XYZ states at BESIII

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Outline

- Introduction
- The charged Z_c states

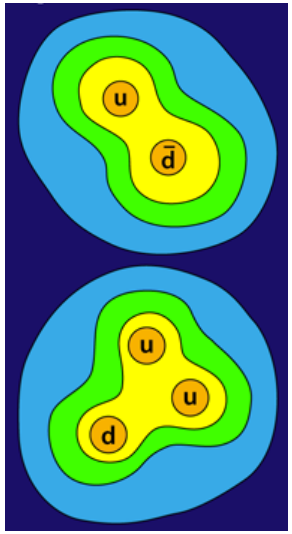
  $Z_c(3900)$, $Z_c(4020)$…
- The exotic X states

  News of X(3823), X(3872) & X(4140)
- The vector-Y states

  Exclusive cross section line shape > 4 GeV
- Summary

Hadrons: normal & exotic

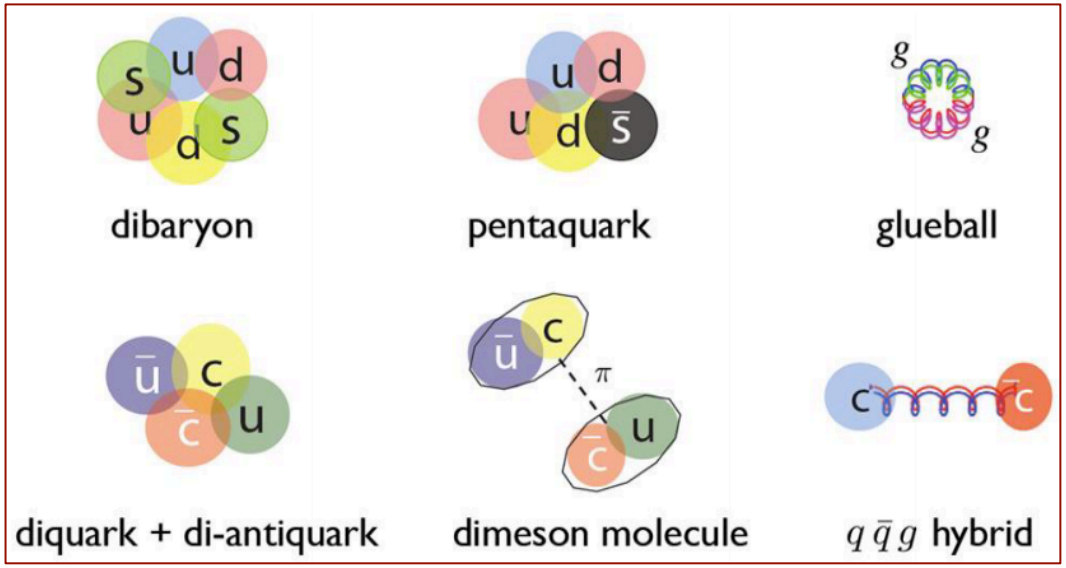
- Quark model: hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks



Normal

vs.

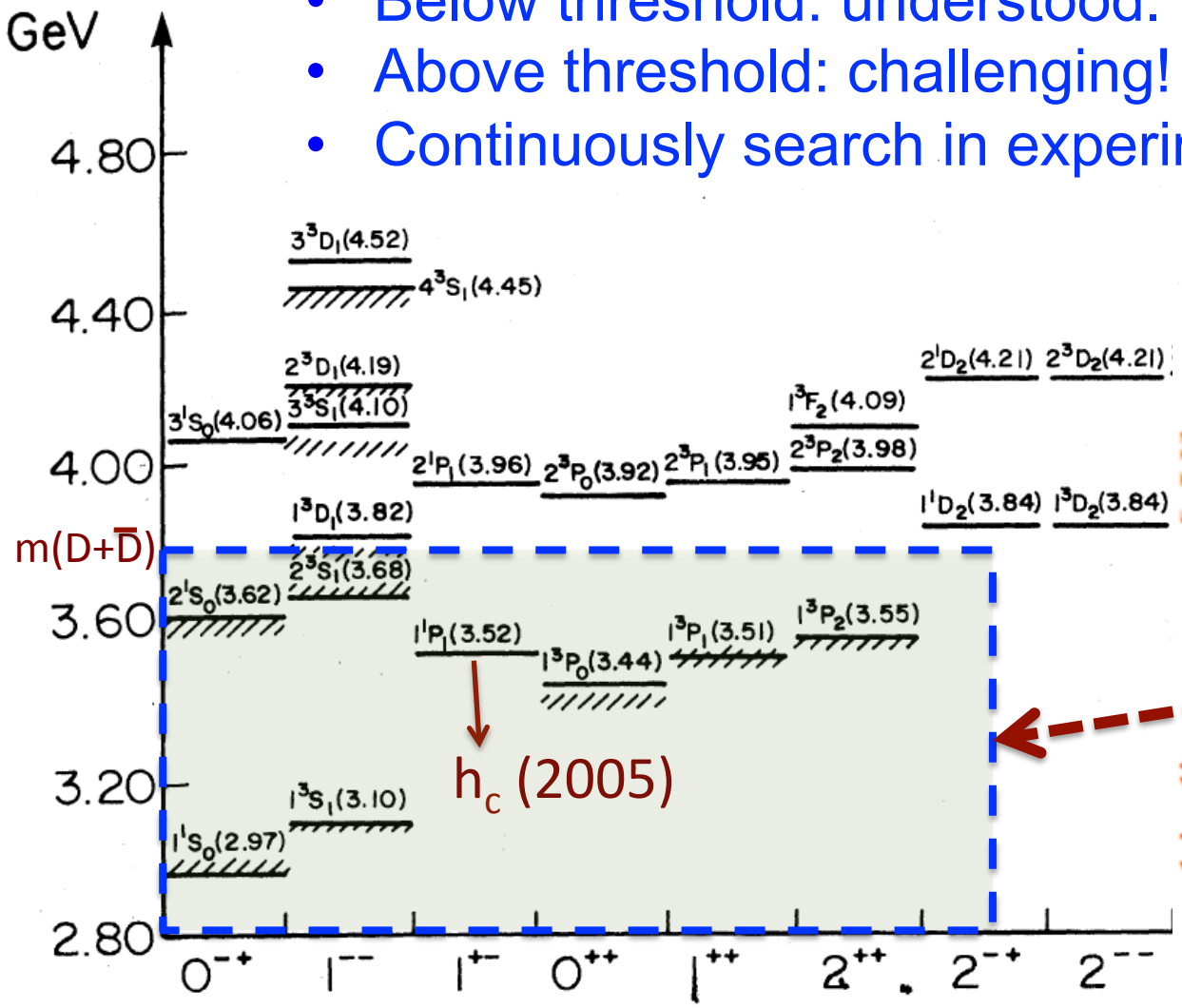
Exotic



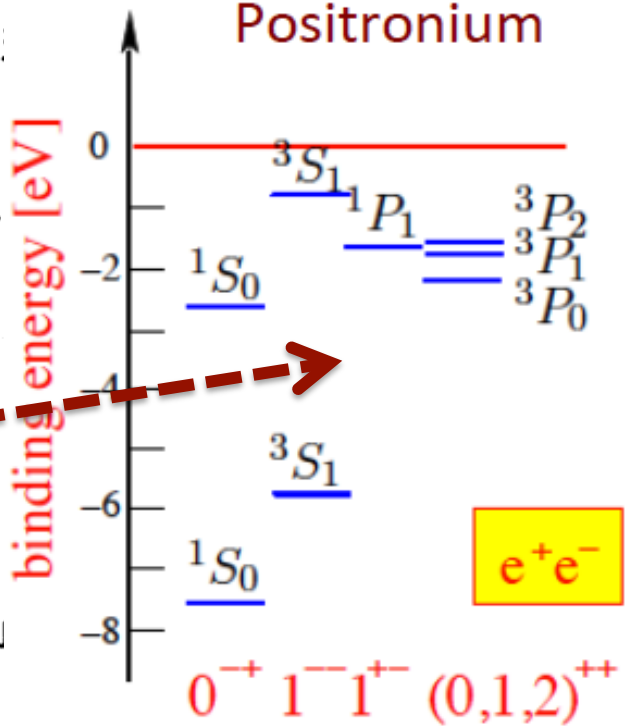
- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - Glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - Hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - Molecule : bound state of more than 2 hadrons
  - …

Why heavy quarkonium?

- Below threshold: understood.
- Above threshold: challenging!
- Continuously search in experiment.



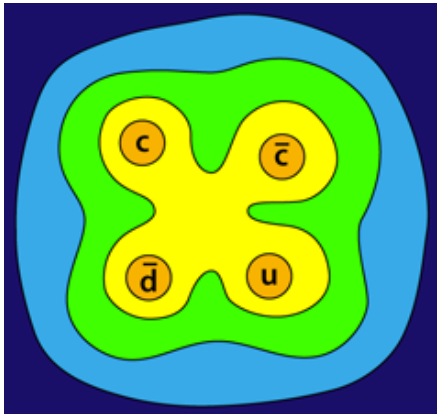
$n^{2s+1}L_J$



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

XYZ particles

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



X(3823)
X(3872)
X(3915)
X(4350)
Y(4008)
Y(4260)
Y(4140)
Y(4360)
Y(4660)
Y(4630)
...
XYZ(3940)

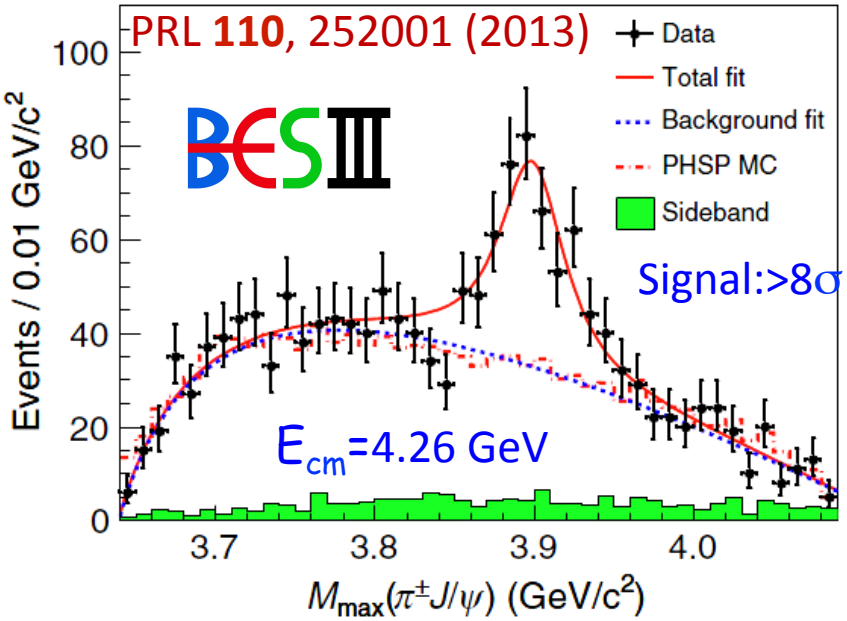
$Z_c(3900)$
$Z_c(4020)$
Z(4430)
Z(4250)
Z(4050)
...

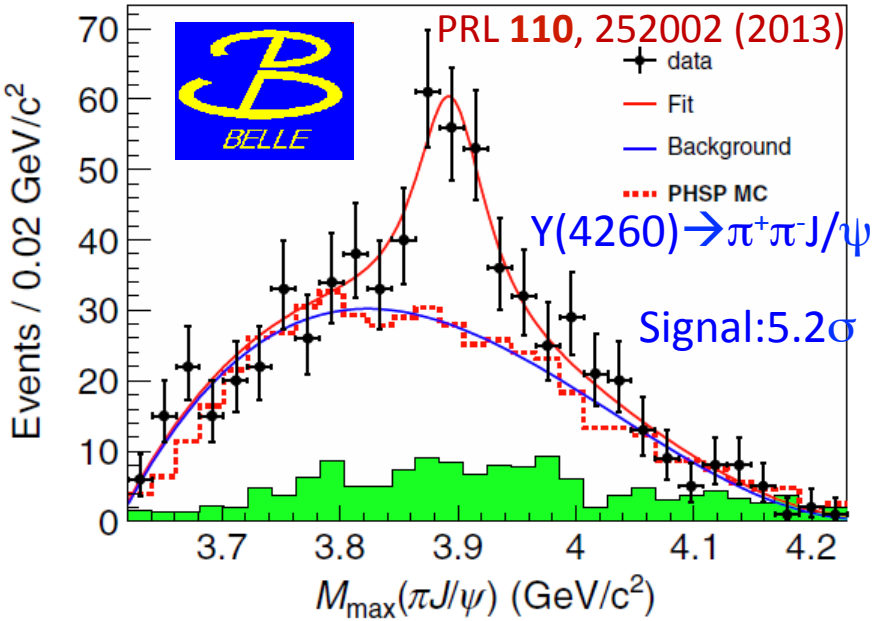
Charmonium?
Hybrid?
Tetraquark?
Molecule?
...

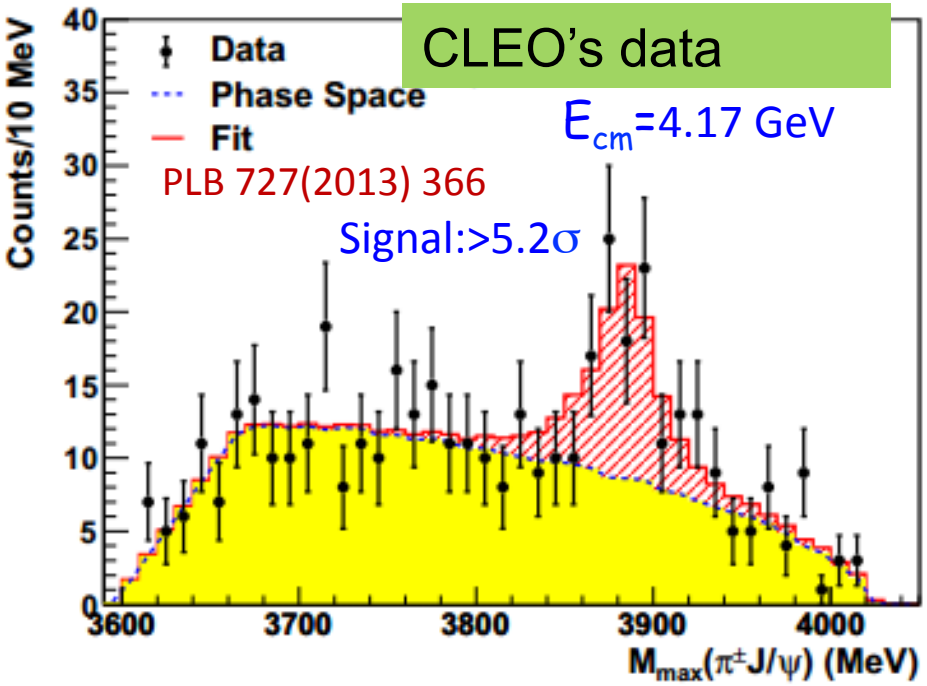
Godfrey & Isgur, PRD32, 189 (1985)

The charged Z_c states

Discovery: $e^+e^- \to \pi^\pm Z_c(3900) \to \pi^+\pi^- J/\psi$@4.26 GeV



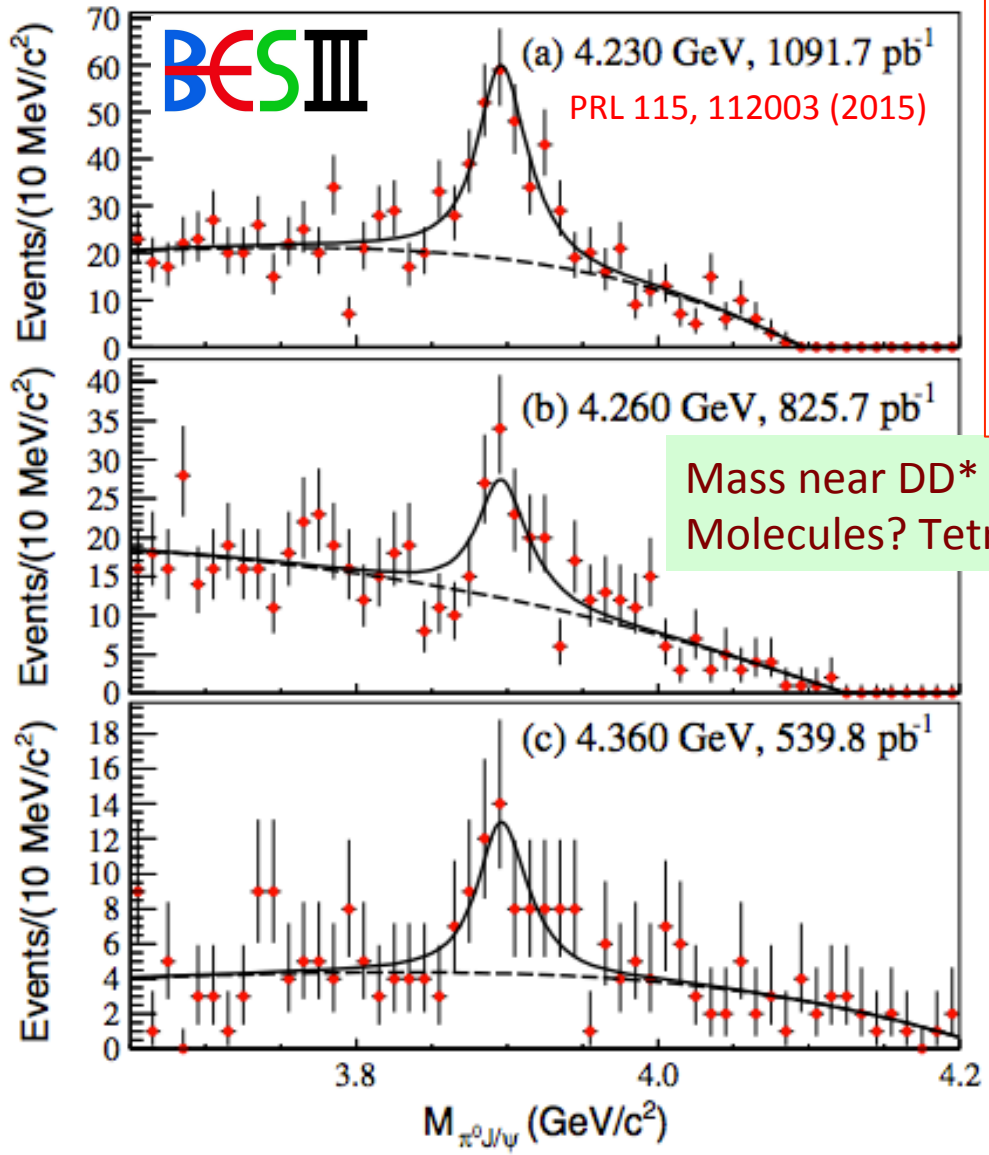




1. BESIII: M=(3899.0±3.6±4.9) MeV; Γ=(46±10±20)MeV
2. Belle: M=(3894.5±6.6±4.5) MeV; Γ=(63±24±26) MeV.
3. CLEO's data: M=3886±6±4 MeV, Γ=33±6±7 MeV.
4. At least four quarks inside!

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±2.3±3.2 MeV

Γ = 29.6±8.2±8.2 MeV

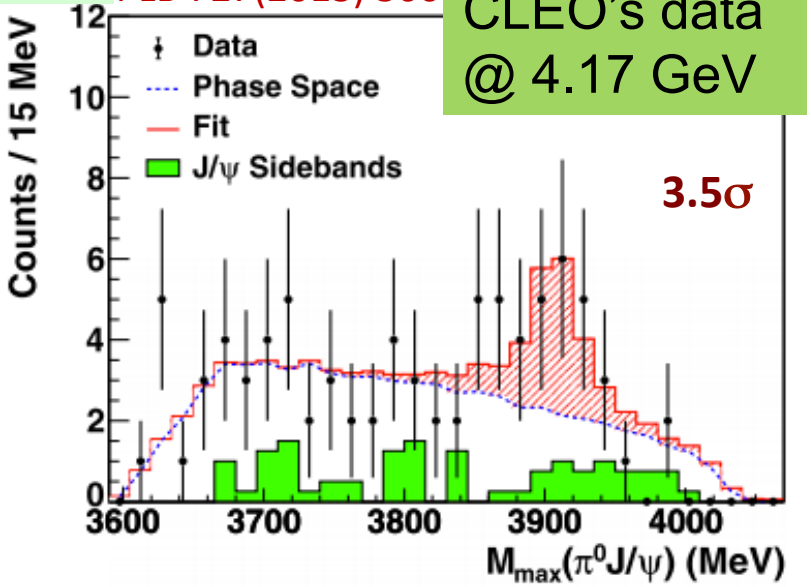
Significance = 10.4σ

Mass near DD* threshold

Molecules? Tetraquark?

PLB 727(2013) 366

CLEO's data @ 4.17 GeV

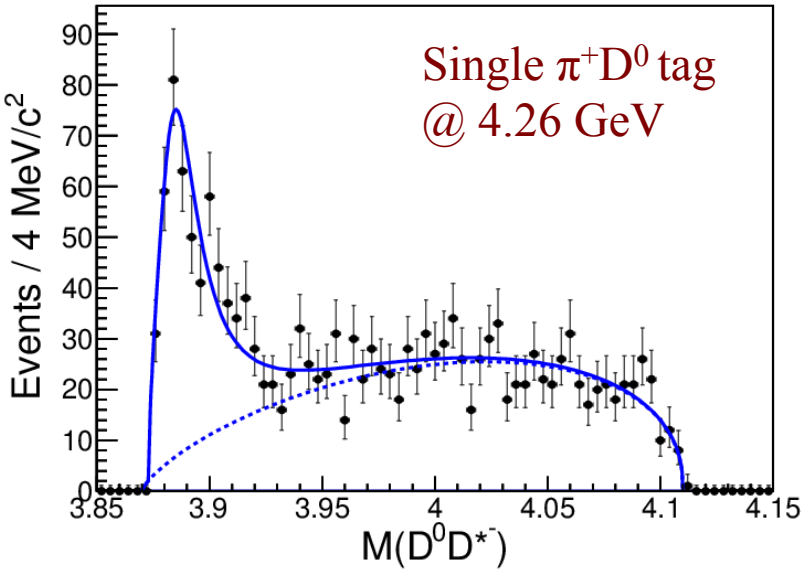


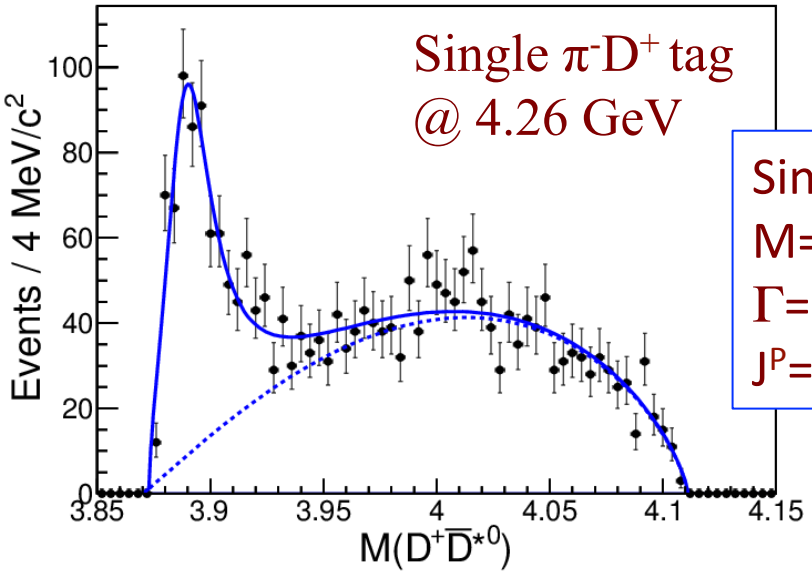
$e^+e^- \to (DD^*)^+\pi^- + c.c.$?

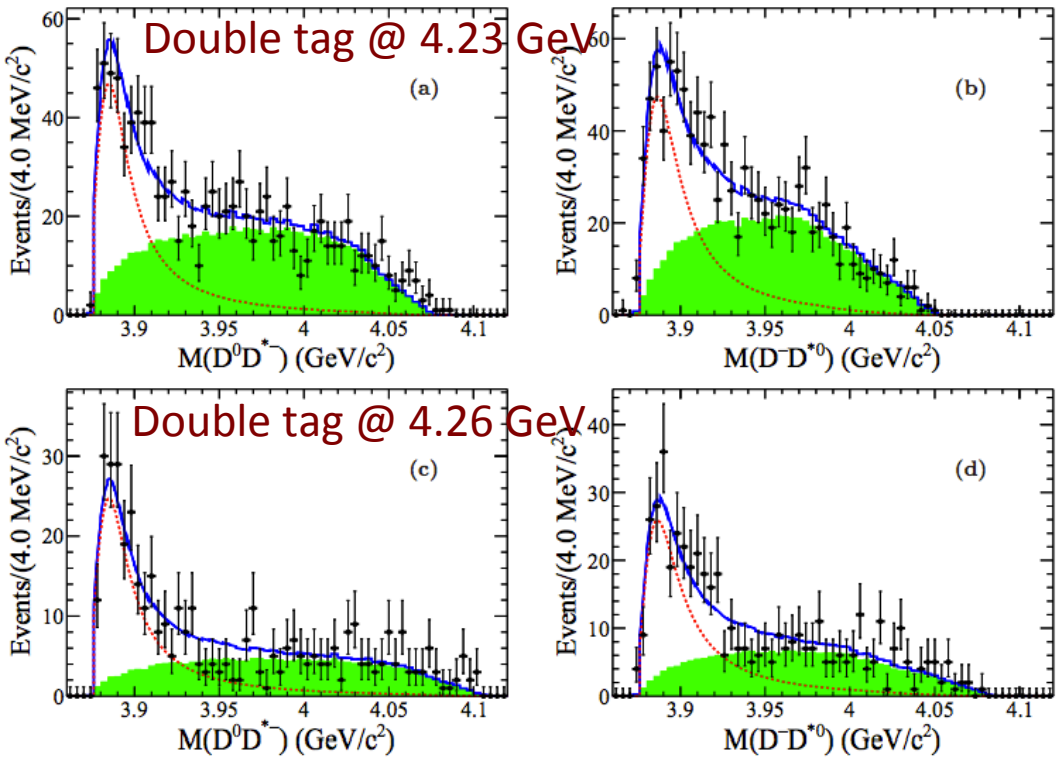
BESIII

PRL 112, 022001 (2014)

arXiv: 1509.01398







Single tag

M=3883.9±1.5±4.2 MeV

Γ=24.8±3.3±11.0 MeV

$J^P=1^+$

Double tag

M=3881.7±1.6±2.1 MeV

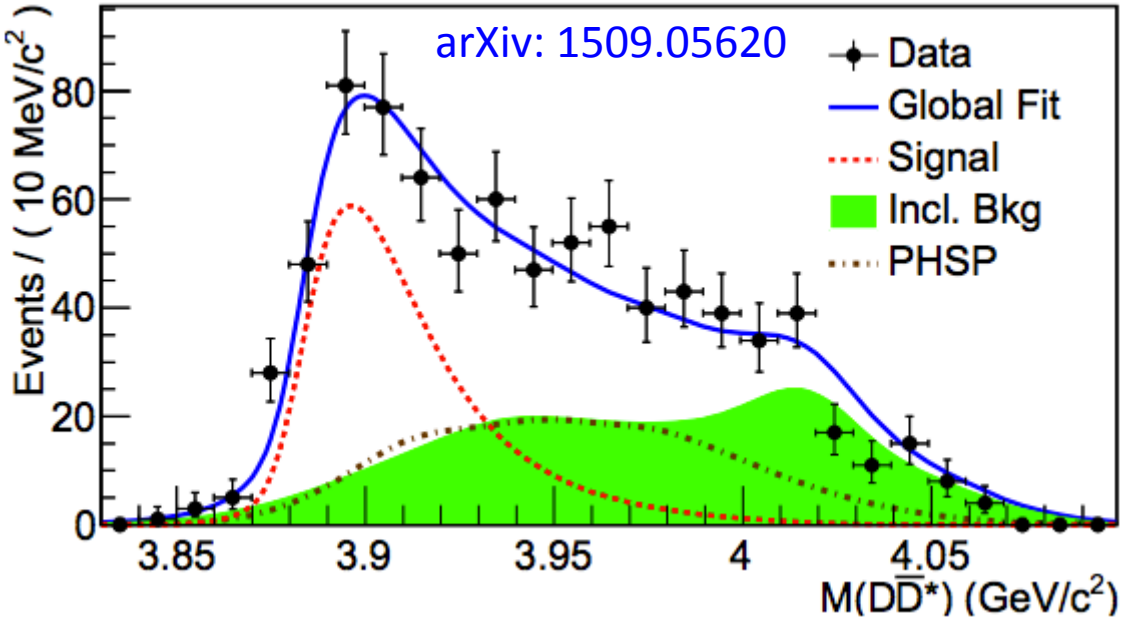
Γ=26.6±2.0±2.3 MeV

$J^P=1^+$

Good agreement between ST & DT method

$Z_c(3900)$ vs. $Z_c(3885)$ → Same resonance ?!

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

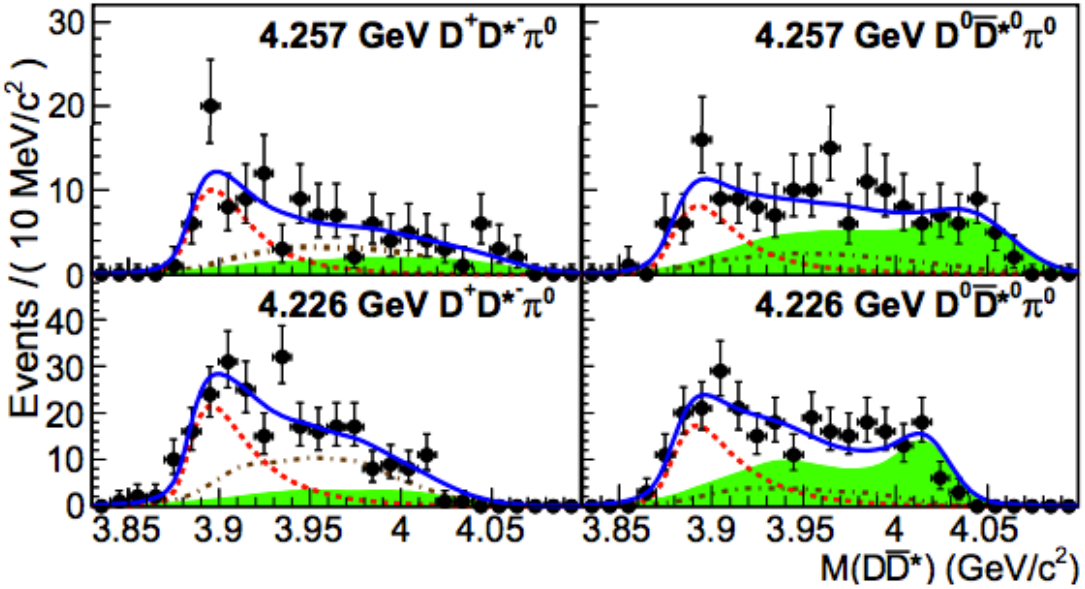


Partial reconstruction method
- Single tag

$M=3885.7^{+4.3}_{-5.7}\pm8.4$ MeV

$\Gamma=35^{+11}_{-12}\pm15$ MeV

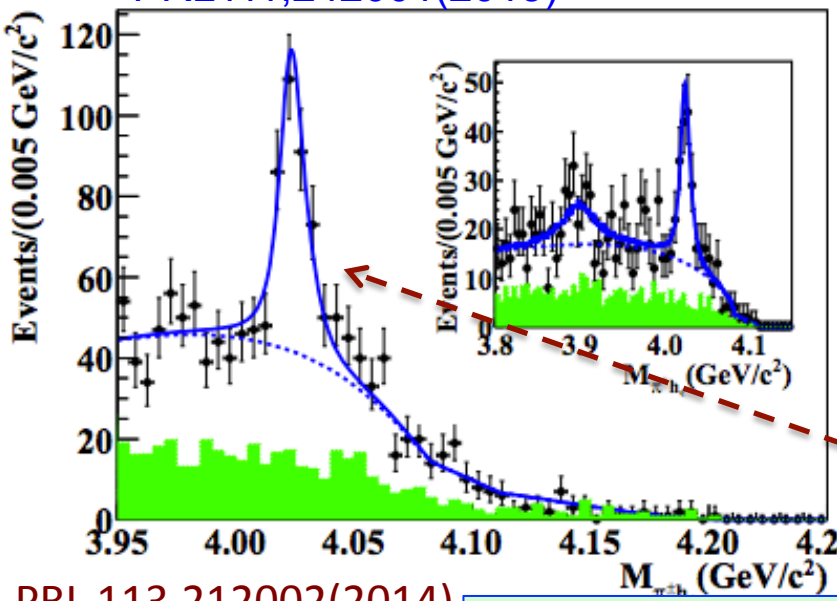
Significance: $>10\sigma$

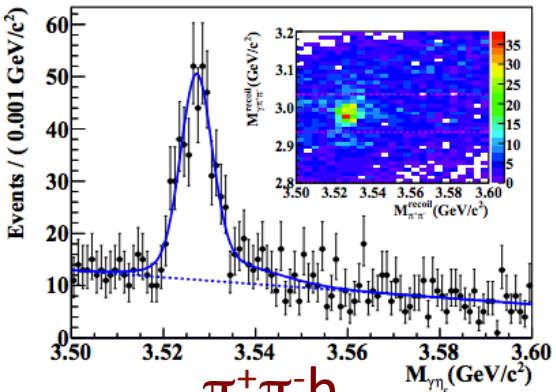


- ✧ Good agreement between neutral state and charged state
- ✧ An iso-spin triplet established in DD* channel
- ✧ Might be same as $Z_c(3900)$
- ✧ Molecule state? Tetraquark?

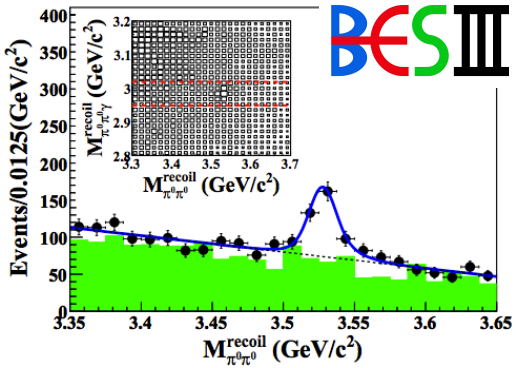
$e^+e^- \to \pi^+\pi^- h_c$ & $\pi^0\pi^0 h_c$

PRL111,242001(2013)





$\pi^+\pi^- h_c$



$\pi^0\pi^0 h_c$

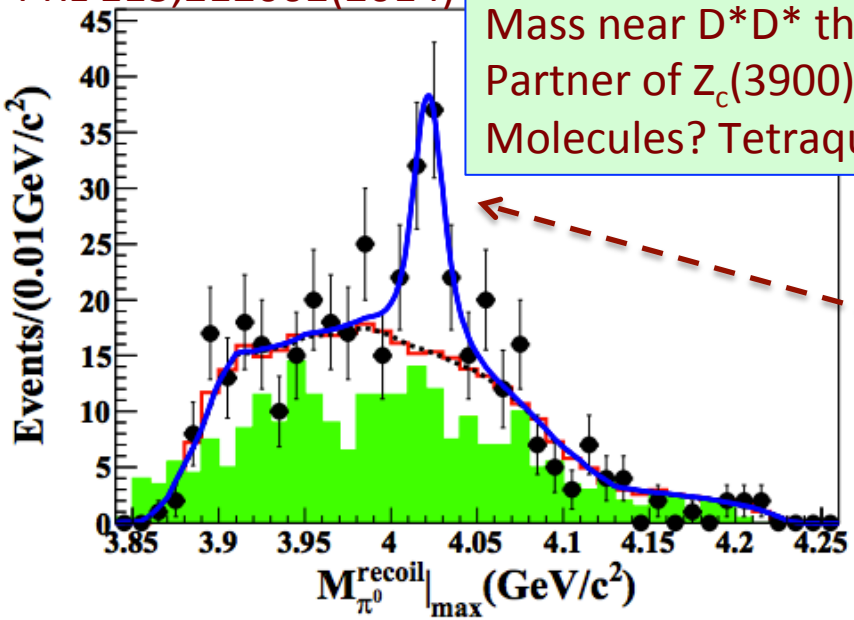
Charged $Z_c(4020)^{\pm}$

Mass=(4022.9±0.8±2.7) MeV

Width=(7.9±2.7±2.6) MeV

Significance: >8.9σ

PRL 113,212002(2014)



Mass near D*D* threshold

Partner of $Z_c(3900)$?

Molecules? Tetraquark?

An spin triplet is established !

Neutral $Z_c(4020)^0$

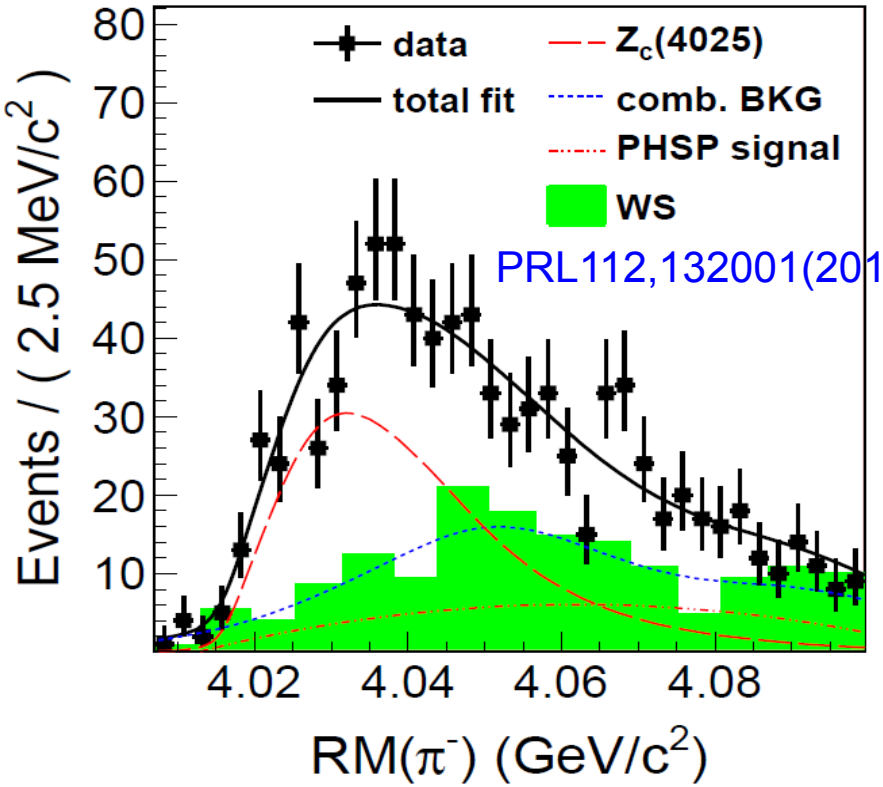
Mass=(4023.9±2.2±3.8) MeV

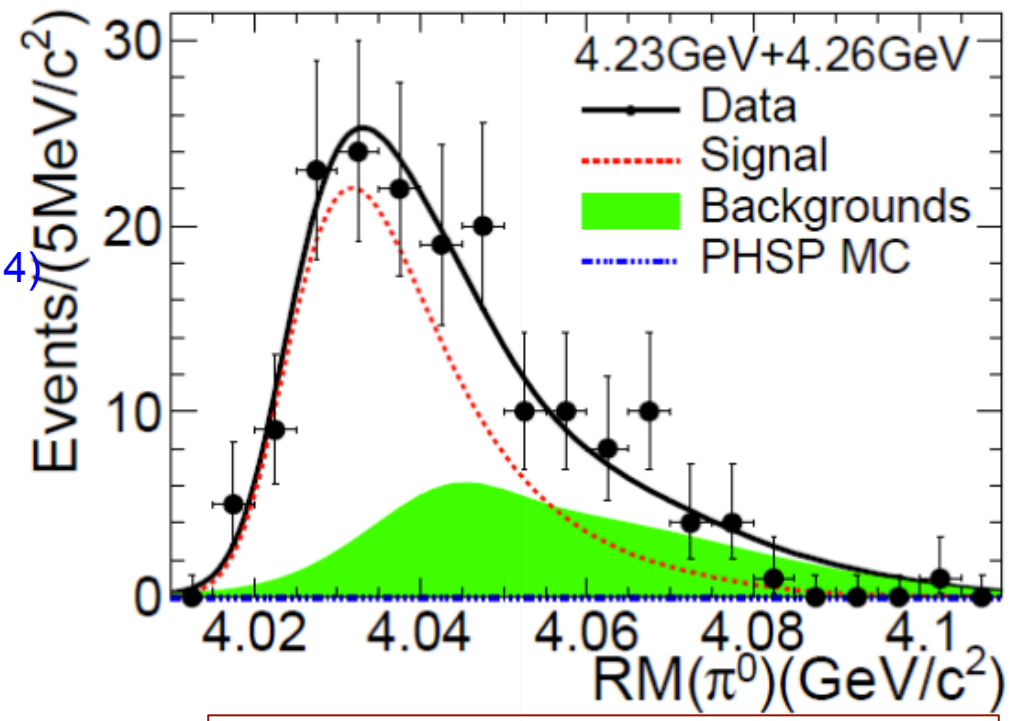
Width: fixed to charged partner

Significance: 5σ

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

arXiv: 1507.02404





Charged $Z_c(4025)$:
$M=(4026.3\pm2.6\pm3.7)$ MeV
$\Gamma=(24.8\pm5.6\pm7.7)$ MeV
Significance: $>10\sigma$

Agrees !

Neutral $Z_c(4025)^0$:
$M=(4025.5^{+2.0}_{-4.7}\pm3.1)$ MeV
$\Gamma=(23.0\pm6.0\pm1.0)$ MeV
Significance: $>5.9\sigma$

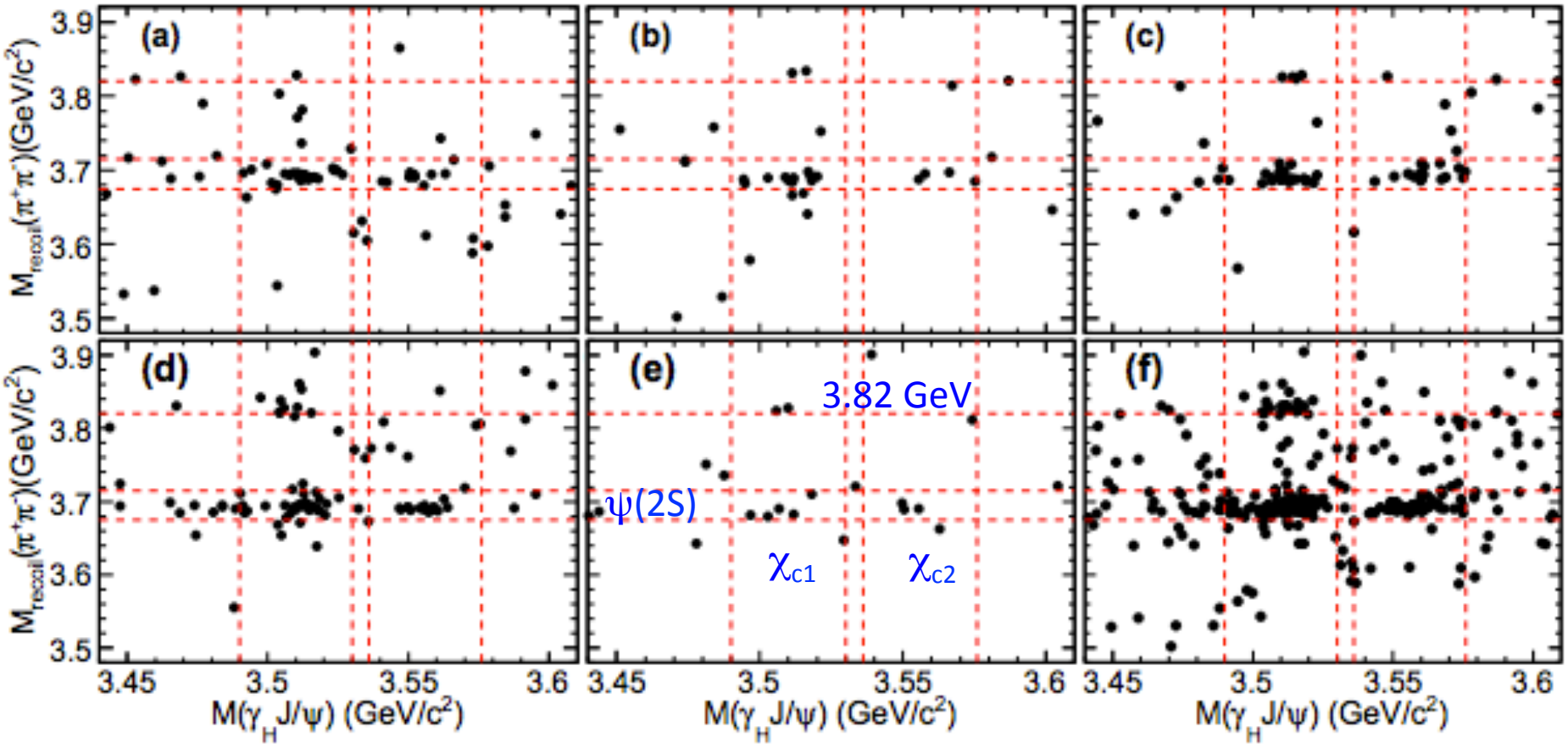
New isospin triplet?

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

The exotic X states

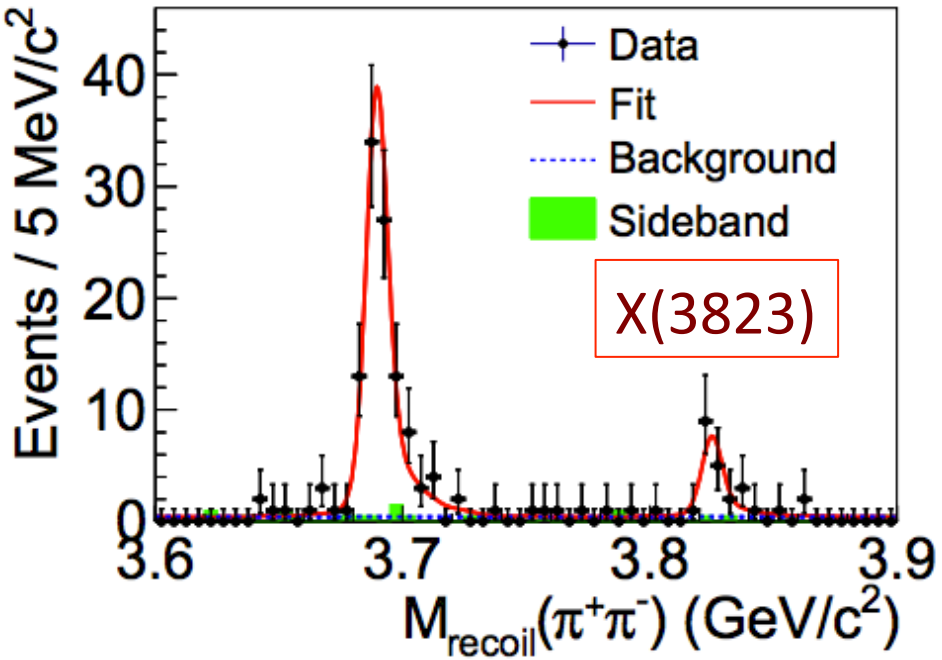
$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^- \gamma \chi_{c1}$

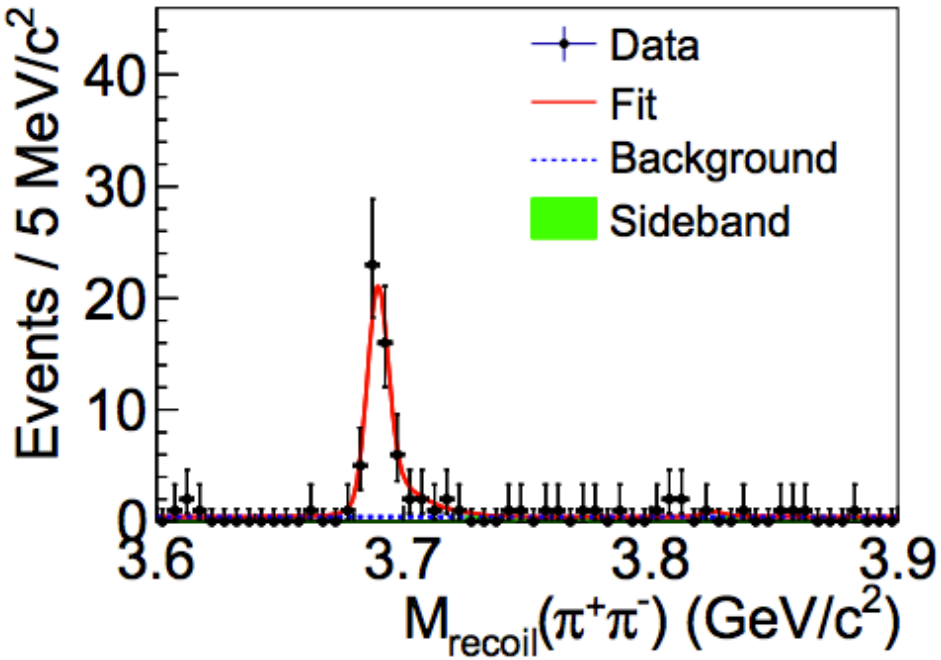
Using 4.67 fb^{-1} data, BESIII search for X(3823) at different E_{cm}



Observation of X(3823) at BESIII

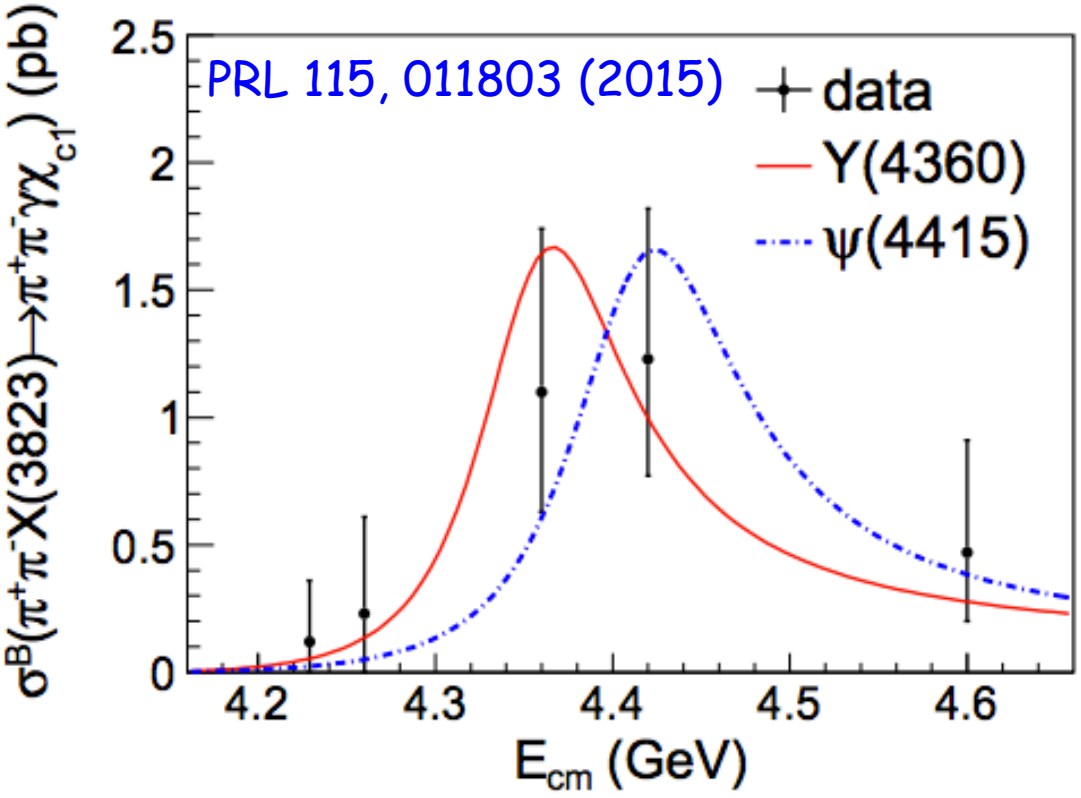
PRL 115, 011803 (2015)





- Simultaneous fit to data sets at different central-of-mass energies.
- M[X(3823)]=3821.7±1.3±0.7 MeV (calibrate by $\psi(2S)$).
- Statistical significance: 6.2σ ($>5.9\sigma$ including sys.), observation!
- Good candidate of $\psi(1^3D_2)$, confirms X(3872)$\neq\psi(1^3D_2)$

Production mechanics of X(3823)

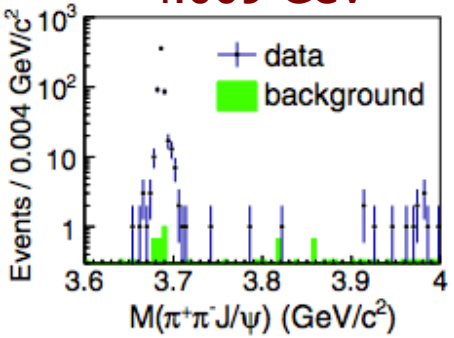


- Whether from Y(4360) or ψ(4415) decay
- Favor the Y(4360) ? [M. B. Voloshin, PRD 91, 114029 (2015)]
- Y(4360)→$\pi^+\pi^-$X(3823)? New decay model of Y(4360)?

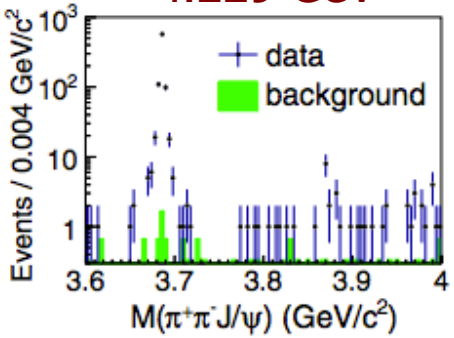
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$N^{\rm obs}$	ϵ	$1+\delta$	$\frac{1}{\lvert 1-\Pi\rvert^2}$	$\sigma_X^B\cdot\mathcal{B}_1$ (pb)	$\sigma_X^B\cdot\mathcal{B}_2$ (pb)	$\sigma_{\psi'}^B$ (pb)	$\mathcal{R}_{\psi'}$
4.230	1092	$0.7^{+1.4}_{-0.7}$ (< 3.7)	0.168	0.755	1.056	$0.12^{+0.24}_{-0.12}\pm0.02$ (< 0.73)	-	$34.1\pm8.1\pm4.7$	-
4.260	826	$1.1^{+1.8}_{-1.2}$ (< 4.5)	0.178	0.751	1.054	$0.23^{+0.38}_{-0.24}\pm0.04$ (< 1.11)	-	$25.9\pm8.1\pm3.6$	-
4.360	540	$3.9^{+2.3}_{-1.7}$ (< 7.9)	0.196	0.795	1.051	$1.10^{+0.64}_{-0.47}\pm0.15$ (< 2.54)	(< 2.05)	$58.6\pm14.2\pm8.1$	$0.20^{+0.13}_{-0.10}$
4.420	1074	$7.5^{+3.6}_{-2.8}$ (< 12.9)	0.145	0.967	1.053	$1.23^{+0.59}_{-0.46}\pm0.17$ (< 2.45)	(< 0.60)	$33.4\pm7.8\pm4.6$	$0.39^{+0.21}_{-0.17}$
4.600	567	$1.9^{+1.8}_{-1.1}$ (< 5.2)	0.157	1.075	1.055	$0.47^{+0.44}_{-0.27}\pm0.07$ (< 1.48)	-	$10.4^{+6.4}_{-4.7}\pm1.5$	-

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

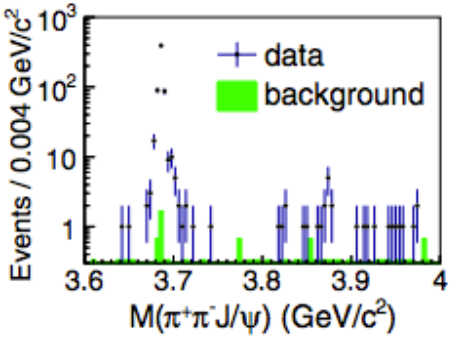
4.009 GeV



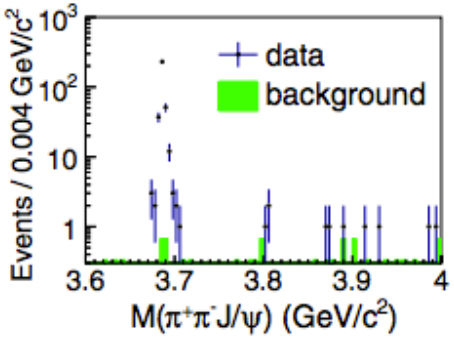
4.229 GeV



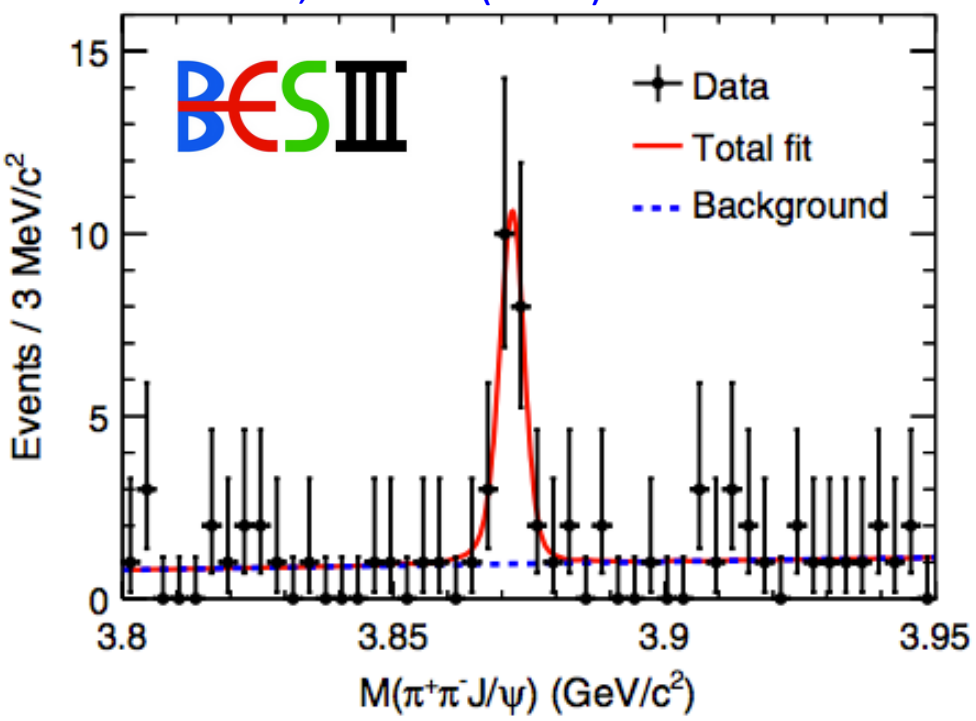
4.260 GeV



4.360 GeV

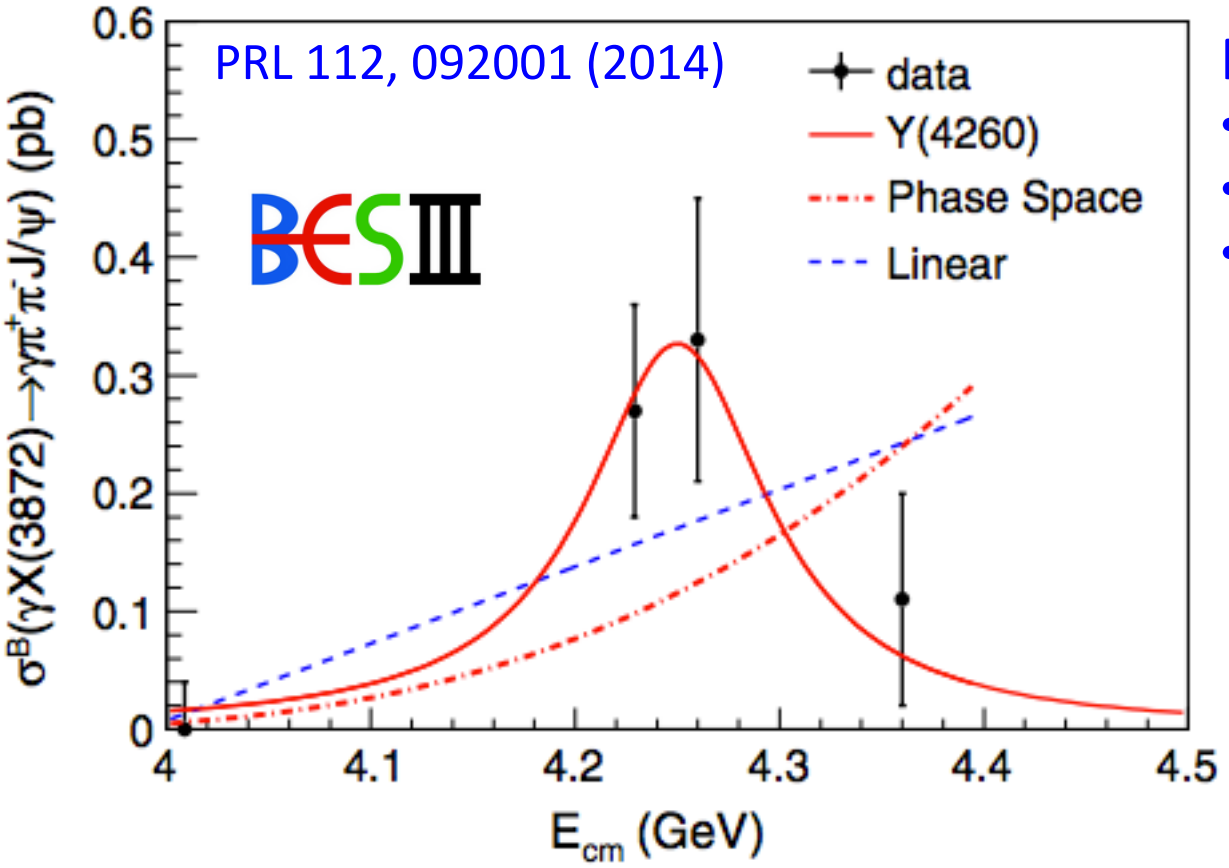


PRL 112, 092001 (2014).



- Analyze ~2.9 fb^{-1} data at 4.009, 4.23, 4.26, 4.36 GeV
- X(3872) was observed with 6.3σ significance.
- M[X(3872)]=3871.9±0.7±0.2 MeV, Γ<2.4 MeV @ 90% C.L.
- Agree with PDG, another independent measurement.

Production mechanics



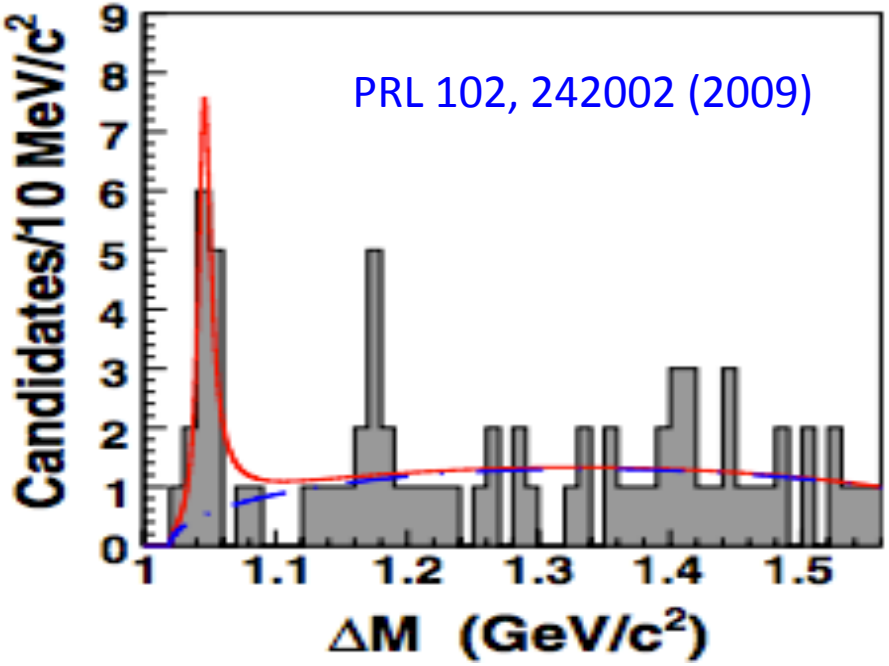
Fit with different shapes

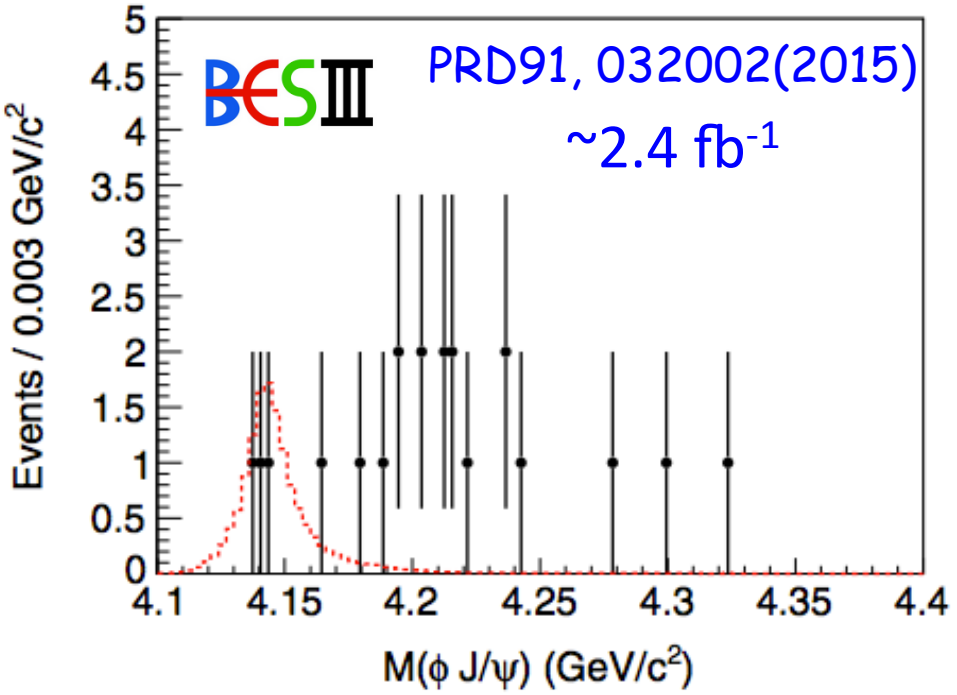
- Y(4260): χ^2/ndf=0.49/3
- E1 PHSP: χ^2/ndf=8.7/3
- Linear: χ^2/ndf=5.5/2

For the first time, bring connections between exotic hadrons (X and Y) !

- Central-of-mass energy dependent cross section peaks at 4.26 GeV
- Strongly suggest the decay Y(4260)→γX(3872)
- The ratio of B[Y(4260)→γX(3872)]~10%.

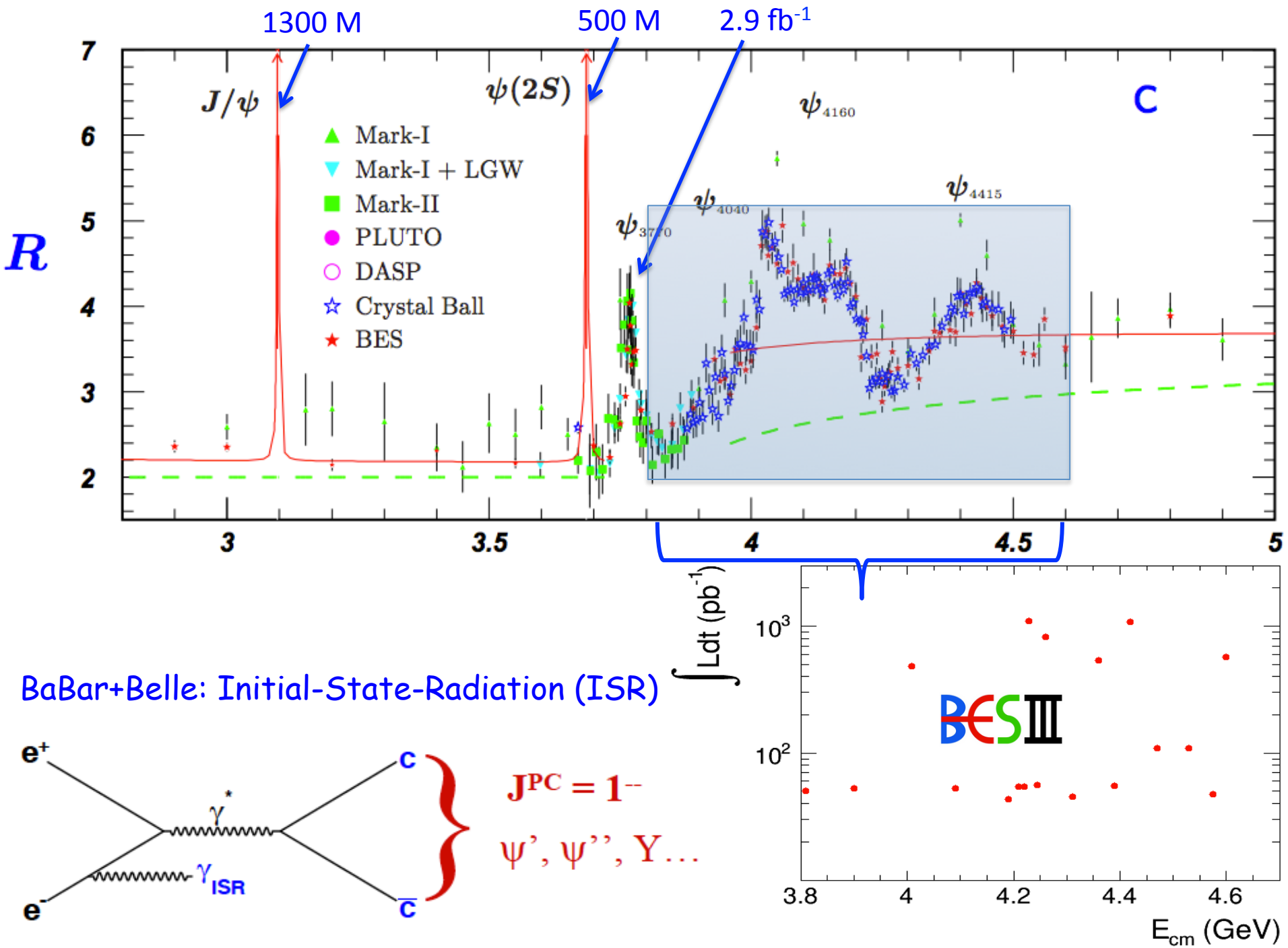
Search X(4140)→φJ/ψ





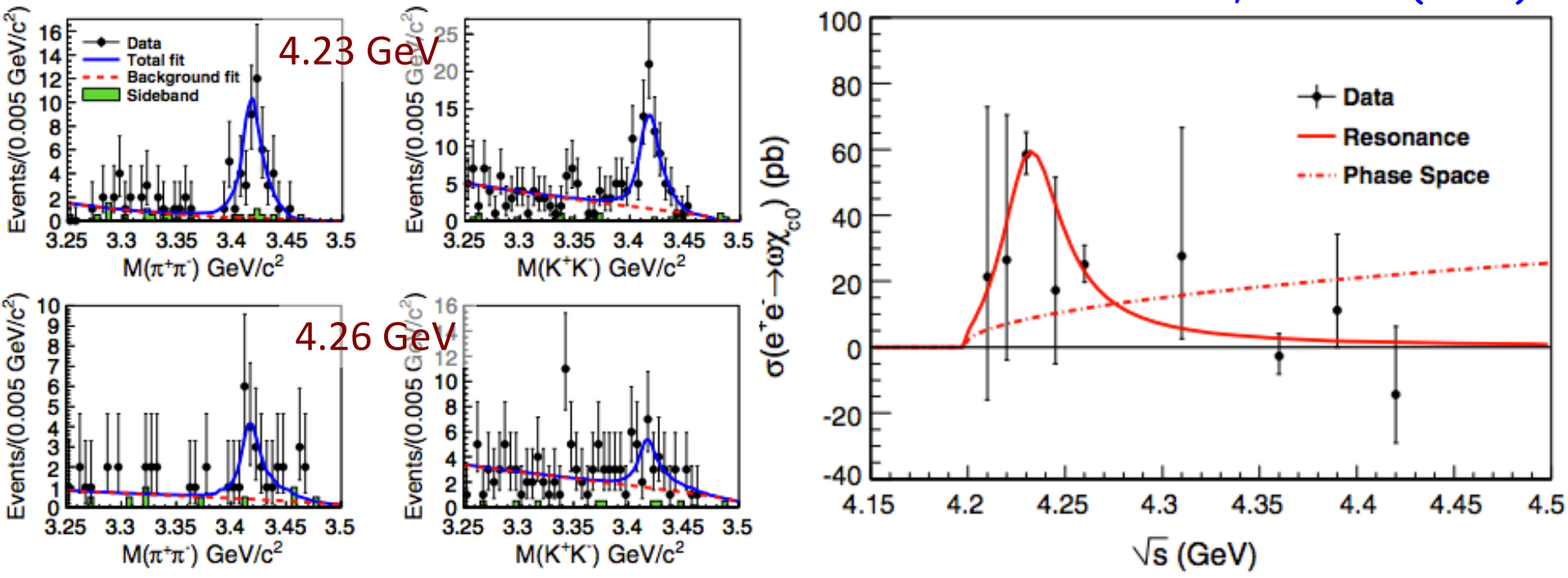
- The X(4140) was reported by CDF with Mass=(4143.0±2.9±1.2) MeV and Width=$11.7^{+8.3}_{-5.0}$±3.7 MeV
- Controversial: CMS (Yes), Belle (No), LHCb (No), BaBar (no)
- BESIII: different process e^+e^-→γφJ/ψ
- No signal, cross section γX(4140)/γX(3872)<10%.

The vector Y-family


1300 M
500 M
2.9 fb-1
R
J/ψ
ψ(2S)
ψ4160
ψ4040
ψ4415
ψ3770
C
Mark-I
Mark-I + LGW
Mark-II
PLUTO
DASP
Crystal Ball
BES
7
6
5
4
3
2
3
3.5
4
4.5
5
∫Ldt (pb-1)
10³
10²
BESIII
3.8
4
4.2
4.4
4.6
Ecm (GeV)
BaBar+Belle: Initial-State-Radiation (ISR)
e+
e-
γ*
γISR
c
c̄
JPC = 1--
ψ', ψ'', Υ…

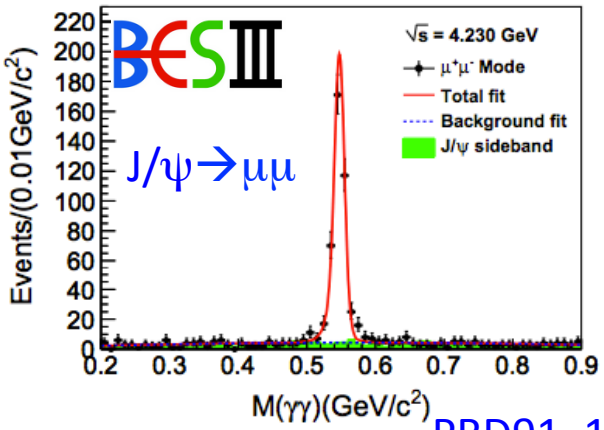
$e^+e^- \to \omega\chi_{c0}$

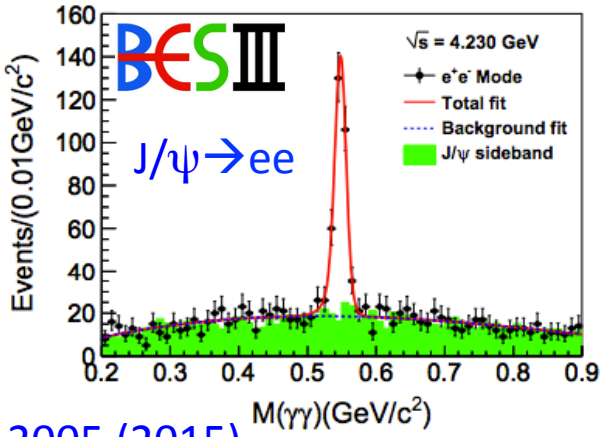
PRL114, 092003 (2015)



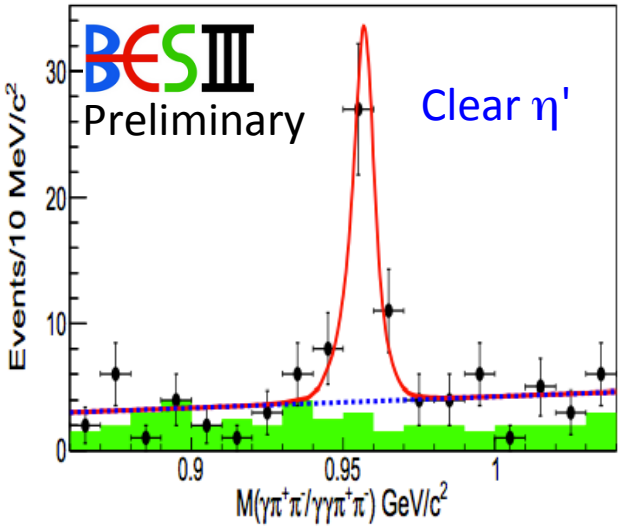
- Using scan data over 4.21 and 4.42 GeV, e+e-$\to\omega\chi_{c0}$ are significant @ E_{cm}=4.23 & 4.26 GeV.
- Cross section peak near 4.23 GeV, fit with BW yields Mass=(4230±8±6) MeV, Width=(38±12±2) MeV.
- A new structure? Tetraquark [PRD 91, 117501 (2015)]? Threshold effect?

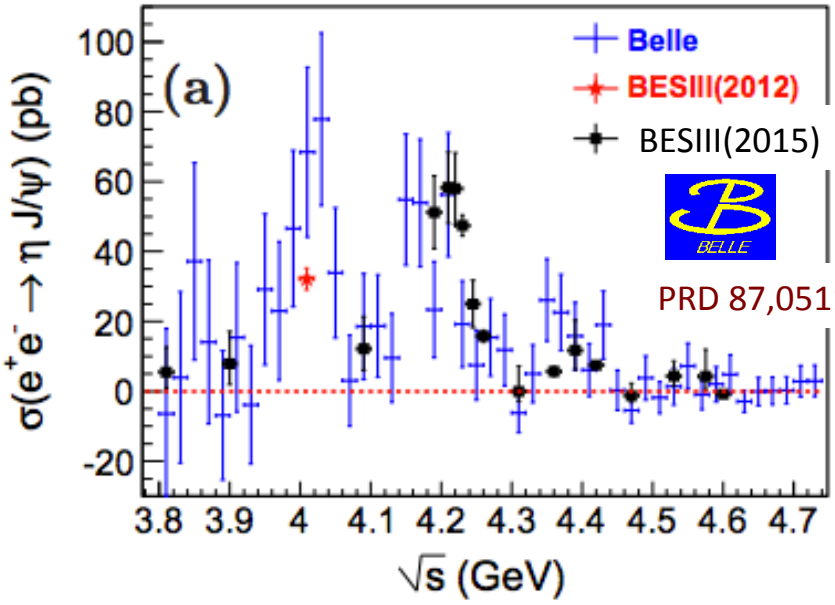
$e^+e^- \to \eta J/\psi$ & $\eta' J/\psi$



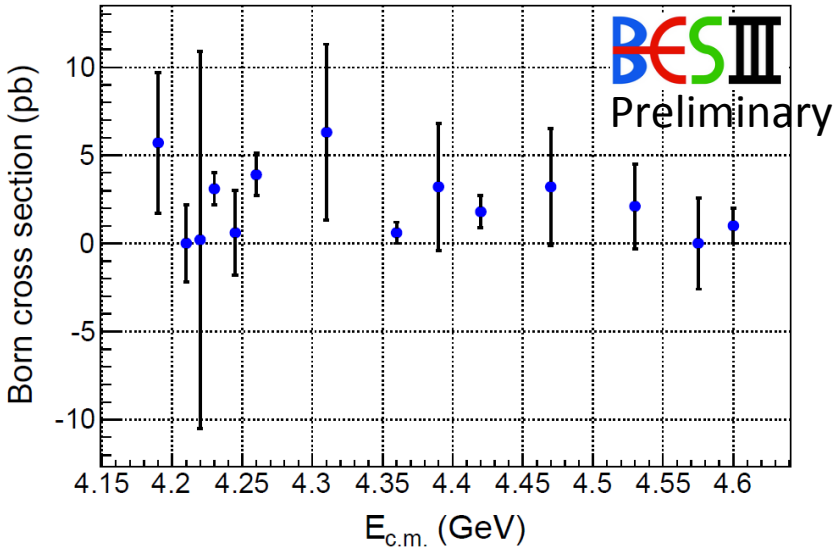


PRD91, 112005 (2015)





PRD 87,051101 (2013)



Belle suggest $\psi(4040)$ & $\psi(4160) \to \eta J/\psi$

BESIII: structure near 4.23 GeV?

More data is needed!

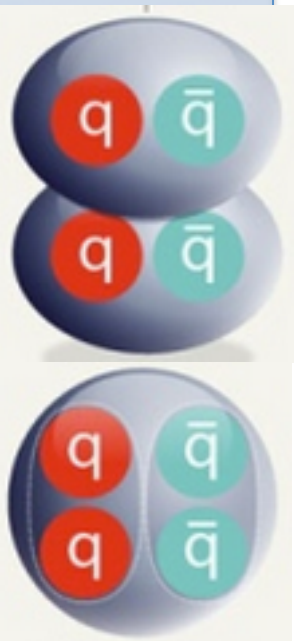
Nature of XYZ states

- Decay to charmonium → contains charm & anti-charm quarks
- Charged feature → can not be pure $c\bar{c}$ bound state
- Minimal combination → Four quarks inside !
- Lattice: diquark-antidiquark operator PRD91,014504(2015)
- Hadron Molecule?

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

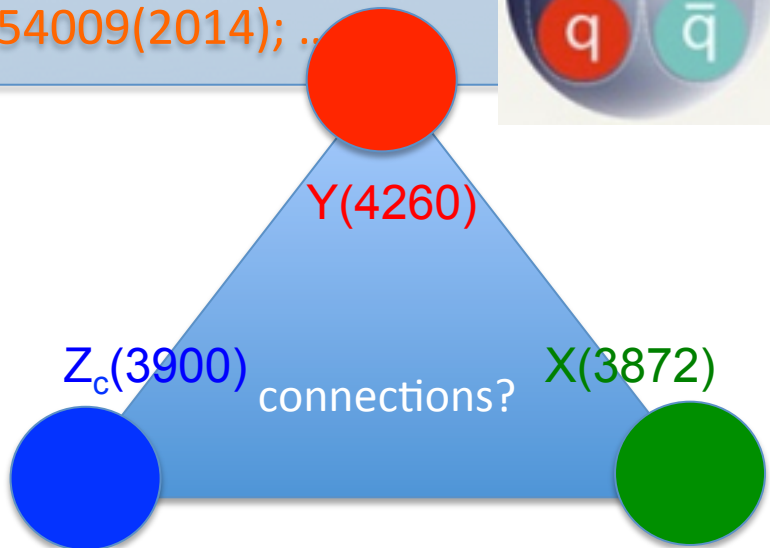
- Tetraquark?

Phys. Rev. D 87,125018(2013); Phys. Rev. D 88, 074506(2013);
Phys. Rev. D 89,054019(2014); Phys. Rev. D 90,054009(2014); ..



Outlook

- ✧ BESIII intensive scan > 4 GeV ?
  (500 pb^{-1}/10 MeV, still proposing…)
- ✧ Belle II is coming, and will
  accumulate 50 ab^{-1} data by 2024.

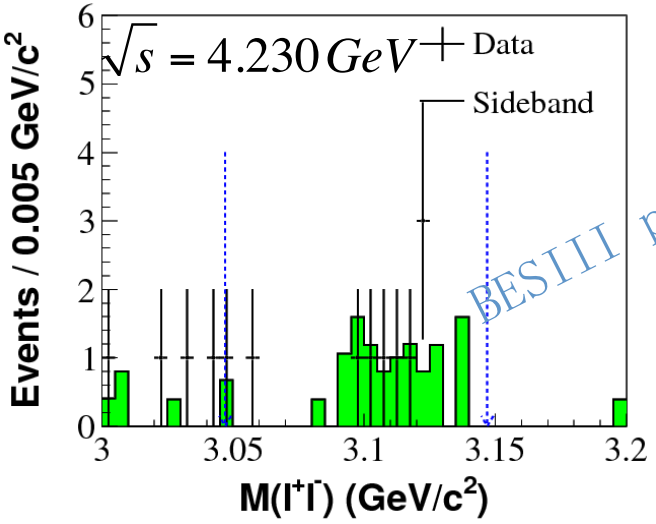


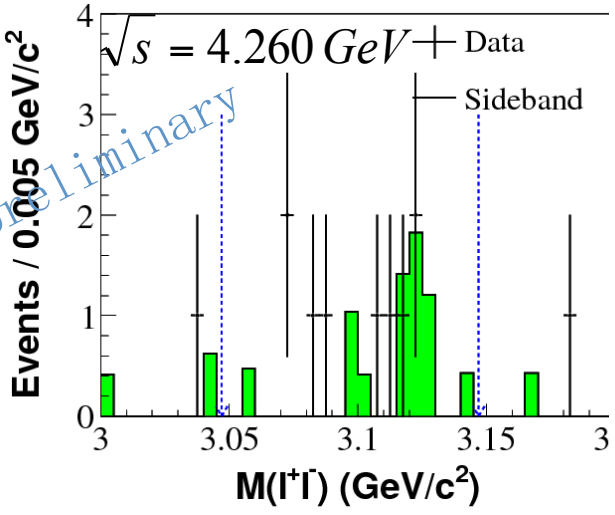
Summary

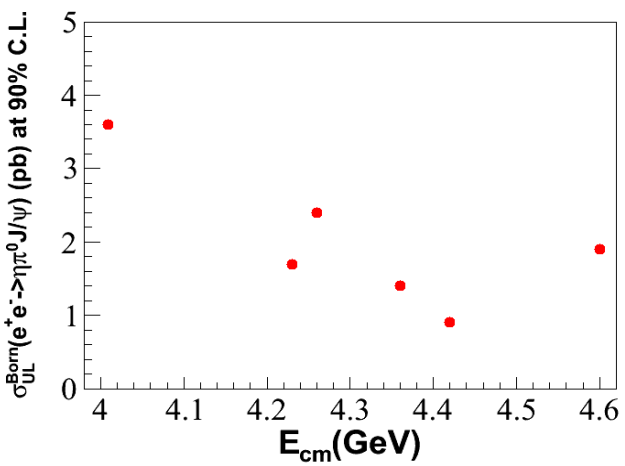
- BESIII produces significant XYZ results…
- X & Y states are difficult to distinguish from normal meson, charged Z_c states provide solid evidence.
- Quark composition is still puzzling.
- More results are coming, we would finally understand them.

Thank you (谢谢)！

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







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

$\sqrt{s}$ (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_{UL}^{Born} (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