Review of X, Y and Z particles in experiment

Zhiqing Liu

Johannes Gutenberg University
Mainz

liuz@uni-mainz.de

GDR-PH-QCD Groupe II, Orsay, 6th Oct, 2014

Outline

- Introduction
- Experiments: Belle, BaBar, LHCb and BESIII…
- Charmonium(like) states

  Stories of "X(3872) and Y(4260)"

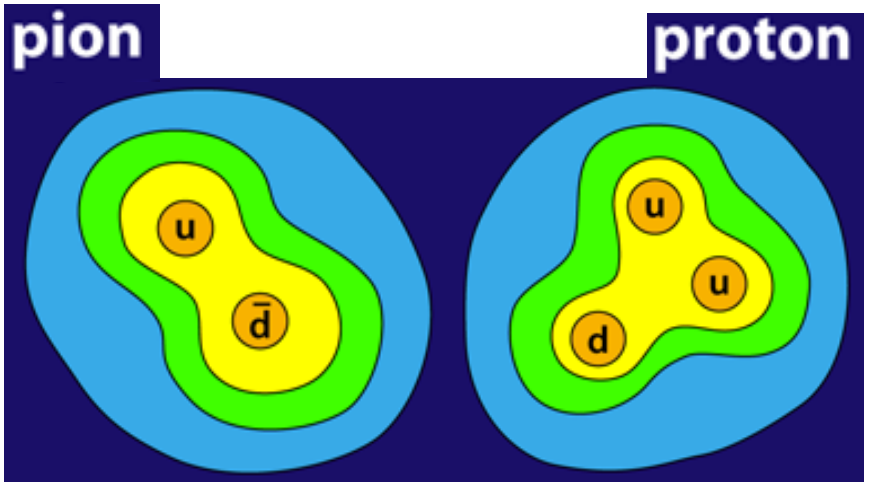
  New charged "Z_c(3900)" and "Z_c(4020)"
- Bottomonium(like) states

  Z_b(10610) and Z_b(10650)
- Summary

Hadrons: normal & exotic

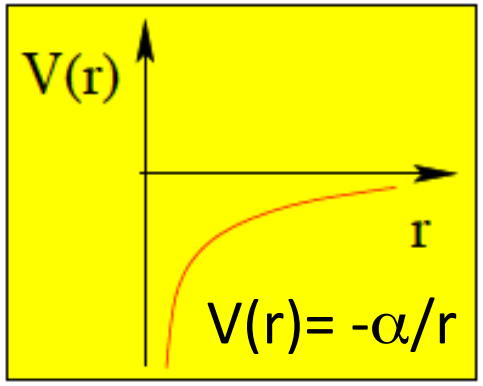
- Hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks

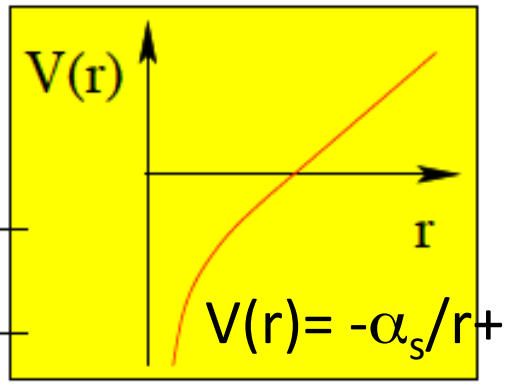
Quark model:



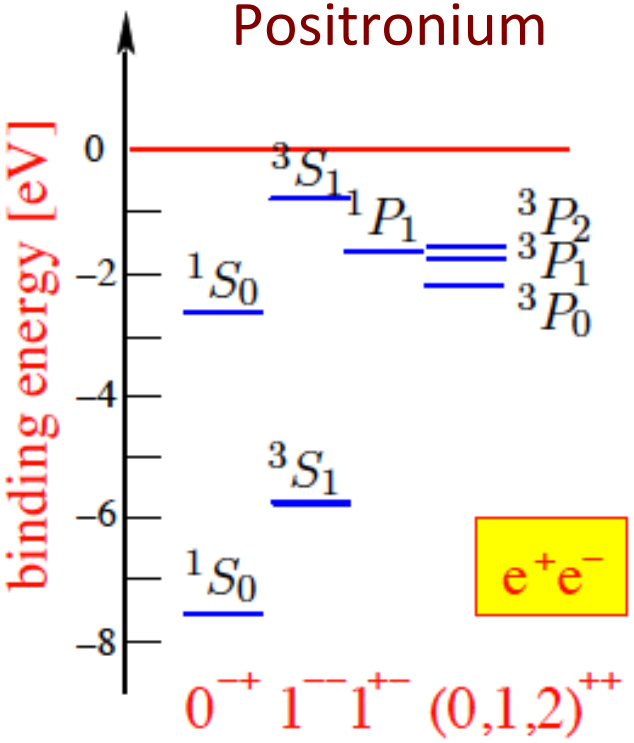
- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - Glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - Hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - Molecule : bound state of more than 2 hadrons
  - …

Charmonium





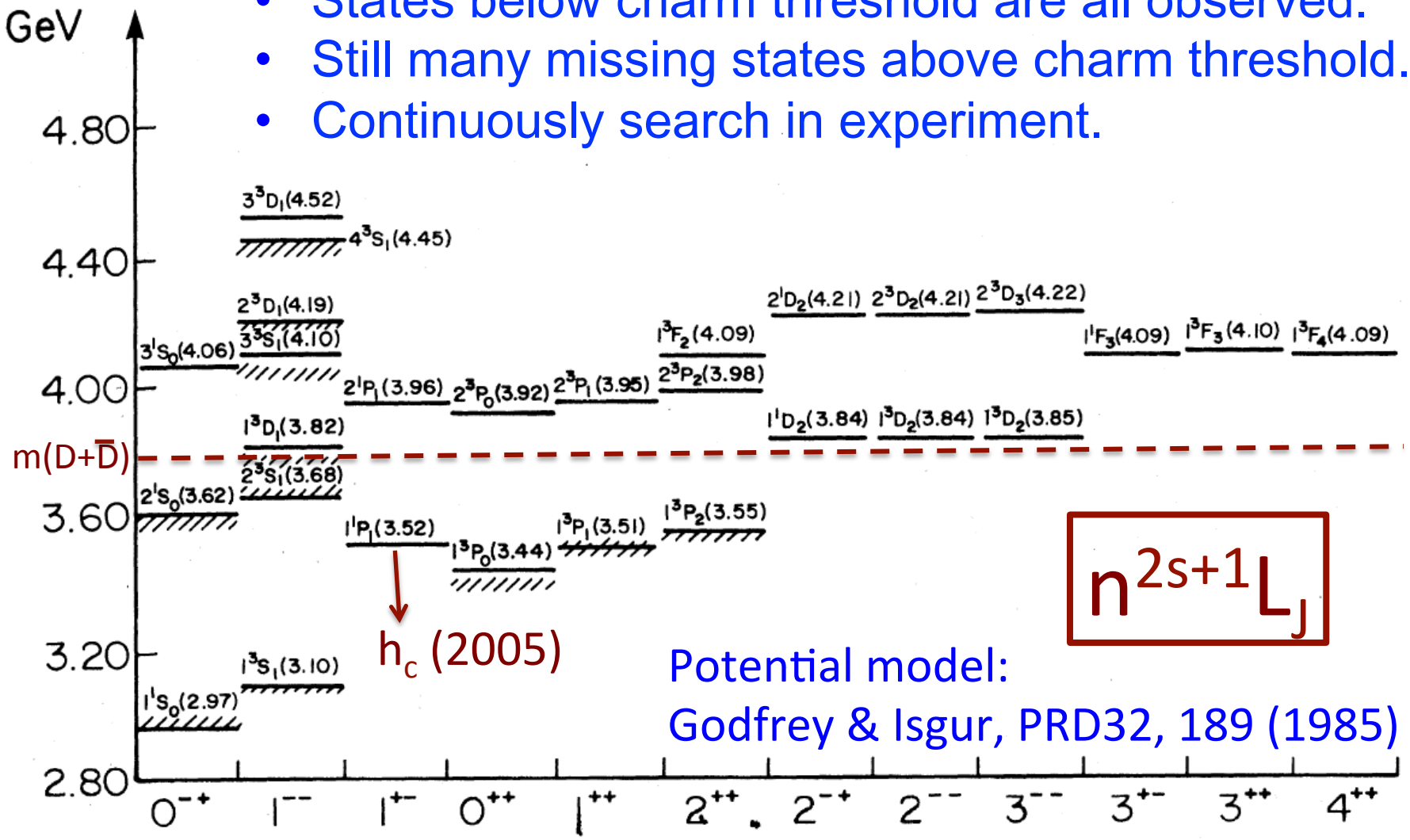
Positronium



Potential Model

Charmonium

- States below charm threshold are all observed.
- Still many missing states above charm threshold.
- Continuously search in experiment.



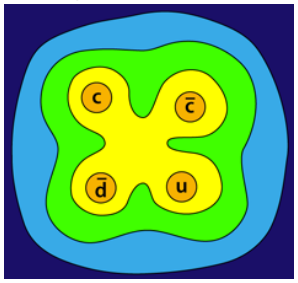
$n^{2s+1}L_J$

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)

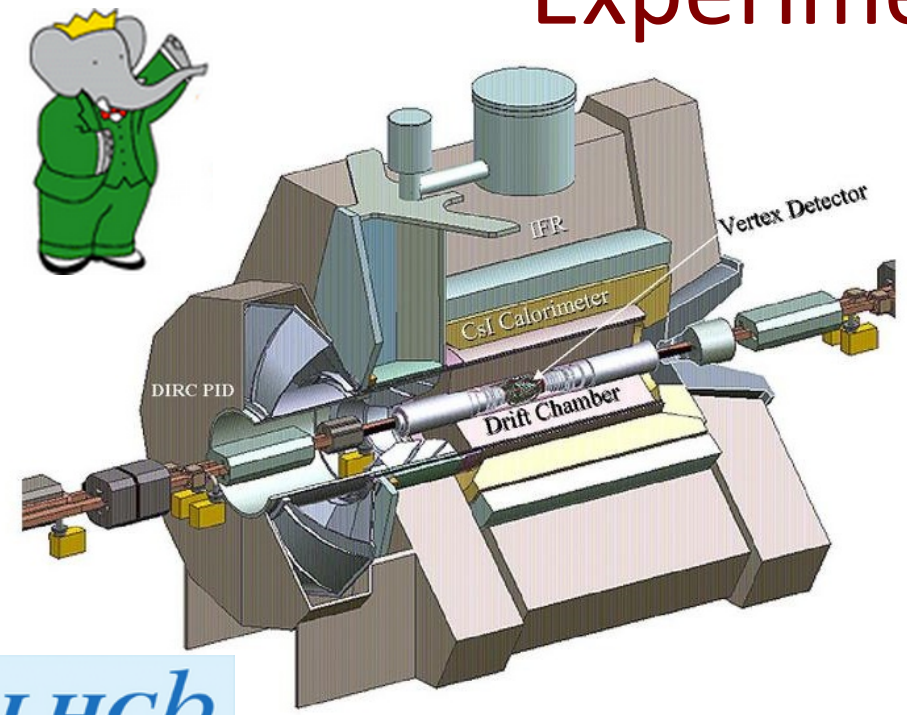
XYZ(3940)

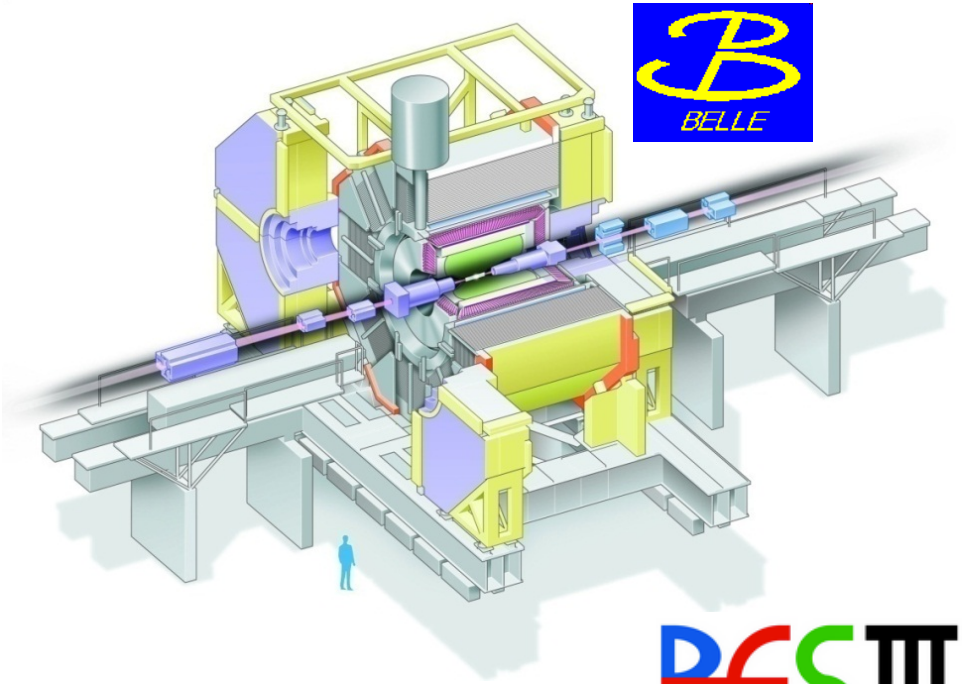
Z(4430)
Z(4250)
Z(4050)
…

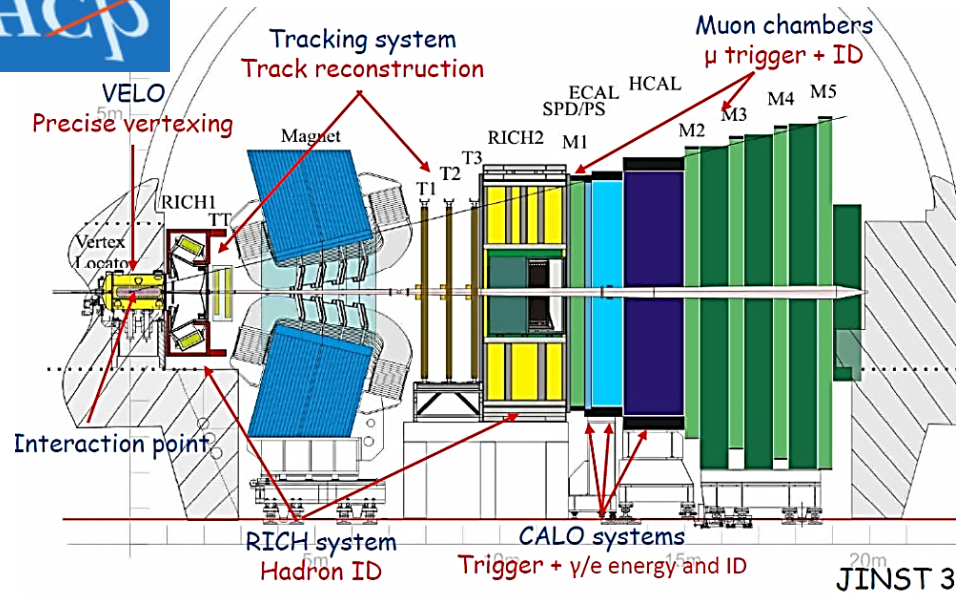
Charmonium?
Hybrid?
Tetraquark?
Molecule?
…

Godfrey & Isgur, PRD32, 189 (1985)

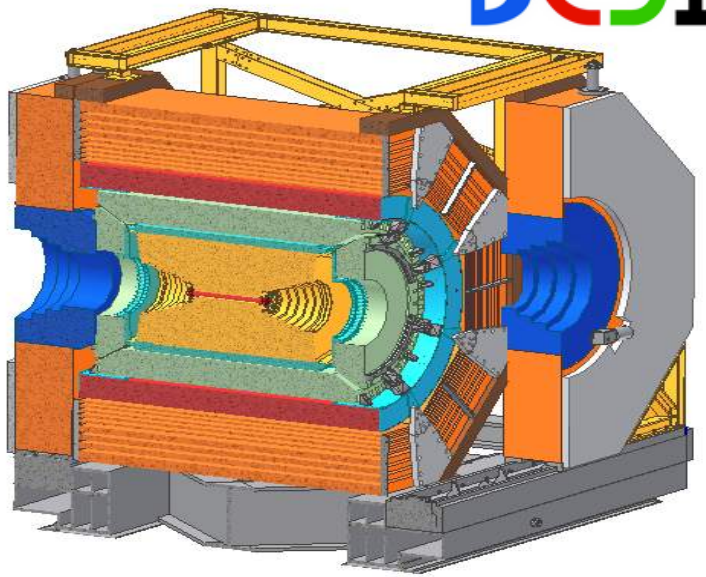
Experimental facilities





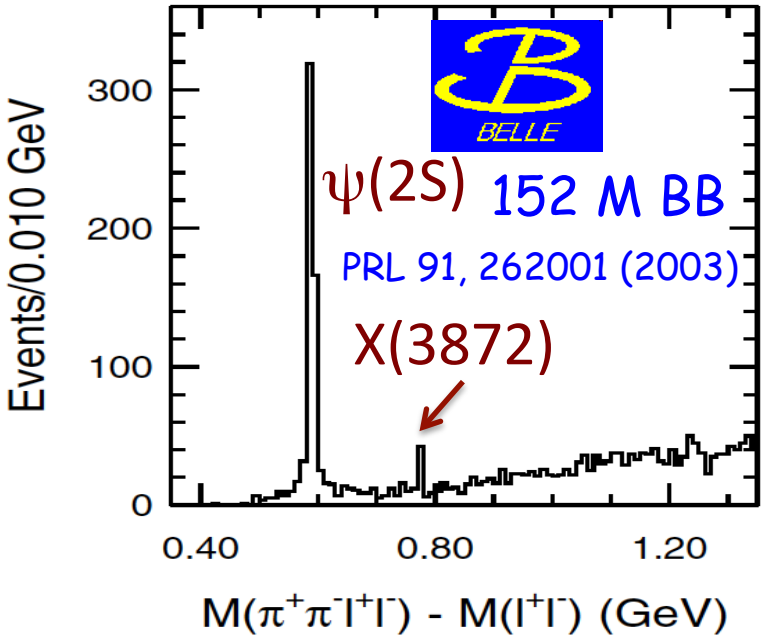


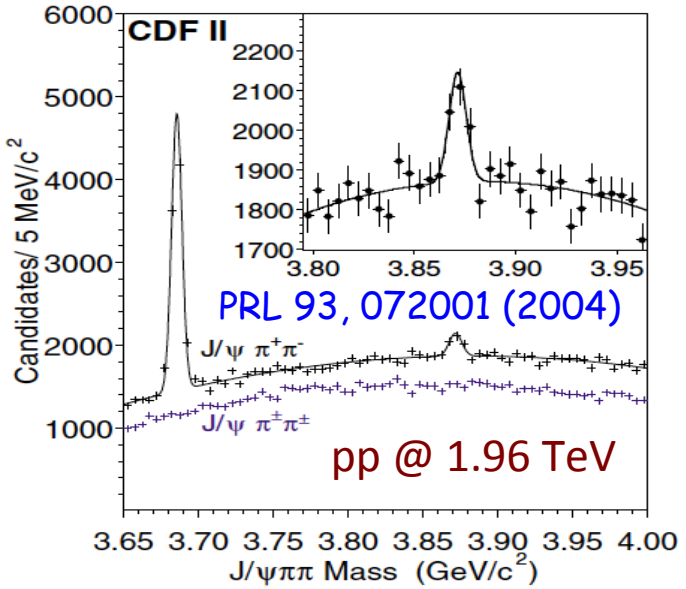
JINST 3



X(3872) and Y(4260)

What is X(3872)?



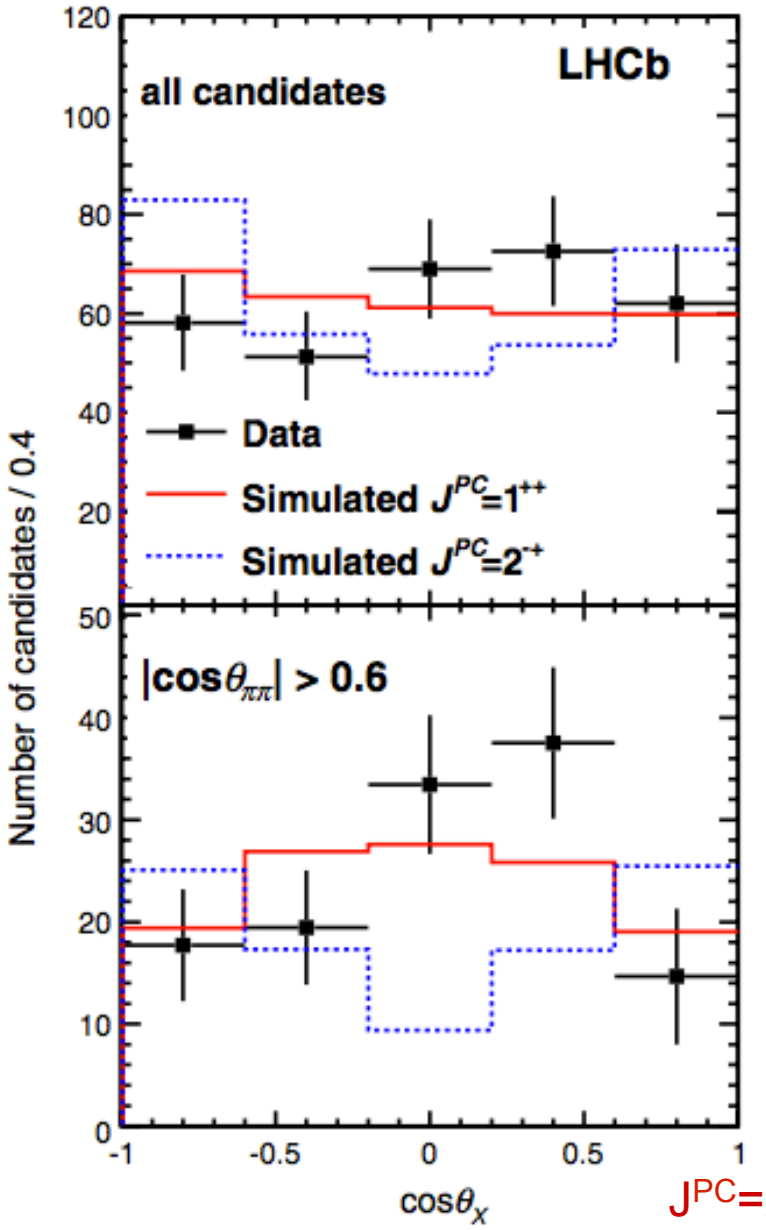


- The first X(3872) particle discovered by Belle in 2003 by $B \rightarrow K\pi^+\pi^- J/\psi$
- Mass 3872.0±0.6±0.5 MeV

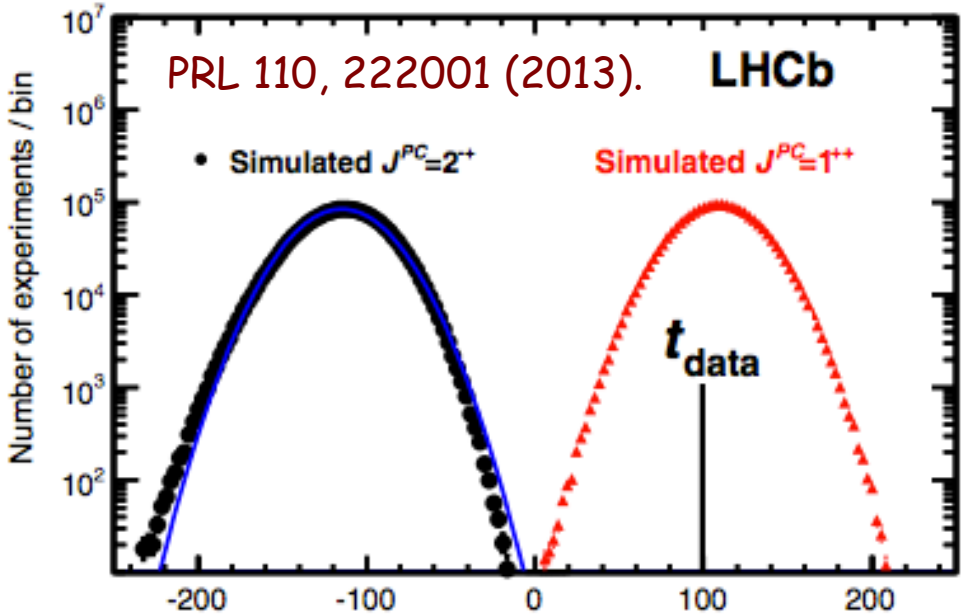
- Immediately confirmed by CDF experiment
- Mass 3871.3±0.7±0.4 MeV

- Nature?
- Near D^0D^{0*} mass threshold [~3871.8 MeV]
- Width: very narrow < 1.2 MeV
- Charmonium? 1^3D_2, 2^3P_2…
- Need properties study, spin-parity…

What is X(3872)?

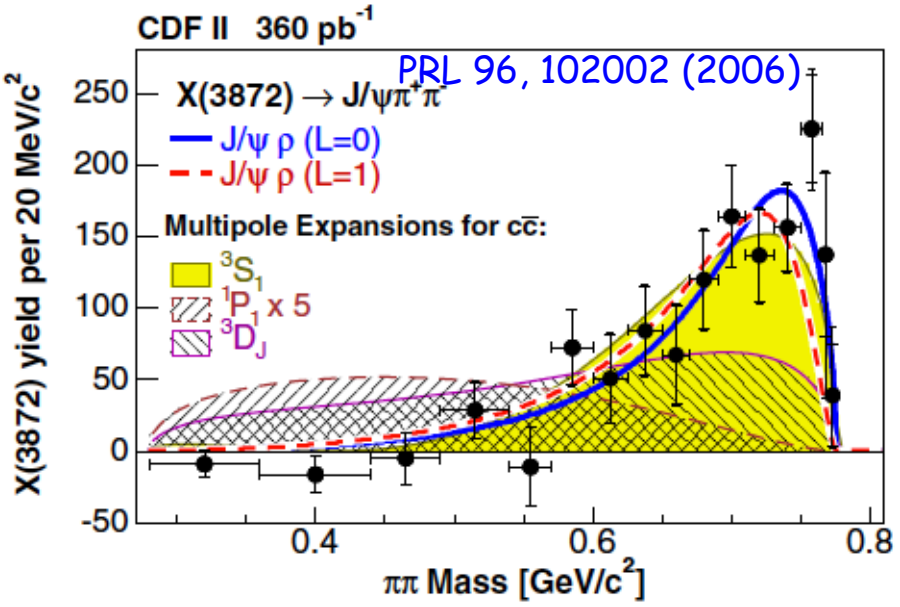


- Both Belle and BaBar observe X(3872)→γJ/ψ decay
- C-parity = +
- CDF further rule out other possibilities, but 1^{++} & 2^{-+}
- LHCb finally determine 1^{++}



$J^{PC}=2^{-+}$ rejected at 8.2σ!

What is X(3872)?



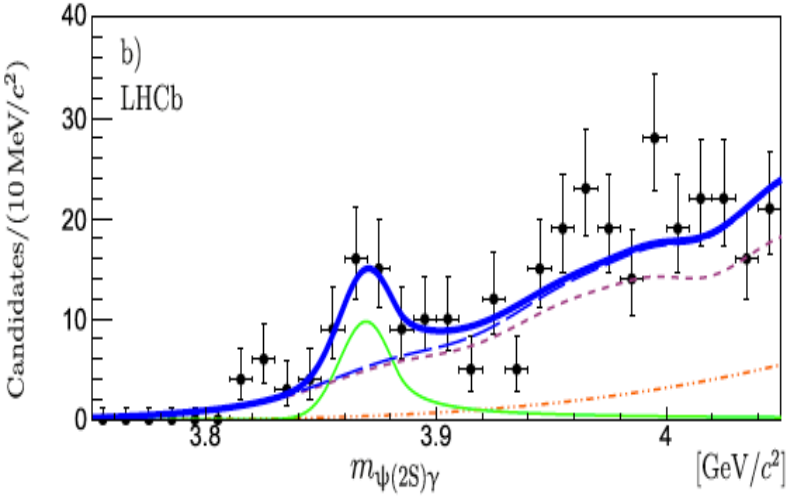
PRL 96, 102002 (2006)

- Dipion mass is dominant by ρ(770) meson → I=1
- X(3872)→ωJ/ψ by Belle & BaBar.
- Ratio ~ 1, hint large isospin violation

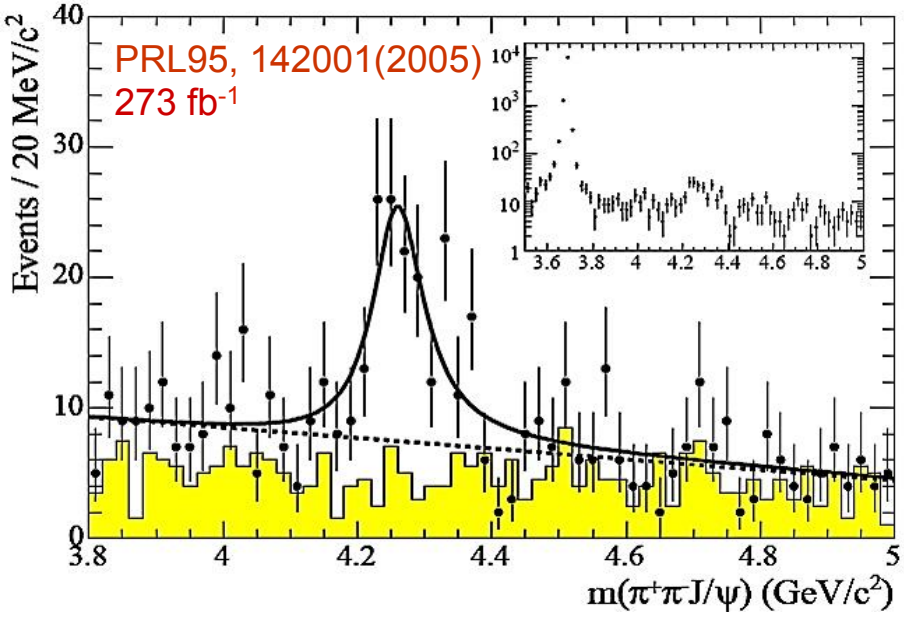
X(3872) nature (very likely exotic):

- Properties not match 2^3P_1 charmonium of potential model.
- If it is not 2^3P_1, where is 2^3P_1?
- Loosely D^0D^{*0} bound state (like deuteron?)?
- Mixture of excited χ_{c1} and D^0D^{*0} bound state?
- Many other possibilities (4 quark state?).

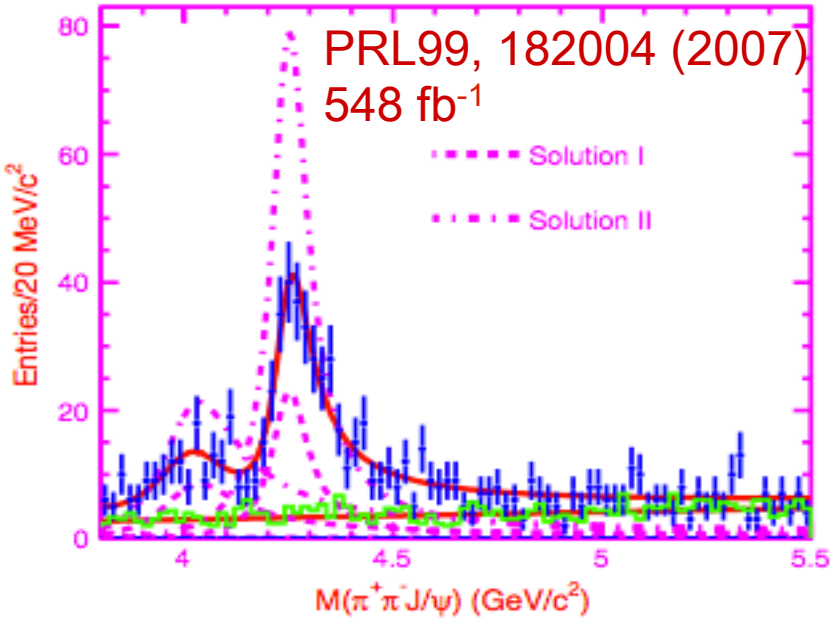
Br[X→γψ(2S)]/Br[X→γJ/ψ]~2.51

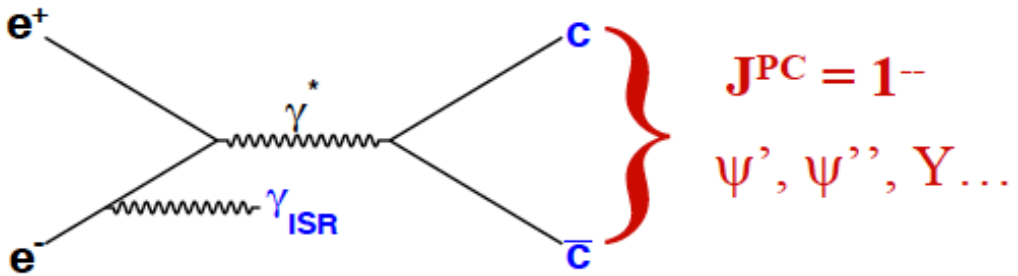


Y(4260) state by ISR



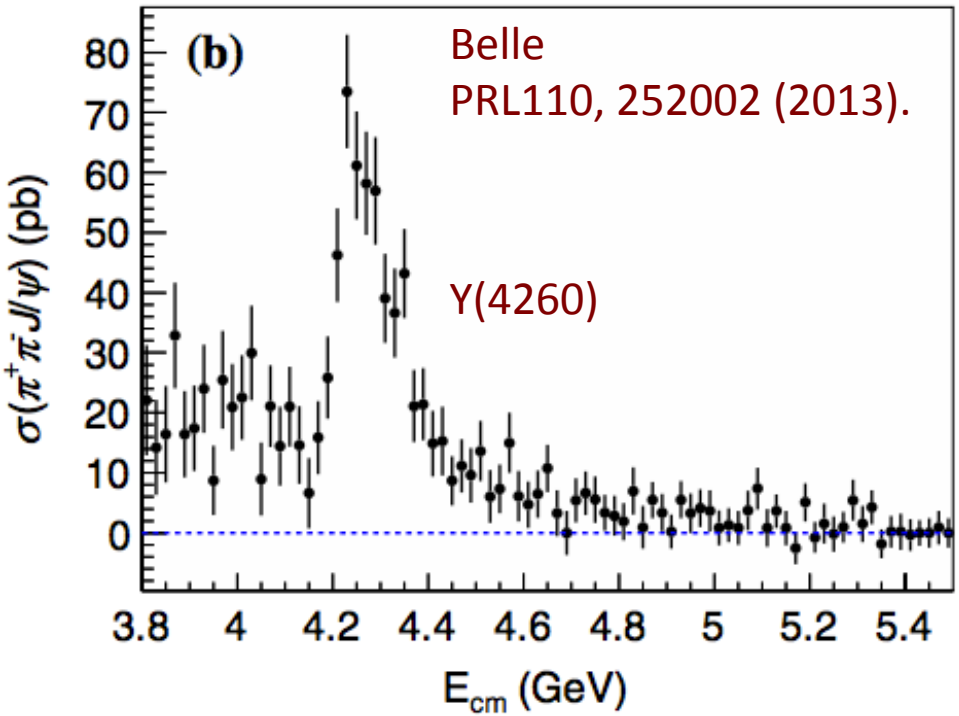
- Using ISR, BaBar and Belle can study 1^{--} Y-family charmonium.
- Y(4260): M~4.26 GeV, Γ~100 MeV
- Potential model: ψ(4040), ψ(4160) & ψ(4415)→ large width to open charm.
- Large decay width to $\pi^+\pi^-J/\psi$, very different

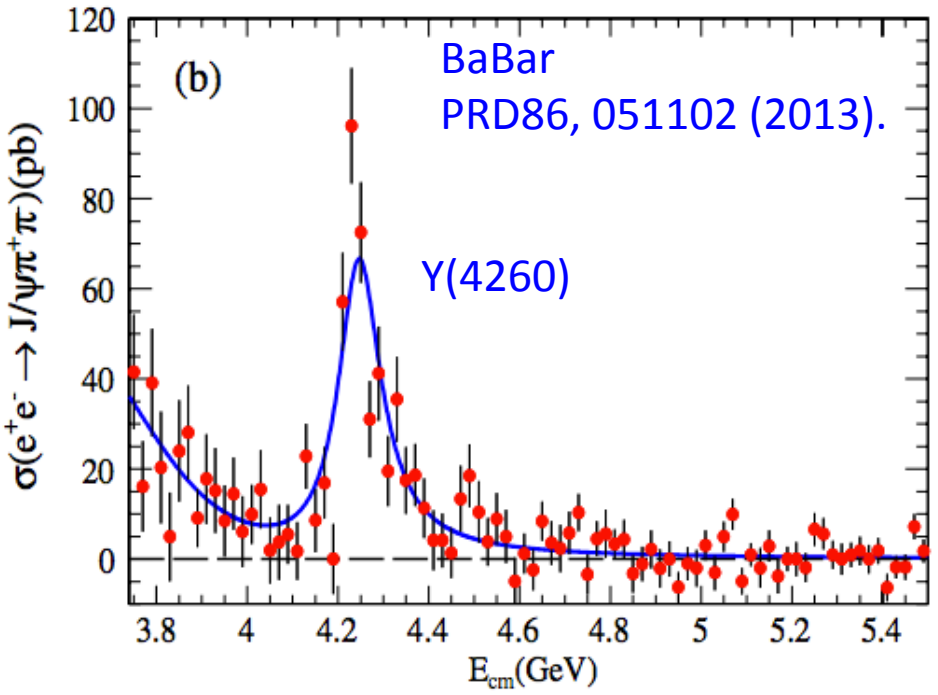




Initial-State-Radiation technique

The Y(4260)→$\pi^+\pi^-$J/ψ

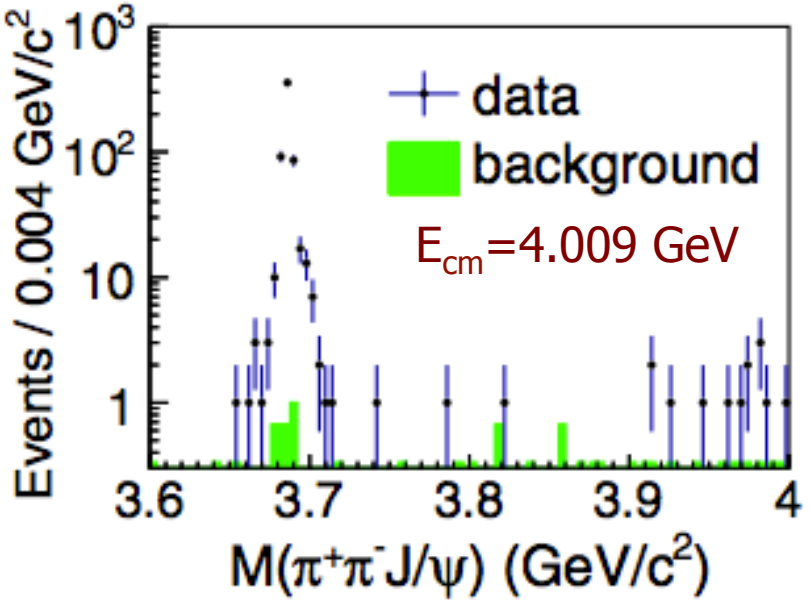


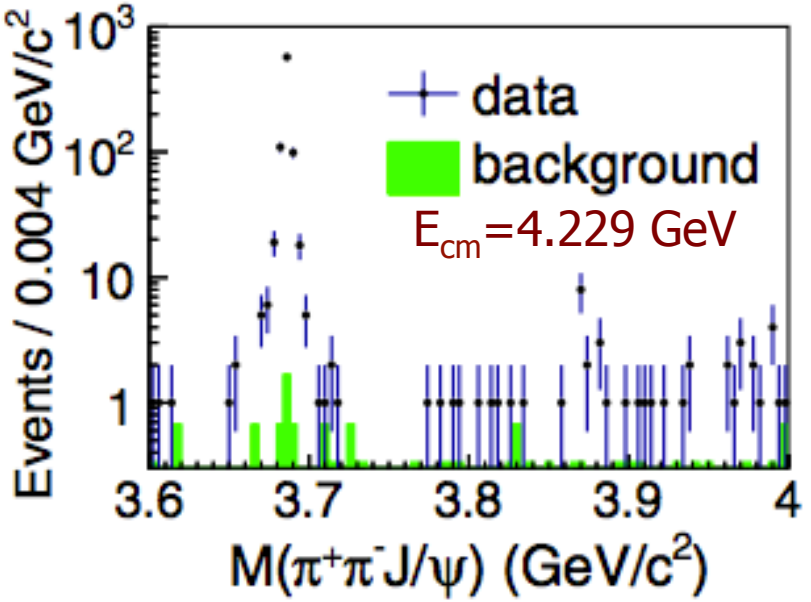


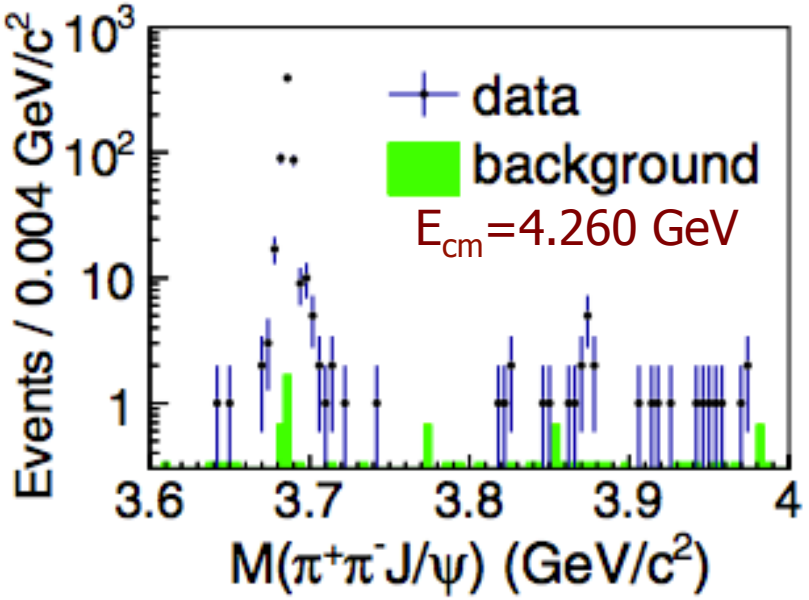
Nature of Y(4260):

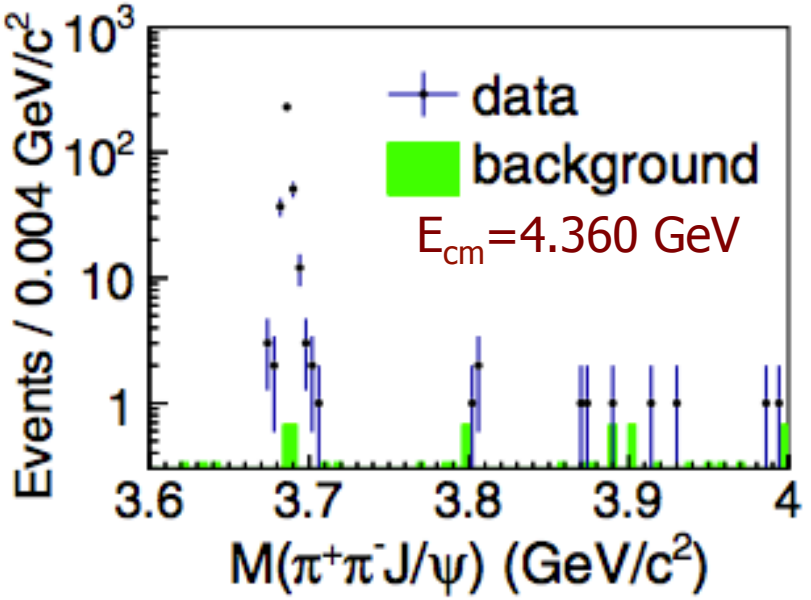
- Property not match vector charomonium [potential model].
- Lattice predicts: Hybrid state mass around 4 GeV?
- Mass near DD_1 meson threshold → Molecule state?
- Other possibilities (4 quark state?).

Connection: $e^+e^- \rightarrow \gamma\pi^+\pi^- J/\psi$ @ BESIII

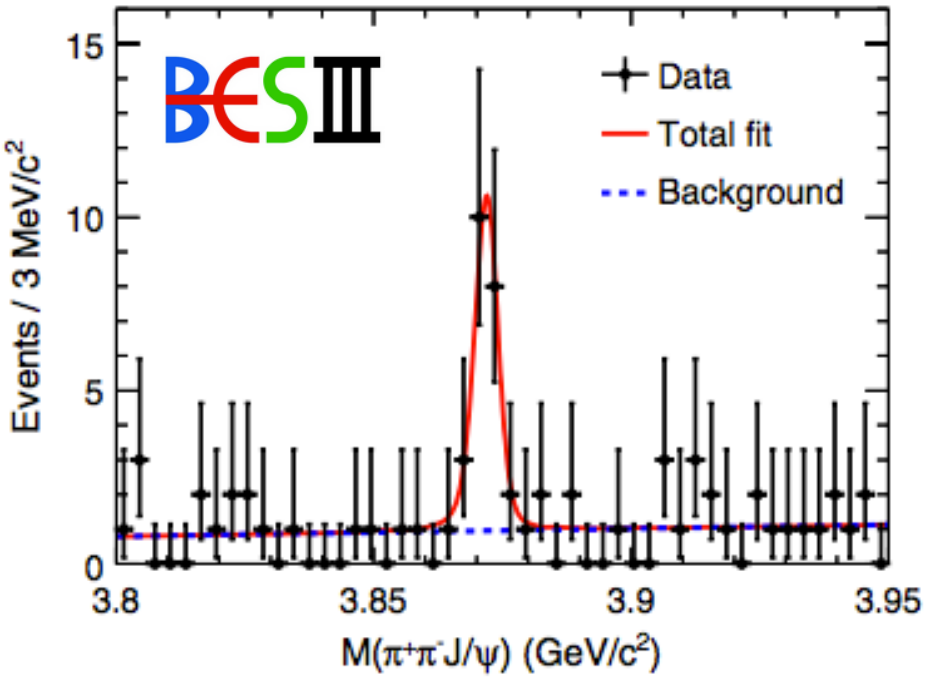


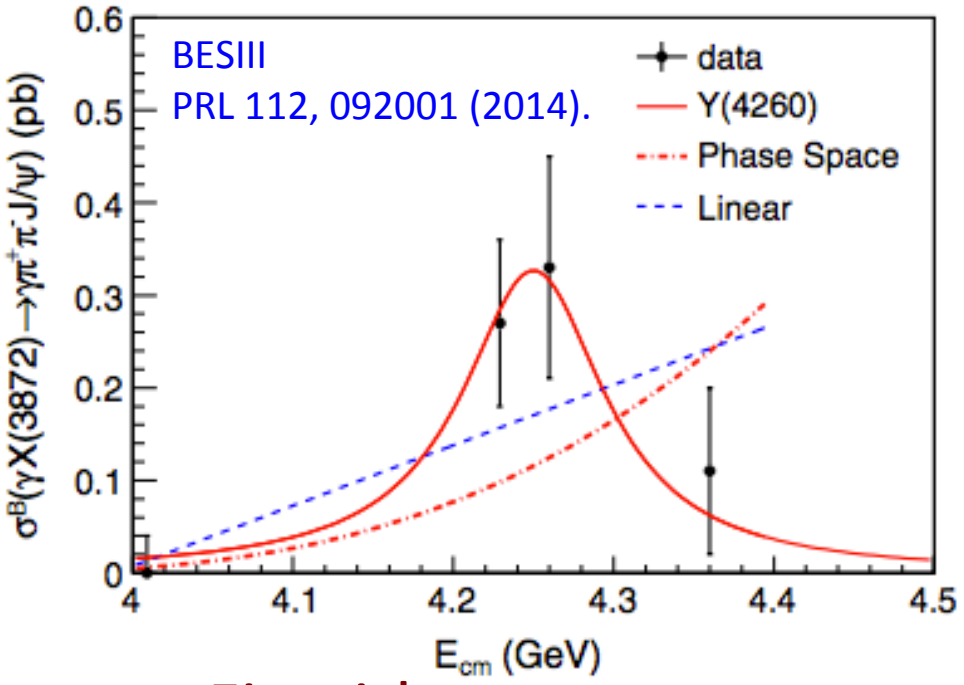






BESIII: Y(4260)→γX(3872)





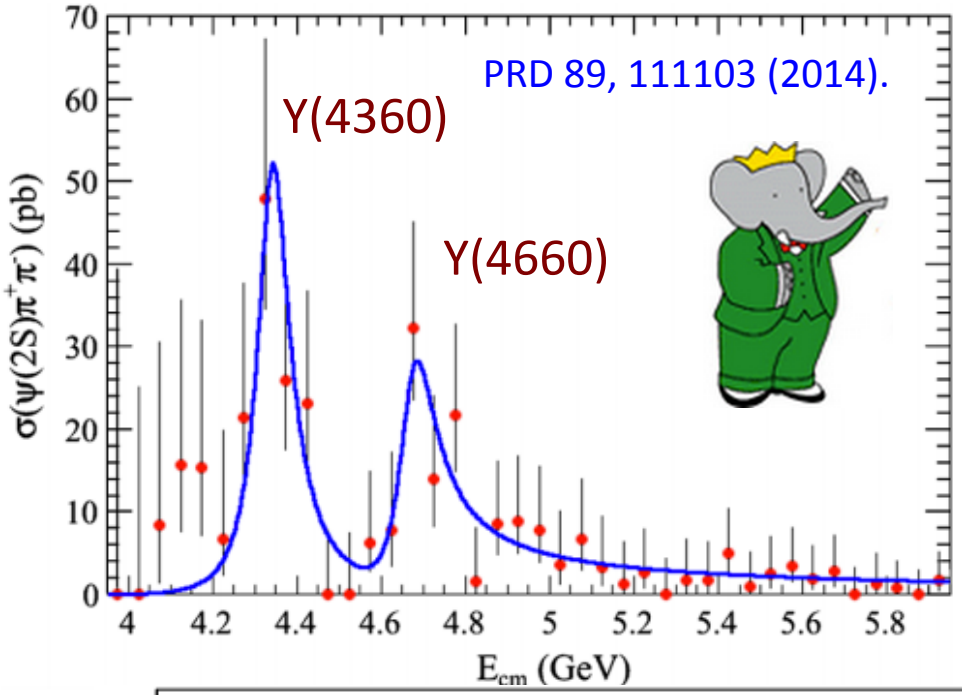
M=3821.9±0.7±0.2 MeV,
Γ<2.4 MeV @ 90% C.L.
6.3σ significance.

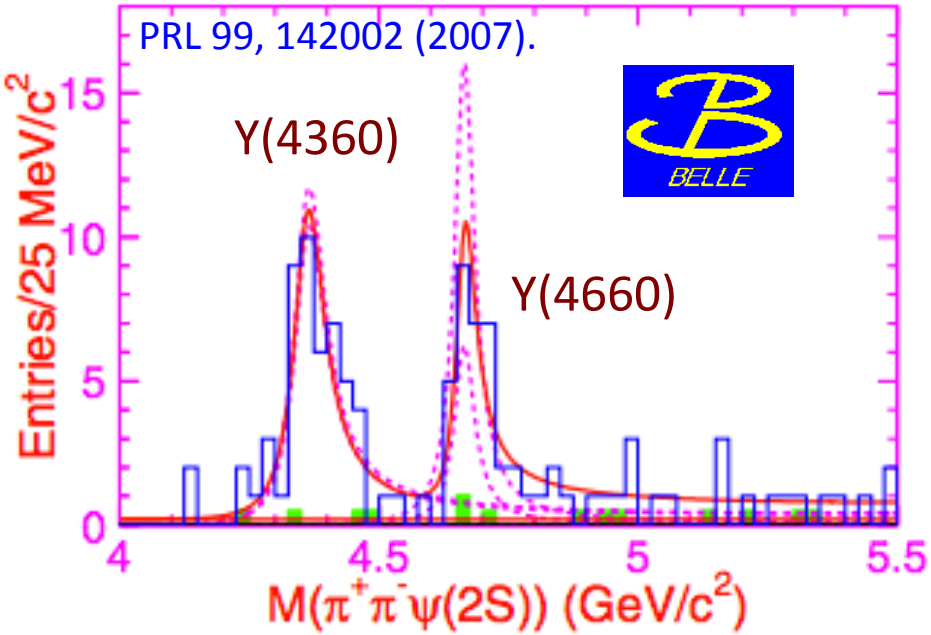
Fit with:

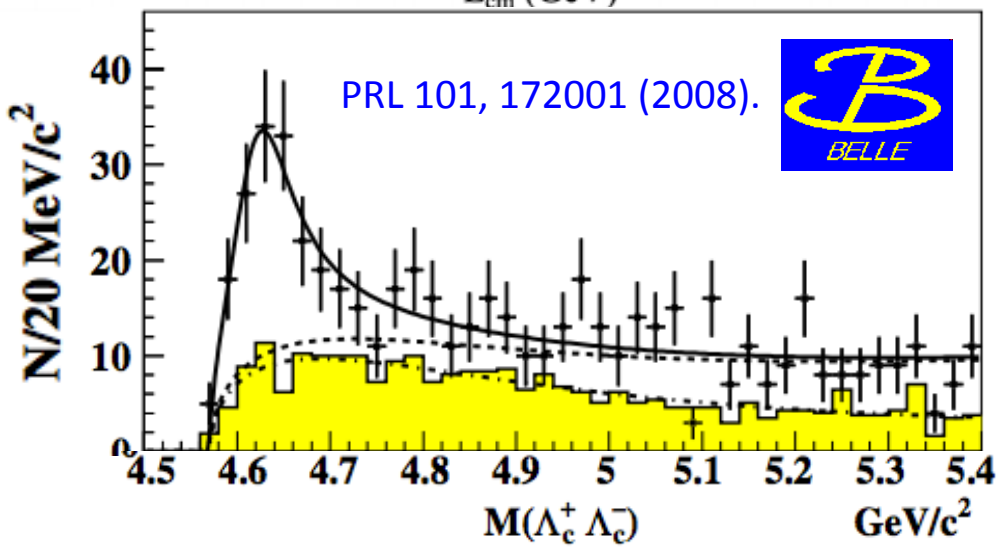
1. Y(4260): χ^2/ndf=0.49/3
2. E1 PHSP: χ^2/ndf=8.7/3
3. Linear: χ^2/ndf=5.5/2

- For the first time, bring X & Y particles together.
- Hints something common for them?

ISR Y-family



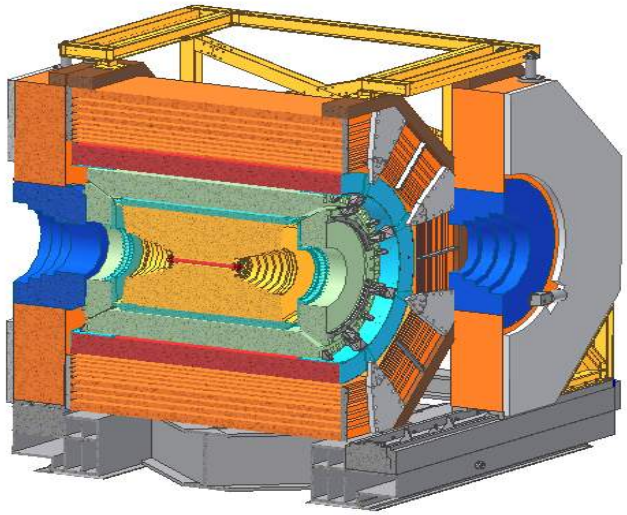




- Y(4360), Y(4660) & Y(4630)…
- All with $J^{PC}=1^{--}$
- Both confirm by Belle and BaBar experiment
- What are they?

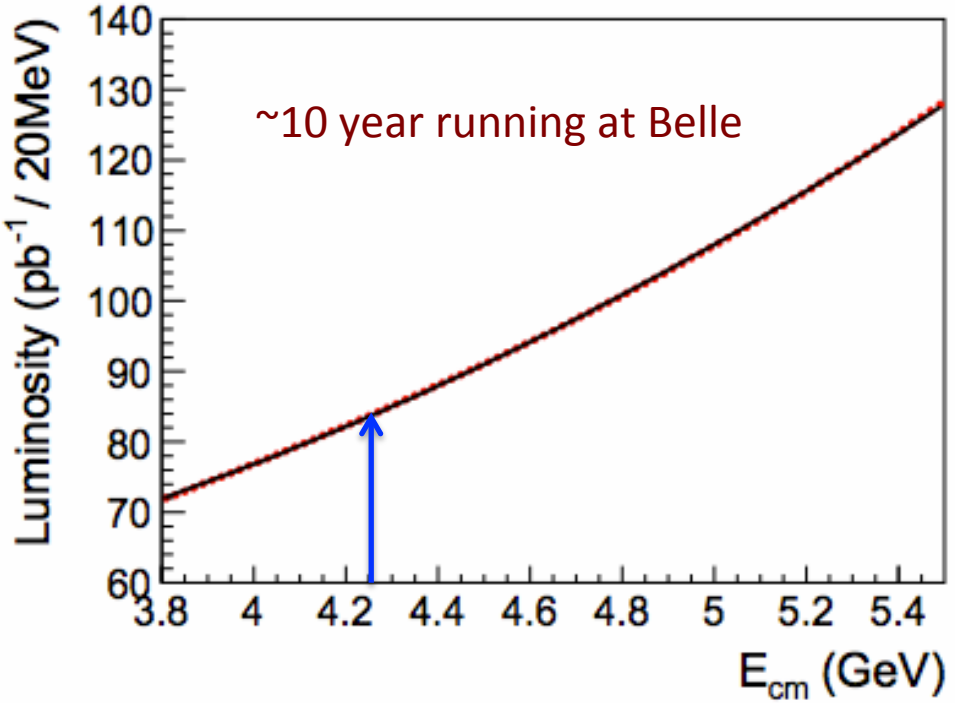
Charged Z_c states at BESIII

Study Y(4260) at BESIII

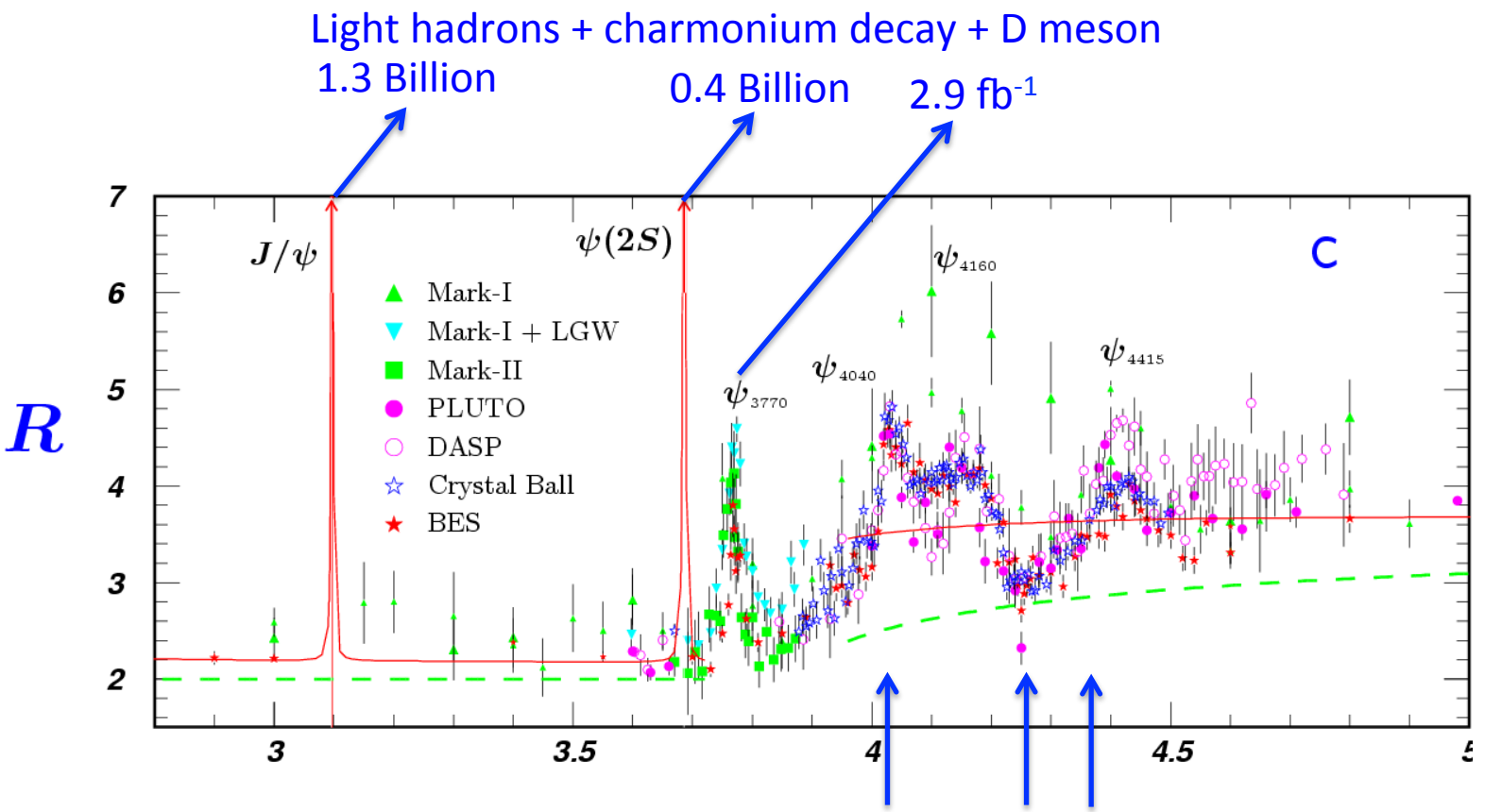


- BESIII is a scan experiment
- CM energy: 2 GeV – 4.6 GeV
- Design Lum=$1*10^{33}$ /cm^2/s
- Focus on one energy point, then more competitive than B factory

- 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.



What do we have at BESIII?

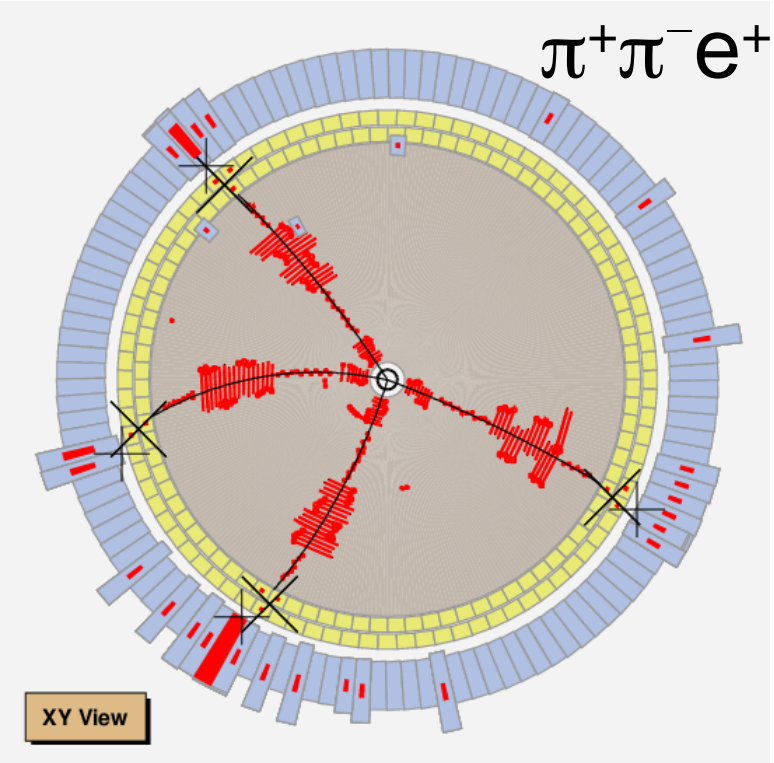


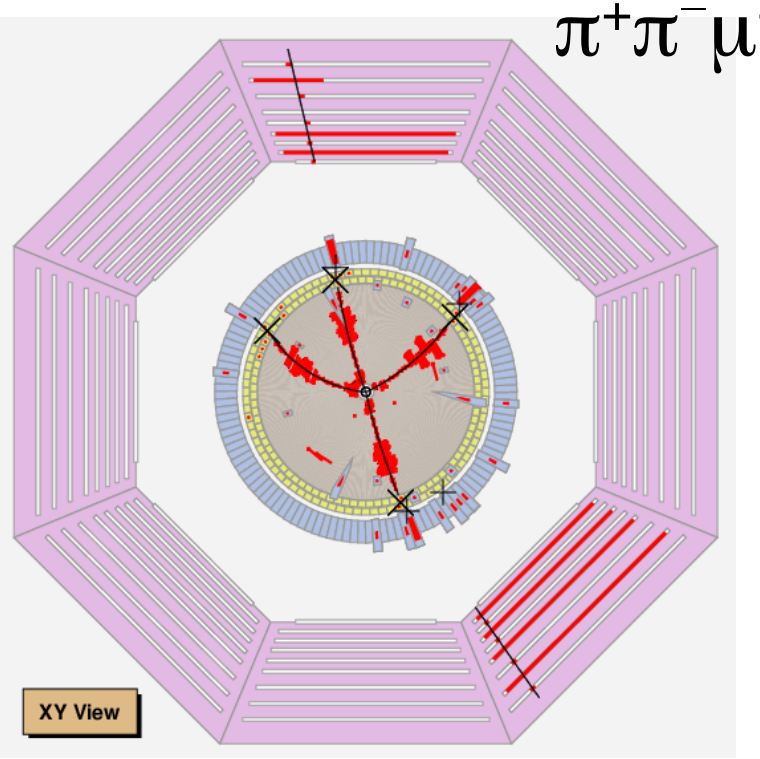
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})
3.900	52.8
4.009	482.0
4.090	51.0
4.190	43.0
4.210	54.7
4.220	54.6
4.230	1090.0
4.245	56.0
4.260	826.8
4.310	44.9
4.360	544.5
4.390	55.1
4.420	44.7

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

Study Y(4260) at BESIII

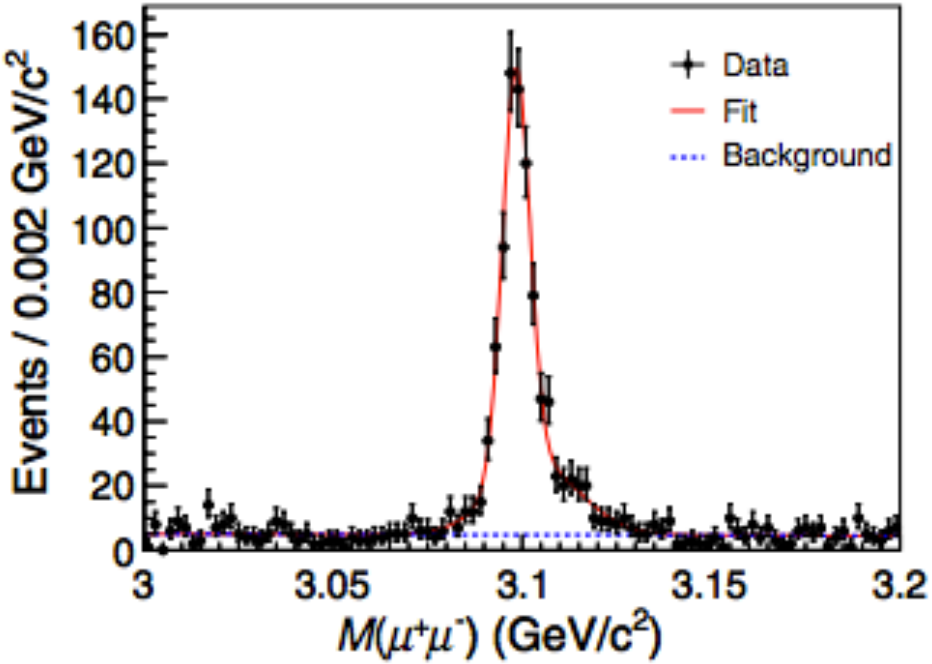
- Dec, 2012 to Jan, 2013, BESIII accumulate 525 pb^{-1} data @ 4.26 GeV, world's largest data set!
- Study $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ exclusive process.

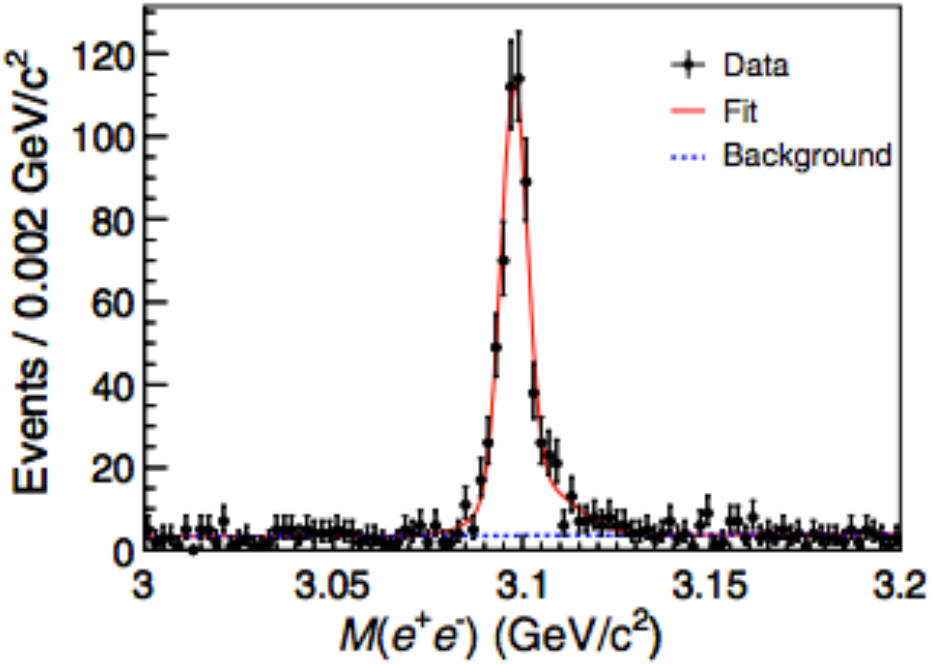




1. Very simple and straightforward analysis.
2. The produced vector charmonium(like) state almost in rest frame.
3. $Y(4260) \rightarrow \pi^+\pi^- J/\psi$, four charged track detected.

Cross Section at BESIII

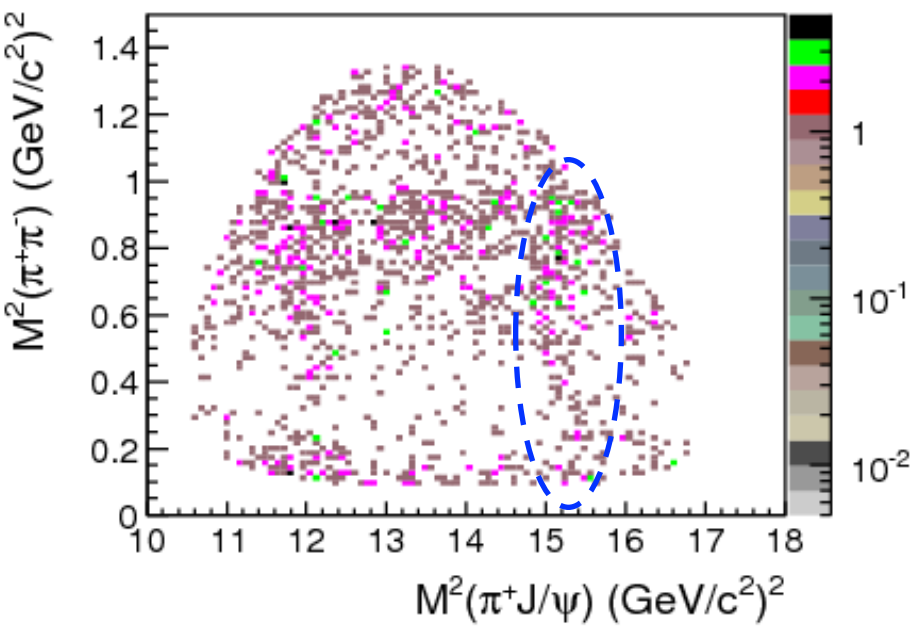


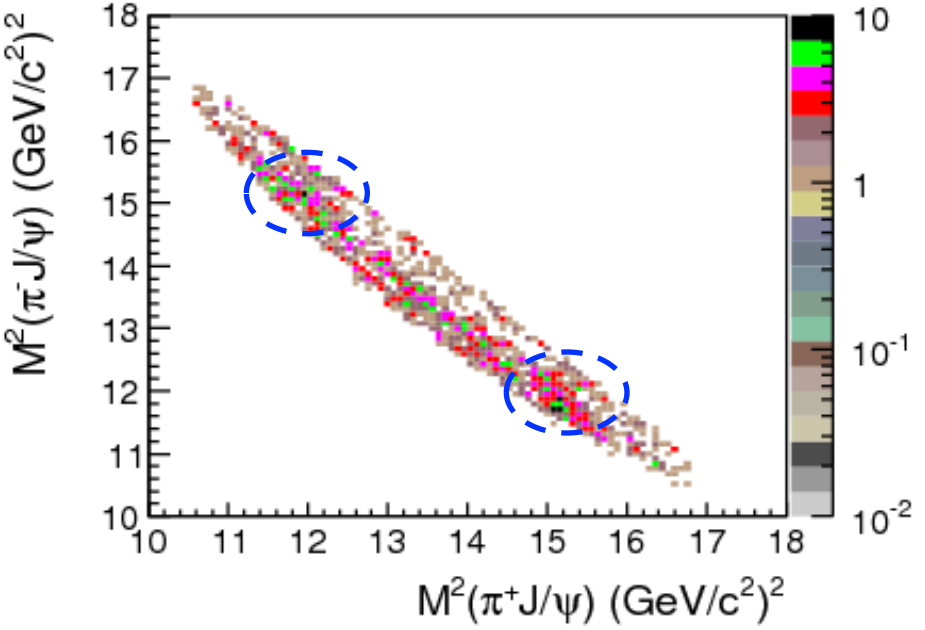


1. Lum=525 pb^{-1} @ BESIII
2. $N(\mu^+\mu^-)$=882±33; $N(e^+e^-)$=595±28.
3. Born cross section: σ^B=(62.9±1.9±3.7) pb @ BESIII.
4. Good agreement with Belle and BaBar.
5. Analysis is valid and unbiased.

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 $M(\pi^-J/\psi)$.

Intermediate state——$Z_c(3900)$

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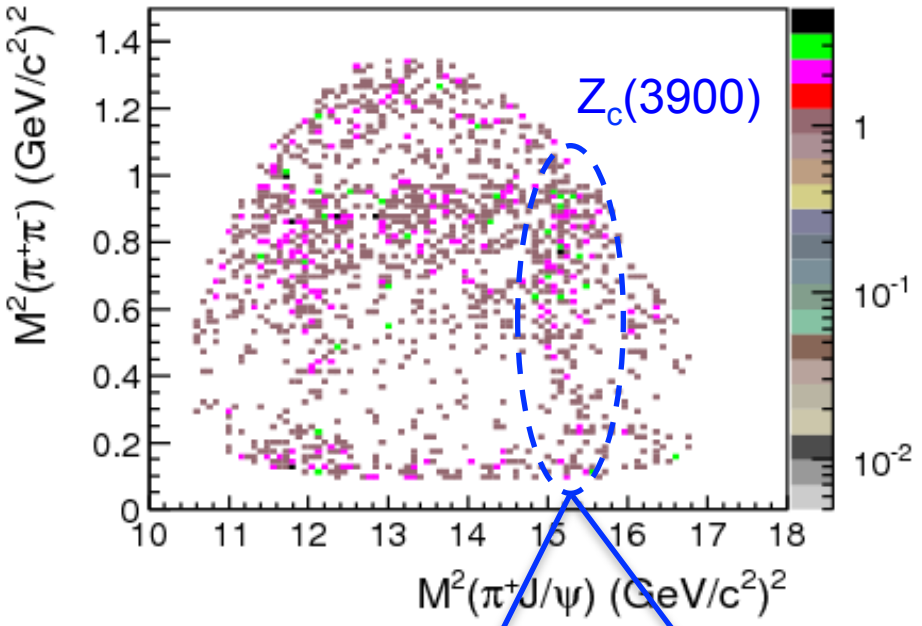
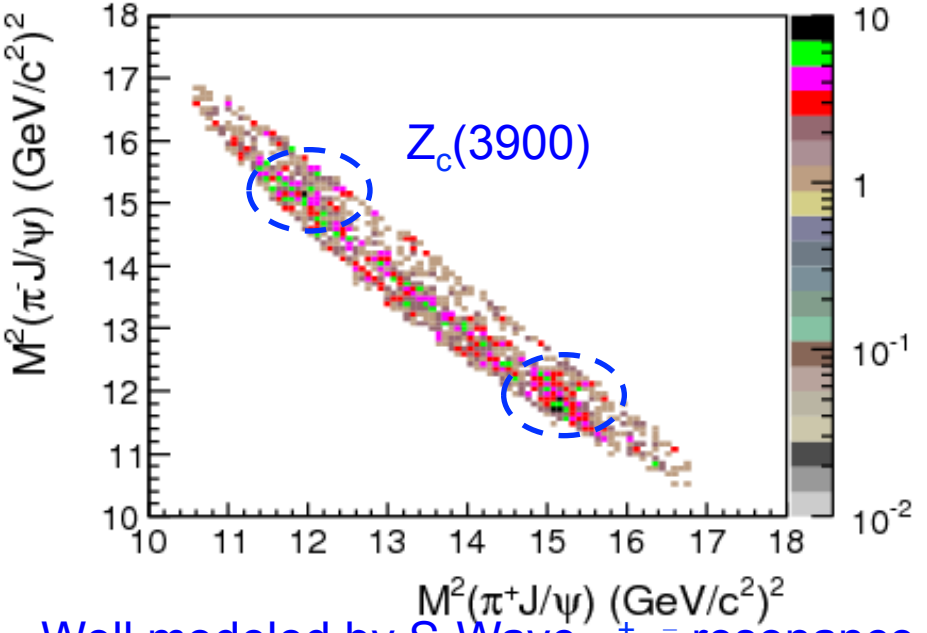
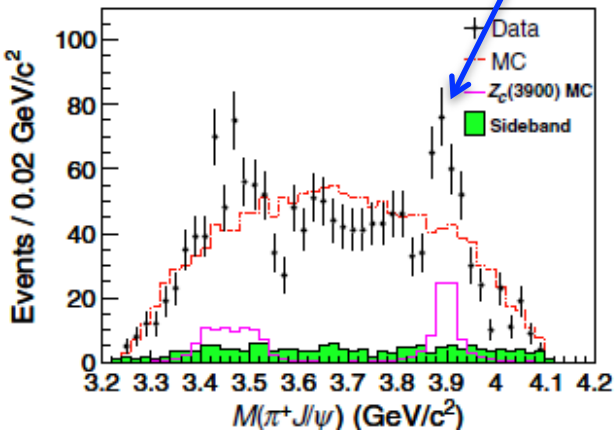
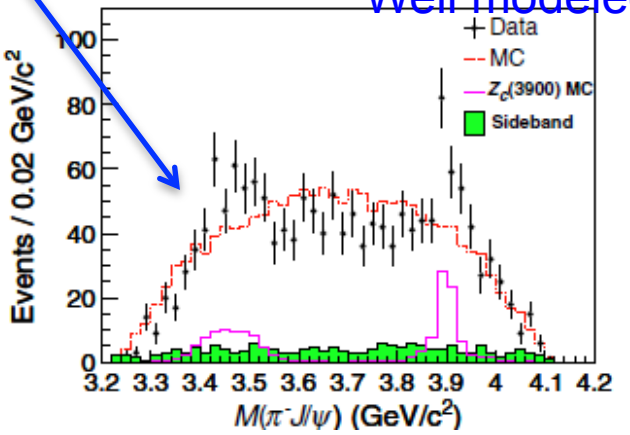
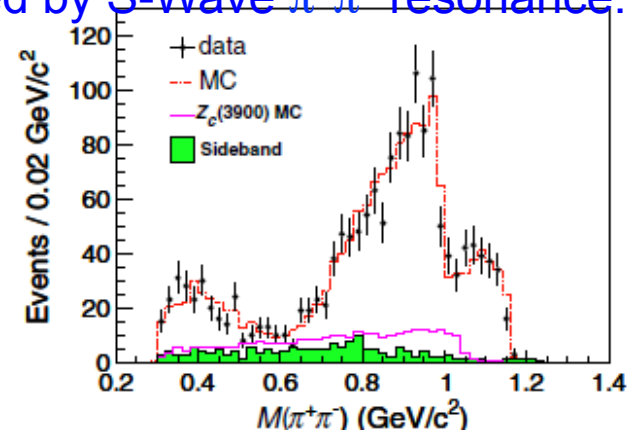




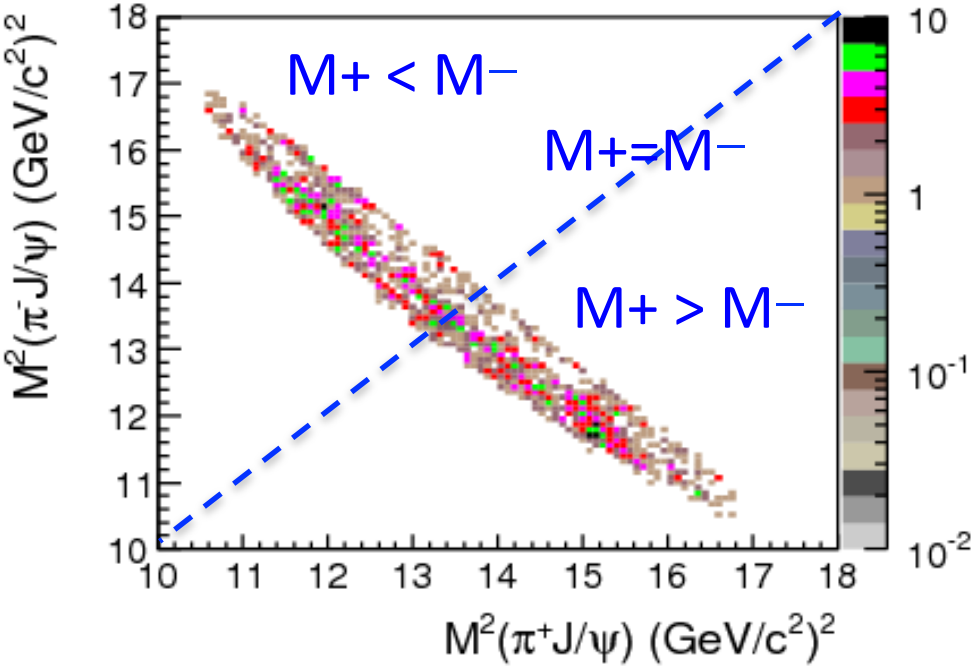
Well modeled by S-Wave $\pi^+\pi^-$ resonance.

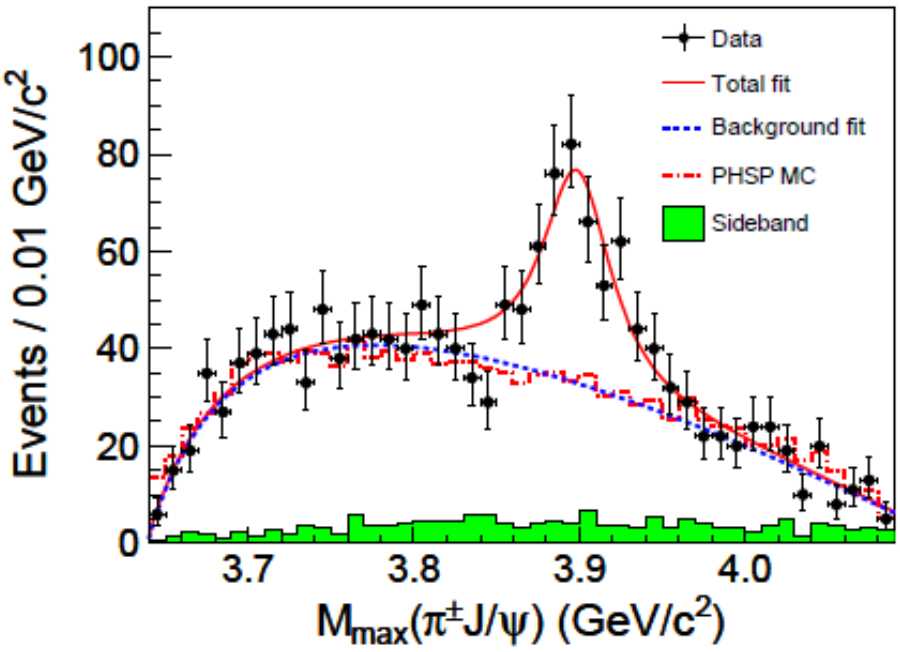






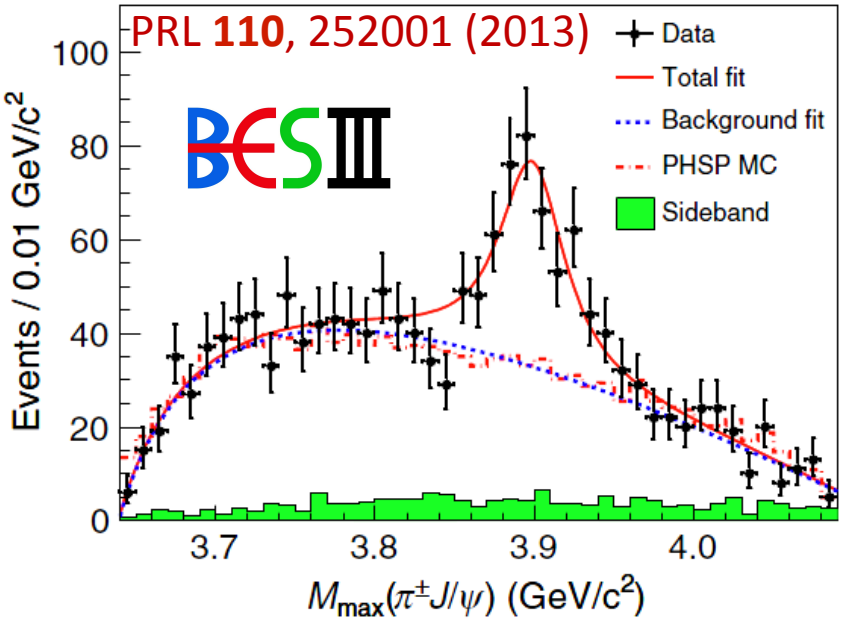
Intermediate state——$Z_c(3900)$

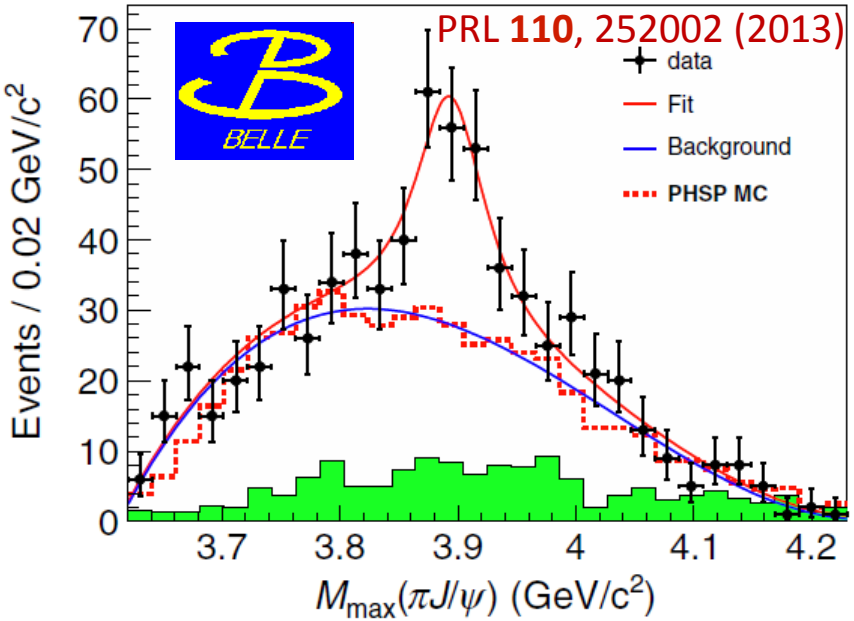


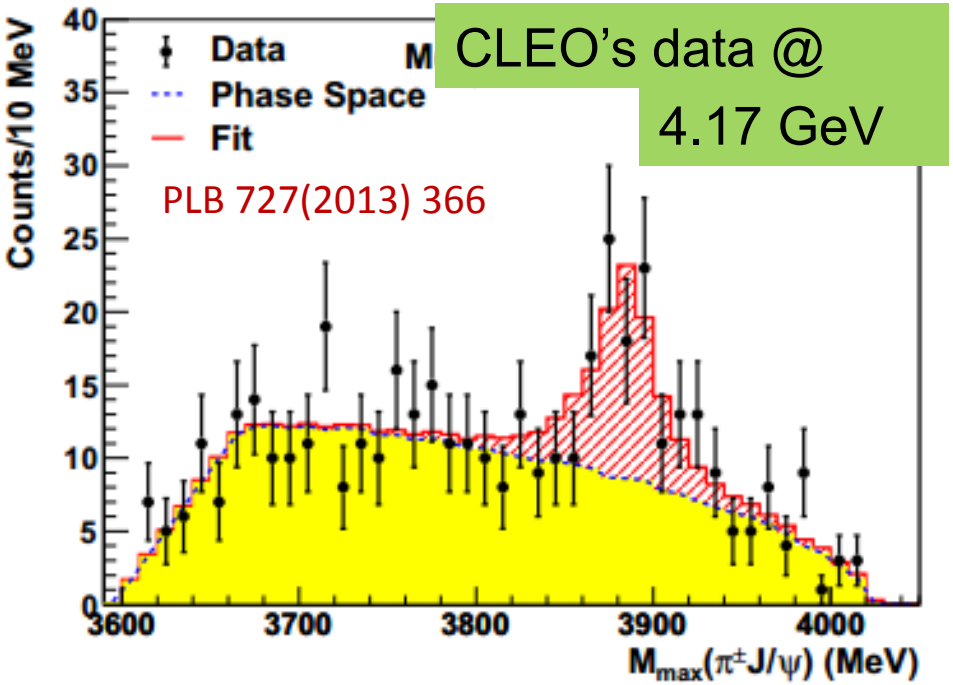


1. First stage, 1D fit to extract resonant parameters.
2. Divided by diagonal line of the dalitz plot and fit $M_{max}(\pi^\pm J/\psi)$ mass distribution; best way to avoid cross counting.
3. S-Wave Breit Wigner; p*q phase space factor; efficiency corrected.
4. M=(3899.0±3.6±4.9) MeV; Γ=(46±10±20) MeV.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

Good News

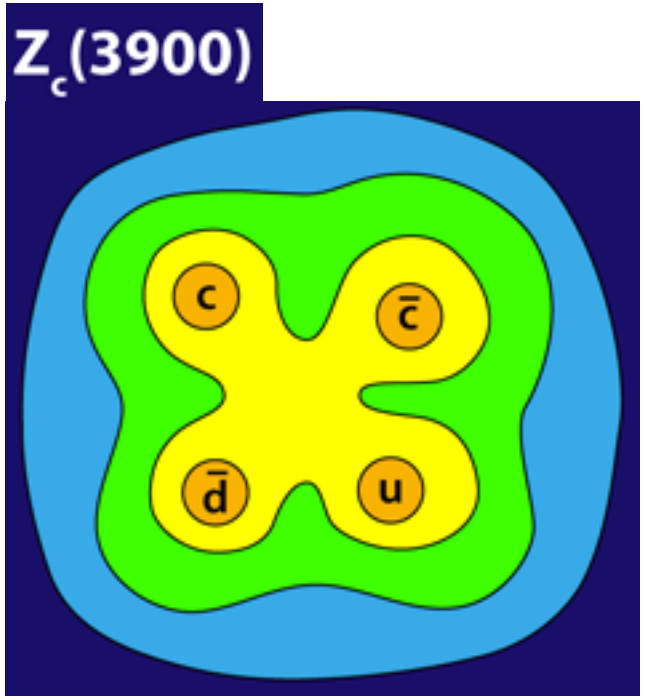






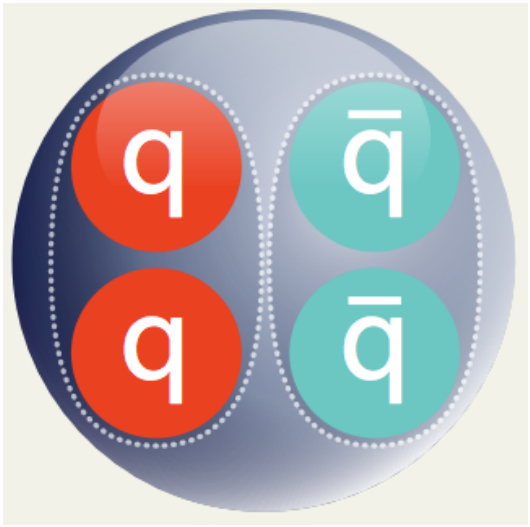
1. BESIII: M=(3899.0±3.6±4.9) MeV; Γ=(46±10±20)MeV
2. Belle: M=(3894.5±6.6±4.5) MeV; Γ=(63±24±26) MeV.
3. CLEO's data: M=3886±6±4 MeV, Γ=33±6±7 MeV.
4. $Z_c(3900)=Z(3900)^{\pm}$.

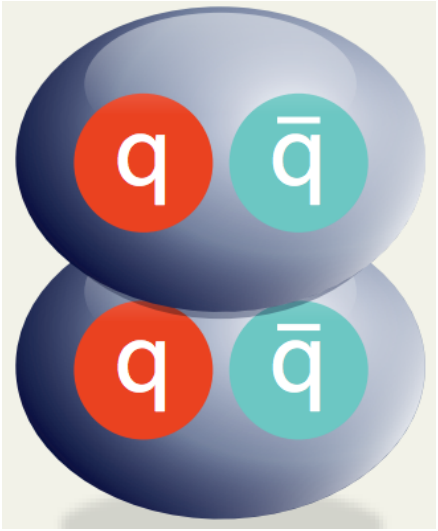
Four quark state



- 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…

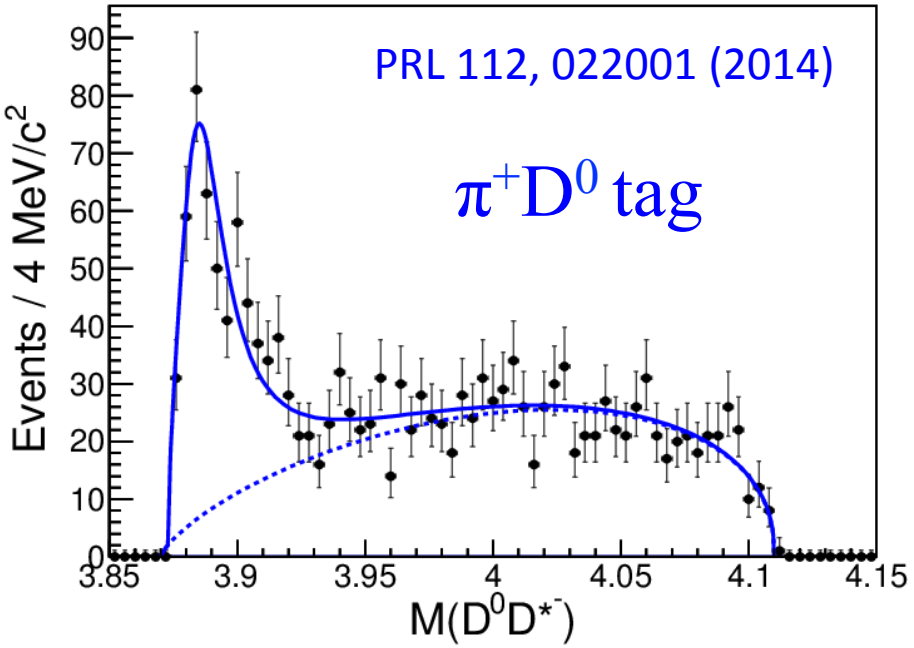
Tetraquark or molecule like?

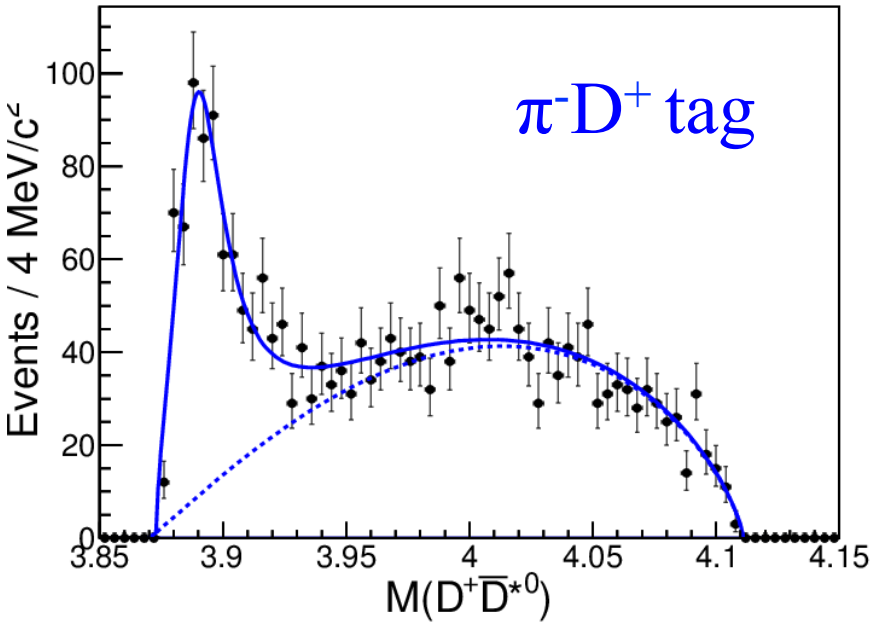




A series of Z_c states at BESIII

Threshold resonance: $e^+e^- \rightarrow (DD^*)^+\pi^- + c.c.$?





- Zc(3900) mas near DD* threshold.
- Angular distribution (πD) disfavor DD_1 component.
- Fit with mass dependent BW, report pole position.
- Polynomial background.

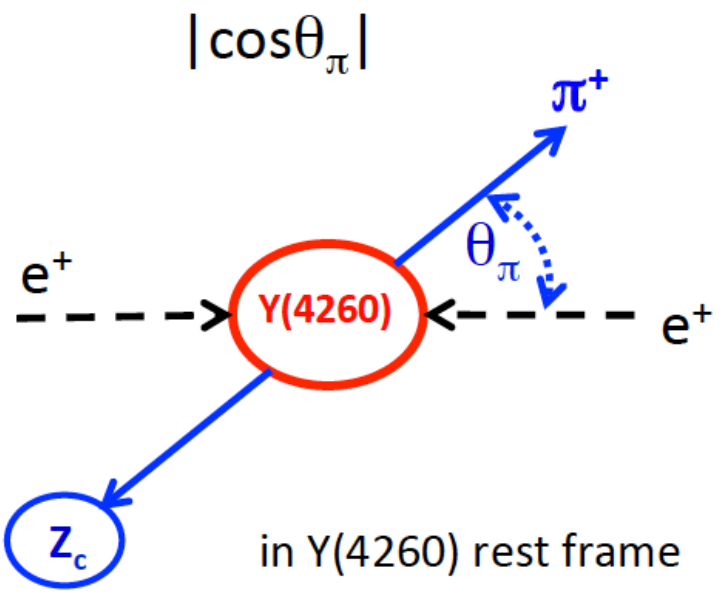
$Z_c(3885) = Z_c(3900)$

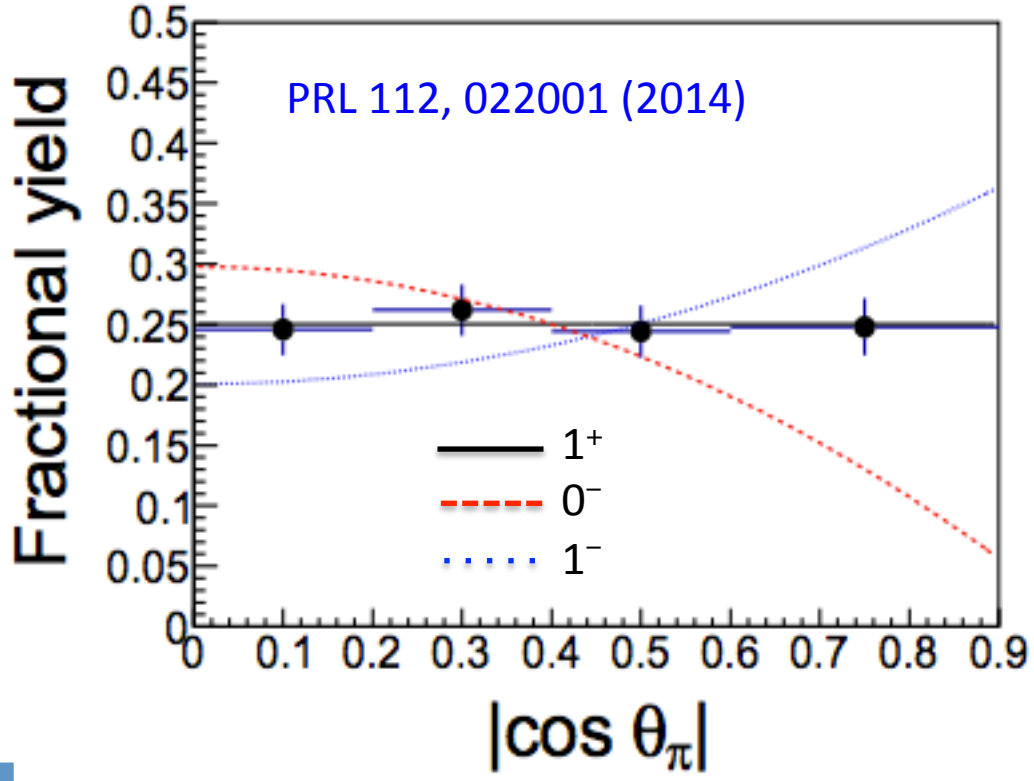
Very large yield !

$\Gamma(DD^*)/\Gamma(\pi^\pm J/\psi) \sim 6.2$

	$Z_c(3885) \rightarrow D\bar{D}^*$
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 $Z_c(3885)$

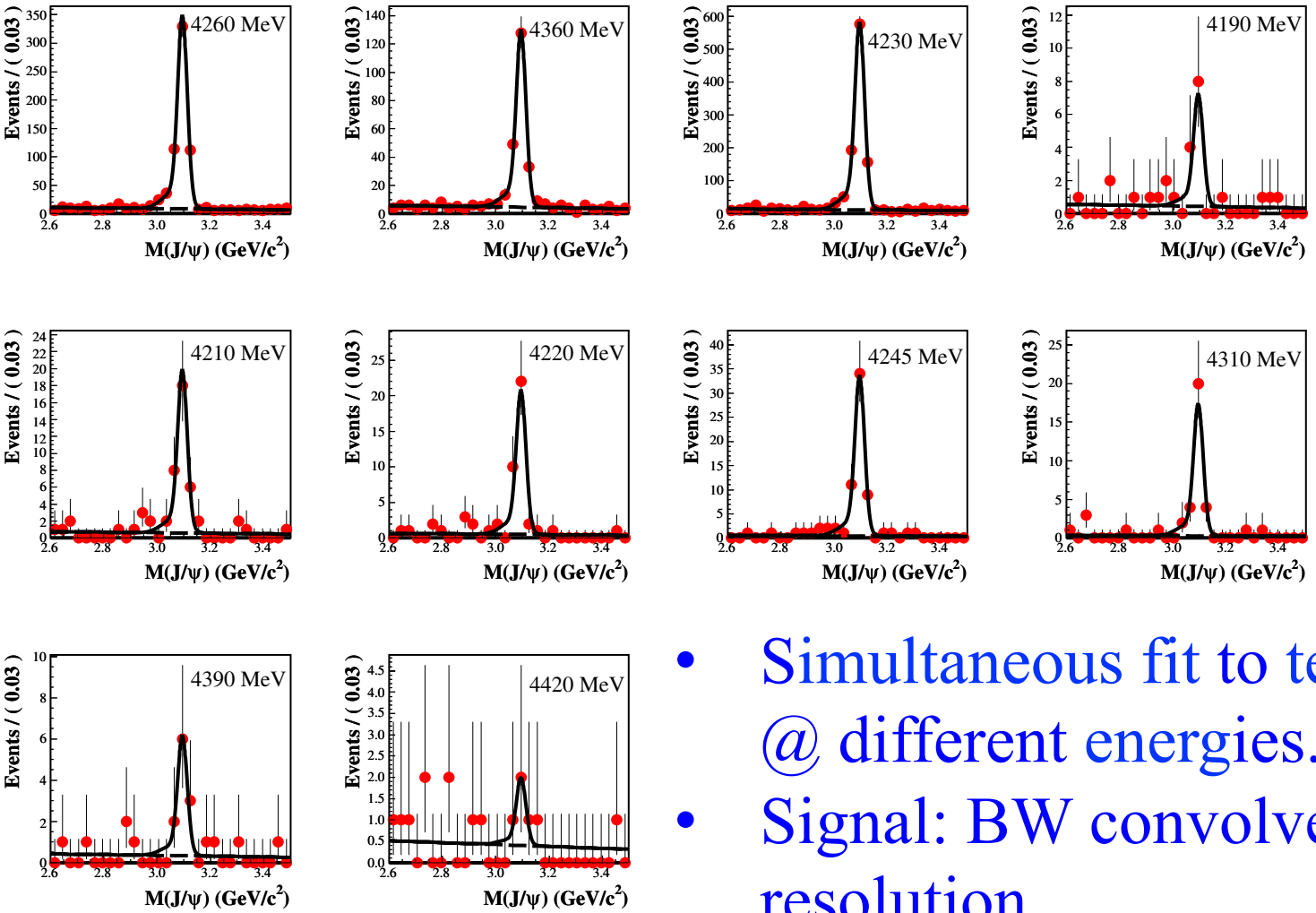




J^P	L	$dN/d\|\cos\theta_\pi\|$
1^+	S-wave	flat
0^-	P-wave	$\sin^2\theta_\pi$
1^-	P-wave	$1+\cos^2\theta_\pi$

Favor $J^P=1^+$

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

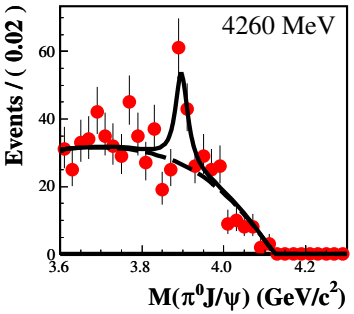


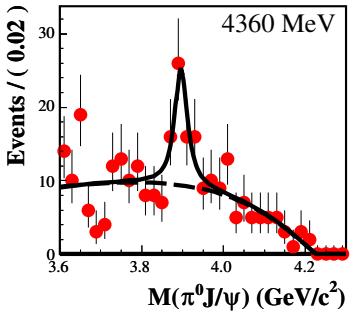
BESIII

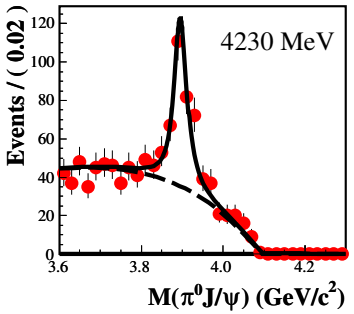
Preliminary

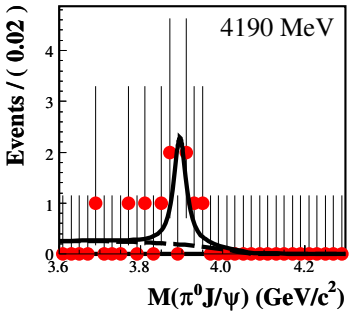
- Simultaneous fit to ten data sets @ different energies.
- Signal: BW convolved with resolution.
- Backgrould: 1st ordered poly.

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



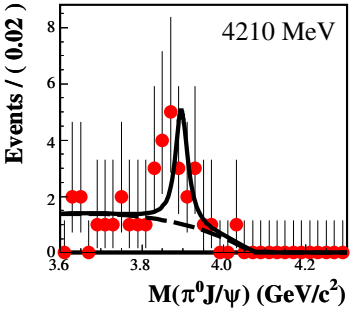


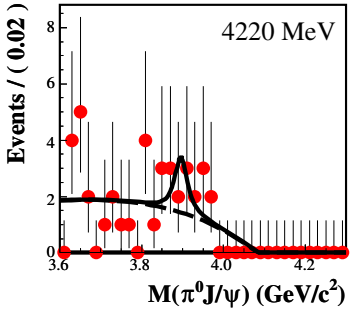


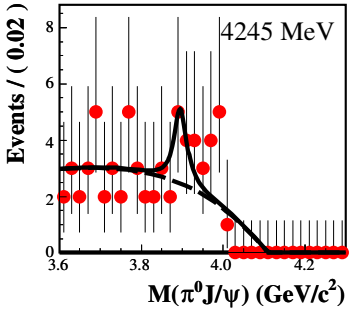


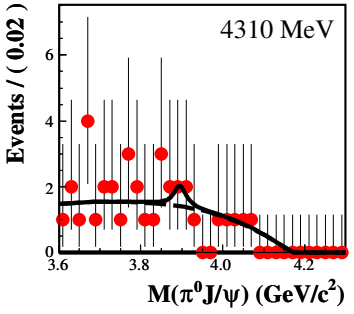
BESIII

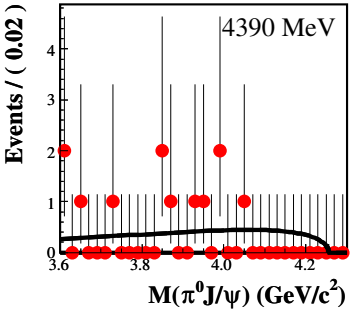
Preliminary

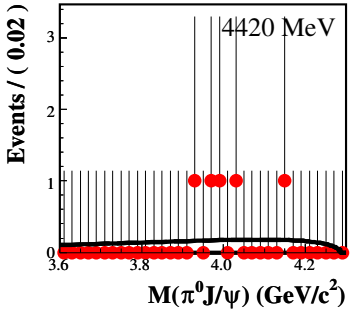












Mass = 3894.8±2.3 MeV

Width = 29.6±8.2 MeV

Significance = 10.4 σ

$Z_c(4020)$ or $Z_c(4025)$?

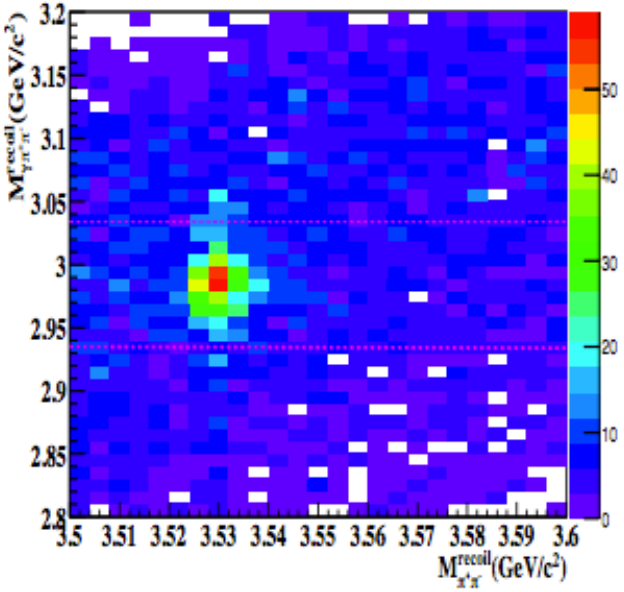
$e^+e^- \rightarrow \pi^+\pi^- h_c$

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

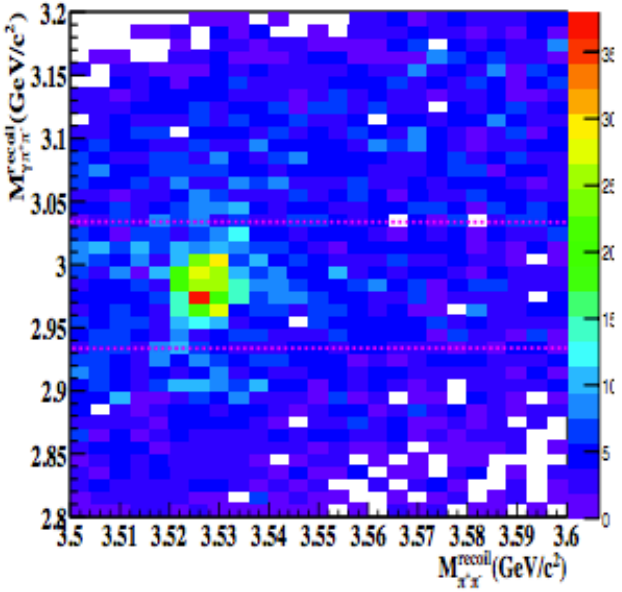
- $h_c \rightarrow \gamma\eta_c$, $\eta_c \rightarrow$hadrons [16 exclusive decay modes]
  - p pbar, $\pi^+\pi^- K^+K^-$, $\pi^+\pi^-$p pbar, $2(K^+K^-)$, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$
  - $2(\pi^+\pi^-)K^+K^-$, $K_S^0K^+\pi^-$+c.c., $K_S^0K^+\pi^-\pi^+\pi^-$+c.c., $K^+K^-\pi^0$
  - ppbarπ^0, $K^+K^-\eta$,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

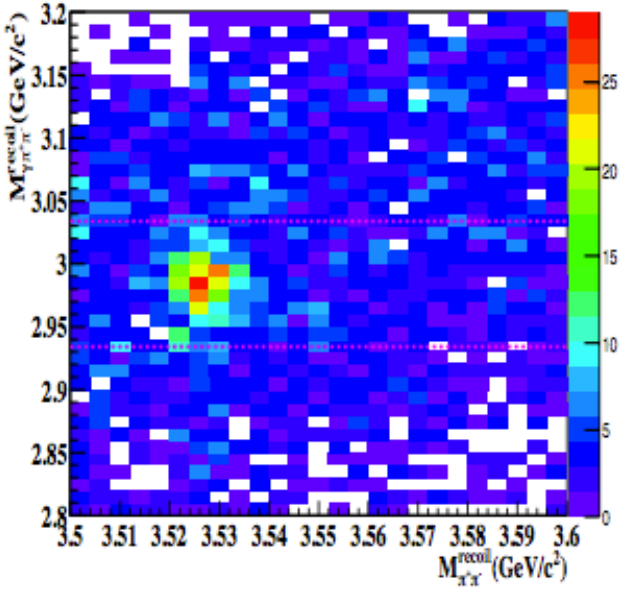
4230 MeV



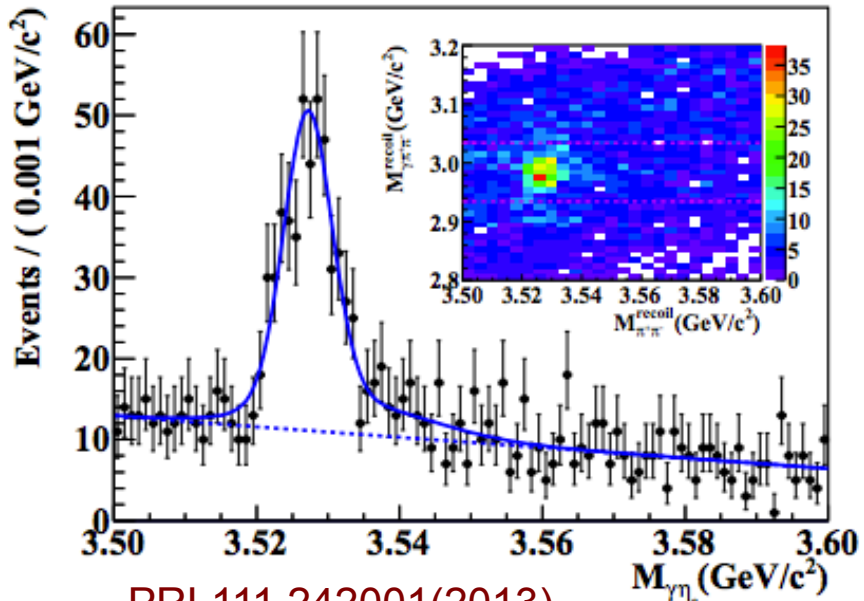
4260 MeV



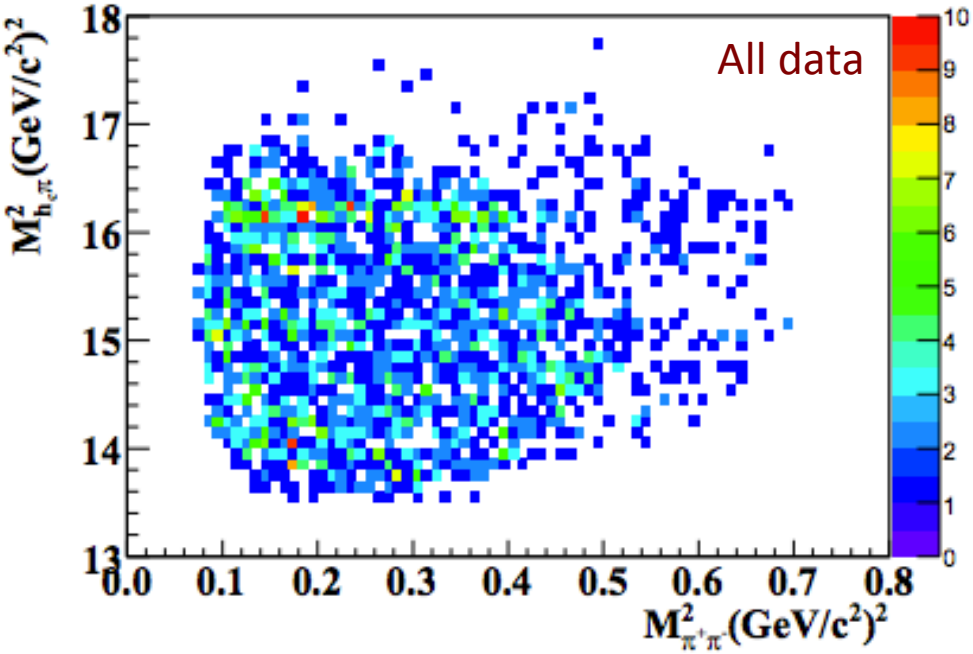
4360 MeV

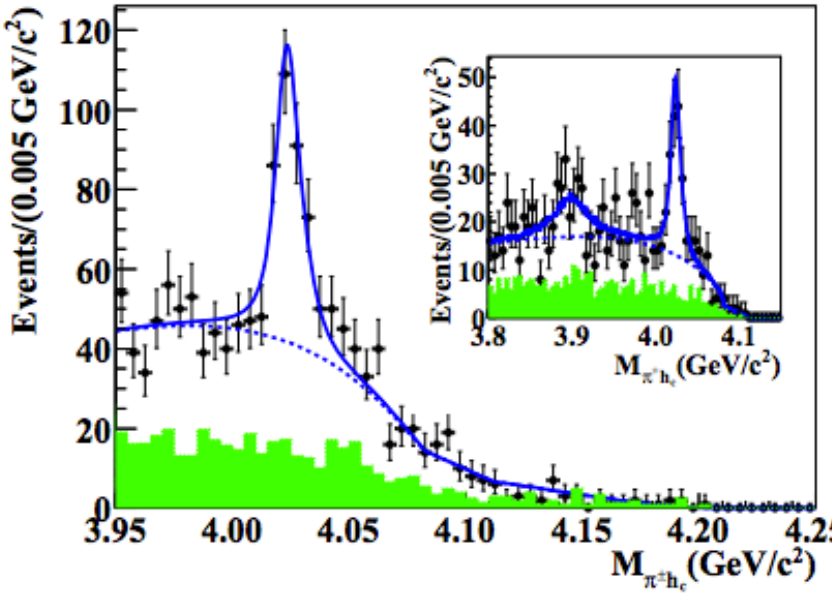


$e^+e^- \rightarrow \pi^+\pi^- h_c$



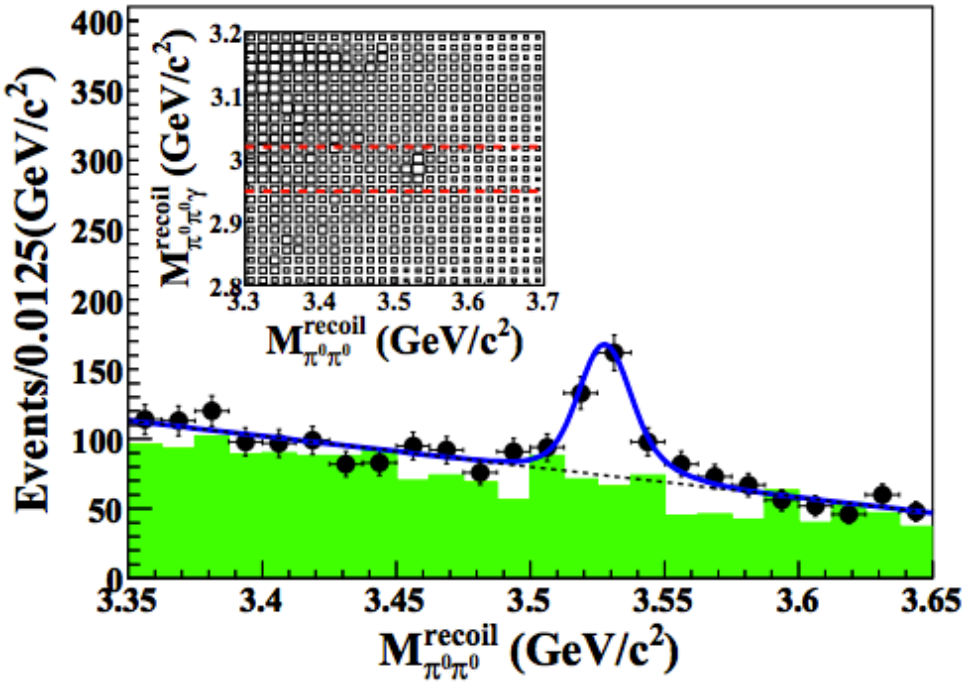
PRL111,242001(2013)

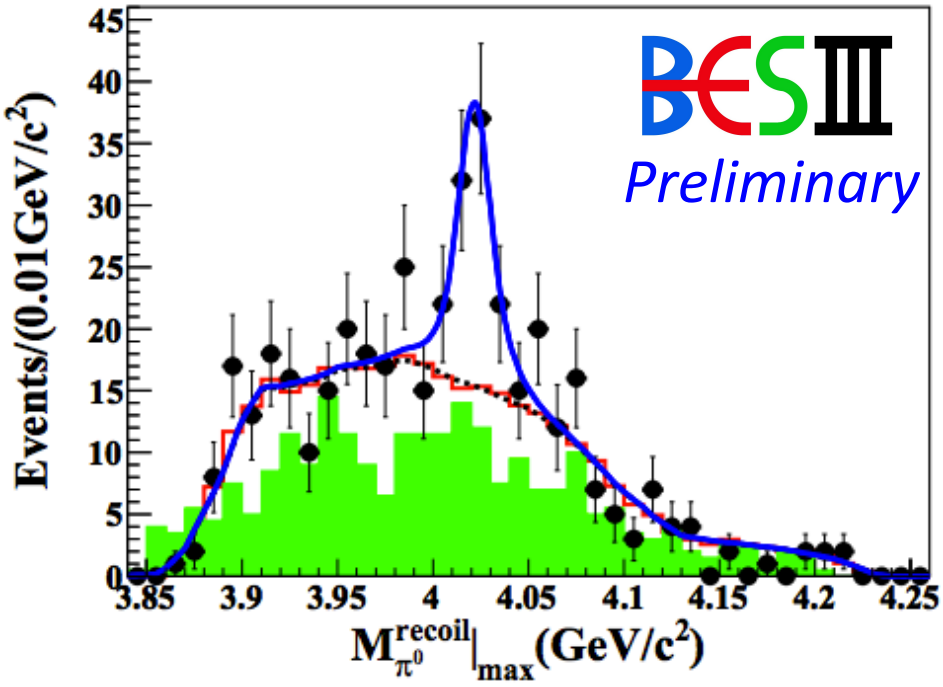




1. Clear $\pi^+\pi^- h_c$ signal in data.
2. Events accumulate $M^2(\pi^\pm h_c)$~16 GeV^2
3. Signal: BW convolving resolution; efficiency & phase space included.
4. $M[Z_c(4020)]=(4022.9\pm0.8\pm2.7)$ MeV; $\Gamma[Z_c(4020)]=(7.9\pm2.7\pm2.6)$ MeV
5. $\sigma[\pi Z_c(4020)]$~10 pb level

Neutral Partner: $e^+e^- \to \pi^0\pi^0 h_c$



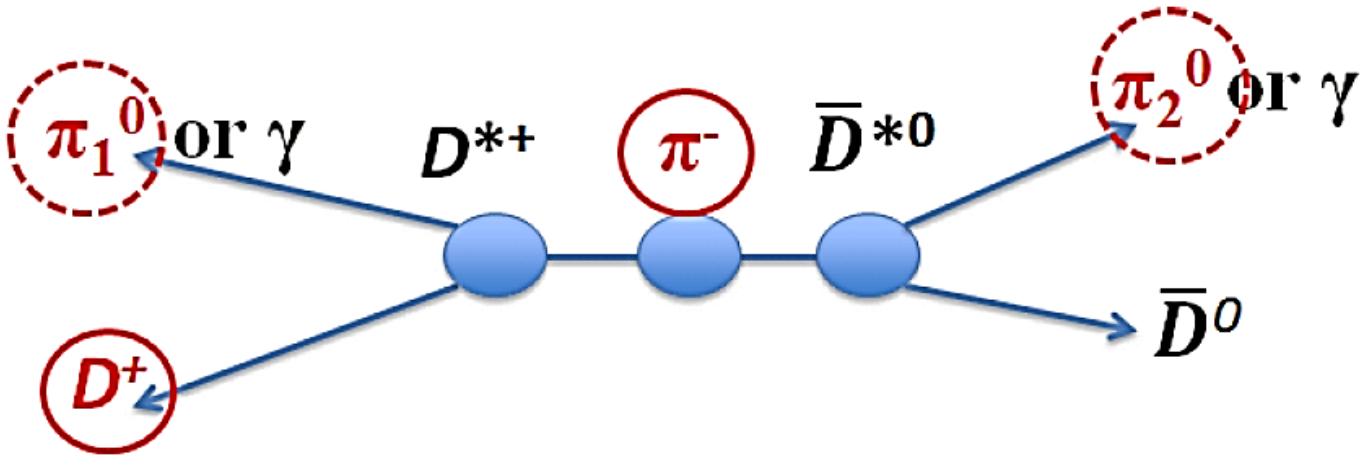


- Using the same analysis technique to study isospin channel.
- Clear $e^+e^- \to \pi^0\pi^0 h_c$ signal observed, isospin symmetry.
- Neutral candidate: $M[Z_c(4020)^0]=(4023.9\pm2.2\pm3.8)$ MeV; width fixed to charged one.
- Significance ~5σ

arXiv: 1409.6577

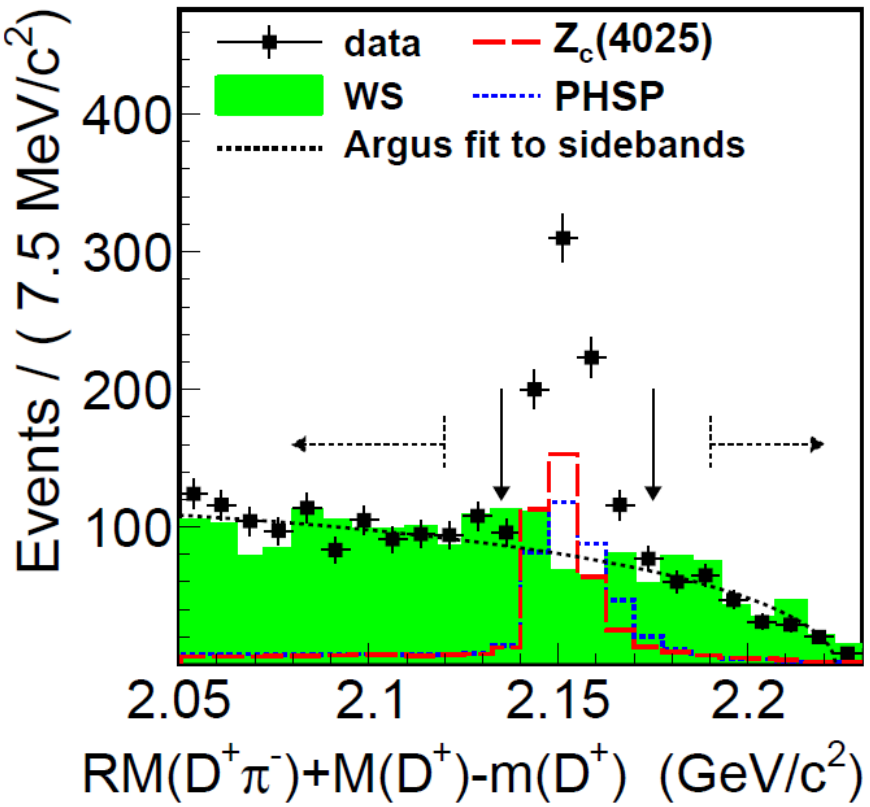
Threshold resonance: $e^+e^- \to \pi^- (D^*\bar{D}^*)^+ + c.c.$

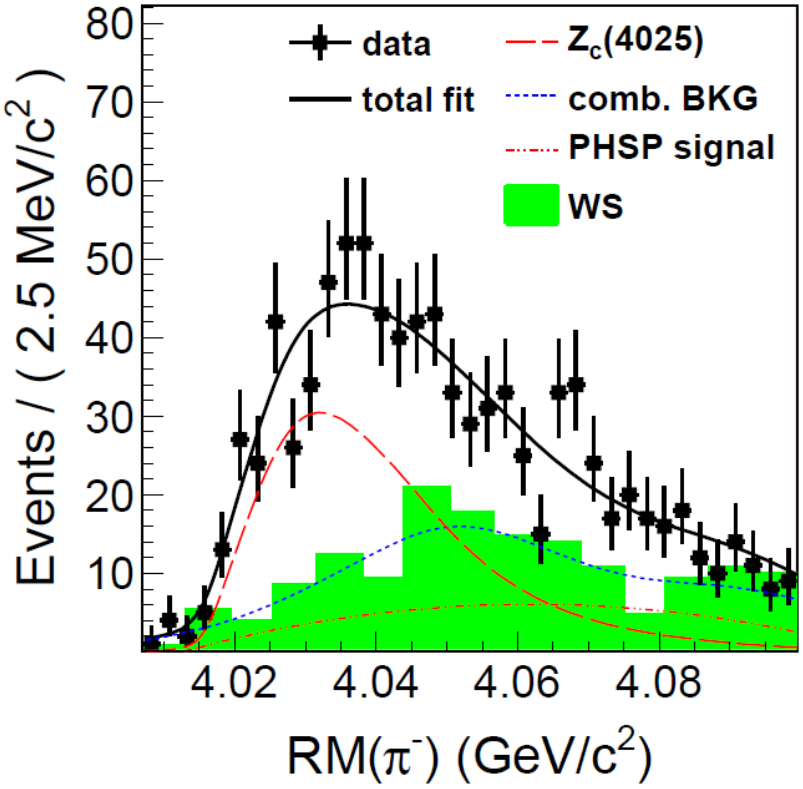
- Mass of $Z_c(4020)$ near $(D^*D^*)^{\pm}$ threshold.
- 827 pb^{-1} data at E_{cm}=4.26 GeV
- Tag a D^+ and a bachelor π^-, reconstruct one π^0 to suppress the background.



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.

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

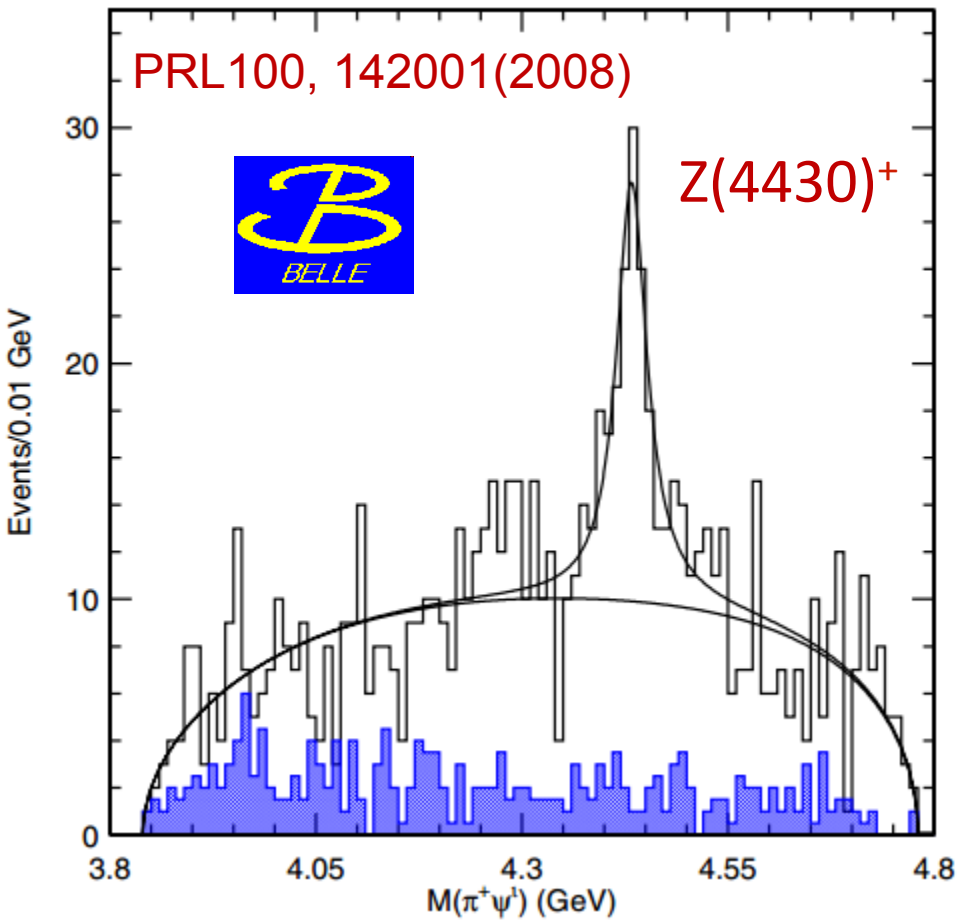


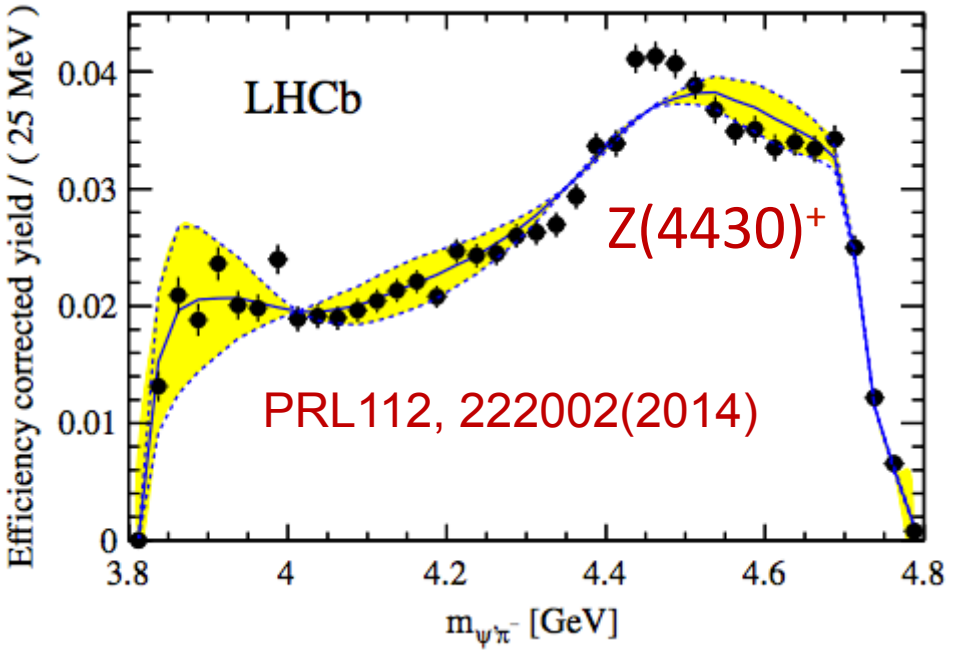


- Fit to $\pi^\pm$ recoil mass (RM) yields 401±47 $Z_c(4025)$ events.
- M=(4026.3±2.6±3.7) MeV; Γ=(24.8±5.6±7.7) MeV.
- $\sigma^B(e^+e^- \to D^*D^*\pi)$=(137±9±15) pb.
- $\sigma[\pi Z_c(4025)]$~90 pb; $\Gamma(Zc(4025) \to D^*D^*)/\Gamma(Zc(4020) \to \pi h_c)$~9.
- Significance >10σ

PRL112,132001(2014)

$Z(4430)^+ \rightarrow \pi^+\psi(2S)$ from B meson decay



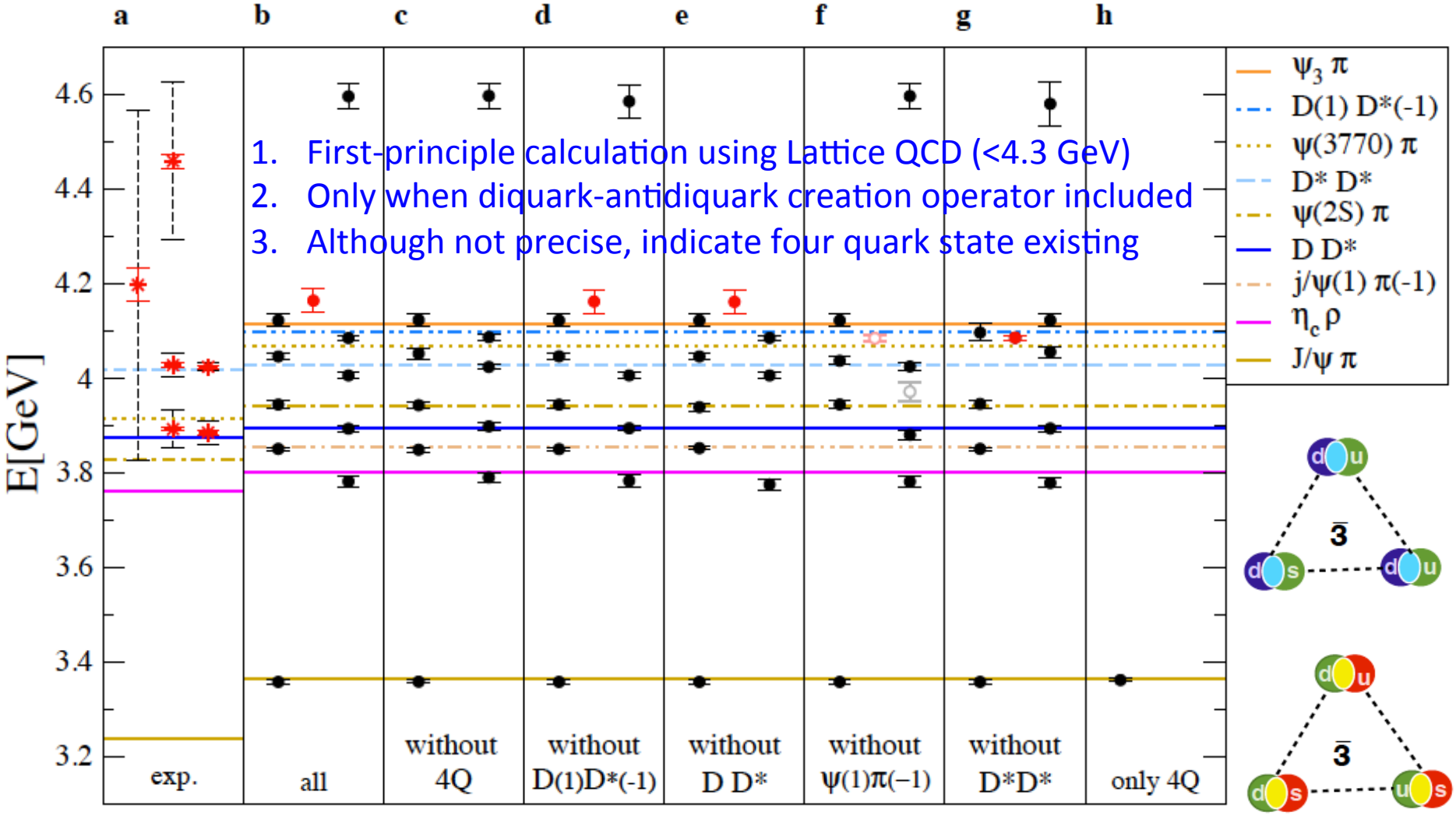


$M=4475\pm7^{+15}_{-25}$ MeV
$\Gamma=172\pm13^{+37}_{-34}$ MeV
Significance: >13.9σ

$M=4433\pm4\pm2$ MeV
$\Gamma=45^{+18}_{-13}{}^{+30}_{-13}$ MeV
Significance: 6.5σ

- First observed by Belle
- Confirmed by LHCb
- Belle & LHCb: $J^P=1^+$

LQCD: Evidence for a charged Z_c^+



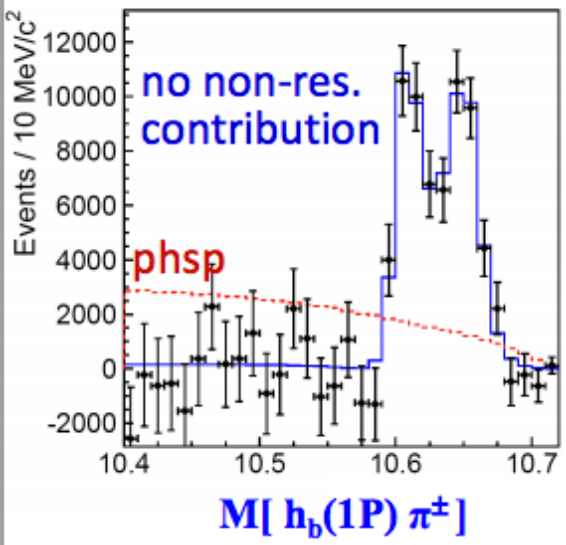
arXiv: 1405.7623

A mirror in the Bottomonium system

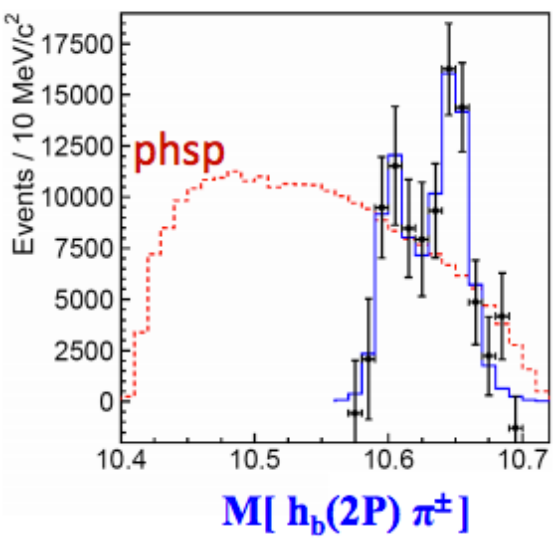
Charged Z_b states

PRL108, 122001(2012)

$\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$



$\Upsilon(5S) \to h_b(2P)\pi^+\pi^-$



Two peaks in all 5 modes

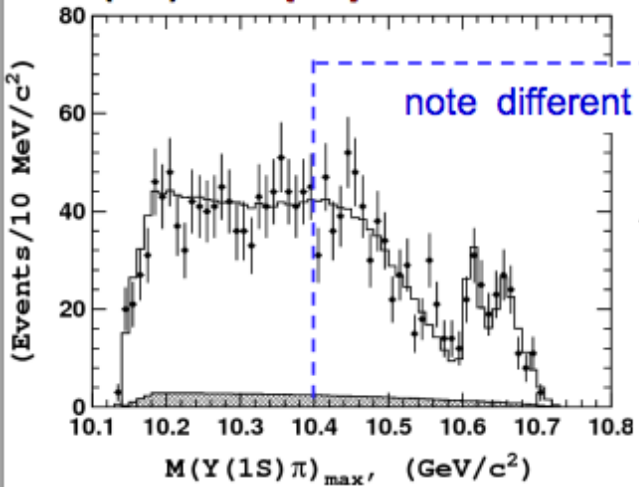
minimal quark content

$|\, b\bar{b}u\bar{d}\,\rangle$

flavor-exotic states

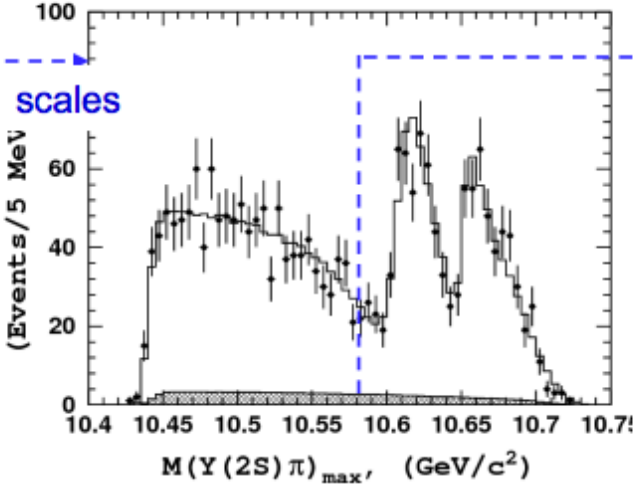
Dalitz plot analysis

$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$

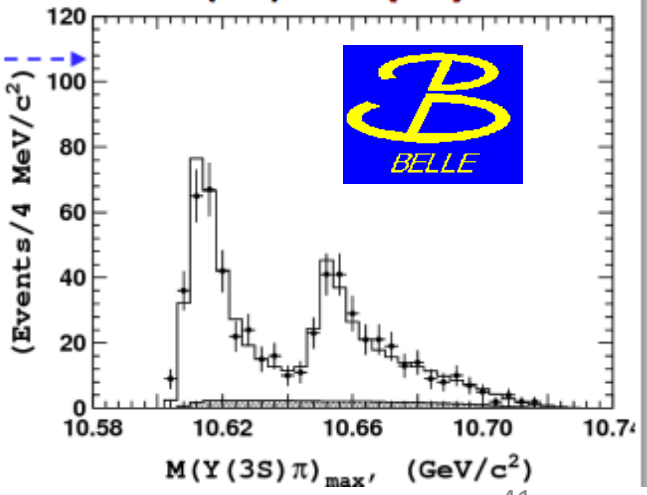


note different scales

$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$



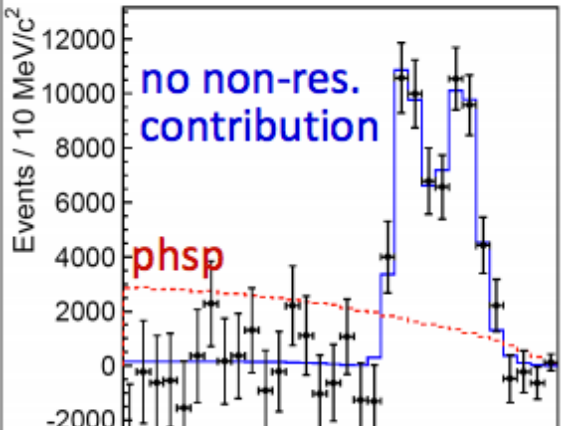
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$



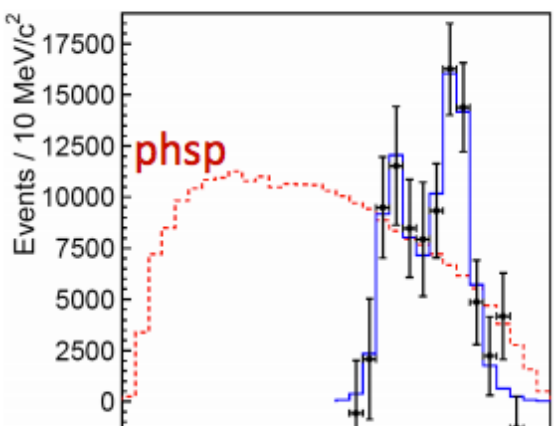
Charged Z_b states

PRL108, 122001(2012)

$\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$



$\Upsilon(5S) \to h_b(2P)\pi^+\pi^-$



Two peaks in all 5 modes

minimal quark content

$|\, b\bar{b}u\bar{d}\,\rangle$

flavor-exotic states

Fit results

Average over 5 channels

$M_1 = 10607.2 \pm 2.0$ MeV

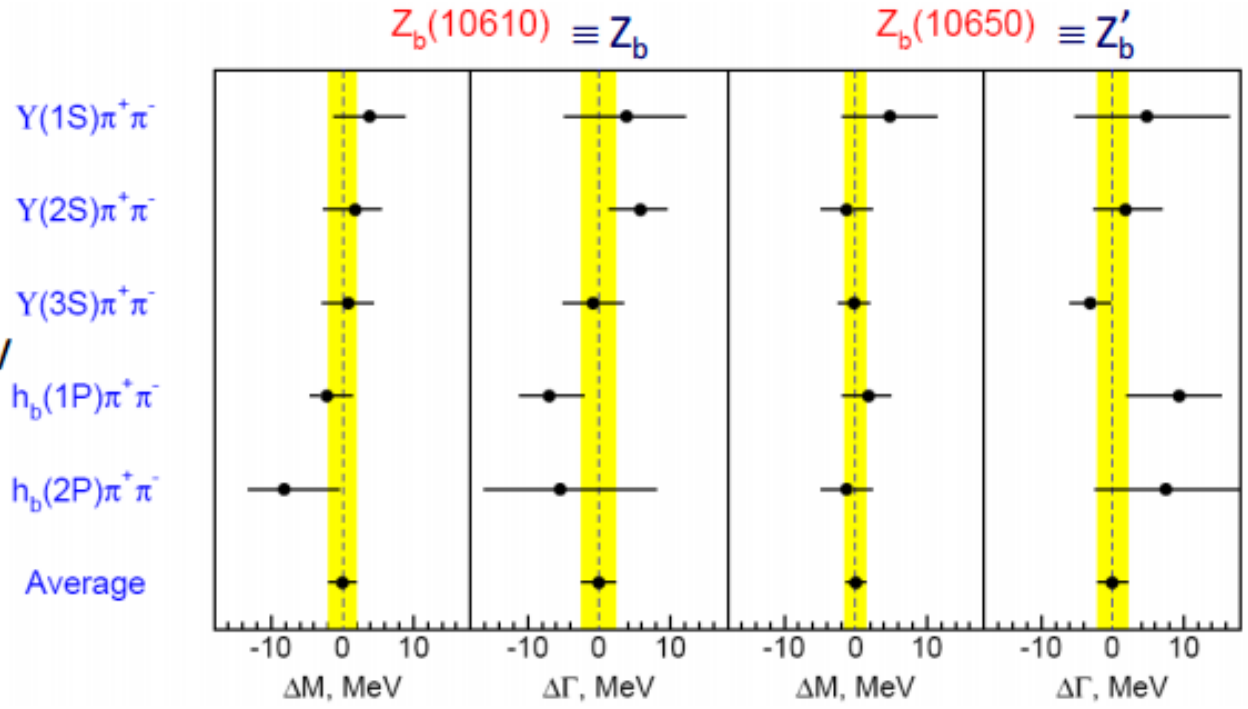
$\Gamma_1 = 18.4 \pm 2.4$ MeV

$M_{Zb} - (M_B + M_{B^*}) = +2.6 \pm 2.1$ MeV

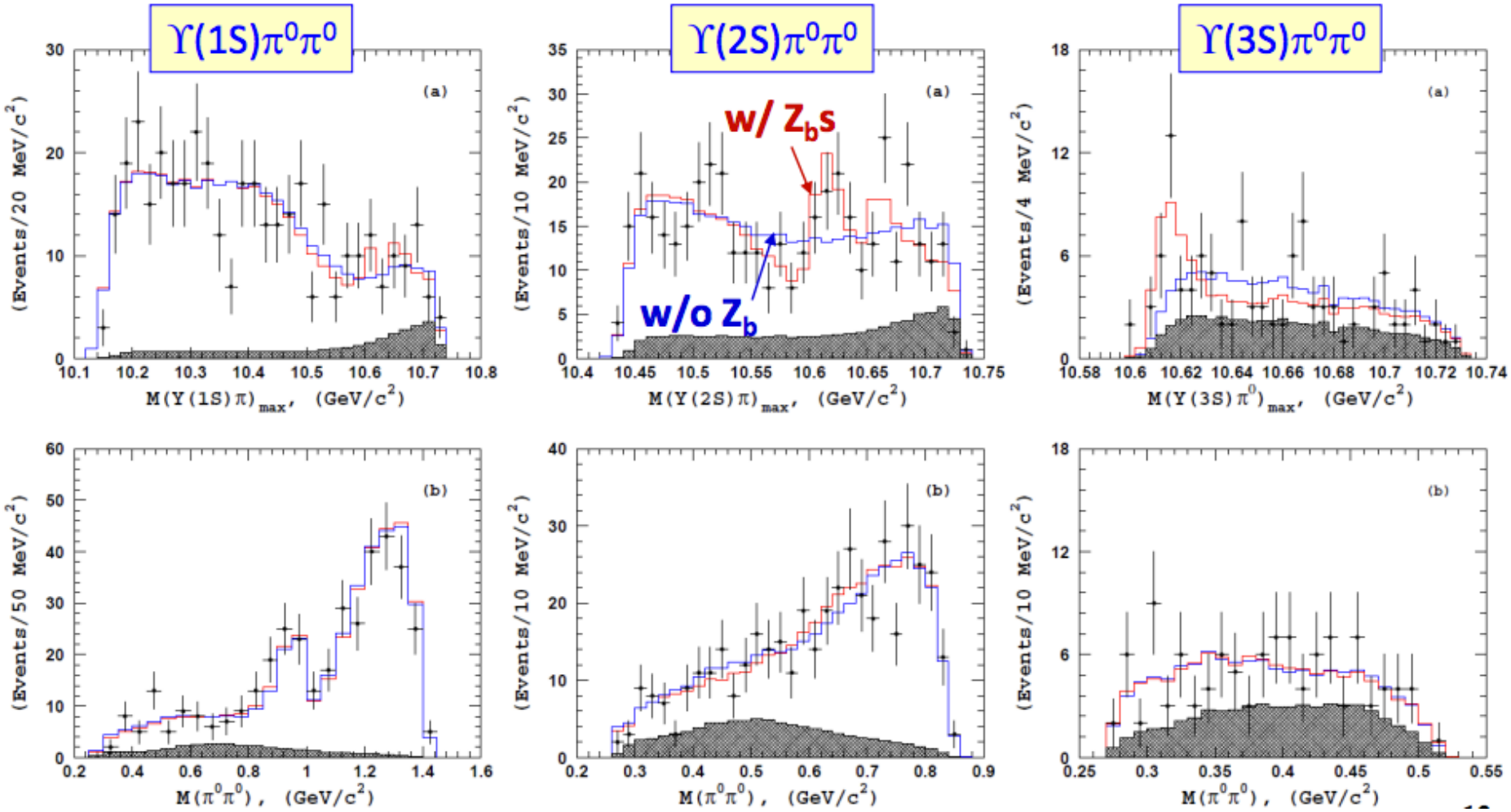
$M_2 = 10652.2 \pm 1.5$ MeV

$\Gamma_2 = 11.5 \pm 2.2$ MeV

$M_{Zb'} - 2M_{B^*} = +1.8 \pm 1.7$ MeV



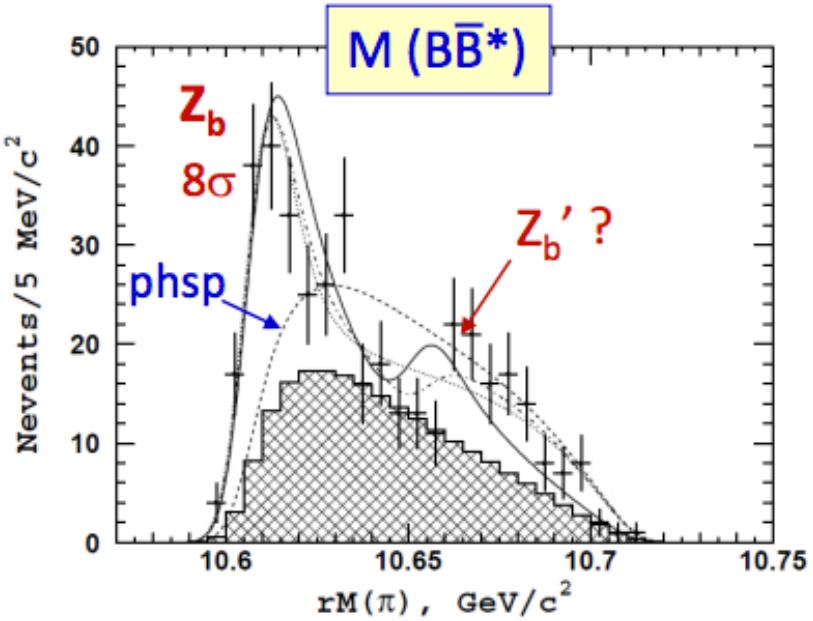
Neutral partner: $Z_b(10610)^0$ & $Z_b(10650)^0$

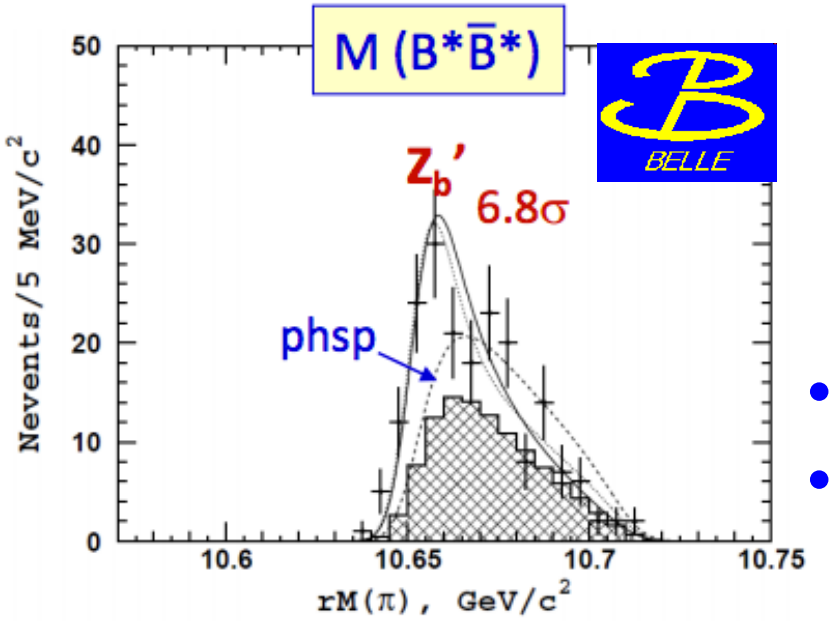


	$\Upsilon(2S)\pi^0$	$\Upsilon(3S)\pi^0$	Combined
Significance of $Z_b(10610)$ *(including systematics)*	4.9σ	4.3σ	6.5σ

observation of $Z_b(10610)^0$

Threshold resonance: $e^+e^- \to \pi^+(B\bar{B}^* \,\&\, B^*\bar{B}^*)^- + c.c.$





Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

$BF[Z_b' \to B\bar{B}^*] = (25 \pm 10)\%$ insignificant

- Similar behavior as the Z_c states
- Same Nature?

Summary

- Huge experimental progress on XYZ particles.
- The charged Z_c and Z_b states share similar feature, should be exotic!
- LQCD support four quark state existing.
- X(3872) and Y(4260)… still keep mysterious?
- BESIII build connection: Y(4260)→γX(3872) radiative decay for the first time.
- Understand them with more data & effort.

Thank you !