Exotics in leptonic machines

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Outline

- Introduction
- The Y states

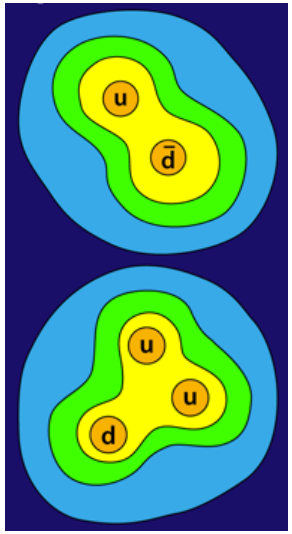
  Abundant structures above 4 GeV
- The X states

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

  $Z_c(3900)$, $Z_c(4020)$, $Z_c(4430)$ …
- Summary

Hadrons: normal & exotic

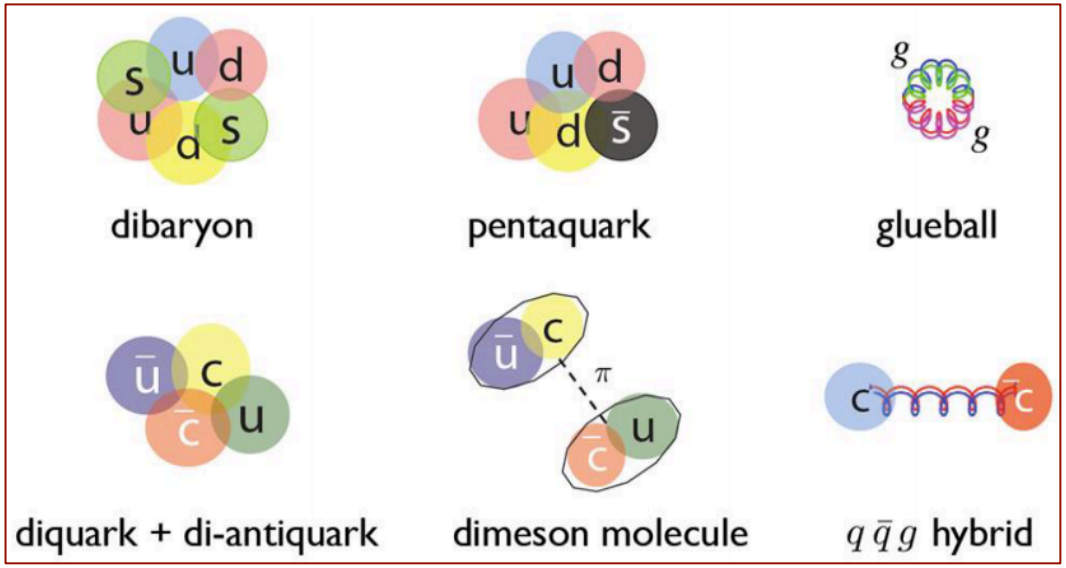
- Quark model: hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks



Normal

vs.

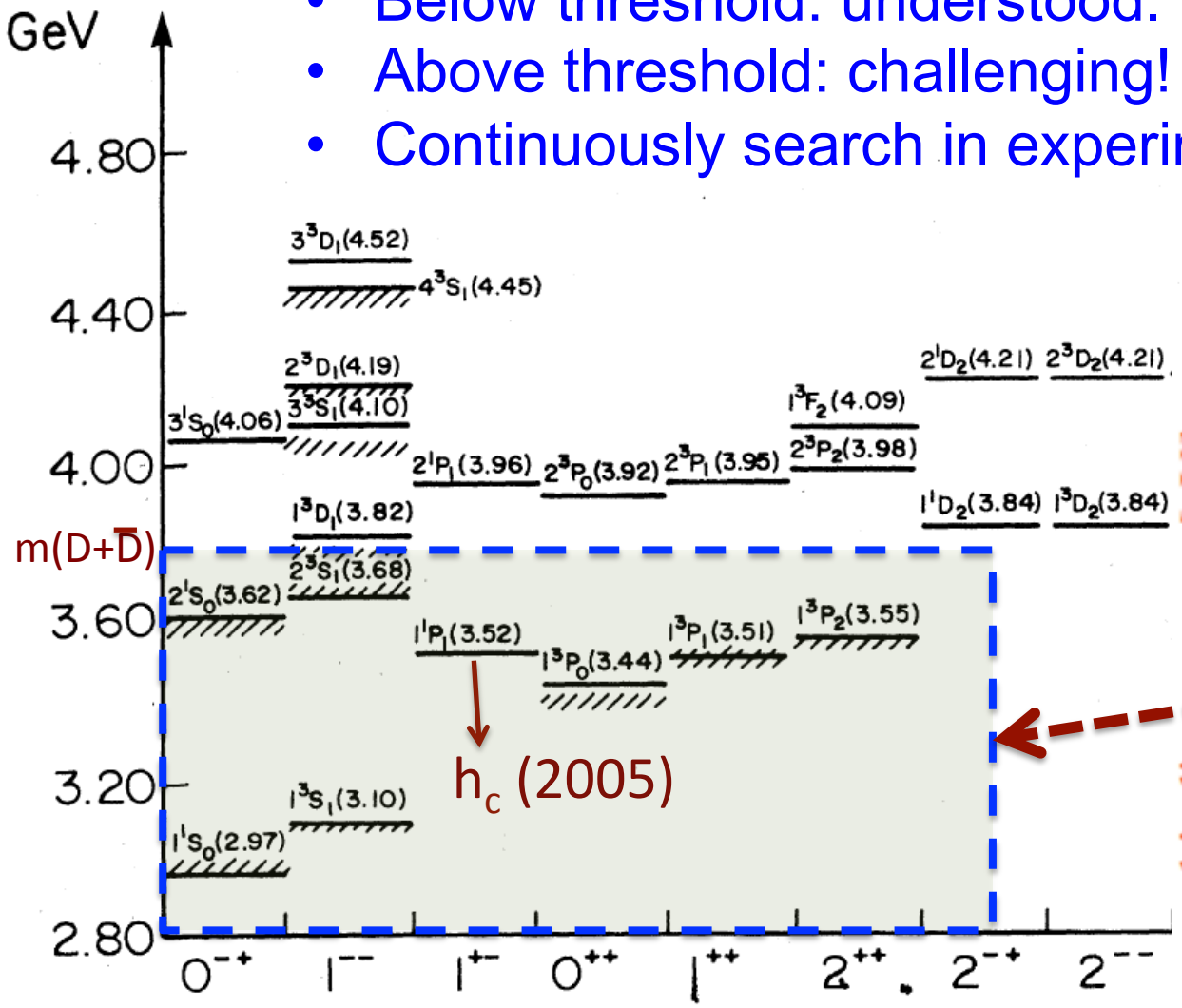
Exotic



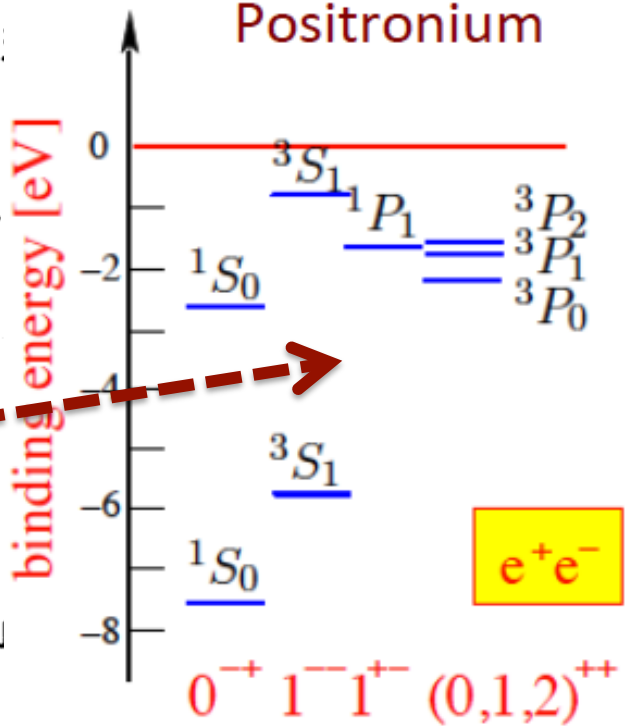
- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - Glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - Hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - Molecule : bound state of more than 2 hadrons
  - …

Why heavy quarkonium?

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



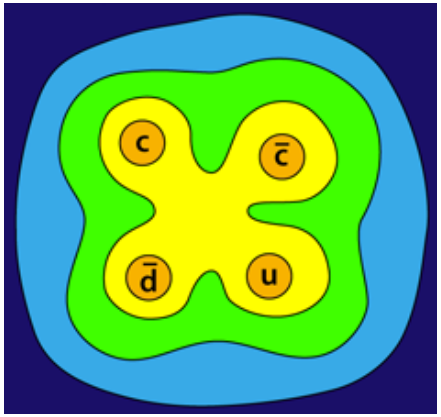
$n^{2s+1}L_J$



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

XYZ particles

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



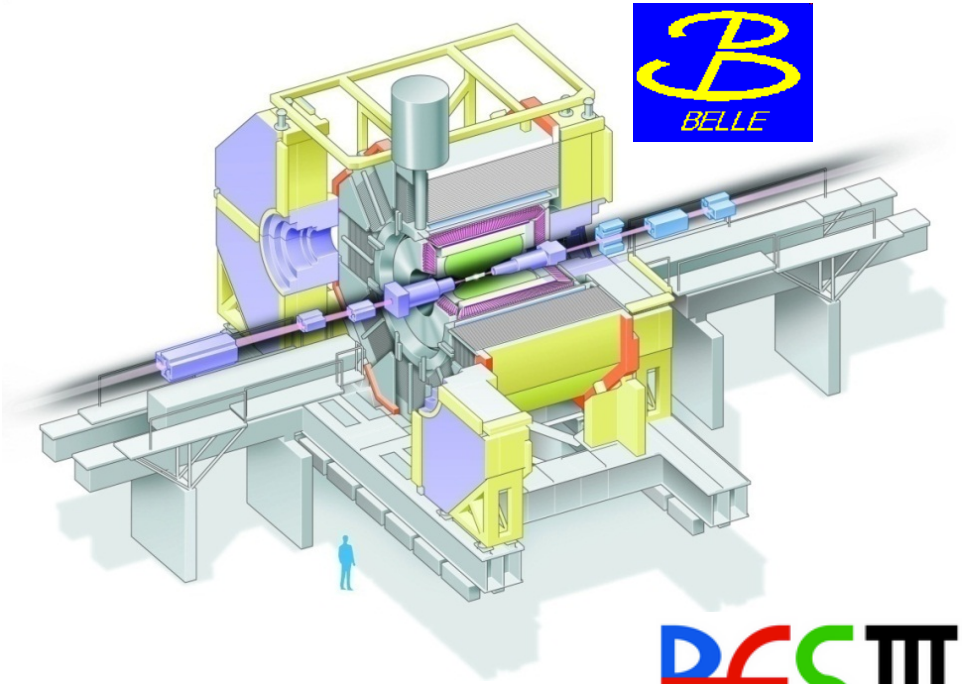
X(3823)
X(3872)
X(3915)
X(4350)
Y(4008)
Y(4260)
Y(4140)
Y(4360)
Y(4660)
Y(4630)
...
XYZ(3940)

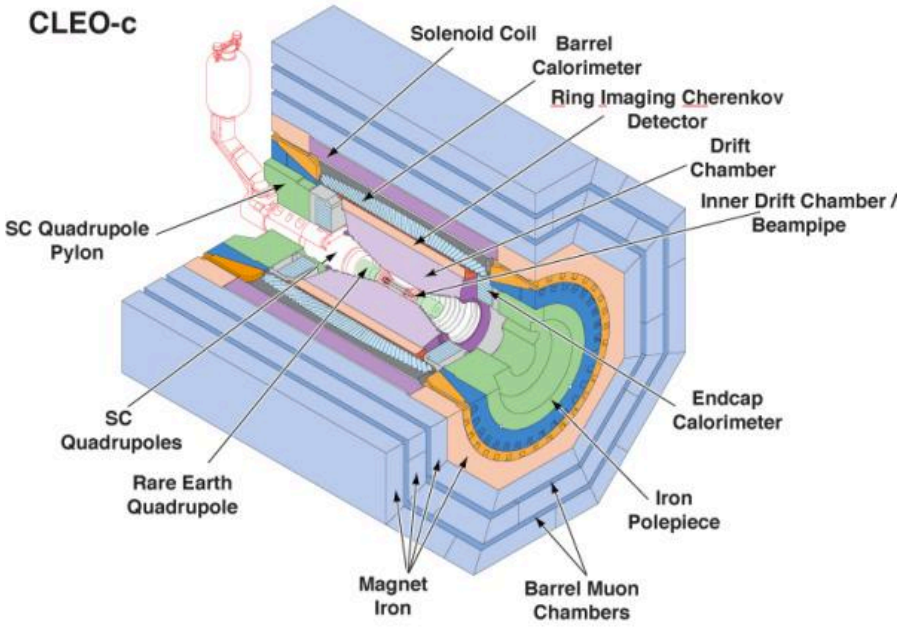
$Z_c(3900)$
$Z_c(4020)$
Z(4430)
Z(4250)
Z(4050)
...

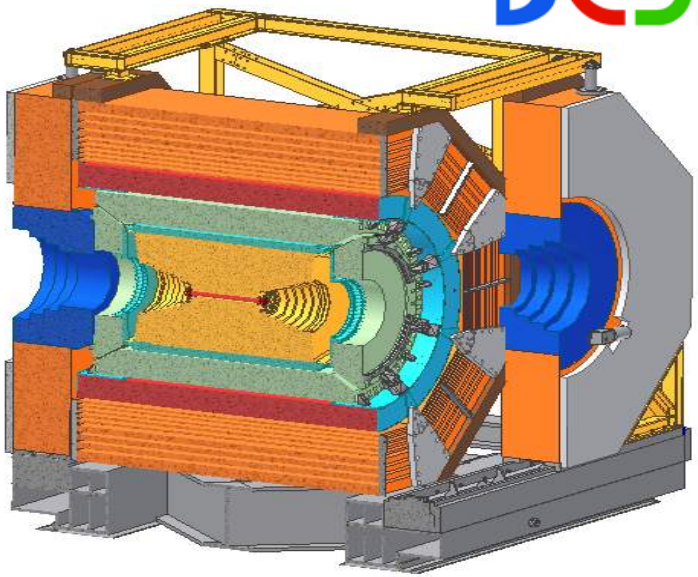
Charmonium?
Hybrid?
Tetraquark?
Molecule?
...

Godfrey & Isgur, PRD32, 189 (1985)

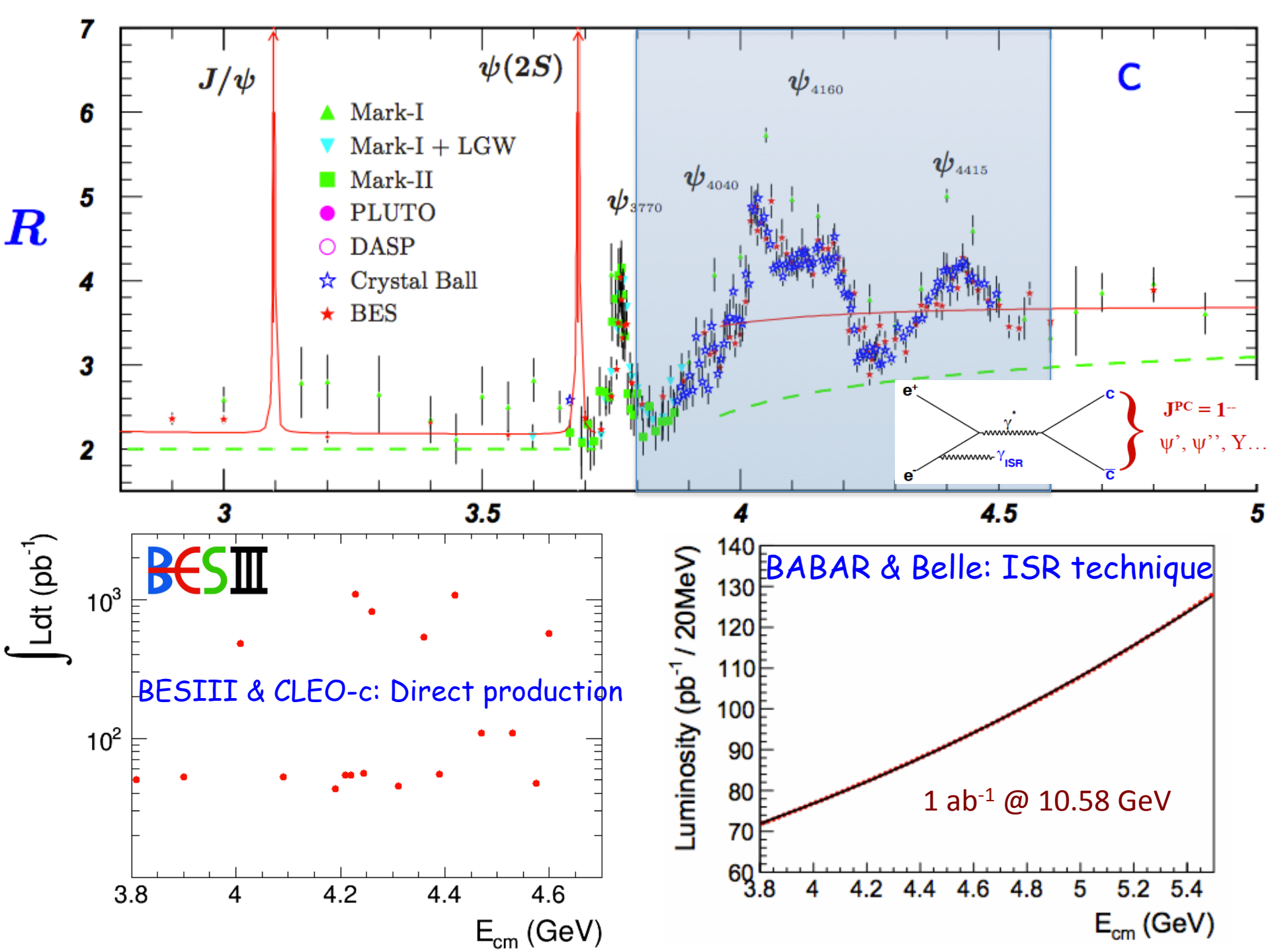
Leptonic machines



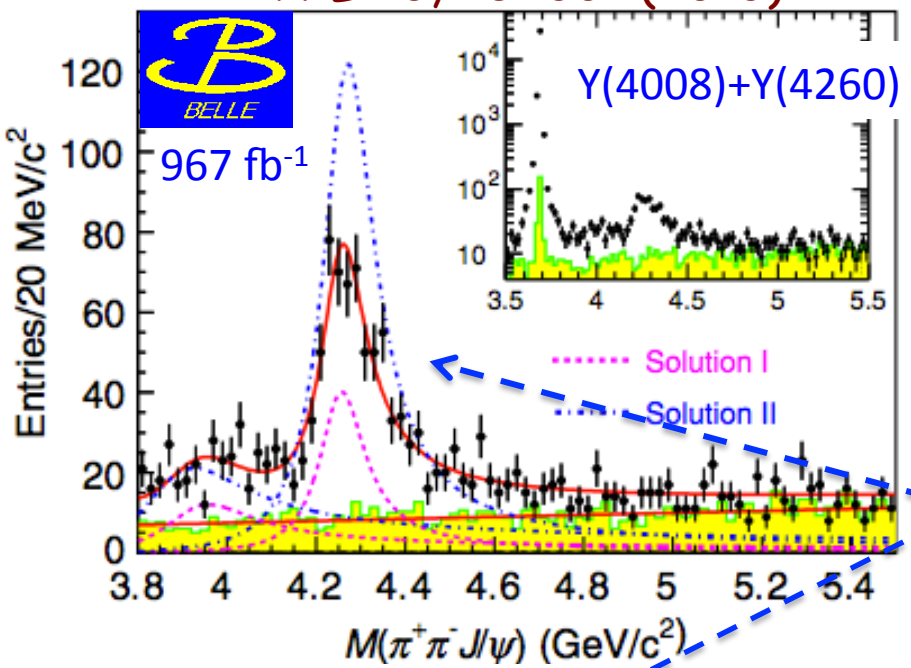




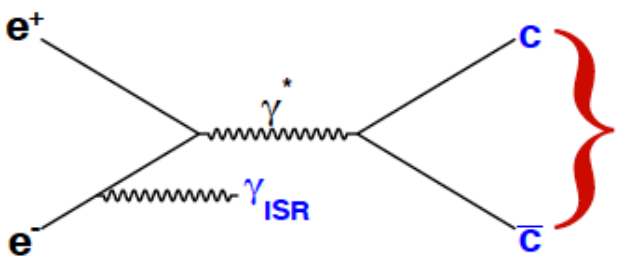
The vector Y-family


R
J/ψ
ψ(2S)
ψ4160
ψ4040
ψ4415
ψ3770
C
Mark-I
Mark-I + LGW
Mark-II
PLUTO
DASP
Crystal Ball
BES
e+
e-
γ*
γISR
c
c̄
JPC = 1−−
ψ', ψ'', Υ…
BESIII
∫Ldt (pb-1)
BESIII & CLEO-c: Direct production
Ecm (GeV)
BABAR & Belle: ISR technique
Luminosity (pb-1 / 20MeV)
1 ab-1 @ 10.58 GeV
Ecm (GeV)

PRL110, 252001 (2013)

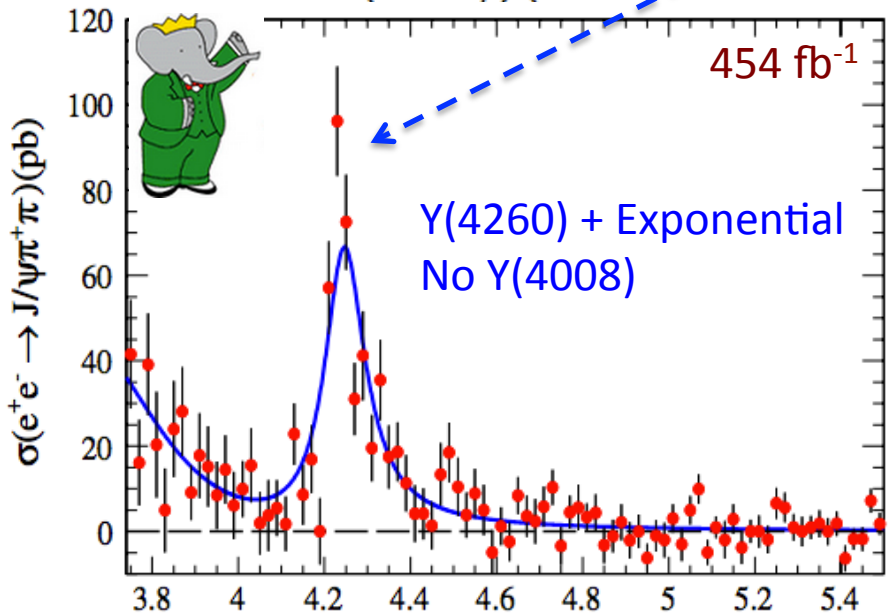


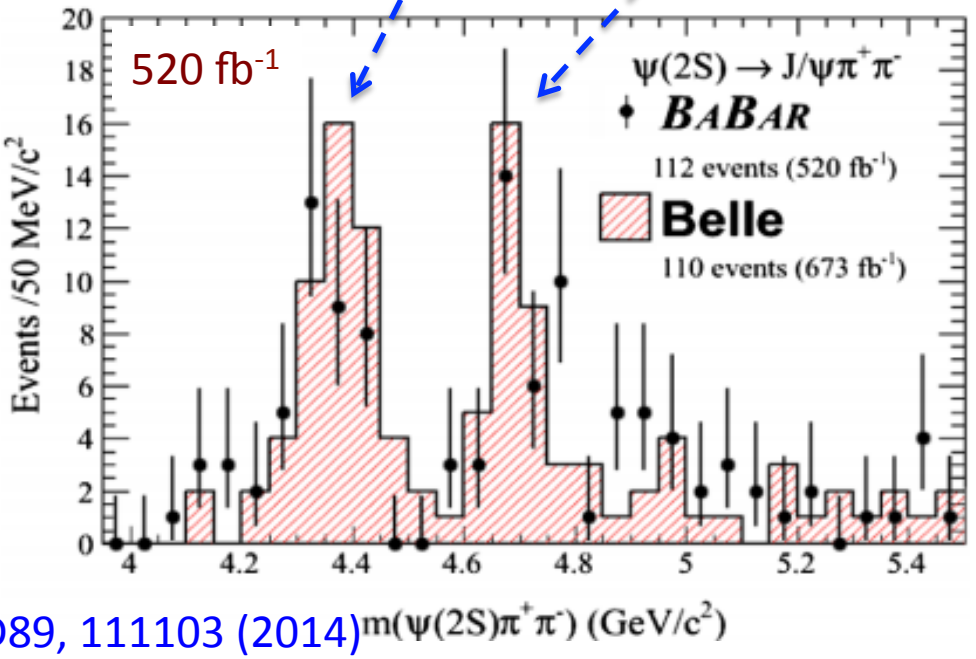
BaBar+Belle: Initial-State-Radiation (ISR)



Y(4008)? BESIII may help.

Y(4260), Y(4360), Y(4660), …



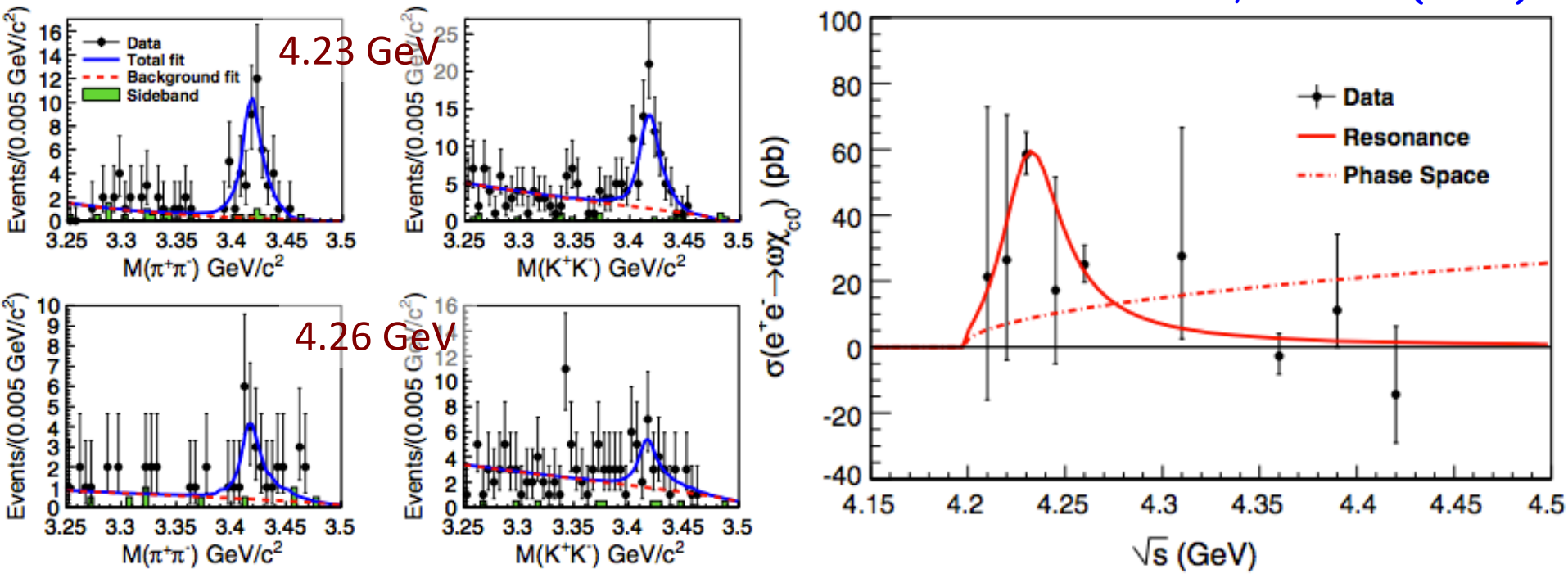


PRD86, 051102 (2013)

PRD89, 111103 (2014)

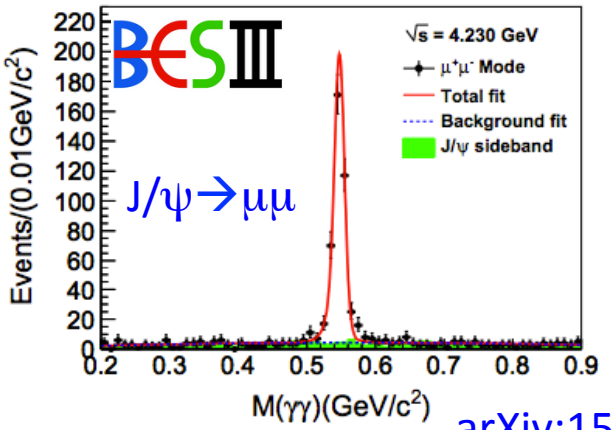
$e^+e^- \to \omega\chi_{c0}$

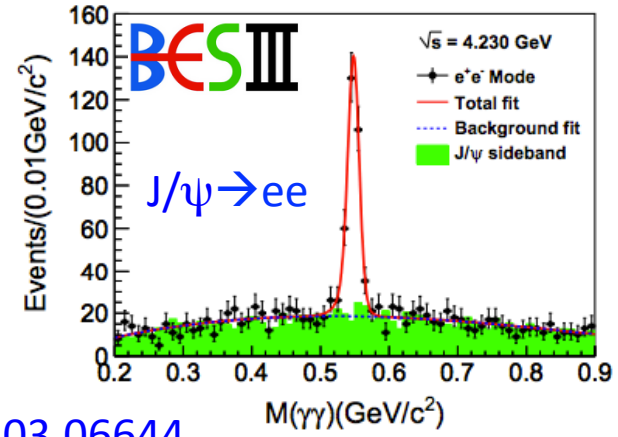
PRL114, 092003 (2015)



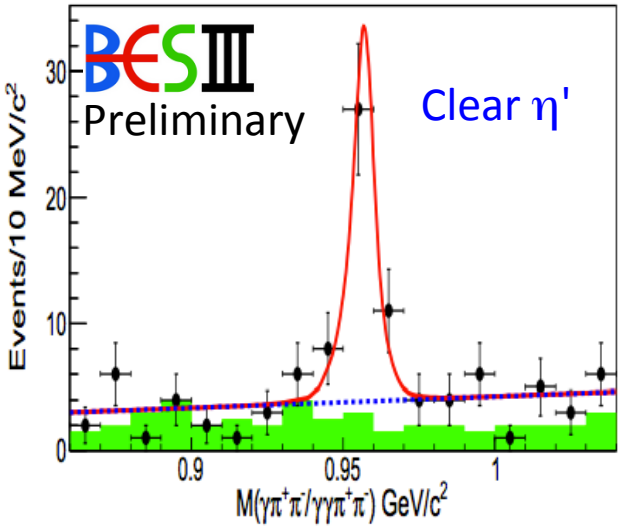
- Using scan data over 4.21 and 4.42 GeV, e+e-$\to\omega\chi_{c0}$ are significant @ E_{cm}=4.23 & 4.26 GeV.
- Cross section peak near 4.23 GeV, fit with BW yields Mass=(4230±8±6) MeV, Width=(38±12±2) MeV.
- A new structure? Tetraquark (arXiv:1412.7196)? Threshold effect?

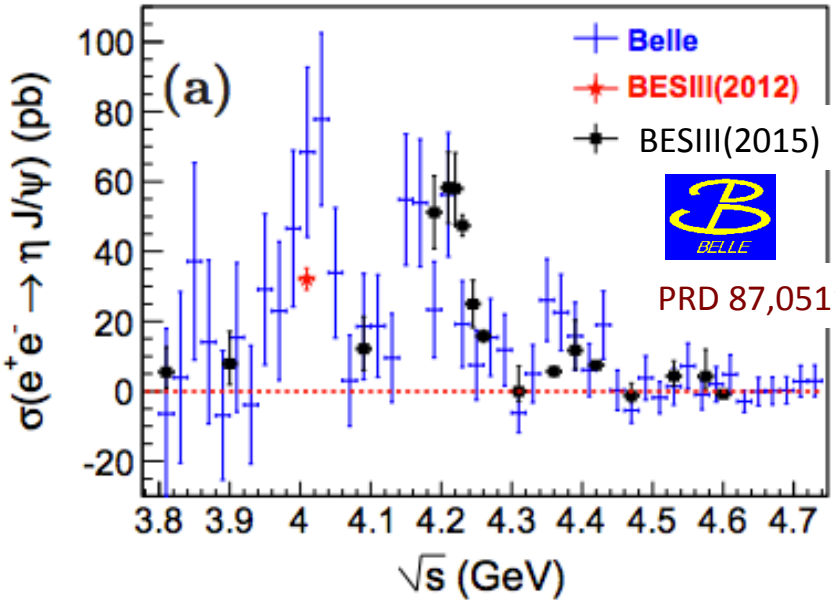
$e^+e^- \to \eta J/\psi$ & $\eta' J/\psi$



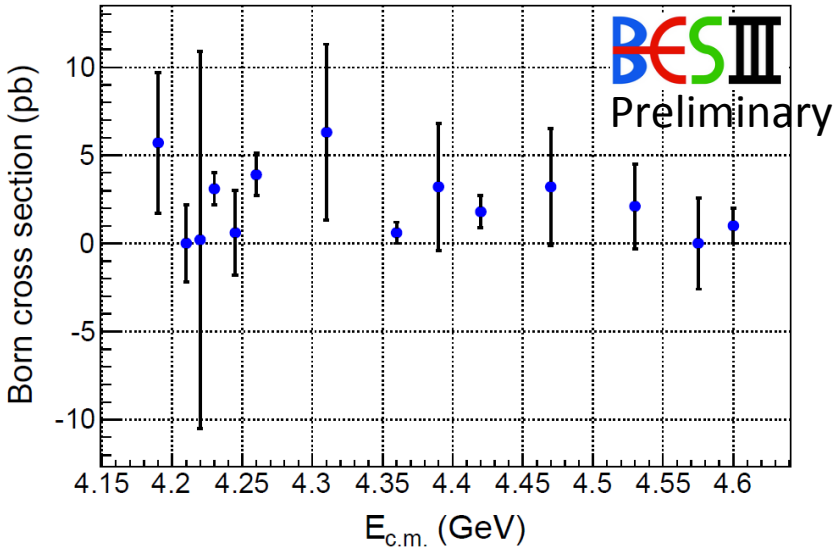


arXiv:1503.06644





PRD 87,051101 (2013)



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

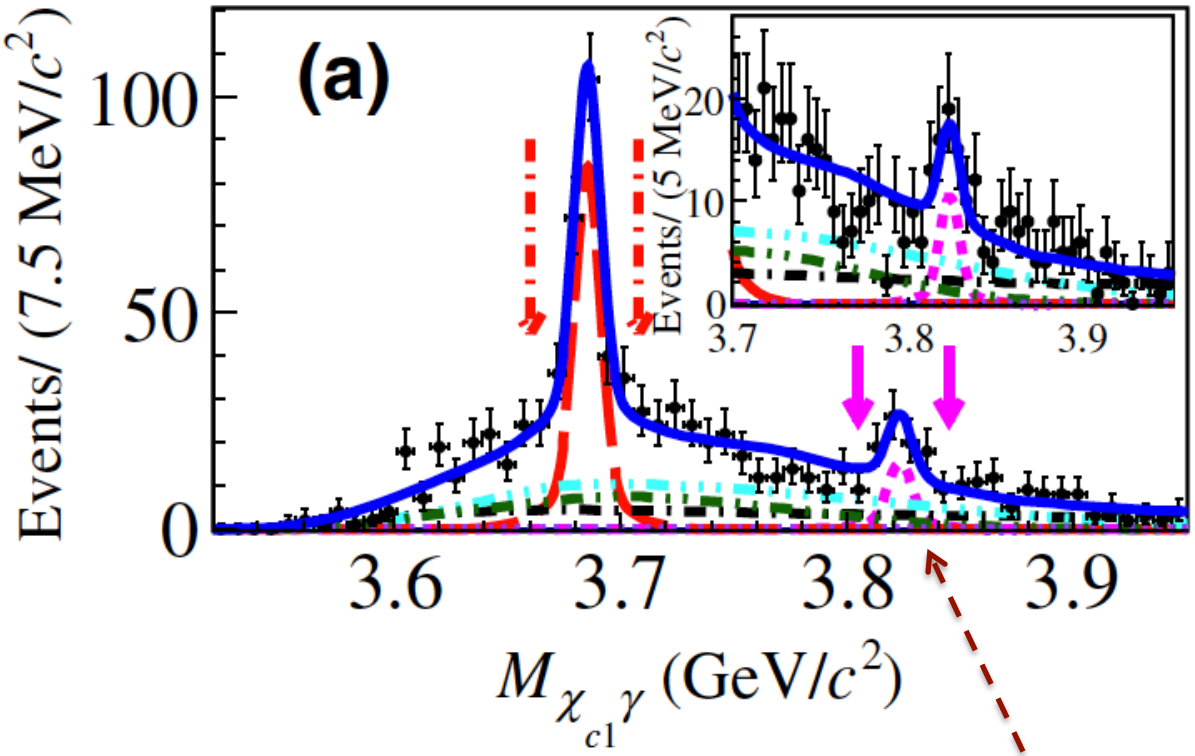
BESIII: structure near 4.23 GeV?

More data is needed!

The exotic X states

Evidence of X(3823) at Belle

PRL 111, 032001 (2013) 772 M B mesons



$$M_{X(3823)} = M^{\text{meas}}_{X(3823)} - M^{\text{meas}}_{\psi'} + M^{\text{PDG}}_{\psi'}$$
$$= 3823.1 \pm 1.8 \pm 0.7 \text{ MeV}.$$

$B \rightarrow K(\gamma\chi_{c1})$

Mass agree with potential model predicted $\psi(1^3D_2)$

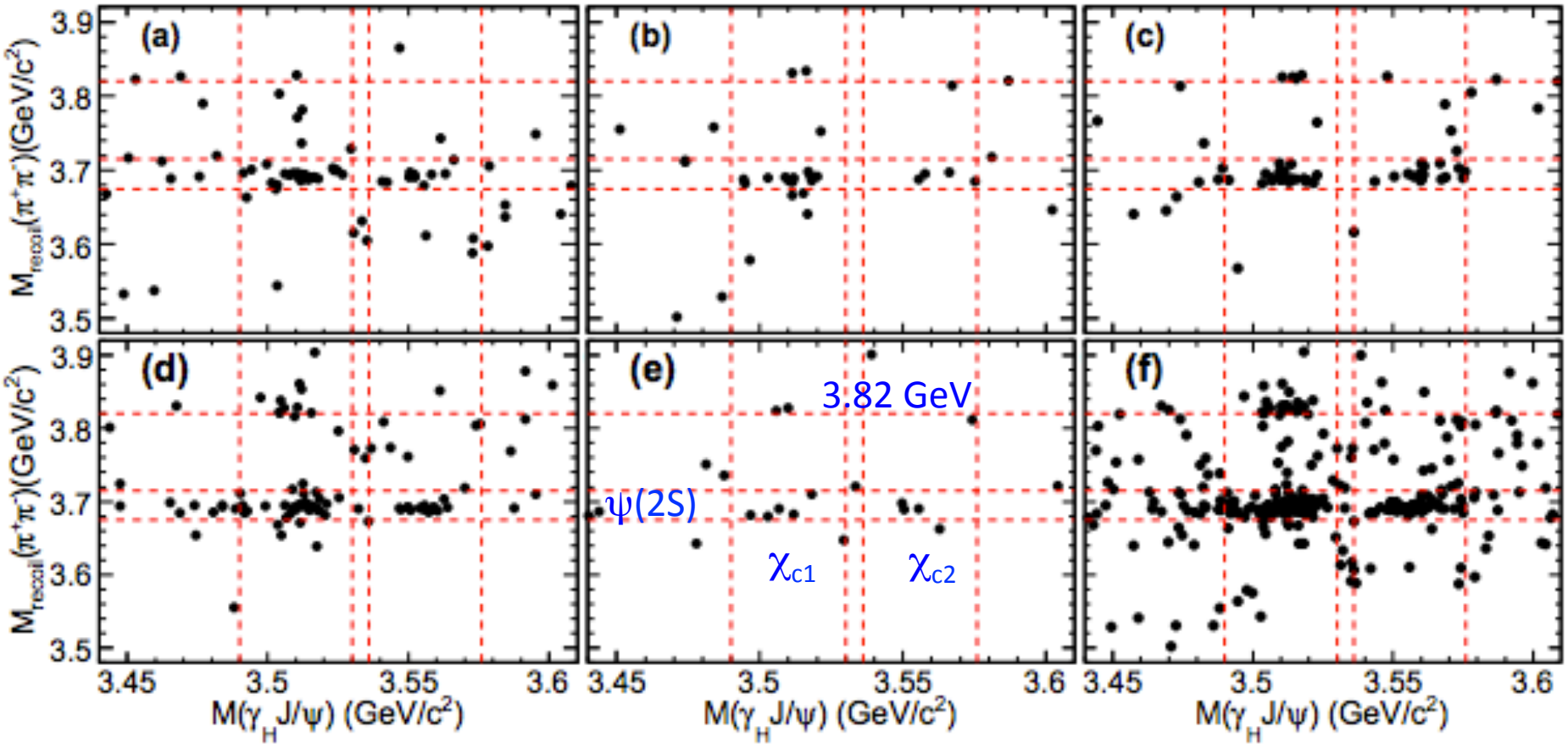
Also in its dominant decay channel $\gamma\chi_{c1}$

Good candidate!

A narrow resonance X(3823) with 3.8σ significance.

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

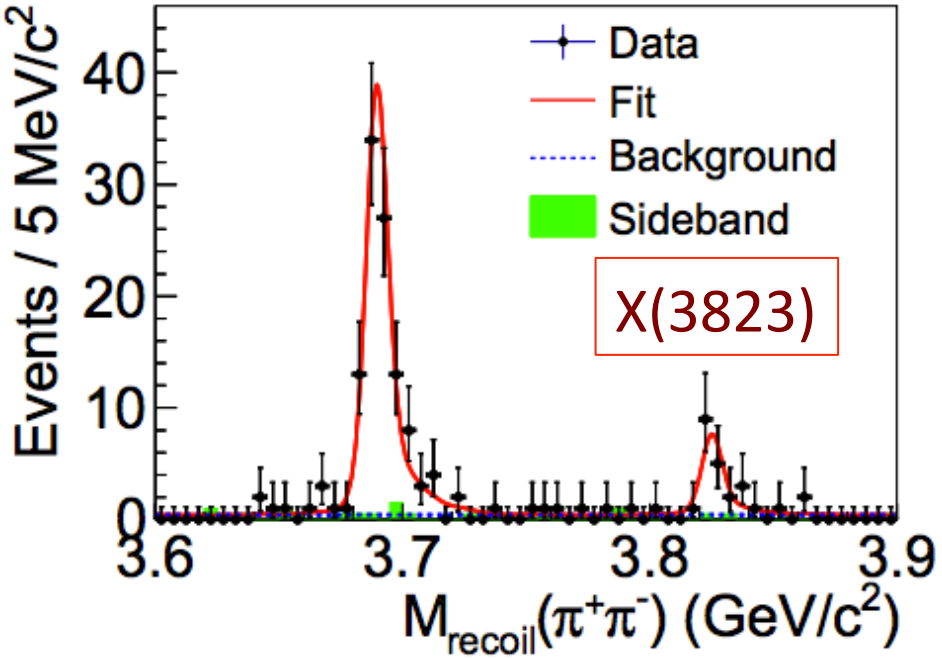
Using 4.67 fb^{-1} data, BESIII search for X(3823) at different E_{cm}

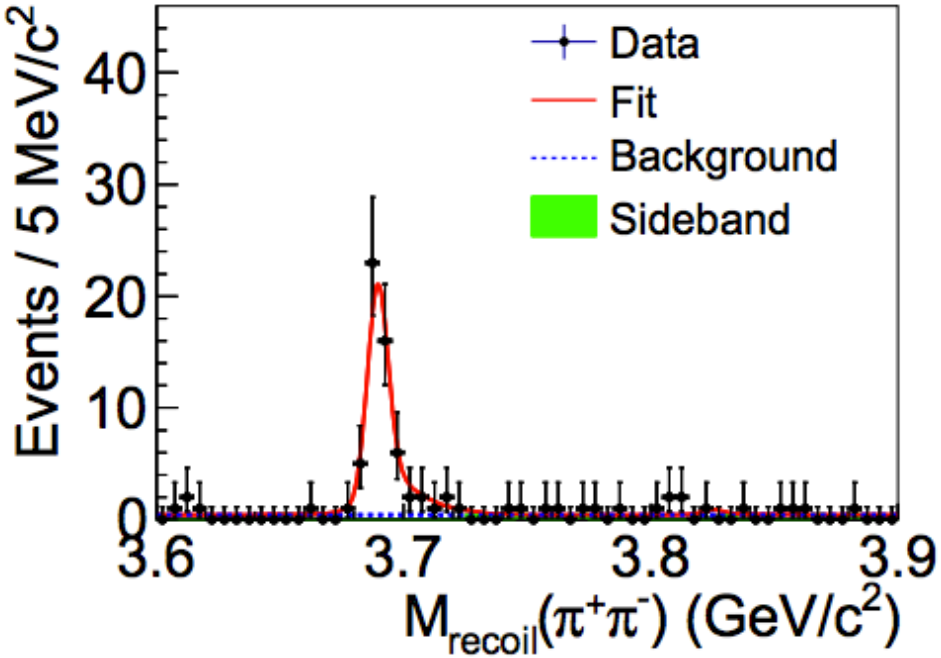


Observation of X(3823) at BESIII

BESIII

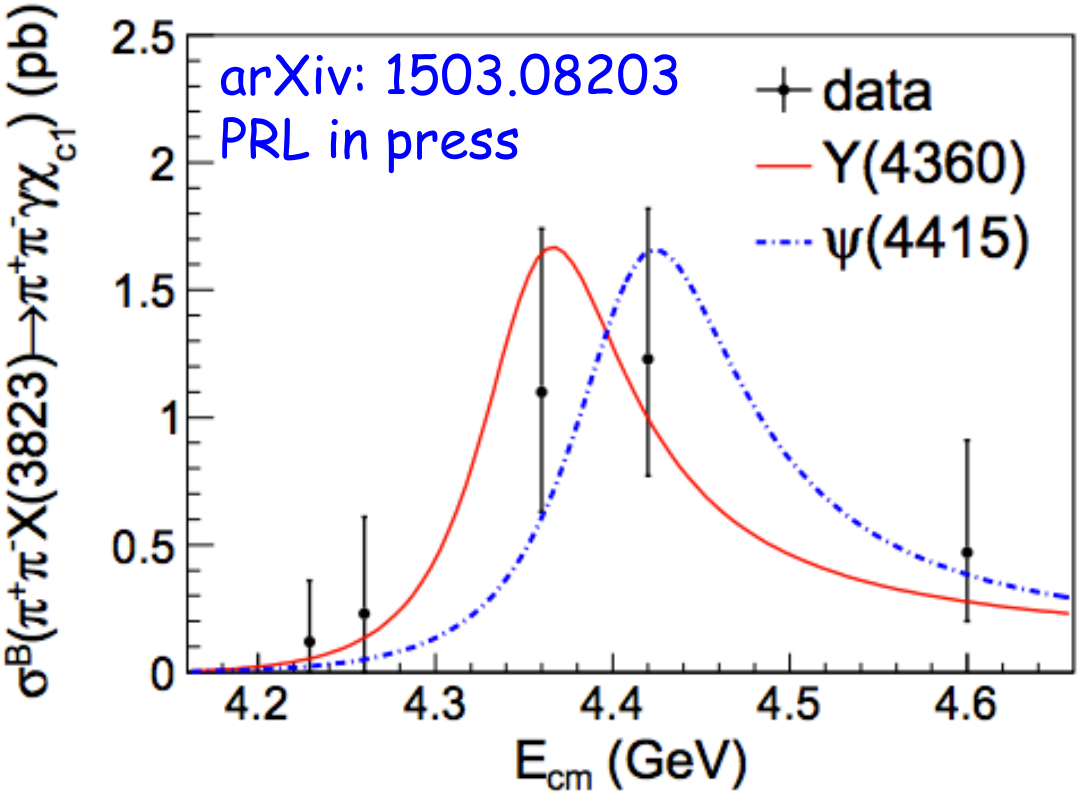
arXiv: 1503.08203 (PRL in press)





- 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, arXiv:1504.02973]

Y(4360)→$\pi^+\pi^-$X(3823)? A 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)	-	$10.4^{+6.4}_{-4.7}\pm1.5$	-

Understand the X(3872)

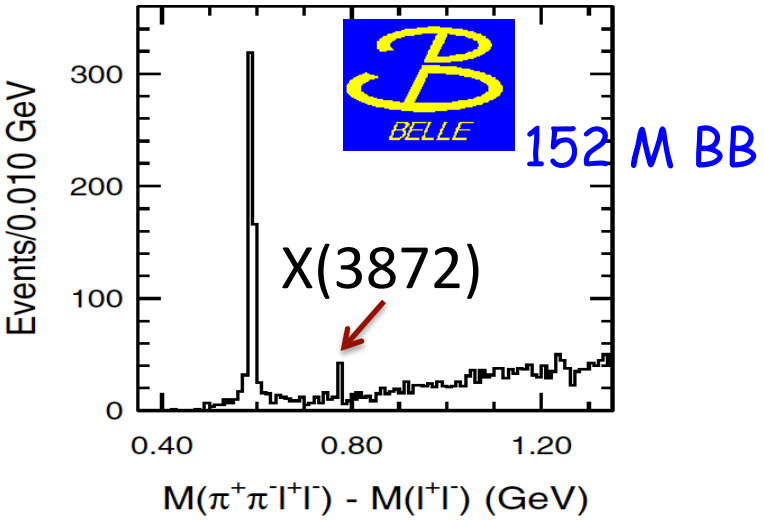
- Mass: Very close to D^0D^{0*} mass threshold.
- Width: Narrow, <1.2 MeV @ 90% C.L.
- $J^{PC}=1^{++}$
- Nature (very exotic)

✧ D^0D^{0*} bound state (molecule)

✧ Tetraquark

✧ Mixture of $\chi_{c1}(2P)$+molecule

PRL 91, 262001 (2003)



- Decay rate: open charm dominant, charmonium ~o(%).
- Production: (Belle + BESIII)

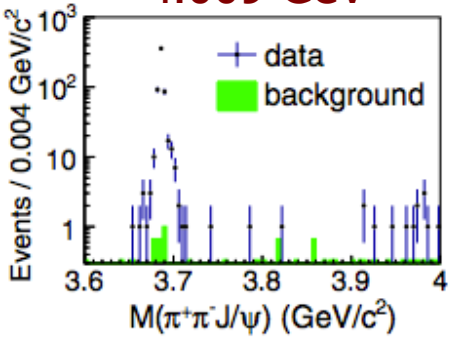
News …

✧ B→KX(3872) decay similar to (cc), K*X(3872) smaller than (cc)

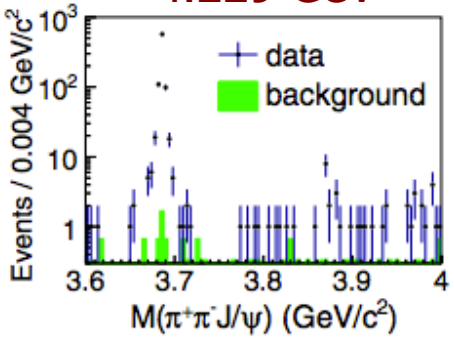
✧ Y(4260)→γX(3872) is unique !

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

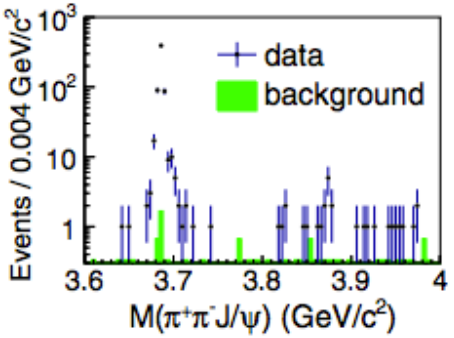
4.009 GeV



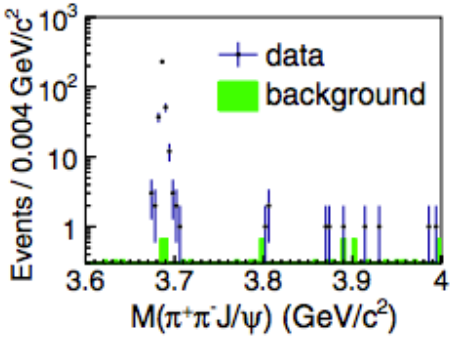
4.229 GeV



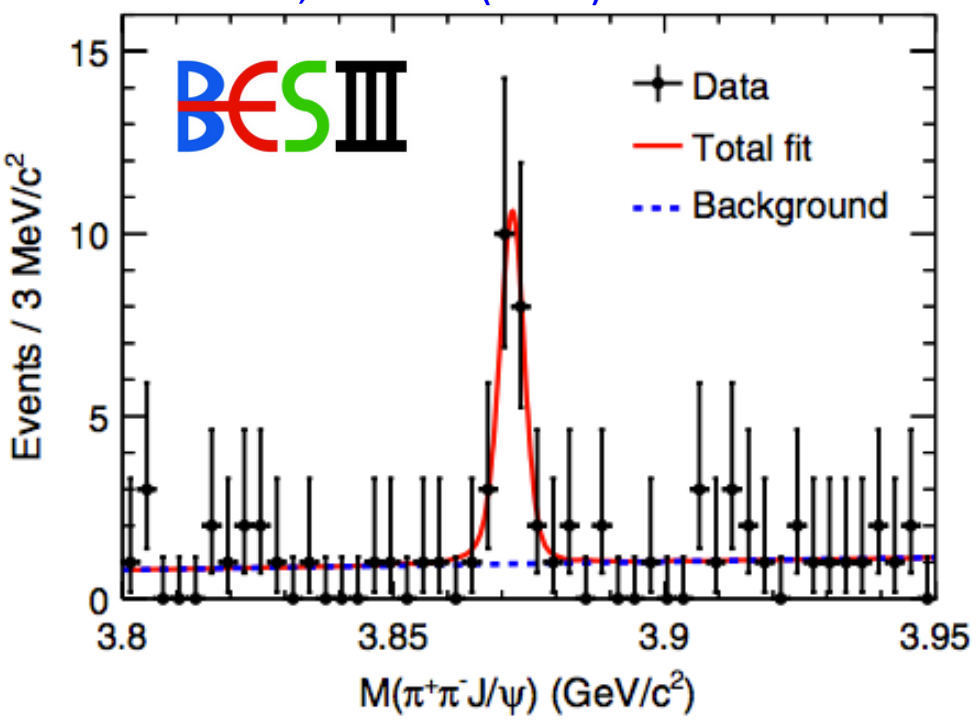
4.260 GeV



4.360 GeV

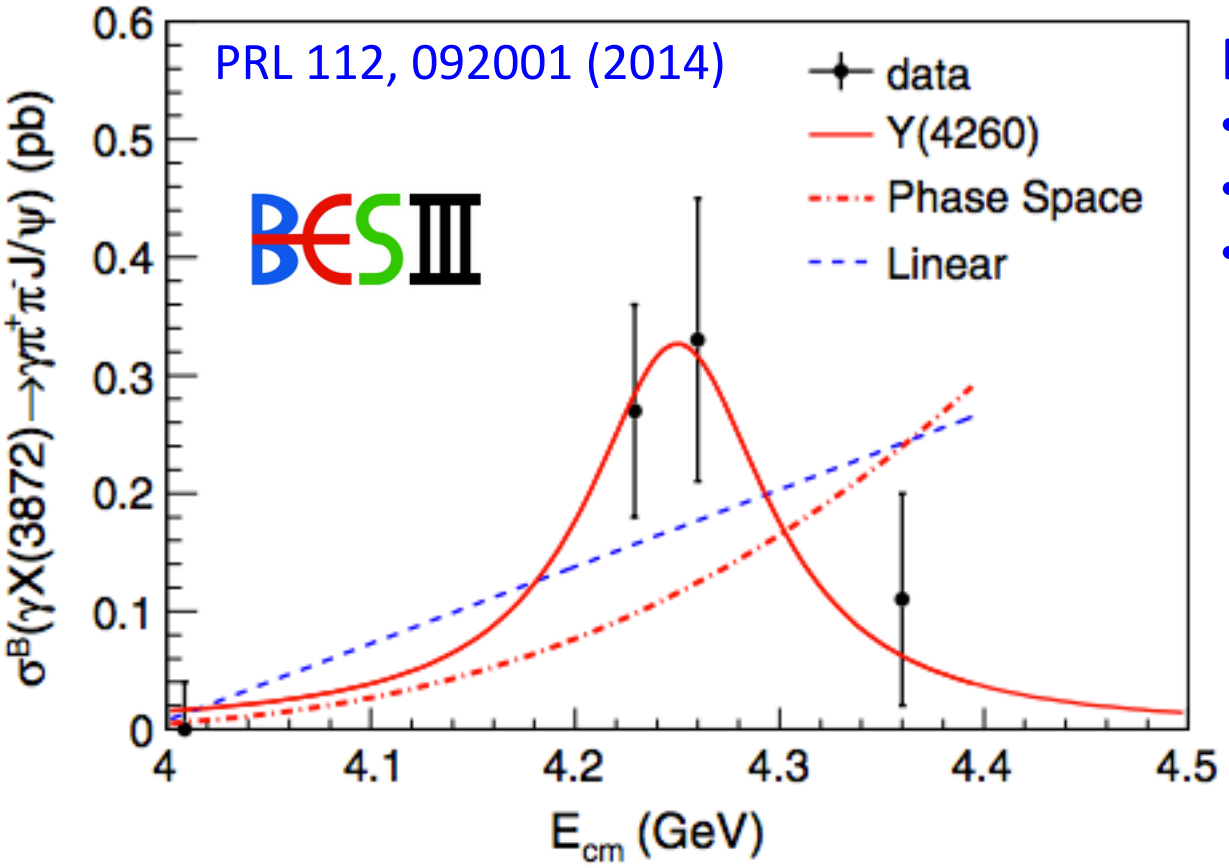


PRL 112, 092001 (2014).



- 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



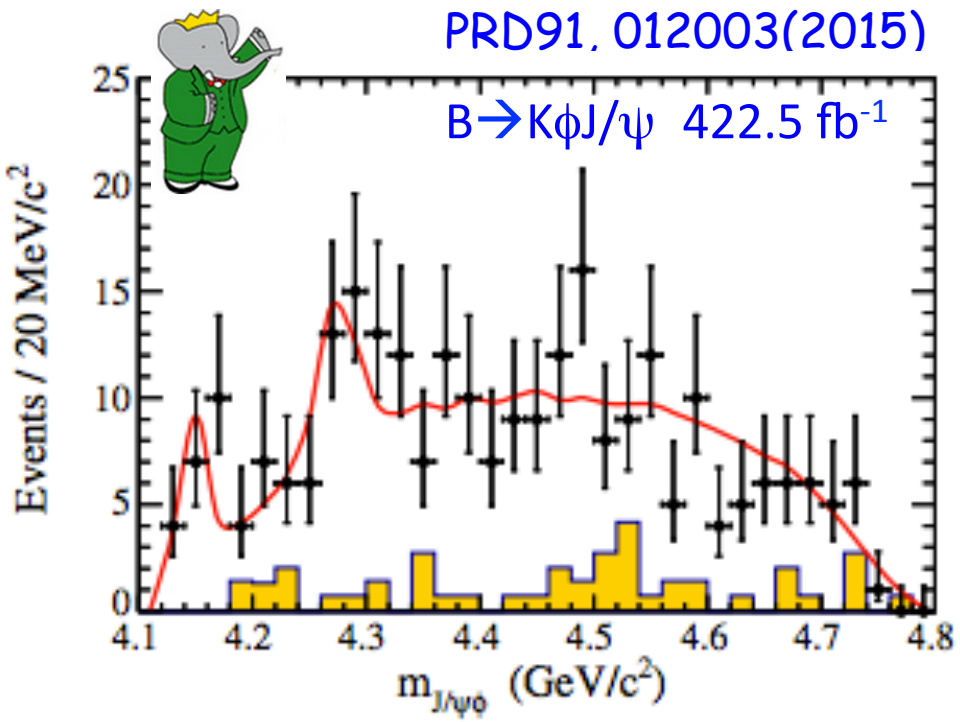
Fit with different shapes

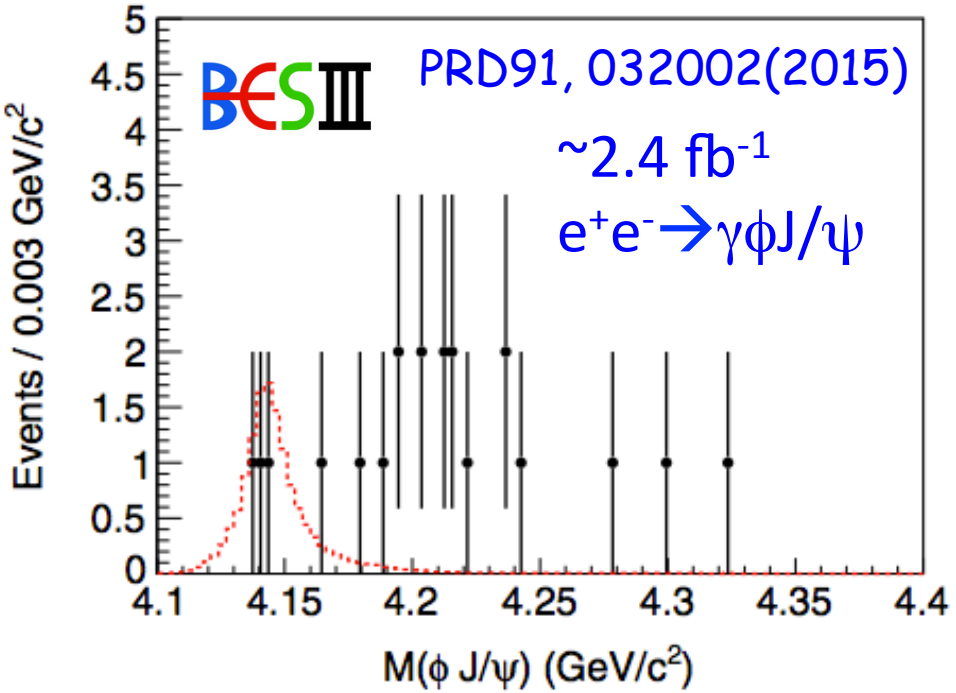
- Y(4260): χ^2/ndf=0.49/3
- E1 PHSP: χ^2/ndf=8.7/3
- Linear: χ^2/ndf=5.5/2

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

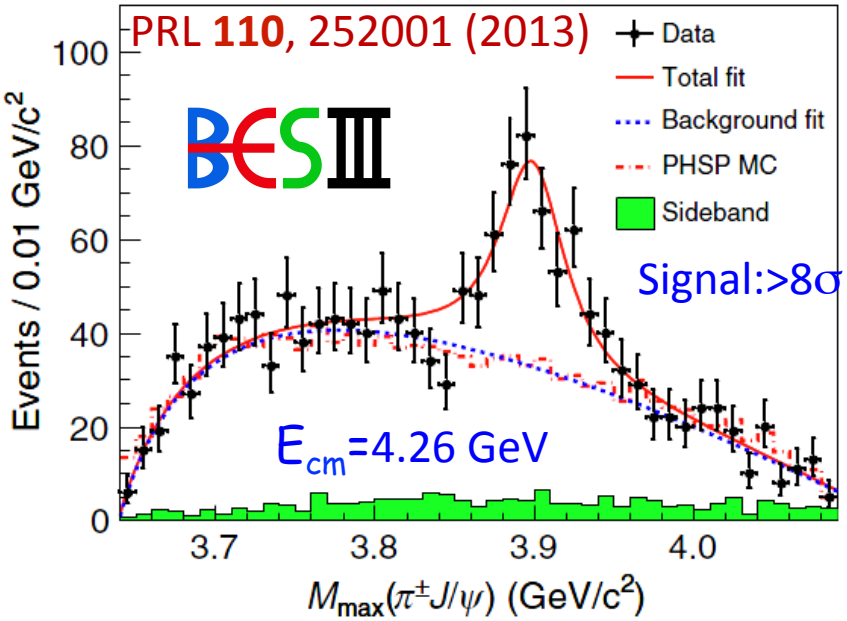


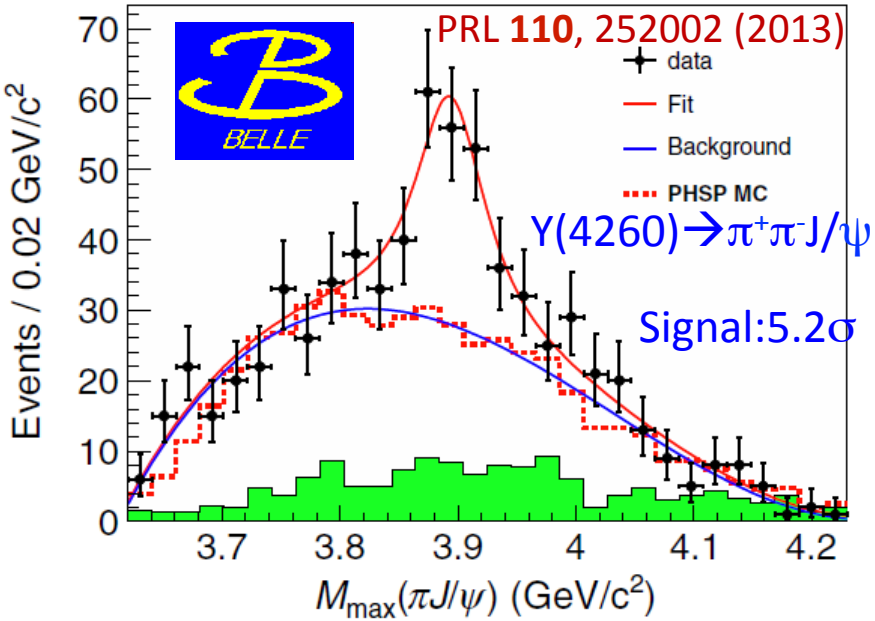


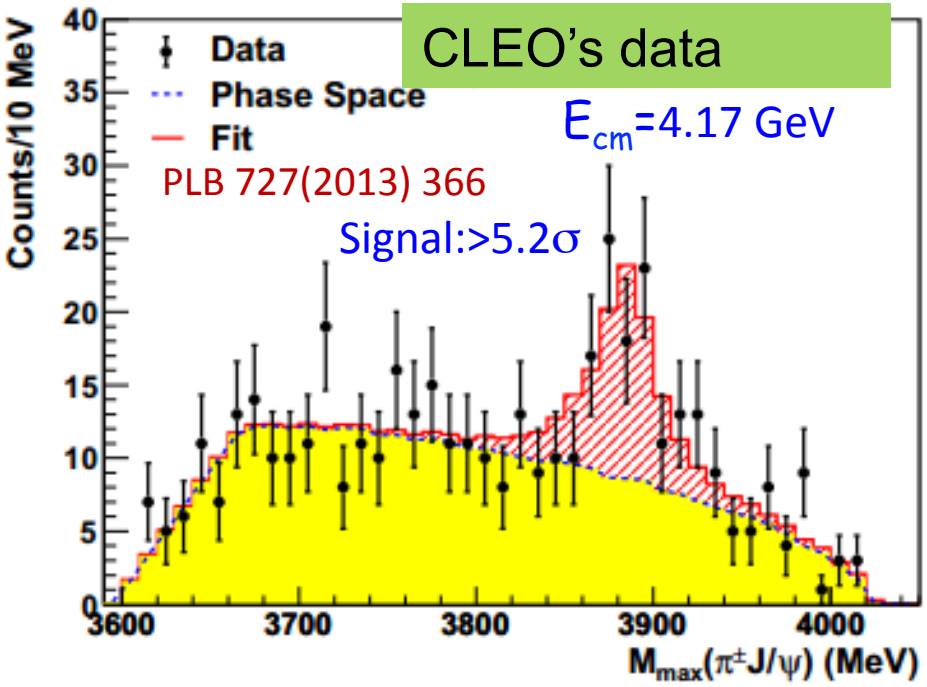
- The X(4140) was reported by CDF with Mass=(4143.0±2.9±1.2) MeV and Width=$11.7^{+8.3}_{-5.0}$±3.7 MeV
- Controversial: CMS (Yes), Belle (No), LHCb (No)
- BABAR: 1.6σ significance, ratio [B→KX*X→φJ/ψ]/[B→KφJ/ψ]<0.133 @ 90%; CDF=(0.149±0.039±0.024); LHCb<0.07 @ 90%
- BESIII: no signal, cross section γX(4140)/γX(3872)<10%.

The Z_c states

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





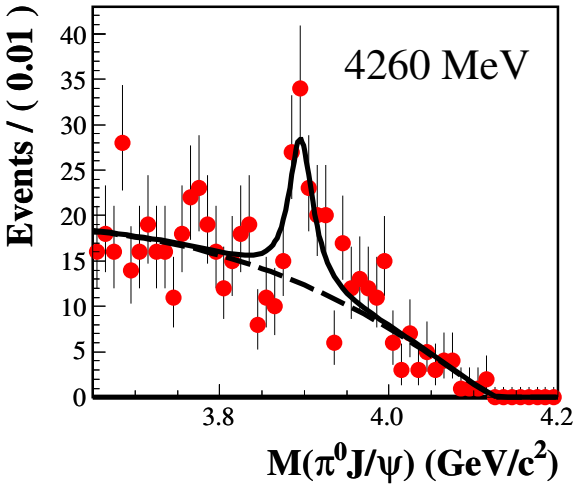


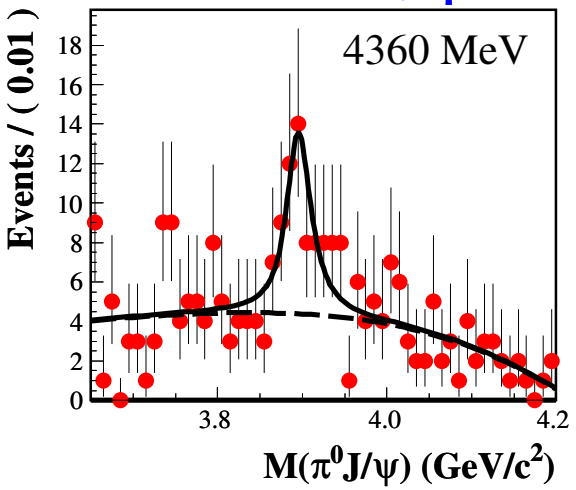
1. BESIII: M=(3899.0±3.6±4.9) MeV; Γ=(46±10±20)MeV
2. Belle: M=(3894.5±6.6±4.5) MeV; Γ=(63±24±26) MeV.
3. CLEO's data: M=3886±6±4 MeV, Γ=33±6±7 MeV.
4. At least four quarks inside!

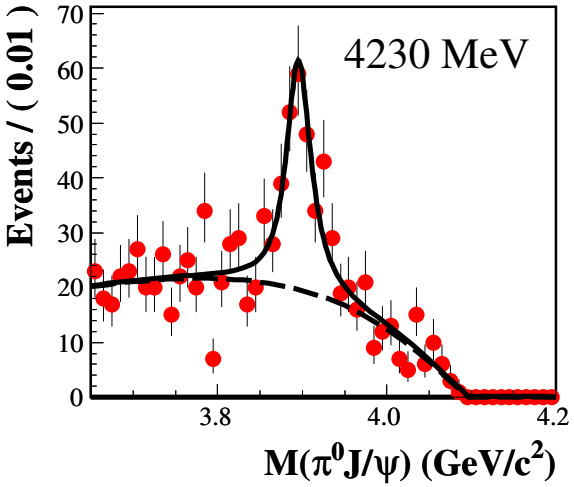
Neutral isospin partner: $Z_c(3900)^0$

BESIII Preliminary

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







A clear structure on $\pi^0 J/\psi$ invariant mass can be observed !

BESIII

Mass = 3894.8±2.3 MeV

Width = 29.6±8.2 MeV

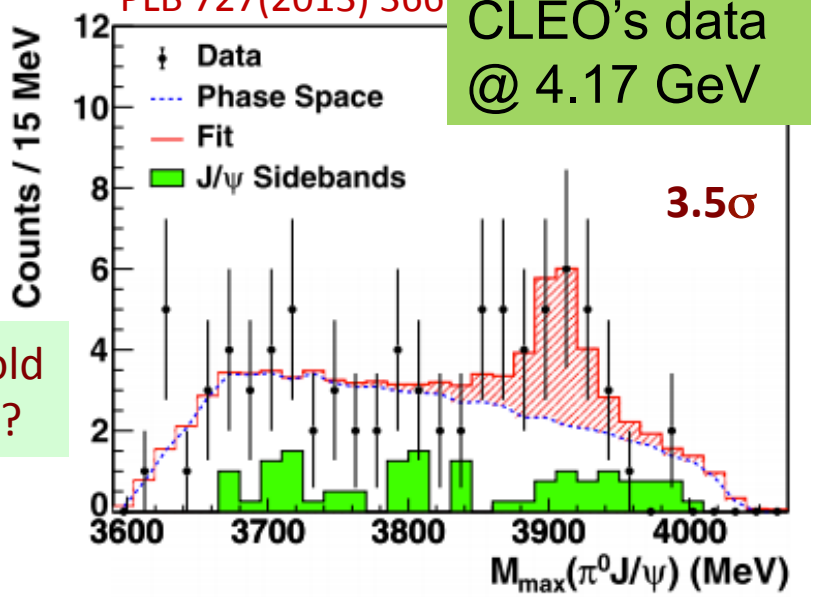
Significance = 10.4σ

Mass near DD* threshold

Molecules? Tetraquark?

PLB 727(2013) 366

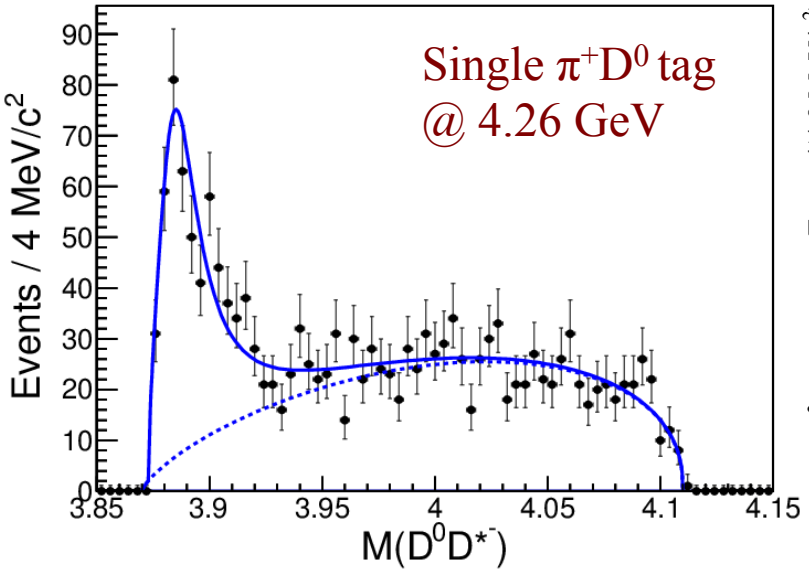
CLEO's data @ 4.17 GeV

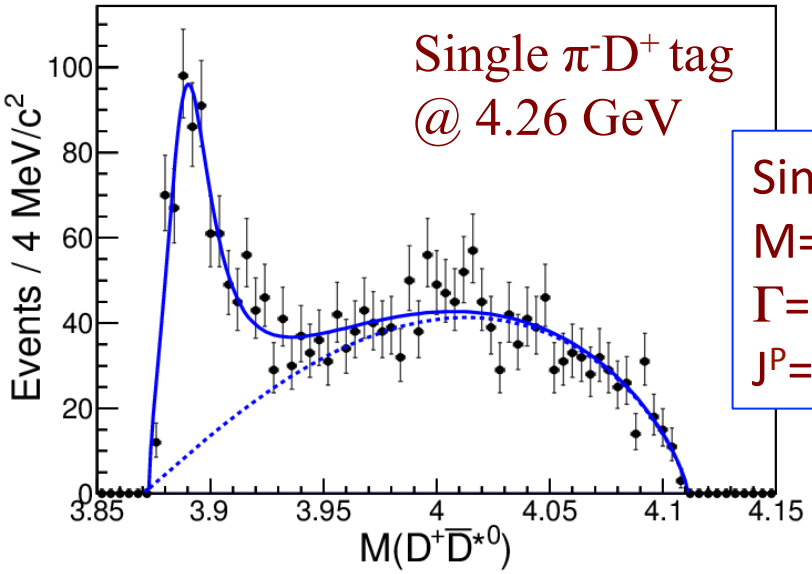


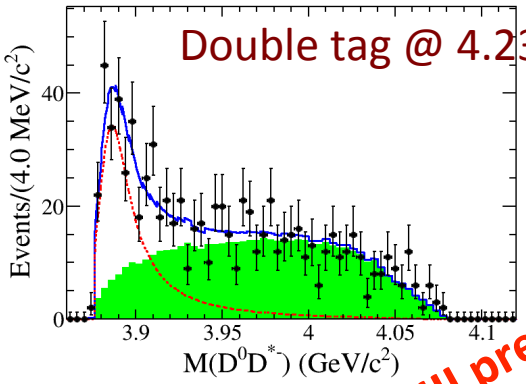
An isospin triplet is established !

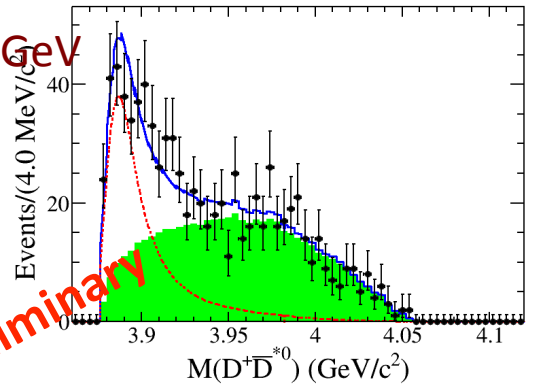
$e^+e^- \to (DD^*)^+\pi^- + c.c.$?

PRL 112, 022001 (2014)

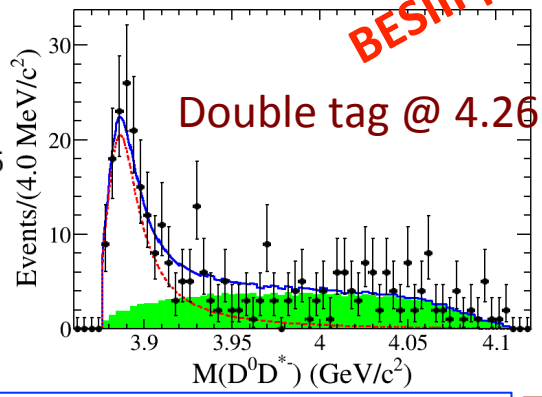


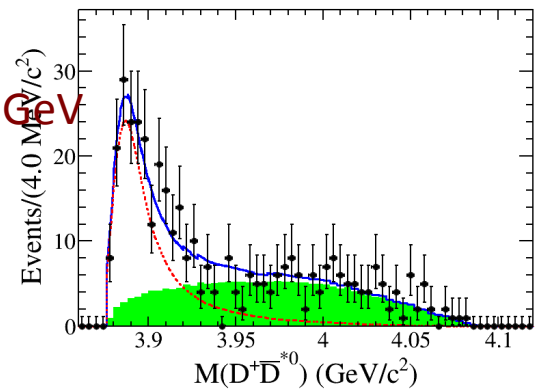






BESIII preliminary





Single tag
M=3883.9±1.5±4.2 MeV
Γ=24.8±3.3±11.0 MeV
$J^P=1^+$

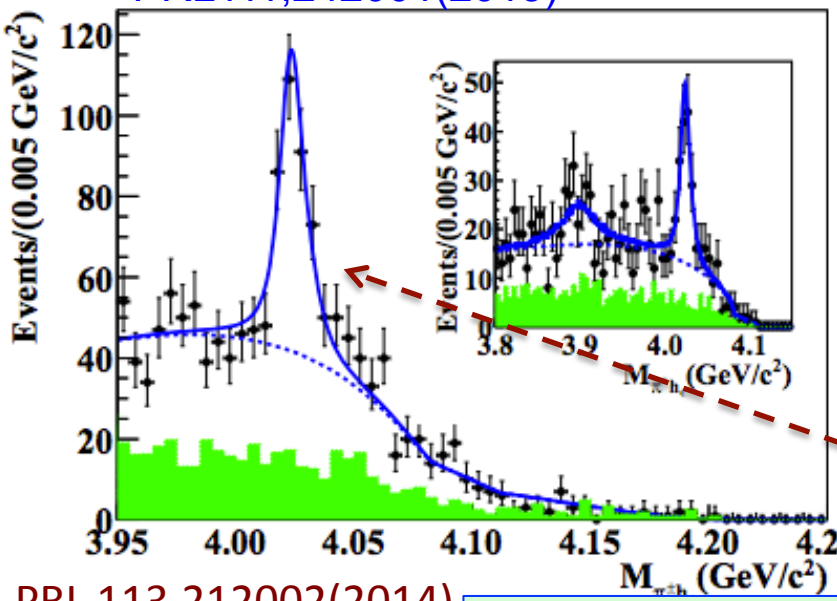
Double tag
M=3884.3±1.2±1.5 MeV
Γ=23.8±2.1±2.6 MeV
$J^P=1^+$

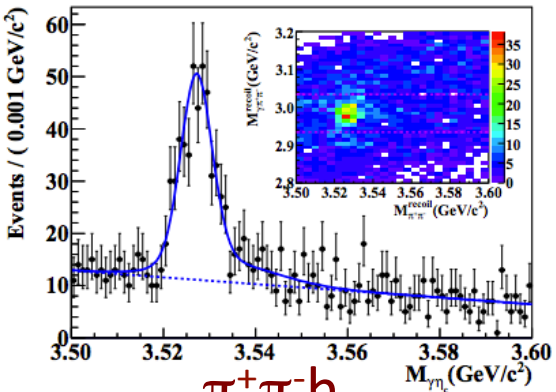
Good agreement between ST & DT method

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

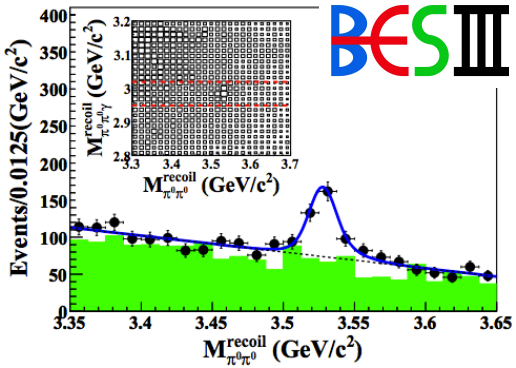
$e^+e^- \to \pi^+\pi^- h_c$ & $\pi^0\pi^0 h_c$

PRL111,242001(2013)





$\pi^+\pi^- h_c$



$\pi^0\pi^0 h_c$

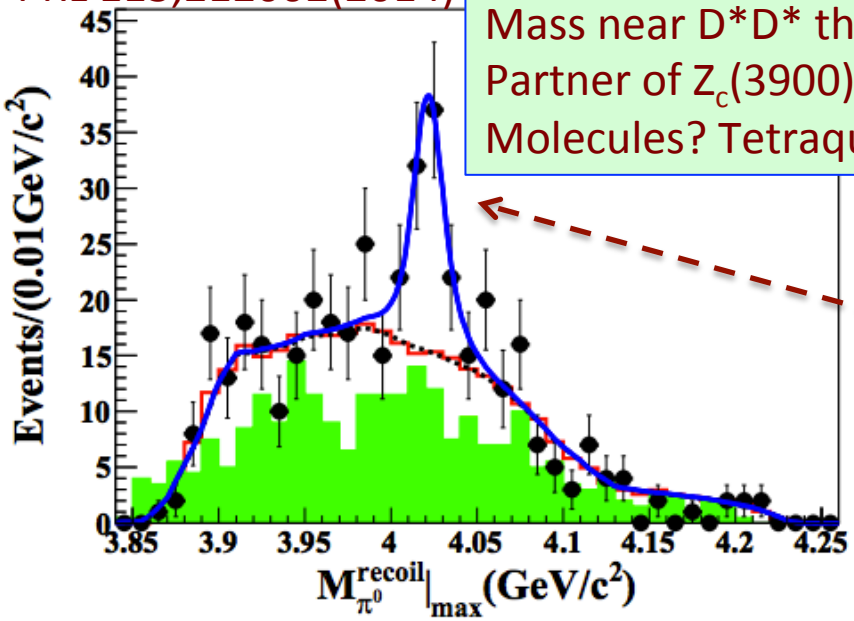
Charged $Z_c(4020)^{\pm}$

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 !

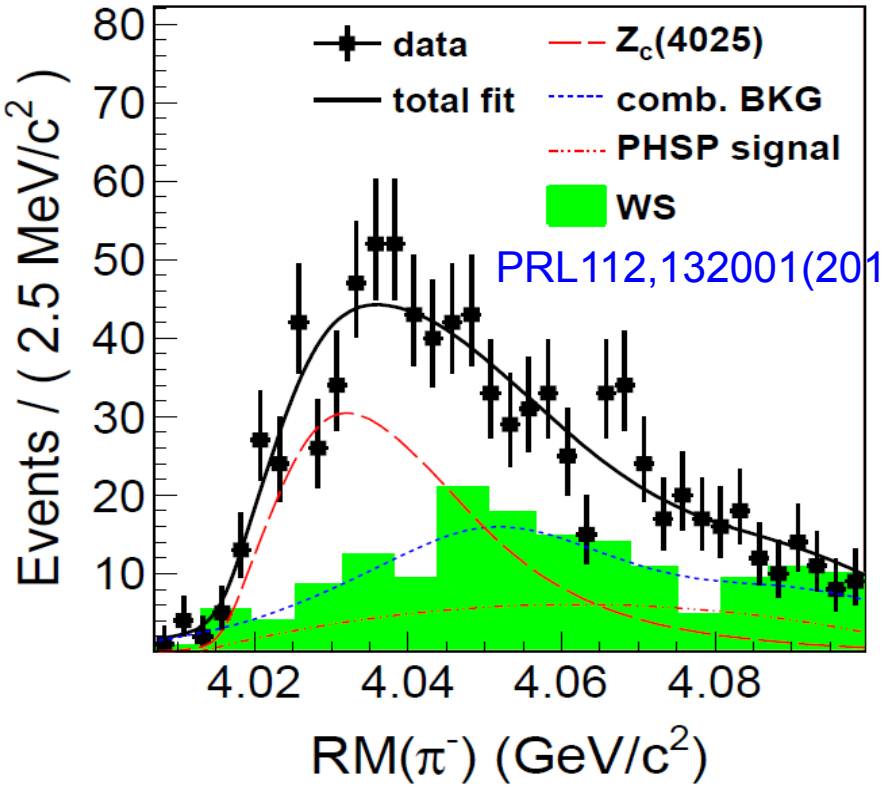
Neutral $Z_c(4020)^0$

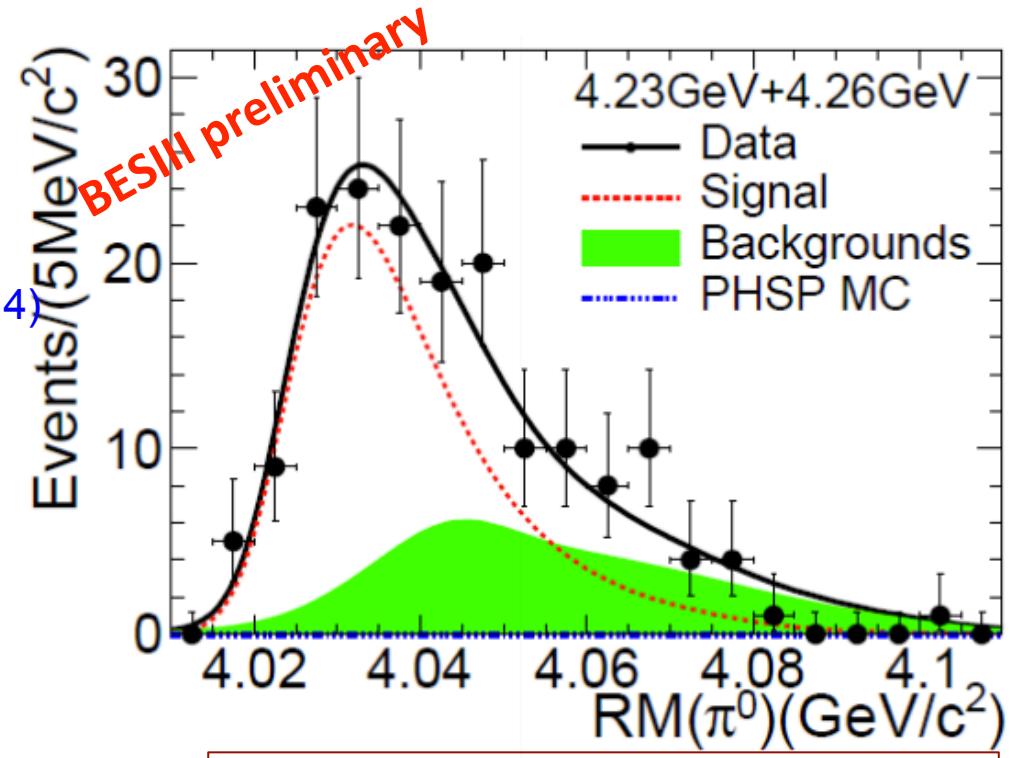
Mass=(4023.9±2.2±3.8) MeV

Width: fixed to charged partner

Significance: 5σ

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





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

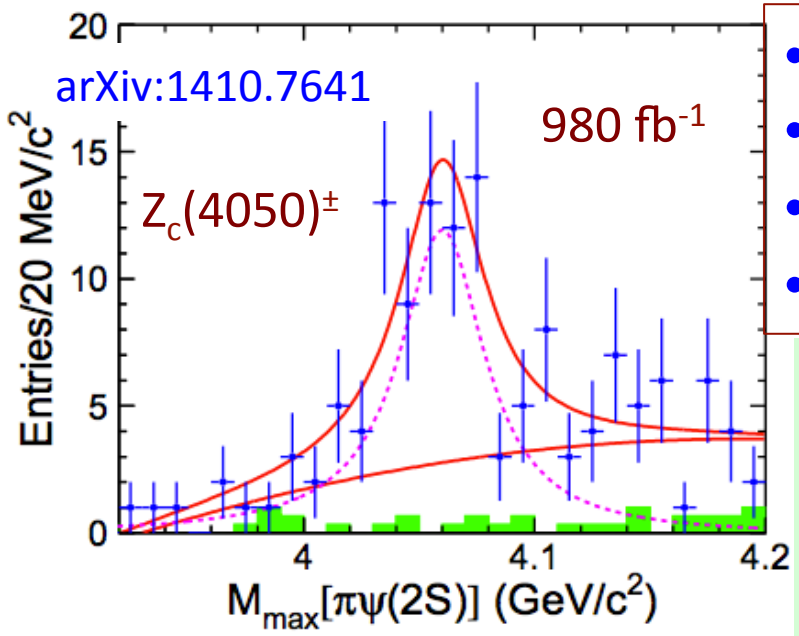
Agrees !

Neutral $Z_c(4025)^0$:
$M=(4025.5^{+2.0}_{-4.7}\pm3.1)$ MeV
$\Gamma=(23.0\pm6.0\pm1.0)$ MeV
Significance: 7.4σ

New isospin triplet?

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

$Z_c(4050)^{\pm}$ & $Z_c(4200)^{\pm}$ by Belle



- $Y(4360)\rightarrow\pi^{\pm}Z_c(4050)\rightarrow\pi^+\pi^-\psi(2S)$
- $M=(4054\pm3\pm1)$ MeV; $\Gamma=(45\pm11\pm6)$ MeV
- 3.5σ evidence
- Y-states tend to produce Z_c states?

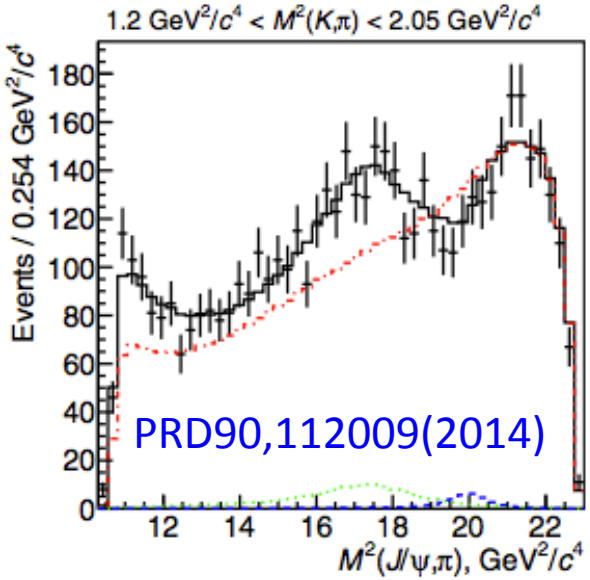
$B\rightarrow K^+Z_c(4200)^-\rightarrow K^+\pi^-J/\psi$

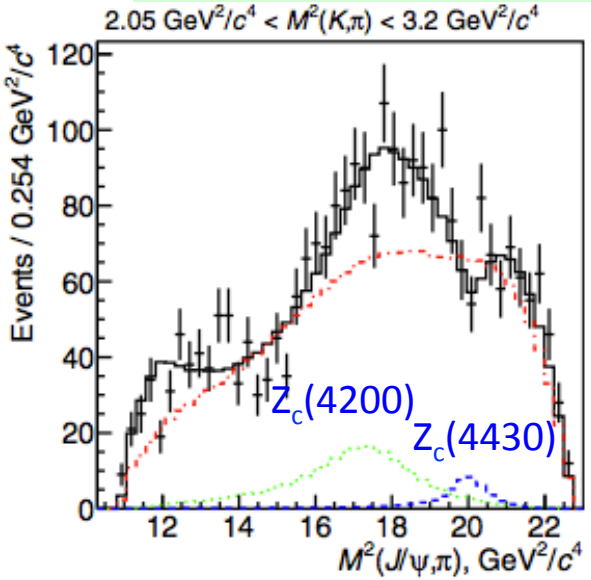
Significance: 6.2σ

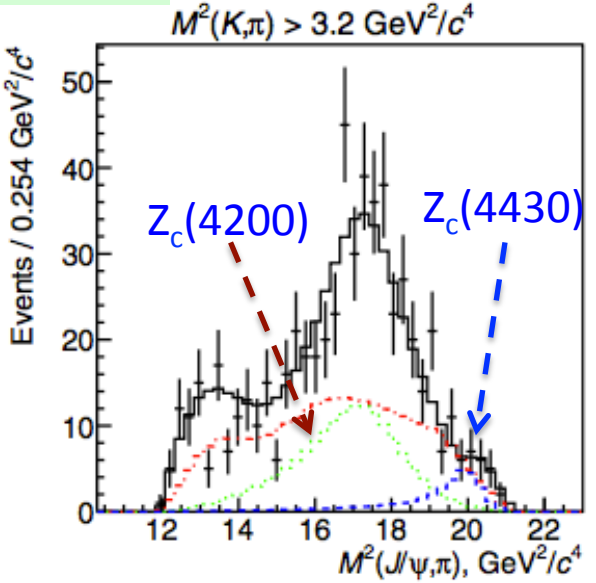
$J^P=1^+$

$Z_c(4430)$: 4.0σ

$$M = 4196^{+31+17}_{-29-13}\ \mathrm{MeV}/c^2,$$
$$\Gamma = 370^{+70+70}_{-70-132}\ \mathrm{MeV}.$$







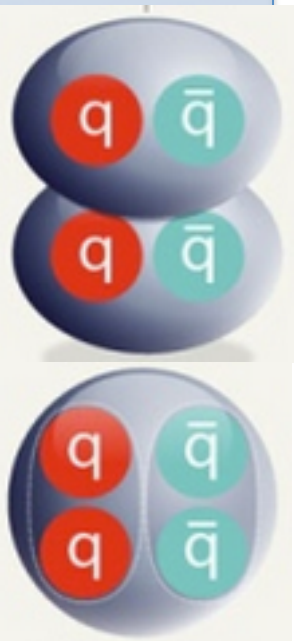
Nature of Z_c states

- 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 (arXiv:1405.7623)
- 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); …

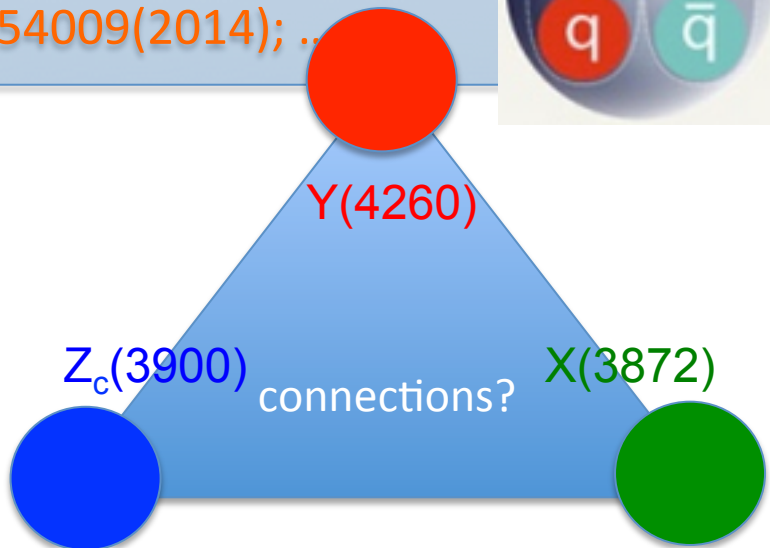
- Tetraquark?

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

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

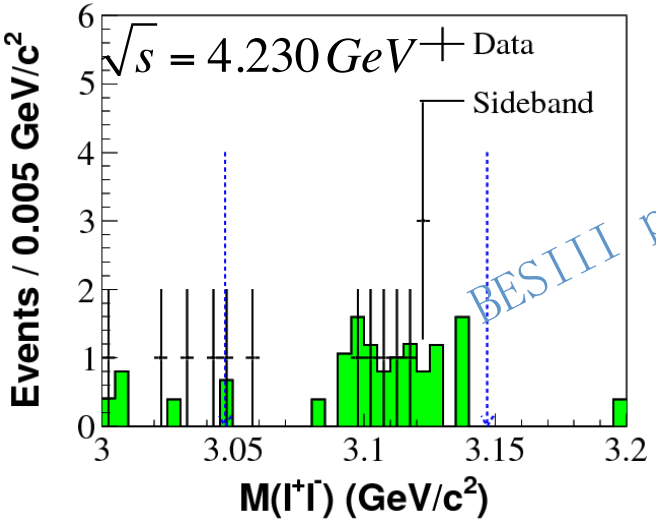


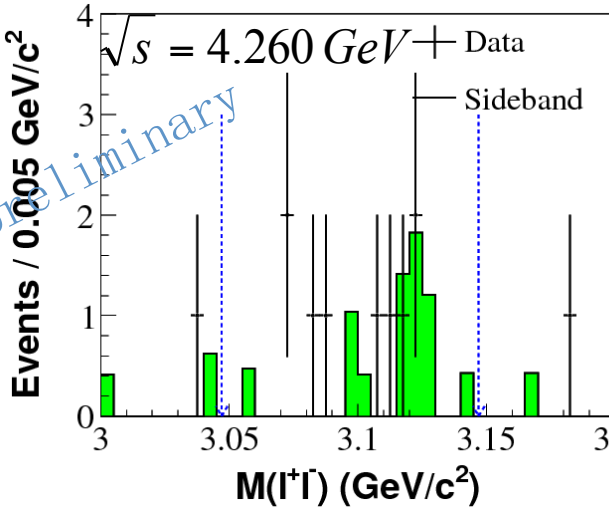
Summary

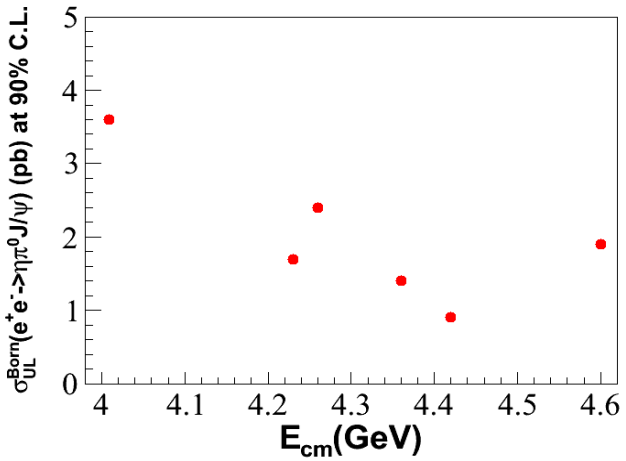
- Leptonic machines make big progresses in the study of exotic hadrons.
- X & Y states are difficult to distinguish from normal meson, charged Z_c states provide solid evidence.
- Quark composition is still puzzling…
- More results are coming, we would finally understand them.

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