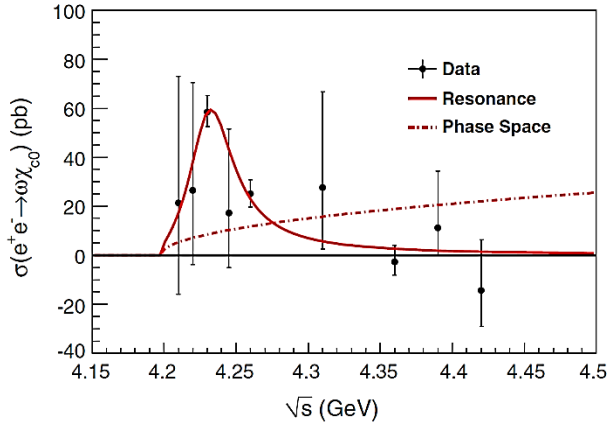
Parameters	Solution I	Solution II
$M(Y4220)$ (MeV/c^2)	4209.5 ± 7.4	
$\Gamma(Y(4220))$ (MeV)	80.1 ± 24.6	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4220))$ (eV)	0.8 ± 0.7	0.4 ± 0.3
$M(Y4390)$ (MeV/c^2)	4383.8 ± 4.2	
$\Gamma(Y(4390))$ (MeV)	84.2 ± 12.5	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4390))$ (eV)	3.6 ± 1.5	2.7 ± 1.0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

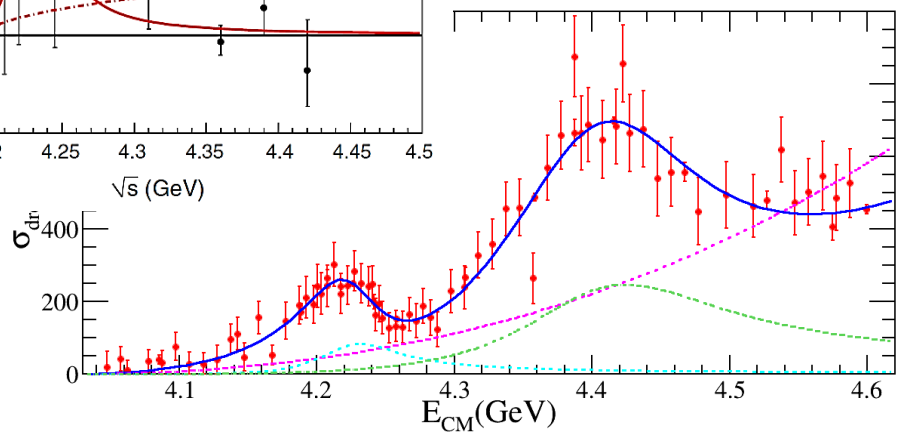
Y(4260)➔Y(4220): what is it?

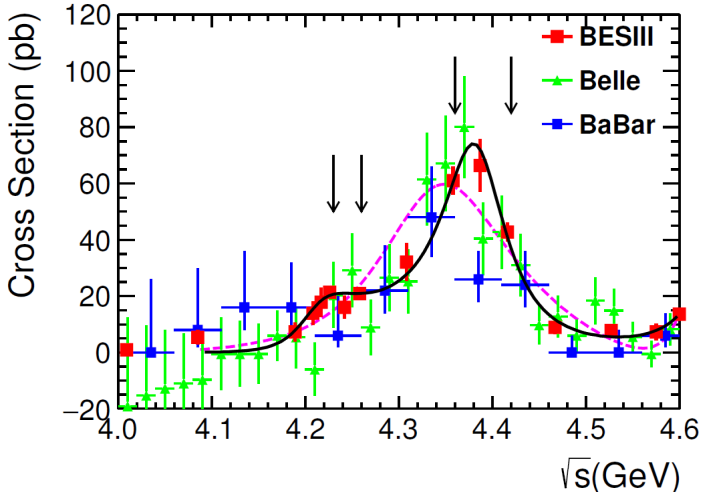












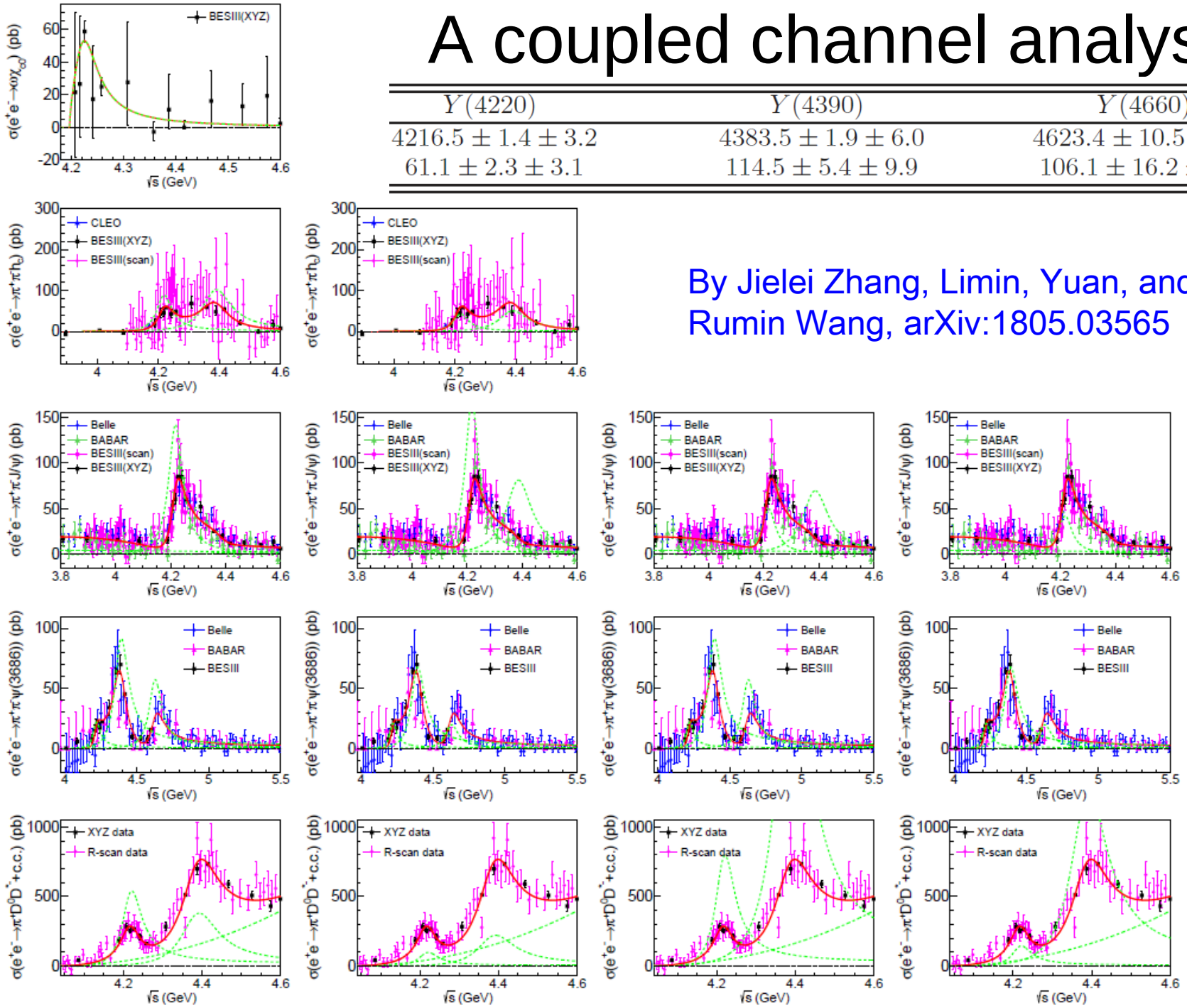
Y(4220) appeared in $\omega\chi_{c0}, \pi^+\pi^- J/psi, \pi^+\pi^-\psi', \pi^+\pi^- h_c, D^0 D^{*-}\pi^+$

Mass~4220 MeV, Width~ 60 MeV!

A coupled channel analysis

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

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



Leptonic width of Y(4220)

For an isospin-zero charmoniumlike state, we expect

$$\mathcal{B}(Y \to \pi\pi h_c) = \tfrac{3}{2} \times \mathcal{B}(Y \to \pi^+\pi^- h_c),$$
$$\mathcal{B}(Y \to \pi\pi J/\psi) = \tfrac{3}{2} \times \mathcal{B}(Y \to \pi^+\pi^- J/\psi),$$
$$\mathcal{B}(Y \to \pi\pi\psi(3686)) = \tfrac{3}{2} \times \mathcal{B}(Y \to \pi^+\pi^-\psi(3686)),$$
$$\mathcal{B}(Y \to \pi D\bar{D}^*) = 3 \times \mathcal{B}(Y \to \pi^+ D^0 D^{*-} + c.c.),$$

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

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

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

More modes being measured:

- **charmed meson pairs, light hadrons+η_c**

J. Zhang et al., arXiv:1805.03565

What is Y(4220)?

- Hybrid?
  - Mass agrees with LQCD
  - Couples to e^+e^- weaker than conventional charmonium
  - Couples to spin-singlet strongly
- $\bar{D}_1D$ molecule?
  - S-wave open threshold [BESIII will release $\sigma(e^+e^- \rightarrow \bar{D}_1D)$ soon]
- $\psi(4S)$ state?
  - Screened potential reduces 4S mass
- $\bar{D}_s^* D_s^*$ molecule?
- $\omega\chi_{c0}$ molecule?

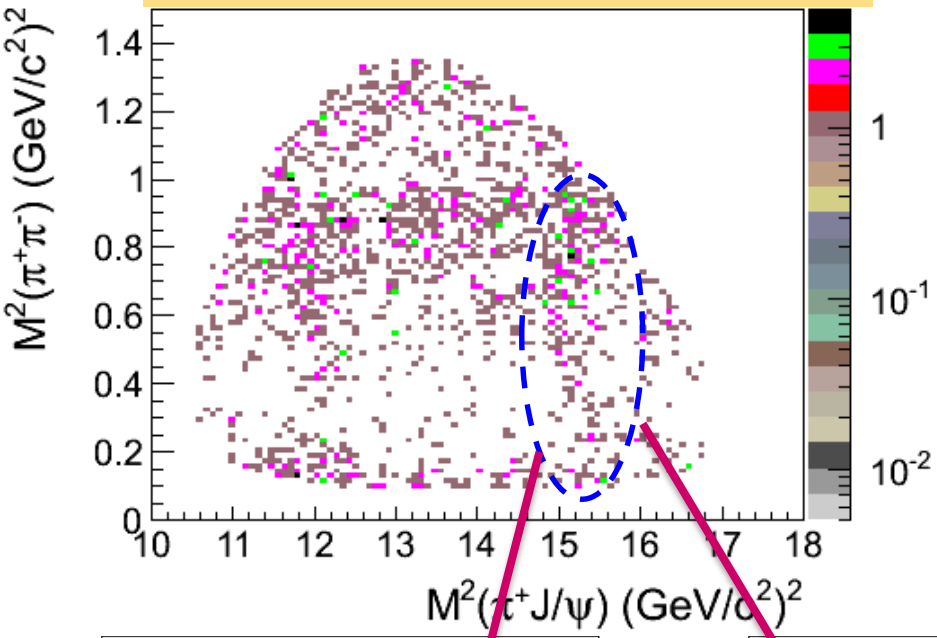
➔ more data and more theoretical efforts

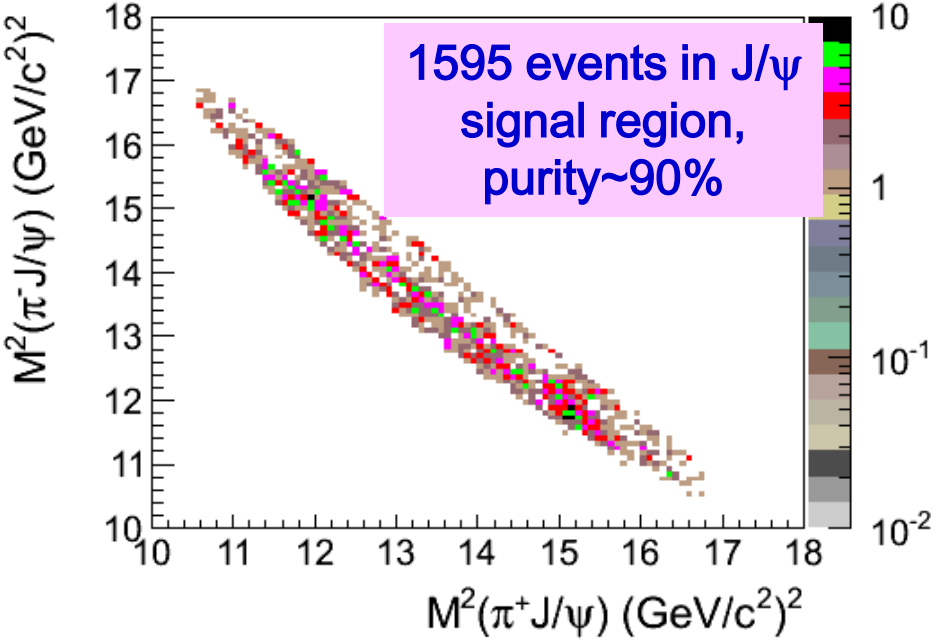
The Z_c states

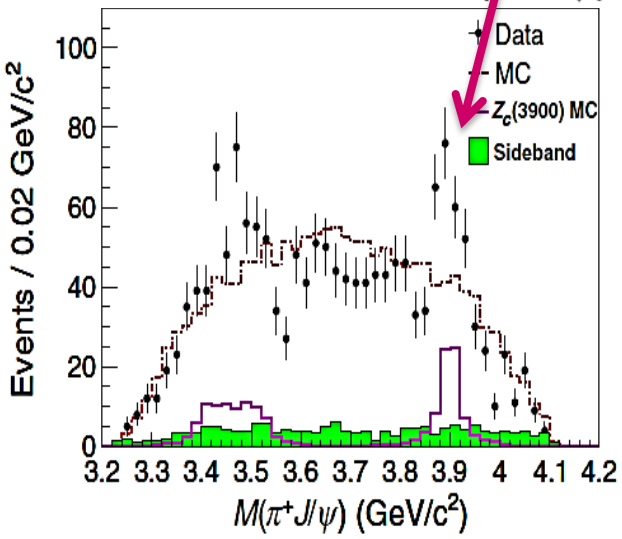
$e^+e^- \to \pi^+\pi^- J/\psi$ at E_{cm}=4.26 GeV

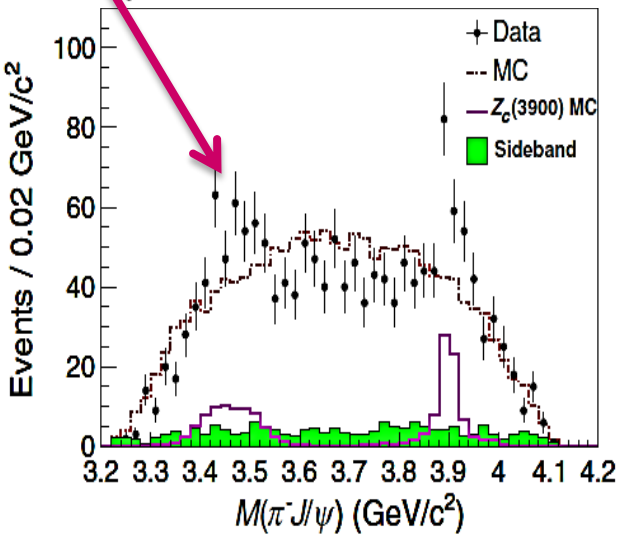
PRL110, 252001 (2013)

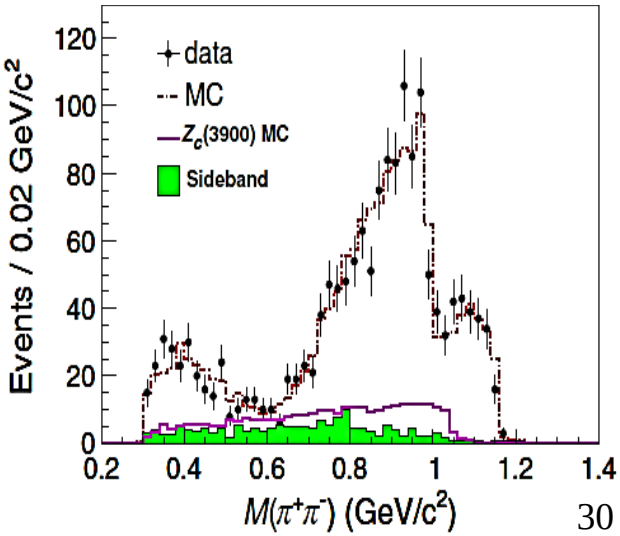
525 pb^{-1} data at 4.260 GeV





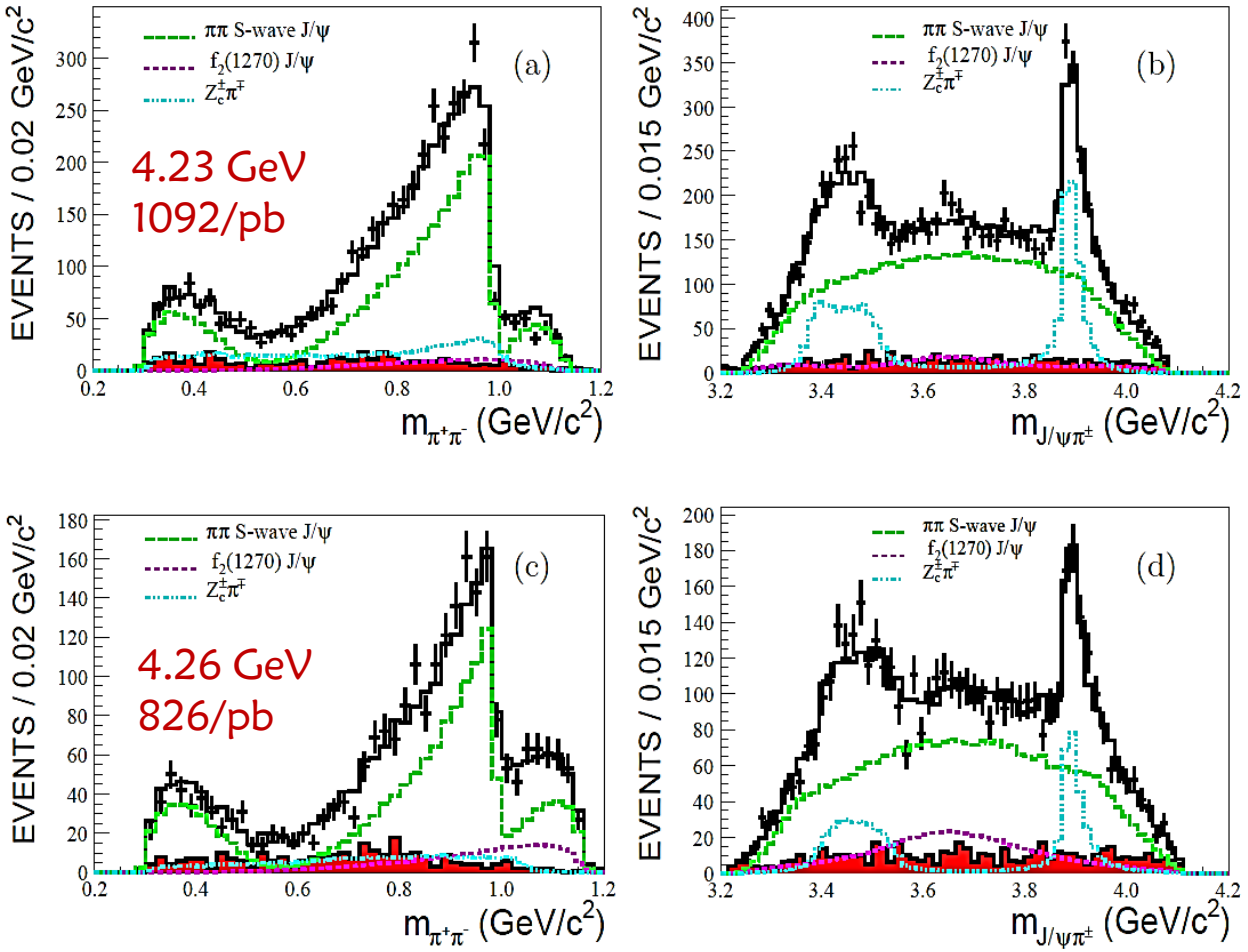






Spin-parity of $Z_c(3900)$

PRL 119, 072001 (2017)



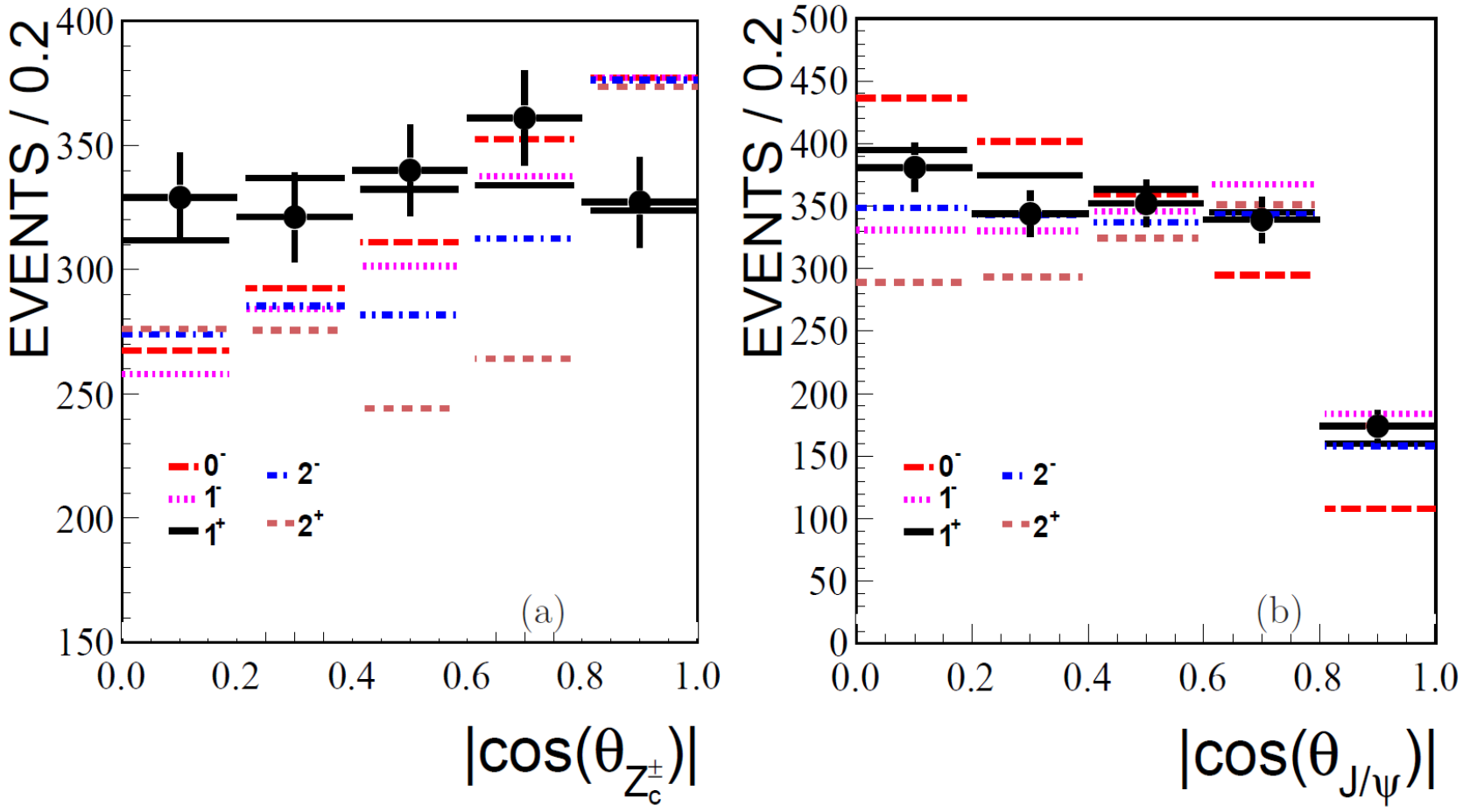
- Asymmetric line shape
- JP=1+ preferred over 0-, 1-, 2-, 2+ by at least 7σ.
- Significant $f_0(980)$ contribution
- ππ D-wave fraction increases as E_{cm} increases

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]

Spin-parity of $Z_c(3900)$

PRL 119, 072001 (2017)



- Z_c enhanced events show clear JP=1+ preference!

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

$$BW(s, M, g_1', g_2') = \frac{1}{s - M^2 + i[g_1'\rho_1(s) + g_2'\rho_2(s)]}$$

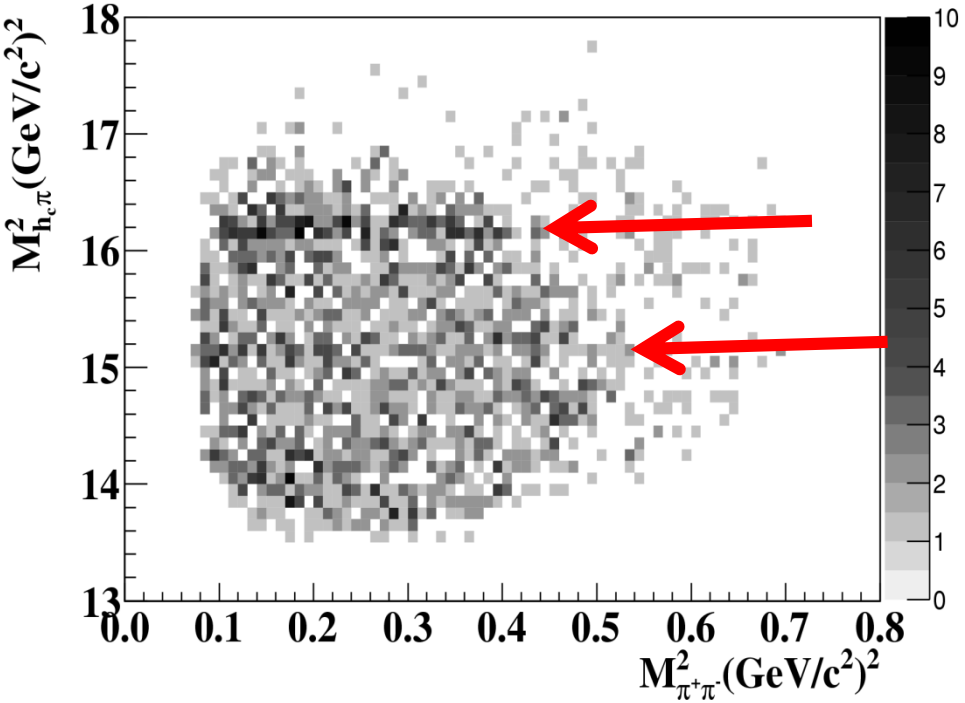
parameter	value
Mass	(3901.5 ± 2.7 ± 38.0) MeV
g_1'	(0.075 ± 0.006 ± 0.025) GeV^2
g_2'/g_1'	27.1 ± 2.0 ± 1.9
M_{pole}	(3881.2 ± 4.2 ± 52.7) MeV
Γ_{pole}	(51.8±4.6±36.0) MeV

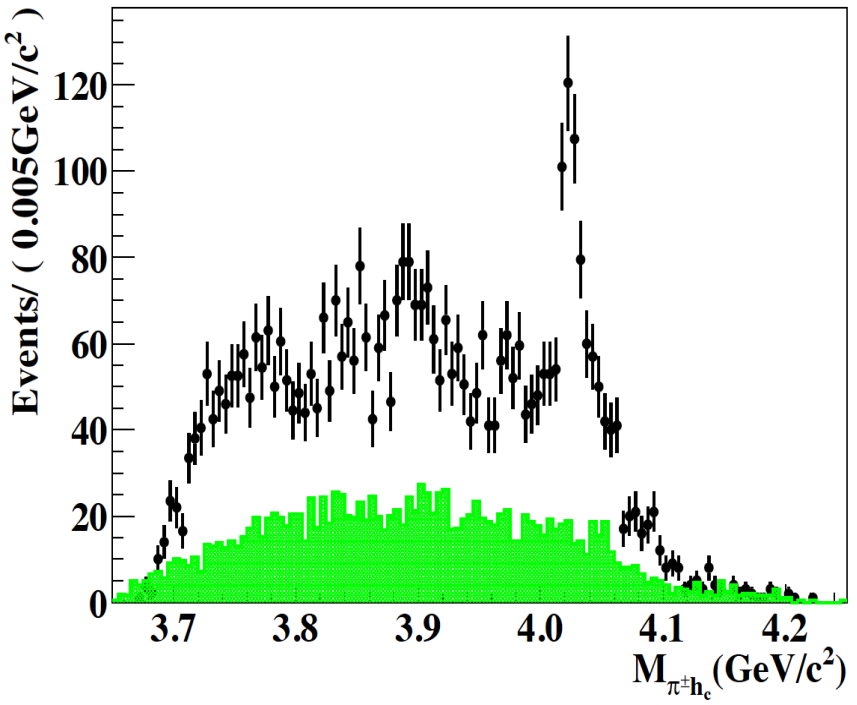
Ecm	$\sigma(e^+e^- \to \pi^+ Z_c + c.c.)$
4.23 GeV	(21.8 ± 1.0 ± 4.4) pb
4.26 GeV	(11.0 ± 1.2 ± 5.4) pb

PRL 119, 072001 (2017)

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

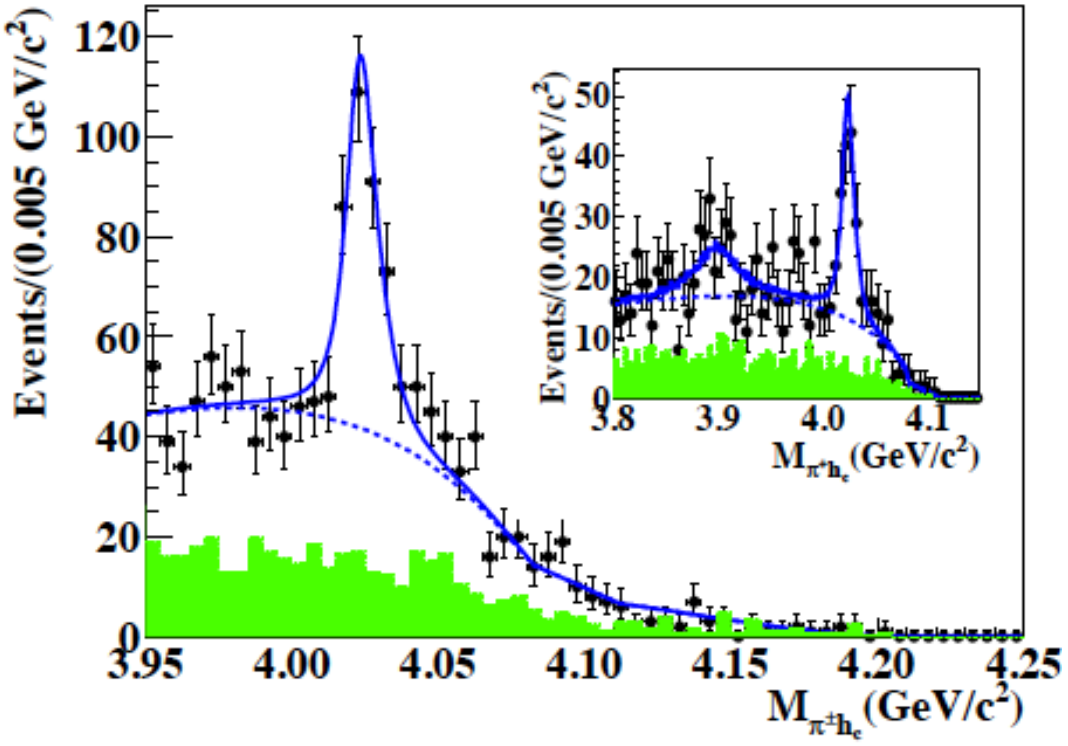
PRL111, 242001 (2013)





- Obvious structure around 4.02 GeV
- Hints of $Z_c(3900)$
- ~1500 events in h_c signal region at 4.230, 4.260 and 4.360 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

$M(Z_c(4020)) =$

$4022.9\pm0.8\pm2.7$ MeV;

$\Gamma(Z_c(4020)) =$

$7.9\pm2.7\pm2.6$ MeV

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

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

$8.7\pm1.9\pm2.8\pm1.4$ pb @ 4.230 GeV

$7.4\pm1.7\pm2.1\pm1.2$ pb @ 4.260 GeV

$10.3\pm2.3\pm3.1\pm1.6$ pb @ 4.360 GeV

Significance: 8.9σ [$Z_c(4020)$]

No significant $Z_c(3900)$ (2.1σ)

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

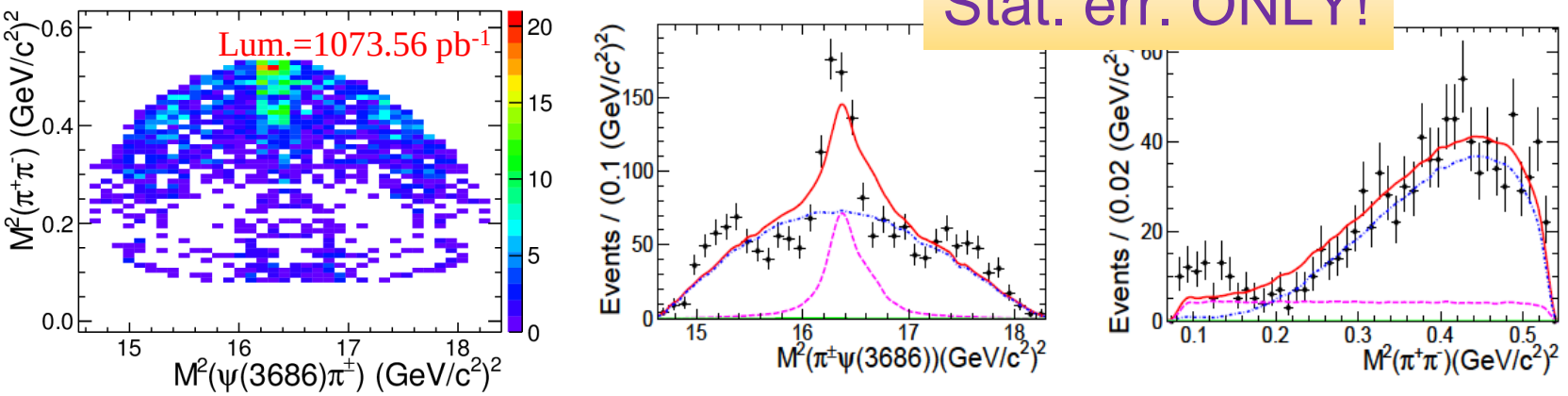
PRD 96, 032004 (2017)

- 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 $M^2(\pi^-\psi(3686))$

$$\frac{p \cdot q/c^2}{(M_R^2 - x)^2 + M_R^2 \cdot \Gamma^2/c^4} + \frac{p \cdot q/c^2}{(M_R^2 - y) + M_R^2 \cdot \Gamma^2/c^4}$$

- The fit yields a mass of $M=4032.1 \pm 2.4\ \mathrm{MeV}/c^2$ and a width of $\Gamma=26.1 \pm 5.3\ \mathrm{MeV}$, with a significance of 9.2σ

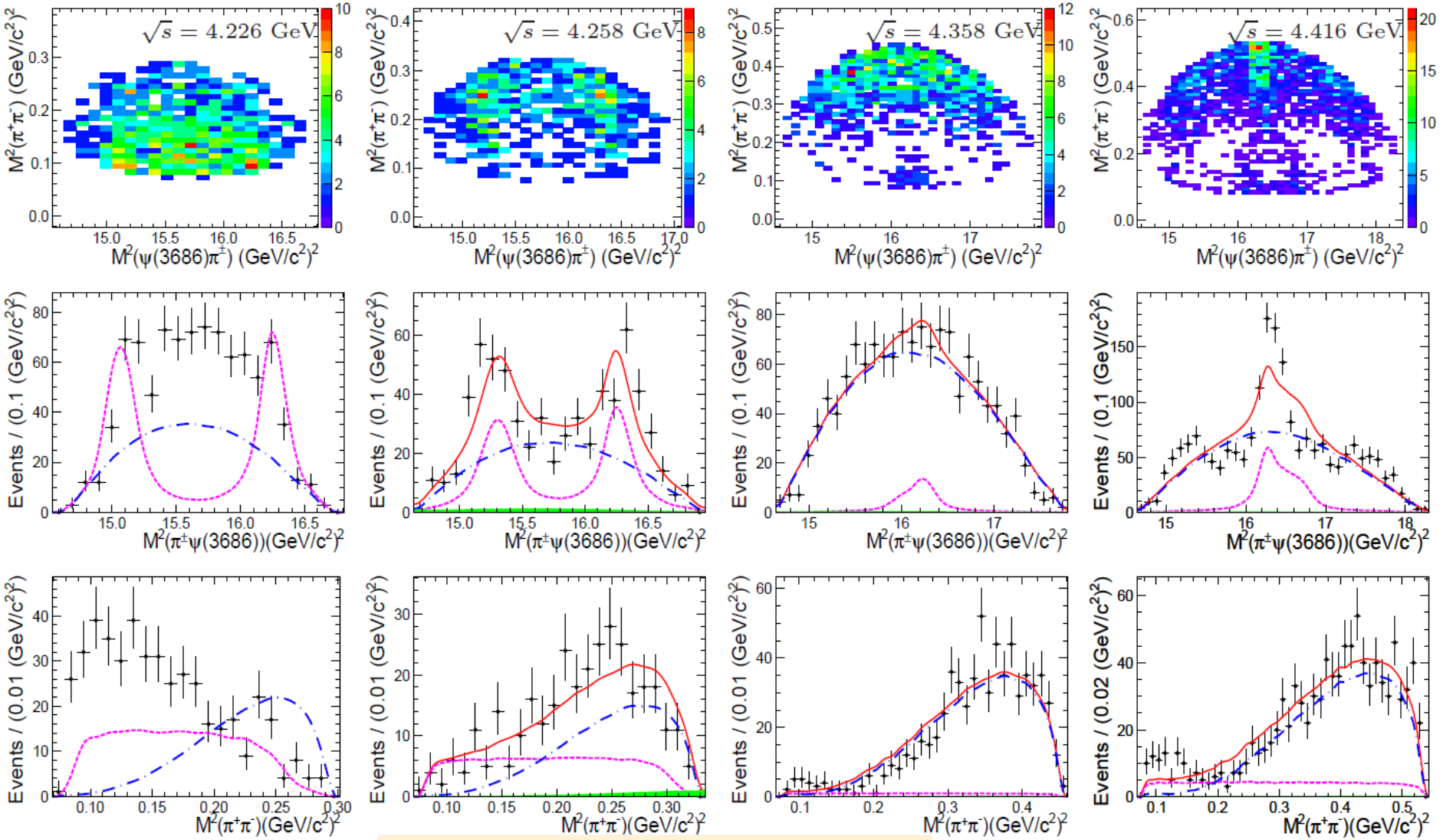
Stat. err. ONLY!



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

Fit of intermediate state

Interference not considered & fits cannot describe data well!

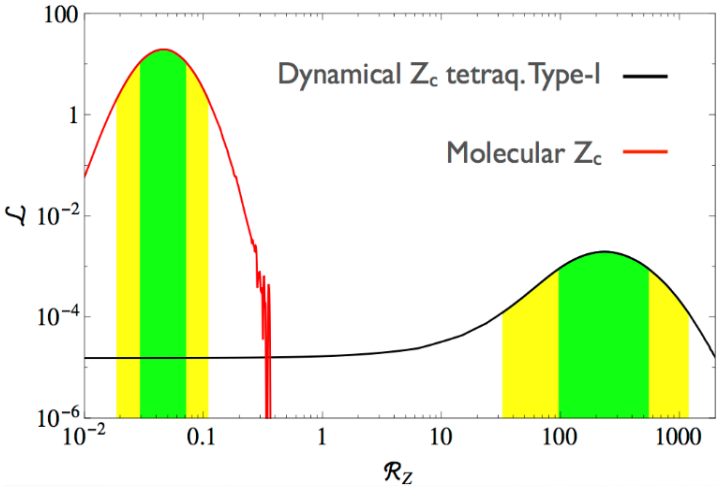


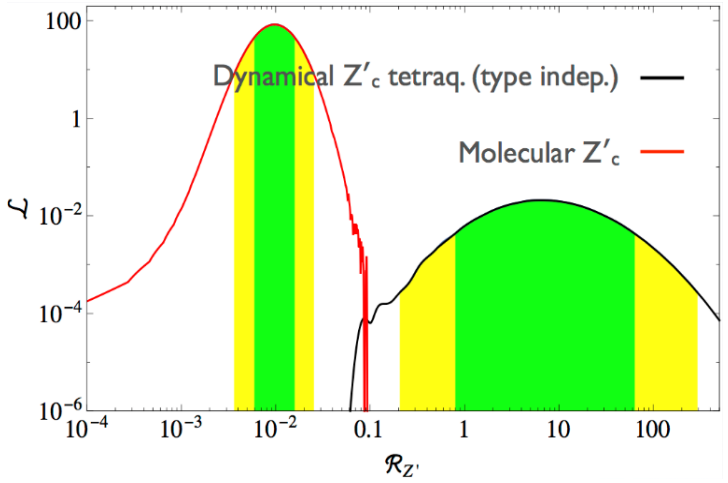
PRD 96, 032004 (2017)

Search for $Z_c \to \rho\eta_c$

New

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





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

$$R_{z\prime} = \frac{B(Z_c' \to \rho\eta_c)}{B(Z_c' \to \pi h_c)}$$

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 $Z_c \to \rho\eta_c$

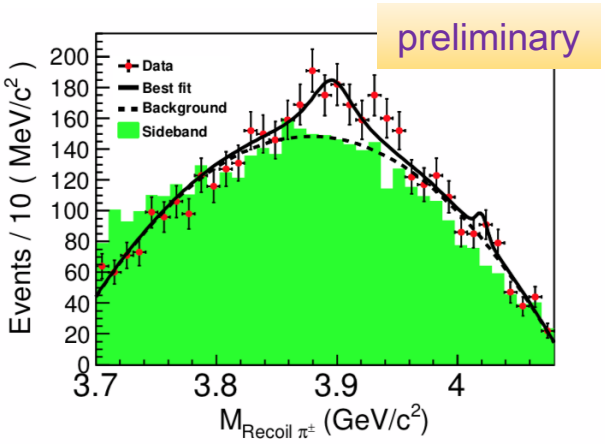
New

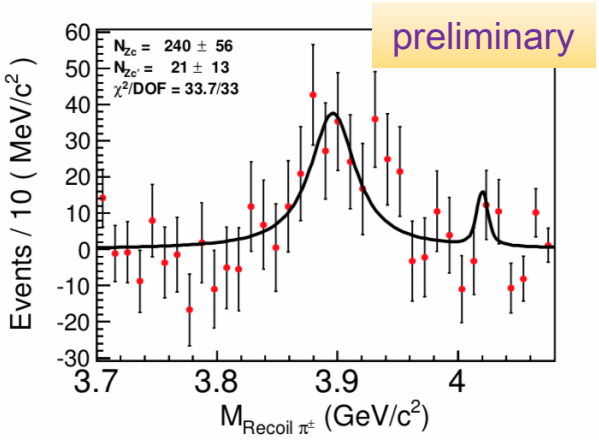
preliminary

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

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

- Strong evidence of $e^+e^- \to \pi Z_c$, $Z_c \to \rho\eta_c$ at $\sqrt{s} = 4.23$, statistical significance is 4.3σ. (3.9σ including systematics)
- $e^+e^- \to \pi Z_c', Z_c' \to \rho\eta_c$ not seen.





$e^+e^- \to \pi Z_c, Z_c \to \rho\eta_c$ @ 4.23 GeV

Evidence for $Z_c \to \rho\eta_c$

preliminary

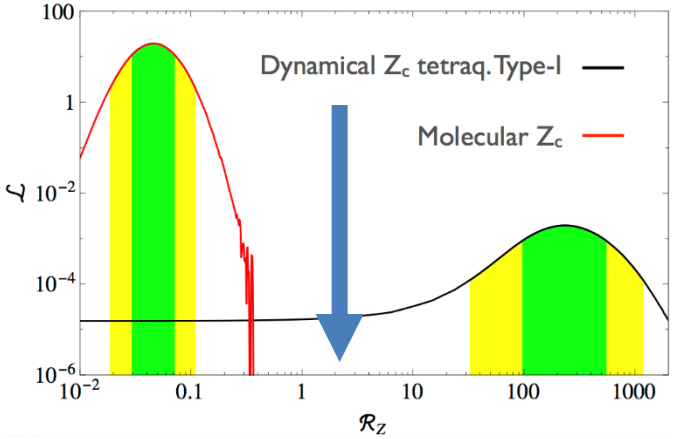
New

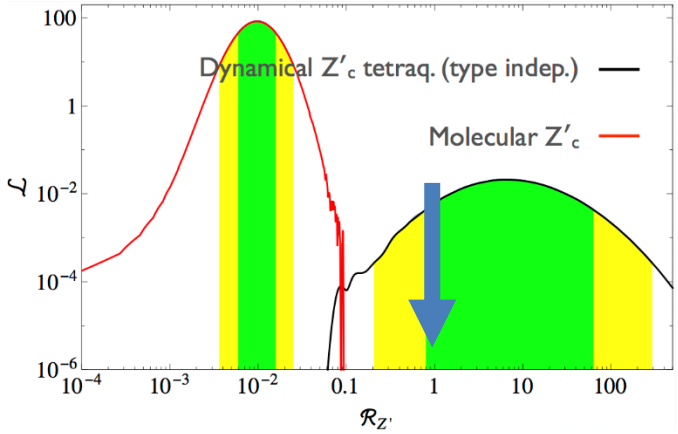
- **Measure Born cross section at 4.23 GeV:**

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

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

	$\sqrt{s} = 4.23$ GeV	$\sqrt{s} = 4.26$ GeV	$\sqrt{s} = 4.36$ 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	$6.6^{+56.8}_{-5.8}$		$0.010^{+0.006}_{-0.004}$





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

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

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

Summary of the Z_c states at BESIII

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

Summary

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

Thanks a lot!

Thanks a lot!

谢谢！

Belle II vs. BESIII

ISR produces events at all CM energies BESIII can reach