Exotics at BESIII

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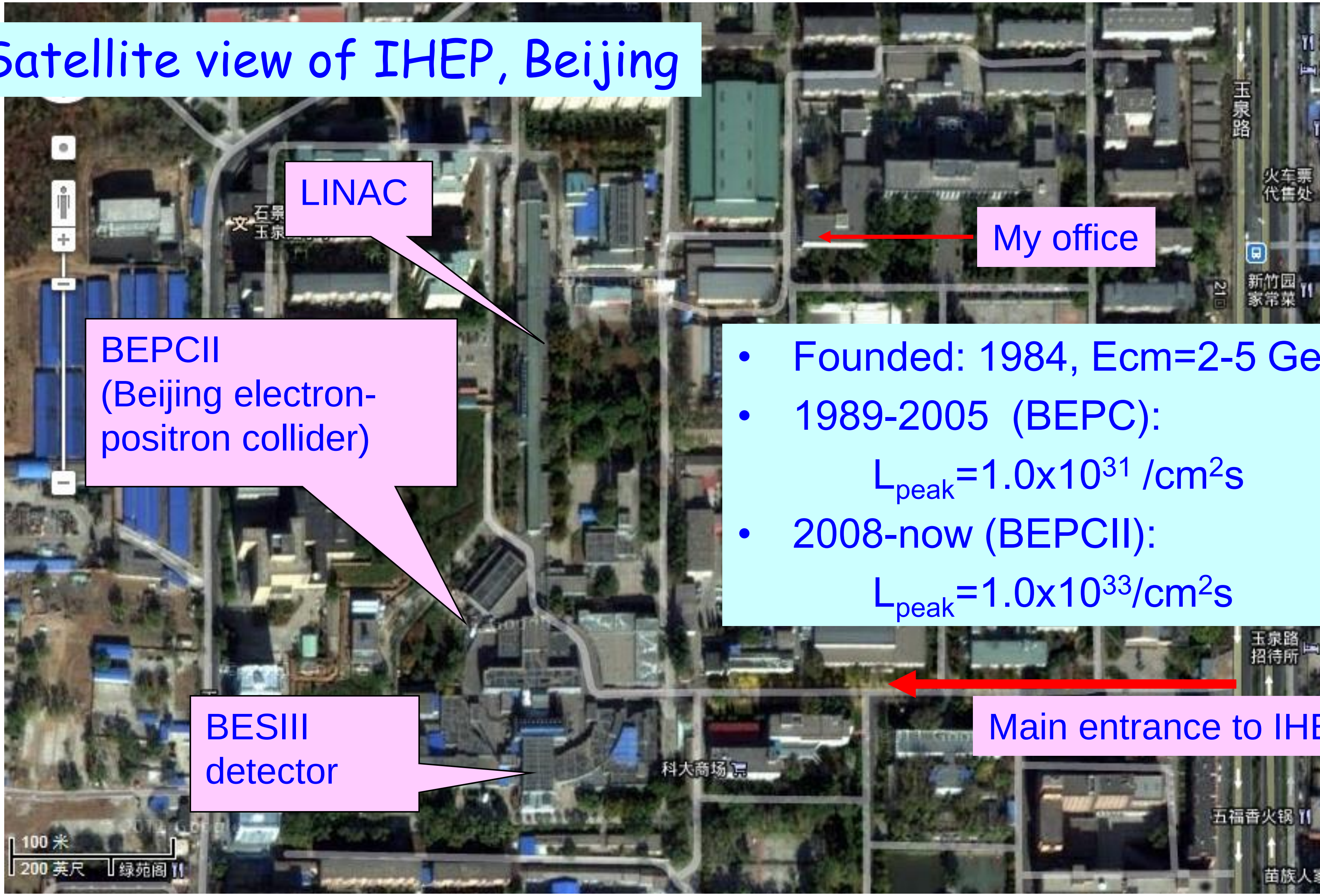
(for the BESIII Collaboration)

14th International Workshop on Meson Production, Properties and Interaction, KRAKÓW, POLAND
2nd - 7th June 2016

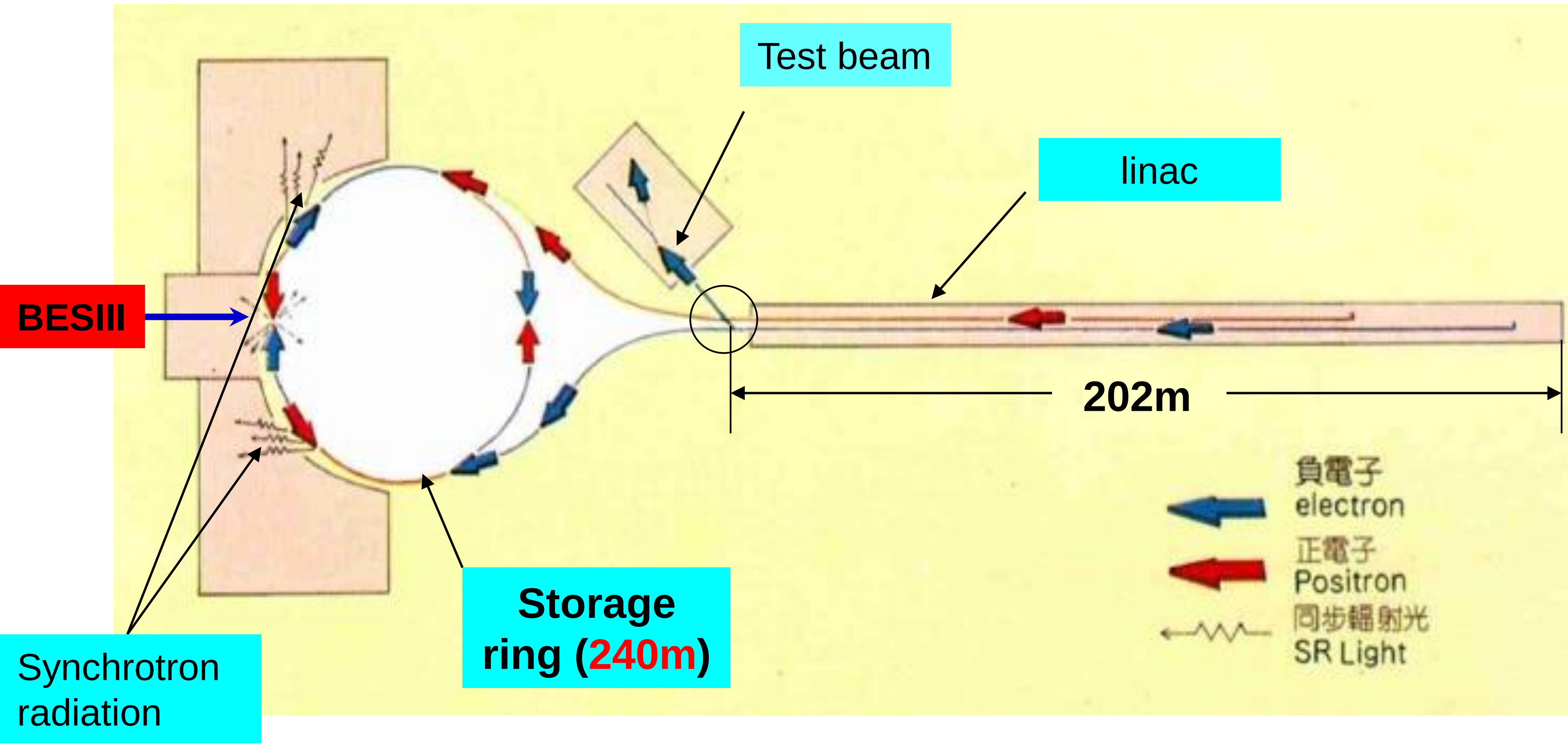
Beijing Electron Positron Collider (BEPC)

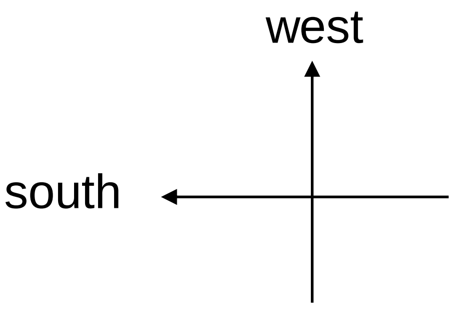
Satellite view of IHEP, Beijing



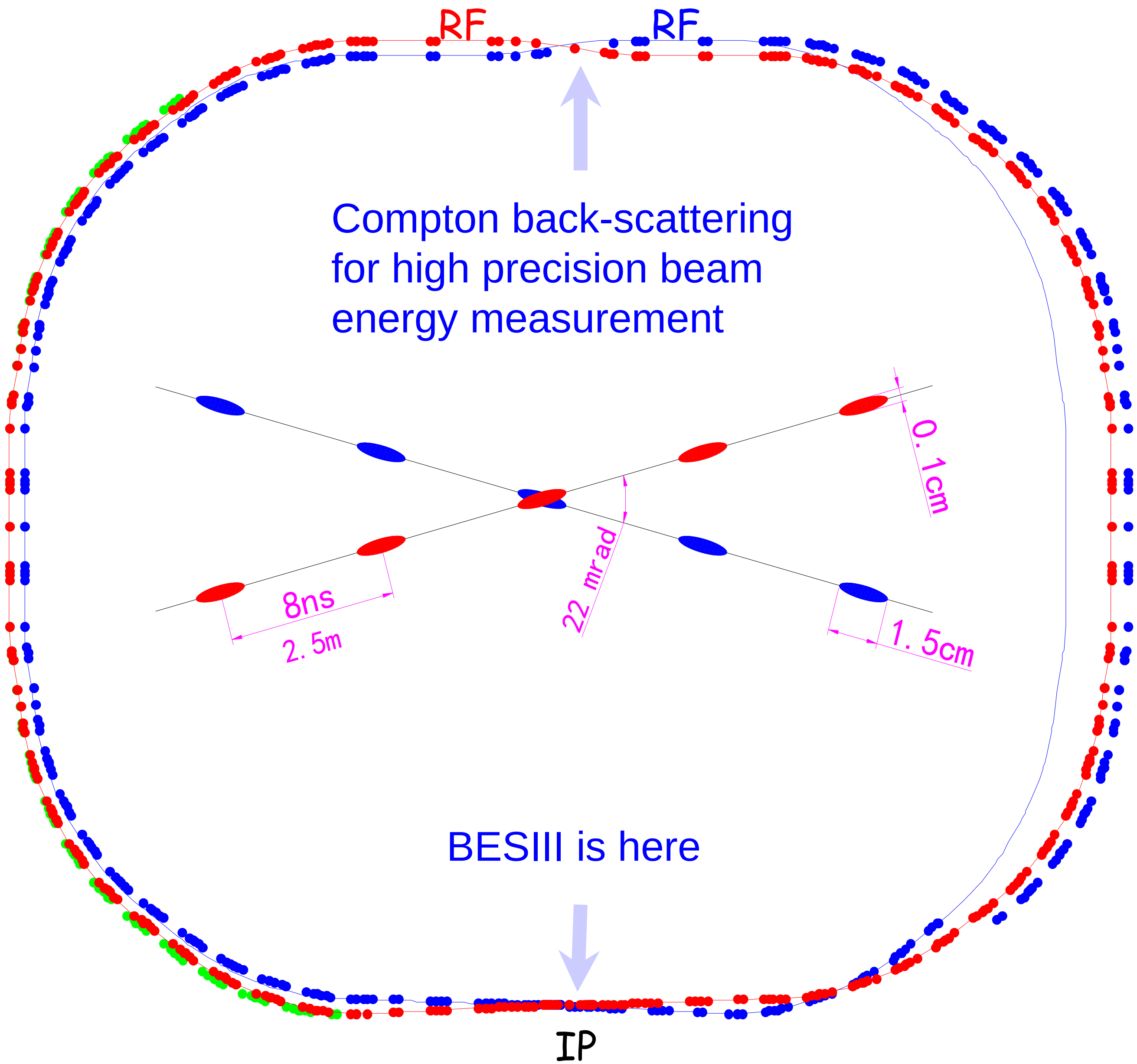
- Founded: 1984, Ecm=2-5 GeV
- 1989-2005 (BEPC):
  $L_{peak}=1.0\text{x}10^{31}$ /cm^{2}s
- 2008-now (BEPCII):
  $L_{peak}=1.0\text{x}10^{33}$/cm^{2}s

BEPCII sketch





BEPC II: a double-ring machine



Beam energy:
1-2.3 GeV

Luminosity:
1×10^{33} $cm^{-2}s^{-1}$
(**reached the designed target this year!**)

Optimum energy:
1.89 GeV

Energy spread:
5.16×10^{-4}

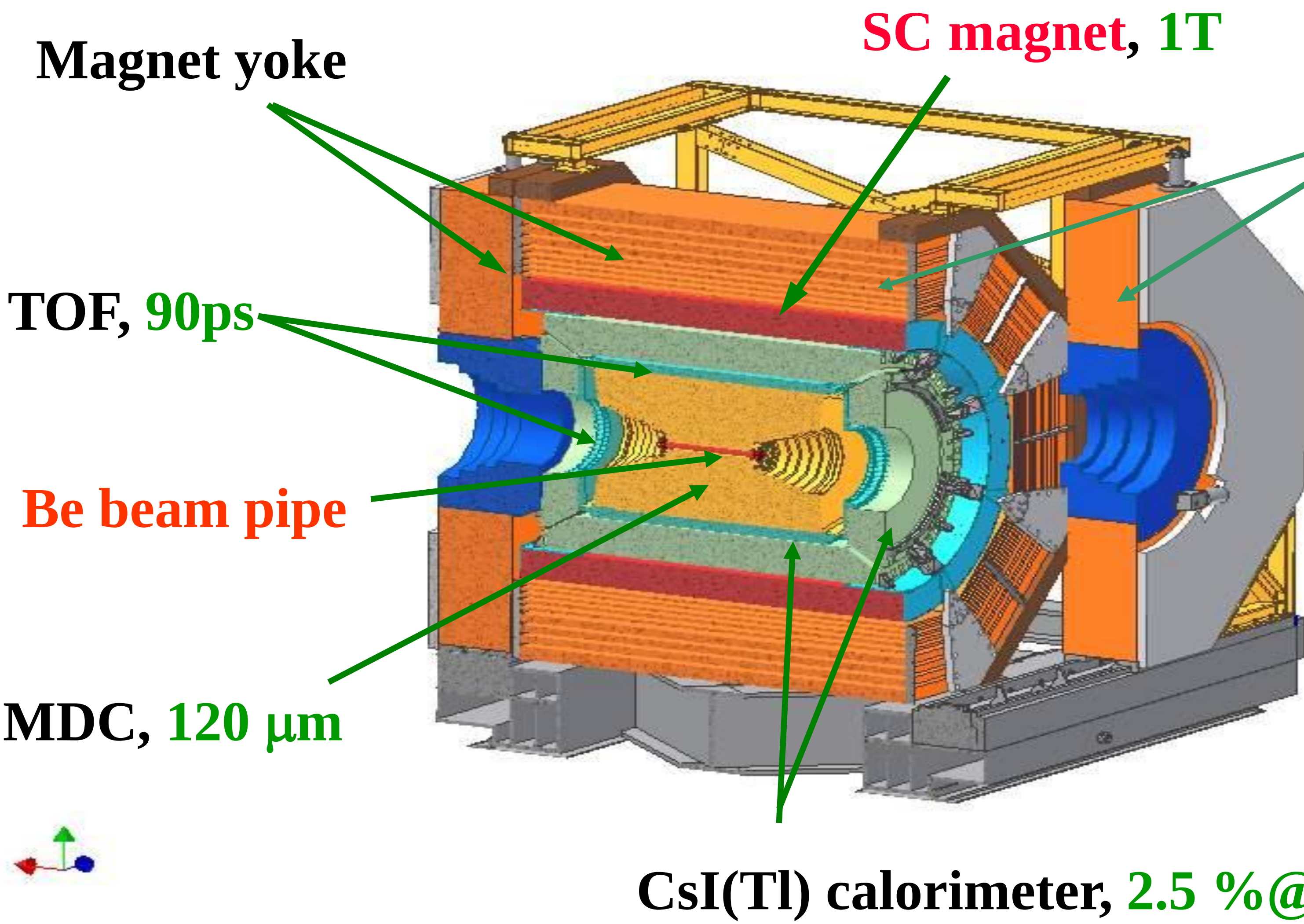
No. of bunches:
93

Bunch length:
1.5 cm

Total current:
0.91 A

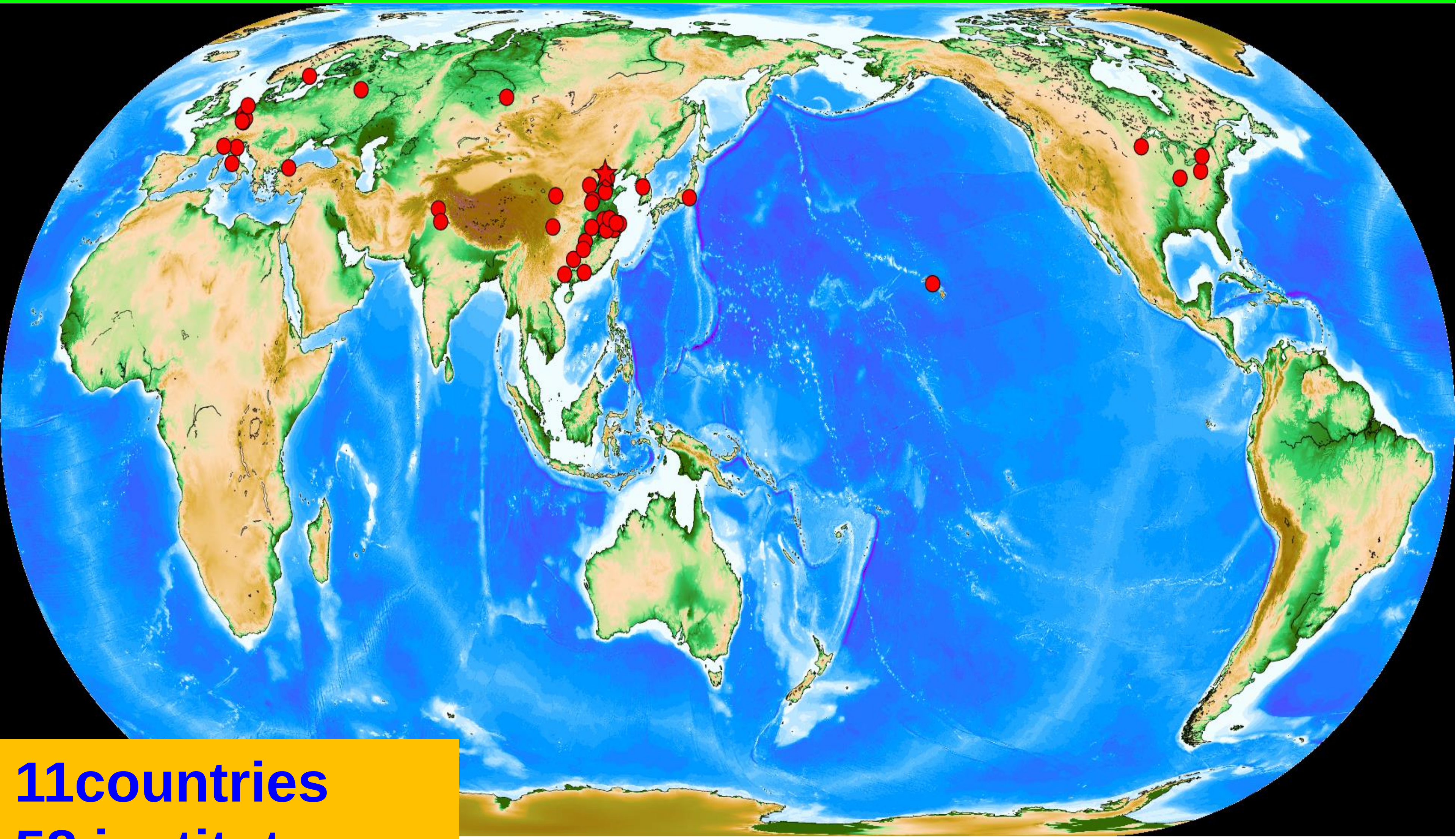
SR mode:
0.25A @ 2.5 GeV

The BESIII Detector



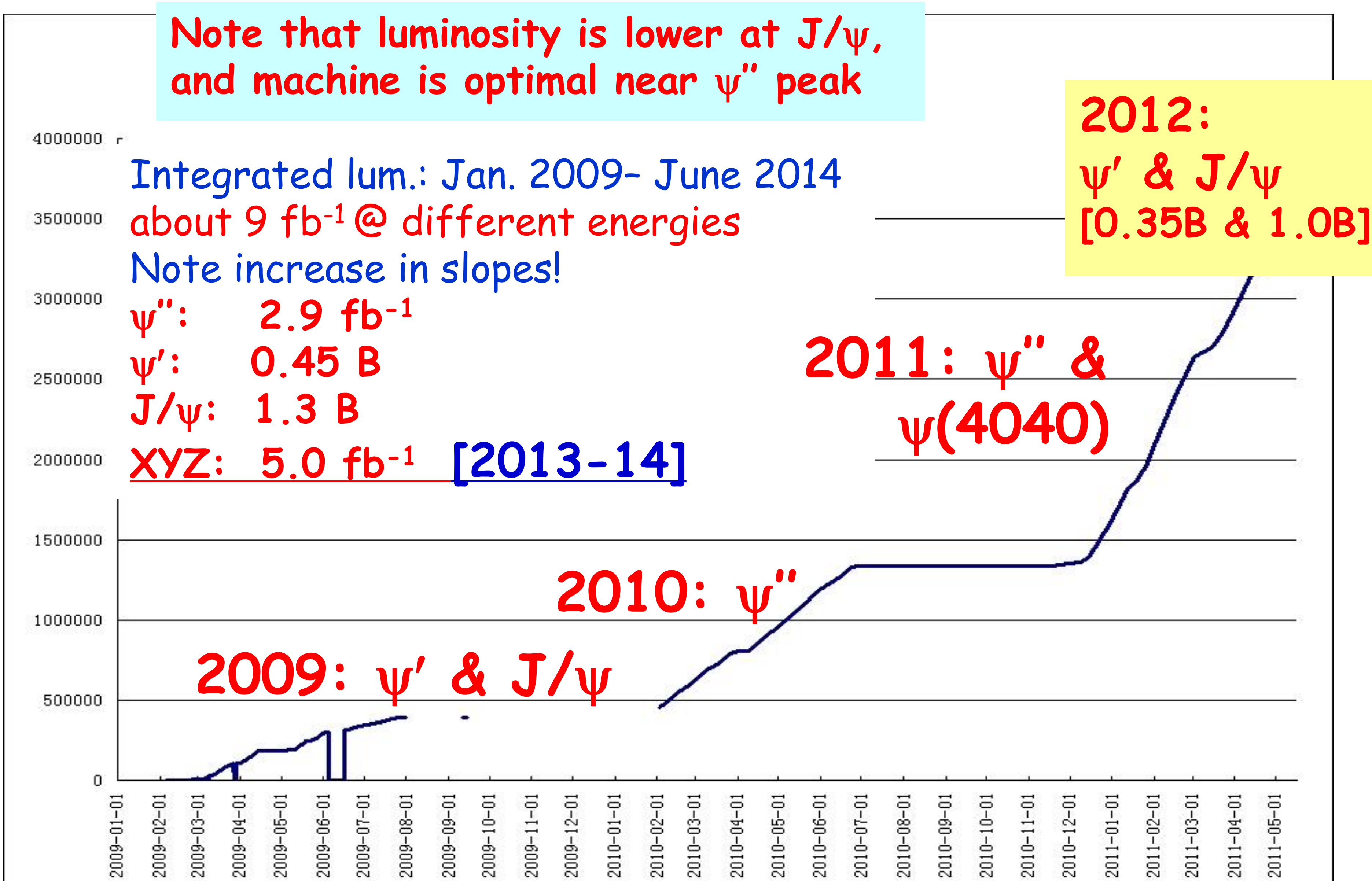
A total weight of 730t, ~40,000 readout channels, data rate 6,000Hz ~50Mb/s

The BESIII Collaboration

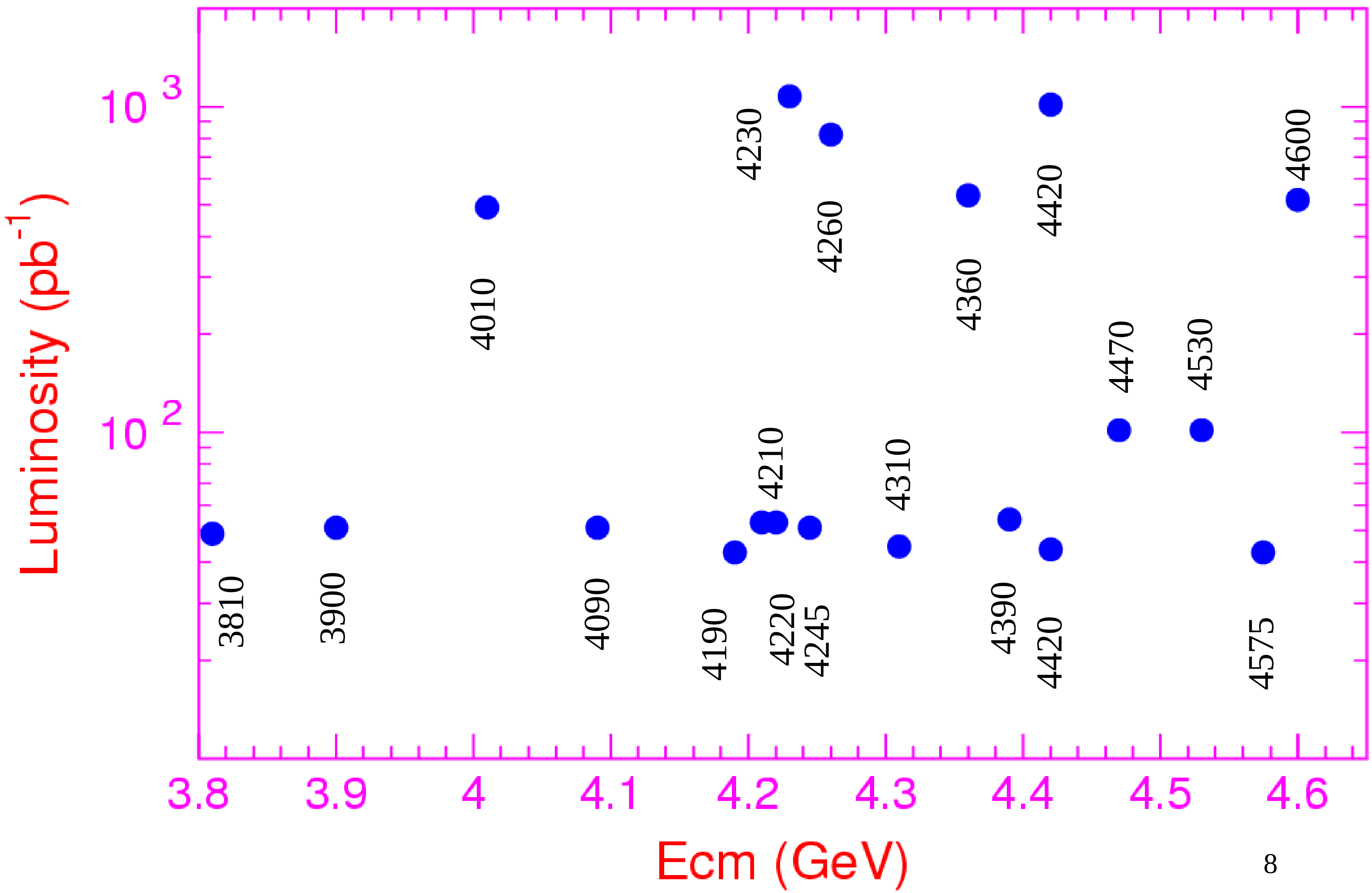


11countries
58 institutes
~450 members

BESIII data samples



BESIII data samples for XYZ study (5/fb)



Outline

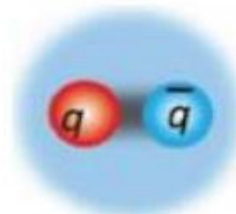
- Exotic states
- The X states
- The Y states
- The Z_c states
- Summary

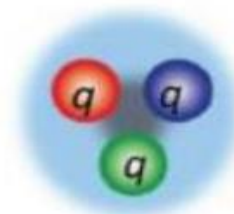
What's exotic state?

- Conventional hadrons consist of 2 or 3 quarks:

Naive Quark Model:

meson

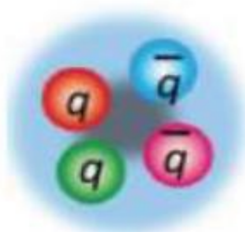




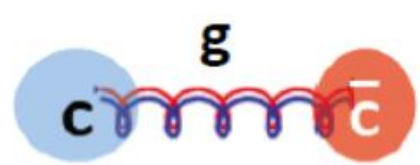
baryon

- QCD predicts the exotic state:

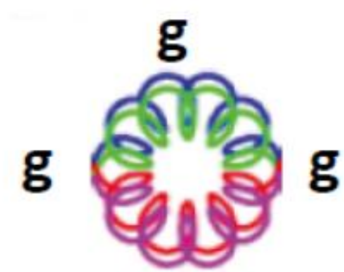
Multi-quark states: (N >= 4)



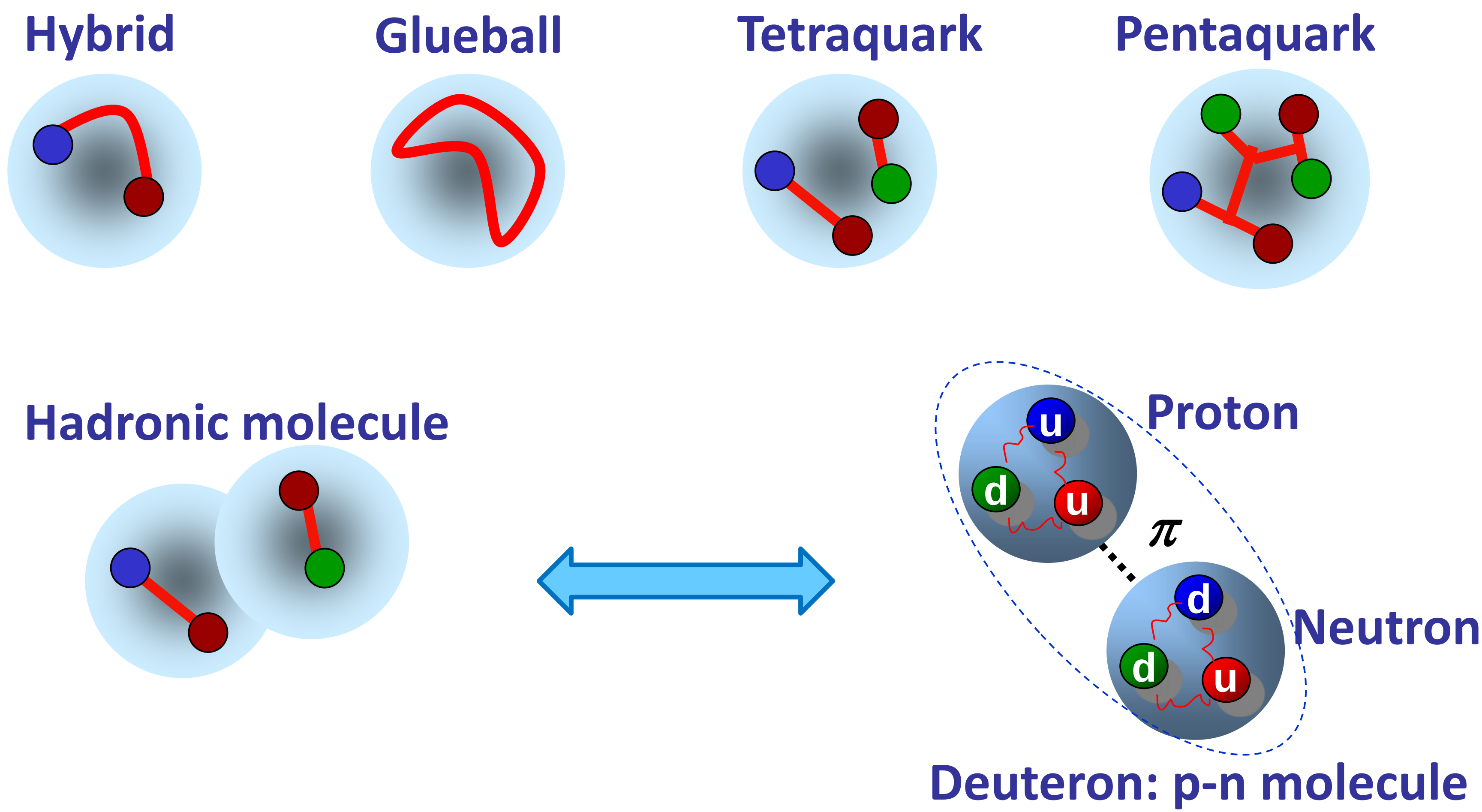
Hybrids: $q\bar{q}g$, qqqg…



Glueballs: gg, ggg

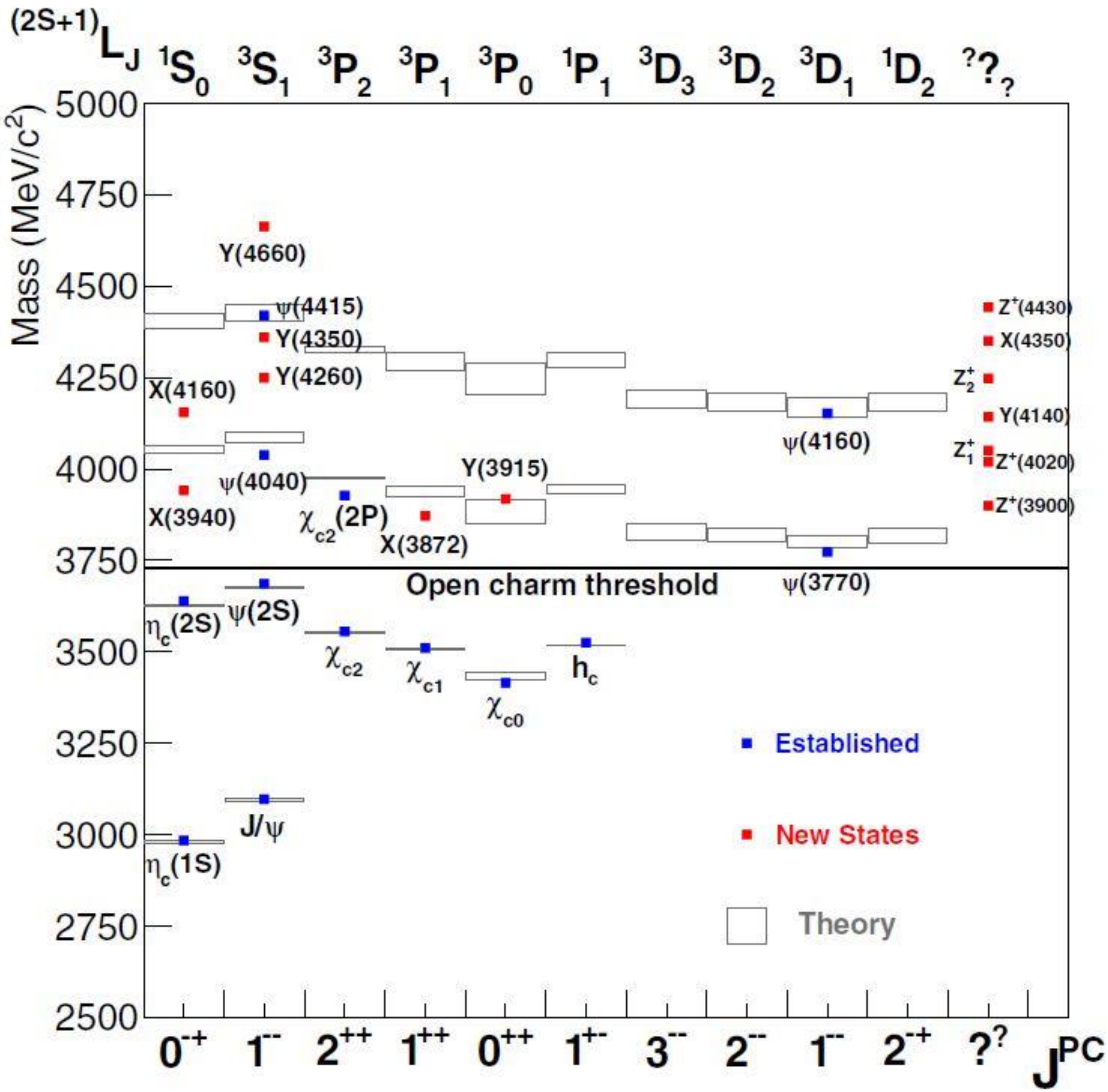


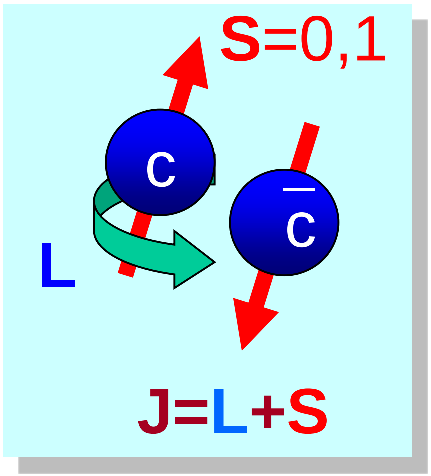
Multi-faces of QCD: Exotic hadrons



Evidence for QCD exotic states is a missing piece of knowledge about the Nature of strong QCD.

Charmonium Spectrum

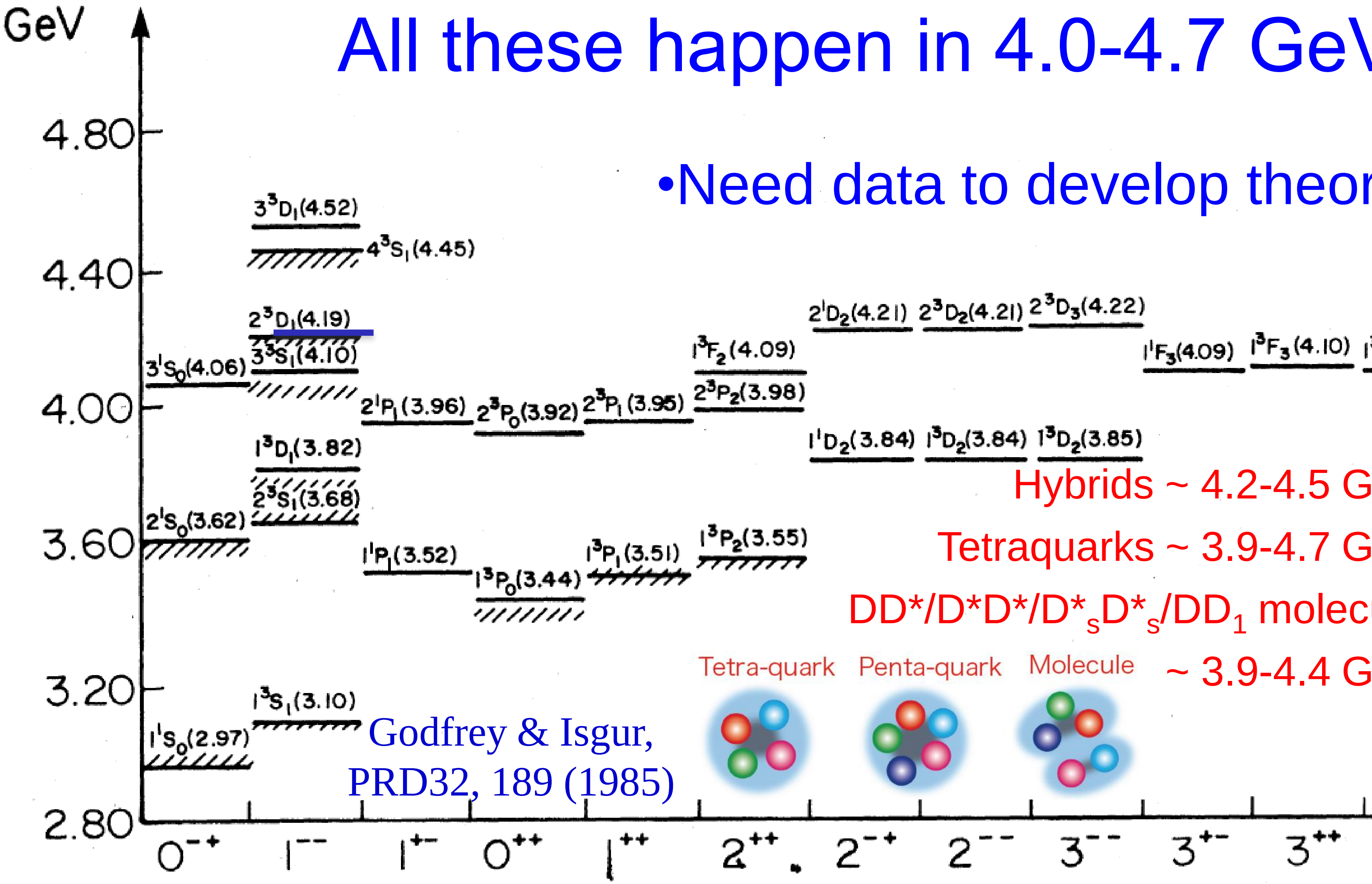




New charmonium-like states, i.e. “XYZ” states, are observed in experiment

All these happen in 4.0-4.7 GeV

•Need data to develop theory.



Hybrids ~ 4.2-4.5 GeV

Tetraquarks ~ 3.9-4.7 GeV

DD*/D*D*/D*$_s$D*$_s$/DD$_1$ molecule

~ 3.9-4.4 GeV

Godfrey & Isgur, PRD32, 189 (1985)

QCD just require hadrons to be colorless, and allow exotics.

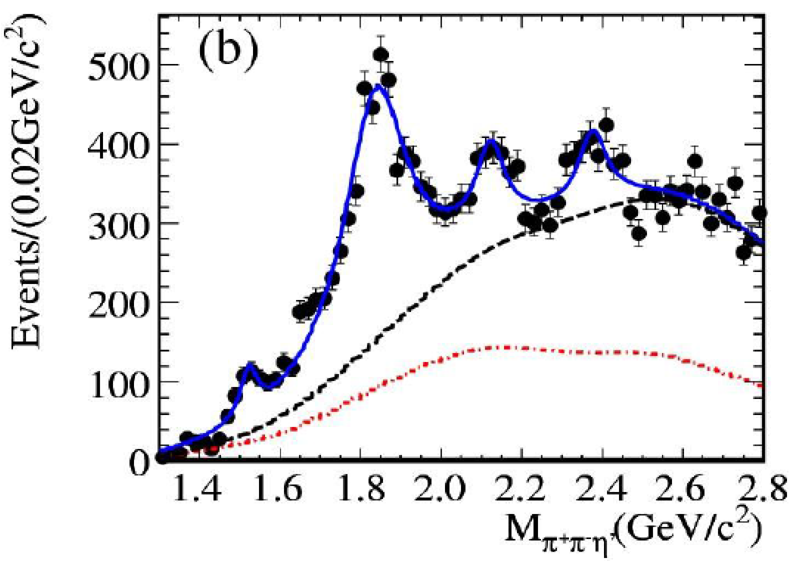
Such exotic states exist ?

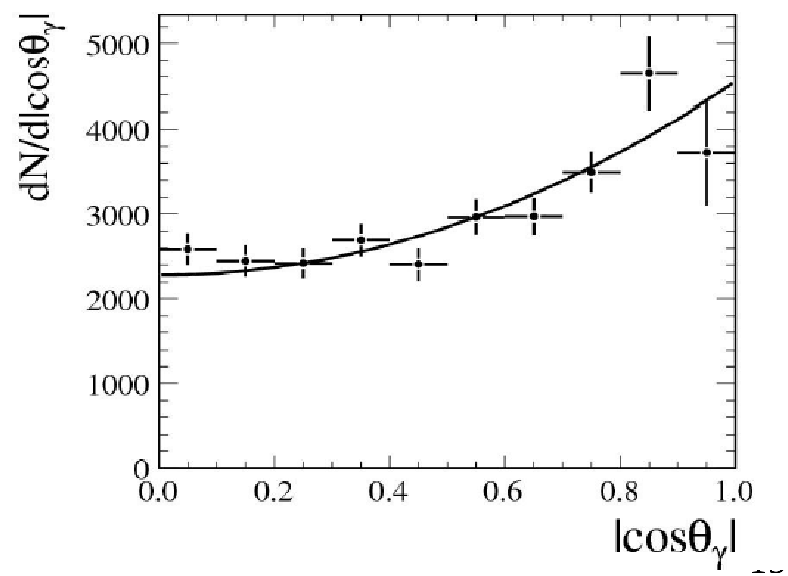
The X states

X(1835) review

- Observed in **$J/\psi \to \gamma\eta'\pi^+\pi^-$** at BESII in 2005
- Nature unclear, interpretations include $p\bar{p}$ bound state, excited η', glueball
- Confirmed in $J/\psi \to \gamma\eta'\pi^+\pi^-$ at BESIII
- Angular distribution consists with pseudoscalar, but other spin-parity assignments not excluded

225 million J/ψ events **PRL 106, 072002 (2011)**



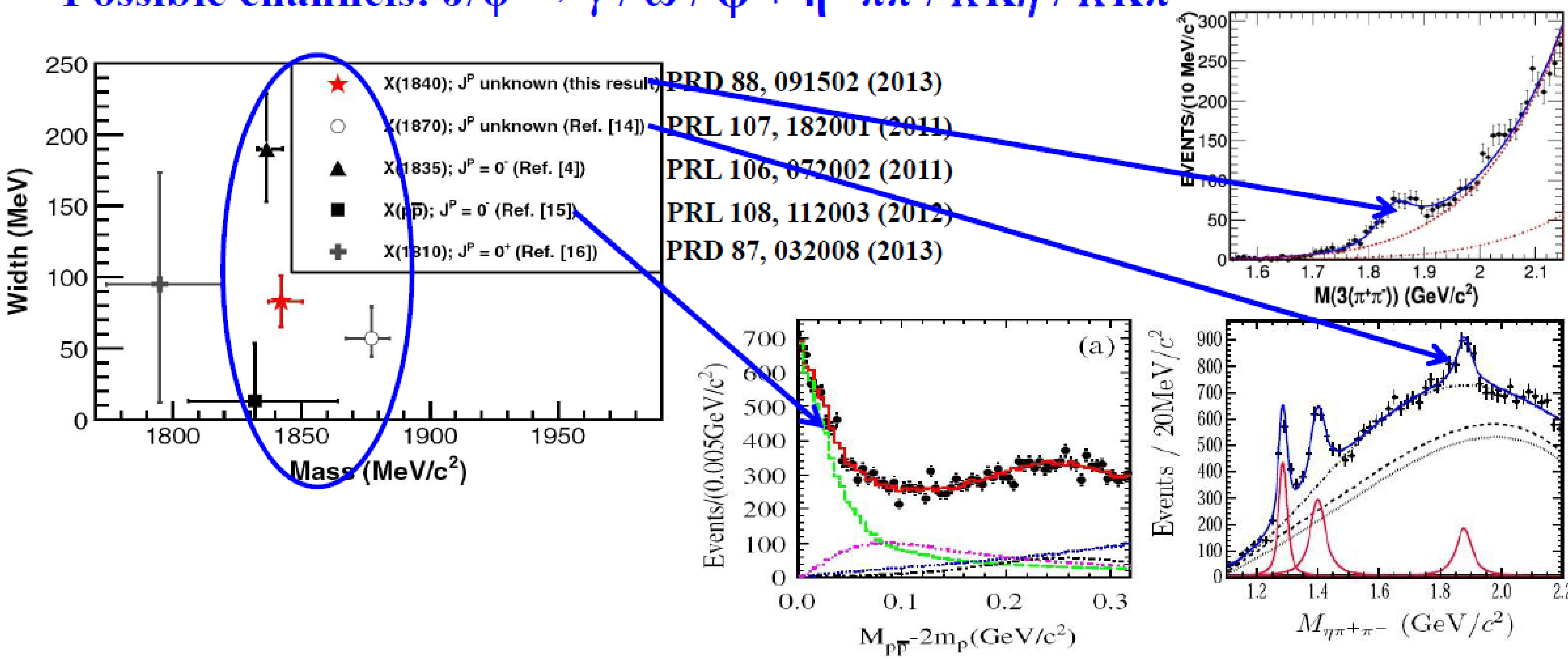


X(1835) review

- Simulated by $p\bar{p}$ threshold enhancement $X(p\bar{p})$ in $J/\psi \to \gamma p\bar{p}$
- Results in the observations of X(1870) in $J/\psi \to \omega(\eta\pi^+\pi^-)$ and X(1840) in $J/\psi \to \gamma 3(\pi^+\pi^-)$

- Are these states observed around 1.8 GeV/c² from the same origin?
- Further investigations on different production and decay mechanisms, precise physical parameters measurement are necessary

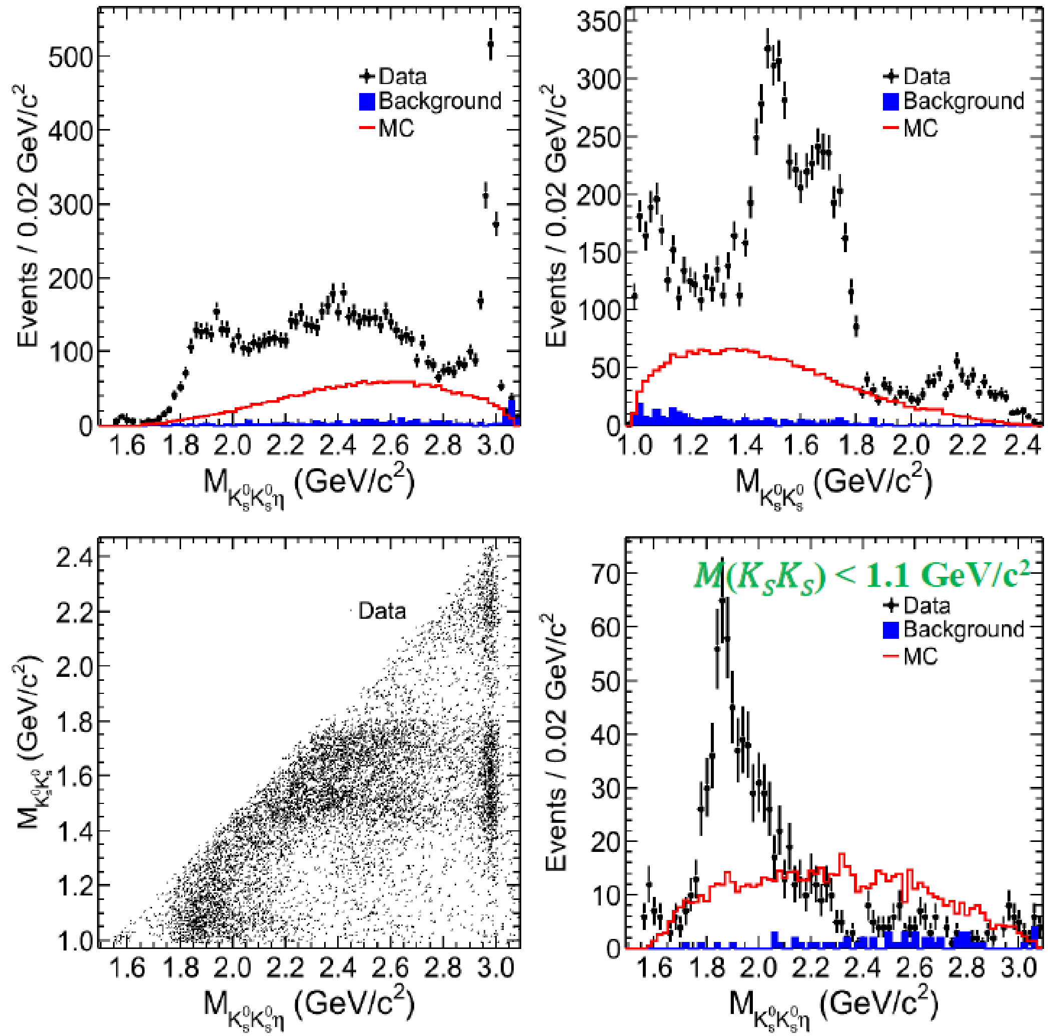
Possible channels: $J/\psi \to \gamma / \omega / \phi + \eta^{(\prime)}\pi\pi / K\bar{K}\eta / K\bar{K}\pi$



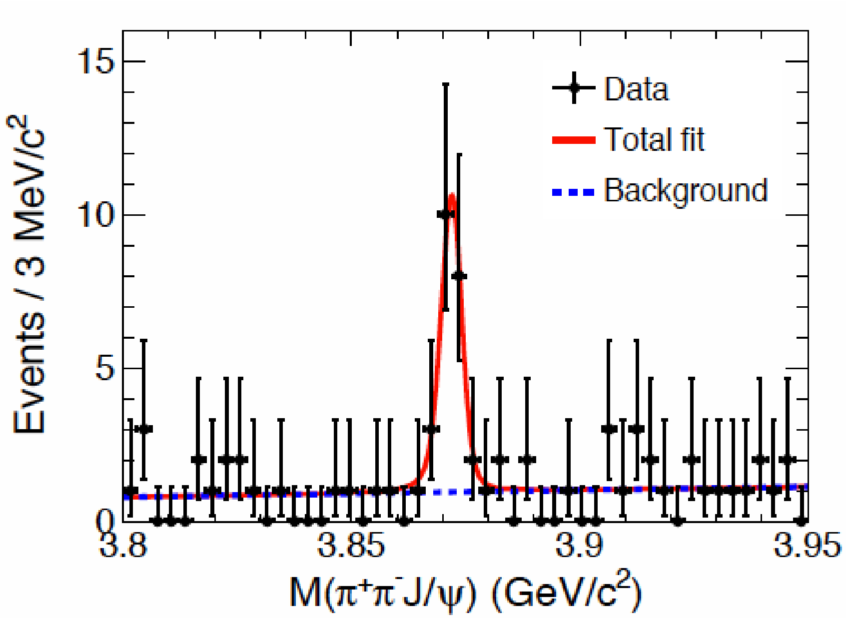
Observation of X(1835) in $J/\psi \to \gamma K_s K_s \eta$

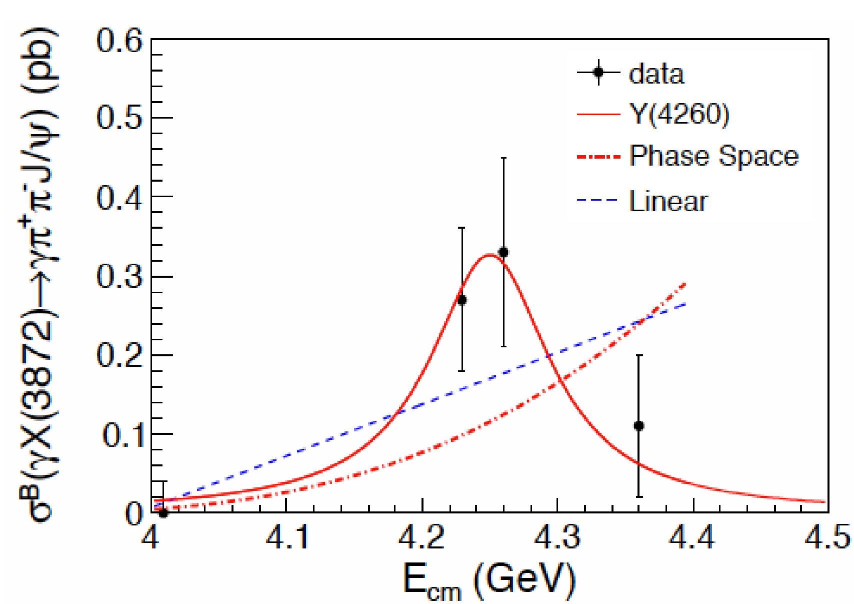
- Why this channel?
  - Unlike $J/\psi \to \gamma K^+K^-\eta$, no background from two potential but forbidden channels of $J/\psi \to K_S K_S \eta$ and $J/\psi \to K_S K_S \eta \pi^0$
- Clear structure on mass spectrum of $K_s K_s \eta$ around 1.85 GeV/c^2
- Strong correlation with the enhancement near $K_s K_s$ mass threshold (interpreted as $f_0(980)$)
- Structure is enhanced for $M(K_S K_S) < 1.1$ GeV/c^2

1.3 billion J/ψ events PRL 115, 091803 (2015)



$e^+e^- \to \gamma X(3872) \to \gamma \pi^+\pi^- J/\psi$



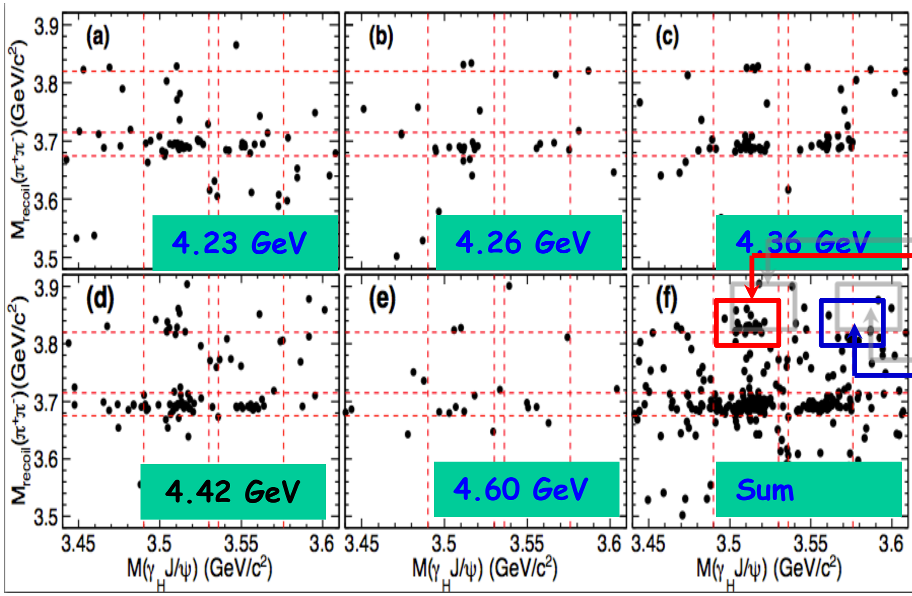


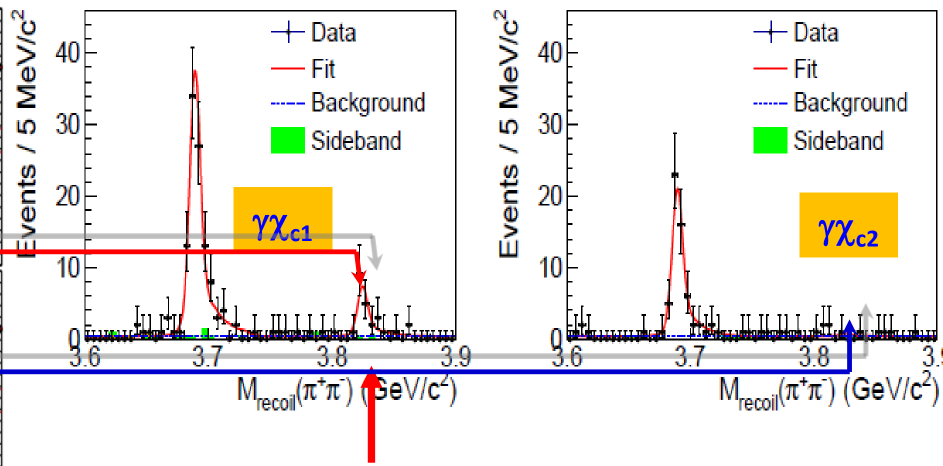
PRL 112 092001 (2014)

- **M = (3871.9±0.7±0.2) MeV, Γ<2.4 MeV, Significance:6.3σ**
- **production in *Y*(4260) decay suggestive, but not conclusive**

$$\frac{\mathcal{B}[Y(4260)\to\gamma X(3872)]}{\mathcal{B}(Y(4260)\to\pi^+\pi^- J/\psi)} = 0.1$$

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

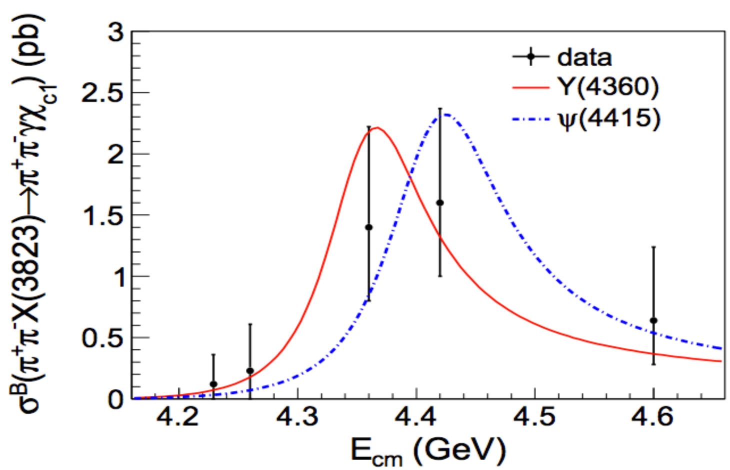




Fit: M=3821.7±1.3±0.7 MeV;

Significance: 6.7σ, observation

Phys. Rev. Lett. 91, 112015 (2015)



- Whether from Y(4360) or y(4415) decay
- Favor the Y(4360) ? [M. B. Voloshin, PRD 91, 114029 (2015)]
- Y(4360)→$\pi^+\pi^-$X(3823)? New decay model of Y(4360)?

Good candidate for $\psi(1^3D_2)$

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

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

The Y states

(vectors)

Study of $J/\psi \rightarrow \eta\phi\pi^+\pi^-$

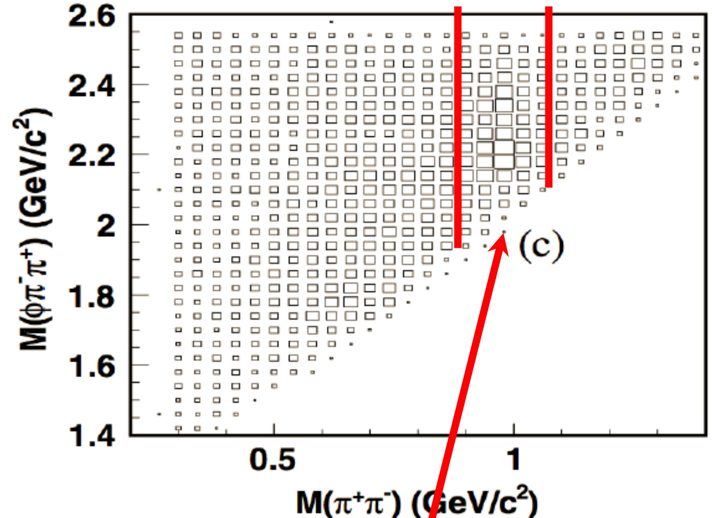
PRD 91,052017 (2015)

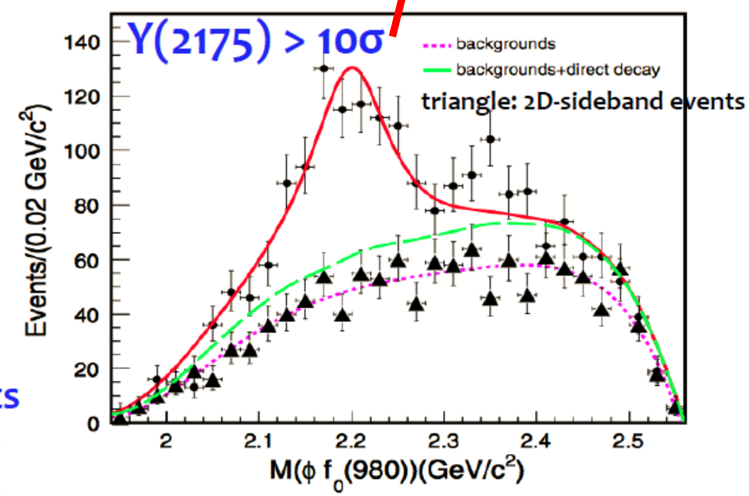
based on 0.225 billion J/ψ events

- Y(2175) was observed by BABAR, then confirmed by BESII, BELLE and BABAR;

- Different interpretations have been proposed:
  - $s\bar{s}$-gluon hybrid? excited ϕ state?
  - tetraquark state? $\Lambda\bar{\Lambda}$ bound state?
  - an ordinary $\phi f_0(980)$ resonance produced by FSI?

- Confirmation and study of the Y(2175) with a large data sample is necessary for clarifying its nature.





Product branching fraction of

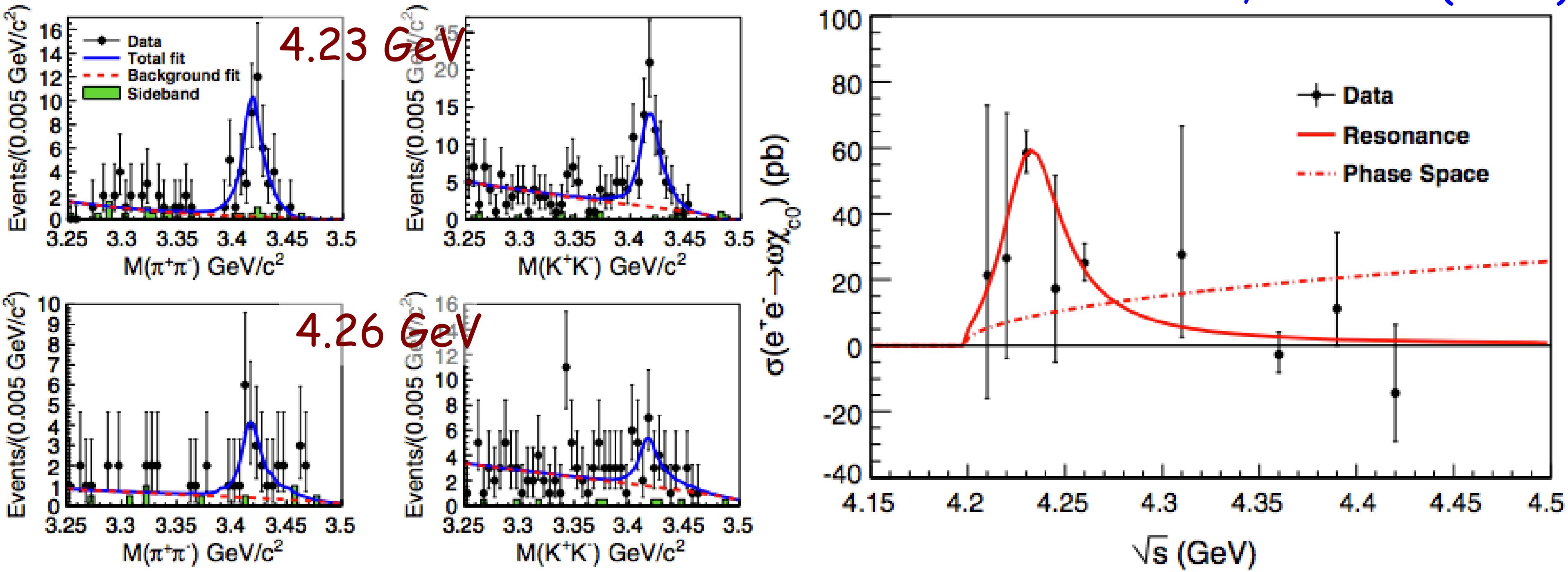
$J/\psi \rightarrow \eta Y(2175)$, $Y(2175) \rightarrow \phi f_0(980)$, $f_0(980) \rightarrow \pi\pi$ is measured to be: $(1.20 \pm 0.14 \pm 0.37) \times 10^{-4}$

Mass and width are in agreement with previous measurements

Collaboration	Process	M (MeV/c^2)	Γ (MeV)
BABAR [2]	$e^+e^- \rightarrow \phi f_0$ (ISR)	$2175 \pm 10 \pm 15$	$58 \pm 16 \pm 20$
BESII [3]	$J/\psi \rightarrow \eta\phi f_0(980)$	$2186 \pm 10 \pm 6$	$65 \pm 23 \pm 17$
BELLE [4]	$e^+e^- \rightarrow \phi f_0$ (ISR)	$2079 \pm 13^{+79}_{-28}$	$192 \pm 23^{+25}_{-61}$
BABAR (updated) [5]	$e^+e^- \rightarrow \phi f_0$ (ISR)	$2172 \pm 10 \pm 8$	$96 \pm 19 \pm 12$
BESIII	$J/\psi \rightarrow \eta\phi f_0(980)$	$2200 \pm 6 \pm 5$	$104 \pm 15 \pm 15$

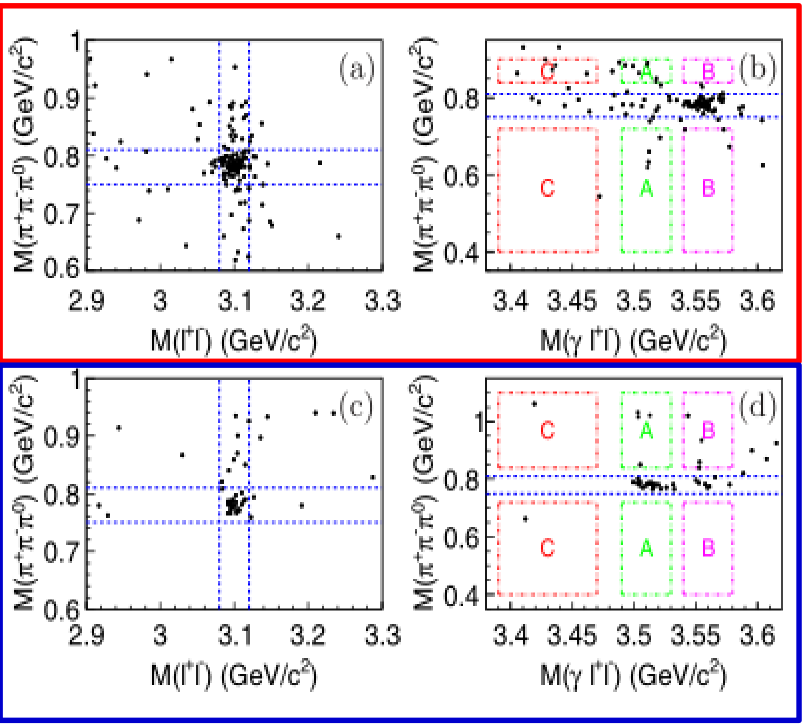
$e^+e^- \rightarrow \omega\chi_{c0}$ [Y(4230)?]

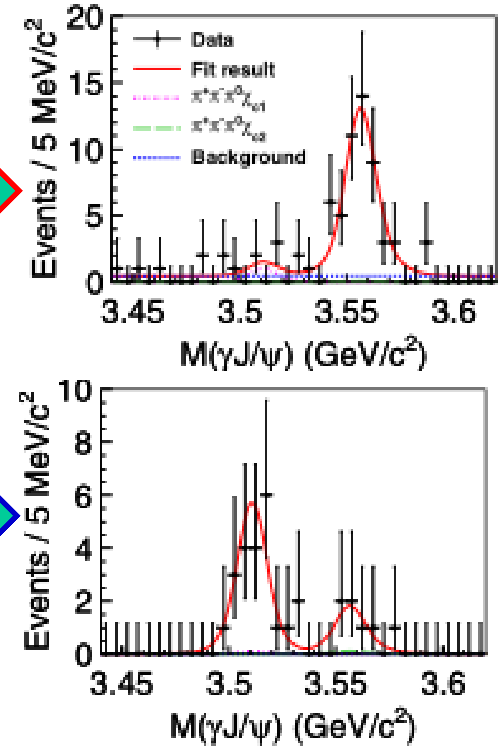
PRL114, 092003 (2015)

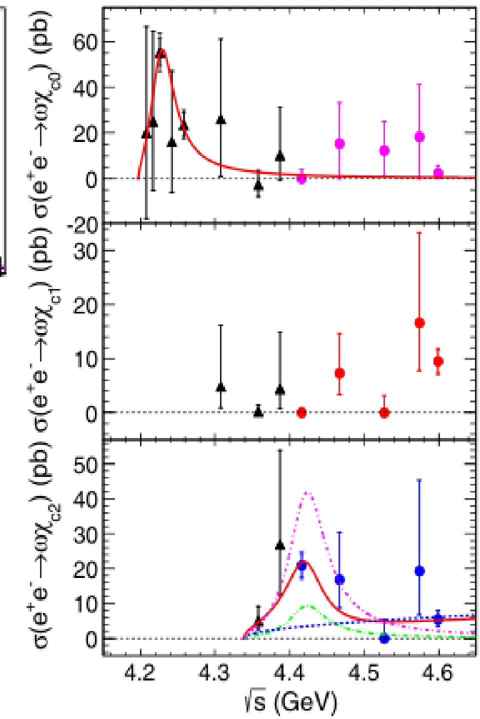


- Using scan data over 4.21 and 4.42 GeV, e+e-$\rightarrow\omega\chi_{c0}$ are significant @ E_{cm}=4.23 & 4.26 GeV.
- Cross section peak near 4.23 GeV, fit with BW yields Mass=(4230±8±6) MeV, Width=(38±12±2) MeV.
- A new structure? Tetraquark [PRD 91, 117501 (2015)]? Threshold effect?

$e^+e^- \to \omega\chi_{c1,2}$ ($\sqrt{s}$=4.42, 4.6 GeV)







- Clear χ_{c2},χ_{c1} are observed at $\sqrt{s}$=4.42, 4.6 GeV, respectively
- The Born cross section have been measured for $e^+e^- \to \omega\chi_{c1,2}$
- $\sigma(e^+e^- \to \omega\chi_{c2})$ is fitted with the coherent sum of the $\psi(4415)$ BW function and a phase-space term. Two solutions are obtained: ······ constructive, --- destructive

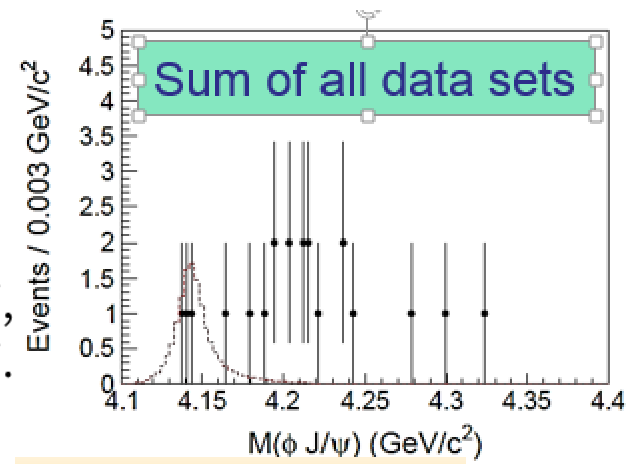
Phys. Rev. D 93, 011102 (2016)

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

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

(GeV/)	Luminosity (pb^{-1})	N^{obs}	cross section (pb)
4.23	1094	0.840	<0.35
4.26	827	0.847	<0.28
4.36	545	0.944	<0.33

Systematic uncertainty is considered.



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

$$\sigma^B\left(e^+e^- \to \gamma X(3872)\right) \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$$
$$= 0.27 \pm 0.09(\text{stat}) \pm 0.02(\text{syst}) \text{ pb at } \sqrt{s} = 4.23 \text{ GeV},$$
$$= 0.33 \pm 0.12(\text{stat}) \pm 0.02(\text{syst}) \text{ pb at } \sqrt{s} = 4.26 \text{ GeV}.$$

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.

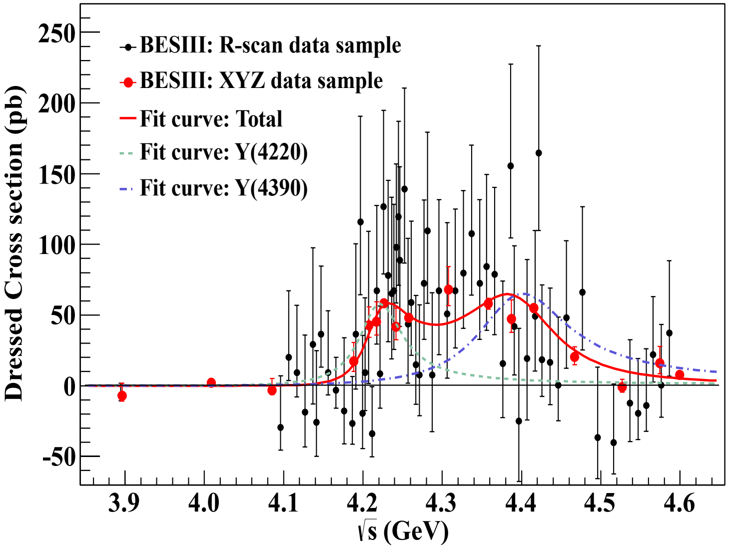
$$\frac{\sigma^B(e^+e^- \to \gamma Y(4140))}{\sigma(e^+e^- \to \gamma X(3872))} \leq 0.1 \text{ at } \sqrt{s}=4.23 \text{ and } 4.26 \text{ GeV}.$$

Phys. Rev. D91, 032002 (2015)

$e^+e^- \to \pi^+\pi^- h_c$ line-shape

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

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



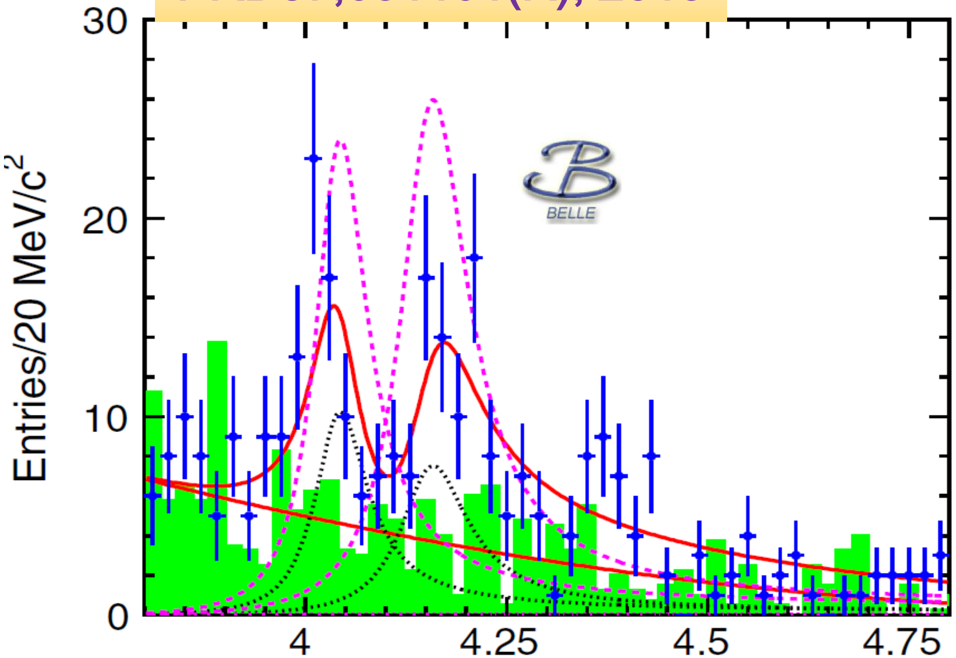
significance of two structures assumption over one structure

> 10.0σ

	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

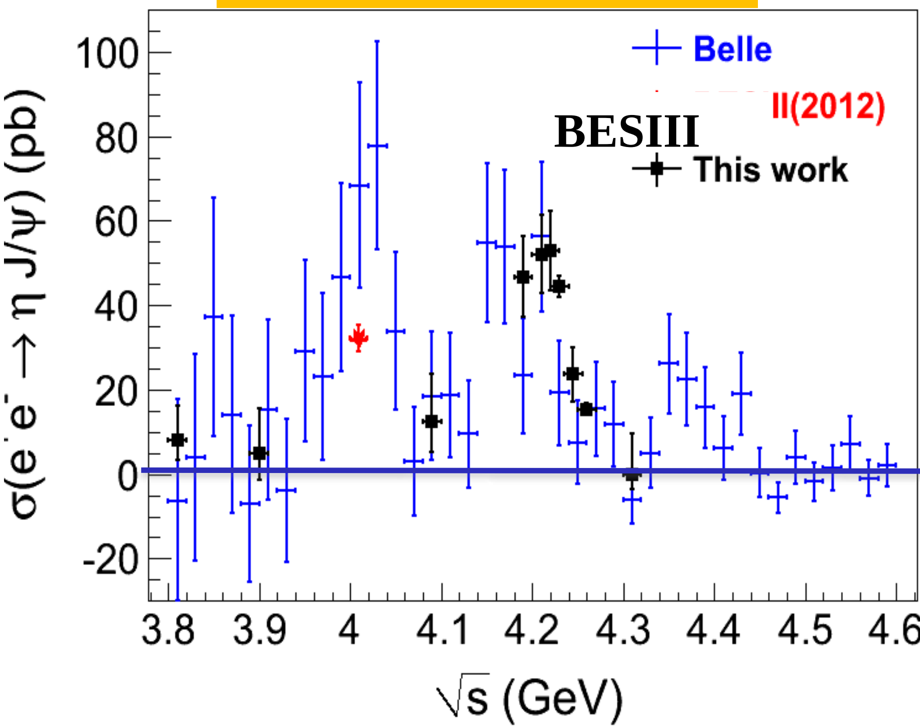
Observation of $e^+e^- \rightarrow \eta J/\psi$

PRD87,051101(R), 2013



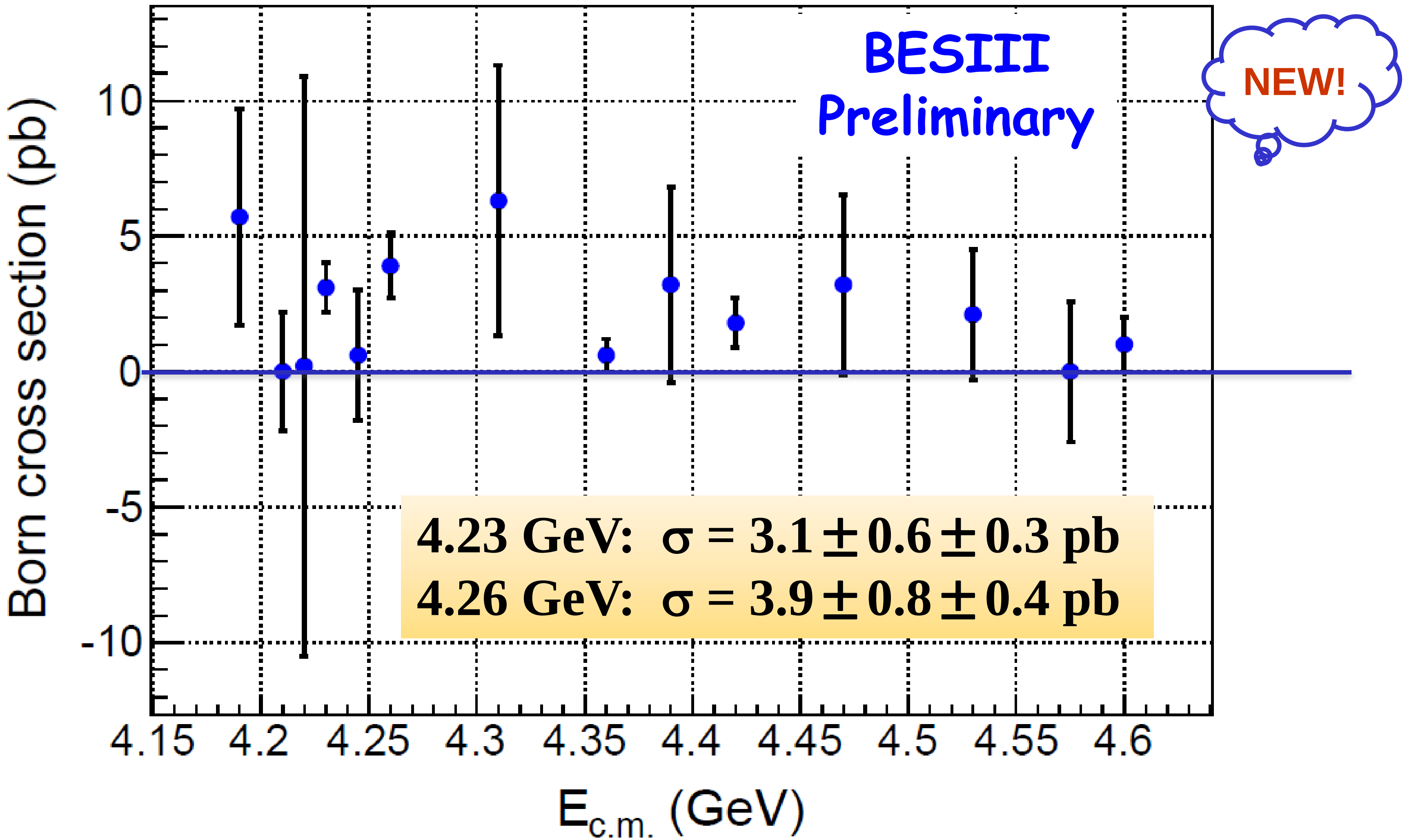
Ψ(4040) and Ψ(4160) with interference

PRD 91,112005 (2015)



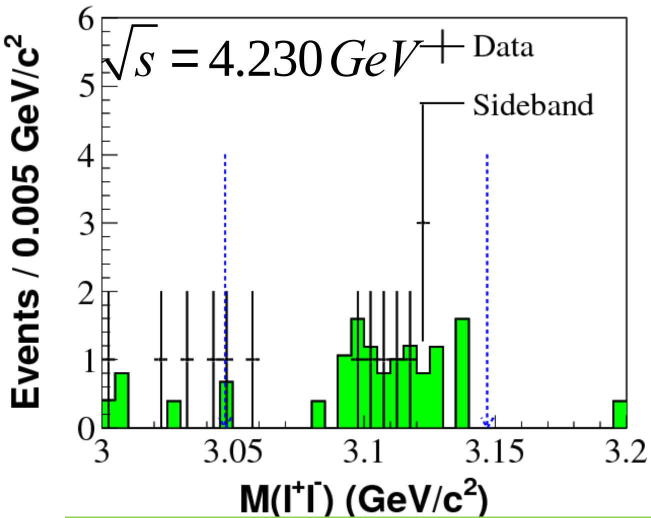
- Agree with previous results with improved precision
- The cross section peaks around 4.2 GeV
- Analysis of high energy points underway at BESIII

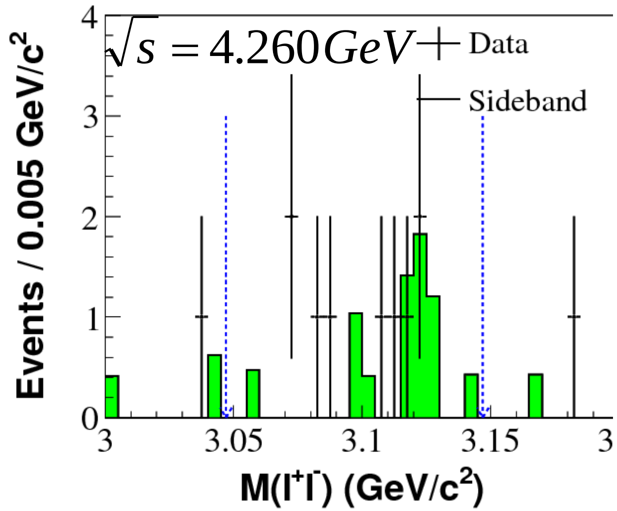
Observation of $e^+e^- \to \eta' J/\psi$

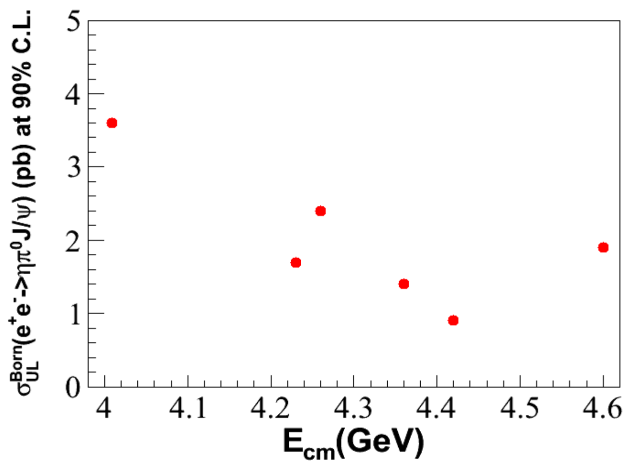


- First observation, cannot tell the line shape due to statistics

Isospin violation Y(4260)→$\pi^0\eta J/\psi$





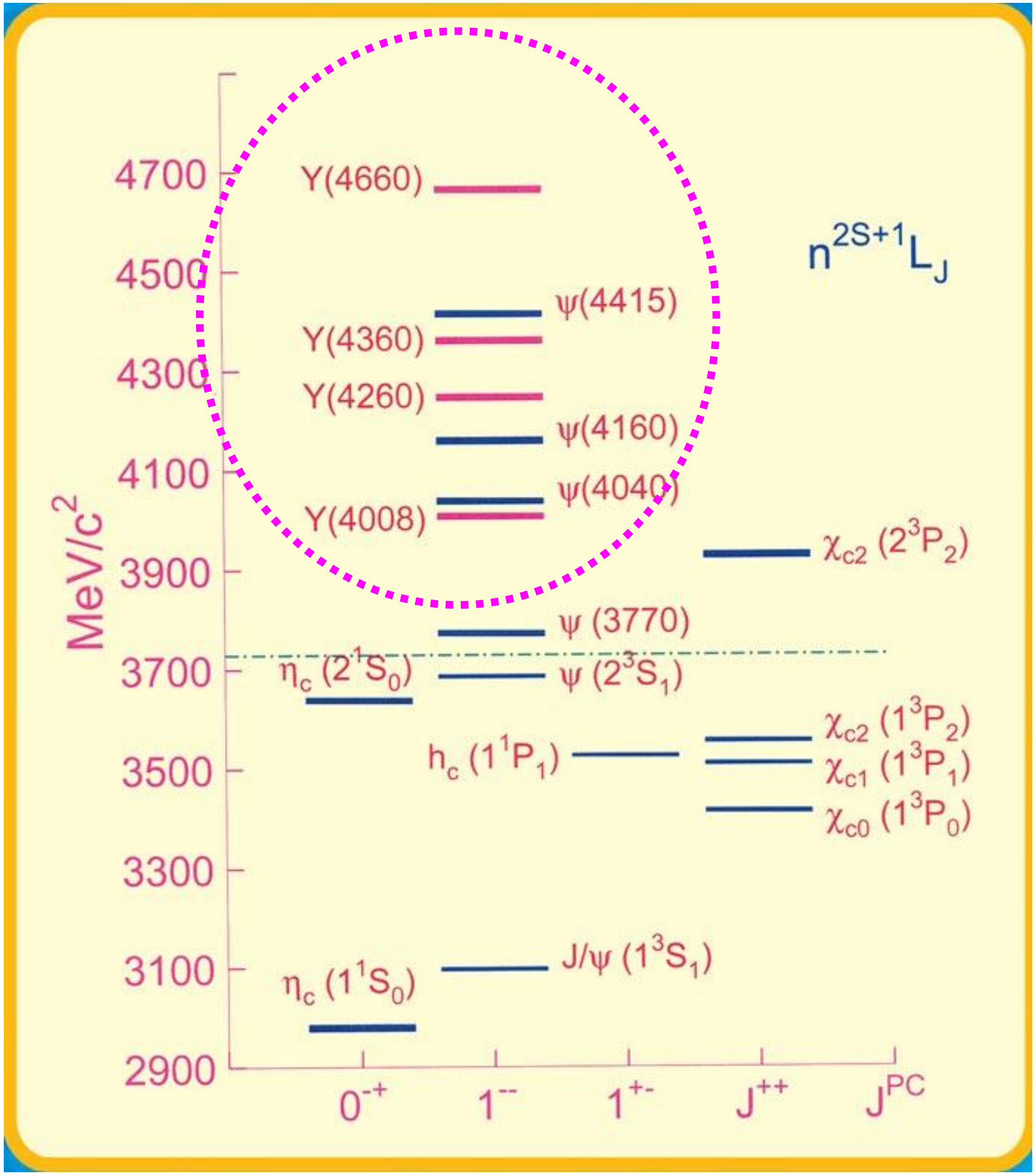


No significant signal observed with current BESIII data !
Can not provide effective constraint to models…

Phys. Rev. D92, 012008 (2015)

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$(1+\delta^r)$	$(1+\delta^v)$	$(\epsilon^{ee}Br^{ee} + \epsilon^{\mu\mu}Br^{\mu\mu})$ (%)	N^{obs}	N^{bkg}	N^{up}	σ^{Born}_{UL} (pb)
4.009	482	0.838	1.044	$2.1 \pm 0.1(sys.)$	5	1	598.1	3.6
4.230	1007	0.844	1.056	$2.2 \pm 0.1(sys.)$	12	11	592.9	1.7
4.260	804	0.847	1.054	$2.2 \pm 0.1(sys.)$	12	8	654.1	2.4
4.360	523	0.942	1.051	$2.2 \pm 0.1(sys.)$	5	4	283.2	1.4
4.420	1023	0.951	1.053	$2.3 \pm 0.1(sys.)$	5	6	342.7	0.9
4.600	567	0.965	1.055	$2.4 \pm 0.1(sys.)$	6	3	418.4	1.9

What are the Y states?

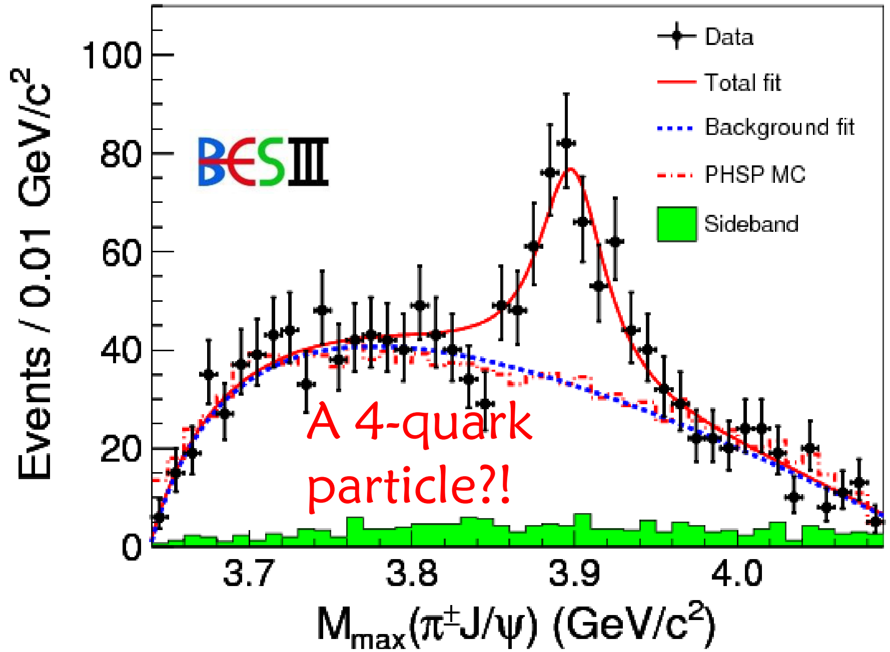


- Between 4 and 4.7 GeV, at most 5 states expected (3S, 2D, 4S, 3D, 5S), 7 observed
- Hybrids are expected in this mass region
- Molecular states?
- Cannot rule out threshold effect/FSI/…
- The Ys are all narrow and similar
- $\pi^+\pi^- h_c$, $\omega\chi_c$, … add complexity

The Z_c states

Discovery of $Z_c(3900)^{\pm}$

BESIII: PRL 110, 252001 (2013)



$Z_c(3900)^+$:

$m = (3899.0 \pm 3.6 \pm 4.9)\ \mathrm{MeV}/c^2$

$\Gamma = (46 \pm 10 \pm 20)\ \mathrm{MeV}$

Mass close to $D\bar{D}^*$ threshold

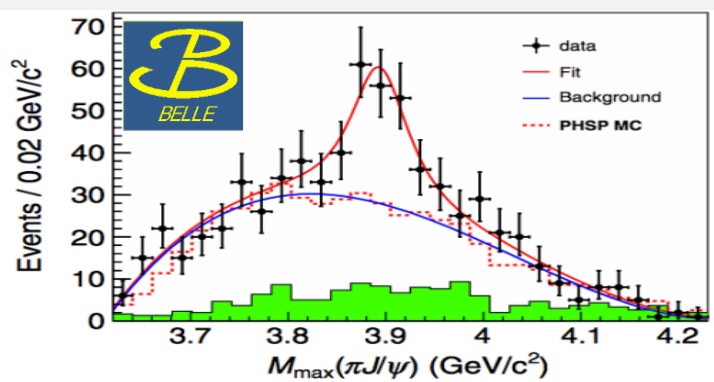
Decays to J/ψ → contains $c\bar{c}$

Electric charge → contains $u\bar{d}$

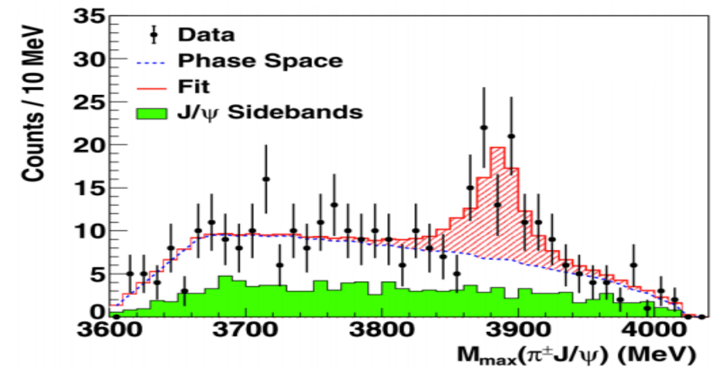
$$\sigma[e^+e^- \to \pi^+\pi^- J/\psi] = 62.9 \pm 1.9 \pm 3.7\ \mathrm{pb\ at\ 4.26\ GeV}$$

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

Belle with ISR data (PRL 110, 252002)

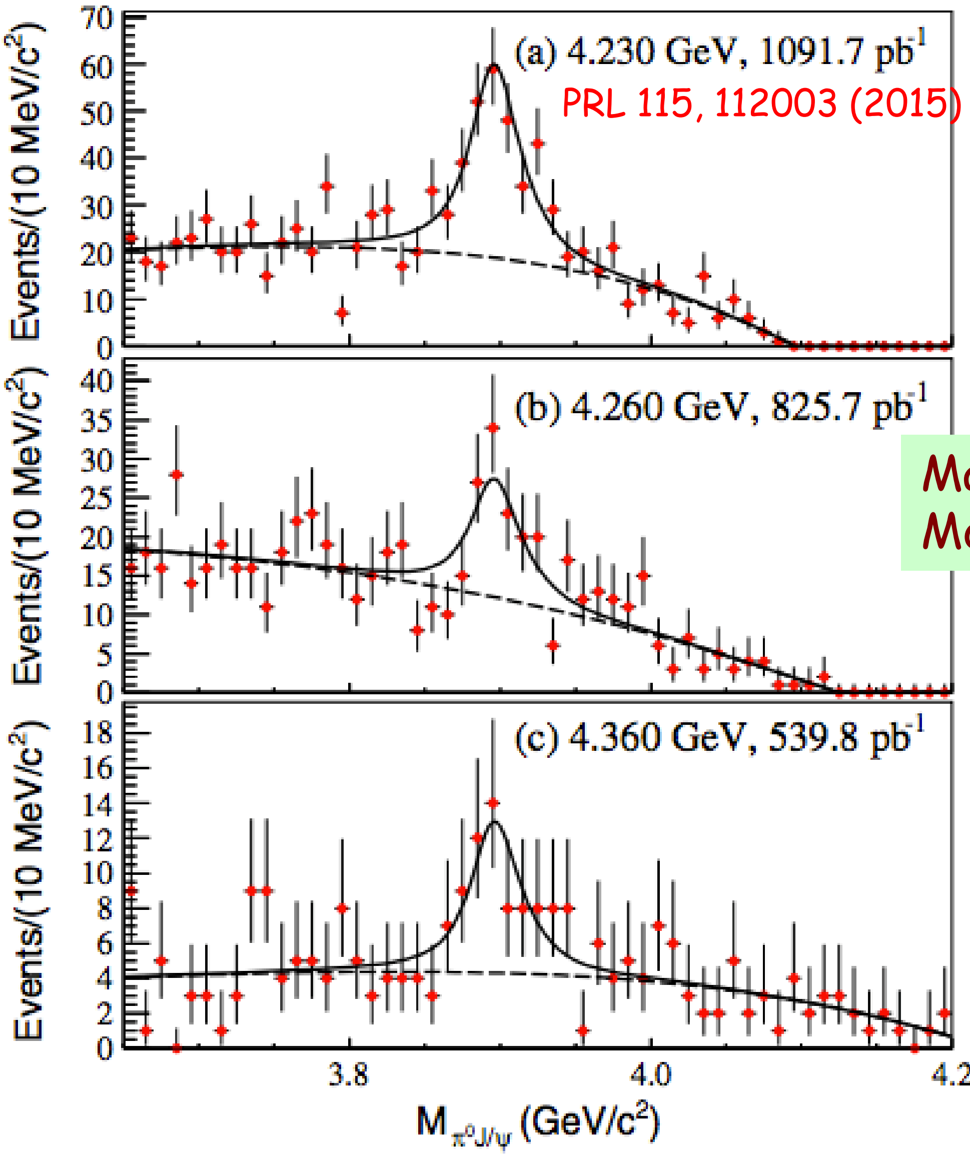


CLE0c data at 4.17 GeV (PLB 727, 366)



Neutral isospin partner: $Z_c(3900)^0$

$e^+e^- \rightarrow \pi^0\pi^0 J/\psi$



A neutral structure on $\pi^0 J/\psi$ invariant mass is observed !

An iso-spin triplet is established !

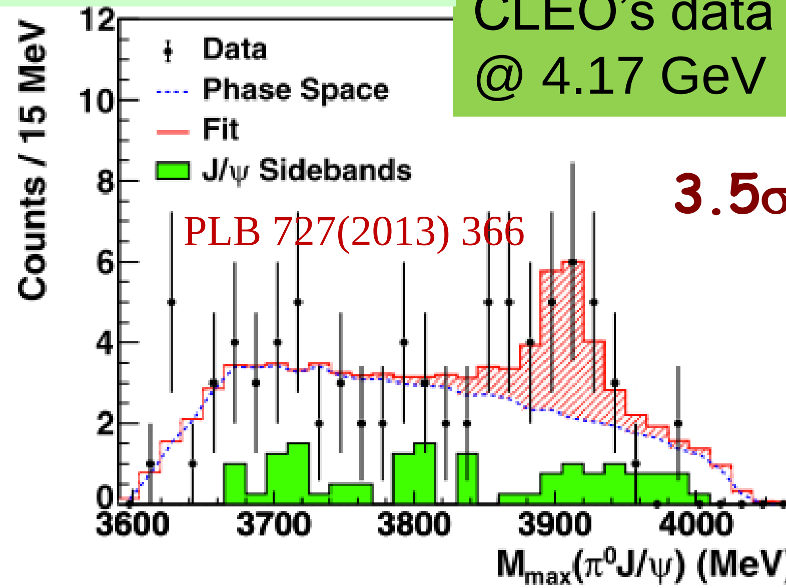
$M = 3894.8 \pm 2.3 \pm 3.2$ MeV

$\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV

Significance = 10.4σ

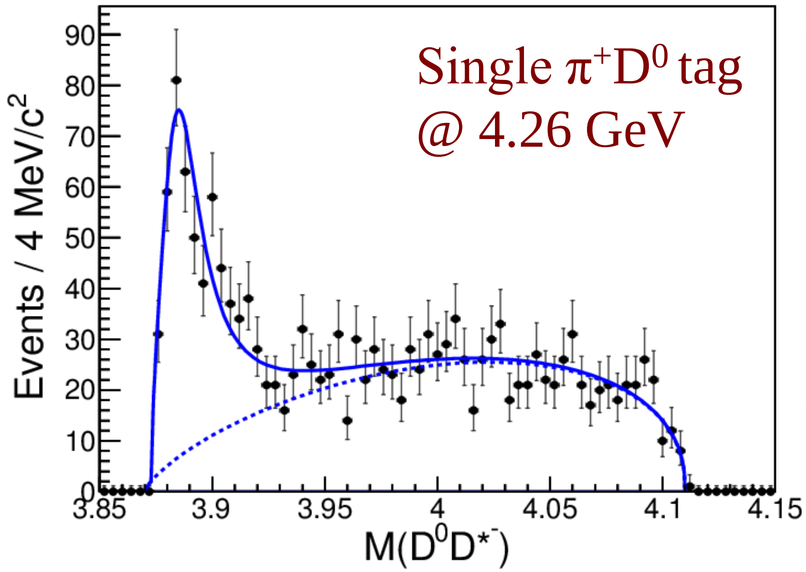
Mass near DD* threshold
Molecules? Tetraquark?

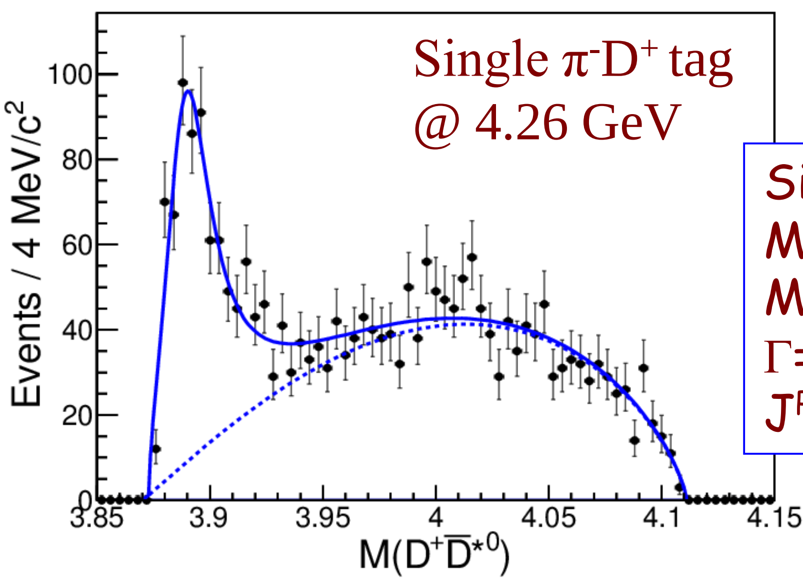
CLEO's data @ 4.17 GeV



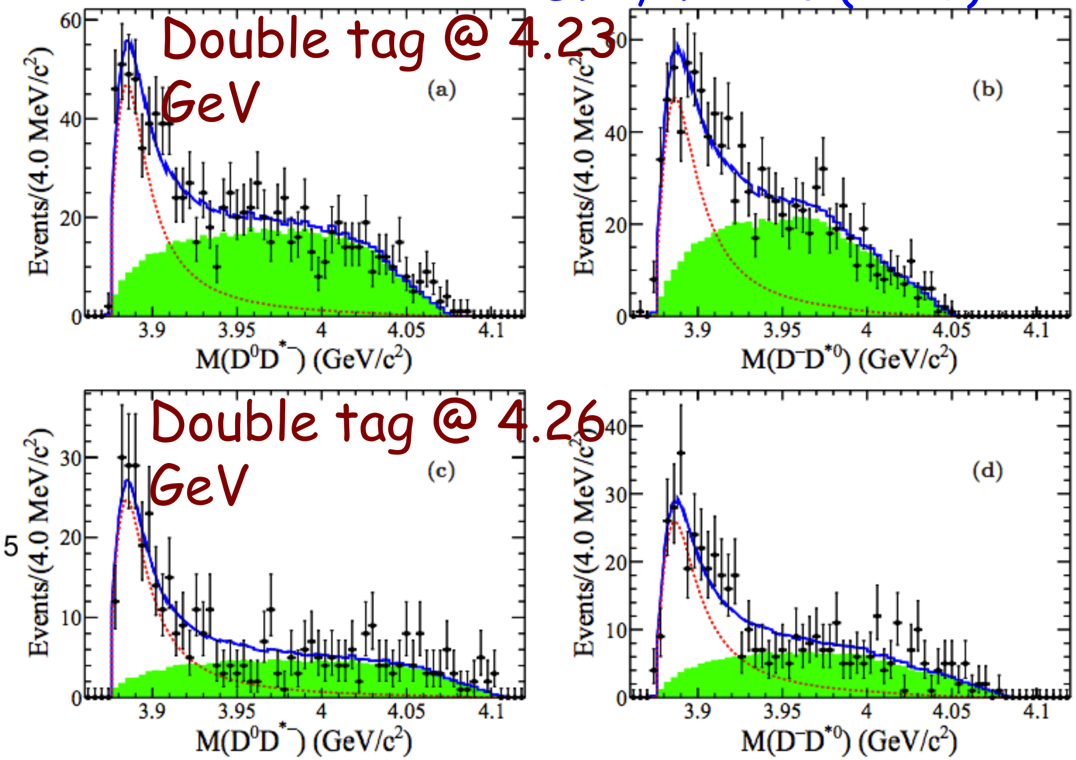
$e^+e^- \rightarrow (DD^*)^+\pi^- + c.c.$

PRL 112, 022001 (2014)





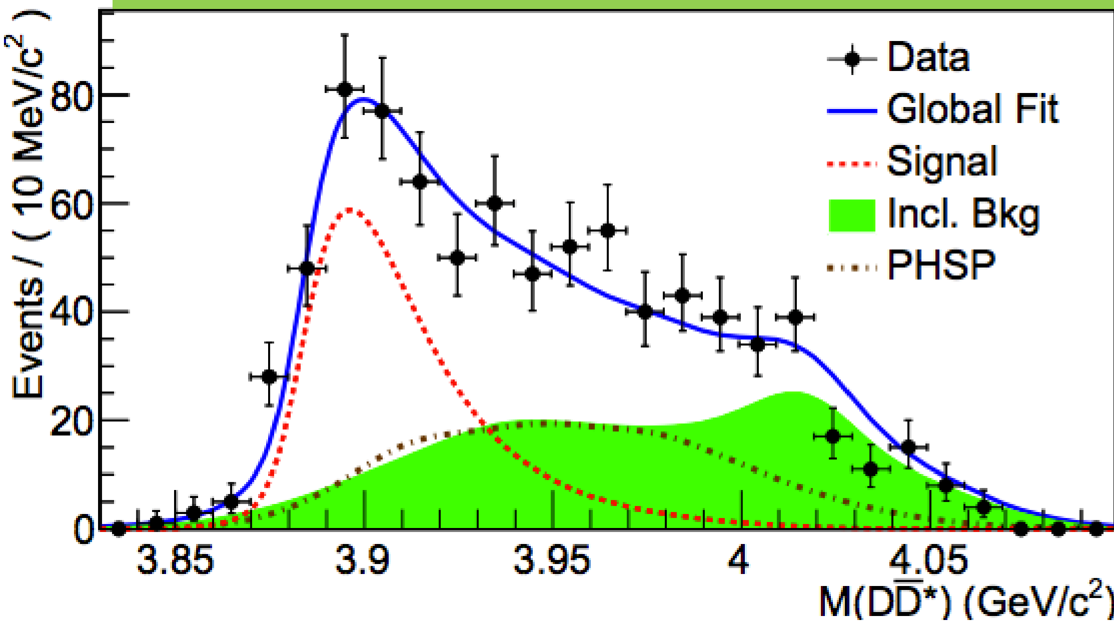
PRD92,092006 (2015)



Single tag	Double tag
$M = 3883.9 \pm 1.5 \pm 4.2$ MeV	$M = 3881.7 \pm 1.6 \pm 2.1$ MeV
$\Gamma = 24.8 \pm 3.3 \pm 11.0$ MeV	$\Gamma = 26.6 \pm 2.0 \pm 2.3$ MeV
$J^P = 1^+$	$J^P = 1^+$

Good agreement between ST & DT method
$Z_c(3900)$ vs. $Z_c(3885)$ → Same resonance ?!

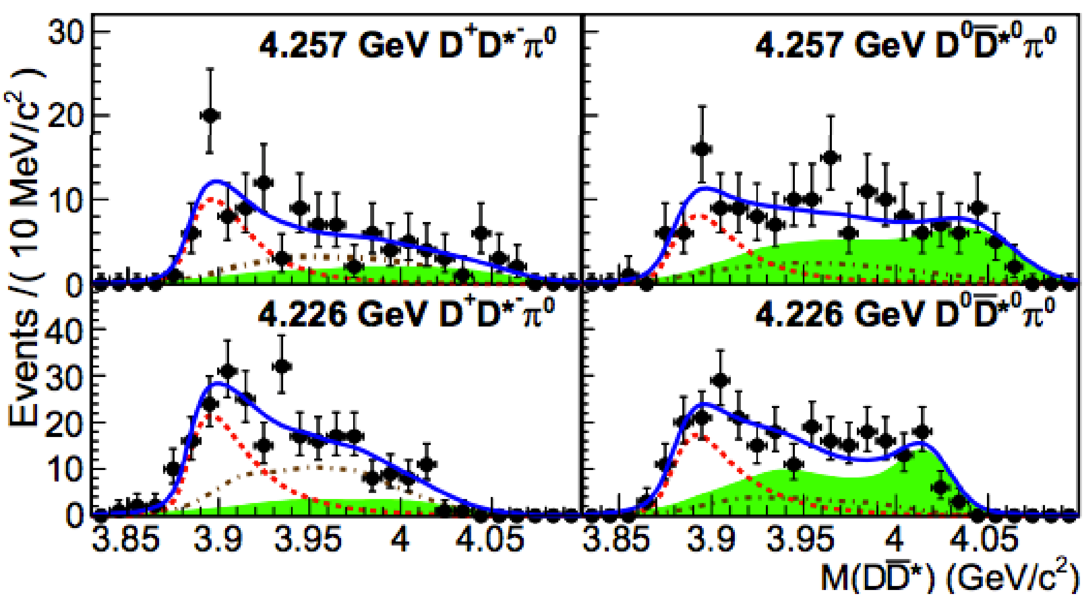
$e^+e^- \rightarrow (DD^*)^0\pi^0 + c.c.$



PRL 115, 222002 (2015)

Partial reconstruction method - Single tag

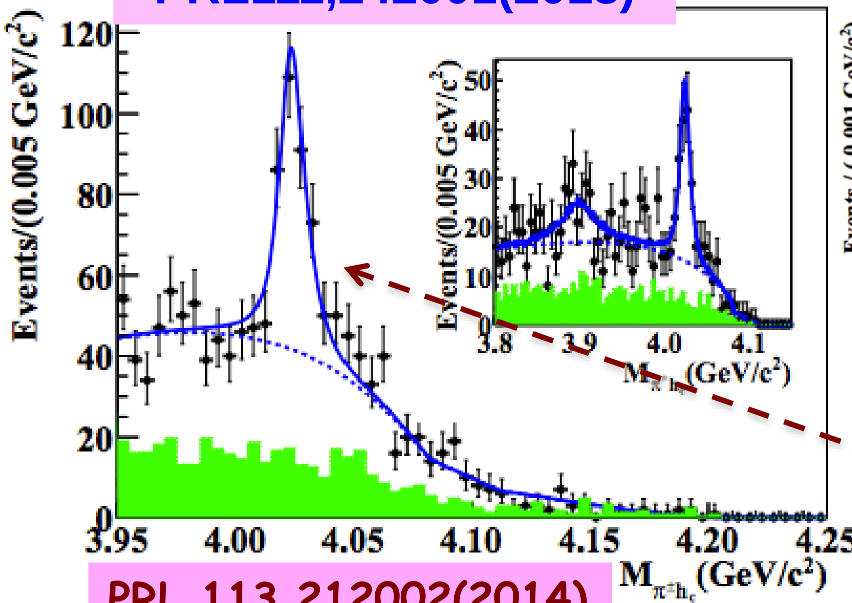
$M = 3885.7^{+4.3}_{-5.7} \pm 8.4$ MeV
$\Gamma = 35^{+11}_{-12} \pm 15$ MeV
Significance: >10σ

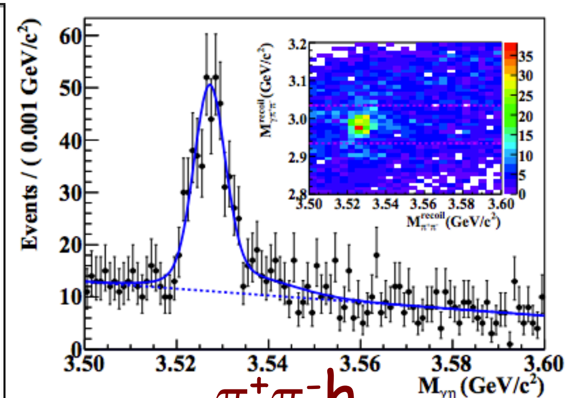


- ✧ Good agreement between neutral state and charged state
- ✧ An iso-spin triplet established in DD* channel
- ✧ Might be same as $Z_c(3900)$
- ✧ Molecule state? Tetraquark?

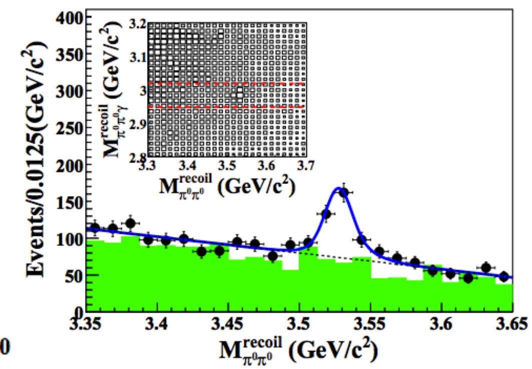
$e^+e^- \rightarrow \pi^+\pi^- h_c$ & $\pi^0\pi^0 h_c$

PRL111,242001(2013)





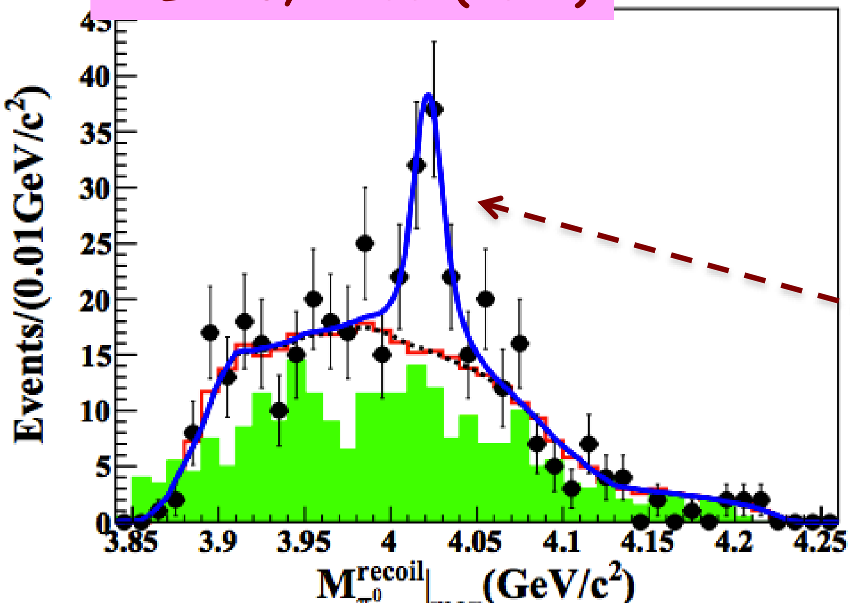
$\pi^+\pi^- h_c$



$\pi^0\pi^0 h_c$

Charged $Z_c(4020)^{\pm}$
Mass=(4022.9±0.8±2.7) MeV
Width=(7.9±2.7±2.6) MeV
Significance: >8.9σ

PRL 113,212002(2014)

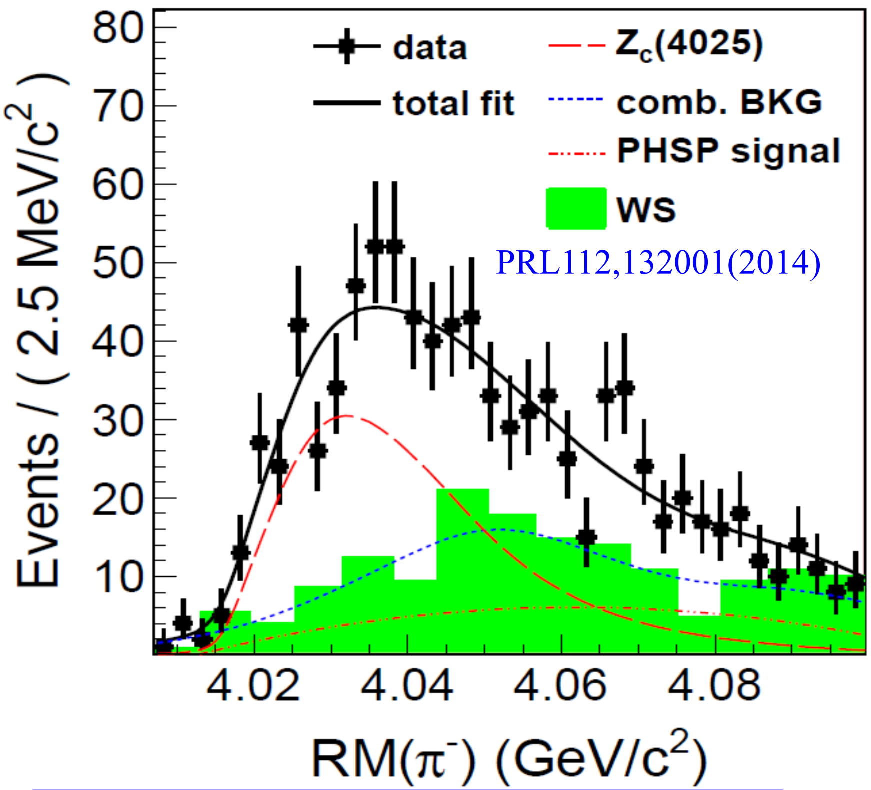


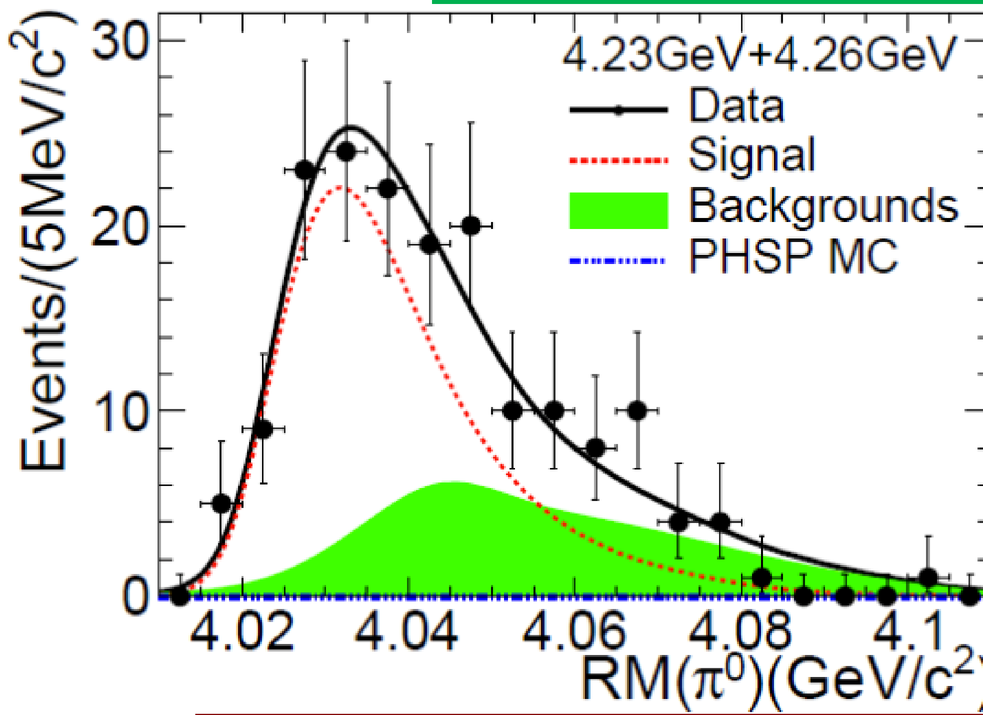
Neutral $Z_c(4020)^0$
Mass=(4023.9±2.2±3.8) MeV
Width: fixed to charged partner
Significance: 5σ

An spin triplet is established !

$e^+e^- \rightarrow \pi^-(D^*D^*)^+/\pi^0(D^*D^*)^0$+c.c.

PRL 115, 182002 (2015)





Charged $Z_c(4025)$:
M=(4026.3±2.6±3.7) MeV
Γ=(24.8±5.6±7.7) MeV
Significance: >10σ

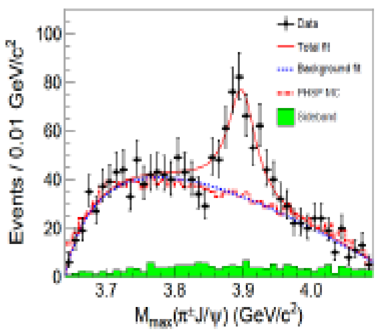
Agrees !

Neutral $Z_c(4025)^0$:
M=($4025.5^{+2.0}_{-4.7}$±3.1) MeV
Γ=(23.0±6.0±1.0) MeV
Significance: >5.9σ

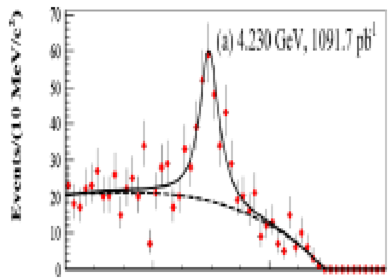
New isospin triplet?

$Z_c(4025)$ and $Z_c(4020)$ have similar mass, but different width.

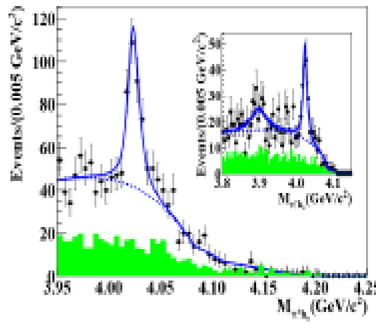
Summary Z_c states at BESIII



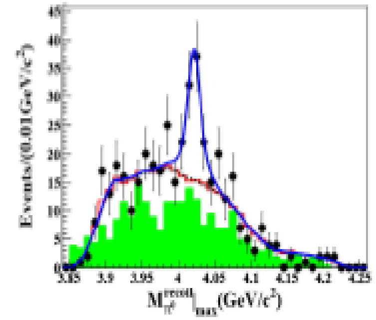
$e^+e^- \to \pi^+ \pi^- J/\Psi$



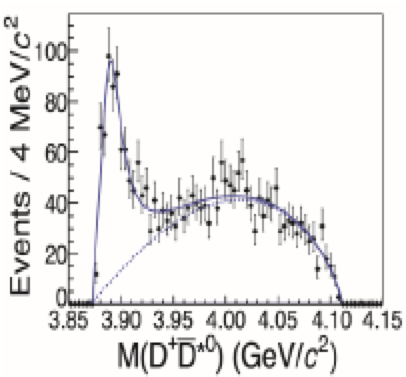
$e^+e^- \to \pi^0 \pi^0 J/\Psi$



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

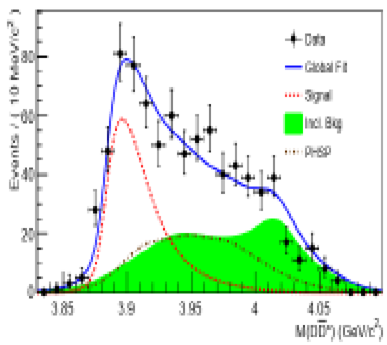


$e^+e^- \to \pi^0 \pi^0 h_c$



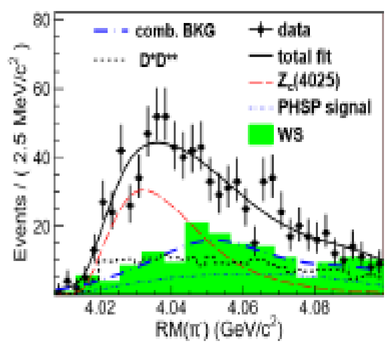
$e^+e^- \to \pi^+ (D\bar{D}^*)^-$

$Z_c(3900)^{\pm}$?



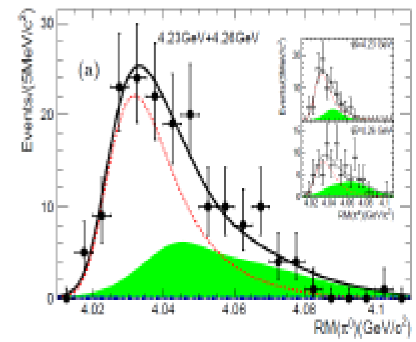
$e^+e^- \to \pi^0 (D\bar{D}^*)^0$

$Z_c(3900)^0$?



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

$Z_c(4020)^{\pm}$?

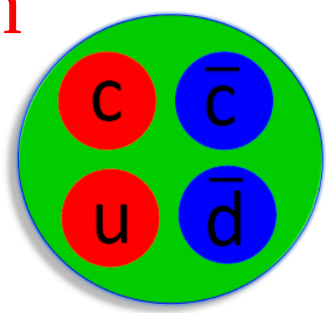


$e^+e^- \to \pi^0 (D^*\bar{D}^*)^0$

$Z_c(4020)^0$?

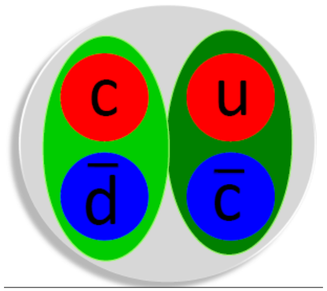
What's the nature of these Z states?

- 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?
- …

We found more questions to answer

- In the X sector
  - Where the X(3872) & X(3823) come from? Resonance decays or continuum production?
  - May other X states be produced and where?
- In the Y/ψ sector
  - Is the Y(4260) a single resonance?
  - What is hidden behind $\pi\pi h_c$? Large coupling to spin-singlet, is a hybrid state observed?
  - Correlation between charm production & charmonium transitions?
  - May we observe the charmonium 3^3D_1 state at ~4.5 GeV?
- In the Z sector
  - Are the Z_c and Z_c' from resonance decays or continuum prod.?
  - Are there excited Z_c states and Z_{cs} states [D^*D_s or DD_s^*]?

Summary

- BESIII produces significant XYZ results…
- X & Y states are difficult to distinguish from normal meson, charged Z_c states provide solid evidence.
- Many neutral Z_c partners are observed, the corresponding isospin triplets are established.
- Quark composition for Z_c is still puzzling.
- More results are coming, we would finally understand them.

Thank you (谢谢)!