XYZ particles at BESIII

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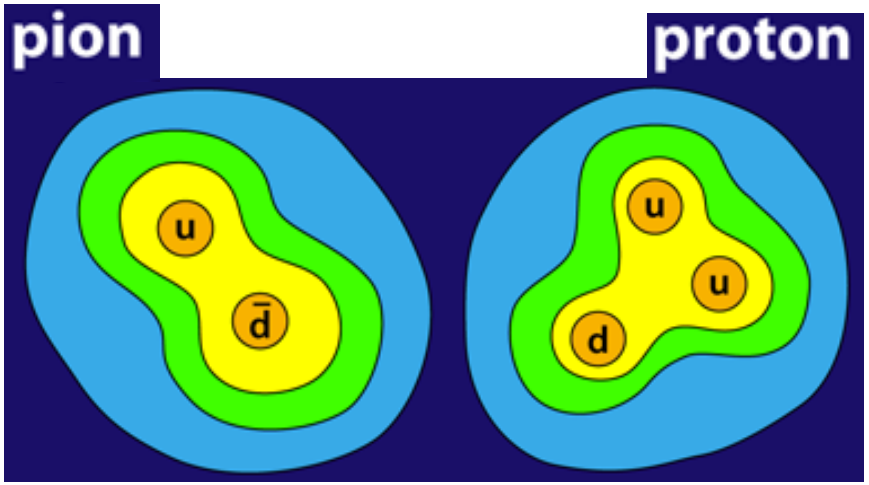
Outline

- Introduction
- BESIII experiment in Beijing, China
- Observation of $Z_c(3900)$.
- Observation of $Z_c(4020)$ & $Z_c(4025)$.
- Observation of $Y(4260) \rightarrow \gamma X(3872)$.
- Summary & outlook

Hadrons: normal & exotic

- Hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks

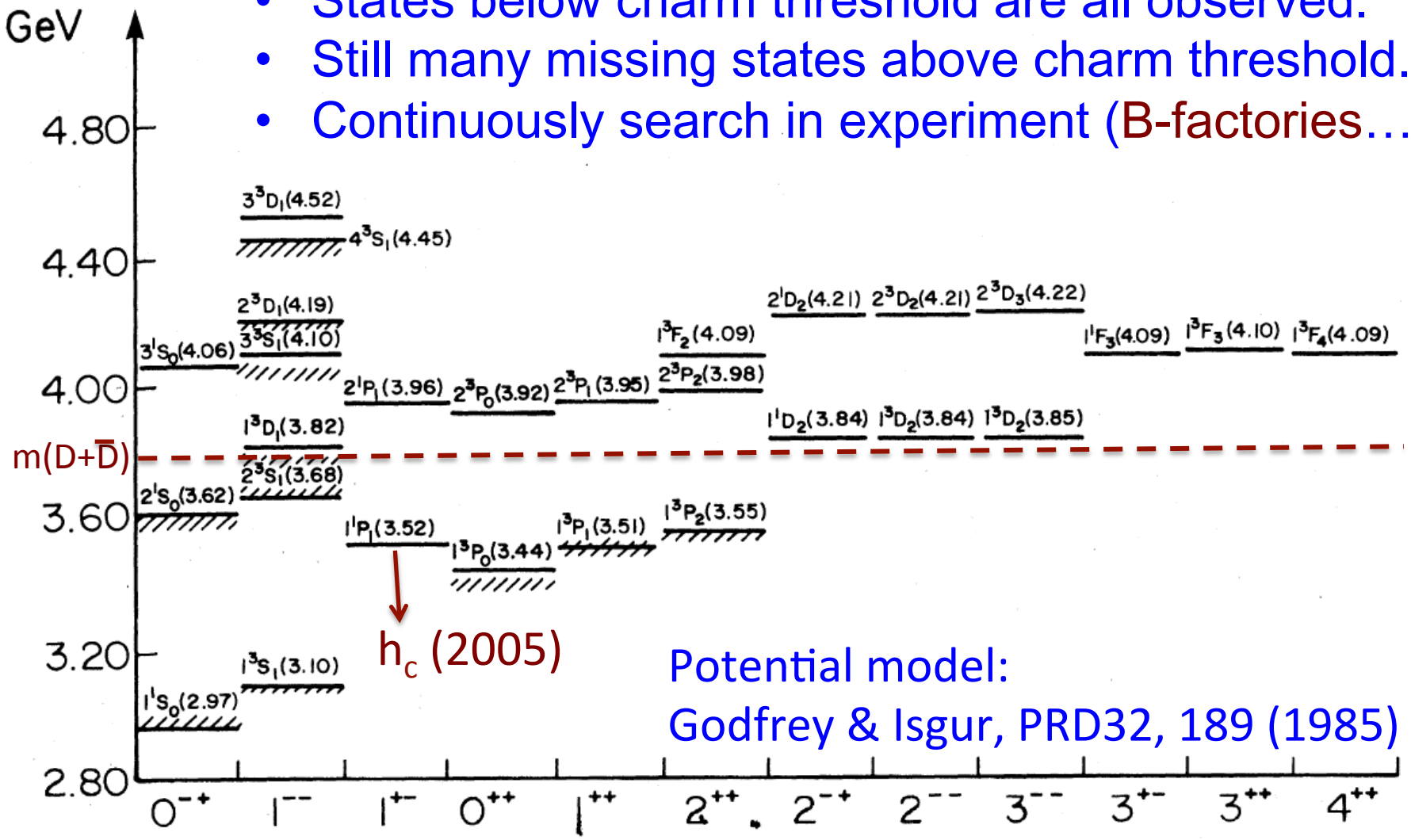
Quark model:



- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - Glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - Hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - Molecule : bound state of more than 2 hadrons
  - …

Charmonium

- States below charm threshold are all observed.
- Still many missing states above charm threshold.
- Continuously search in experiment (B-factories…).

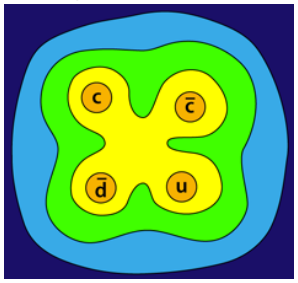


Potential model:
Godfrey & Isgur, PRD32, 189 (1985)

Charmonium and XYZ particles

- Not an obvious charmonium state
- But charmonium in the final state
- XYZ or charmoniumlike particles

What are they ?



$Z_c(3900)$

X(3872)

Y(4260)

X(3915)
X(4160)
Y(4008)
Y(4140)
X(4350)
Y(4360)
Y(4660)

XYZ(3940)

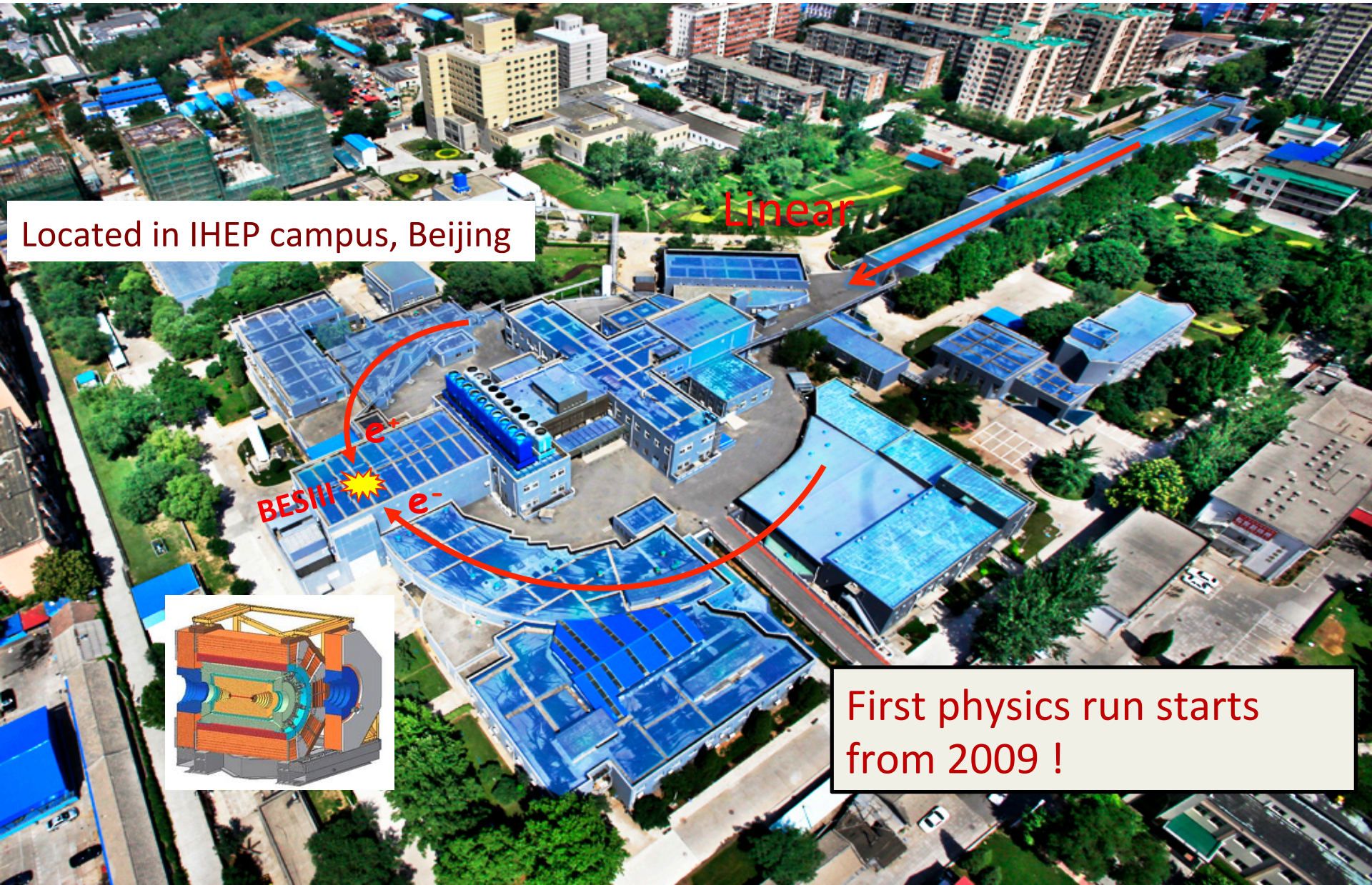
Z(4430)
Z(4250)
Z(4050)

...

Charmonium?
Hybrid?
Tetraquark?
Molecule?
...

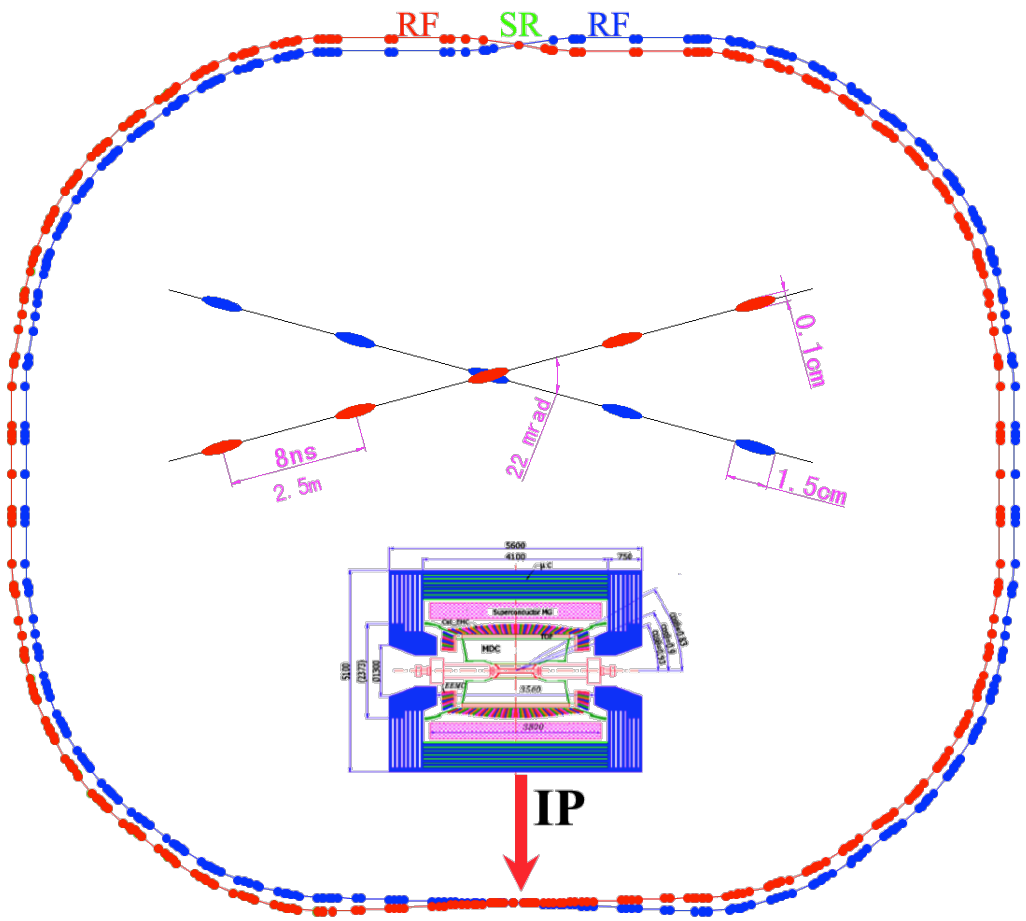
Godfrey & Isgur, PRD32, 189 (1985)

Beijing Electron Positron Collider (BEPC II)

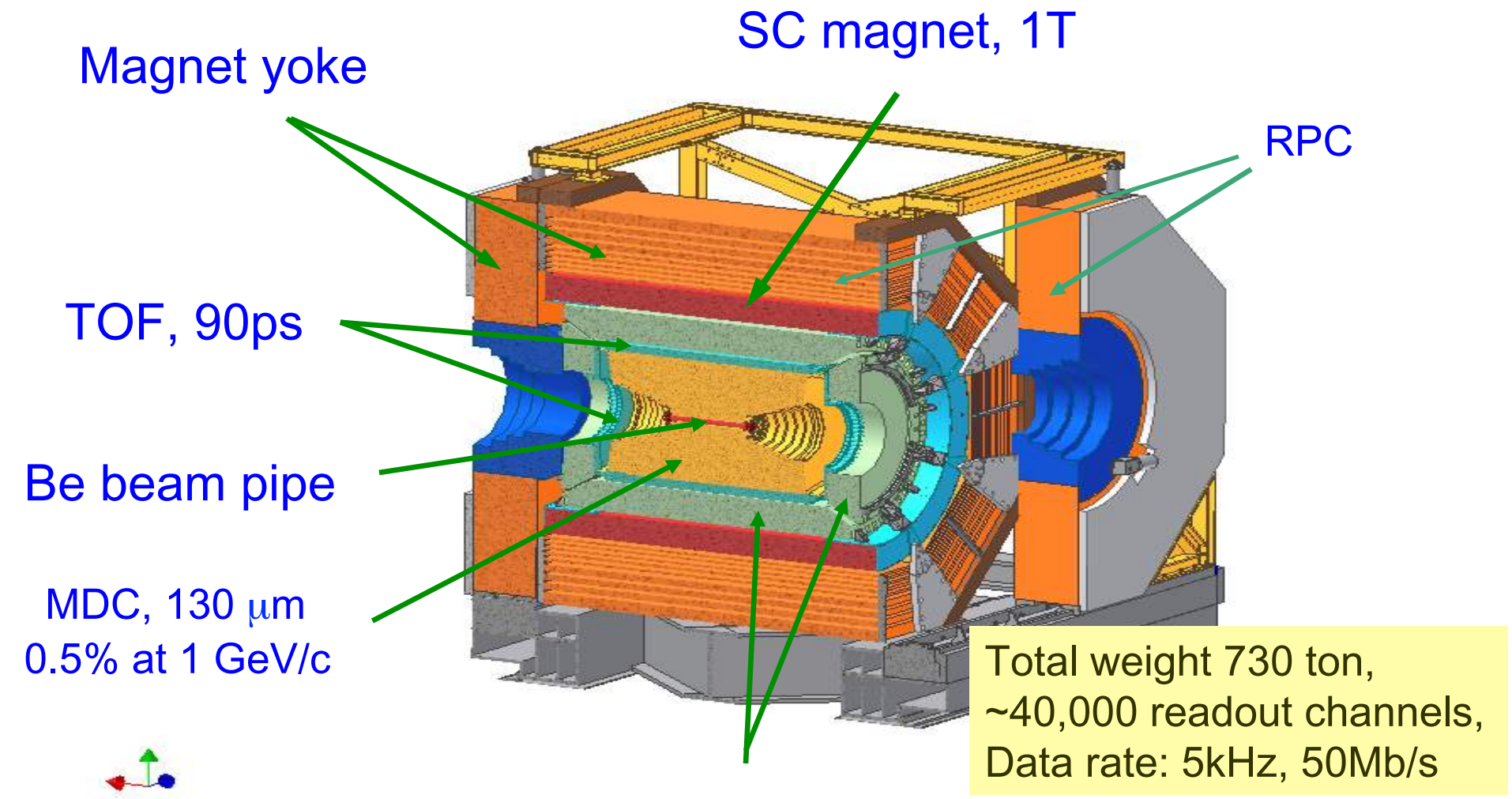


BEPC II storage ring

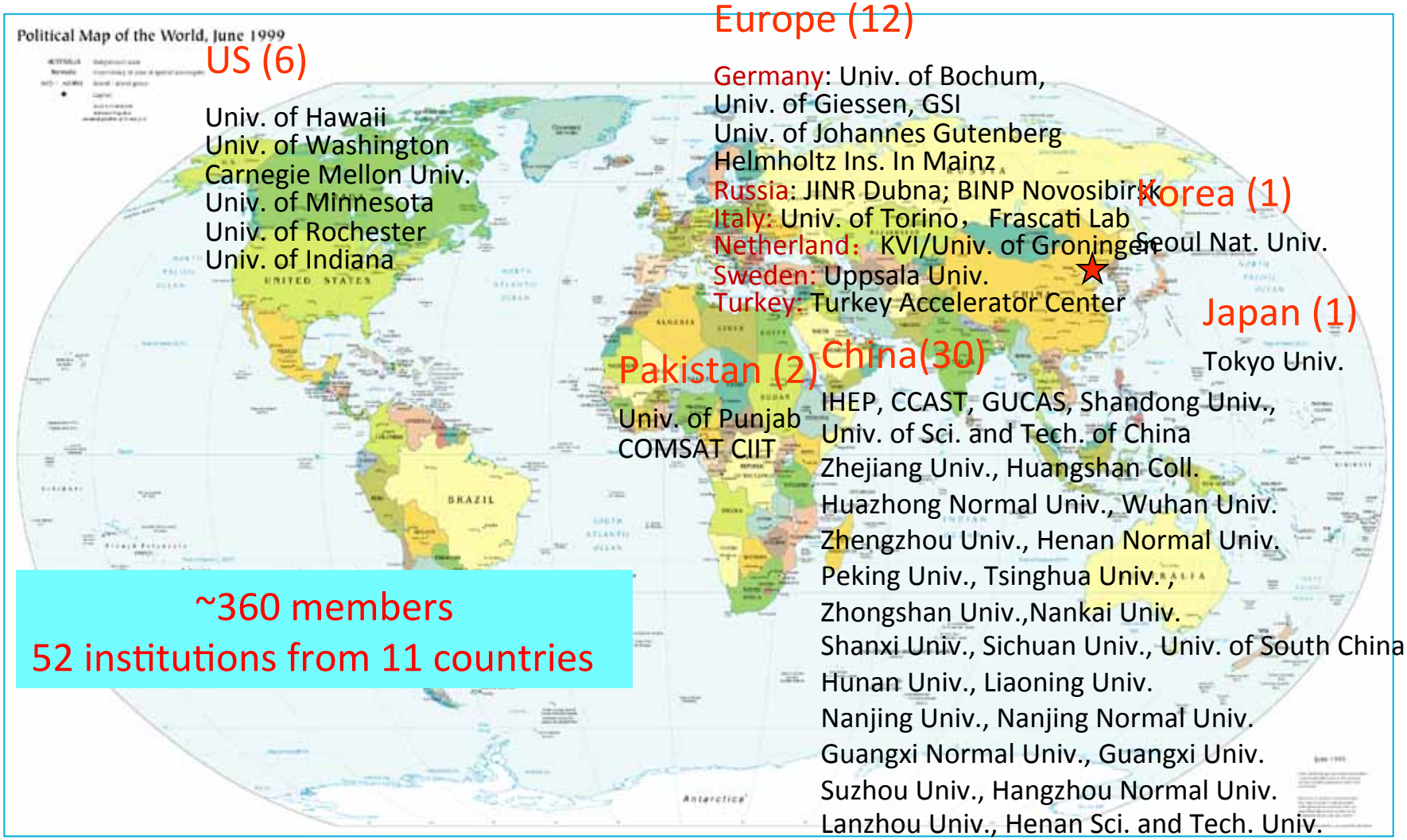
Double ring:
symmetric collider
CMS energy:
2.0 - 4.6 GeV
Design Luminosity @ ψ(3770):
(70% achieved, ~20 pb^{-1} /day)
1×10^{33} $cm^{-2}s^{-1}$
Energy spread:
1.1 MeV @ 3.686 GeV
No. of bunches:
93
Bunch length:
1.5 cm
Total current:
0.91 A
Circumference:
237 m



BEijng Spectrometer (BESIII) Detector



The BESIII Collaboration



US (6)

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

Europe (12)

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， 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(30)

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.
Hong Kong Univ., Hong Kong Chinese Univ.

~360 members
52 institutions from 11 countries

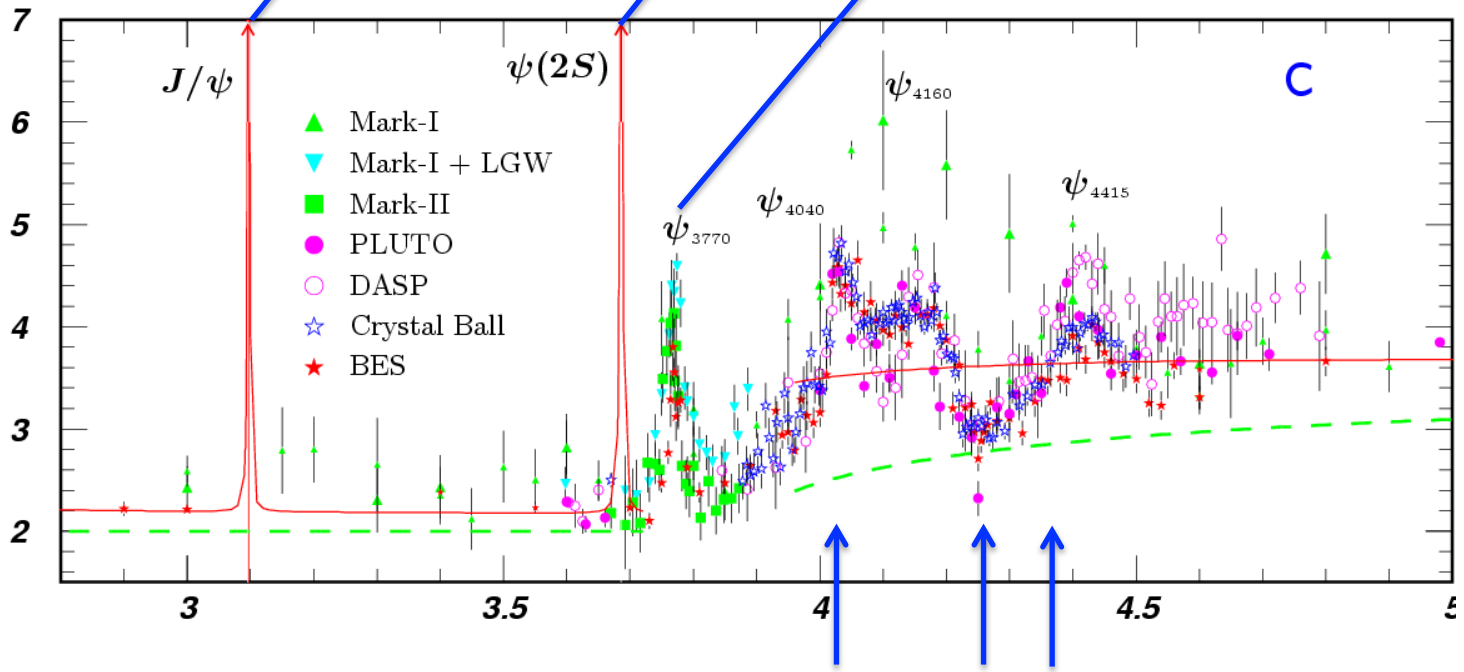
What do we do at BESIII?

Light hadrons + charmonium decay + D meson

1.3 Billion

0.4 Billion

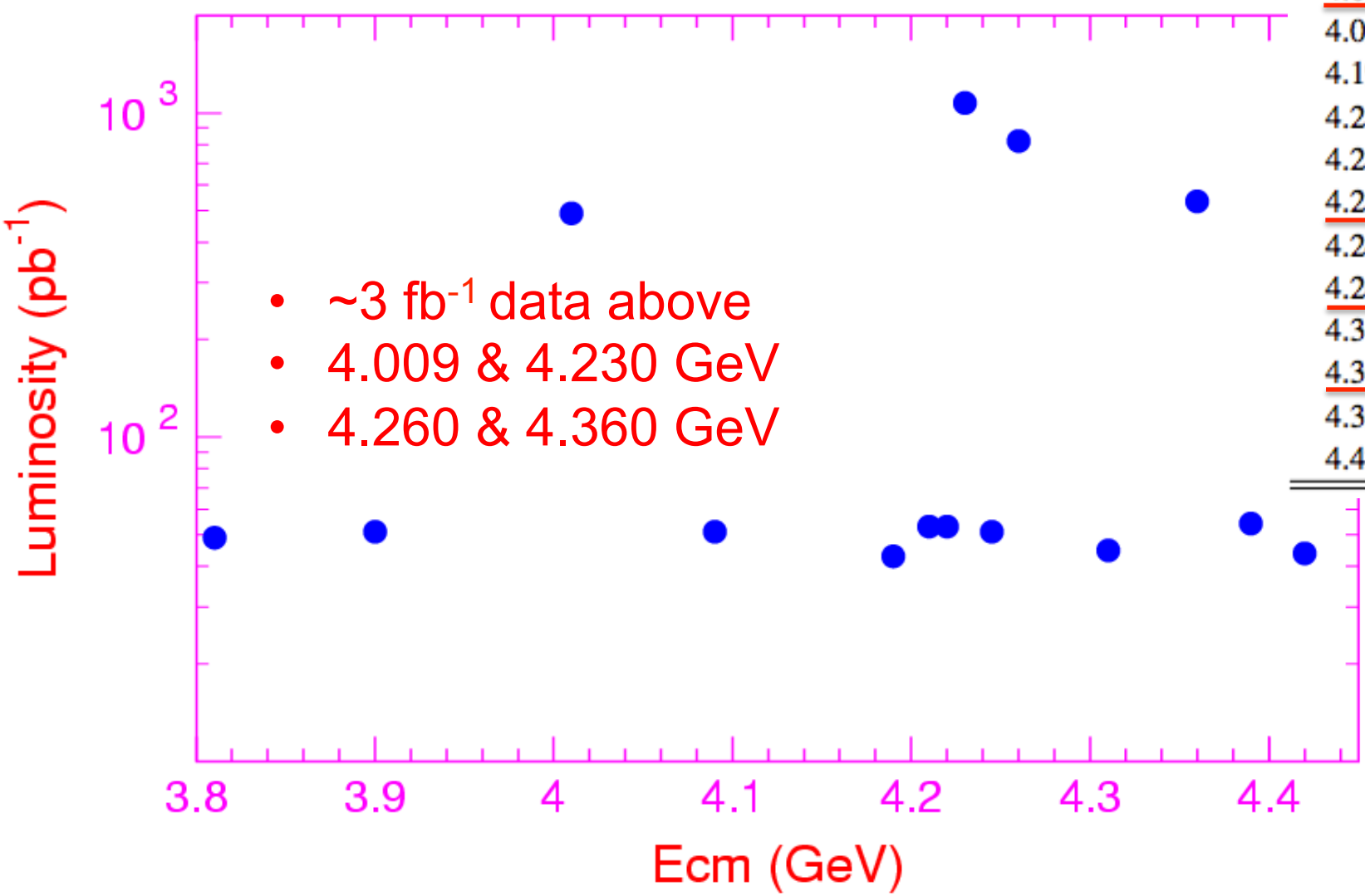
2.9 fb^{-1}



$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})
3.900	52.8
4.009	482.0
4.090	51.0
4.190	43.0
4.210	54.7
4.220	54.6
4.230	1090.0
4.245	56.0
4.260	826.8
4.310	44.9
4.360	544.5
4.390	55.1
4.420	44.7

- High potential in studying XYZ particles above threshold !
- Huge data near 4.26 GeV, 4.36 GeV…

Above open charm threshold



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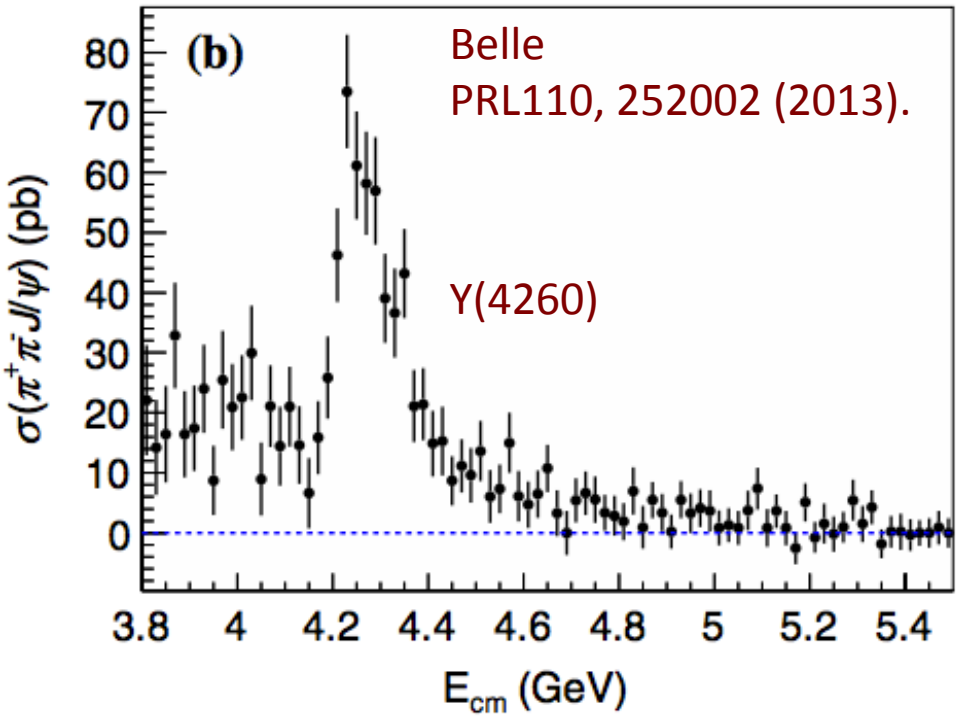
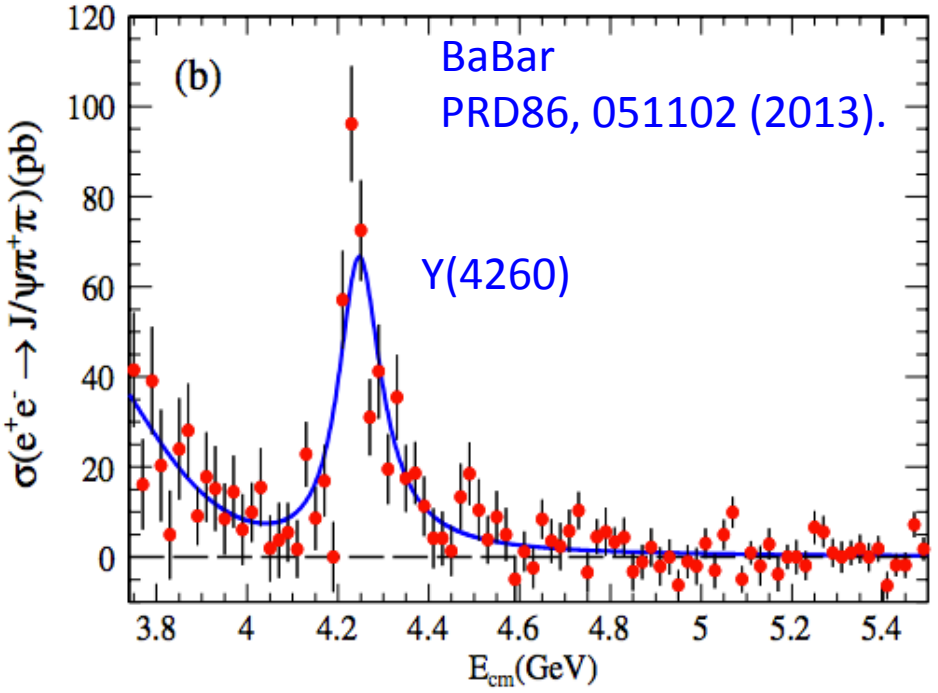
Discovery of charged $Z_c(3900)$ state

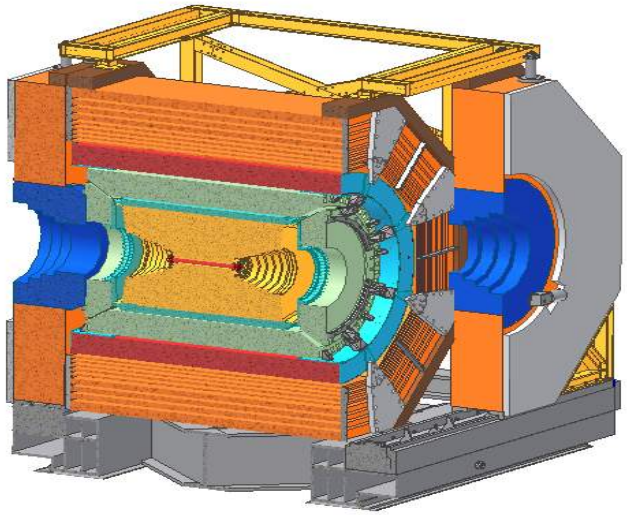
The Y(4260)→$\pi^+\pi^-$J/ψ





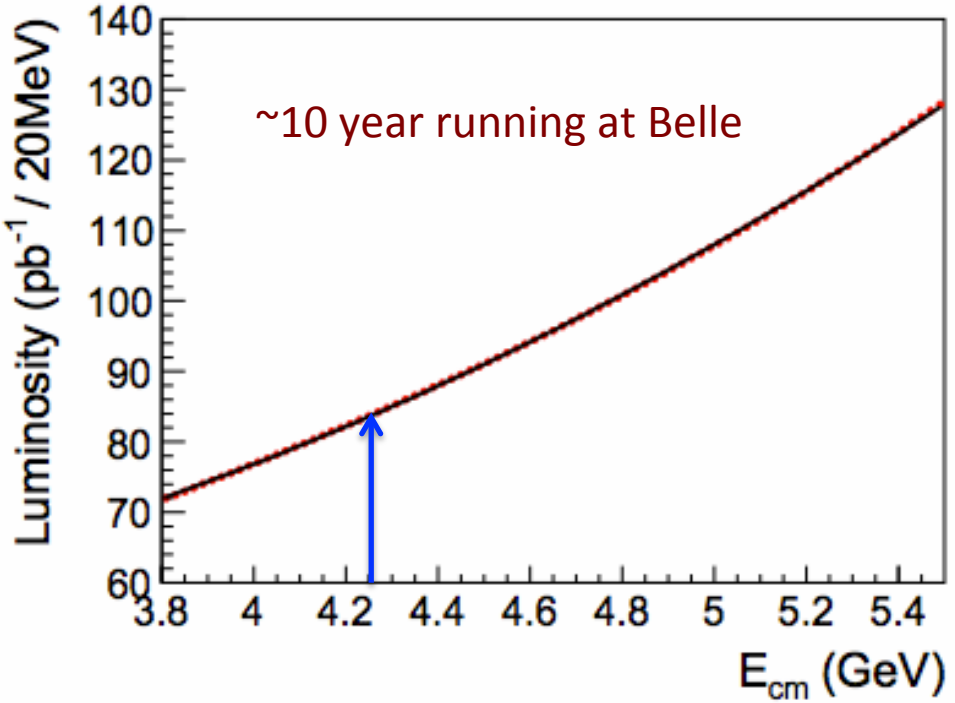
1. The Y(4260) resonance was observed by BABAR and Belle.
2. Based on data set ~10.58 GeV, using the initial-state-radiation (ISR) method.
3. The Y(4260) also interpreted to be an exotic hadron candidate.

Study Y(4260) at BESIII



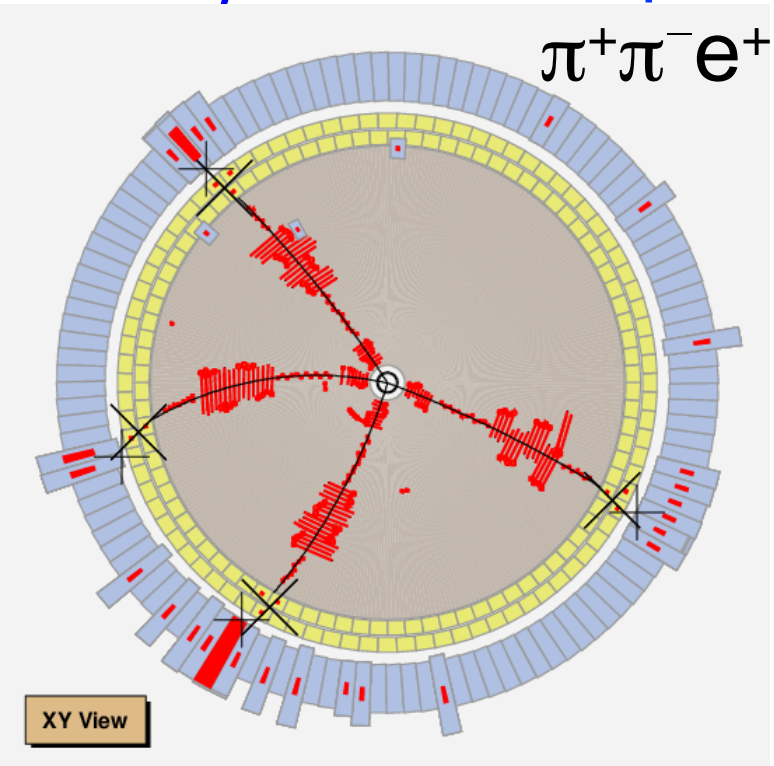
- BESIII is a symmetric collider.
- CM energy: 2 GeV – 4.6 GeV
- Design Lum=$1*10^{33}$ /cm^2/s
- Focus on one energy point, then more competitive than B factory

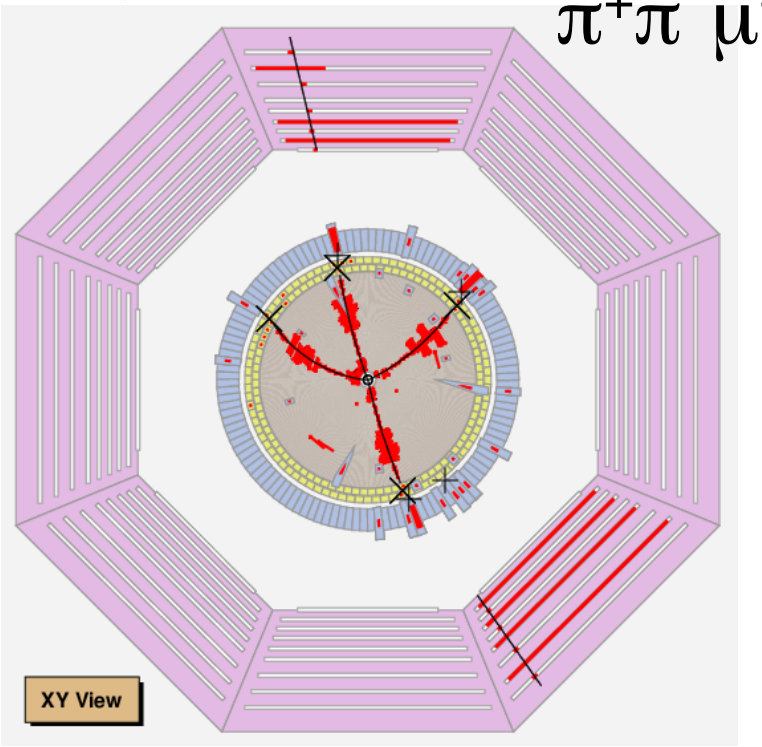
- Effective ISR luminosity (QED).
- L(total)~967 fb^{-1} @ ~10 GeV.
- ~85 pb^{-1}/20 MeV at 4.26 GeV.
- What's about BESIII?
- ~20 pb^{-1} /day around 4.26 GeV.



Study Y(4260) at BESIII

- Dec, 2012 to Jan, 2013, BESIII accumulate 525 pb^{-1} data @ 4.26 GeV, world's largest data set!
- Study $e^+e^- \to \pi^+\pi^- J/\psi$ exclusive process.

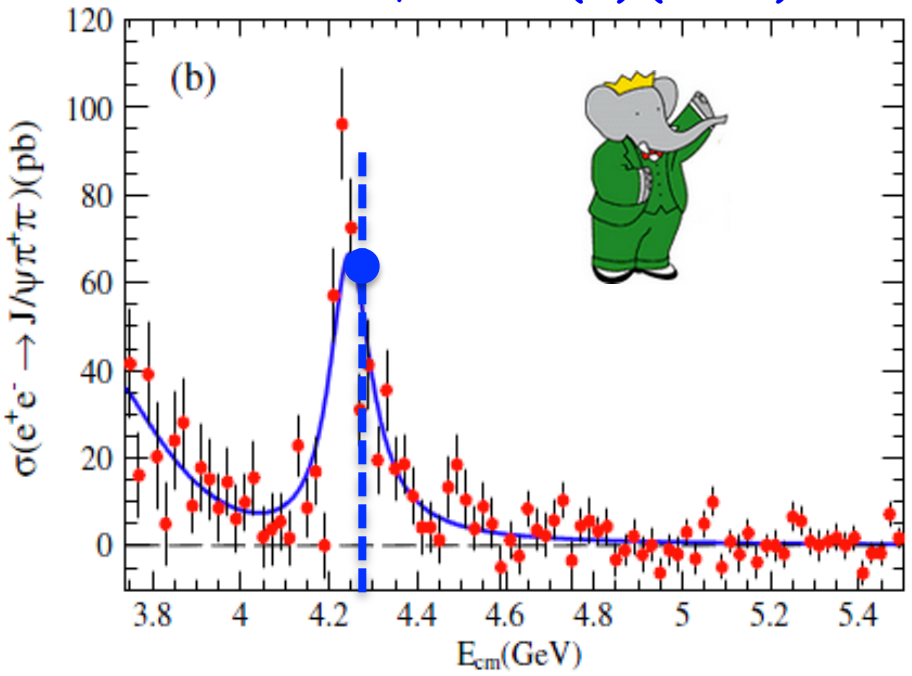




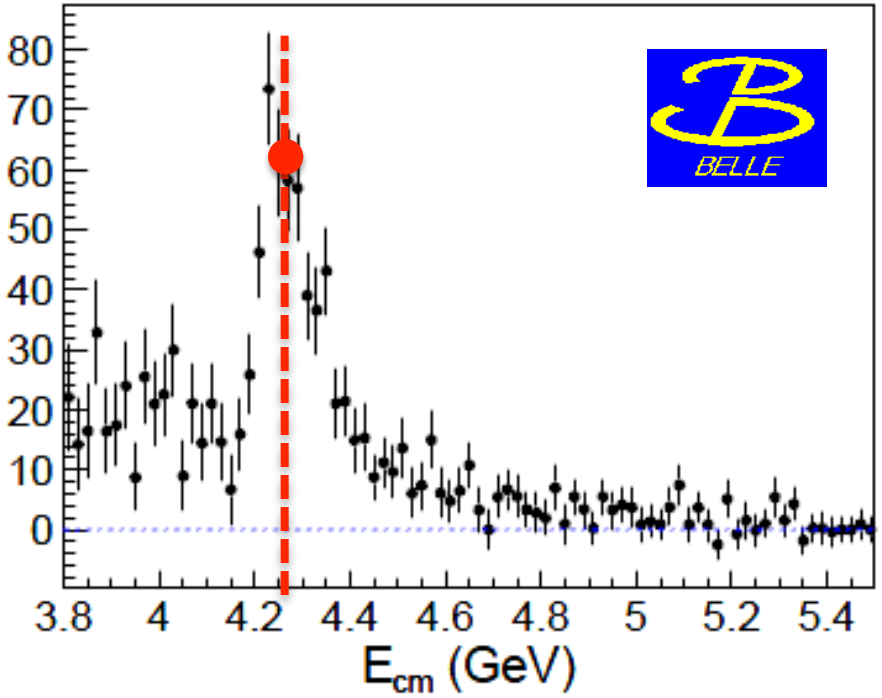
1. Very simple and straightforward analysis.
2. The produced vector charmonium(like) state almost in rest frame.
3. $Y(4260) \to \pi^+\pi^- J/\psi$, four charged track detected.

Cross Section at BESIII

PRD **86**,051102(R) (2012).



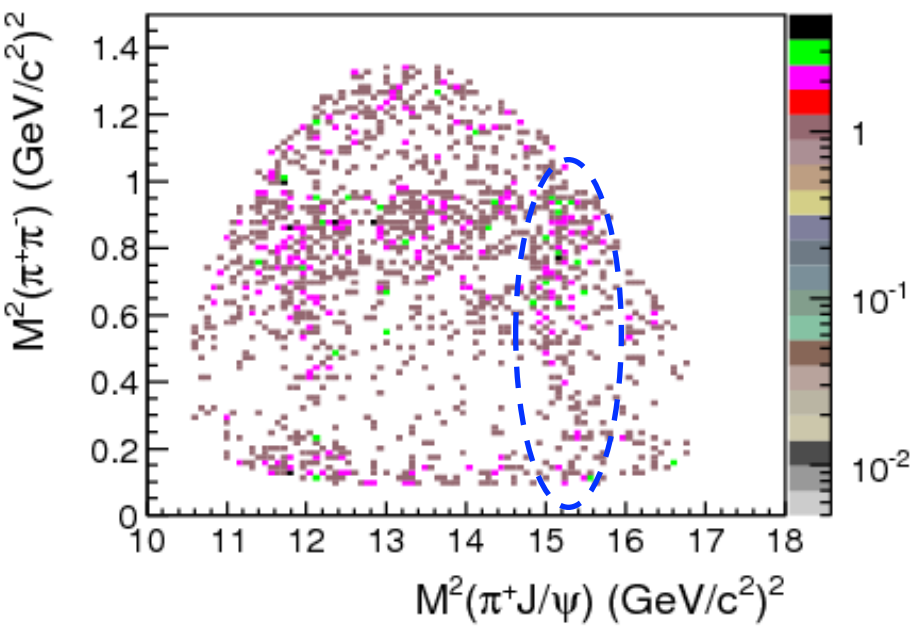
PRL **110**,252002 (2013).

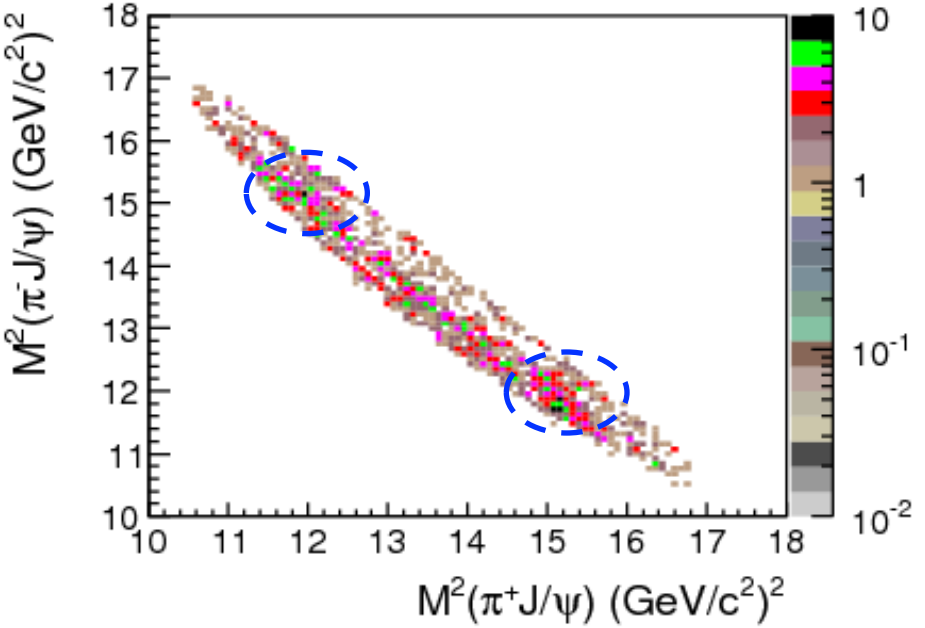


1. Lum=525 pb^{-1} @ BESIII
2. $N(\mu^+\mu^-)$=882±33; $N(e^+e^-)$=595±28.
3. Born cross section: σ^B=(62.9±1.9±3.7) pb @ BESIII.
4. Good agreement with Belle and BaBar.
5. Analysis is valid and unbiased.

Intermediate state——$Z_c(3900)$

- Requiring J/ψ mass window: [3.08,3.12] GeV, we have 1595 signal events, with purity ~90%.





1. Intermediate states both in $M(\pi^+\pi^-)$ mass distribution and $M(\pi^\pm J/\psi)$ mass distribution.
2. A clear band in the $M(\pi^\pm J/\psi)$ invariant mass projection.
3. Phase space reflection between $M(\pi^+J/\psi)$ and $M(\pi^-J/\psi)$.

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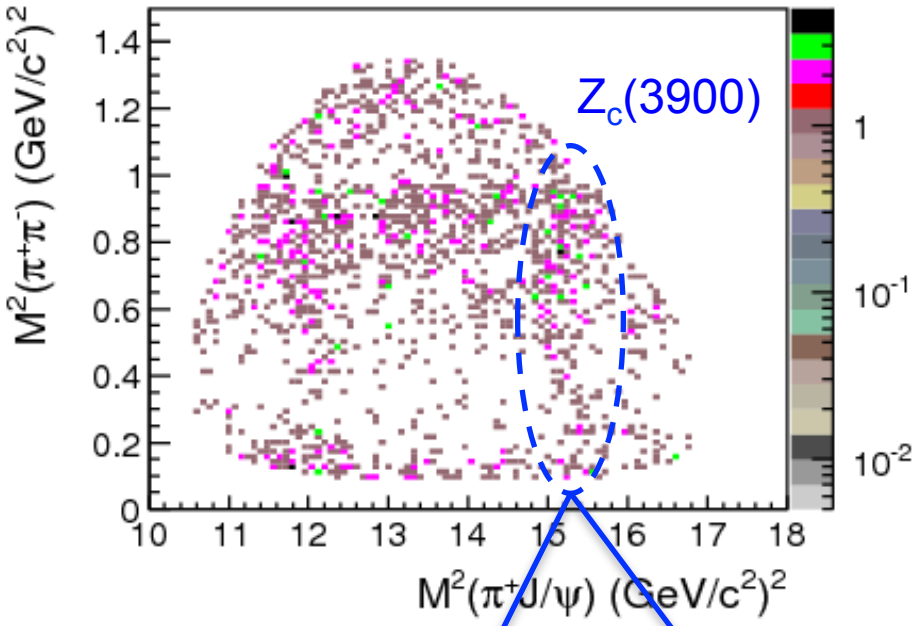
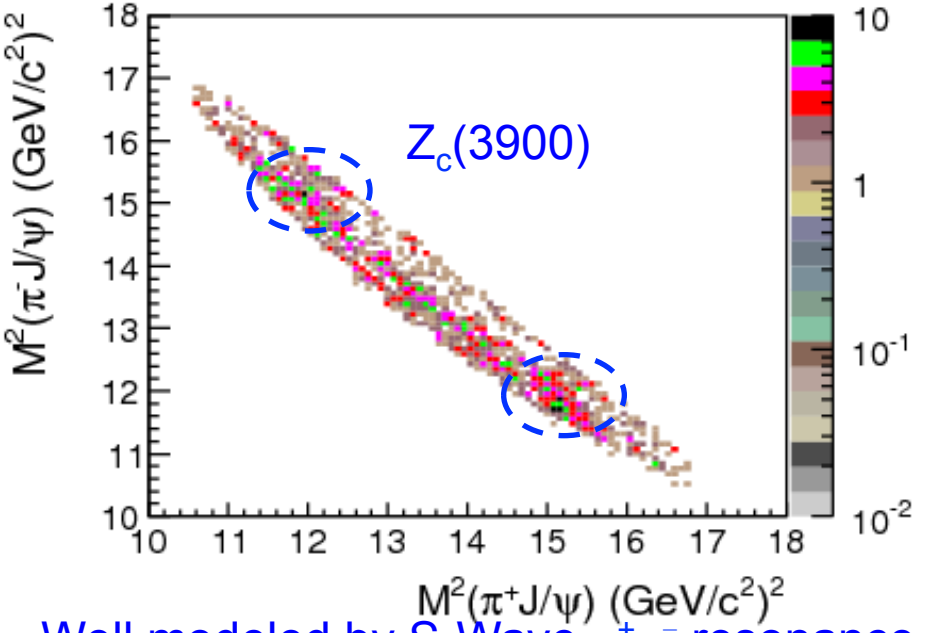
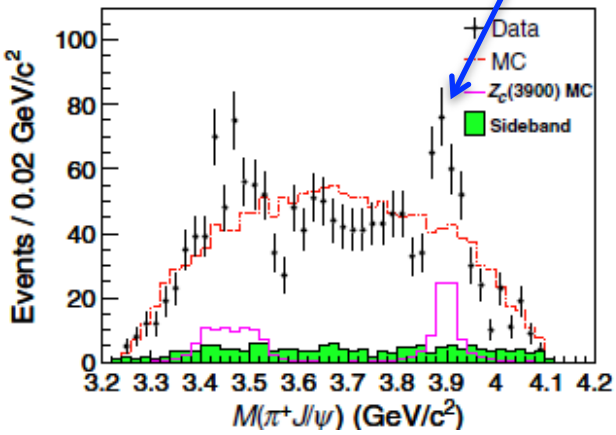
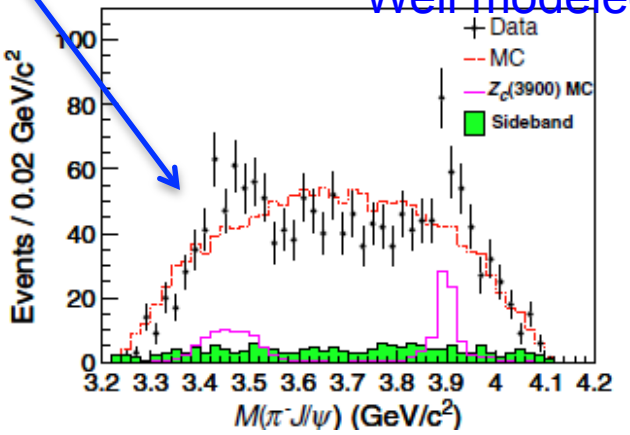
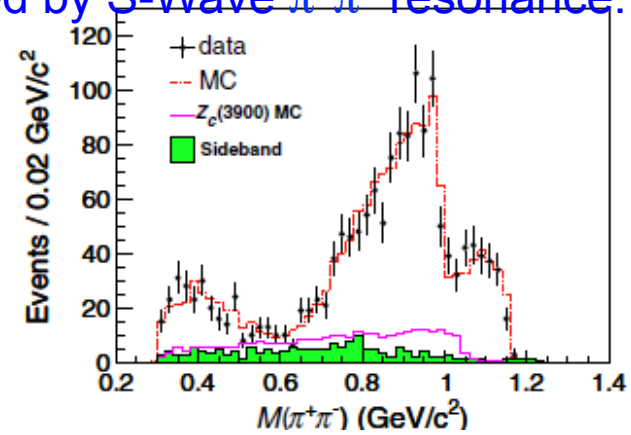




Well modeled by S-Wave $\pi^+\pi^-$ resonance.







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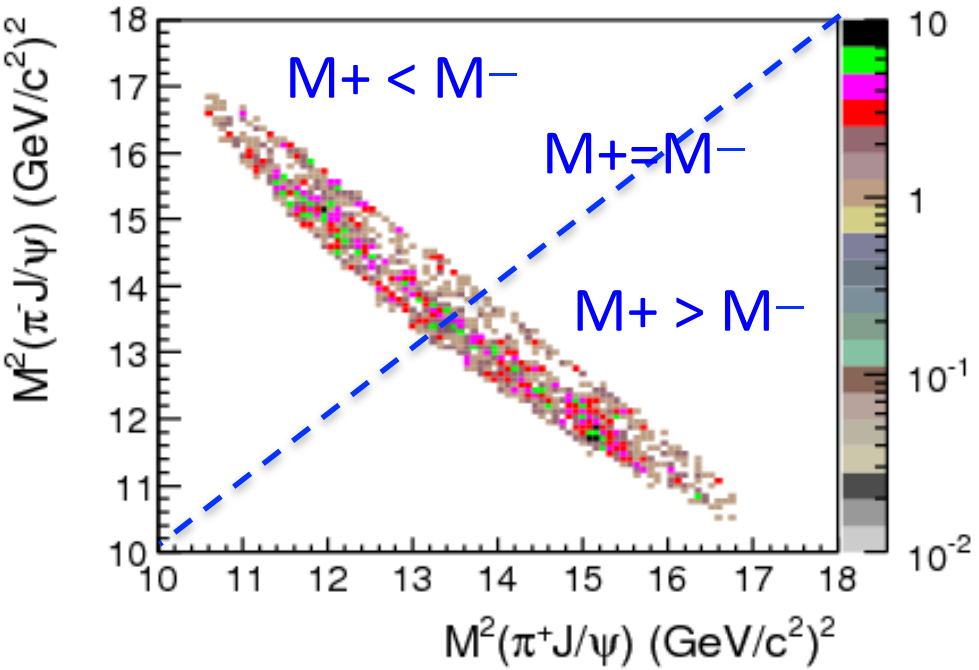
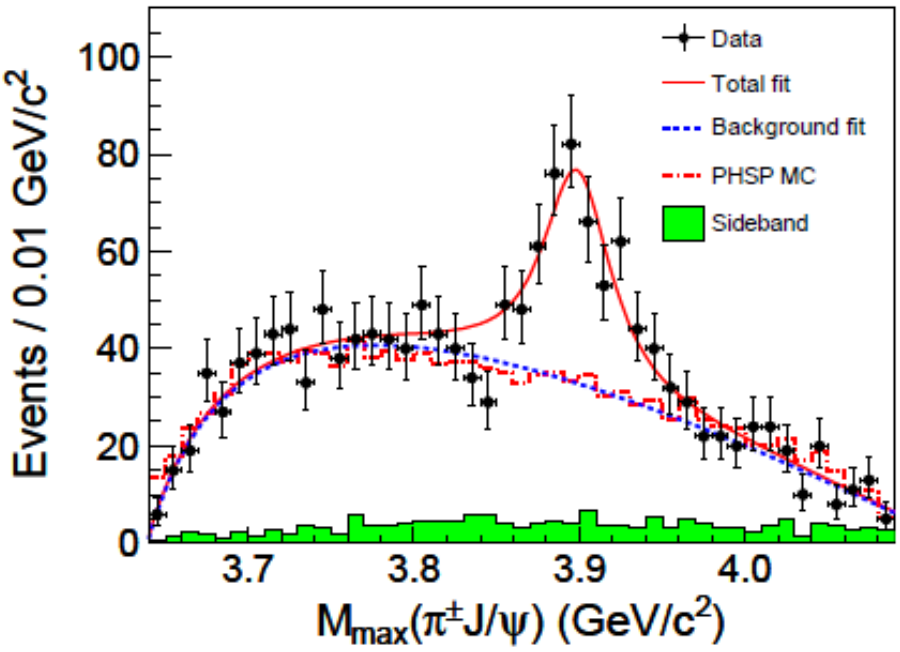
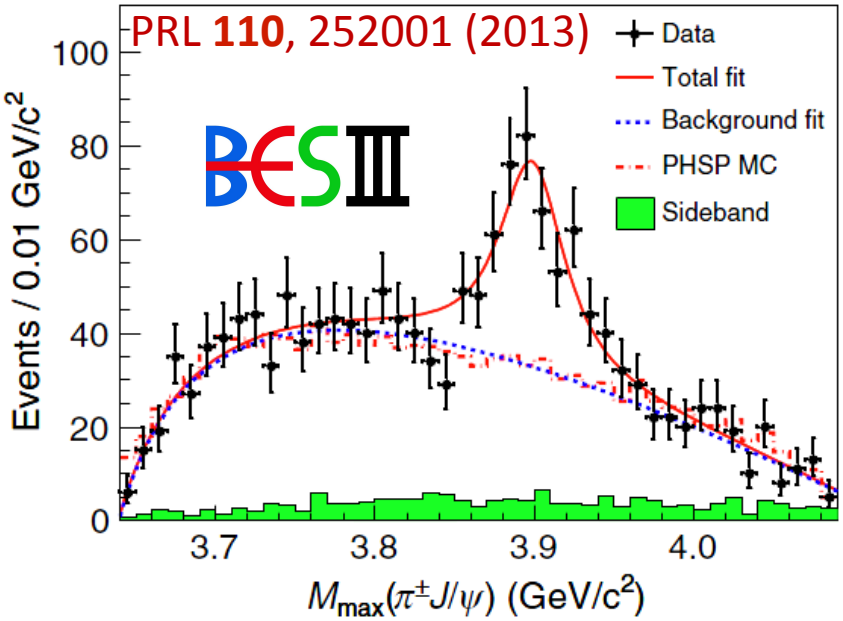
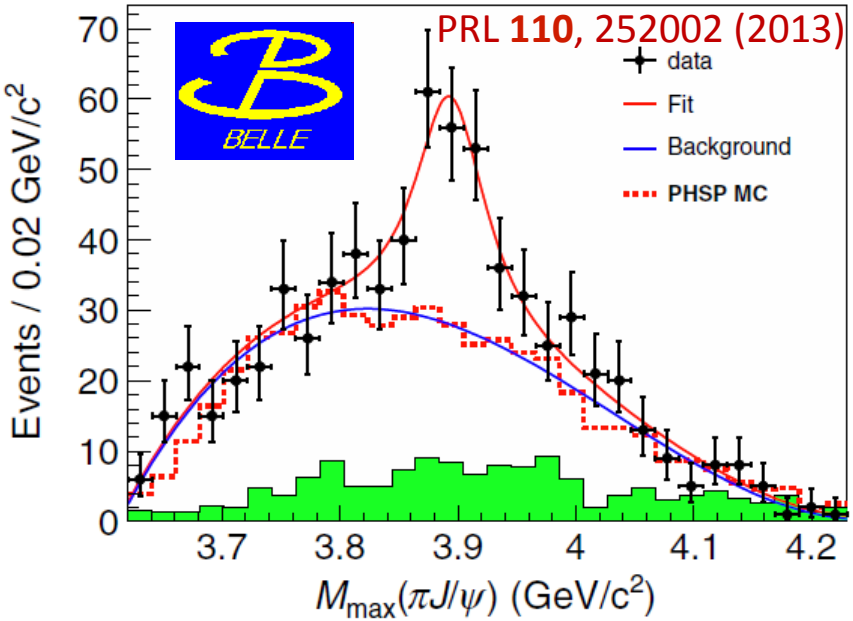


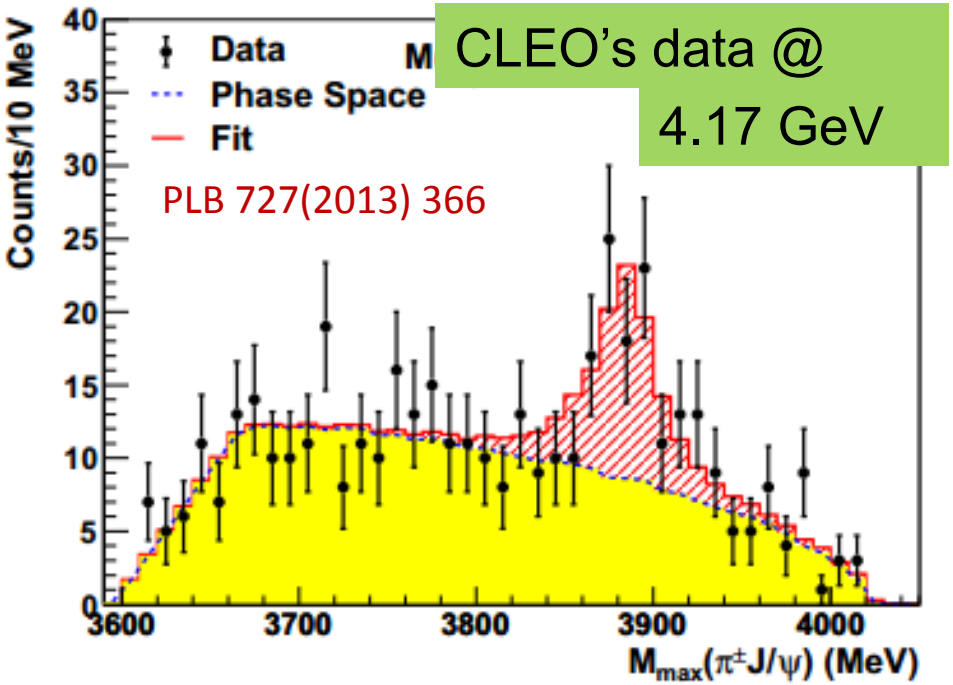


1. First stage, 1D fit to extract resonant parameters.
2. Divided by diagonal line of the dalitz plot and fit $M_{max}(\pi^\pm J/\psi)$ mass distribution; best way to avoid cross counting.
3. S-Wave Breit Wigner; p*q phase space factor; efficiency corrected.
4. M=(3899.0±3.6±4.9)MeV; Γ=(46±10±20)MeV.
5. Statistical significance: >8σ, discovery!

Good News



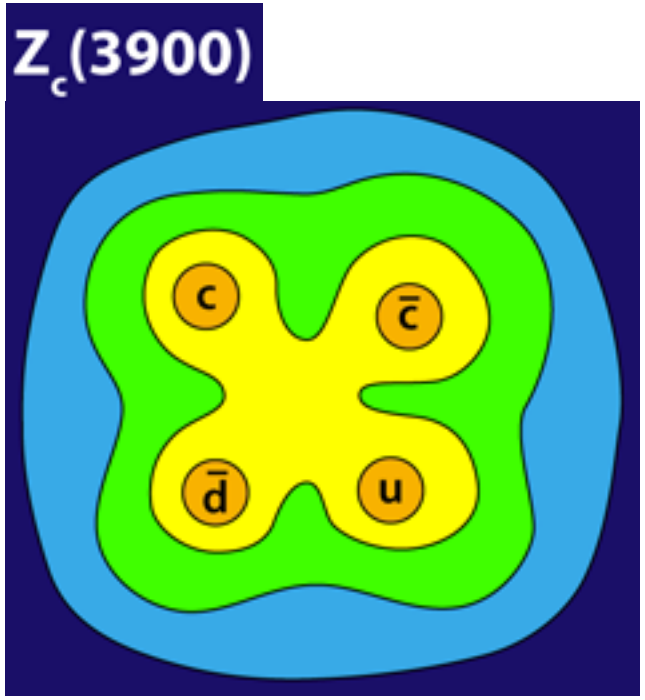




CLEO's data @ 4.17 GeV

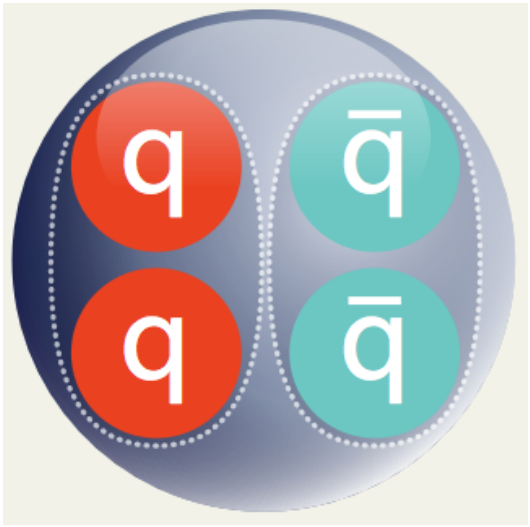
1. BESIII: M=(3899.0±3.6±4.9) MeV; Γ=(46±10±20)MeV
2. Belle: M=(3894.5±6.6±4.5) MeV; Γ=(63±24±26) MeV.
3. CLEO's data: M=3886±6±4 MeV, Γ=33±6±7 MeV.
4. $Z_c(3900)=Z(3900)^{\pm}$.

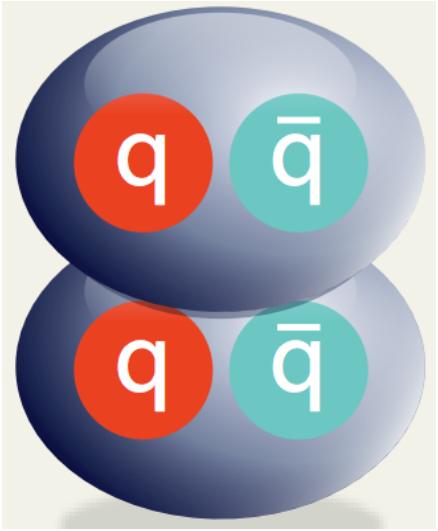
Exotic hadron



- Decay to charged pion ($\pi^{\pm}$) and charmonium (J/ψ)
- Carry electric charge, can't be normal charmonium state !
- Coupling to charmonium, must have charm and anti-charm inside !
- Minimal combination is 4 quarks…

Tetraquark or molecule like?





Exotic hadron

- Solid evidences from several experiments for the observation of $Z_c(3900)$ at the same time !

- Wide discussions about its nature.

Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

***Physics* looks back at the standout stories of 2013.**

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas

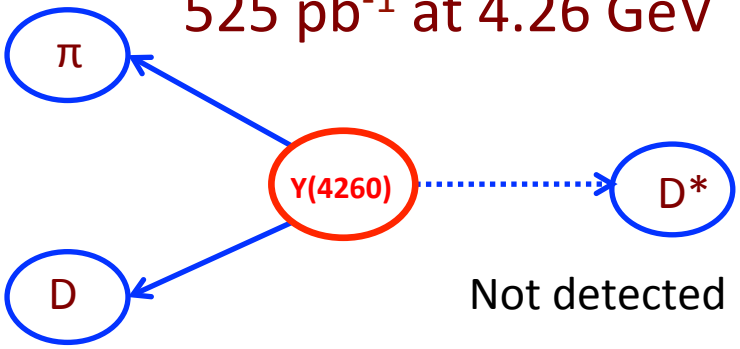
Images from popular *Physics* stories in 2013.

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

A series of charged charmoniumlike states at BESIII

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



$\pi^{\pm}(DD^*)^{\mp}$ includes 4 decay modes:

1) $\pi^+ D^0 D^{*-} + c.c.,\ D^{*-} \rightarrow \pi^0 D^-$

2) $\pi^+ D^- D^{*0} + c.c.,\ D^{*0} \rightarrow \gamma/\pi^0 D^0$

We only reconstruct the bachelor pion and a single D.

Type I: If we tag a π^+ and D^0, we select the events:

$\pi^+ D^0 D^{*-}$ and $\pi^+ D^- D^{*0}$ $(D^{*0} \rightarrow \gamma/\pi^0 D^0)$

Type II: If we tag a π^+ and D^-, we select the events:

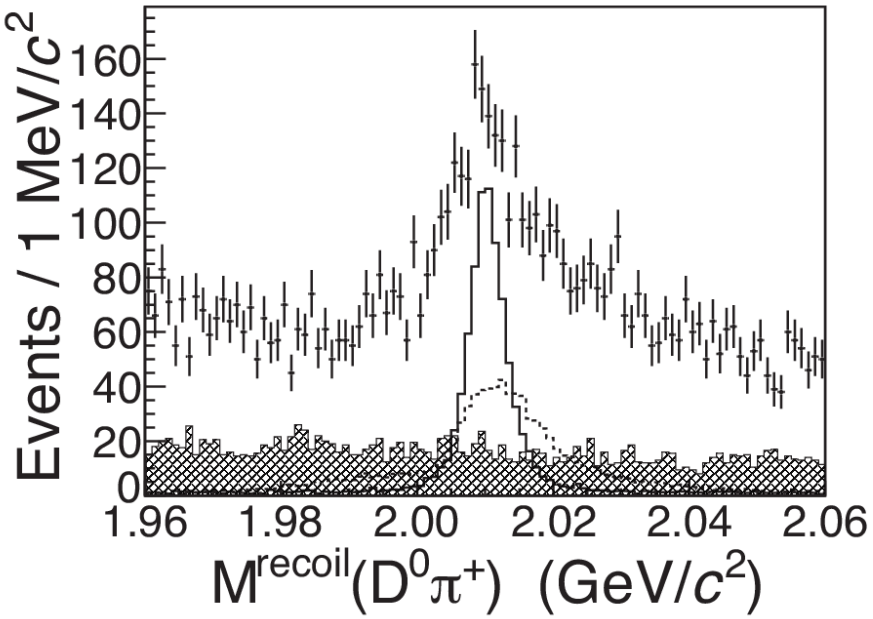
$\pi^+ D^0 D^{*-}$ $(D^{*-} \rightarrow \pi^0 D^-)$ and $\pi^+ D^- D^{*0}$ $(D^{*0} \rightarrow \gamma/\pi^0 D^0)$

- Sometimes there are cross feeding events, but it's OK.

Recoil mass of πD

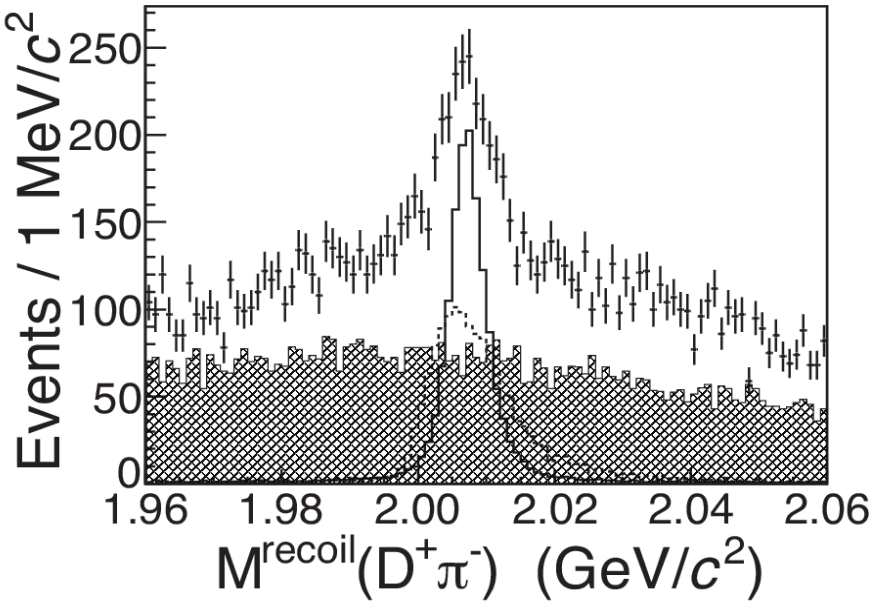
I: π^+D^0 tagging method

Dots with error bars: Data
Solid: $e^+e^-\to\pi^+D^0D^{*-}$
Dash: $e^+e^-\to\pi^+D^-D^{*0}$, where DD* from Z_c
Hatch: Events from D^0 sideband



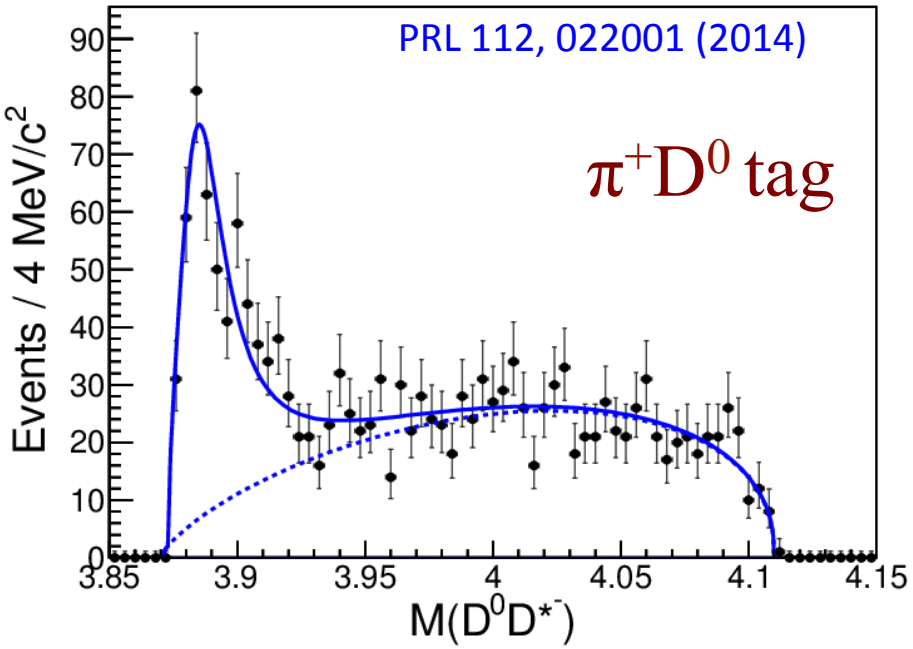
II: π^+D^- tagging method

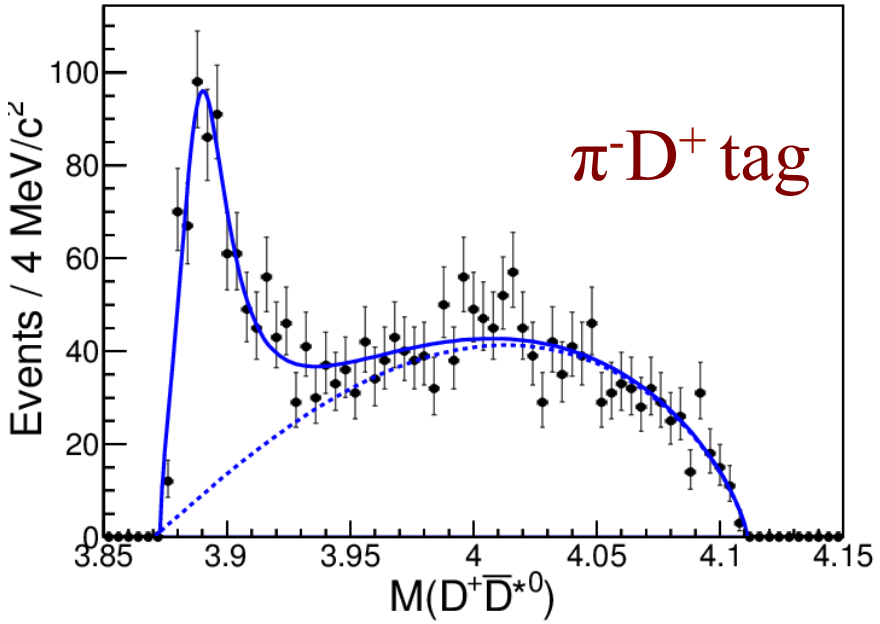
Dots with error bars: Data
Solid: $e^+e^-\to\pi^+D^-D^{*0}$
Dash: $e^+e^-\to\pi^+D^0D^{*-}$, where DD* from Z_c
Hatch: Events from D^- sideband



- Clear signal of D*
- Mass constraint to D*, $\chi^2<30$

Mass Spectrum by recoil π





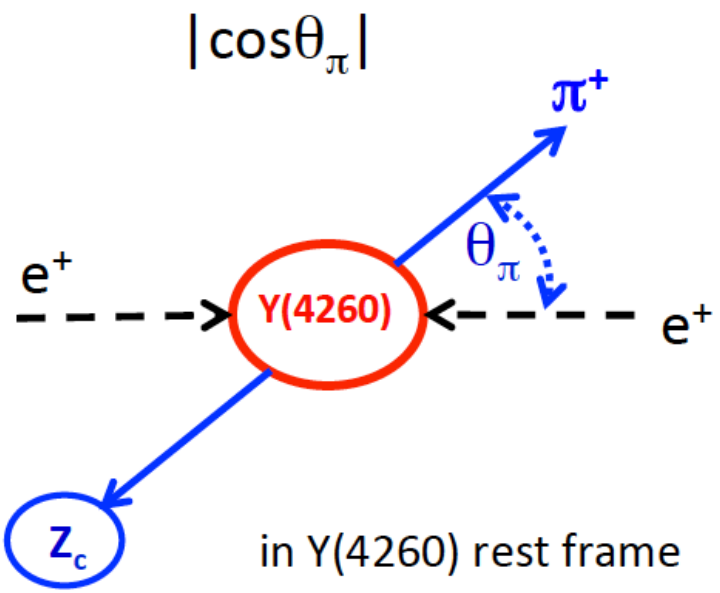
- Peak near threshold.
- Angular distribution (πD) disfavor DD_1 component.
- Fit with mass dependent BW, report pole position.
- Polynomial background.

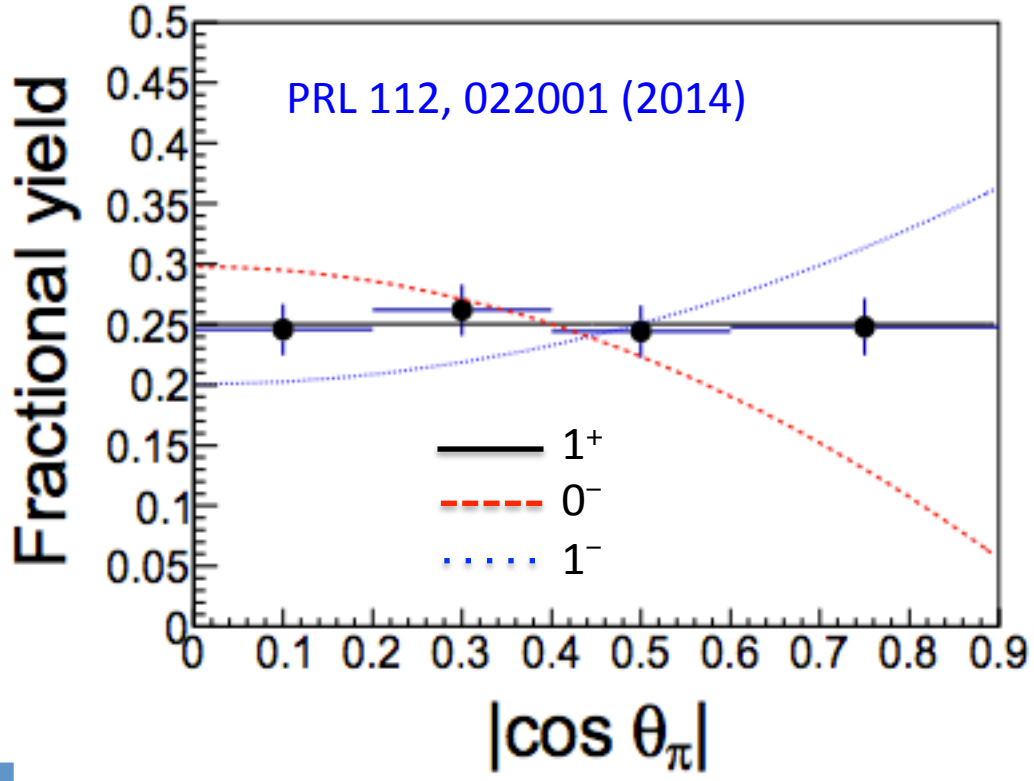
$Z_c(3885)=Z_c(3900)$

Production rate are much higher than $\pi^{\pm}J/\psi$!

	$Z_c(3885) \to D\bar{D}^*$
Mass (MeV/c^2)	$3883.9 \pm 1.5 \pm 4.2$
Γ (MeV)	$24.8 \pm 3.3 \pm 11.0$
$\sigma \times \mathcal{B}$ (pb)	$83.5 \pm 6.6 \pm 22.0$

Spin-Parity of $Z_c(3885)$





J^P	L	$dN/d|\cos\theta_\pi|$
1^+	S-wave	flat
0^-	P-wave	$\sin^2\theta_\pi$
1^-	P-wave	$1+\cos^2\theta_\pi$

Favor $J^P=1^+$

$Z_c(4020)$ & $Z_c(4025)$

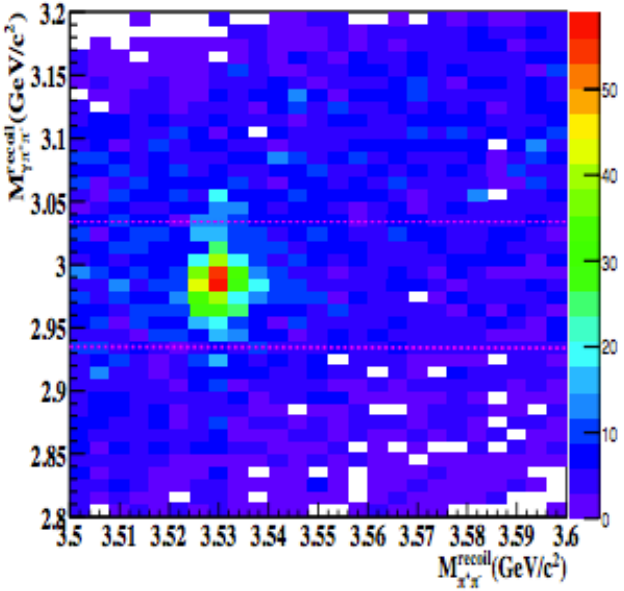
$e^+e^- \rightarrow \pi^+\pi^- h_c$

Data above/near 4 GeV, with luminosity 3.3 fb^{-1}

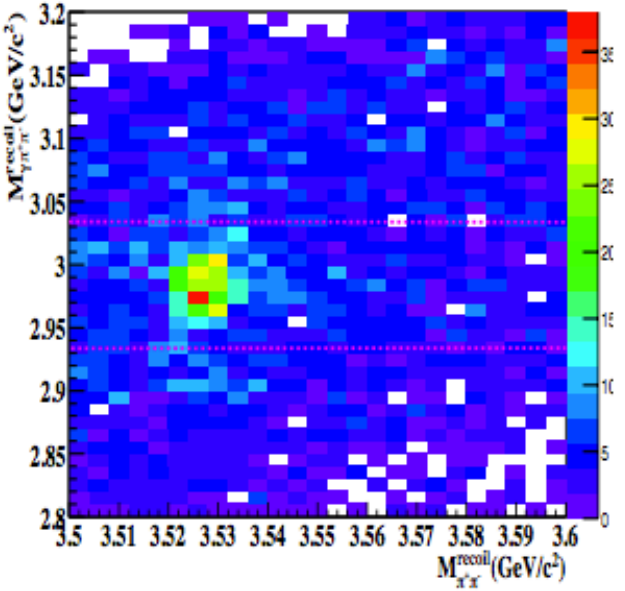
- $h_c \rightarrow \gamma\eta_c$, $\eta_c \rightarrow$hadrons [16 exclusive decay modes]
  - p pbar, $\pi^+\pi^- K^+K^-$, $\pi^+\pi^-$p pbar, $2(K^+K^-)$, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$
  - $2(\pi^+\pi^-)K^+K^-$, $K_S^0K^+\pi^-$+c.c., $K_S^0K^+\pi^-\pi^+\pi^-$+c.c., $K^+K^-\pi^0$
  - ppbarπ^0, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)\eta$, $2(\pi^+\pi^-\pi^0)$
  - ~50% h_c decay & 40% of η_c decay.

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})
3.900	52.8
4.009	482.0
4.090	51.0
4.190	43.0
4.210	54.7
4.220	54.6
4.230	1090.0
4.245	56.0
4.260	826.8
4.310	44.9
4.360	544.5
4.390	55.1
4.420	44.7

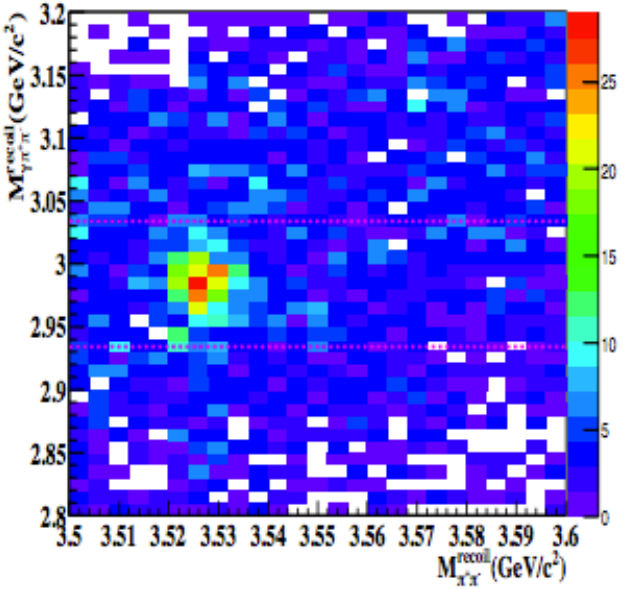
4230 MeV



4260 MeV

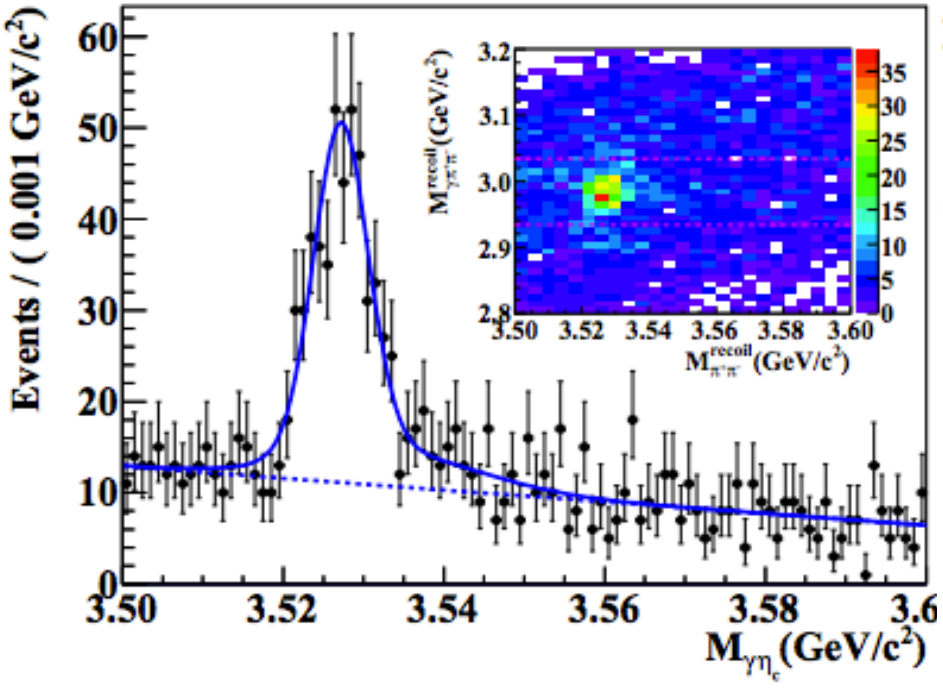


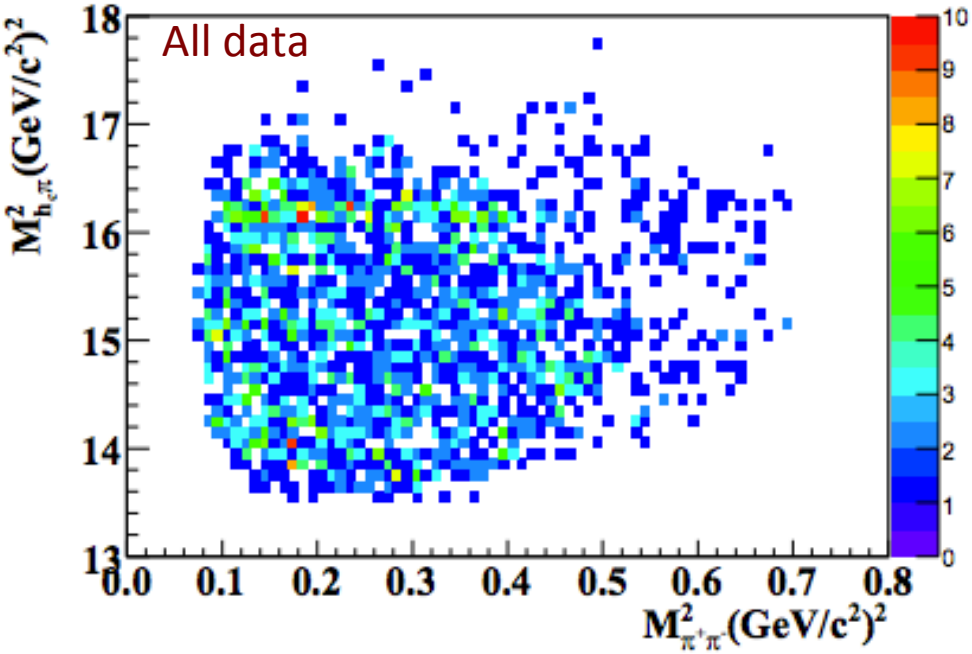
4360 MeV



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

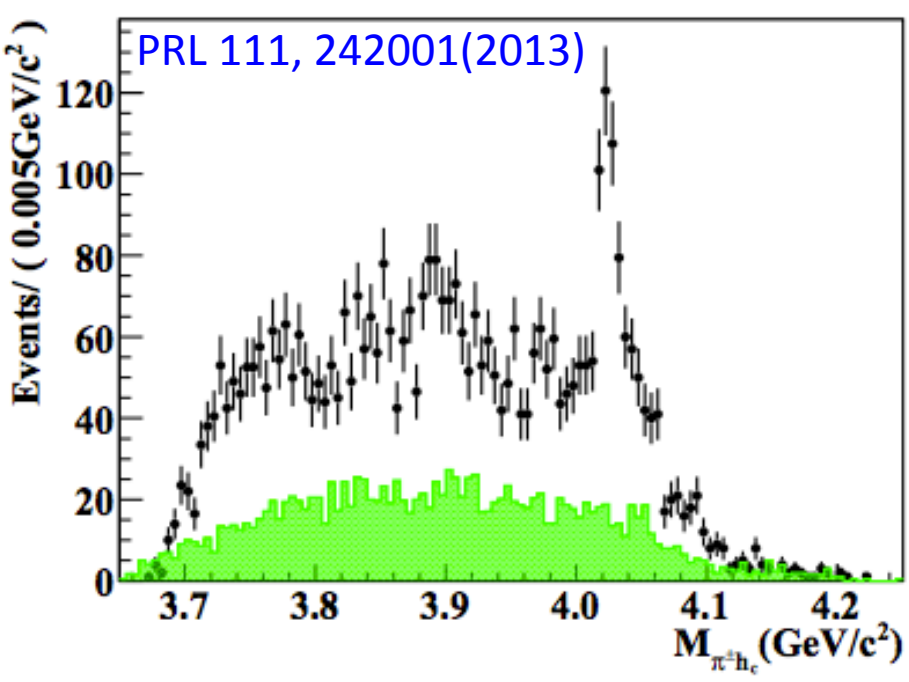
4.26 GeV data

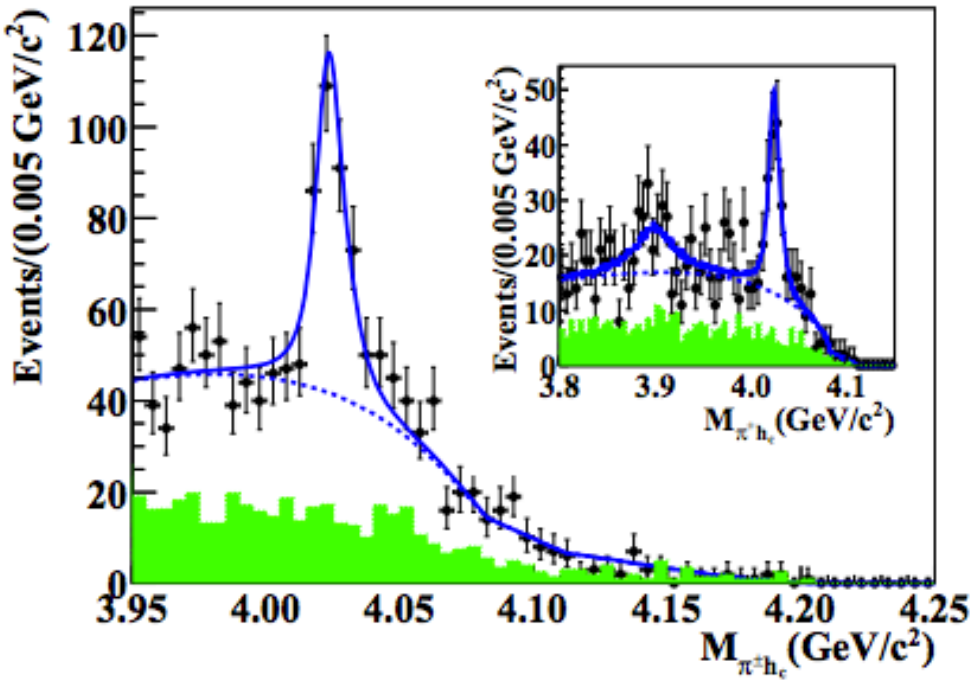




1. Clear h_c signal in data.
2. h_c signal region: [3.518, 3.538] GeV, sideband: [3.49, 3.51] & [3.56, 3.58] .
3. Events accumulate around $M(\pi^\pm h_c)$~16 GeV^2

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

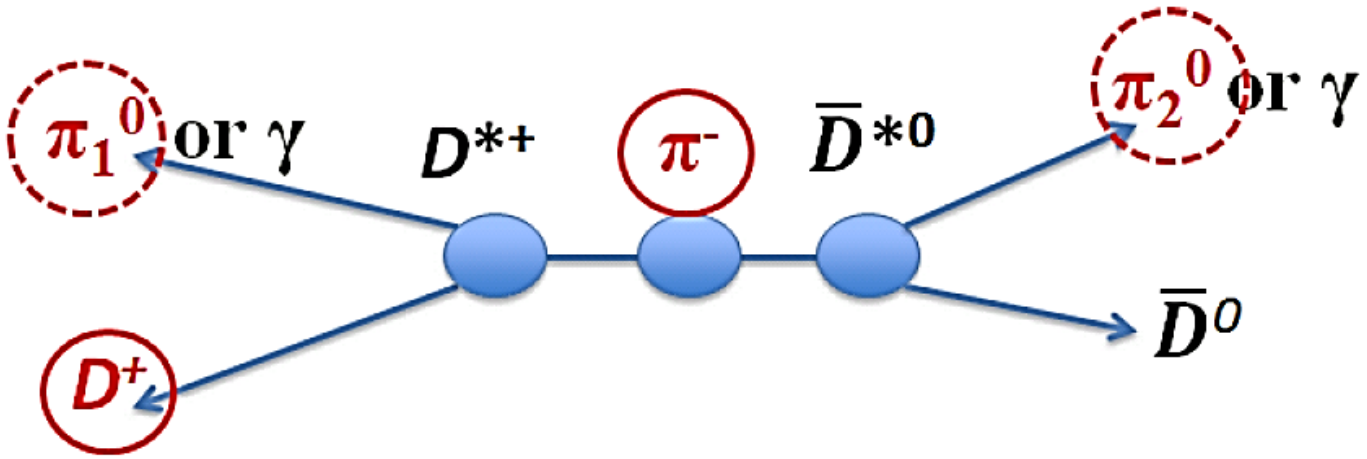




1. 1D projection of $M(\pi^\pm h_c)$ invariant mass distribution.
2. Signal: BW function convolving Gaussian+bkg; efficiency has been applied; phase space included.
3. $M[Z_c(4020)]=(4022.9\pm0.8\pm2.7)$ MeV; $\Gamma[Z_c(4020)]=(7.9\pm2.7\pm2.6)$ MeV.

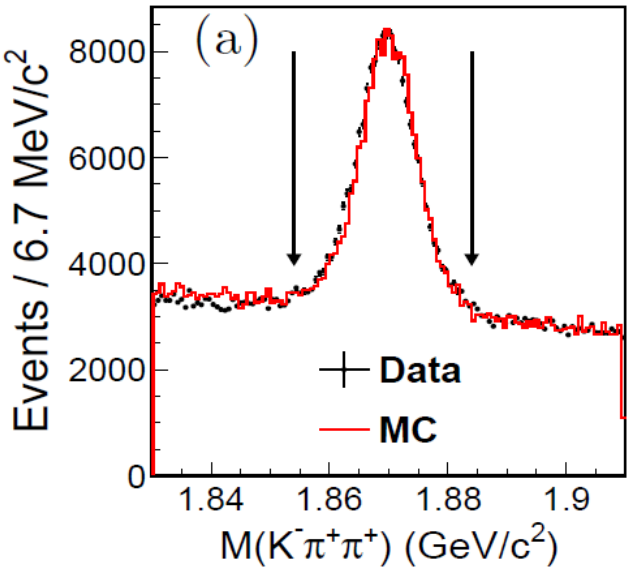
$e^+e^- \to \pi^- (D^*\bar{D}^*)^+ + c.c.$ at BESIII

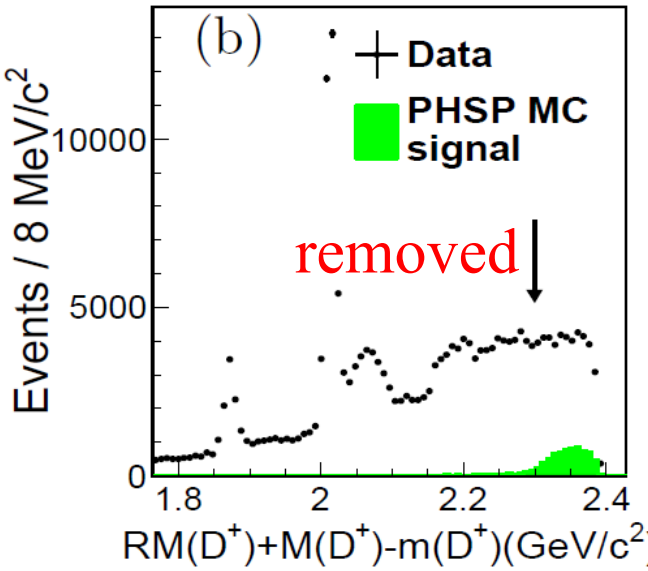
- 827 pb^{-1} data at E_{cm}=4.26 GeV
- Tag a D^+ and a bachelor π^-, reconstruct one π^0 to suppress the background.



Topology of the decays of the signal process. Thick line circled D^+ and π^- are detected in the final states and at least one of the dashed line circled π_1^0 or π_2^0 is tagged.

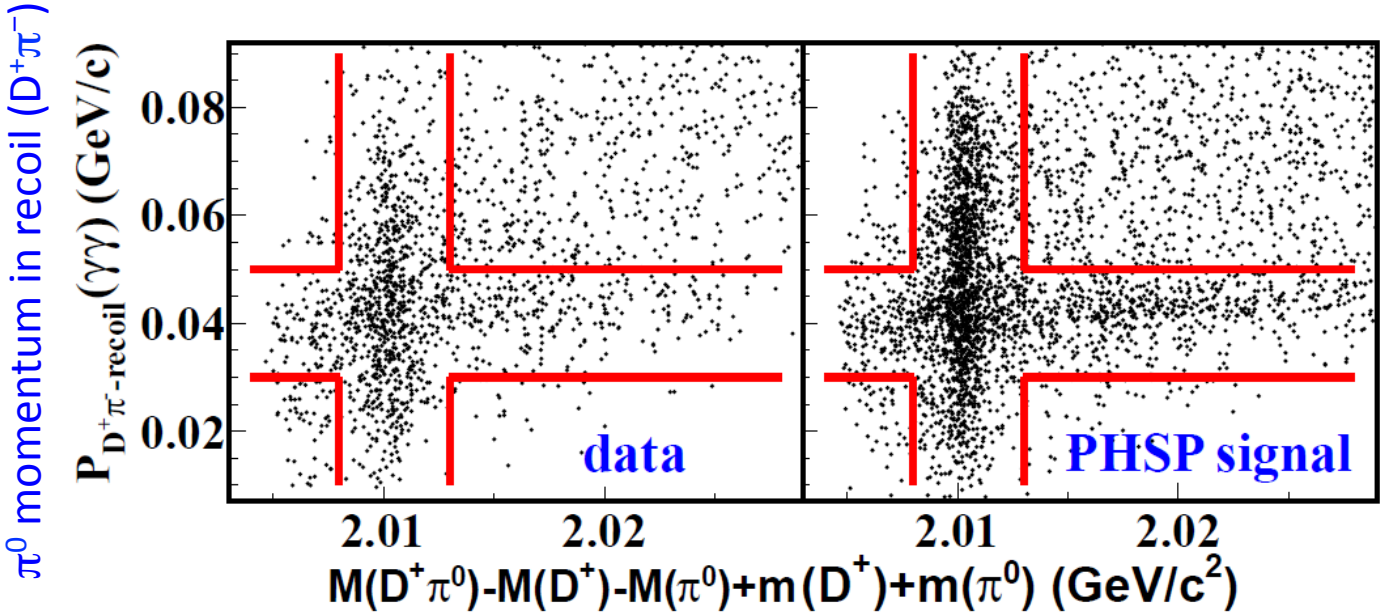
$e^+e^- \to \pi^- (D^*D^*)^+ + c.c.$ at BESIII



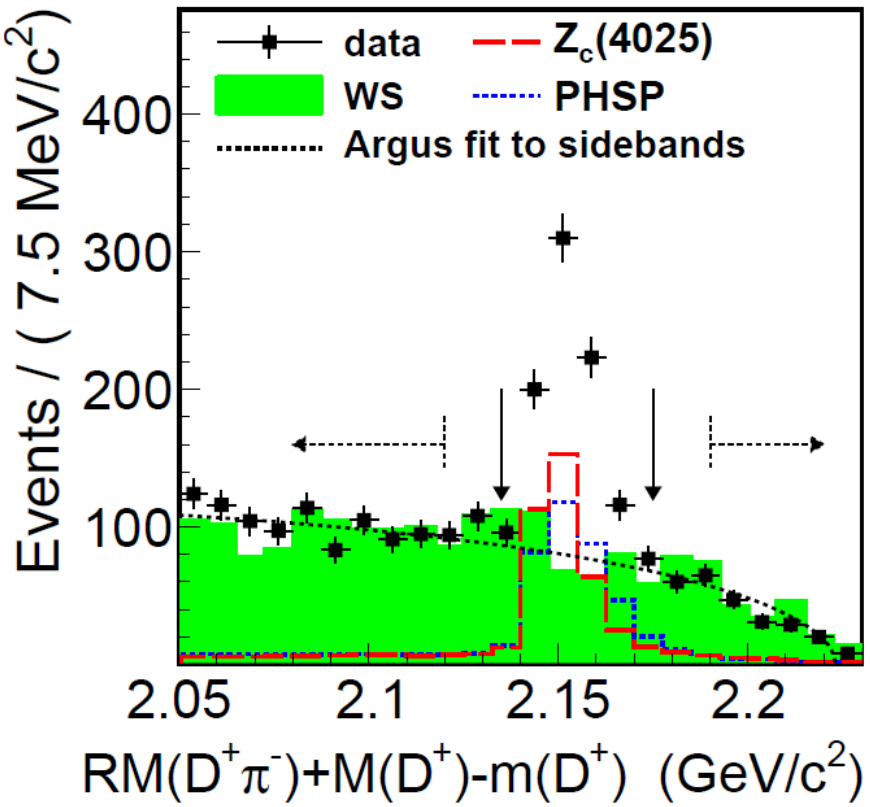


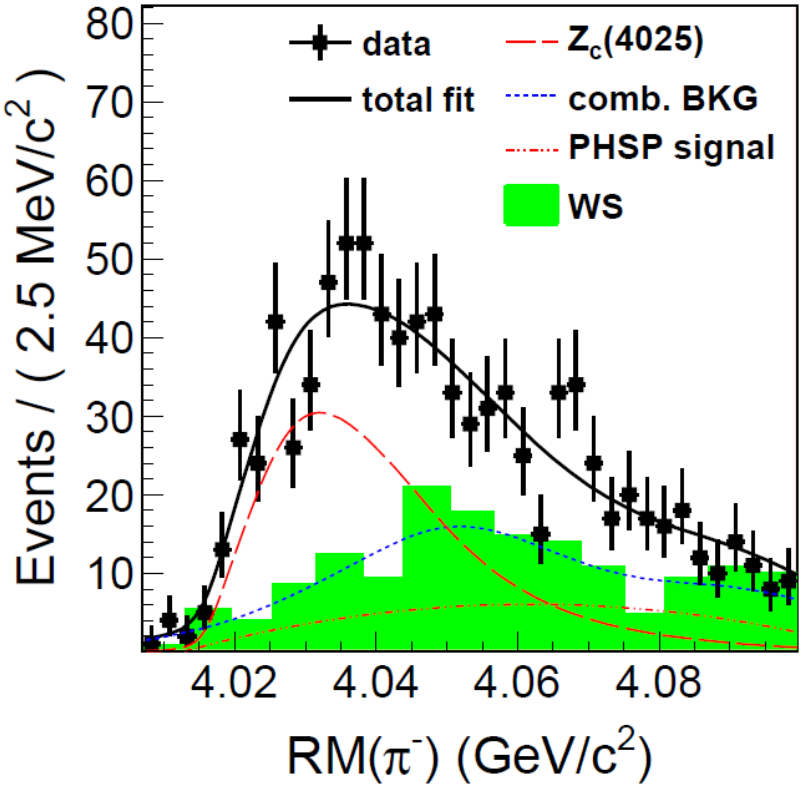
Remove DD, DD^*, D^*D^*, D_sD_s, …

RM=(Recoil Mass)



$e^+e^- \to \pi Z_c(4025) \to \pi^- (D^*\bar{D}^*)^+ + c.c.$





Fit to $\pi^\pm$ recoil mass (RM) yields 401±47 $Z_c(4025)$ events.

M[$Z_c(4025)$] =(4026.3±2.6±3.7) MeV; Γ[$Z_c(4025)$] =(24.8±5.6±7.7) MeV

$$\sigma(e^+e^- \to \pi^\pm (D^* \bar{D}^*)^\mp) = (137 \pm 9 \pm 15)\ \text{pb}$$

Significance >10σ

$$R = \frac{\sigma(e^+e^- \to \pi^\pm Z_c^\mp(4025) \to \pi^\pm (D^* \bar{D}^*)^\mp)}{\sigma(e^+e^- \to \pi^\pm (D^* \bar{D}^*)^\mp)} = (65 \pm 9 \pm 6)\%$$

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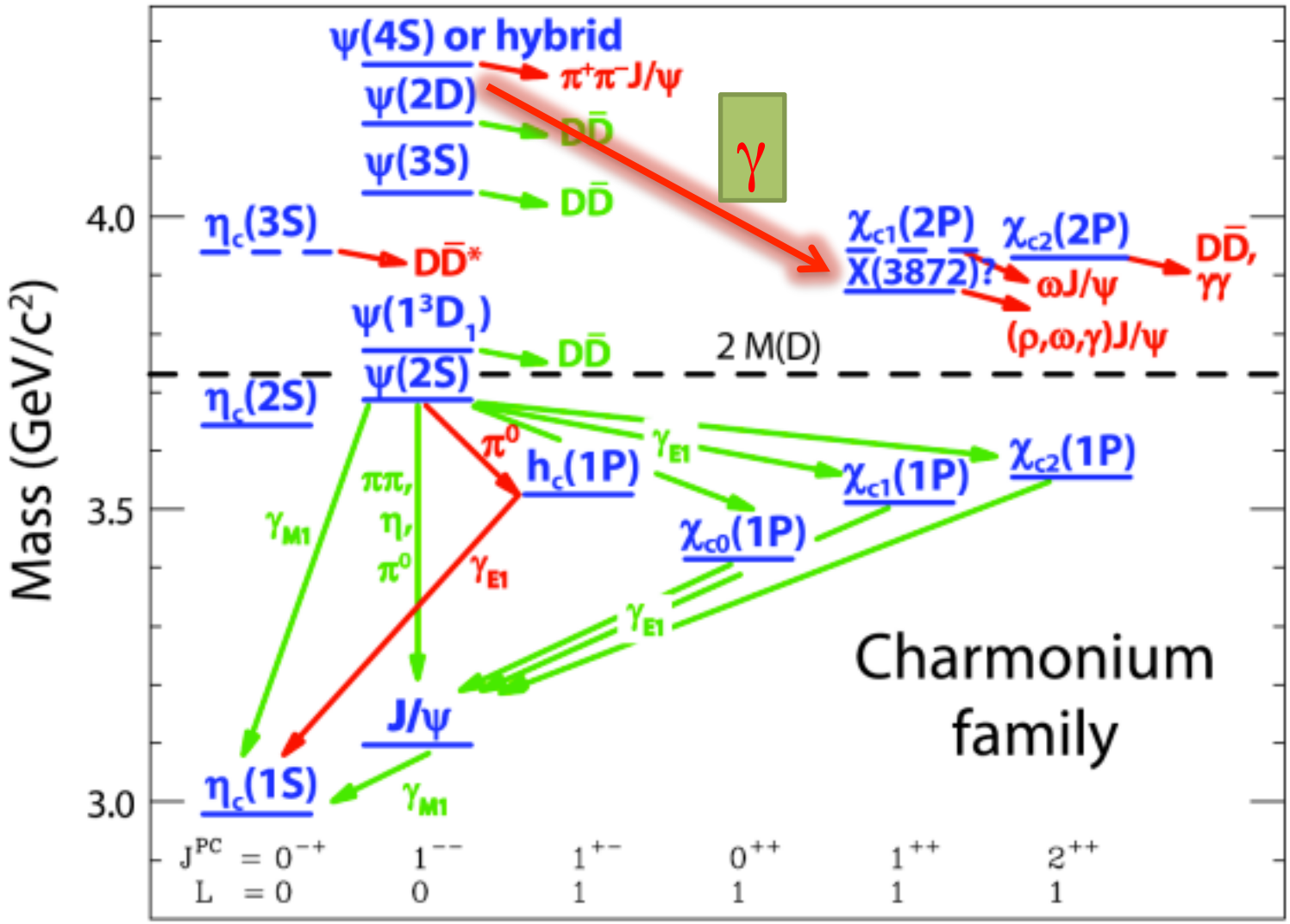
$Y(4260) \rightarrow \gamma X(3872)$

Produce X(3872) at BESIII

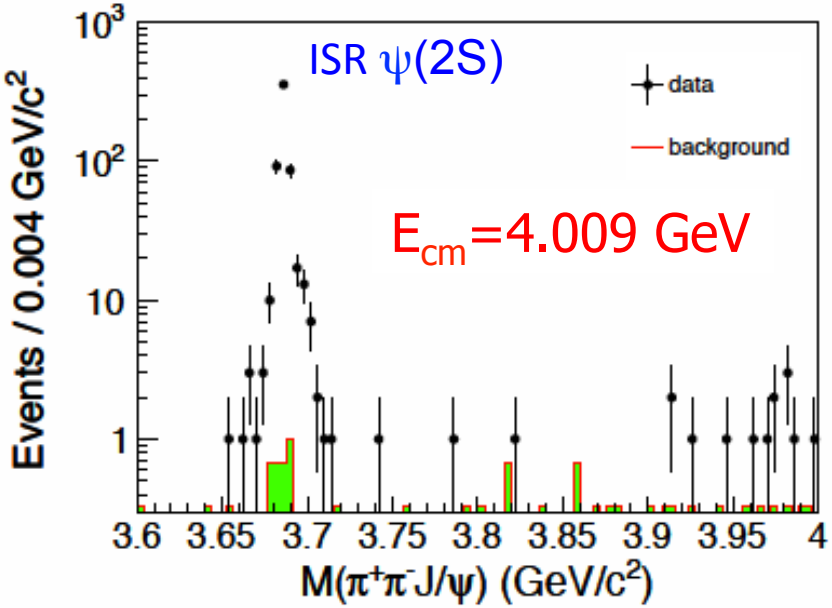


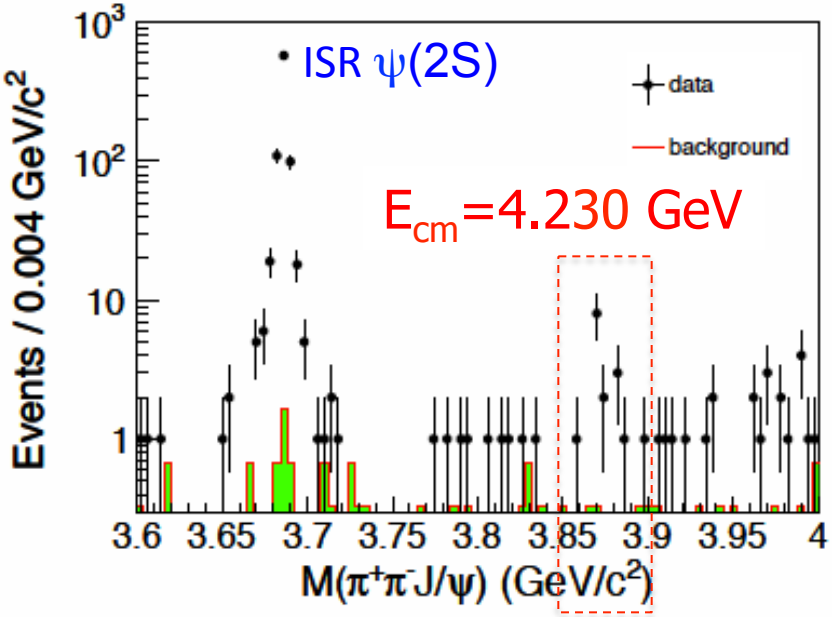
BESIII can produce lots of vector charmonium and charmoniumlike state.

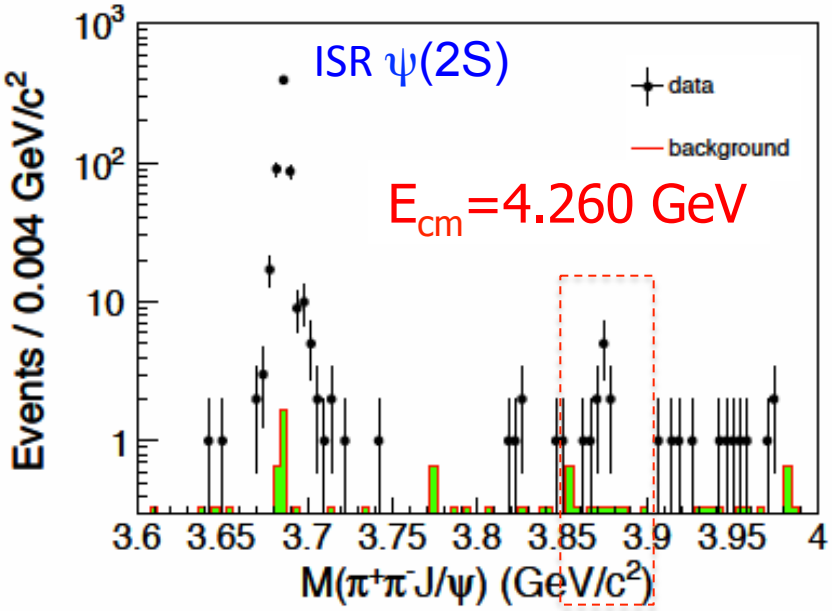
ψ(4040)
Y(4260)
Y(4360)
…

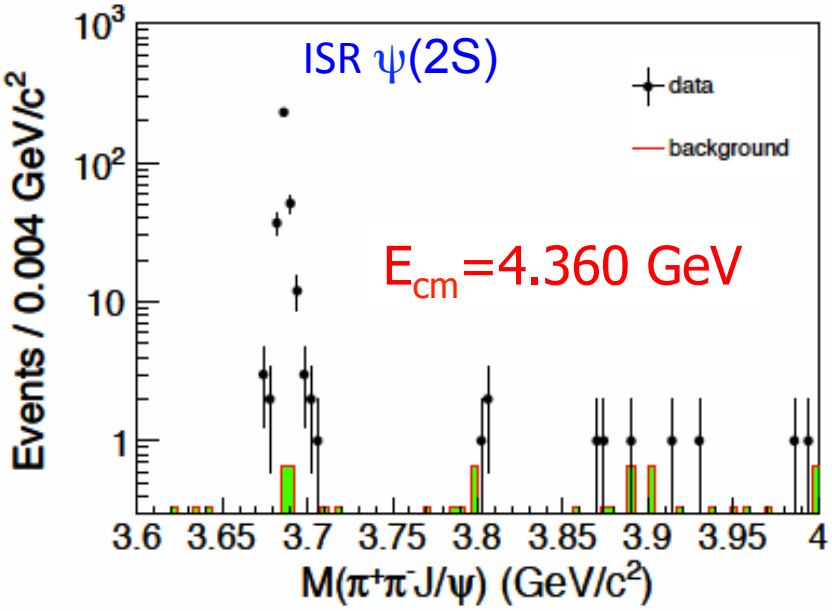
LHCb:
$J^{PC}=1^{++}$

$e^+e^- \rightarrow \gamma(\pi^+\pi^- J/\psi)$ at BESIII

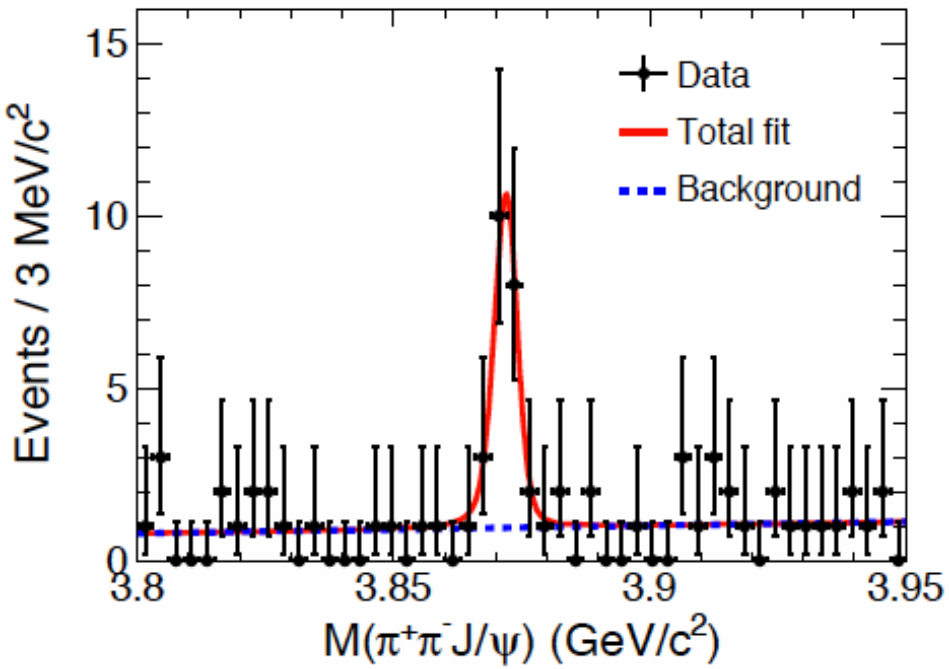


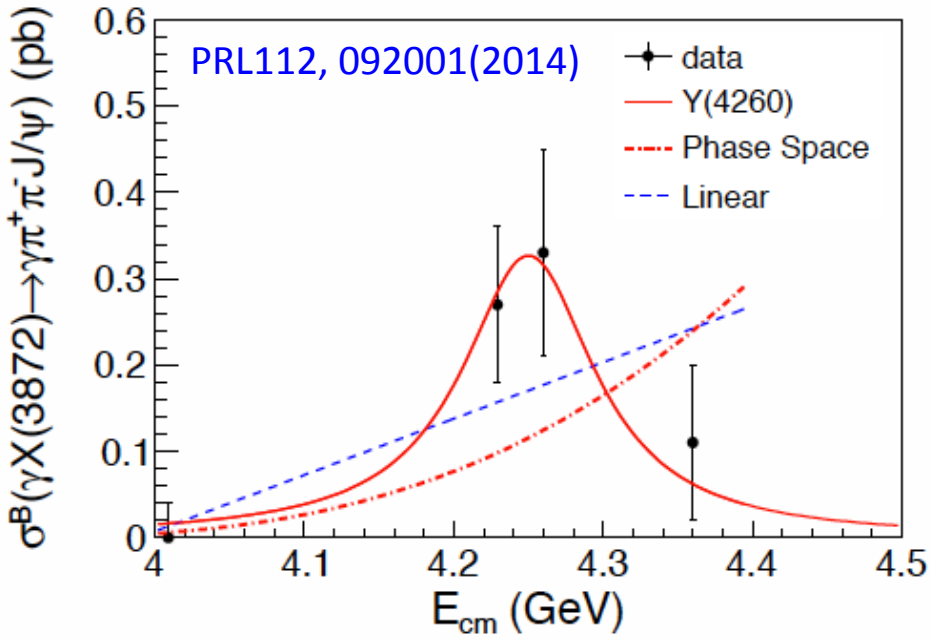






Y(4260)→γX(3872)





M=(3871.9±0.7±0.2) MeV

Γ<2.4 MeV

Significance: 6.3 σ

Fit with:

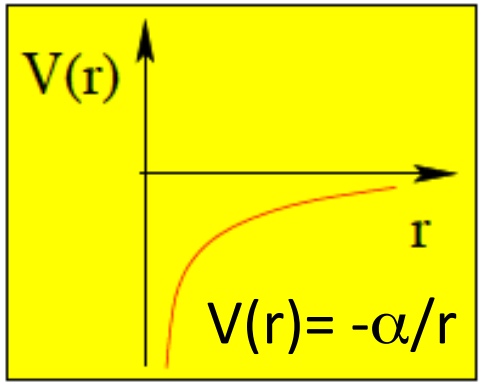
1. Y(4260): χ^2/ndf=0.49/3
2. E1 PHSP: χ^2/ndf=8.7/3
3. Linear: χ^2/ndf=5.5/2

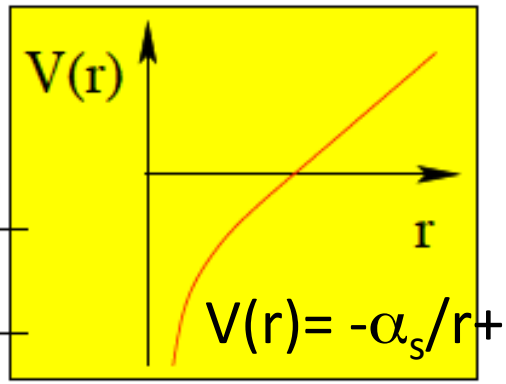
$$\frac{\mathcal{B}[Y(4260)\to\gamma X(3872)]}{\mathcal{B}(Y(4260)\to\pi^+\pi^- J/\psi)} = 0.1$$

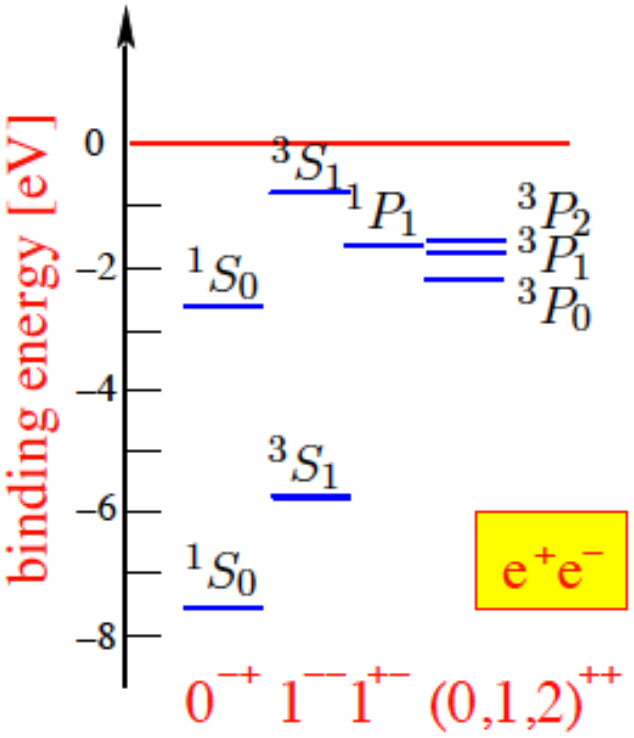
What's next @ BESIII

1. PWA of Y(4260)→$\pi^+\pi^-J/\psi$ with more data, more precise mass and width measurement of $Z_c(3900)$ and its Spin-parity.
2. Neutral partners, such as Z^0 and $Z^{0\prime}$
3. Line shape study of $\pi^+\pi^-J/\psi$, also $\pi Z_c(3900)$.
4. Try to distinguish different multi-quark models: tetraquark, hadron molecule.
5. Search for new decay modes, production rate…
6. Other puzzling XYZ states…

Some words…

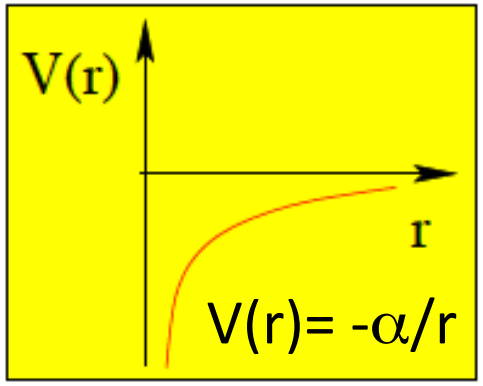


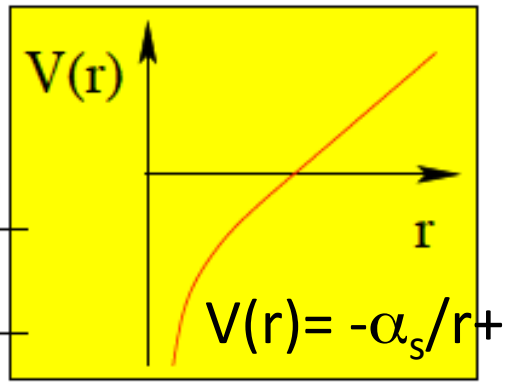




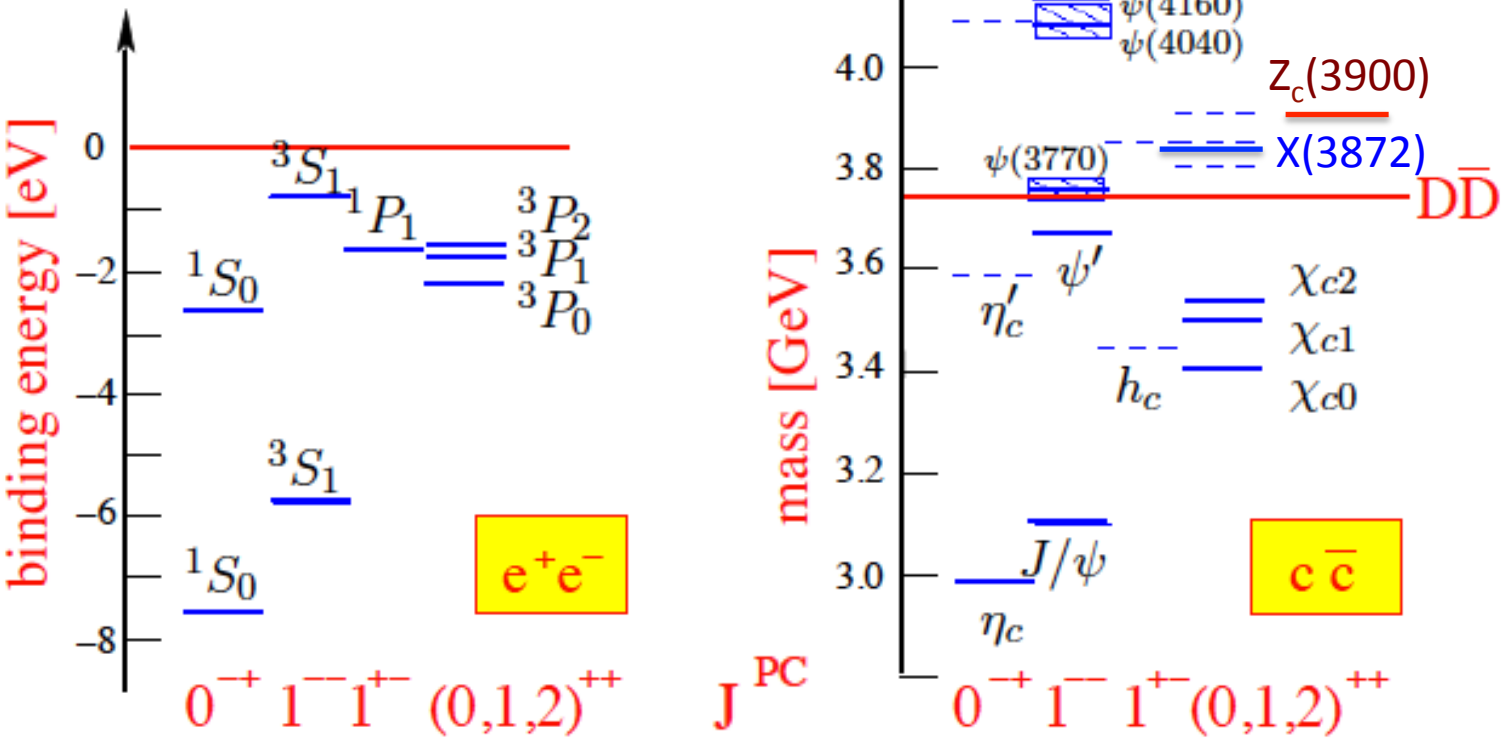
Spectrum and decay are well described by potential model.

Some words…

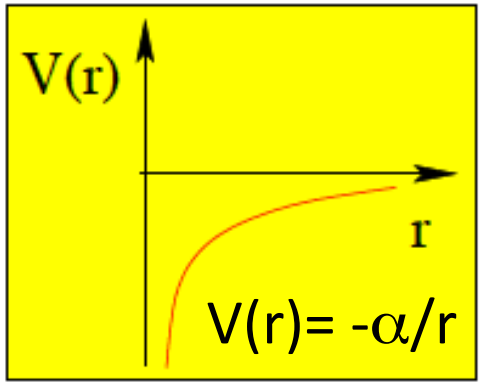


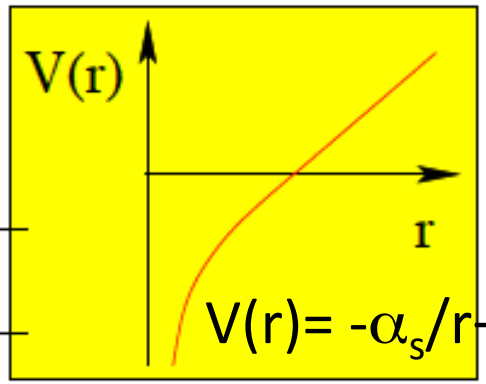


XYZ particles



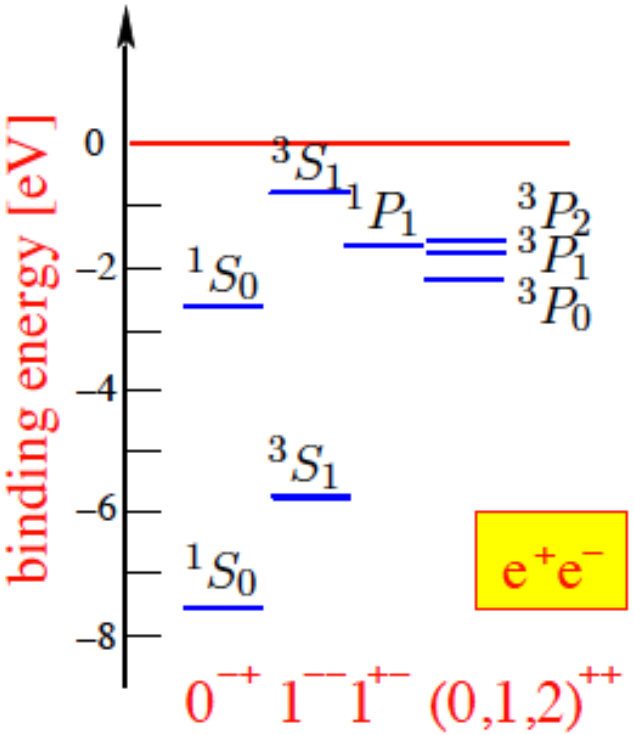
Some words…





- Far from mature
- Identify the XYZ spectrum and decay behavior.

XYZ particles



Summary

- BESIII observed a charged Charmoniumlike state $Z_c(3900)$.
- Possible partner particle $Z_c(4020)$ & $Z_c(4025)$ also found.
- Observed $Y(4260) \rightarrow \gamma X(3872)$ radiative transition for the first time.
- Understand them with more data & effort.

Thank you !