Studies of charmonium(-like) states at BESIII

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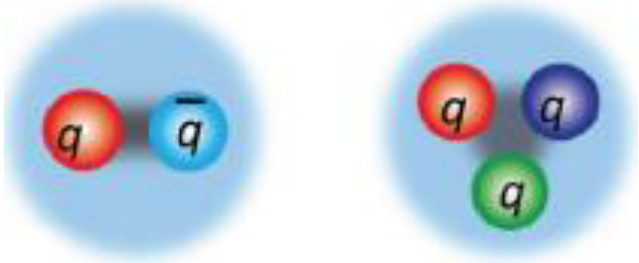
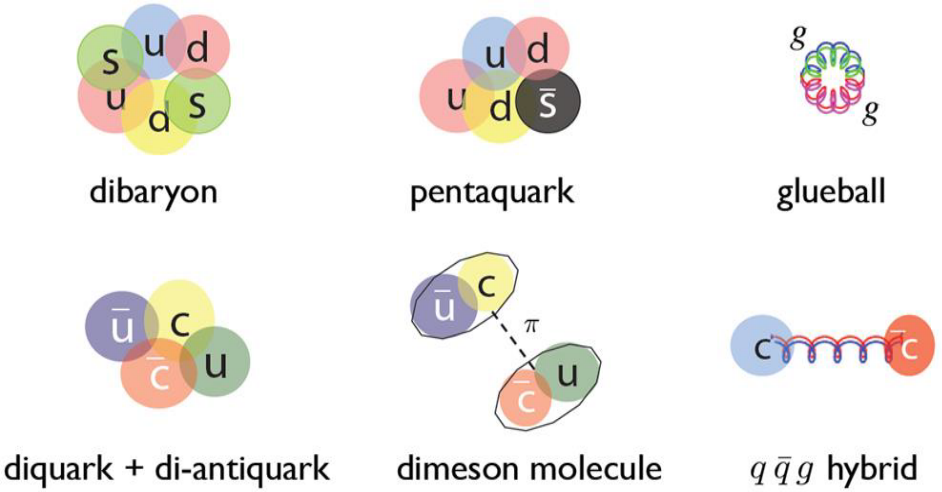
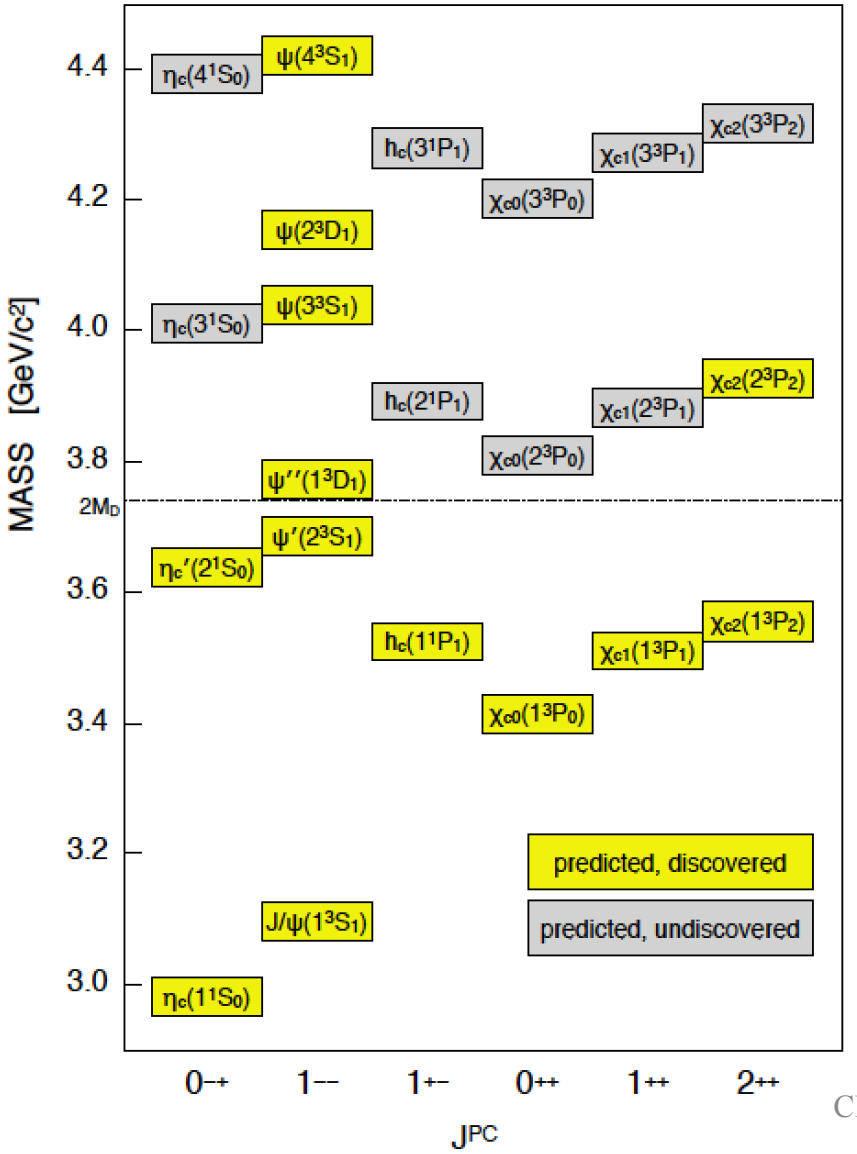
Hadrons：normal & exotic

- 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.





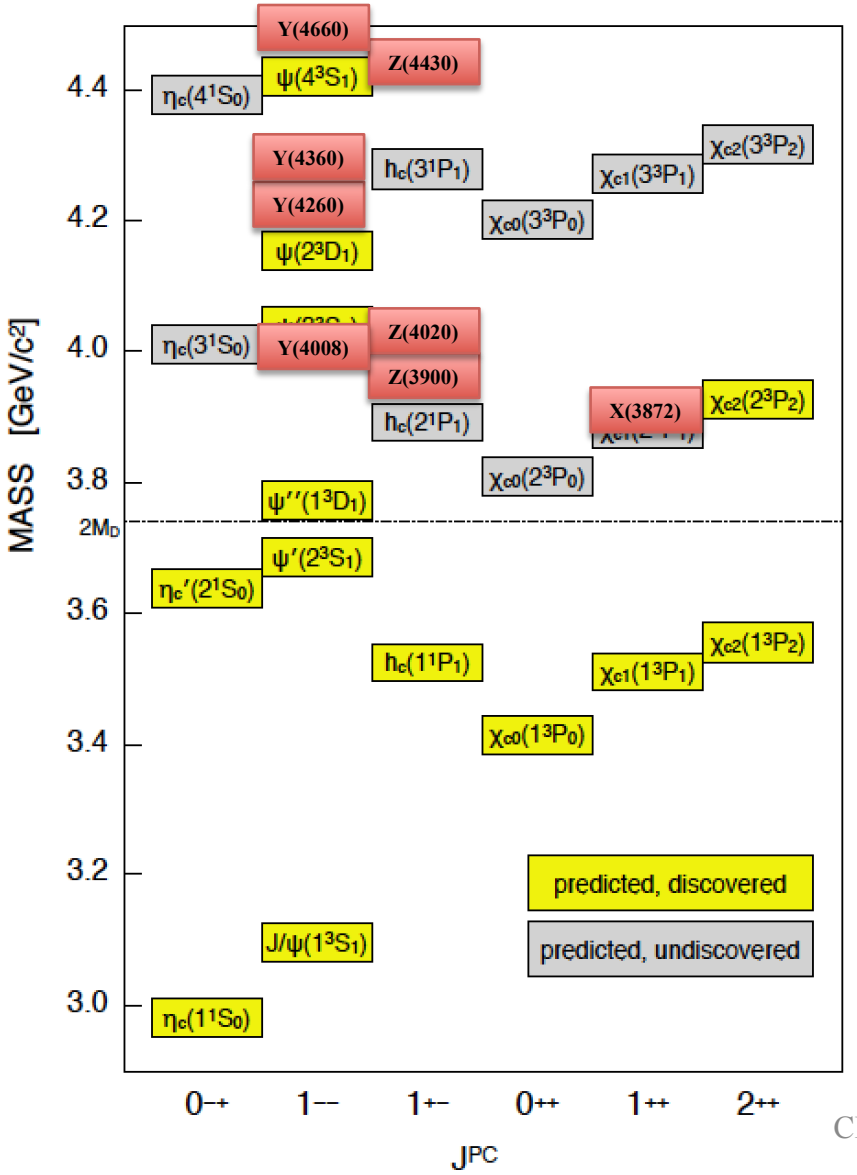
Charmonium spectroscopy



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.**

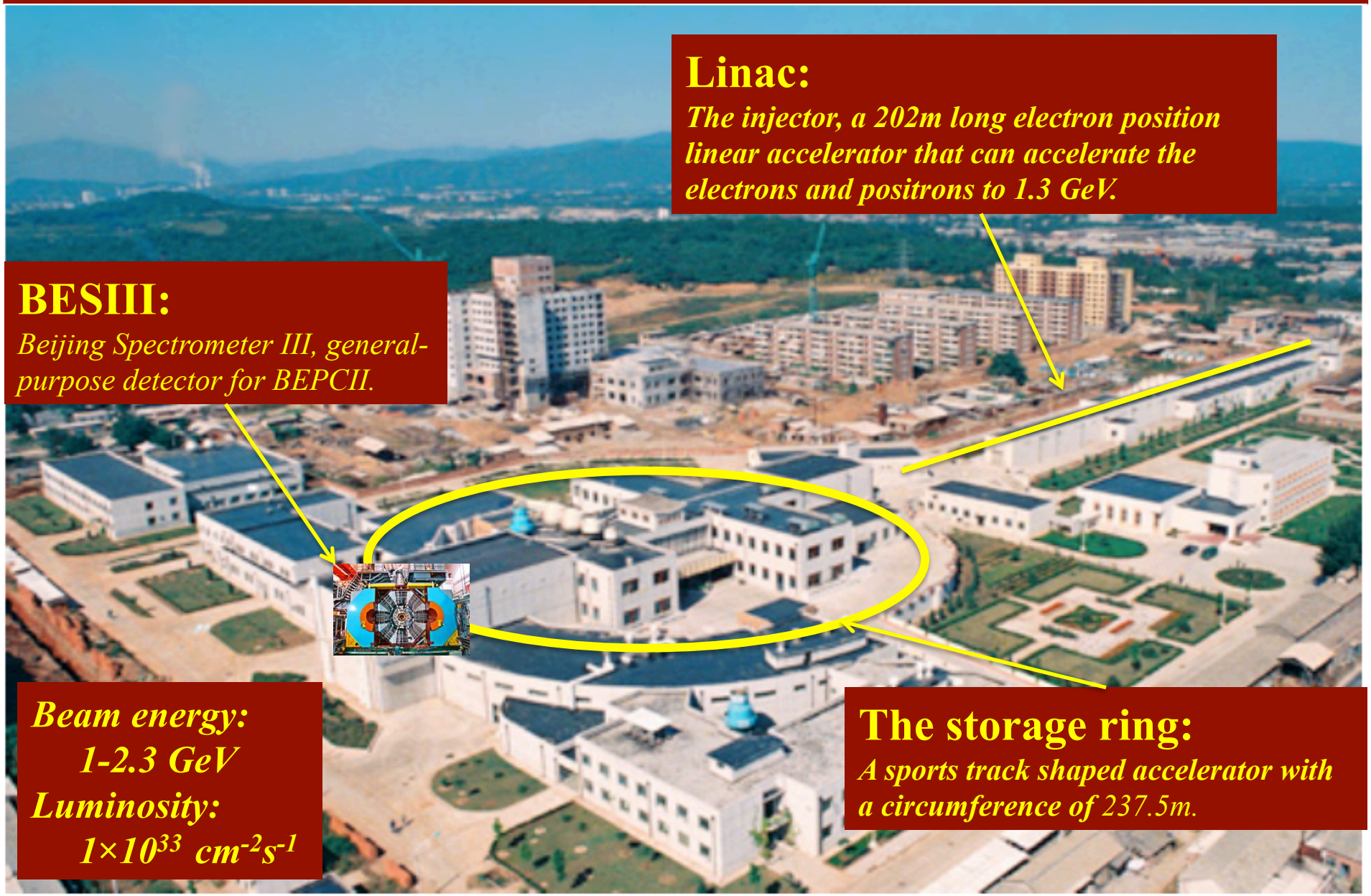
***Y*: neutral, vectors in e^+e^- colliders.**

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

What are they?

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

Beijing Electron Positron Collider II (BEPCII)



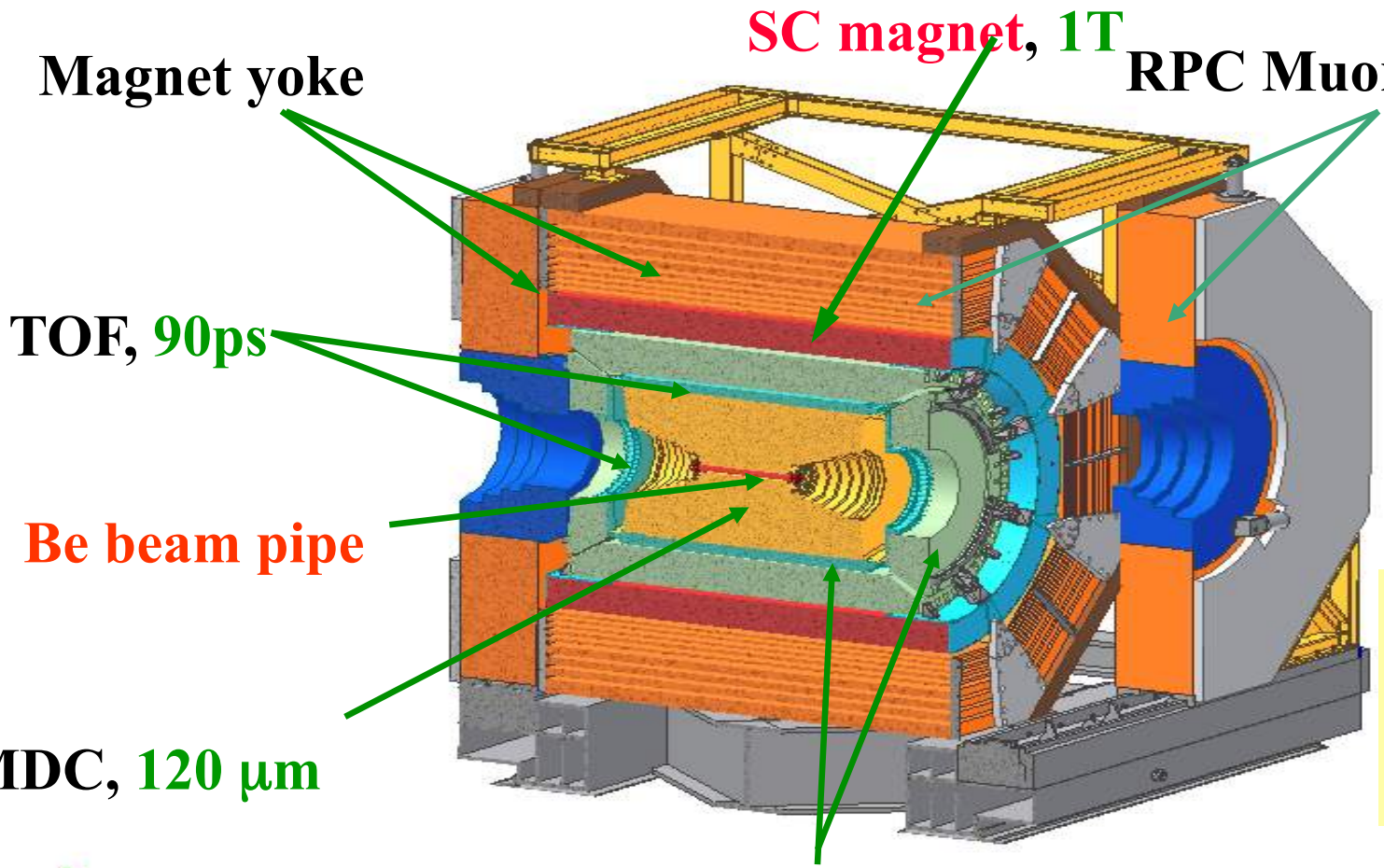
Linac:
The injector, a 202m long electron position linear accelerator that can accelerate the electrons and positrons to 1.3 GeV.

BESIII:
Beijing Spectrometer III, general-purpose detector for BEPCII.

Beam energy:
1-2.3 GeV
Luminosity:
$1\times10^{33}\ cm^{-2}s^{-1}$

The storage ring:
A sports track shaped accelerator with a circumference of 237.5m.

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

Pakistan (2)

Univ. of Punjab
COMSAT CIIT

Korea (1)

Seoul Nat. Univ.

Japan (1)

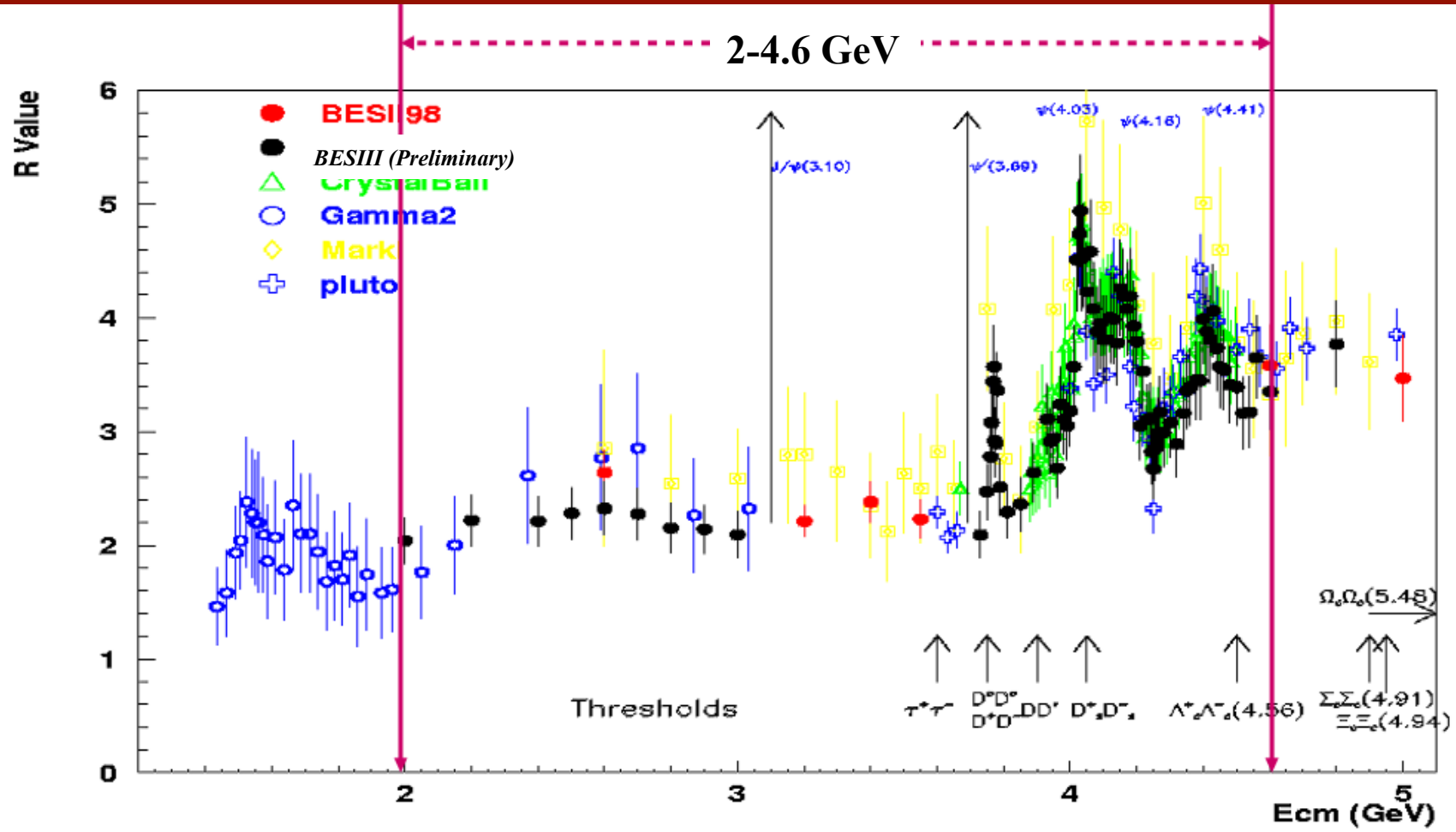
Tokyo Univ.

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.

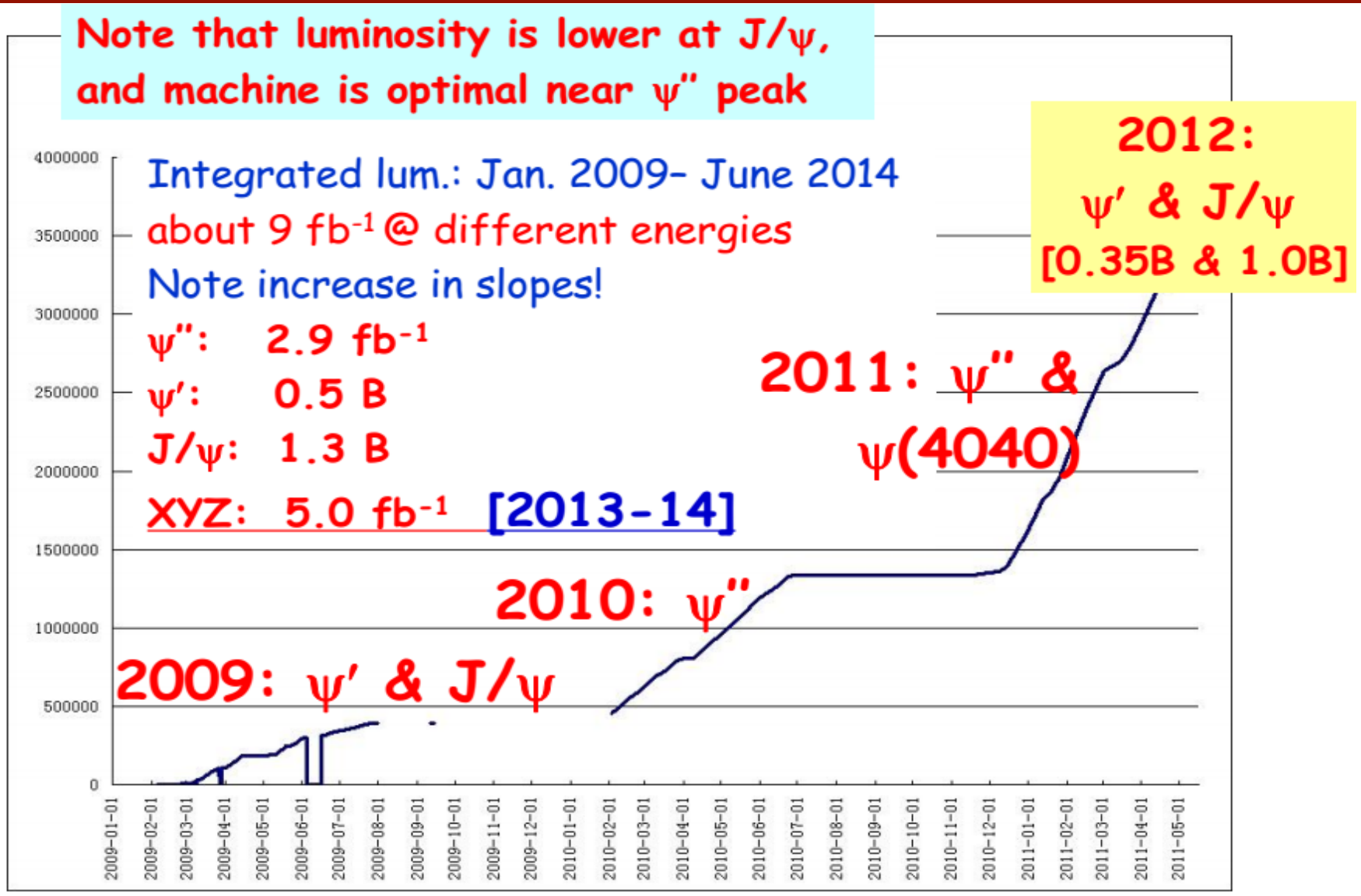
~400 members
53 institutions from 11 countries

E_{cm} range @ BESIII/BEPCII

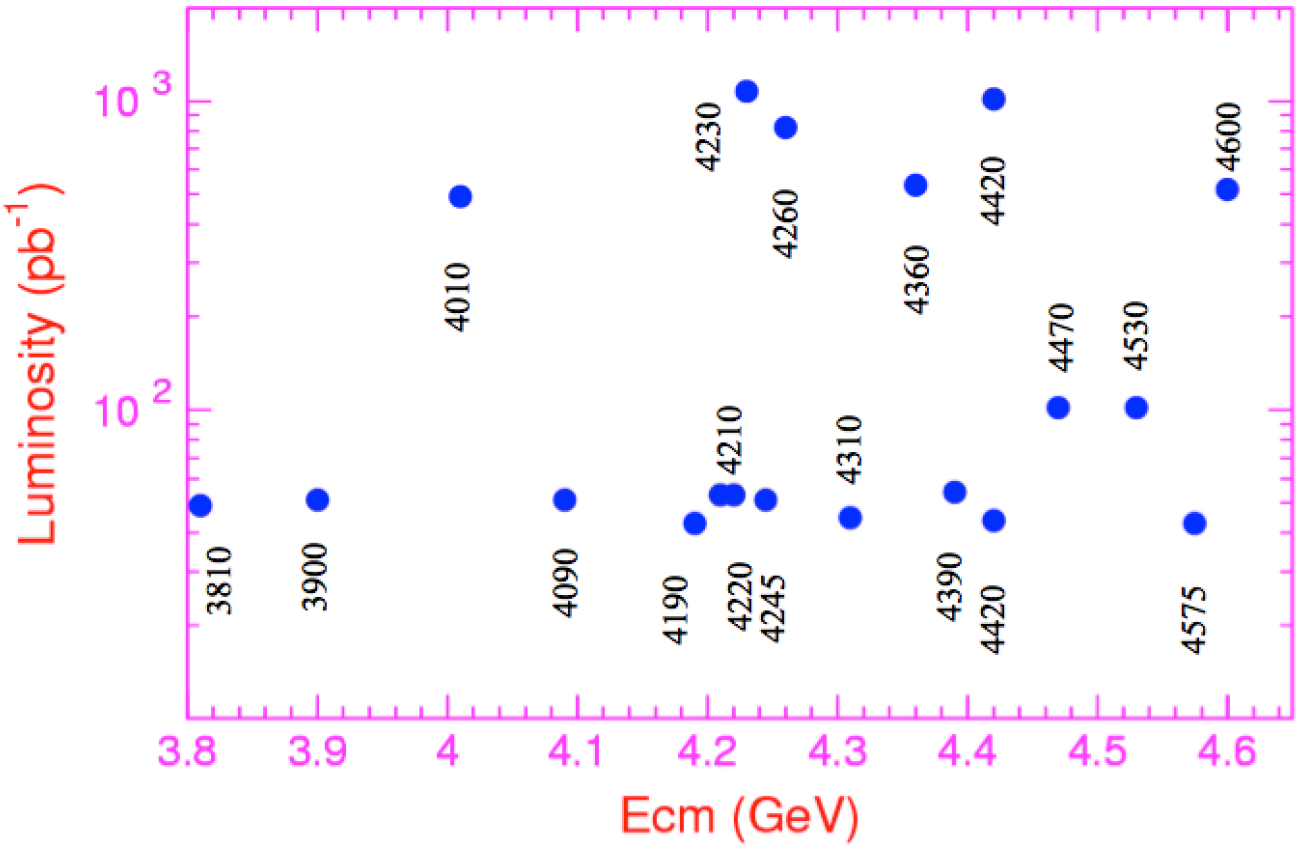


Physics programs at BESIII include light-hadron and charmonium spectroscopy, electroweak and strong physics at the charm scale, tau-physics, R value measurement and searches for rare processes.

Data collected over time



BESIII data samples for XYZ study (5/fb)

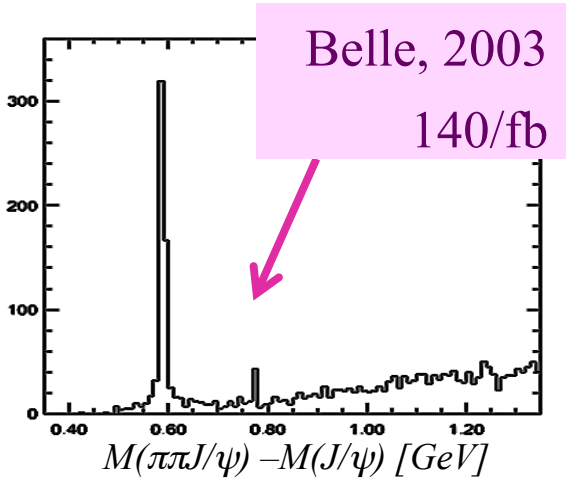


For the *XYZ* states study, BESIII has accumulated about 5 fb^{-1} data. Around ψ(4040), Y(4260), and Y(4360) peaks, we collected the largest data sample in the world so far for the study of their decays. Data samples with small statistics at other energy points are collected for the line-shape study.

The X states

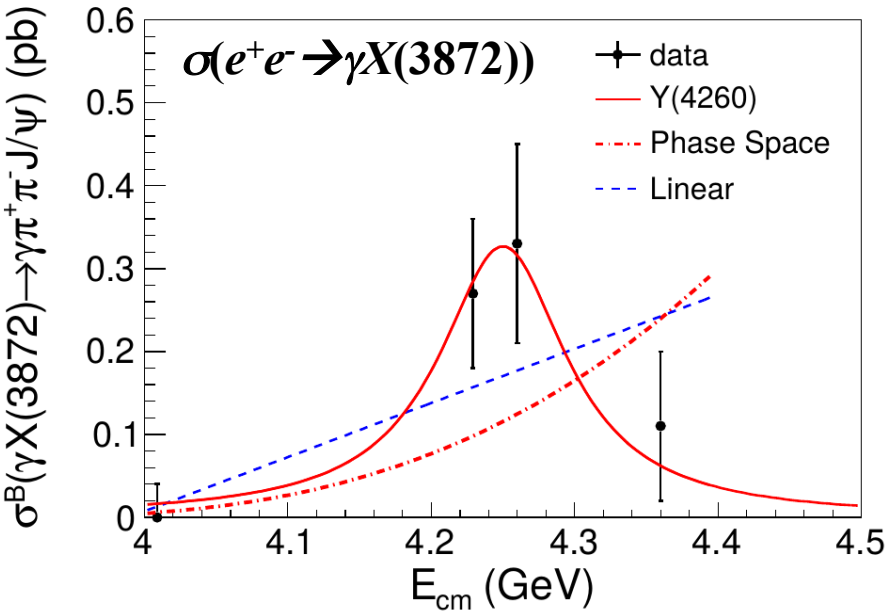
X(3872)

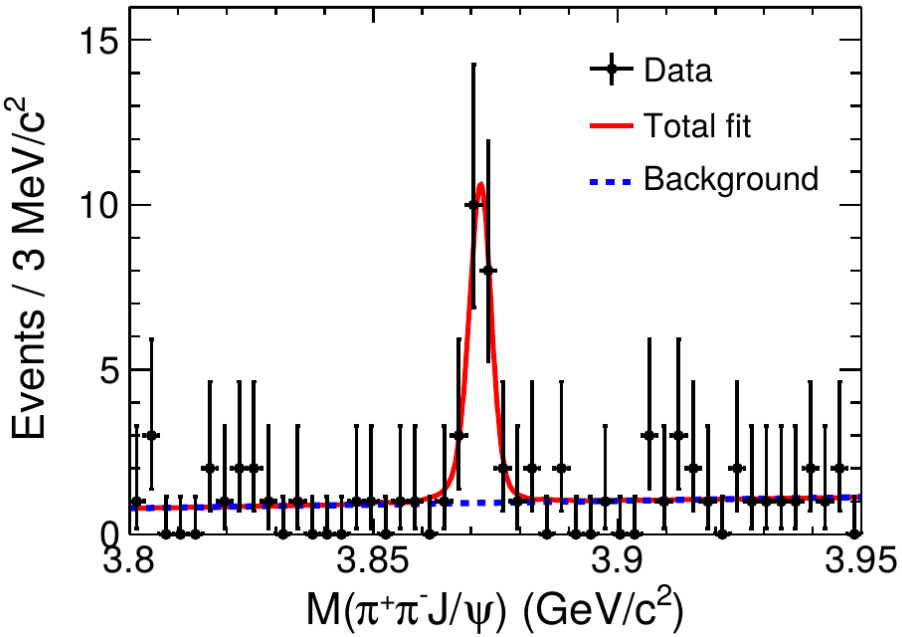
- Mass: Very close to $D^0\overline{D}^{*0}$ threshold
- Width: Very narrow, < 1.2 MeV
- $J^{PC}=1^{++}$ *(CDF, LHCb)*
- Production
  - in $p\bar{p}$/pp collison – rate similar to charmonia
  - In B decays – *KX*
  - Y(4260)→γ+X(3872)
- Decays
  - Open charm (~50%)
  - Charmonium: ππJ/ψ, πππJ/ψ, γJ/ψ, γψ'
- Nature (very likely exotic)
  - Loosely $D^0\overline{D}^{*0}$ bound state (like deuteron?)?
  - Mixture of excited χ_{c1} and $D^0\overline{D}^{*0}$ bound state?
  - Tetraquark?
  - Charmonium?



Cross sections of $e^+e^- \to \gamma X(3872)$

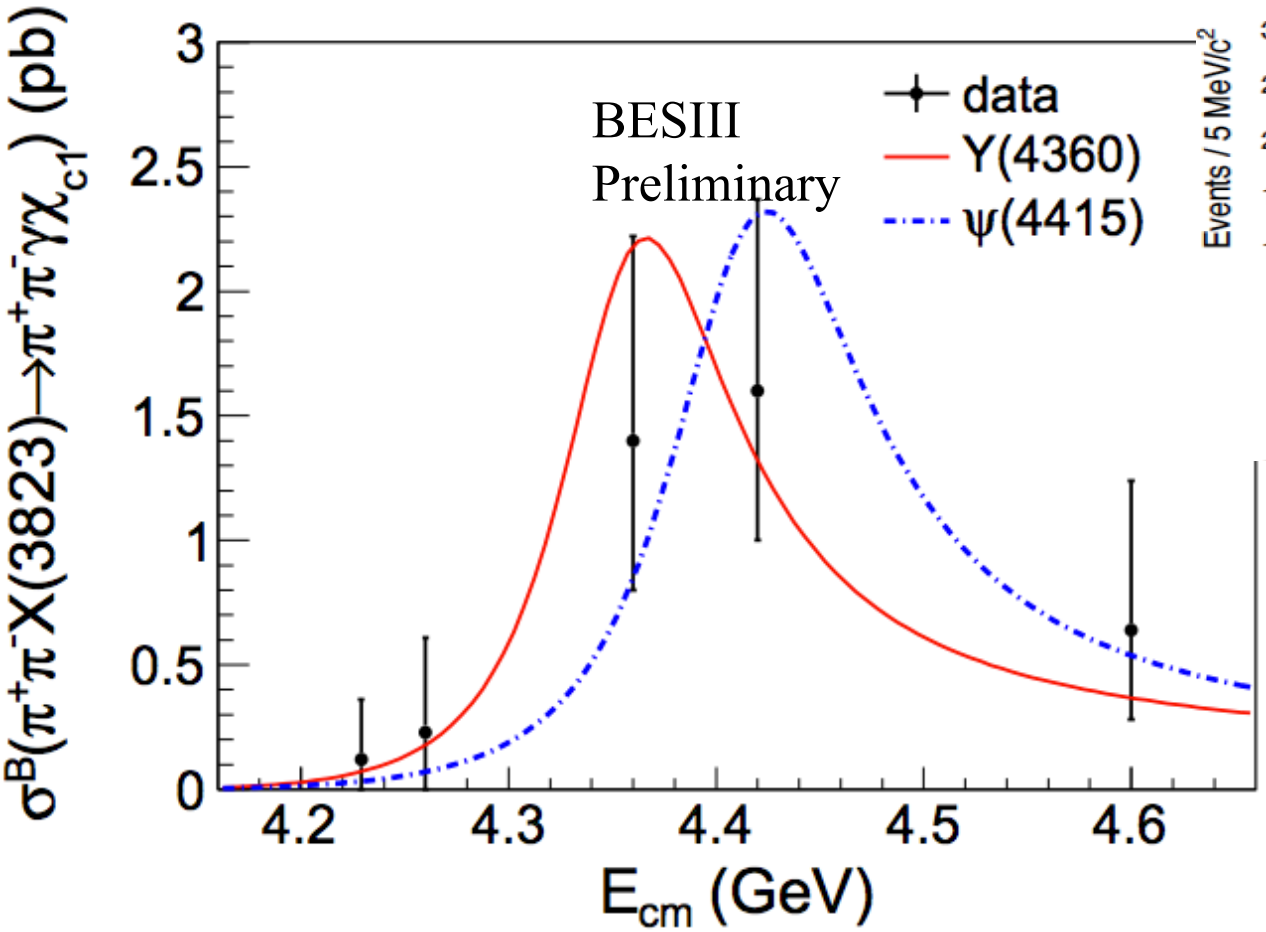
BESIII [PRL 112, 092001 (2014)]

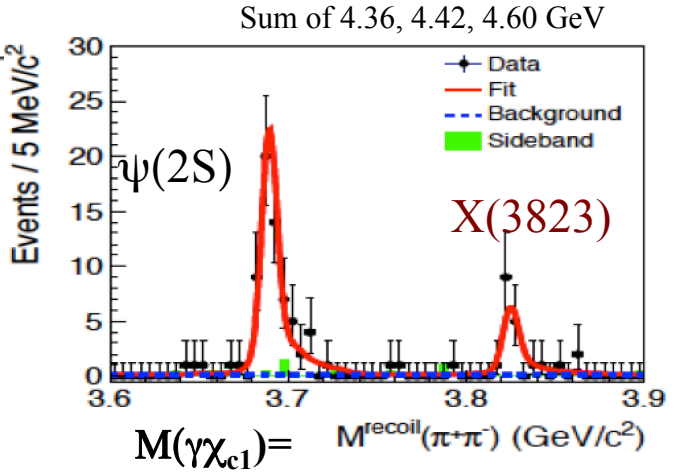




- BESIII observed $e^+e^- \to \gamma X(3872)$, $X(3872) \to \pi^+\pi J/\psi$.
- It seems that $X(3872)$ is from the radiative transition from $Y(4260)$. $R(B(e^+e^- \to \gamma X(3872))/B(e^+e^- \to \pi^+\pi J/\psi)) \sim 11\%$, large transition rate.
- Together with $Y(4260) \to \pi Z_c(3900)$, indicates commonality in the nature of the exotics states $X(3872)$, $Y(4260)$, and $Z_c(3900)$.

$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^- \gamma\chi_{c1}$





M=3821.7±1.3±0.7 MeV;
Significance: 6.7σ, observation.

Consistent with BELLE's 3.7σ evidence (PRL111, 032001)

1. Energy dependent cross section of $e^+e^- \to \pi^+\pi^- X(3823)$.
2. Both Y(4360) and ψ(4415) line shape give reasonable description.

X(3823) as the $\psi(1^3D_2)$

- Mass: D-wave ~3.810-3.840 GeV by potential model.
- X(3823) mass agree with $\psi(1^3D_2)$ prediction.

- Width: narrow
- X(3823) should be narrow (<16 MeV @ 90% C.L.).

- Production ratio:
- $R=B[X(3823)\rightarrow\gamma\chi_{c2}]/B[X(3823)\rightarrow\gamma\chi_{c1}]<0.43$ @ 90% C.L.
- Agree with prediction R~0.2.

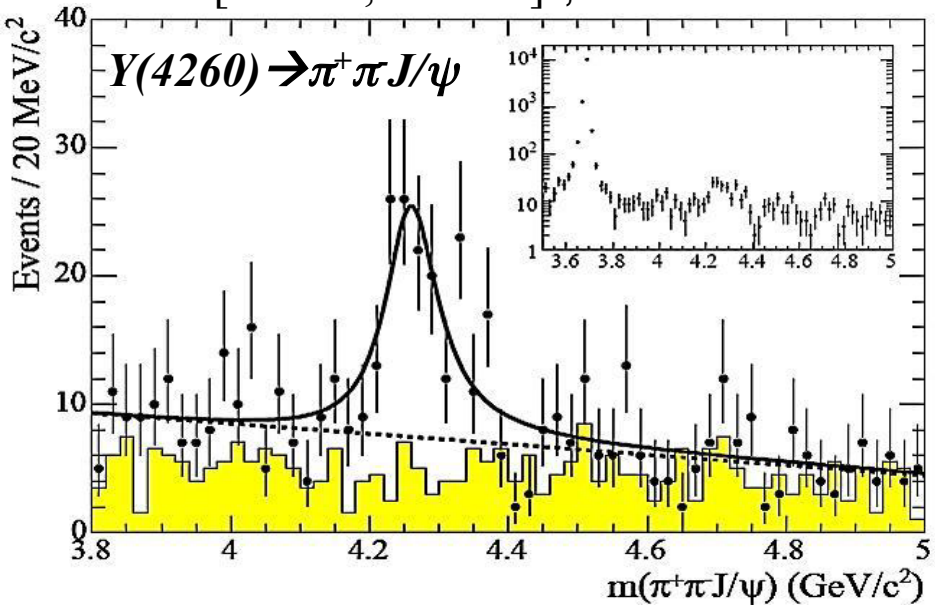
- Exclusions: $1^1D_2\rightarrow\gamma\chi_{c1}$ forbidden; $1^3D_3\rightarrow\gamma\chi_{c1}$ amplitude=0.

The Y states (vectors)

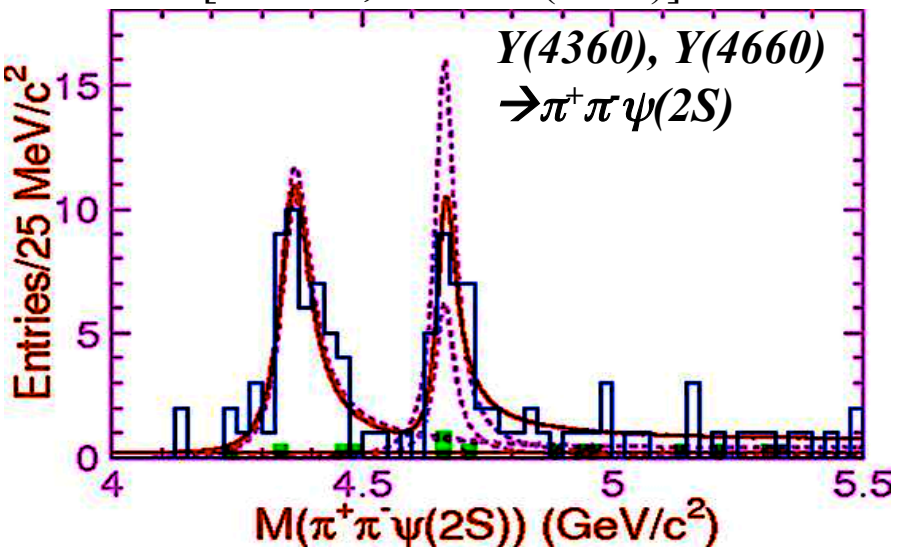
Y-family states

- 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.

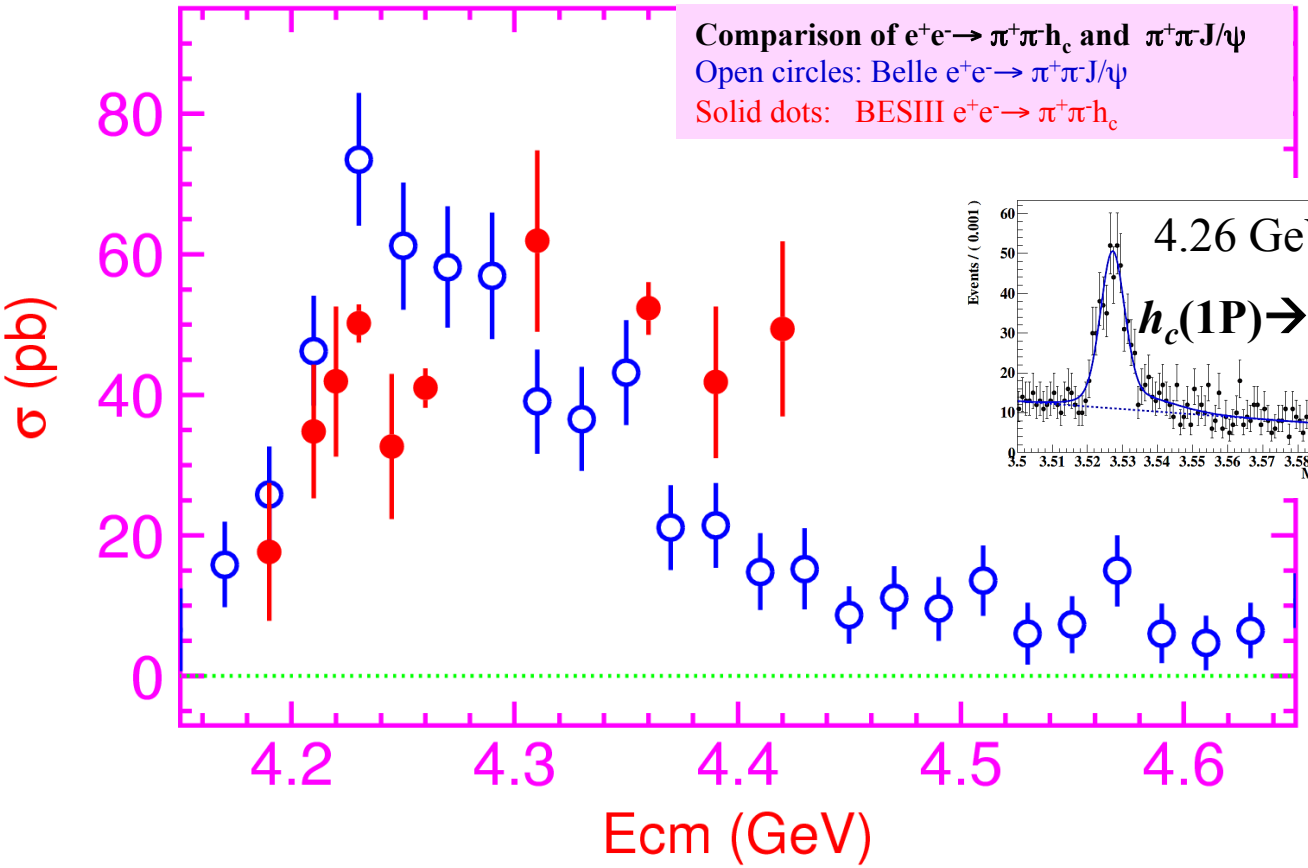
BaBar: [PRL95, 142001] , 273fb-1

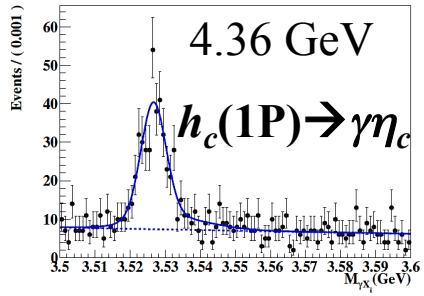


Belle [PRL 99, 142002 (2007)] 673fb^{-1}



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





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

$h_c(1P)$ $c\bar{c}$ $\uparrow\downarrow$

- 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? Need more data at high energies to complete the line shape measurement.

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

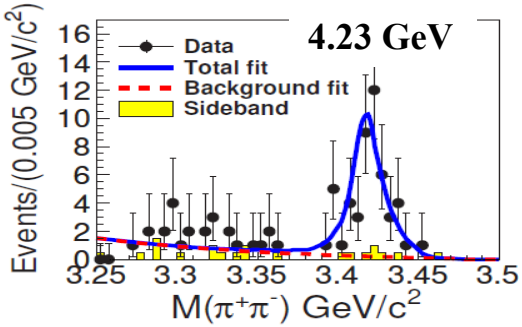
$e^+e^- \rightarrow \omega\chi_{c0}$ are observed at 4230 MeV and 4260 MeV. Signal does not arise from the decays of the $Y(4260)$.

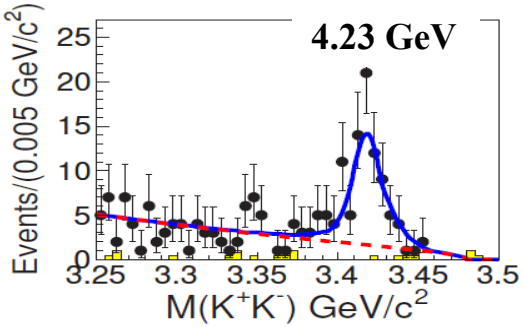
Fit with a single BW

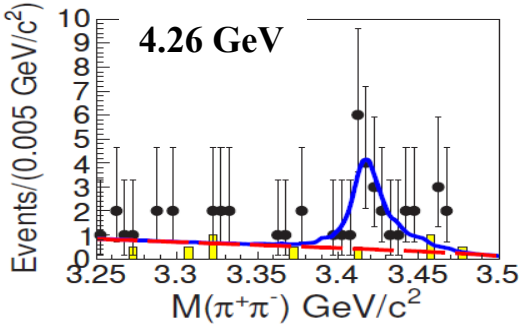
Mass = 4230±8±6 MeV

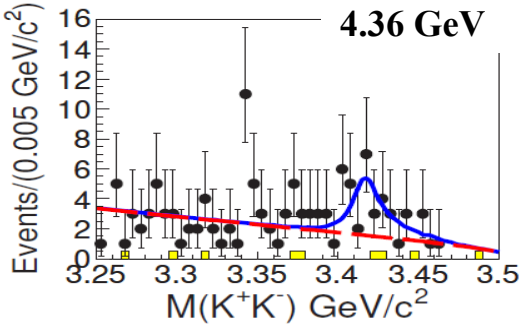
Width = 38±12±2 MeV

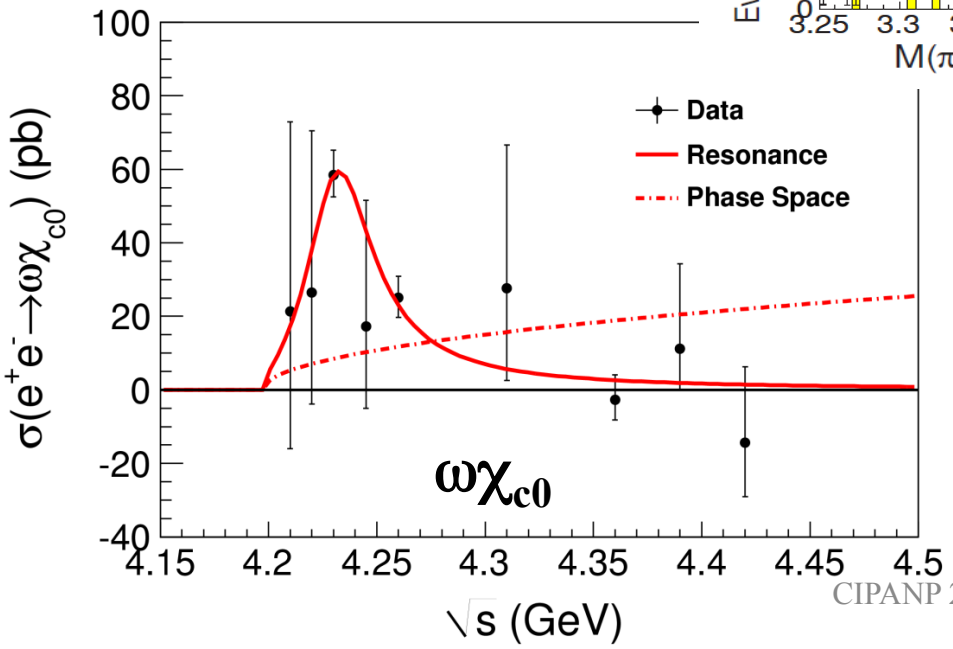
Significance $> 9\sigma$











A tetraquark? (arXiv: 1412.7196)

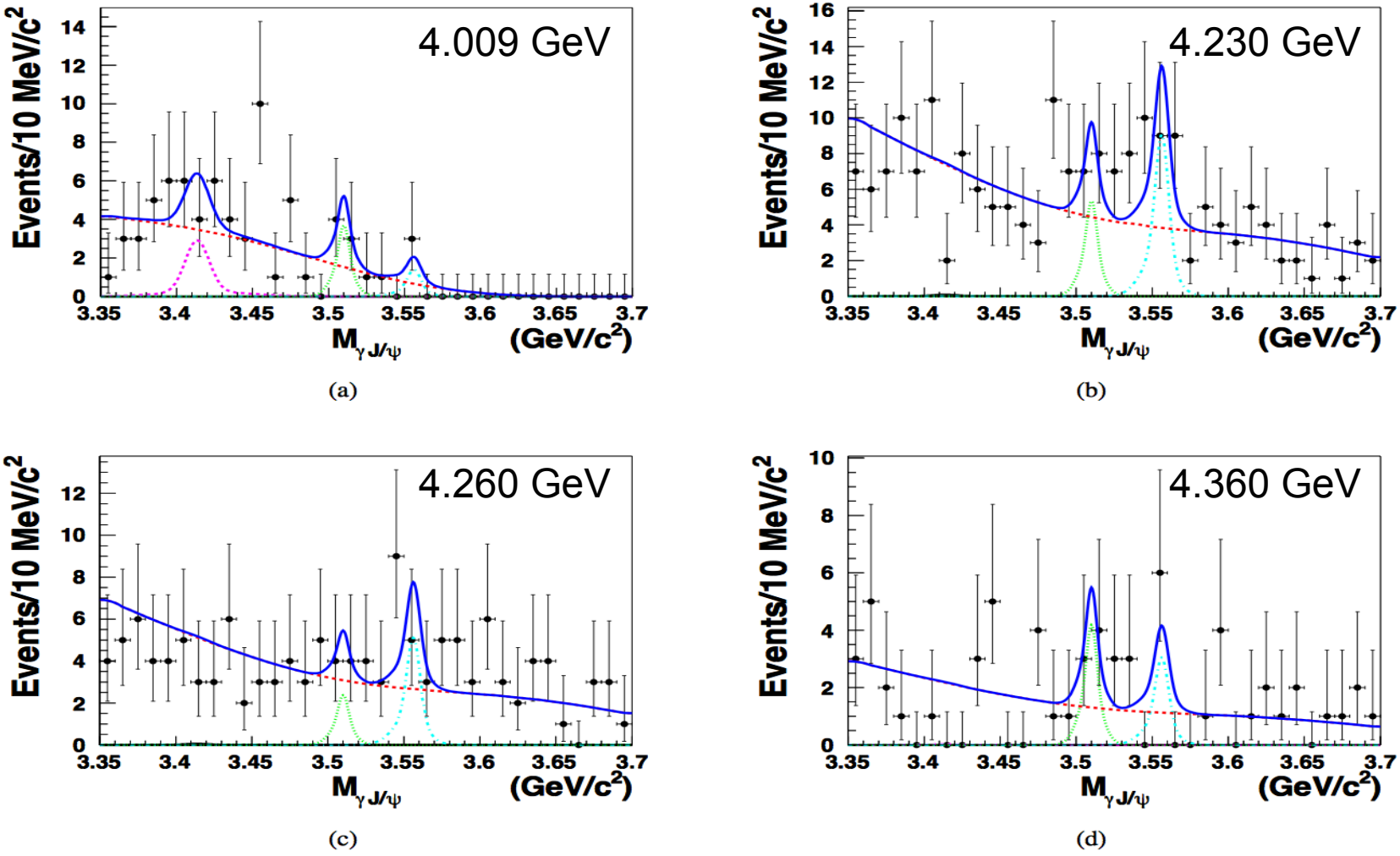
ψ(4S)? (arXiv: 1405.3831)

Threshold effect?

…

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

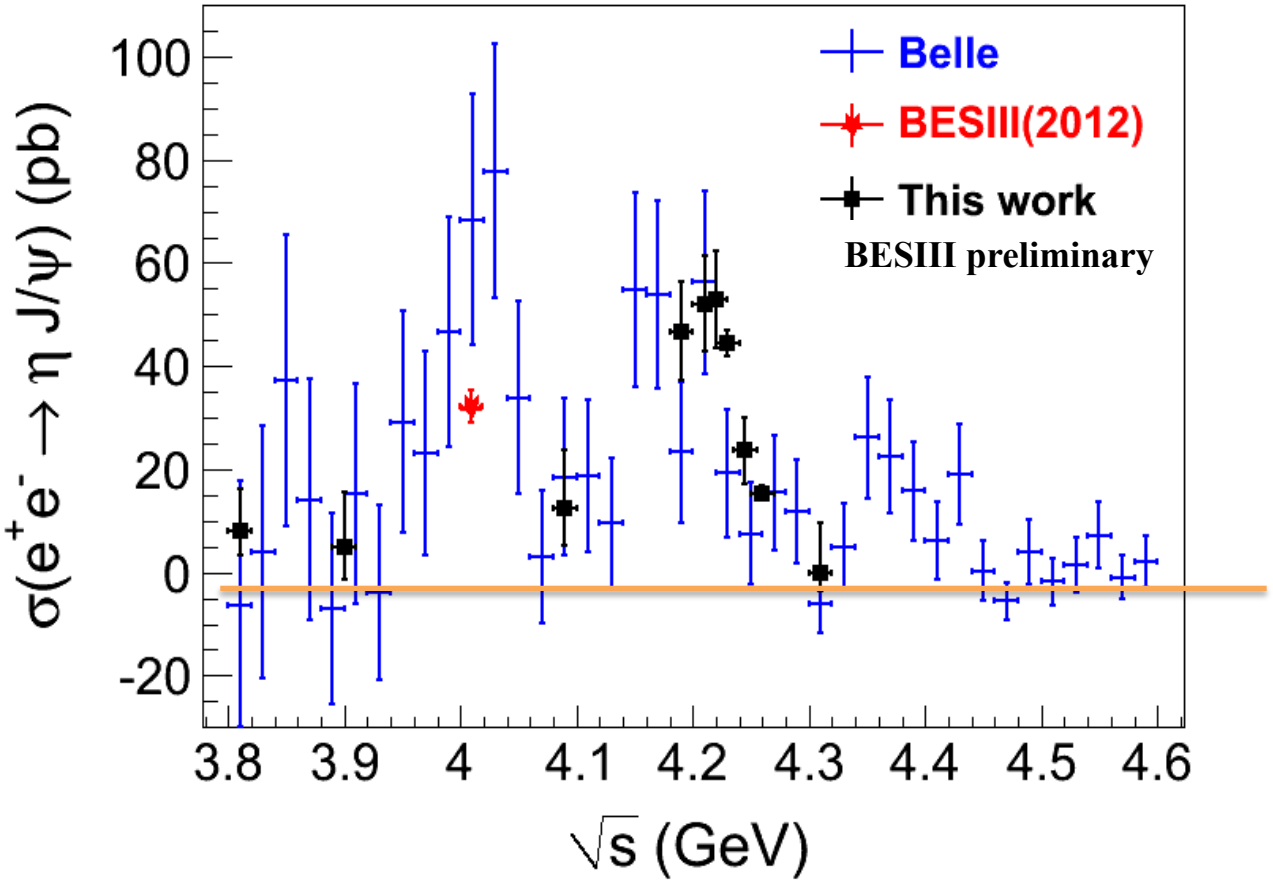
Evidence for $e^+e^- \rightarrow \gamma\chi_{cJ=1,2}$



We find evidence for the processes $e^+e^- \rightarrow \gamma\chi_{c1}$ and $e^+e^- \rightarrow \gamma\chi_{c2}$ with statistical significances of 3.0σ and 3.4σ, respectively. No evidence of $e^+e^- \rightarrow \gamma\chi_{c0}$ is observed.

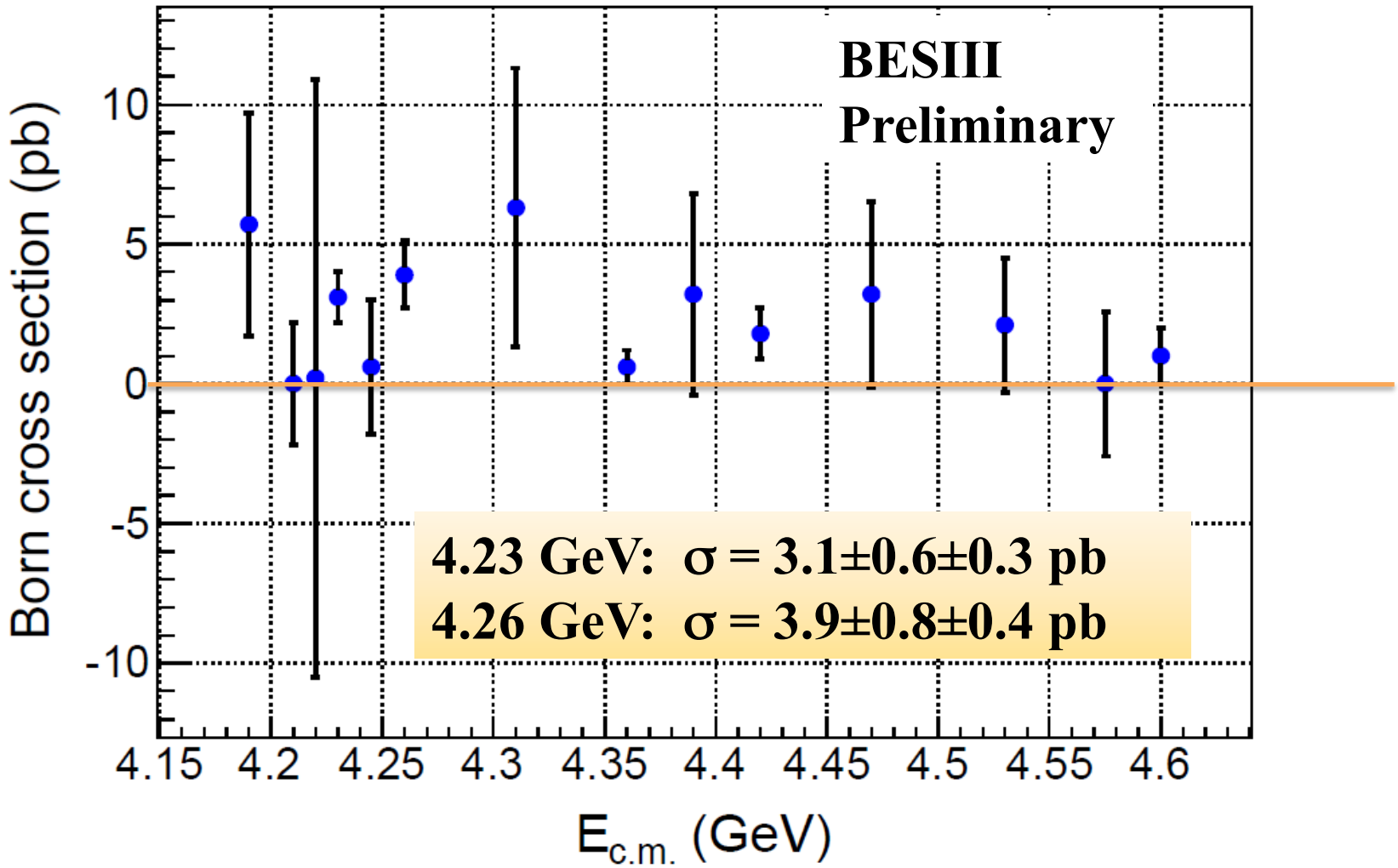
BESIII: arXiv:1411.6336, CPC (in press)

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



- The cross section peaks around 4.2 GeV
- Analysis of high energy points underway

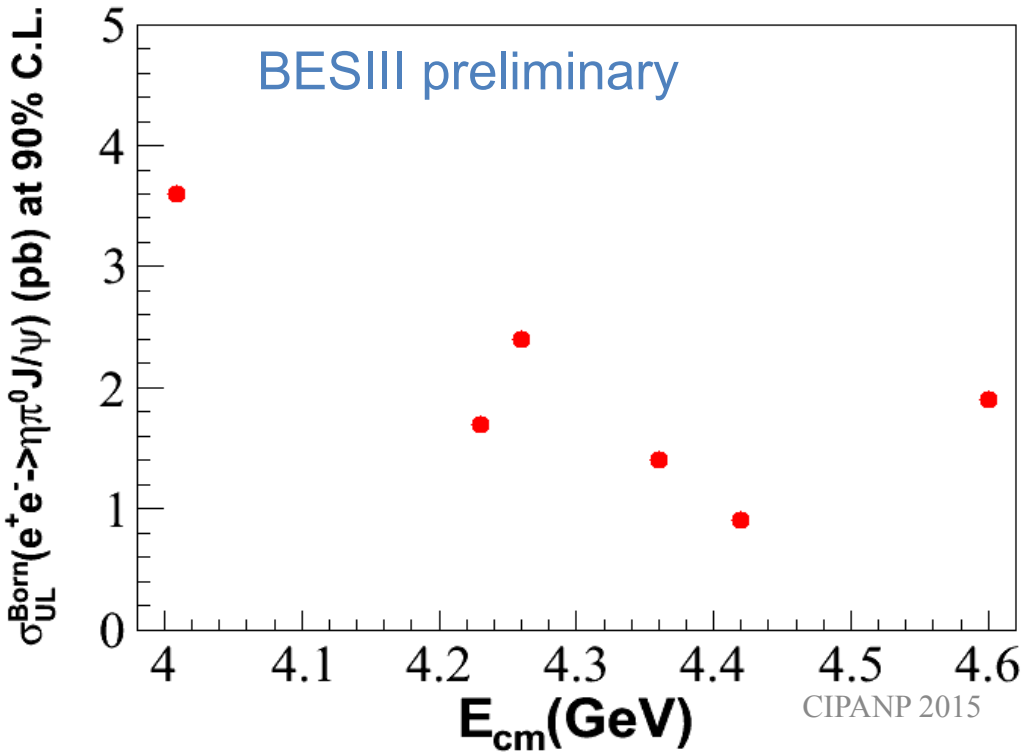
Observation of $e^+e^- \rightarrow \eta' J/\psi$



First observation, cannot tell the line shape due to statistics

No Y(4260)→ $\eta\pi^0 J/\psi$

- Model predictions of e^+e^-→ $\eta\pi^0 J/\psi$
- 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

No significant e^+e^- → γY(4140)

Upper limit at the 90% C.L. for $\sigma^B \cdot \mathcal{B} = \sigma^B\left(e^+e^- \to \gamma Y(4140)\right) \cdot \mathcal{B}(Y(4140) \to \phi J/\psi)$

$\sqrt{s}$ (GeV/c^2)	Luminosity (pb^{-1})	$(1+\delta)$	n^{prod}	$\sigma^B \cdot \mathcal{B}$ (pb)
4.23	1094	0.840	<339	<0.35
4.26	827	0.847	<207	<0.28
4.36	545	0.944	<179	<0.33

The Y(4140) has positive C-parity and can be searched for through radative transitions from other vectors

Compared with $X(3872)$ production. PRL 112, 092001

$$\sigma^B\left(e^+e^- \to \gamma X(3872)\right) \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$$

$= 0.27 \pm 0.09(\text{stat}) \pm 0.02(\text{syst})$ pb at $\sqrt{s}$= 4.23 GeV,

$= 0.33 \pm 0.12(\text{stat}) \pm 0.02(\text{syst})$ pb at $\sqrt{s}$ = 4.26 GeV.

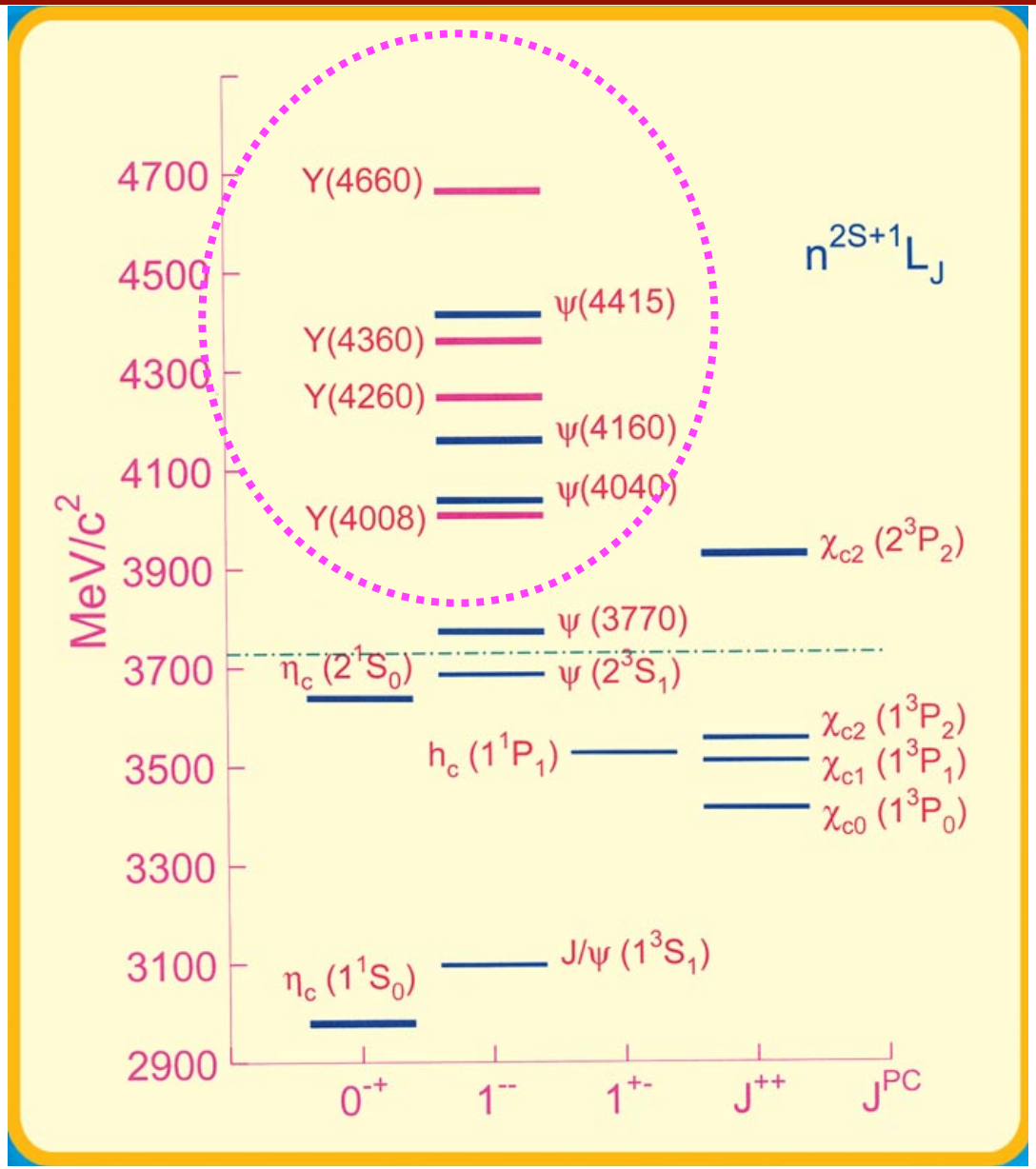
Take $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ = 5%. arXiv: 0910.3138

And $\mathcal{B}(Y(4140) \to \phi J/\psi)$ = 30%, molecular calculation, PRD 80, 054019.

$$\frac{\sigma^B(e^+e^- \to \gamma Y(4140)}{\sigma(e^+e^- \to \gamma X(3872))} \leq 0.1 \text{ at } \sqrt{s}\text{=4.23 and 4.26 GeV.}$$

Phys. Rev. D 91, 032002 (2015)

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
- $\pi^+\pi^- h_c$, $\omega\chi_c$, … add complexity but also give hints for their composition

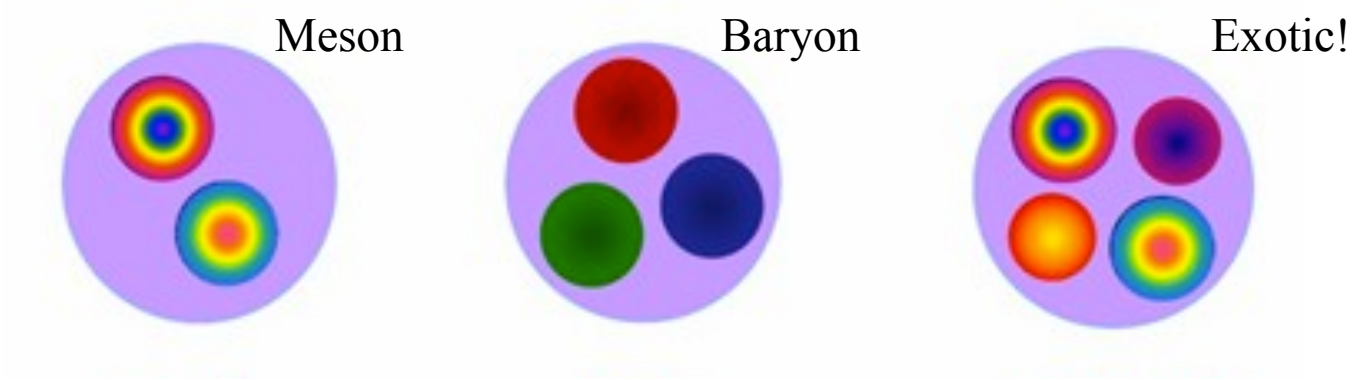
The Z_c states

$Z_c^{\pm}$: charged charmonium-like states

- $Z_c^{\pm}$ decay to charmonium demonstrates a ccbar pair.
- Electric charge demonstrates two or more light quarks:

$$N_{quark} \geq 4$$

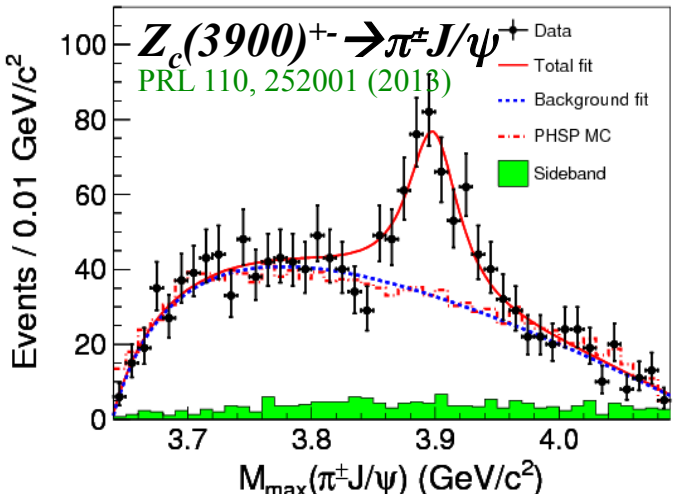
- A clear signature for an exotic hadronic state.

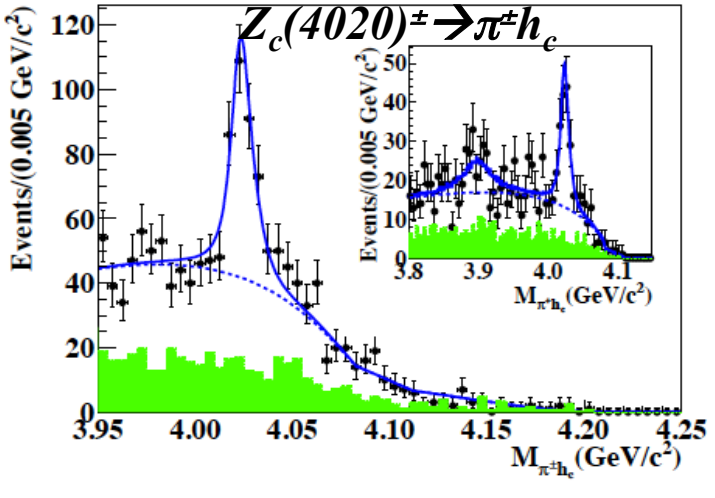


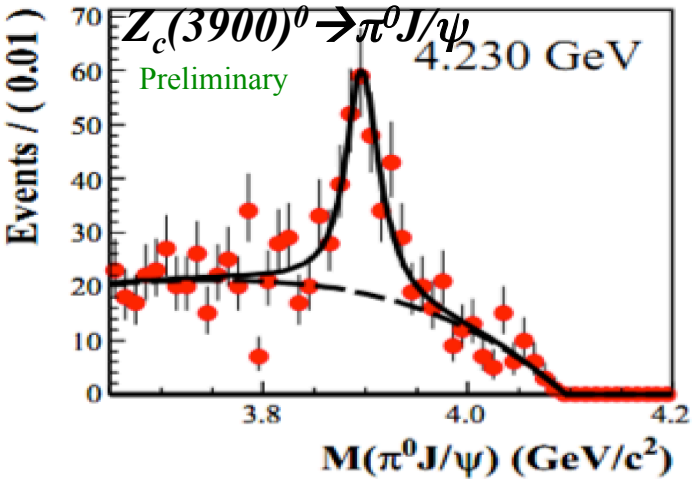
- Search in final states $\pi J/\psi$, πh_c, $\pi\psi(2S)$ $\pi\chi_{cJ}$...

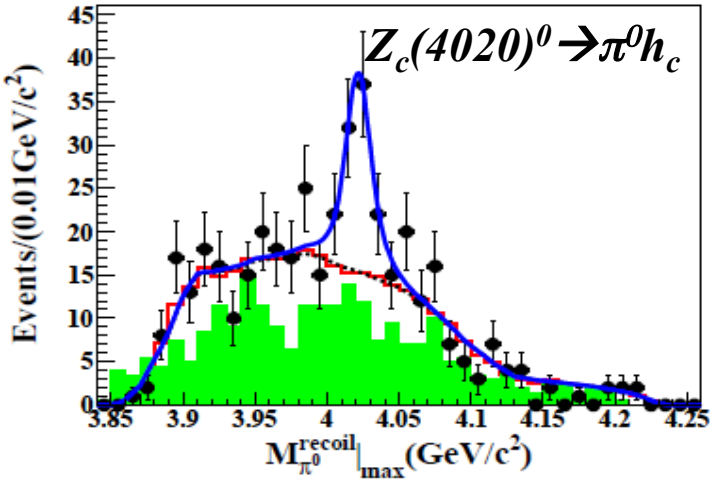
Z_c at BESIII

BESIII observed four-quark state candidates $Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$, and their neutral partners $Z_c(3900)^0$ and $Z_c(4020)^0$ in $e^+e^- \to \pi + Zc$, $Zc \to \pi + J/\psi/h_c$ processes. (details see Zhentian's talk on 5.22)



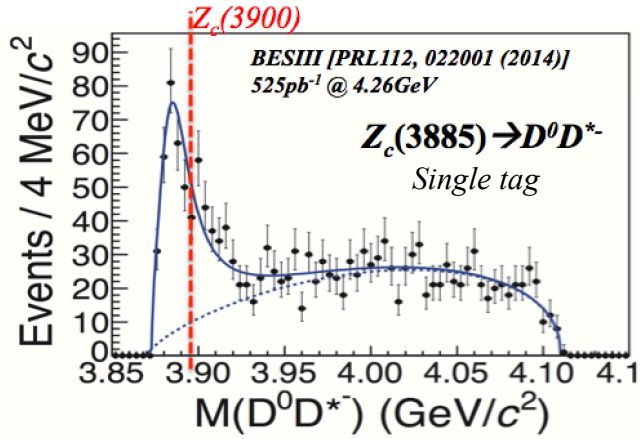


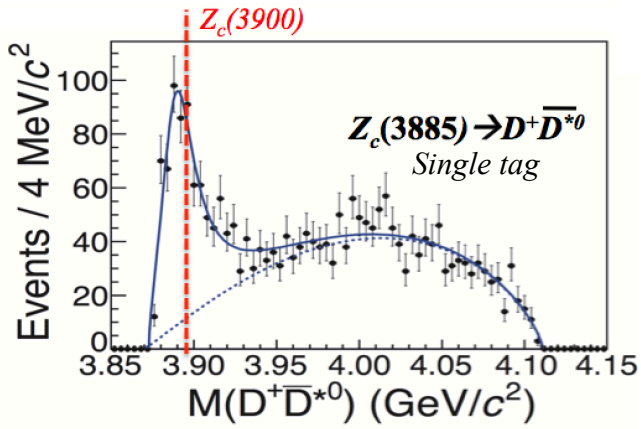




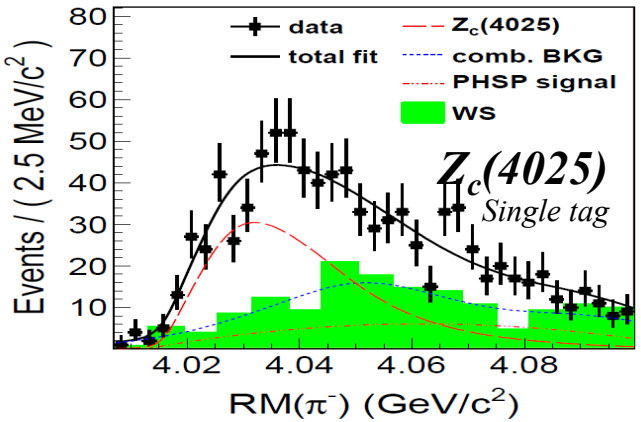
Z_c at BESIII

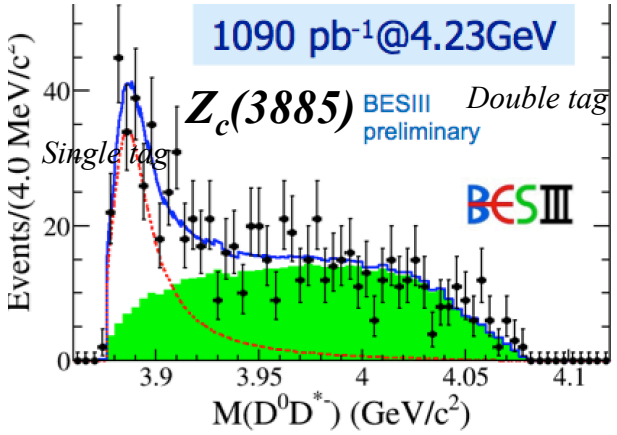
In $e^+e^-\rightarrow\pi D^*D(D^*)$ processes, BESIII observed $Z_c(3885)\rightarrow DD^*$ and $Z_c(4025)\rightarrow D^*D^*$, whose masses are close to $Z_c(3900)$ and $Z_c(4020)$ and could be considered as the same states. Comparison between $Z_c\rightarrow$pion+charmonium and $Z_c\rightarrow D(D^*)$ productions can be used to understand the nature of Z_c. (details see Zhentian's talk on 5.22)

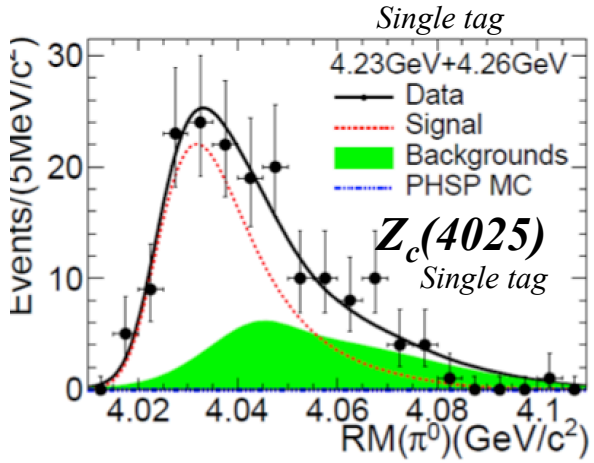




PRL112, 132001 (2014)
827pb^{-1} @ 4.26GeV

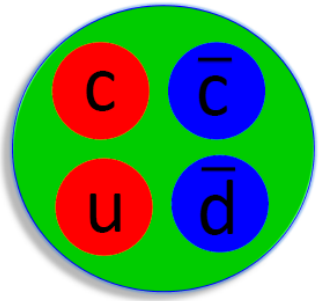






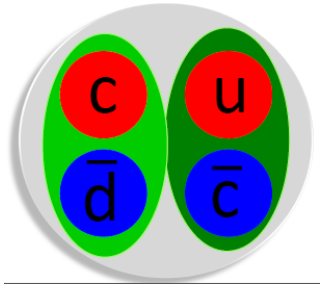
What's the nature of these Z_c states?

- At least 4 quarks, not a conventional meson
- Tetraquark state?



Phys. Rev. D87,125018(2013); Phys. Rev. D88, 074506(2013);
Phys. Rev. D89,054019(2014); Phys. Rev. D90,054009(2014); etc

- $D^{(*)}\bar{D}^{(*)}$ molecule state?



Phys. Rev. Lett. 111, 132003 (2013); Phys. Rev. D 89, 094026 (2014)
Phys. Rev. D 89, 074029 (2014); Phys. Rev. D 88, 074506 (2013); etc

- FSI?
- Cusp?
- …

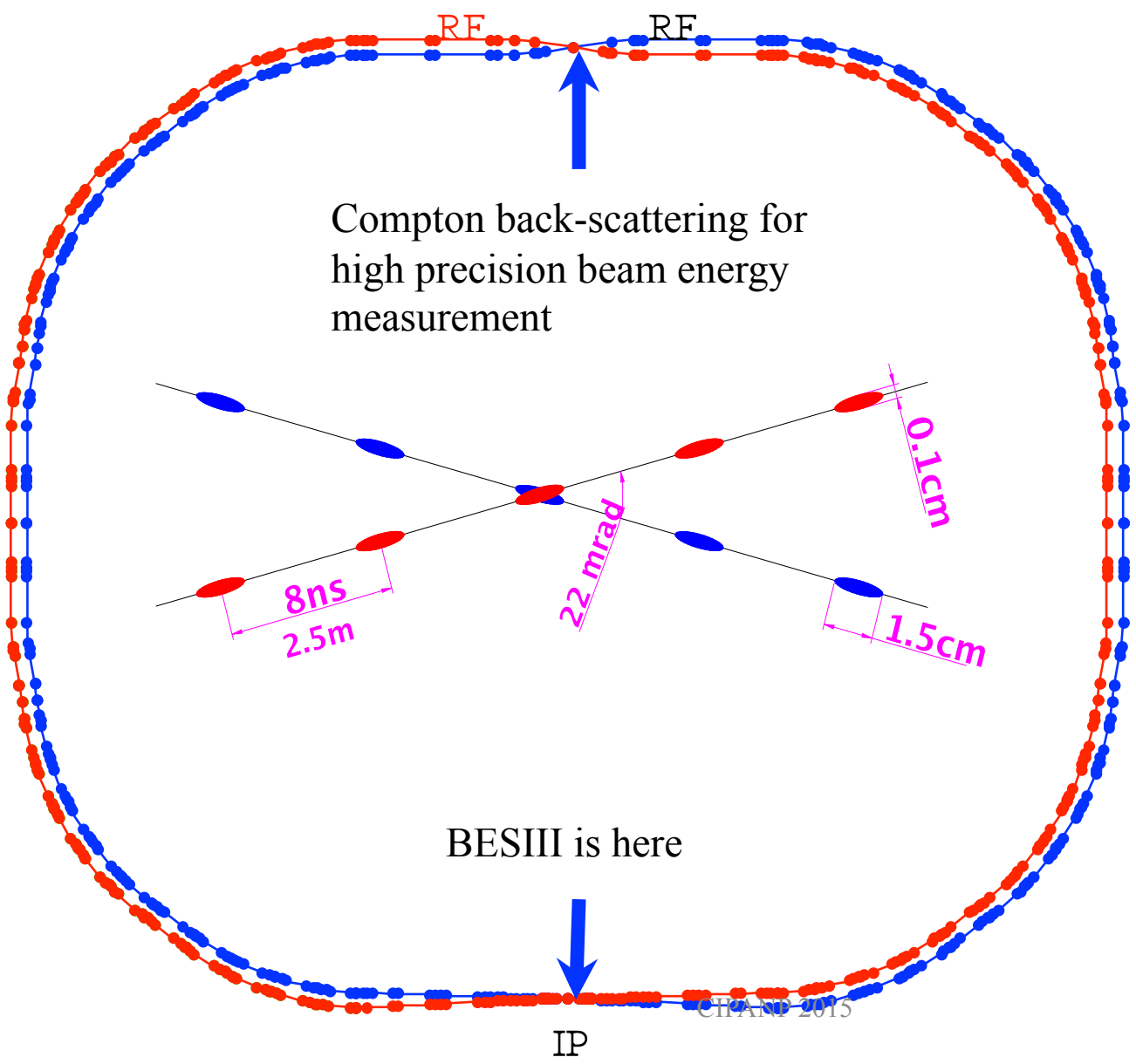
Summary

- Lots of progress has been made in the study of charmonium-like states at BESIII.
- Observation of $e^+e^- \rightarrow \gamma X(3872)$ & $\pi^+\pi^- X(3823)$.
- Measurements of many hidden charm final states.
- Observation of Z_c states.
- BESIII may continue data taking until 2020-2022.

Thank you!

Backup

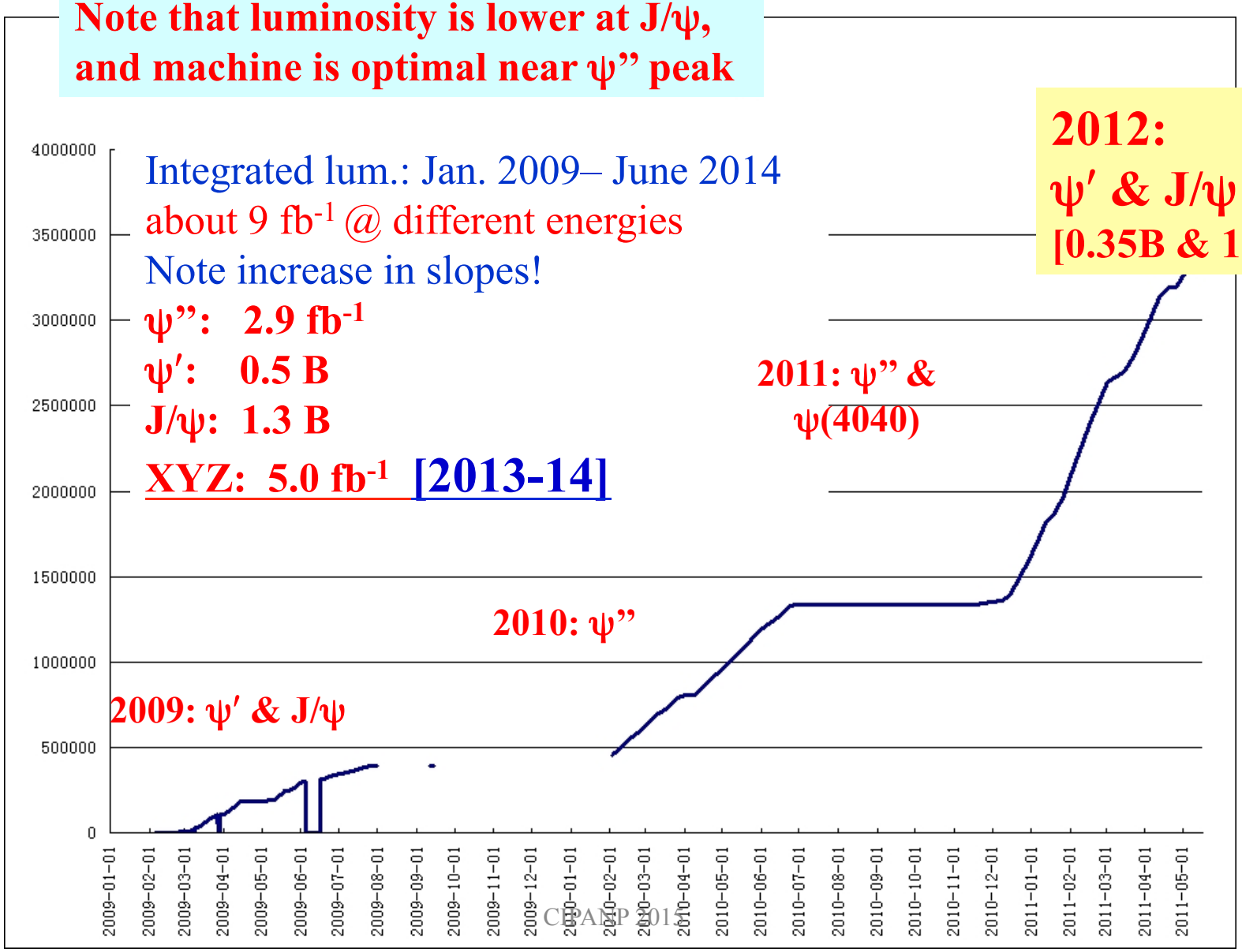
BEPC II: a double-ring machine



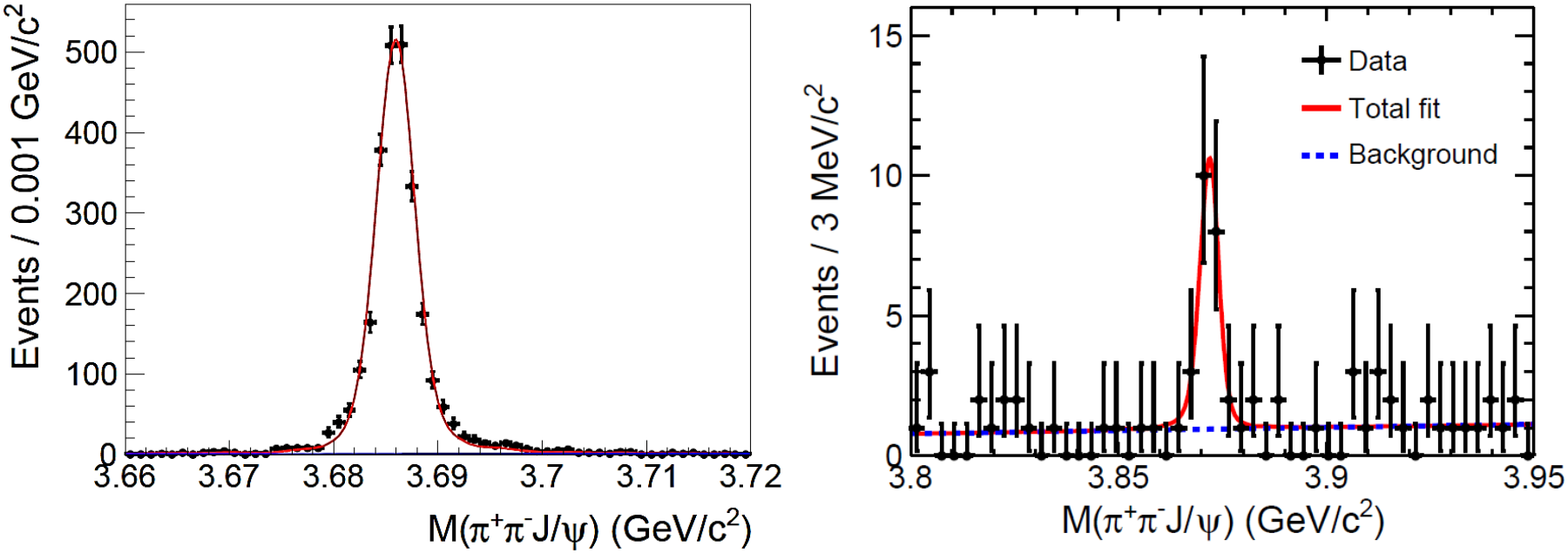
Beam energy:
1-2.3 GeV
Luminosity:
1×10^{33} $cm^{-2}s^{-1}$
Optimum energy:
1.89 GeV
Energy spread:
5.16×10^{-4}
No. of bunches:
93
Bunch length:
1.5 cm
Total current:
0.91 A
SR mode:
0.25A @ 2.5 GeV

BESIII data samples

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



Observation of $e^+e^- \to \gamma X(3872)$



ISR ψ' signal is used for mass, and mass resolution calibration.
N=1818; ΔM=0.34±0.04 MeV; $\Delta\sigma_M$=1.14 ±0.07 MeV

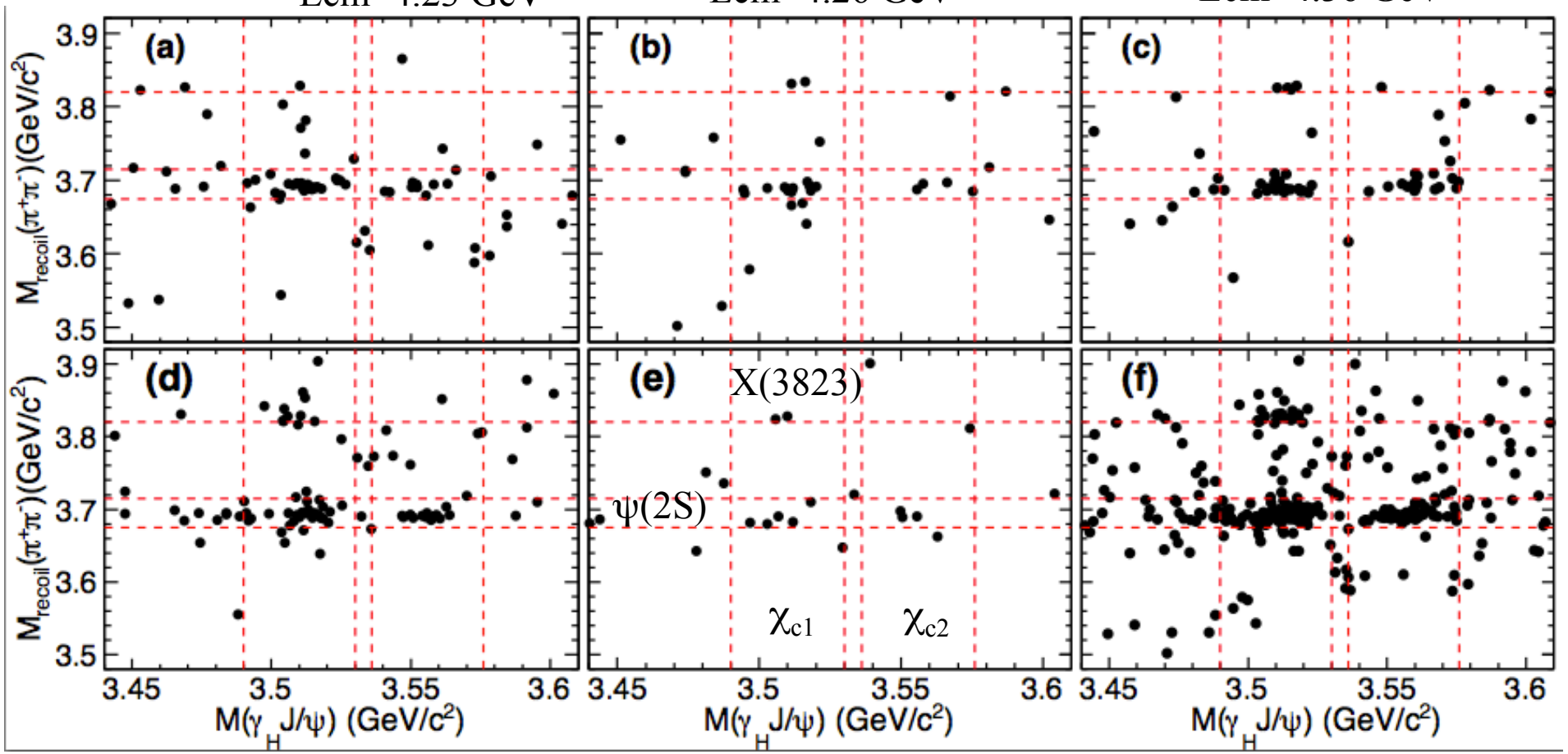
N(X(3872)) = 20.1±4.5 **6.3σ**

M(X(3872)) = 3871.9±0.7±0.2 MeV [PDG: 3871.68 ±0.17 MeV]

arXiv: 1310.4101,
PRL 112, 092001 (2014)

$e^+e^- \rightarrow \pi^+\pi^- X(3823) \rightarrow \pi^+\pi^-\gamma\chi_{c1}$

Preliminary



Ecm=4.42 GeV

Ecm=4.60 GeV

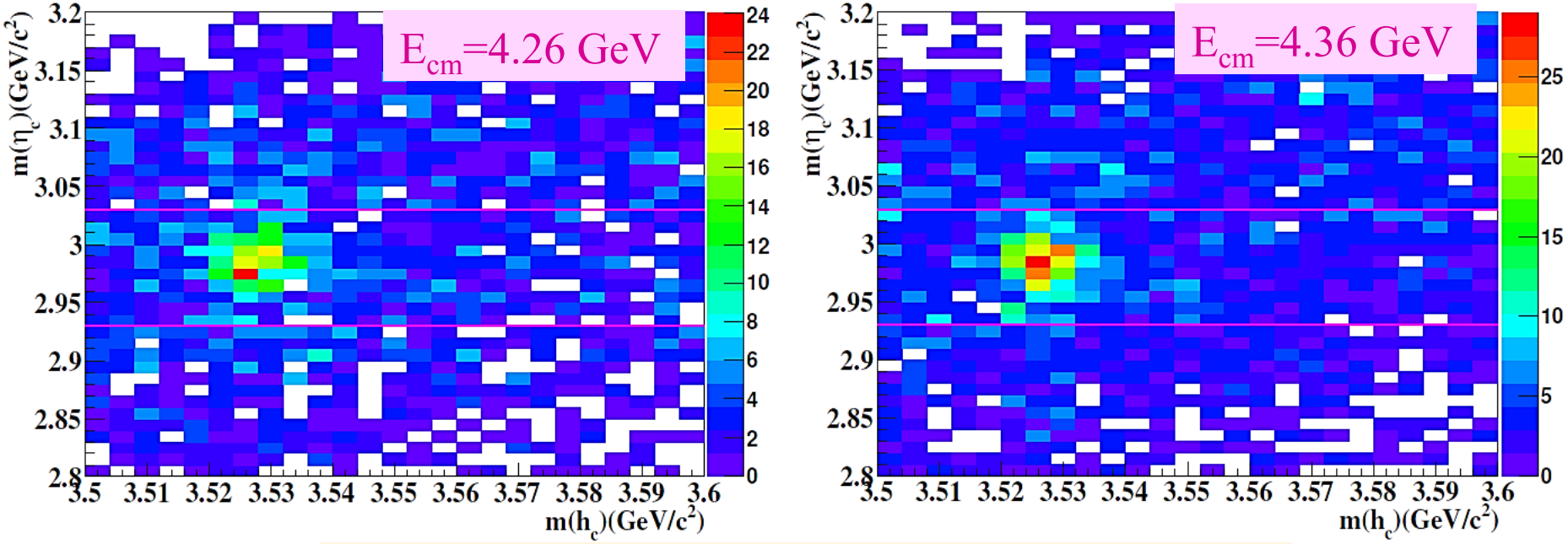
The sum

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

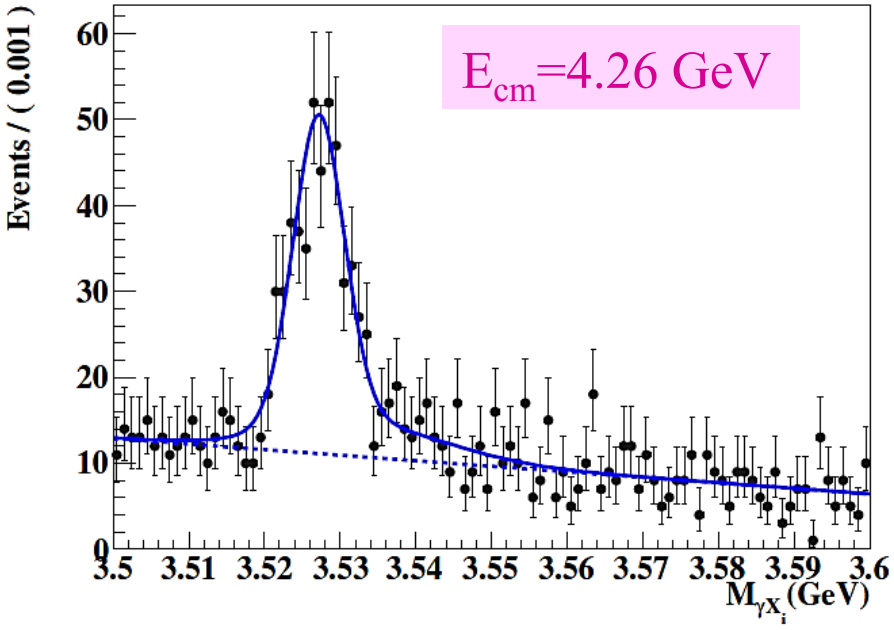
$e^+e^- \to \pi^+\pi^- h_c(1P)$ at BESIII

- $h_c \to \gamma\eta_c$, $\eta_c \to$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., $K^+K^-\pi^0$
  - $p\bar{p}\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)\eta$, $2(\pi^+\pi^-\pi^0)$

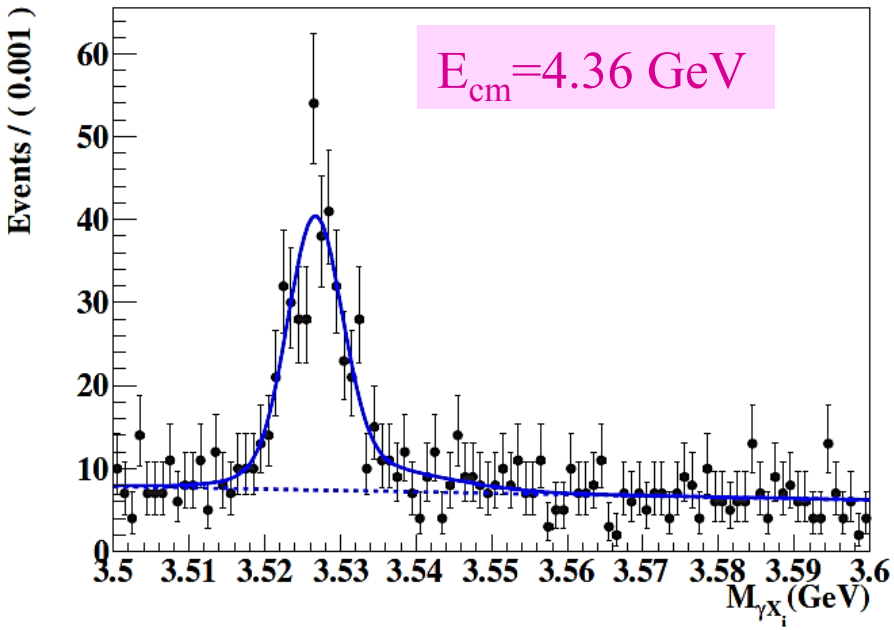


BESIII: arXiv:1309.1896, PRL111, 242001

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



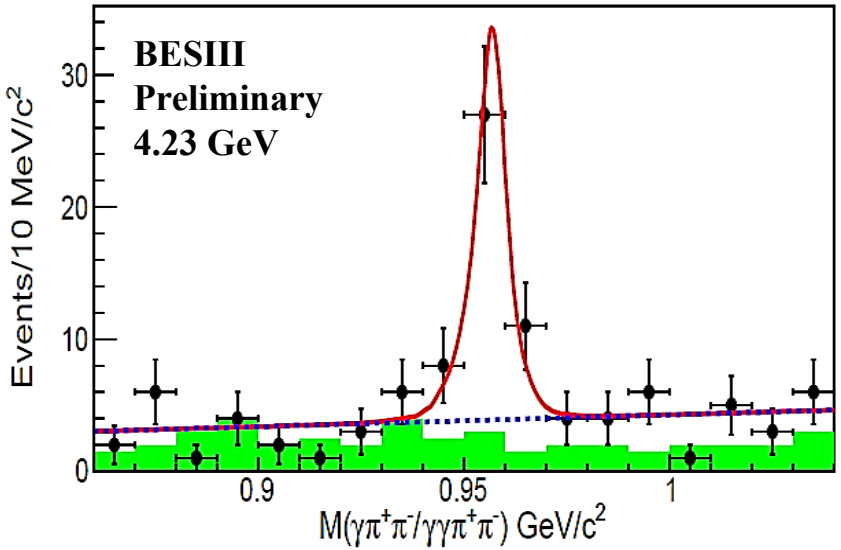
$N(h_c)$=416±28
Lum=827/pb
σ^B= 41.0±2.8±7.4 pb

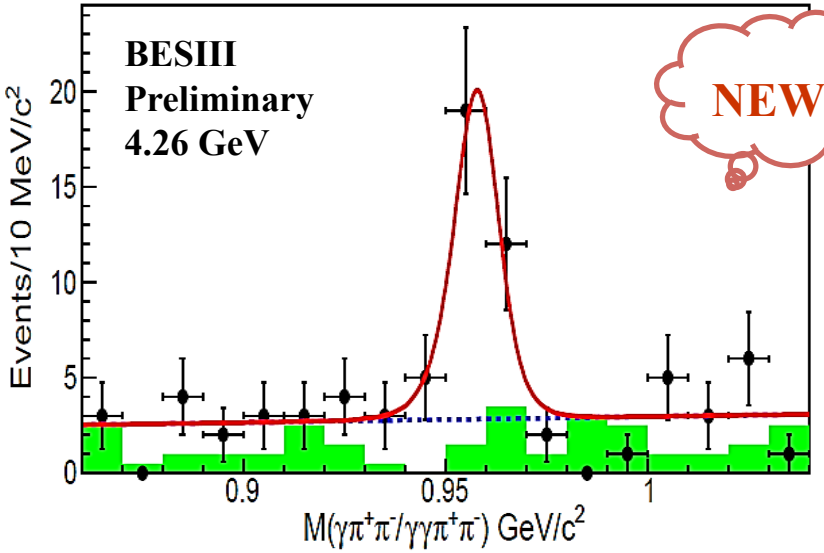


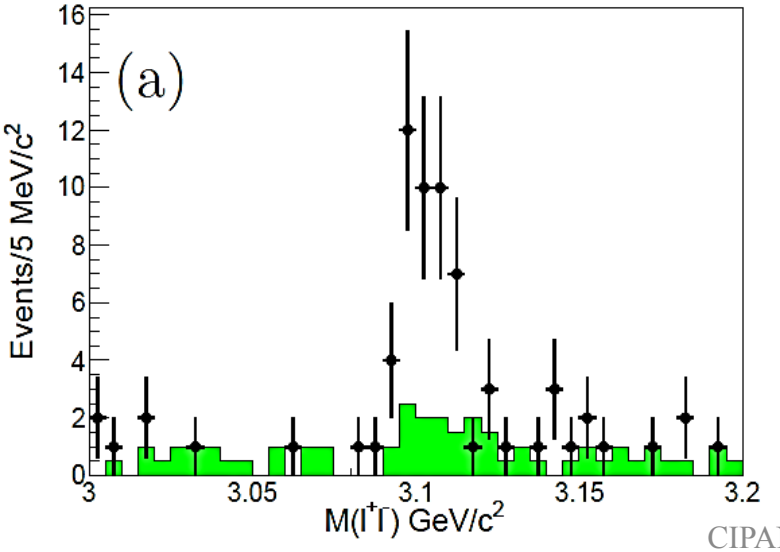
$N(h_c)$=357±25 Lum=544/pb
σ^B= 52.3±3.7±9.2 pb

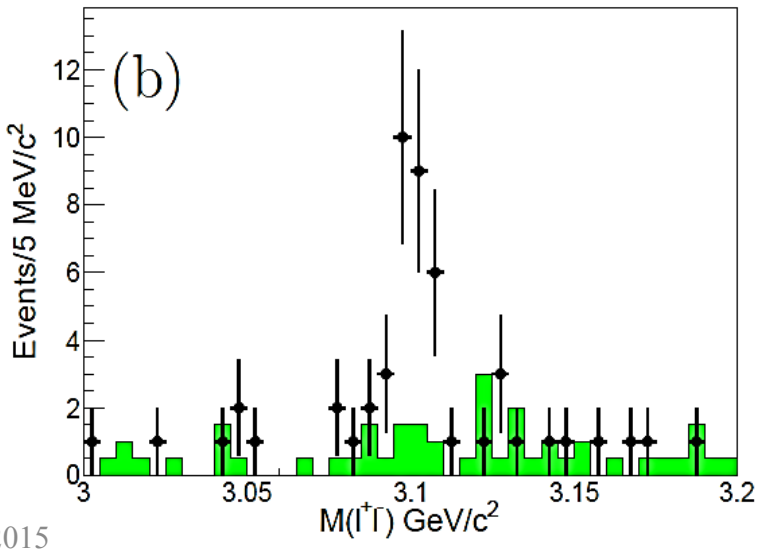
BESIII: arXiv:1309.1896, PRL111, 242001

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

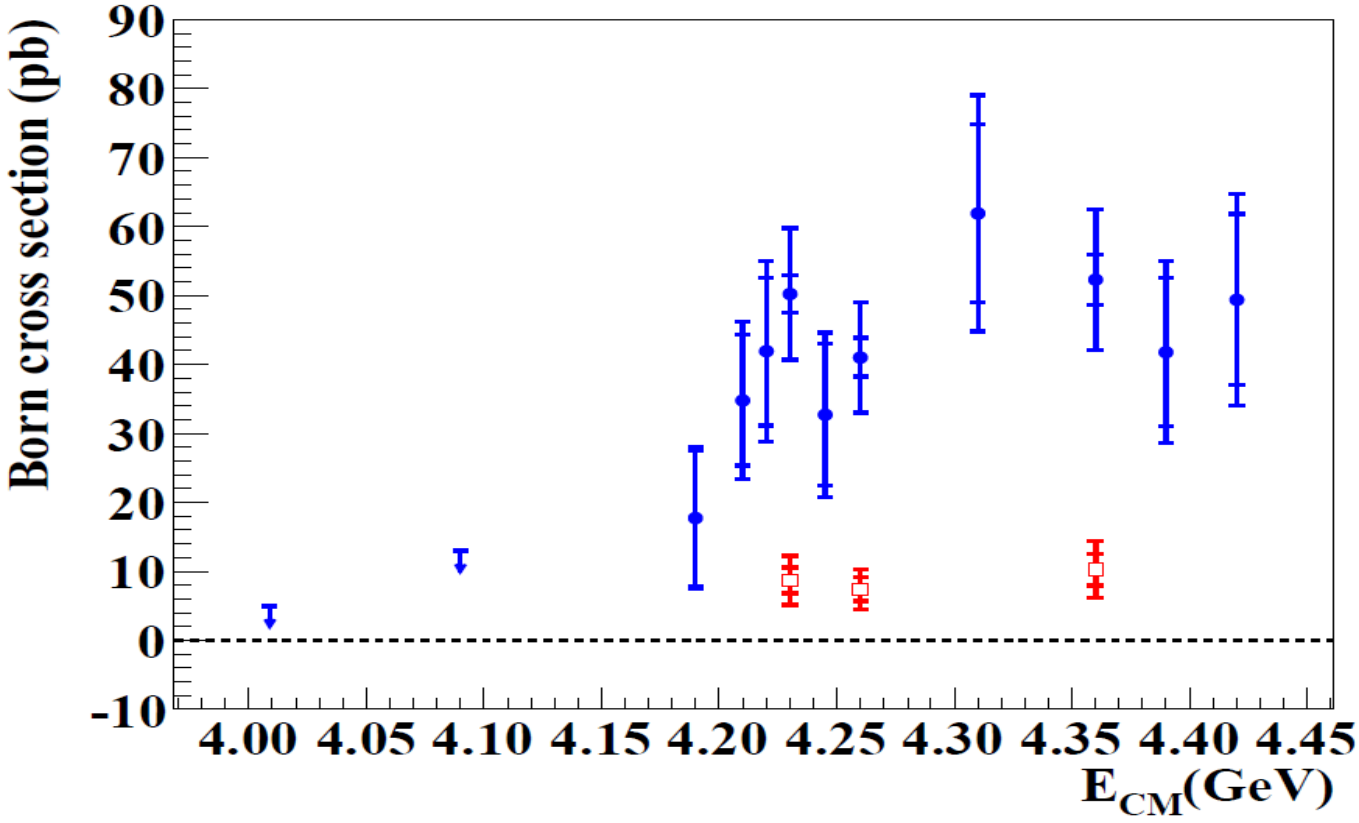






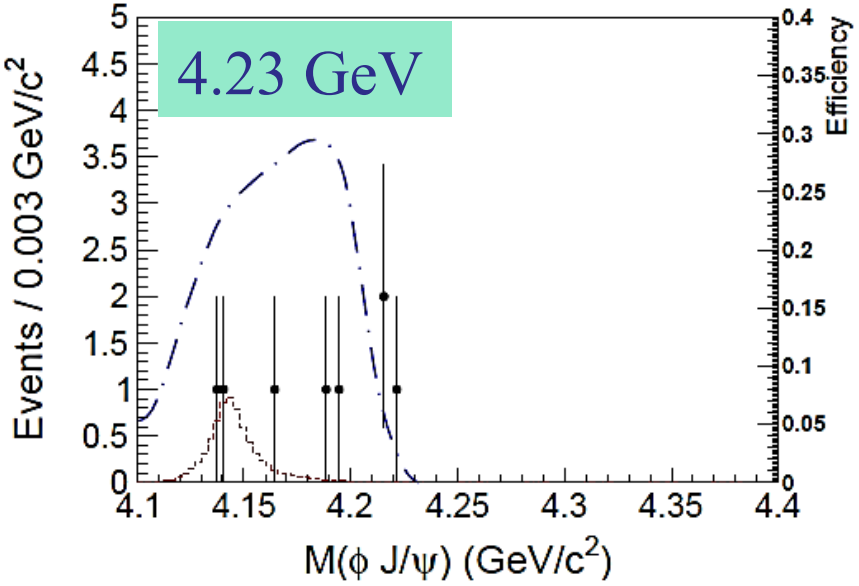


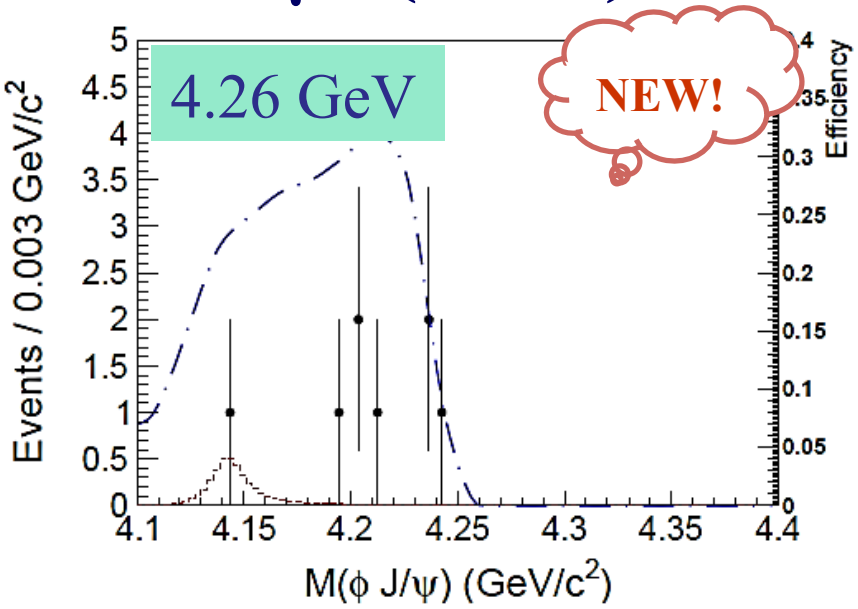
Observation of $e^+e^- \to \pi^+\pi^- h_c(1P)$

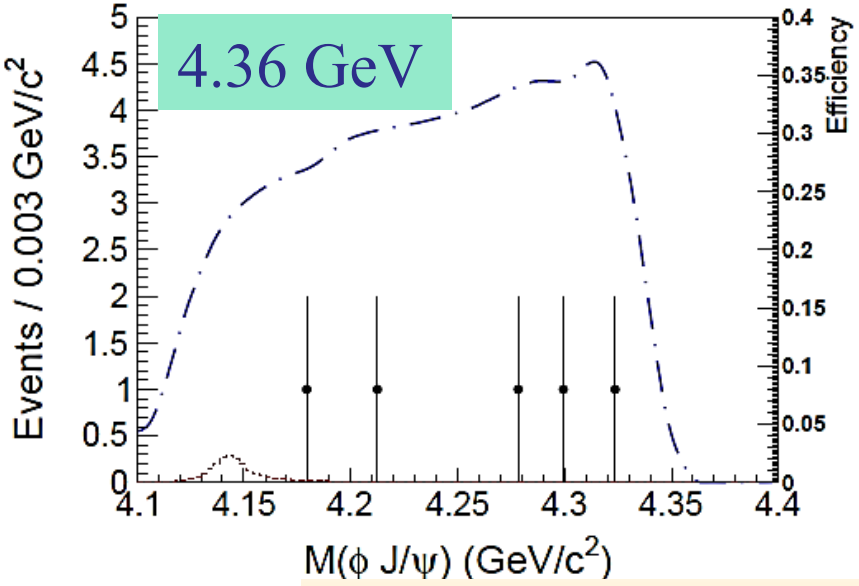


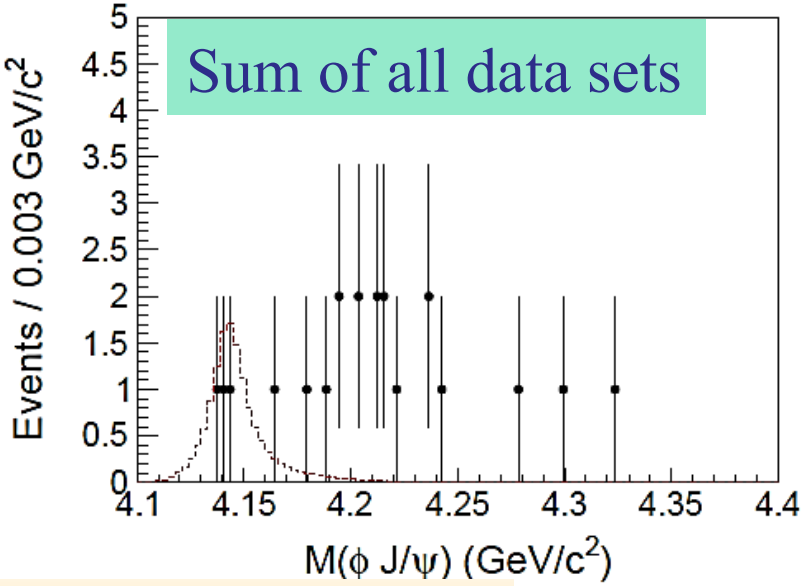
- $\sigma(e^+e^- \to \pi^+\pi^- h_c) \sim \sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ but line shape different
- Local maximum ~ 4.23 GeV
- Hint for a vector $c\bar{c}g$ hybrid? [PRD78, 056003 (Guo); 094504 (Dudek): $c\bar{c}$ in spin-singlet in hybrids!]

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



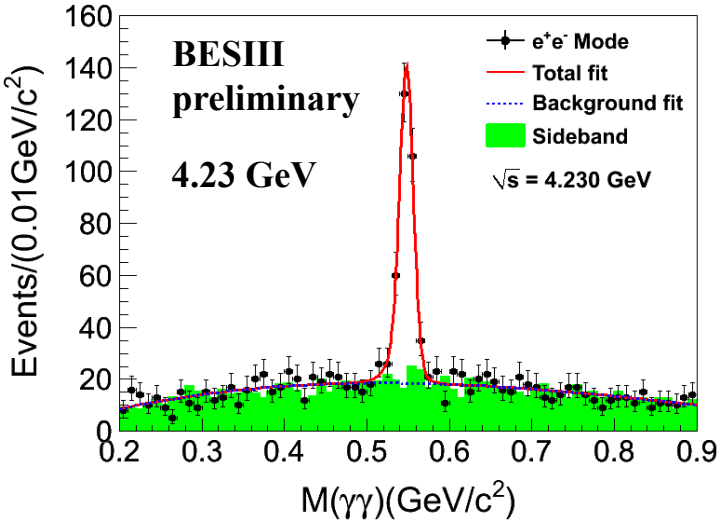


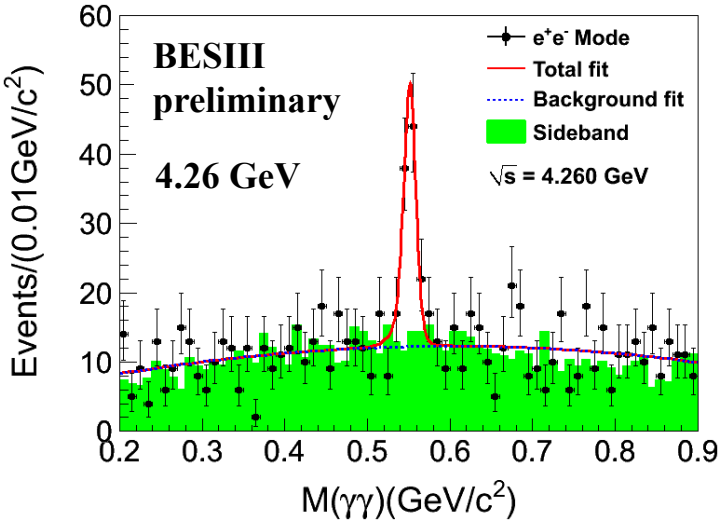


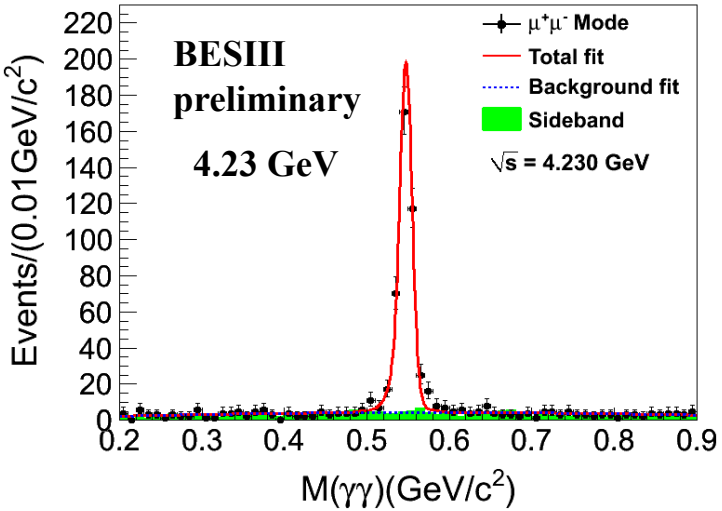


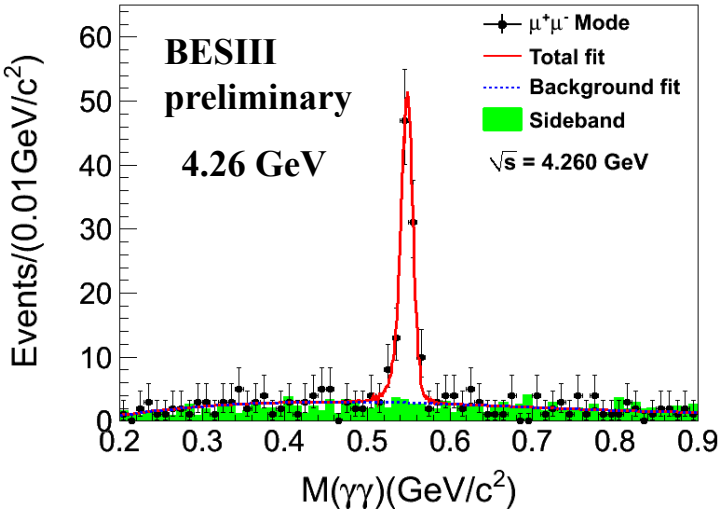
BESIII: arXiv:1412.1867, PRD (in press)

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!