Hadronic Transitions in e^+e^- Collisions above 4 GeV at BESIII

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06-09-2016

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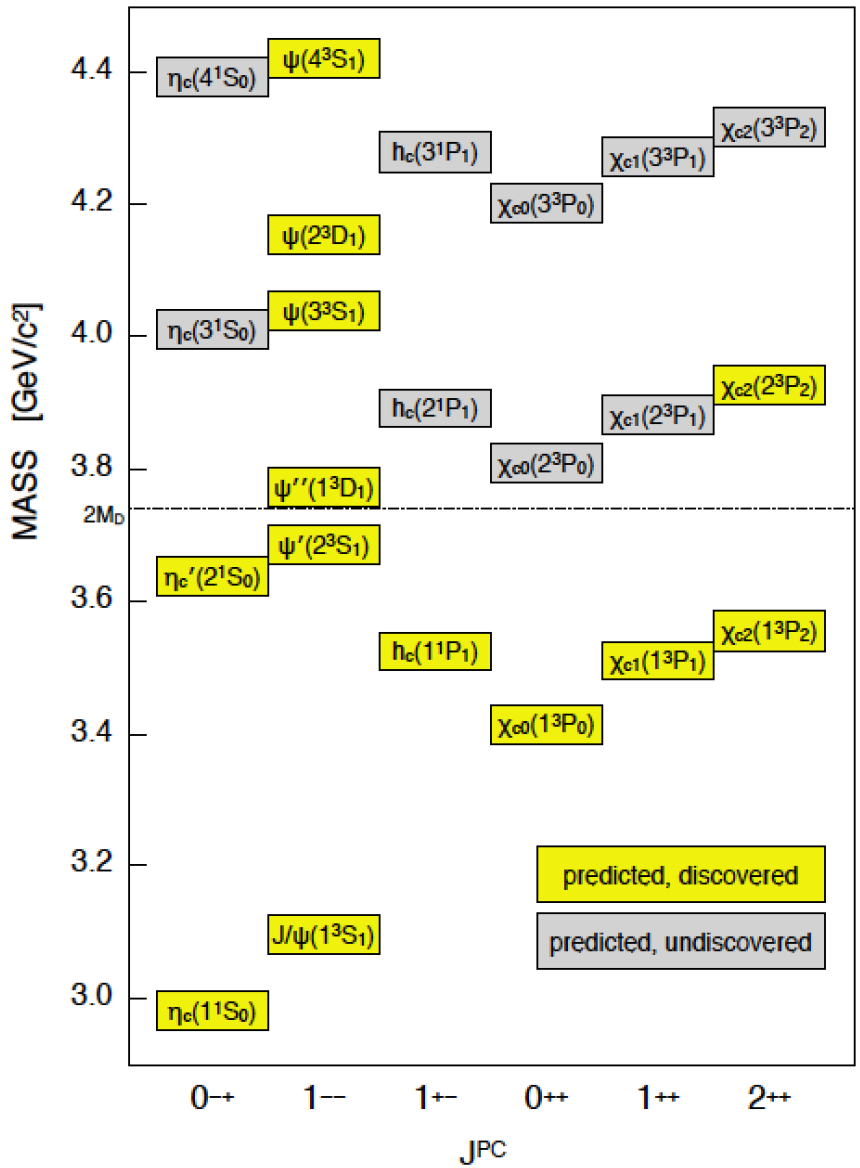
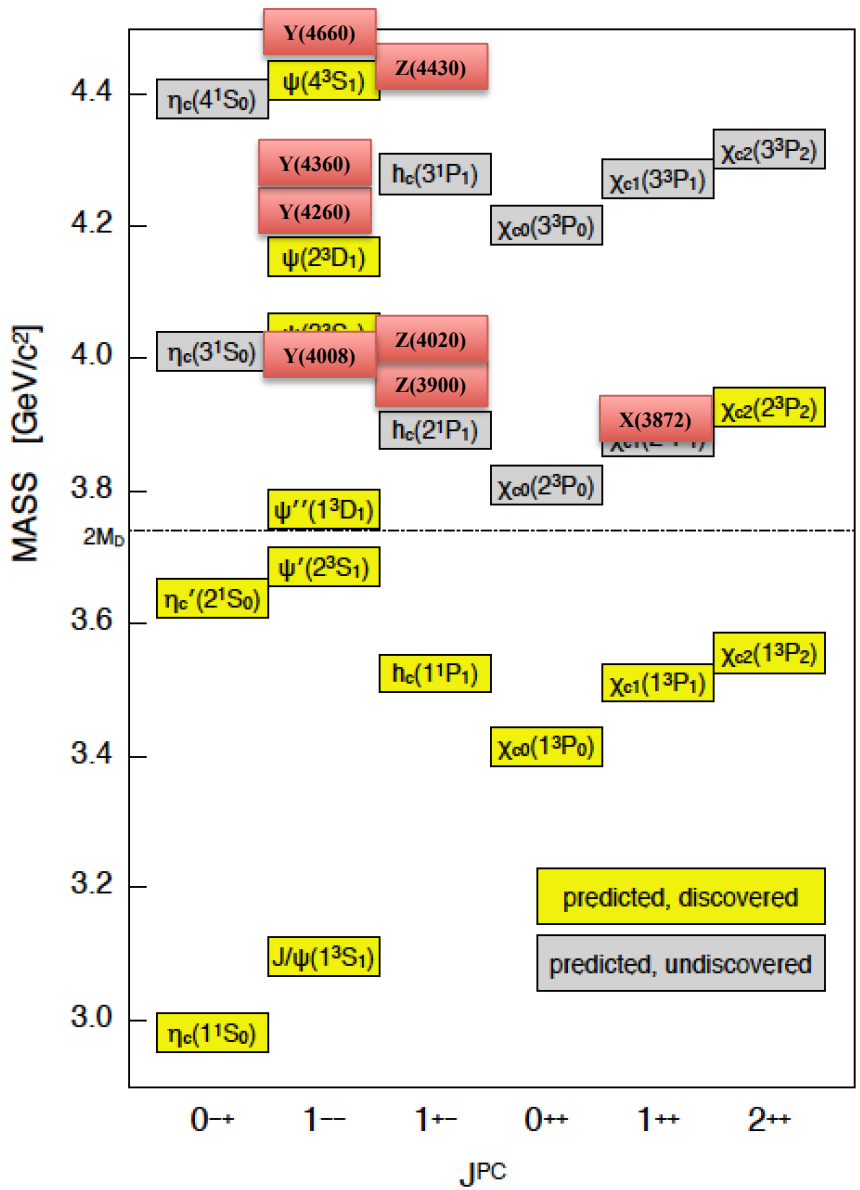
Charmonium spectroscopy



Below open-charm threshold, all states have been observed. Charm anti-charm potential models describe spectrum very well.

Many missing states above open-charm threshold.

There are lots of XYZ states



A number of new states above open-charm threshold.

Charmonium in the final state, but not an obvious charmonium state (charmoniumlike or *XYZ*)

***X*: neutral, in B decays, Y transitions and hadron machines.**

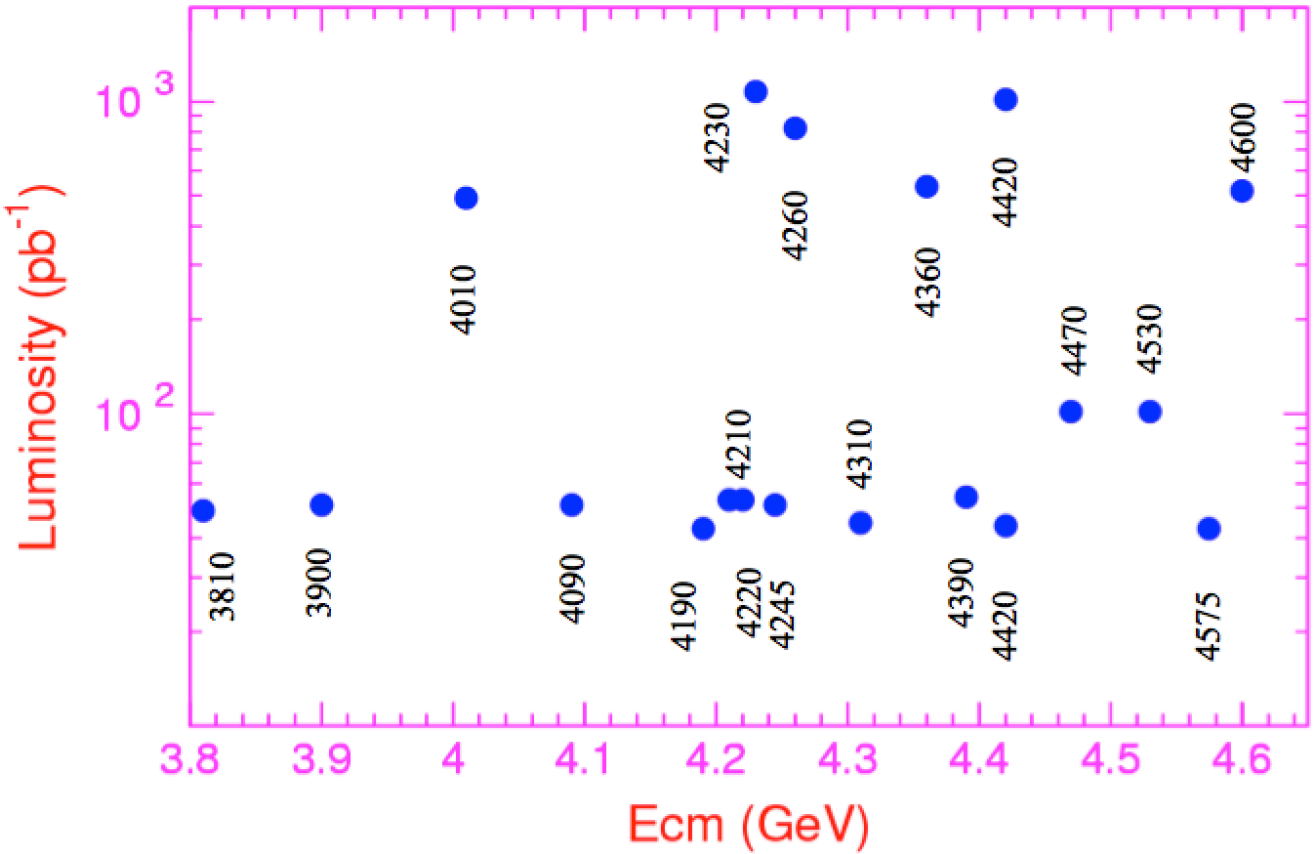
***Y*: neutral, vectors in e^+e^- colliders.**

***Z*$^{\pm}$: charged quarkonium-like**

What are they?

- Charmonium?
- Tetraquark?
- Molecule?
- Hybrid?
- Hadrocharmonium?
- …

BESIII data samples for XYZ study (5/fb)

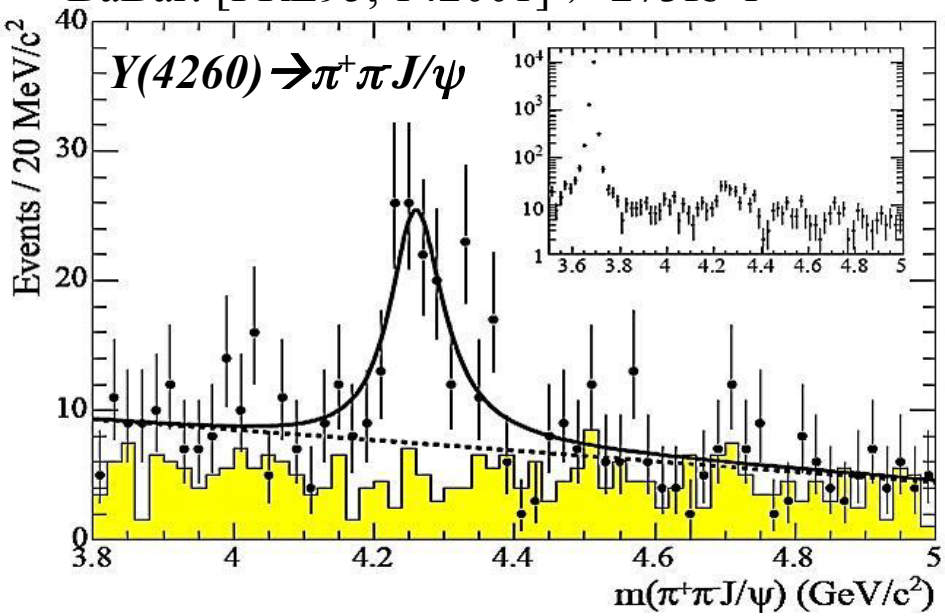


For the *XYZ* states study, BESIII has accumulated about 5 fb^{-1} data. Around $\psi(4040)$, $Y(4260)$, and $Y(4360)$ peaks, we collected the largest data sample in the world so far for the study of their decays. Data samples with small statistics at other energy points are collected for the line-shape study.

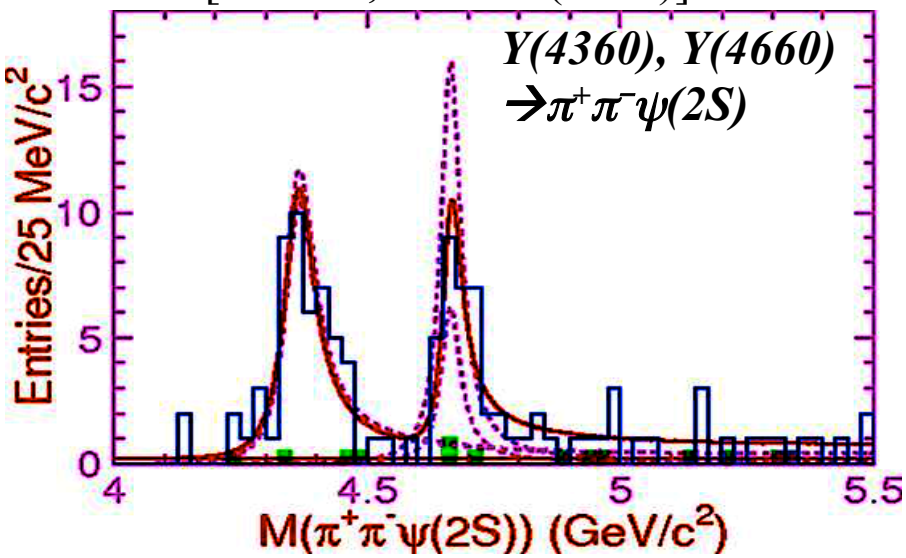
Y-family states

- A family of vectors ($J^{PC}=1^{--}$) observed in e^+e^- colliders.
- In the process $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$, the BaBar experiment observed the $Y(4260)$, then confirmed by CLEO and Belle.
- Properties are different from 1^{--} charmonium: strong coupling to $\pi\pi J/\psi$, no significant enhancement in open charm production.
- At BESIII, vector ψ/Y states can be produced directly.

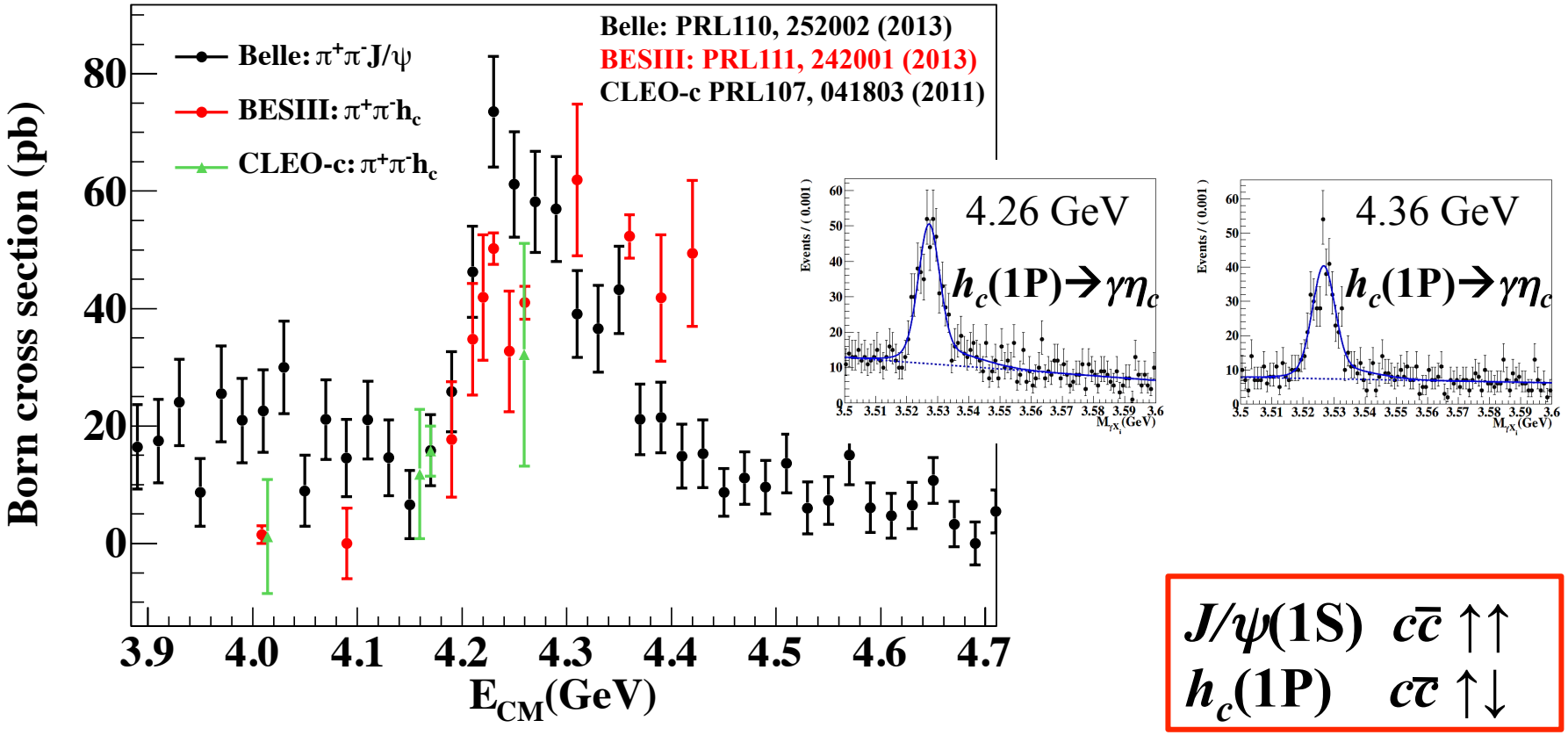
BaBar: [PRL95, 142001] , 273fb-1



Belle [PRL 99, 142002 (2007)] 673fb^{-1}



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

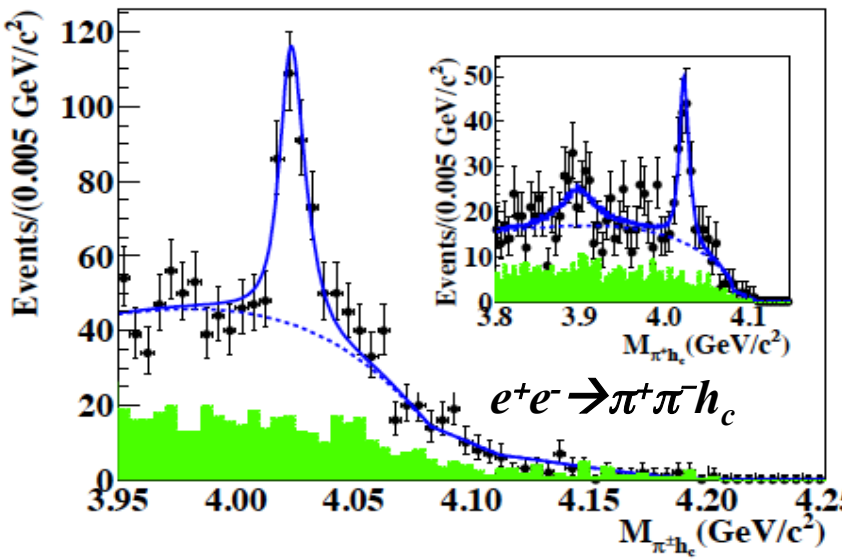


$J/\psi(1S)$ $c\bar{c}$ ↑↑
$h_c(1P)$ $c\bar{c}$ ↑↓

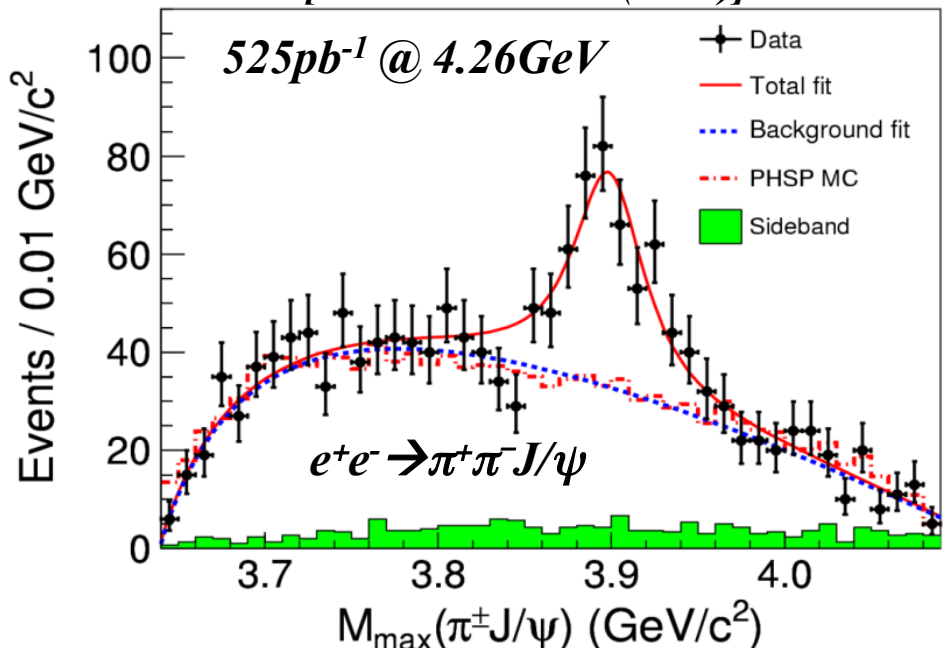
- Reconstruct $h_c \to \gamma\eta_c$, $\eta_c \to$hadrons [16 exclusive decay modes]
- $\sigma(e^+e^- \to \pi^+\pi^- h_c) \sim \sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ but line shape different
- Local maximum ~ 4.23 GeV for $e^+e^- \to \pi^+\pi^- h_c$
- Broad structure at high energy region?

$Z_c(3900)^\pm$ and $Z_c(4020)^\pm$ in $e^+e^- \to \pi^+\pi^- h_c(1P), \pi^+\pi^- J/\psi$

BESIII [PRL 111 242001 (2013)]



BESIII[PRL 110 252001 (2013)]



$$\frac{\sigma[e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- J/\psi]}{\sigma[e^+e^- \to \pi^+\pi^- J/\psi]} = (21.5 \pm 3.3 \pm 7.5)\% \text{ at } 4.26 \text{ GeV}$$

Narrow $\pi^\pm h_c$ structure observed

***M = 4022.9±0.8±2.7 MeV**

***Γ= 7.9±2.7±2.6 MeV**

***Significance : 8.9σ**

Hint for $Z_c(3900) \to \pi^\pm h_c$?

***Significance is only 2.1σ**

$J/\psi(1S)$	$c\bar{c} \uparrow\uparrow$
$h_c(1P)$	$c\bar{c} \uparrow\downarrow$

$$\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- h_c) < 11 \text{ pb}$$

$$\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- J/\psi) = 13 \pm 5 \text{ pb}$$

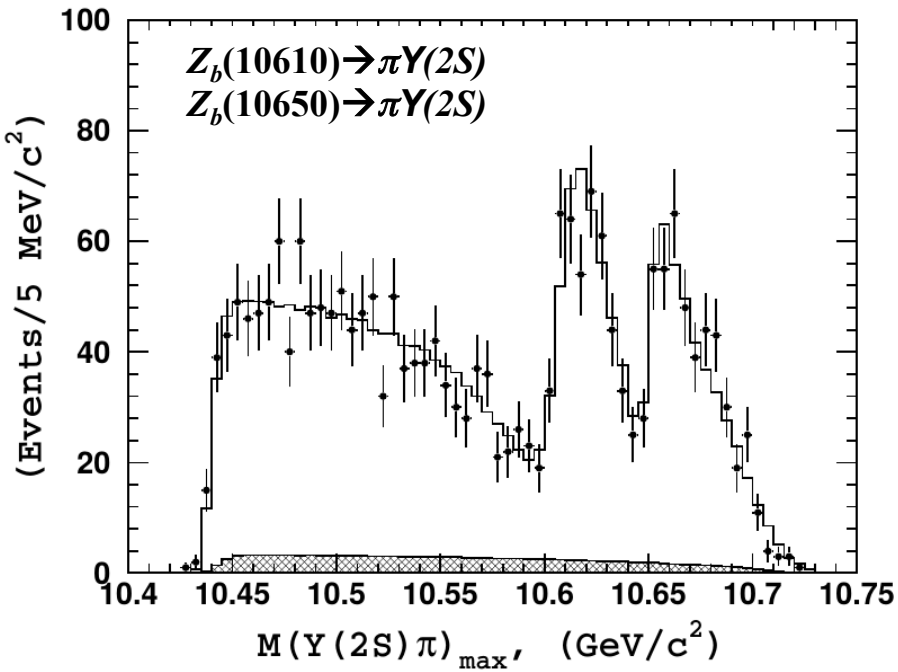
Both $\pi\pi J/\psi$ and $\pi\pi h_c$ have large non-Z_c components.

$Z_c(3900)$ mainly decays to $\pi J/\psi$ and $Z_c(4020)$ mainly decays to πh_c

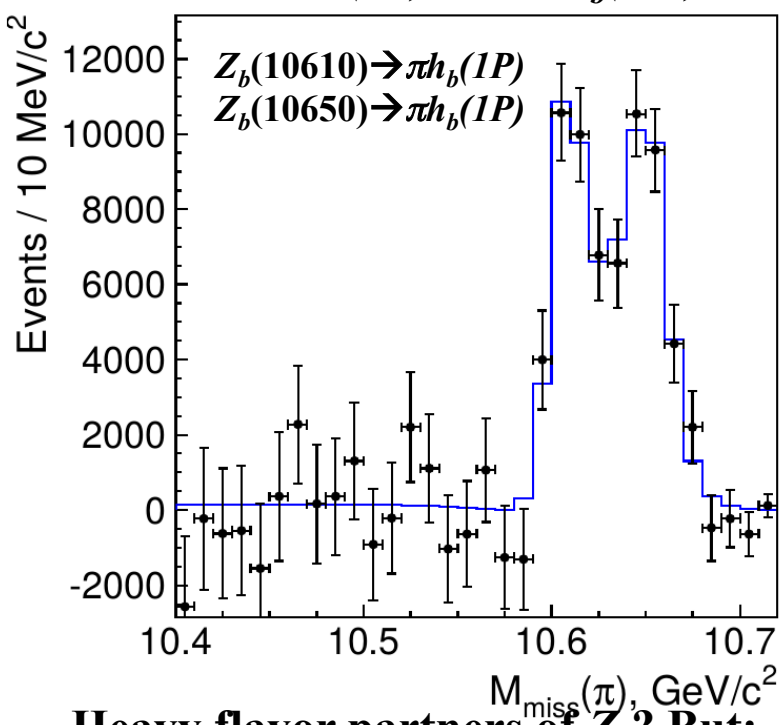
$Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$

Belle [PRL108,122001 (2012)] 121.4 fb^{-1}

$e^+e^- \to \Upsilon(5S) \to \pi^+\pi^-\Upsilon(nS)$



$e^+e^- \to \Upsilon(5S) \to \pi^+\pi^- h_b(mP)$



$Z_b(10610)$ $M = 10607.2 \pm 2.0$ MeV/c^2
$\Gamma = 18.4 \pm 2.4$ MeV
$J^P = 1^+$

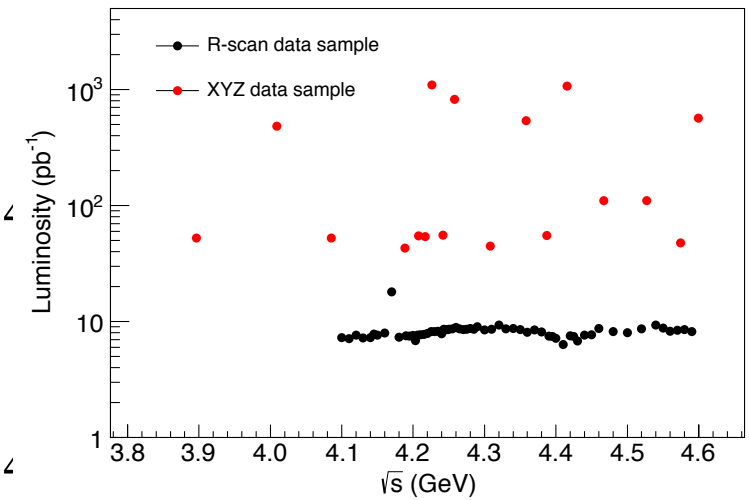
$Z_b(10650)$ $M = 10652.2 \pm 1.5$ MeV/c^2
$\Gamma = 11.5 \pm 2.2$ MeV
$J^P = 1^+$

Heavy flavor partners of Z_c? But:

$\pi\pi\Upsilon$ have large non-Z_b components
$\pi\pi h_b$ have small non-Z_b components

XYZ+R-Scan Data for $\pi^+\pi^- h_c$ cross-section lineshape measurement at BESIII

- Data samples:
  - XYZ sample:
    - 17 energy points from 3896 MeV to 4
    - total luminosity: 5.26 fb^{-1}
  - R-scan data sample:
    - 62 energy points from 4097 MeV to 4
    - total luminosity: 0.51 fb^{-1}



- Decay channel: $e^+e^- \to \pi^+\pi^- h_c$, $h_c \to \gamma\eta_c$, $\eta_c \to X_i$

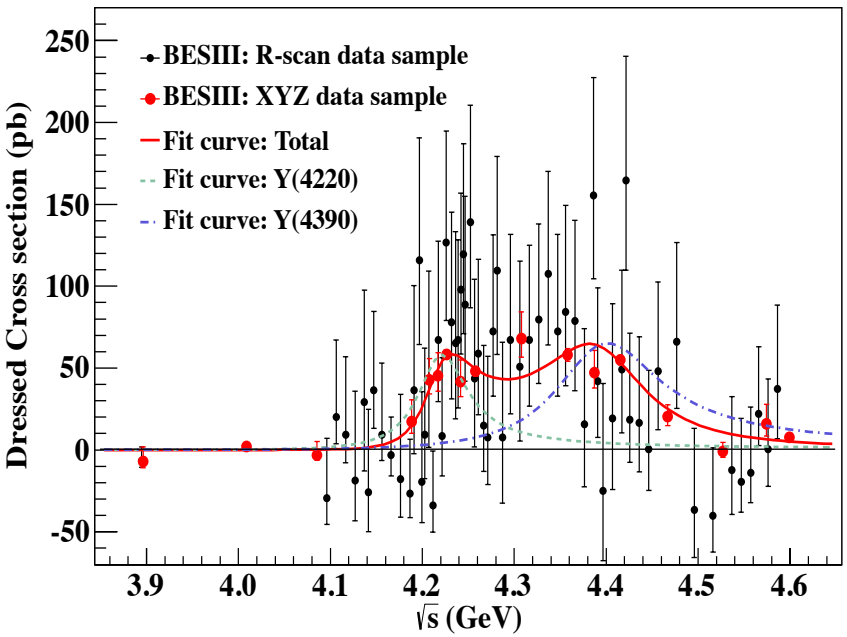
X_i={pp-bar, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-$pp-bar, $2(K^+K^-)$, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$, $2(\pi^+\pi^-)K^+K^-$, $K_S^0K^+\pi^-$ +c.c., $K_S^0K^+\pi^-\pi^+\pi^-$ +c.c., $K^+K^-\pi^0$, pp-barπ^0, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)\eta$, $2(\pi^+\pi^-\pi^0)$ }

Fit to the $\pi^+\pi^- h_c$ cross section

$$\sigma(m) = \left| B_1(m)\sqrt{\frac{P(m)}{P(M_1)}} + e^{i\phi} B_2(m)\sqrt{\frac{P(m)}{P(M_2)}} \right|^2$$

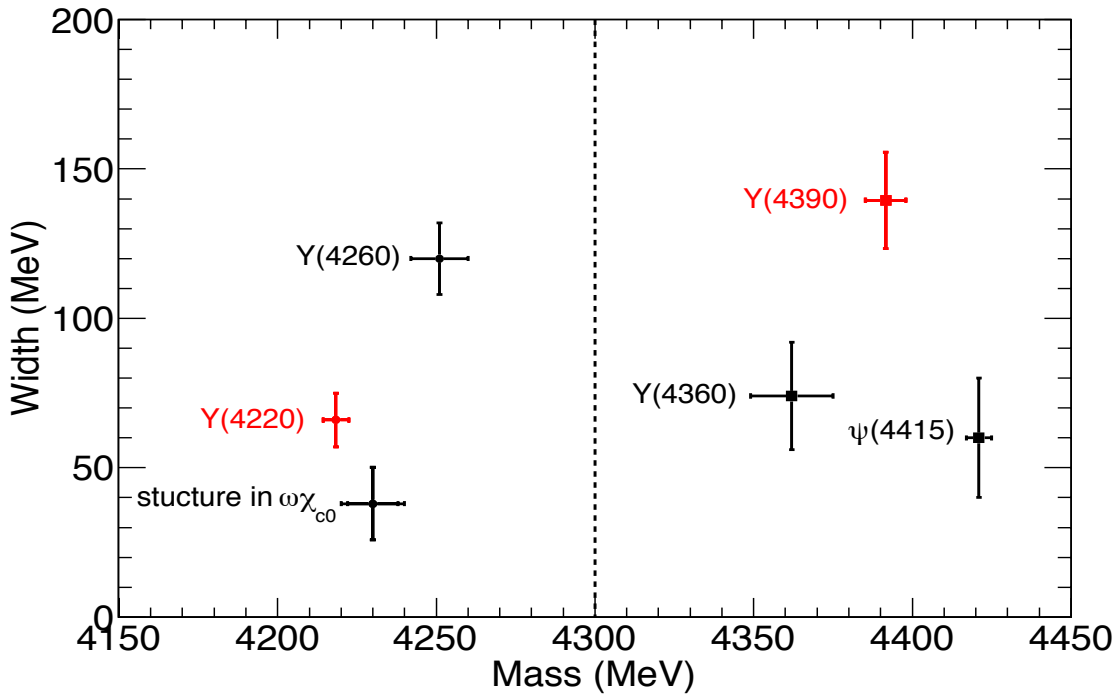
$B_i(m)$: constant width Breit-Wigner function
$P(m)$: 3-body phase space factor
ϕ: relative phase between two resonances

significance of two structures assumption over one structure > 10 σ



	M (MeV)	Γ_{tot} (MeV)	Γ_{ee}•Br (eV)	ϕ (rad)
Y(4220)	4218.4±4.0±0.9	66.0±9.0±0.4	4.6±4.1±0.8	--
Y(4390)	4391.6±6.3±1.0	139.5±16.1±0.6	11.8±9.7±1.9	3.1±1.5±0.2

Fit to the $\pi^+\pi^- h_c$ cross section



- Cross section of $e^+e^- \to \pi^+\pi^- h_c$ has been measured at 79 energy points from 3896 MeV to 4600 MeV
  - The cross section drops in high energy region, likely two resonant structures
  - The significance of the two resonant structures assumption over one structure is larger than 10σ
  - Parameters of the two resonances are different from those of *Y*(4260), *Y*(4360), and the *ψ*(4415)

Observation of $e^+e^- \rightarrow \omega\chi_{c0}$

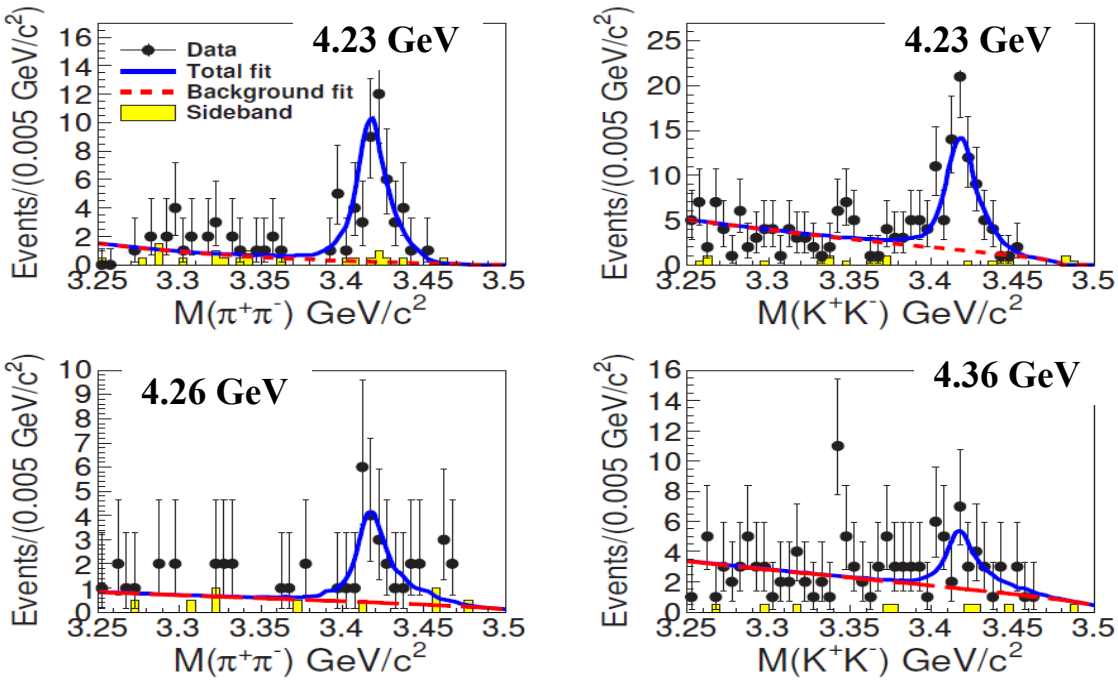
$e^+e^- \rightarrow \omega\chi_{c0}$ are observed at 4230 MeV and 4260 MeV. Signal does not arise from the decays of the $Y(4260)$.

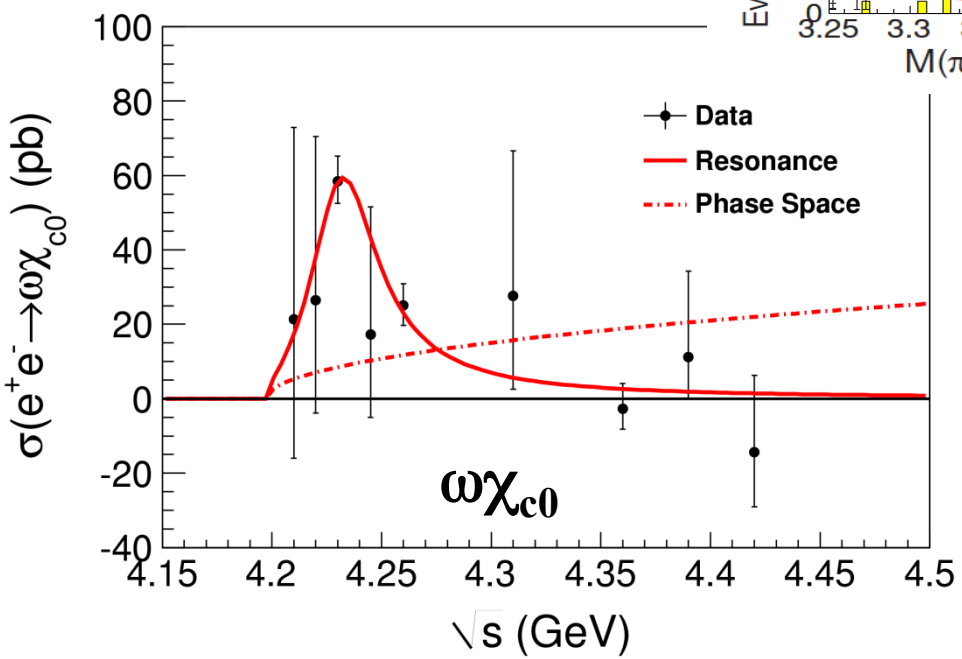
Fit with a single BW

Mass = 4230±8±6 MeV

Width = 38±12±2 MeV

Significance > 9σ





A tetraquark? [PRD 91, 117501(2015)]

ψ(4S)? [EPJC 74, 3208 (2014)]

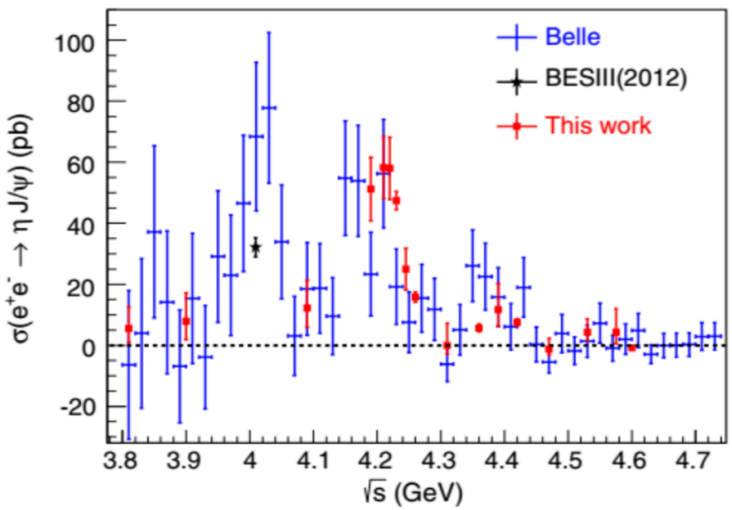
Threshold effect?

…

Phys. Rev. Lett. 114, 092003 (2015)

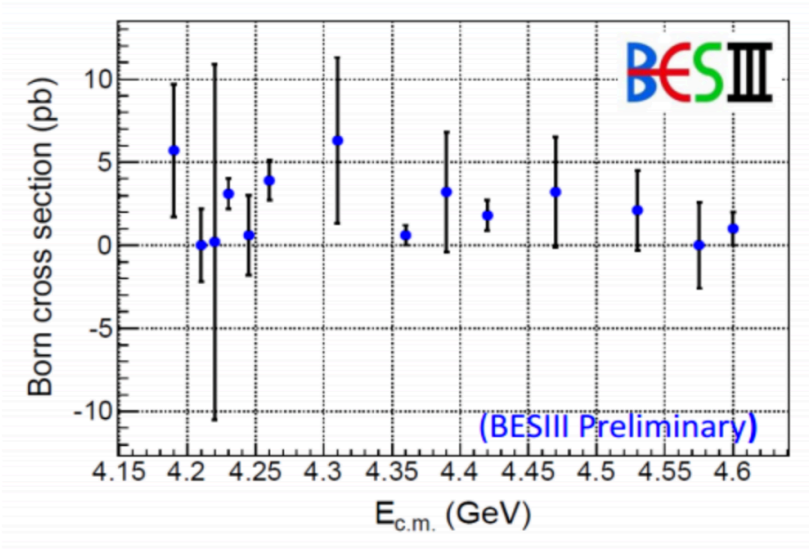
Observation of $e^+e^- \rightarrow \eta(\eta')J/\psi$

$e^+e^- \rightarrow \eta J/\psi$



- Agree with previous results with improved precision
- Structure around 4.2 GeV
- $\psi(4160) \rightarrow \eta J/\psi$

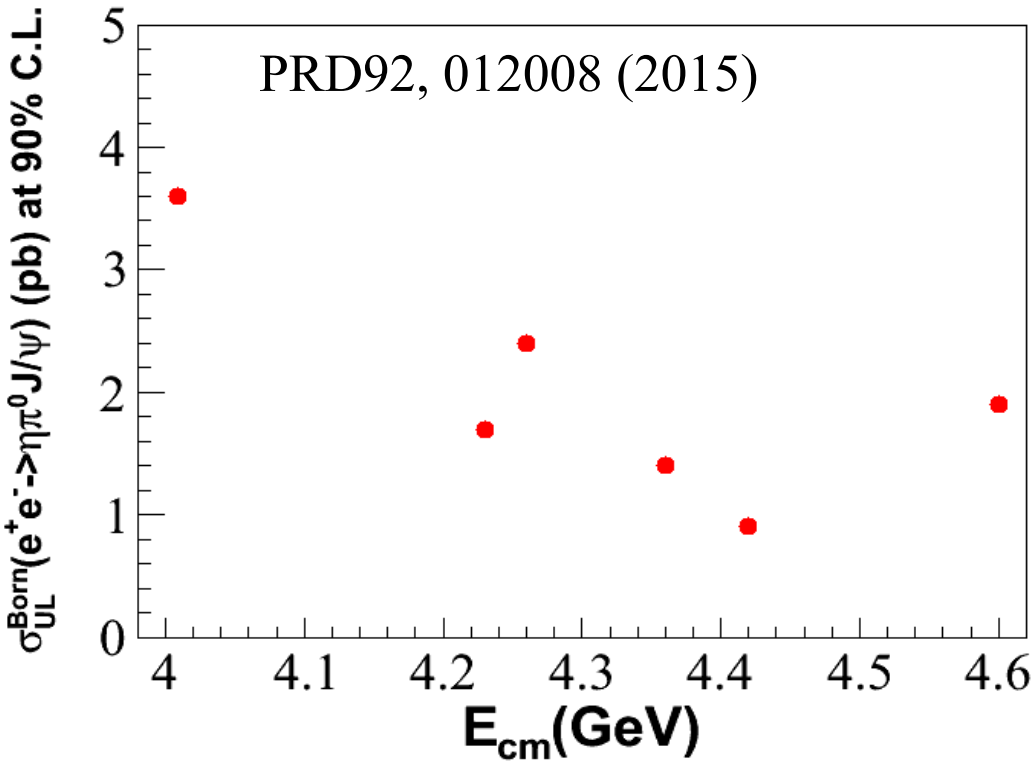
$e^+e^- \rightarrow \eta' J/\psi$



- Cannot tell the line shape due to statistics
- Cross-section is much lower than $\eta J/\psi$

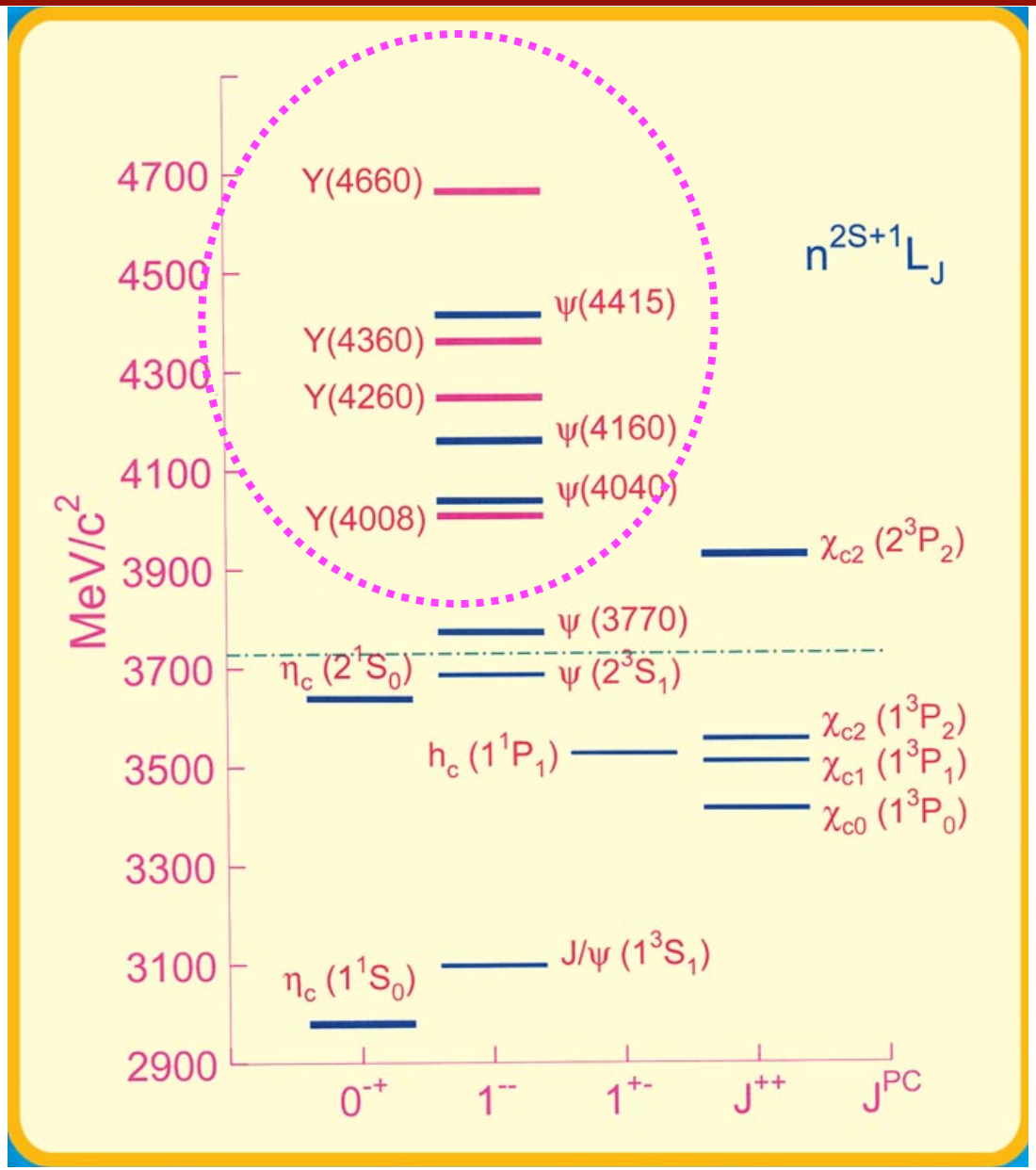
No Y(4260)→ $\eta\pi^0 J/\psi$

- Model predictions of $e^+e^- \rightarrow \eta\pi^0 J/\psi$
- Hadro-quarkonium/tetraquark of Z_b and Z_c:
  - M.Voloshin, PRD 86 034013
  - A. Ali et al., PRL 104 162001, PRL 106 092002
  - L. Maiani et al., PRD 87 111102
- Y(4260) as a D_1D molecule: X. Wu et al., PRD 89, 054038



- Upper limits well above prediction of D_1D molecule model (0.05 pb at 4.290 GeV) [X. G. Wu et al., PRD 89, 054038]
- Need ~100 times more luminosity to reach the sensitivity

What are the Y states?

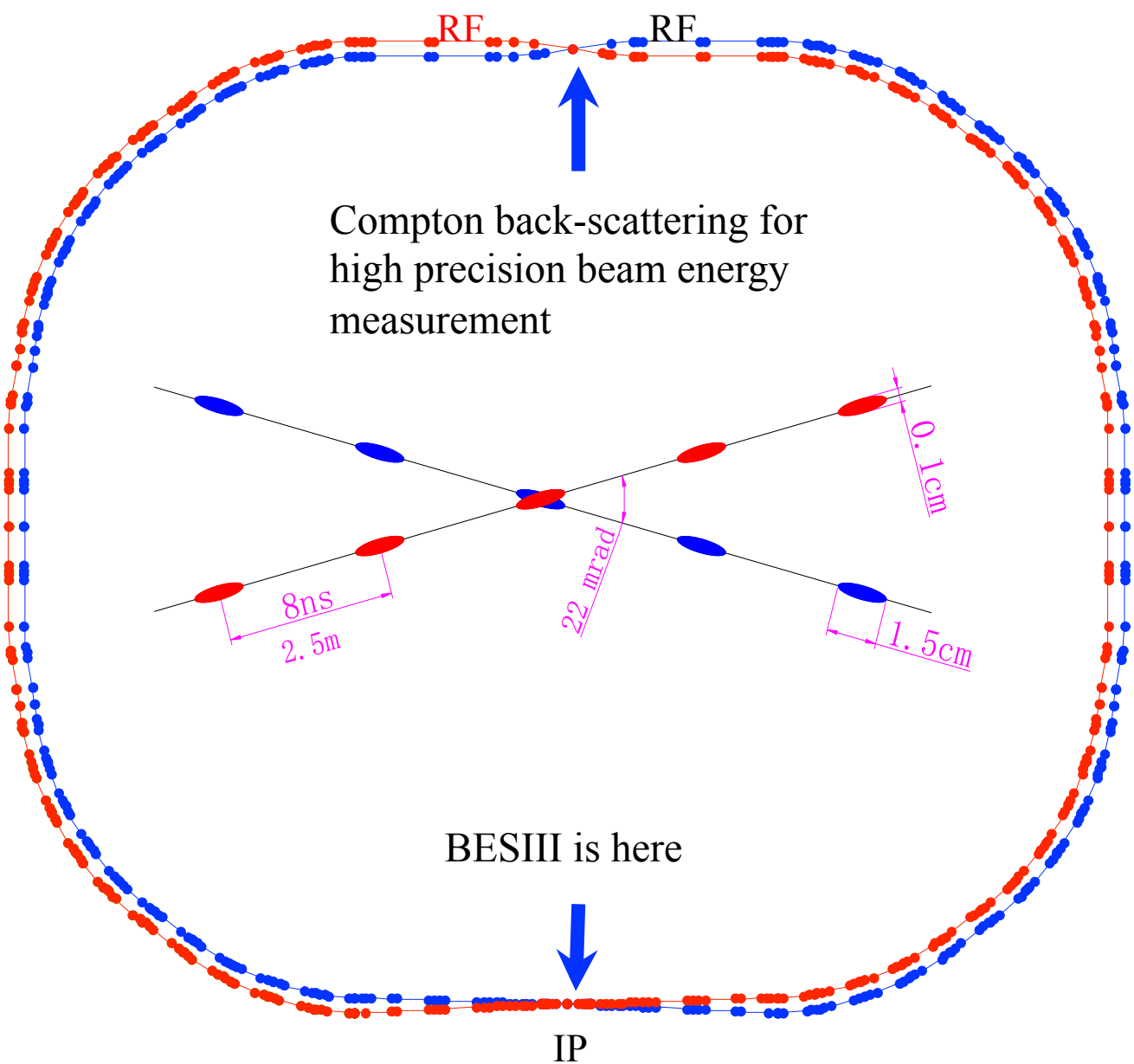


- Between 4 and 4.7 GeV, at most 5 states expected (3S, 2D, 4S, 3D, 5S), 7 observed
- Hybrids are expected in this mass region
- Molecular states?
- Cannot rule out threshold effect/FSI/…
- The Ys are all narrow and similar
- $\pi^+\pi^- h_c$, $\omega\chi_c$, … have add complexity but also give hints for their composition

Thank you!

Backup

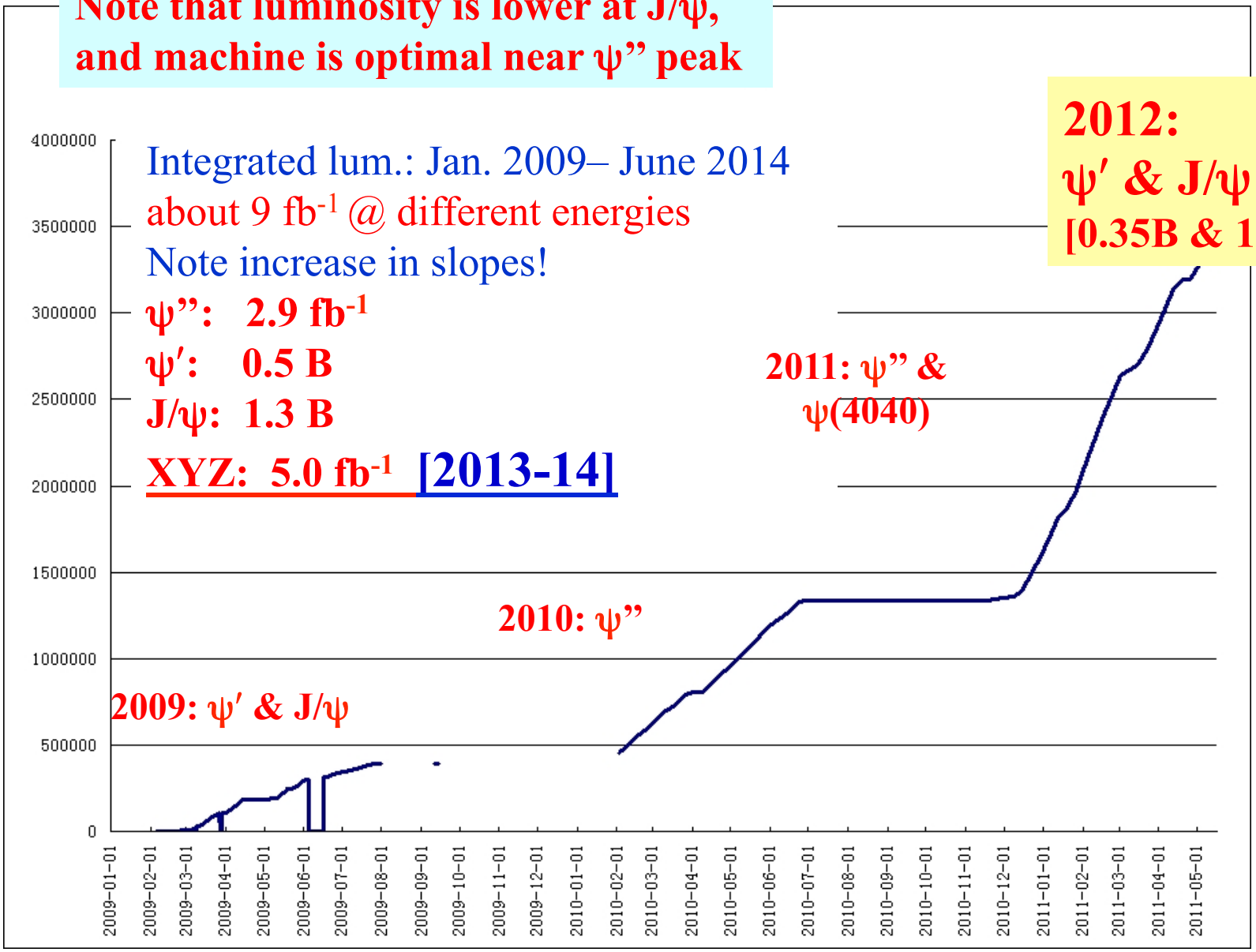
BEPC II: a double-ring machine



Beam energy:
1-2.3 GeV
Luminosity:
1×10^{33} $cm^{-2}s^{-1}$
Optimum energy:
1.89 GeV
Energy spread:
5.16×10^{-4}
No. of bunches:
93
Bunch length:
1.5 cm
Total current:
0.91 A
SR mode:
0.25A @ 2.5 GeV

BESIII data samples

Note that luminosity is lower at J/ψ, and machine is optimal near ψ" peak

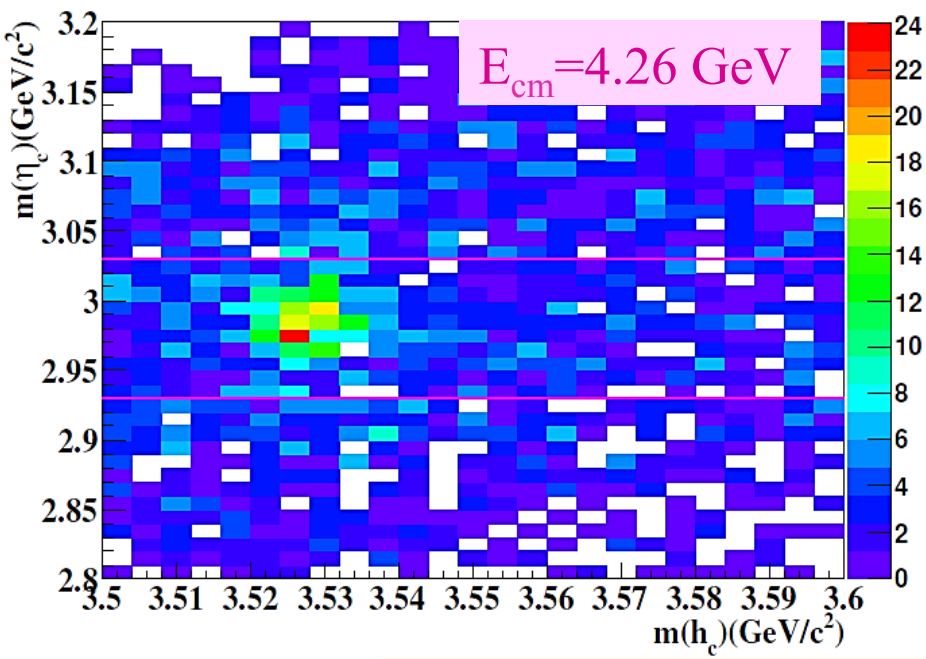


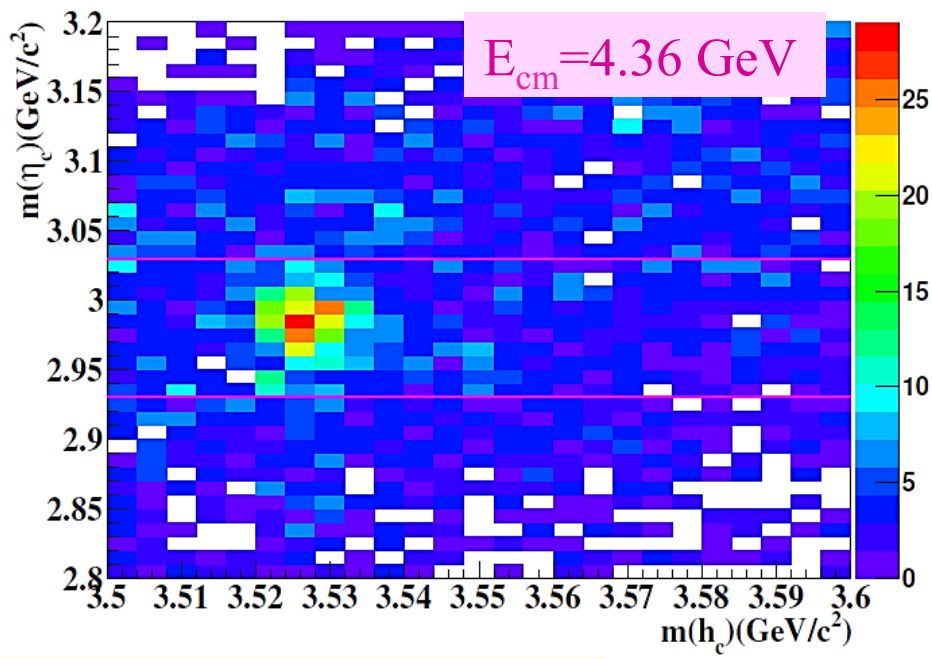
List of Y-family states

State	Mass (MeV/c^2)	Width (MeV/c^2)	Decay mode	Experiment
$Y(4008)$	4008^{+121}_{-49}	226±97	$\pi^+\pi^- J/\psi$	Belle
$Y(4260)$	4250±9	108±12	$\pi^+\pi^- J/\psi$ $\pi^0\pi^0 J/\psi$ $K^+K^- J/\psi$	BaBar CLEO Belle
$Y(4360)$	4361±13	74±18	$\pi^+\pi^- \psi(2S)$	Belle BaBar
$Y(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	$\Lambda_c^+\Lambda_c^-$	Belle
$Y(4660)$	4664±12	48±15	$\pi^+\pi^- \psi(2S)$	Belle BaBar

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

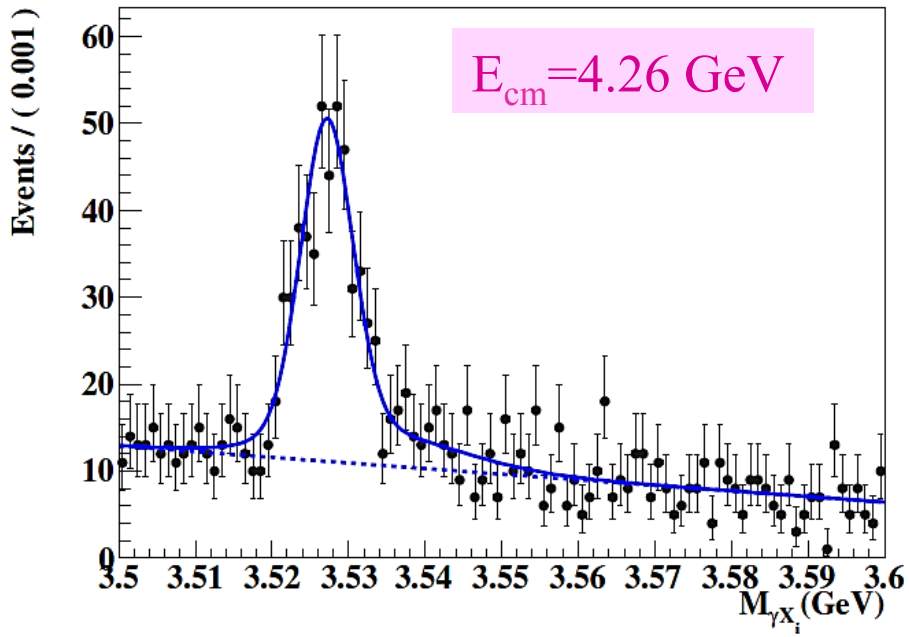
- $h_c \to \gamma\eta_c$, $\eta_c \to$hadrons [16 exclusive decay modes]
  - $p\bar{p}$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-p\bar{p}$, $2(K^+K^-)$, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$
  - $2(\pi^+\pi^-)K^+K^-$, $K_S^0K^+\pi^-$+c.c., $K_S^0K^+\pi^-\pi^+\pi^-$+c.c., $K^+K^-\pi^0$
  - $p\bar{p}\pi^0$, $K^+K^-\eta$,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

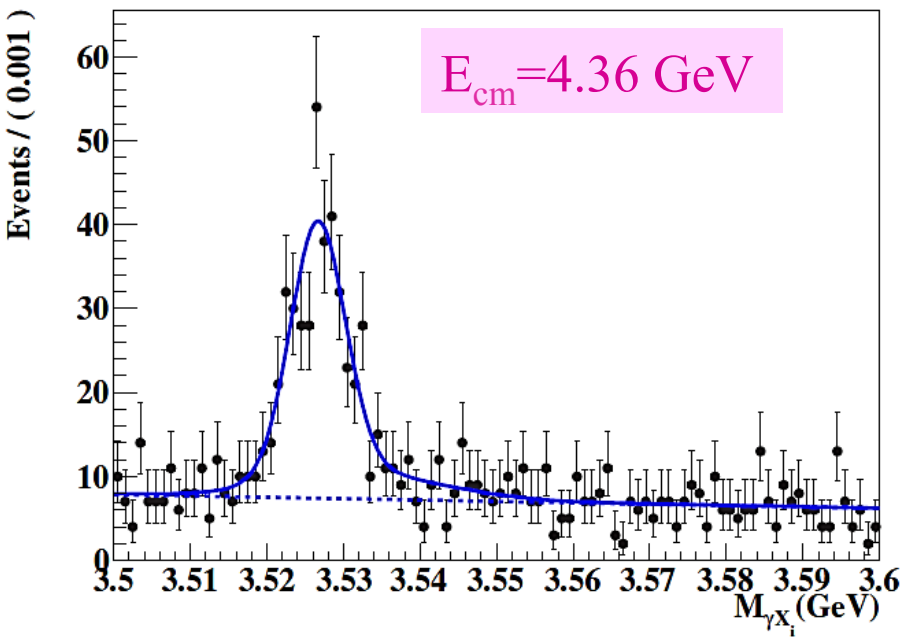




BESIII: arXiv:1309.1896, PRL111, 242001

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



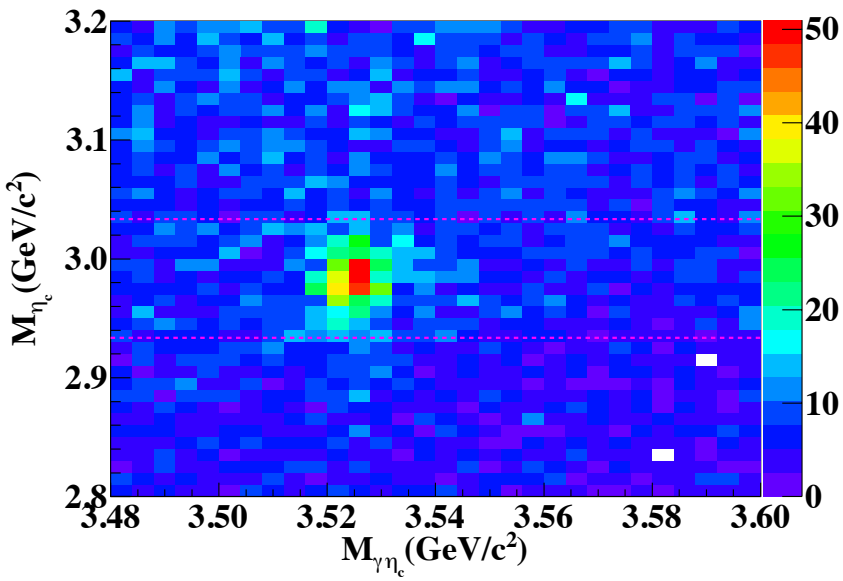


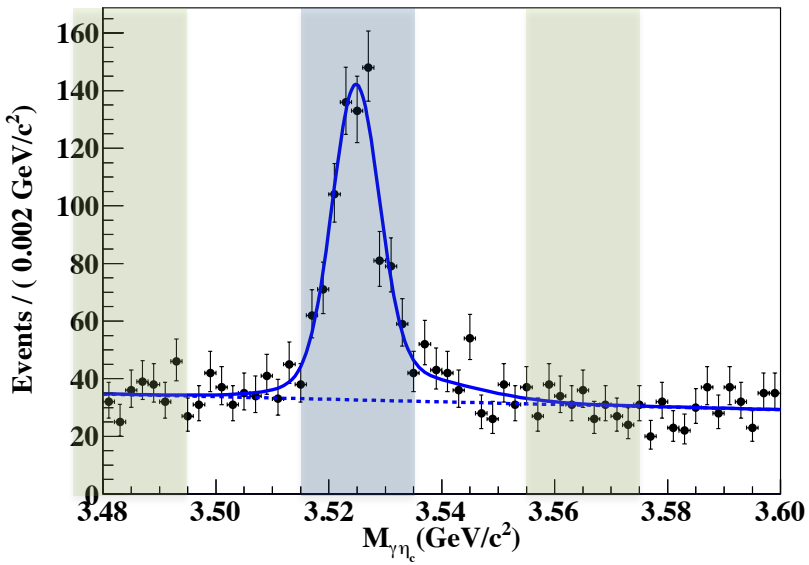
$N(h_c)$=416±28
Lum=827/pb
σ^B= 41.0±2.8±7.4 pb

$N(h_c)$=357±25 Lum=544/pb
σ^B= 52.3±3.7±9.2 pb

BESIII: arXiv:1309.1896, PRL111, 242001

Fit to the $\pi^+\pi^- h_c$ cross section: signal at 4415 MeV



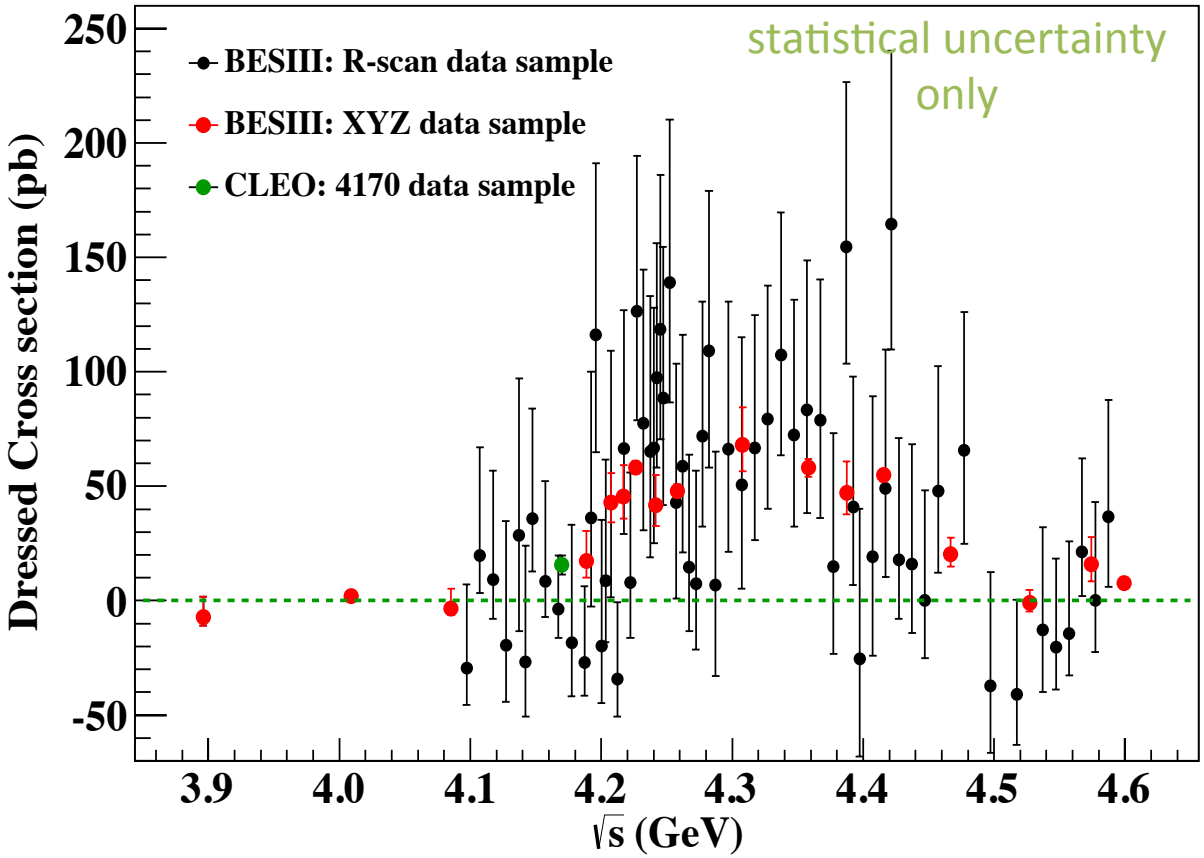


Number of signal events extracted from $\pi^+\pi^-$ recoil mass spectrum:

- XYZ sample: fit to the mass spectrum
- R-scan sample: calculate by counting the entries in h_c signal region and the entries in h_c sideband regions

Fit to the $\pi^+\pi^- h_c$ cross section

$$\sigma^{\text{dressed}} = \frac{N^{\text{obs}}}{\mathcal{L}(1+\delta)\sum_{i=1}^{16}\epsilon_i \mathcal{B}(\eta_c \to X_i)\mathcal{B}(h_c \to \gamma\eta_c)}$$



Fit to the $\pi^+\pi^- h_c$ cross section: Systematic uncertainty

Cross section measurement

Total: 15.2%-18.0% depending on CM energies

- Luminosity: 1%
- Branching fraction of $h_c \to \gamma\eta_c$:11.8%
- Detection efficiency and branching fraction of η_c: 6.4%-9.1%
  - efficiency: 5.5%-10.8%, depend on the η_c decay modes and CM energies
- ISR correction factor: 0.1%-2.0%
- Number of signal events extraction: 2.0%-10.0%

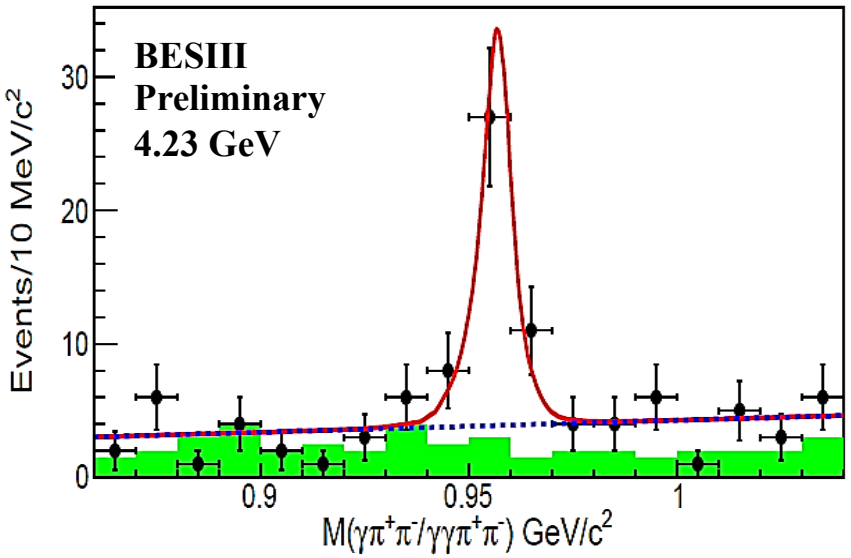
Fit to the $\pi^+\pi^- h_c$ cross section: Systematic uncertainty

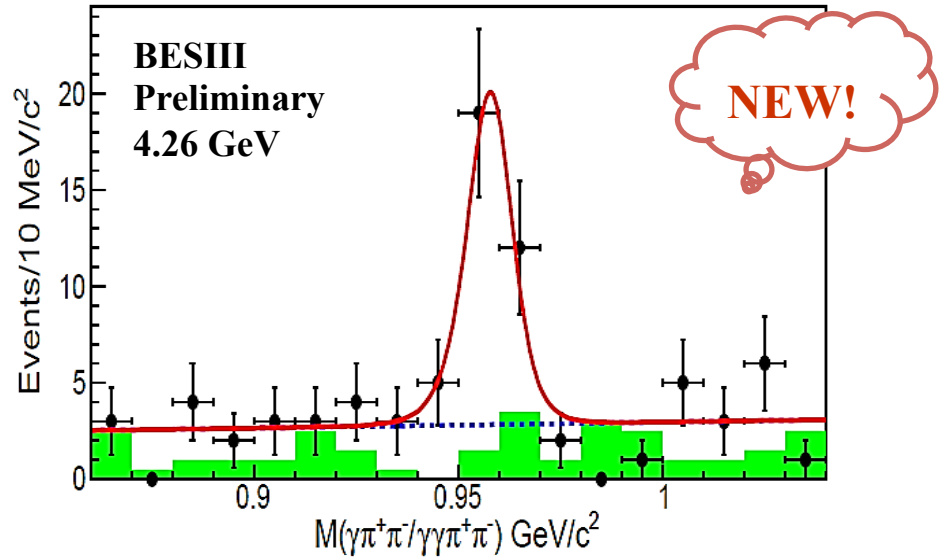
Parameters of the structures

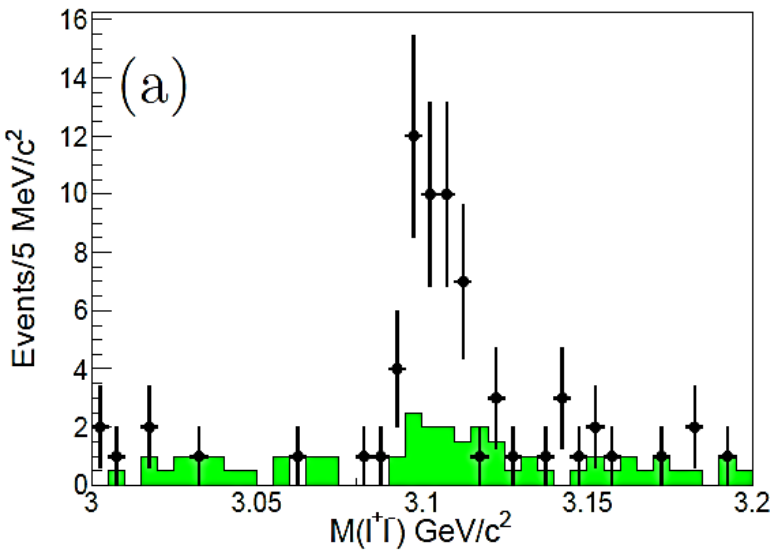
Sources	$Y(4220)$			$Y(4390)$			ϕ (rad)
	M (MeV/c^2)	Γ (MeV)	Γ^{el} (eV)	M (MeV/c^2)	Γ (MeV)	Γ^{el} (eV)	
CM energy[1(2)]	0.8(0.1)	−(0.1)	−(0.2)	0.8(0.1)	−(0.2)	−(0.3)	−(0.1)
CM energy spread	0.1	0.3	0.3	0.1	0.1	0.7	0.1
Cross section[1(2)]	0.1(−)	−(−)	0.2(0.7)	0.6(−)	0.5(−)	0.4(1.7)	0.1(−)
Total	0.9	0.4	0.8	1.0	0.6	1.9	0.2

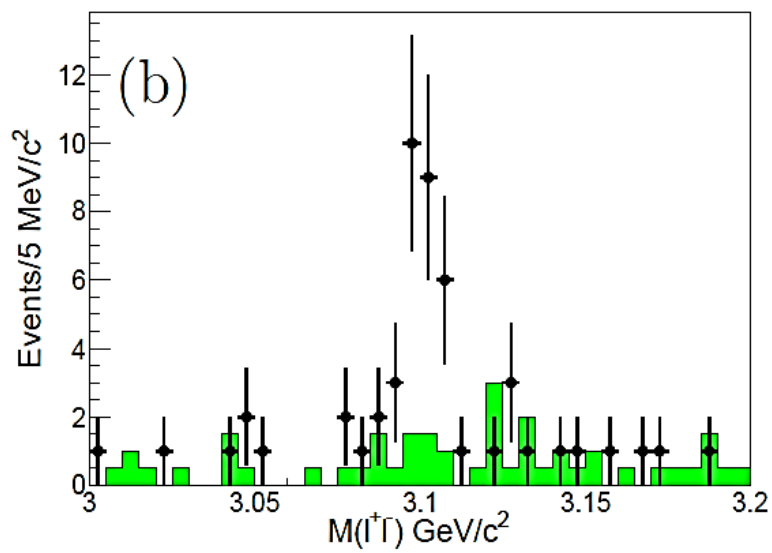
- CM energy[1]: systematic uncertainty of center-of-mass energy measurement
- CM energy[2]: assumptions made in the center-of-mass energy measurement for R-scan data sample
- Cross section[1]: systematic uncertainties of the cross section measurement which are different in each energy point
- Cross section[2]: systematic uncertainties of the cross section measurement which are common in each energy point

Observation of $e^+e^- \rightarrow \eta' J/\psi$

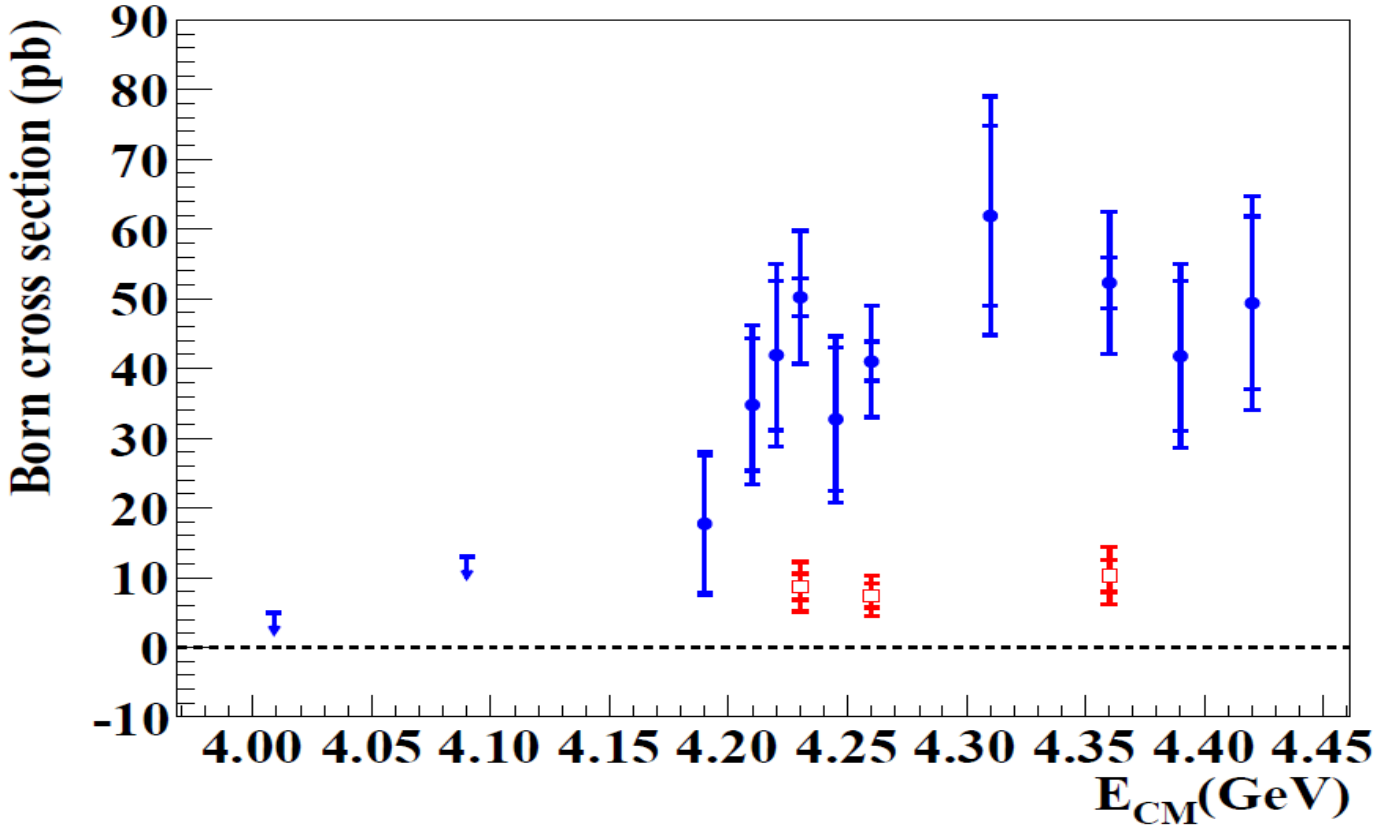






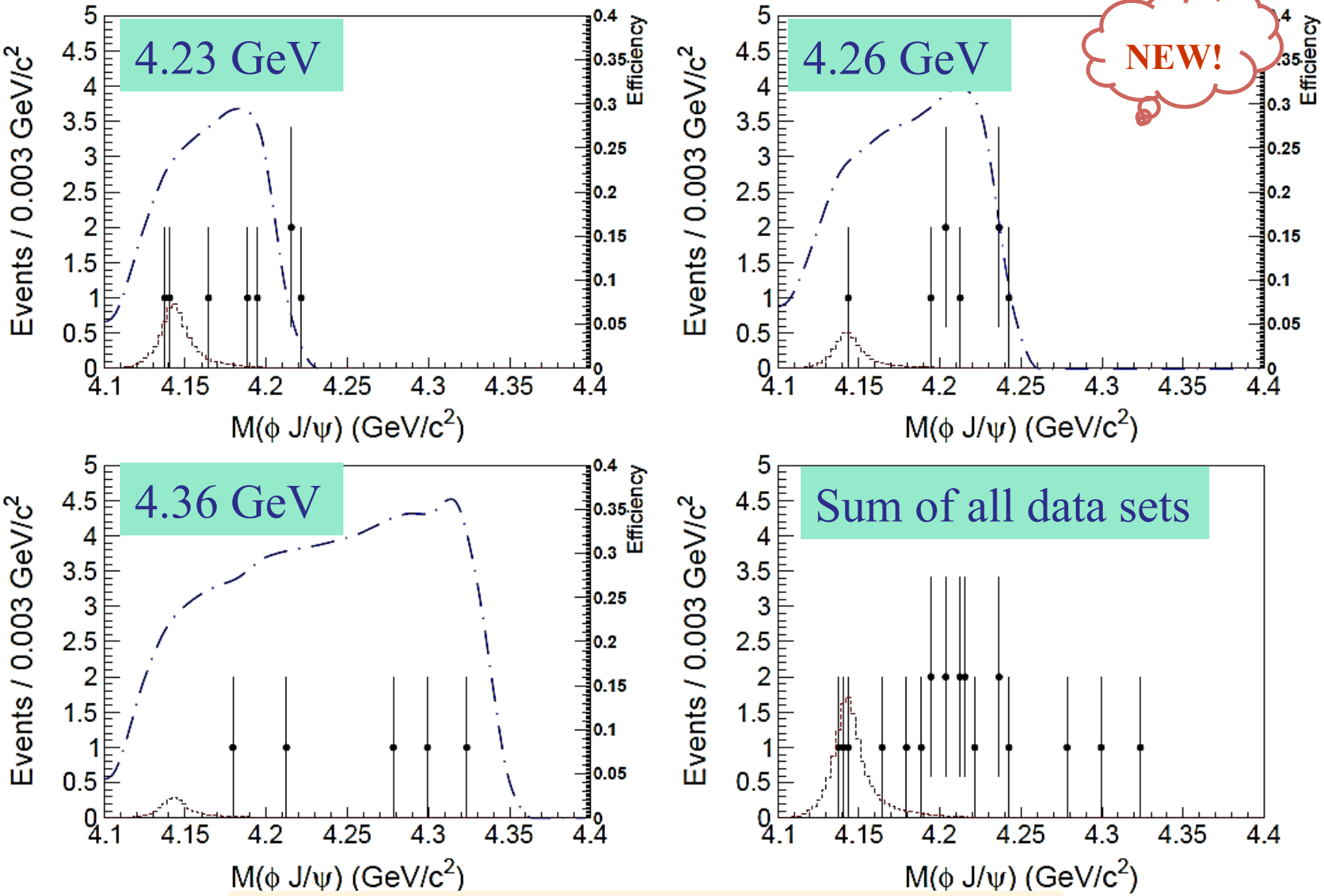


Observation of $e^+e^- \to \pi^+\pi^- h_c(1P)$



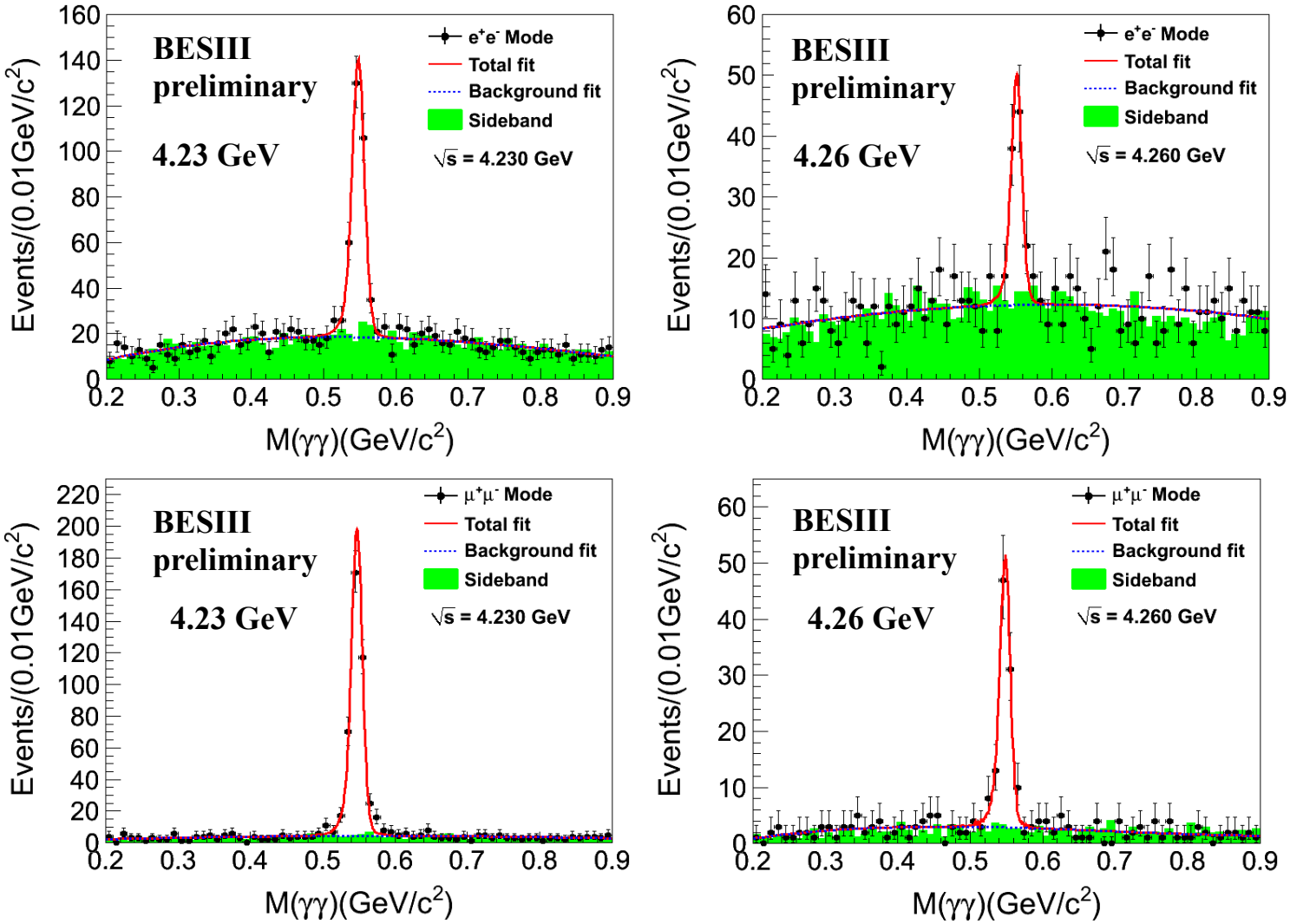
- $\sigma(e^+e^- \to \pi^+\pi^- h_c) \sim \sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ but line shape different
- Local maximum ~ 4.23 GeV
- Non-Zc $\pi\pi h_c$ take a large proportion

No significant $e^+e^- \rightarrow \gamma Y(4140)$



BESIII: arXiv:1412.1867, PRD (in press)

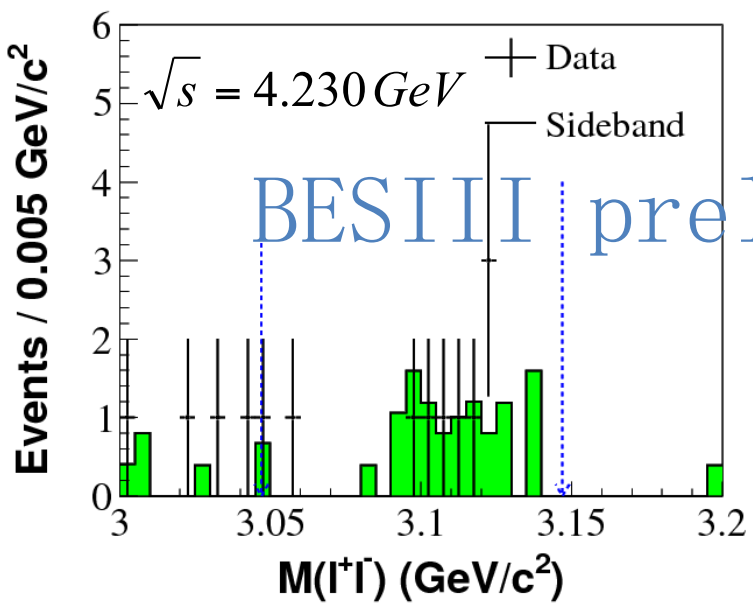
Observation of $e^+e^- \rightarrow \eta J/\psi$

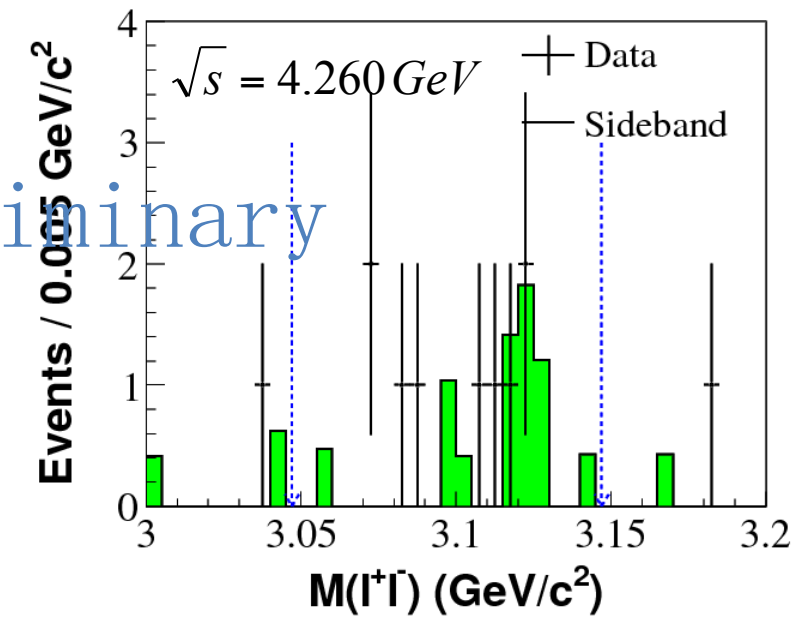


No significant $e^+e^- \rightarrow \eta\pi^0 J/\psi$

- Model predictions of $e^+e^- \rightarrow \eta\pi^0 J/\psi$
- Hadro-quarkonium/tetraquark of Z_b and Z_c:
  - M.Voloshin, PRD 86 034013
  - A. Ali et al., PRL 104 162001, PRL 106 092002
  - L. Maiani et al., PRD 87 111102
- Y(4260) as a D_1D molecule: X. Wu et al., PRD 89, 054038
- Select an η and a π^0, then check the J/ψ signal

NEW!

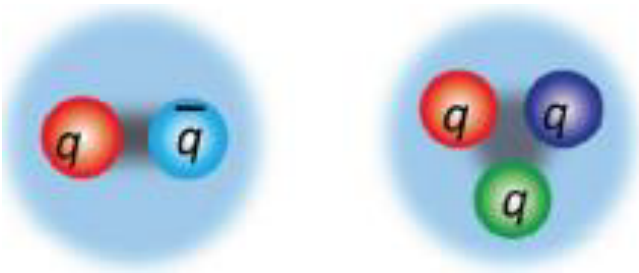


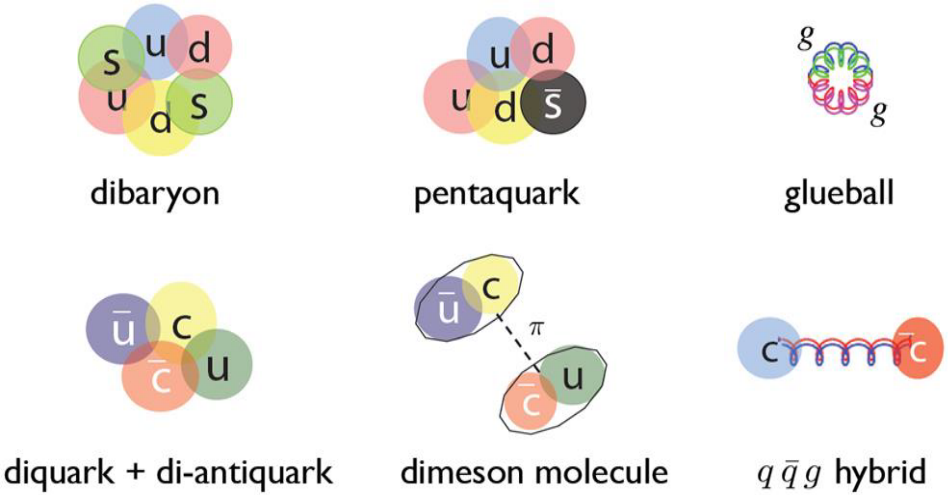


BESIII preliminary

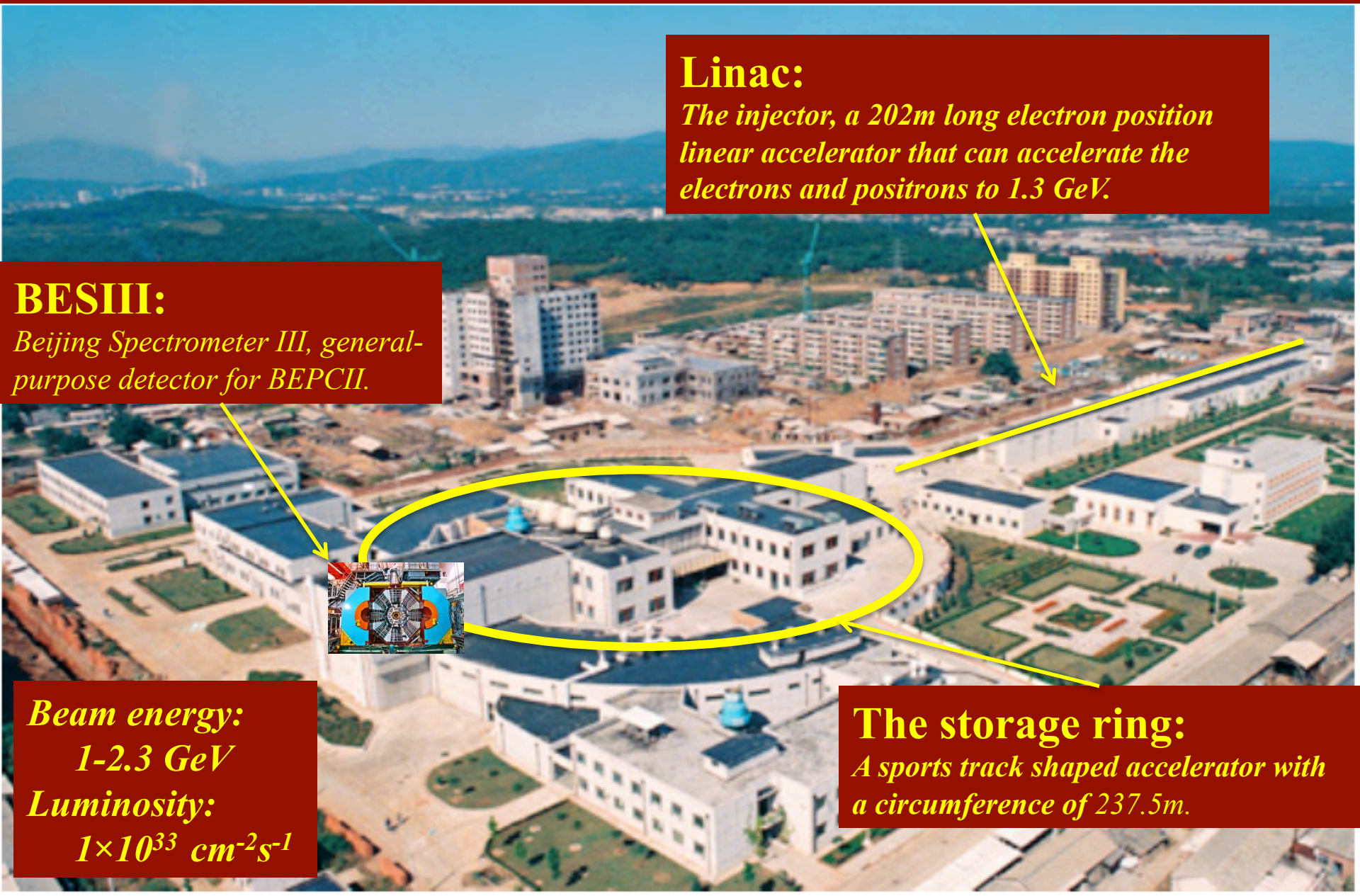
Hadrons: normal & exotic

- In the quark model, hadrons are dominantly bound states of qqbar (mesons) or qqq (baryons)
- But QCD allows hadrons with $N_{quarks} \neq 2, 3$
  - Glueball: $N_{quarks} = 0$ (gg, ggg, …)
  - Hybrid: $N_{quarks} = 2$ + excited gluon
  - Multiquark state: $N_{quarks} > 3$
  - Molecule: bound state of 2 or more hadrons
  - …
- It is a long history of searches for these exotic hadrons, however, no solid experimental evidence was found until recent breakthroughs in the charmonium region.

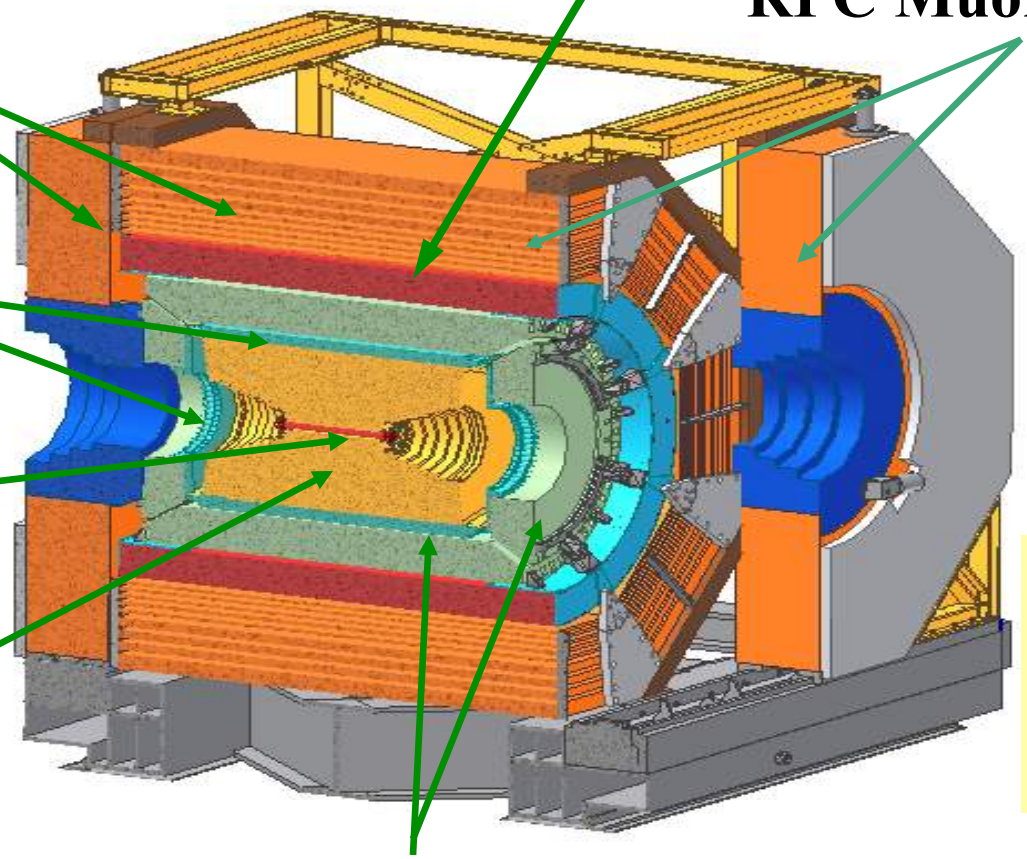




Beijing Electron Positron Collider II (BEPCII)



The BESIII Detector



A total weight of 730t, ~40,000 readout channels, data rate 6,000Hz ~50Mb/s

BESIII Collaboration

US (5)

Univ. of Hawaii
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Rochester
Univ. of Indiana

Europe (13)

Germany: Univ. of Bochum,
Univ. of Giessen, GSI
Univ. of Johannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. of Torino, Univ. of Ferrara, Frascati Lab
Netherland: KVI/Univ. of Groningen
Sweden: Uppsala Univ.
Turkey: Turkey Accelerator Center

Korea (1)

Seoul Nat. Univ.

Japan (1)

Tokyo Univ.

Pakistan (2)

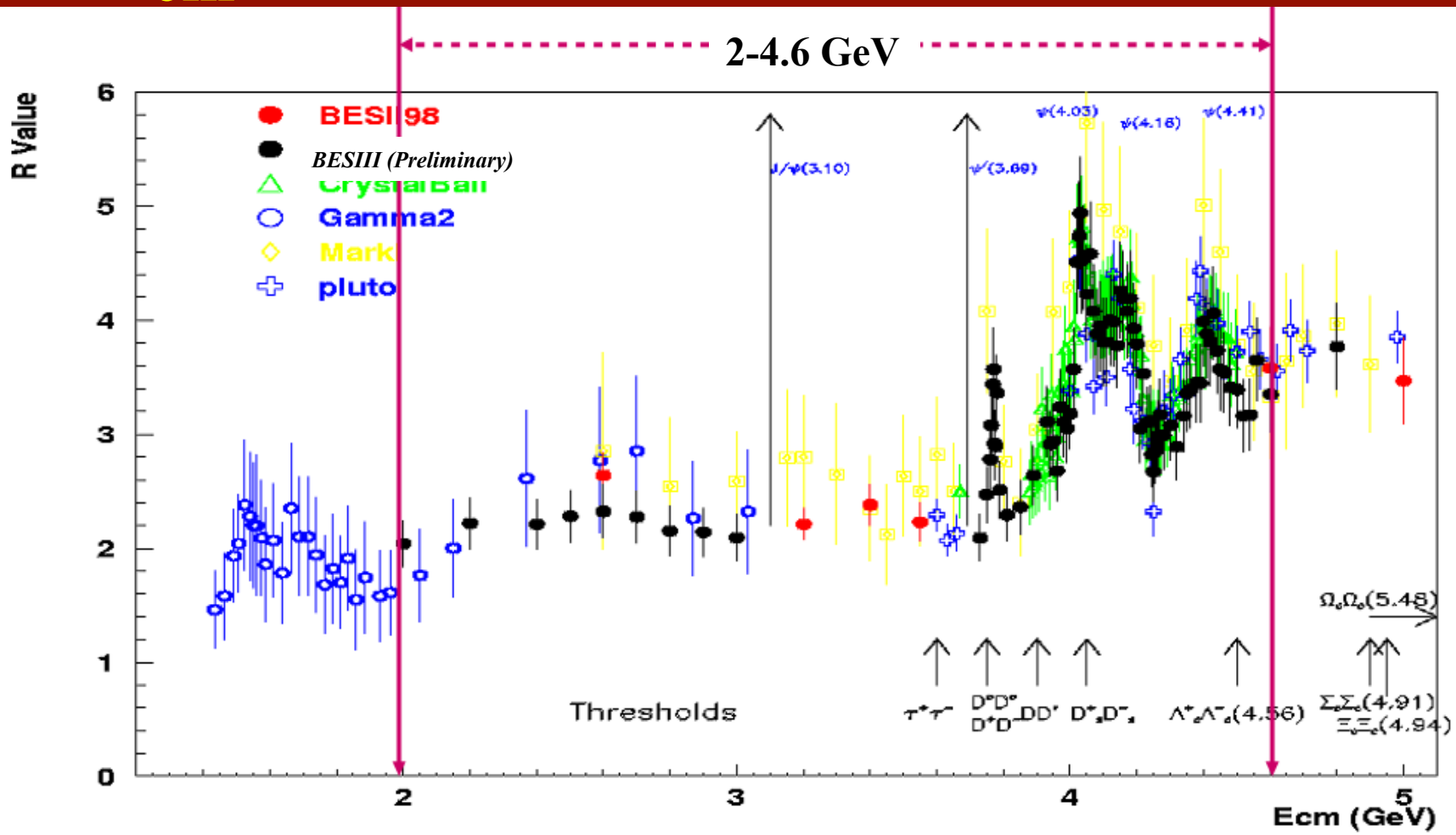
Univ. of Punjab
COMSAT CIIT

China(31)

IHEP, CCAST, GUCAS, Shandong Univ.,
Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ. ,
Zhongshan Univ.,Nankai Univ.
Shanxi Univ., Sichuan Univ., Univ. of South China
Hunan Univ., Liaoning Univ.
Nanjing Univ., Nanjing Normal Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.
Beihang Univ., Beijing Petrol Chemical Univ.

~400 members
53 institutions from 11 countries

E_{cm} range @ BESIII/BEPCII



Physics programs at BESIII include light-hadron and charmonium spectroscopy, electroweak and strong physics at the charm scale, tau-physics, R value measurement and searches for rare processes.

Data collected over time