Studies of charmonium-like states at BESIII

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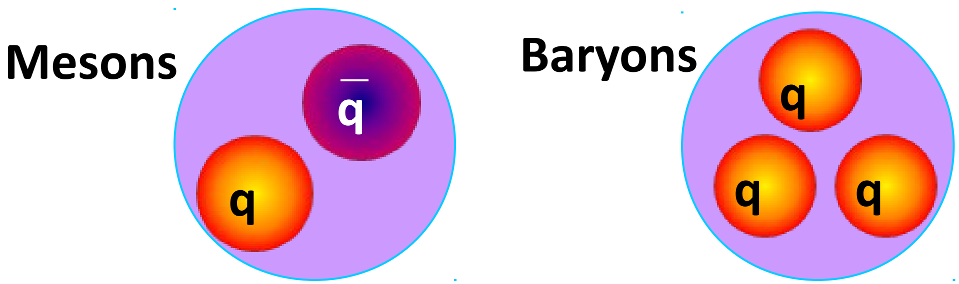
Overview

- Exotic hadrons
- The BES-III experiment
- Y(4260) and Y(4360)
- Y(4230)
- X(3872) and X(3823)
- Z^+_c states
- Summary

Search for exotics hadrons

Conventional hadrons:



QCD predicts more, "exotic" states: $q\bar{q}g$, ggg, $q\bar{q}q\bar{q}$, …

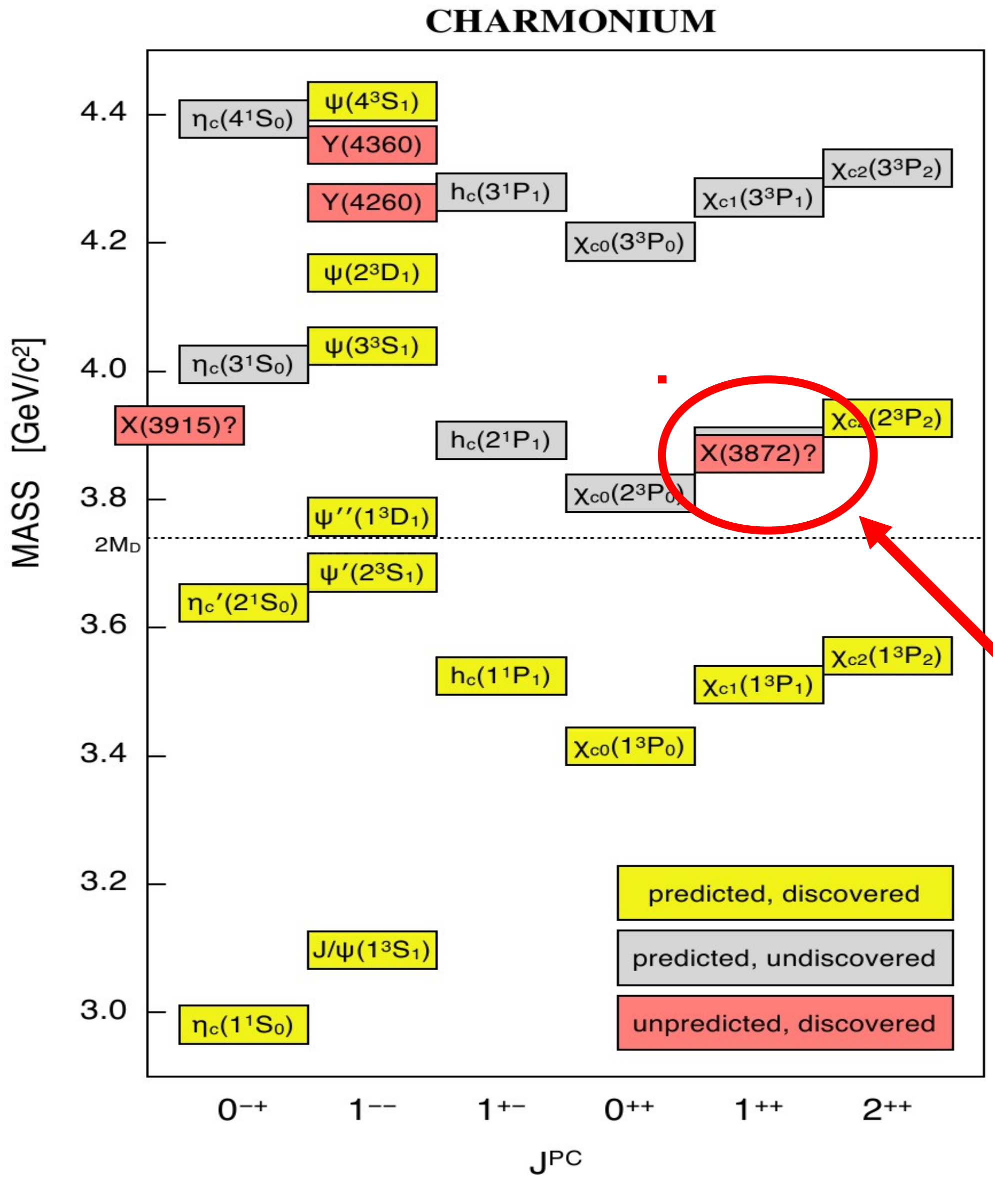
… Baryons can be constructed from quarks by using the combinations (qqq), ($qqqq\bar{q}$), etc, while mesons are made out of ($q\bar{q}$), ($qq\bar{q}\bar{q}$), etc … … the lowest baryon configuration (qqq) gives just the representations 1, 8, and 10 that have been observed, while the lowest meson configuration ($q\bar{q}$) similarly gives just 1 and 8."

Gell-Mann, 1964

No clear evidence of unconventional hadron was found during more than 40 years

- "The absence of exotics is one of the most obvious features of QCD" – R. L. Jaffe, 2005
- "The story of pentaquark shows how poorly we understand QCD" – F. Wilczek, 2005

Search for unconventional hadron in heavy quarkonium



- **Very limited number of conventional states & precise prediction for masses of quarkonium**
- **New "smoking gun": charged resonance in charmonium transition**
- **Clear signature of final state**

In 2003 BELLE had observed first "unanticipated" charmonium state: X(3872)

Unpredicted heavy quarkonium states

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B \to K(\gamma \psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (\ldots)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	$15^{+11}_{-\ 7}$	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^- \Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

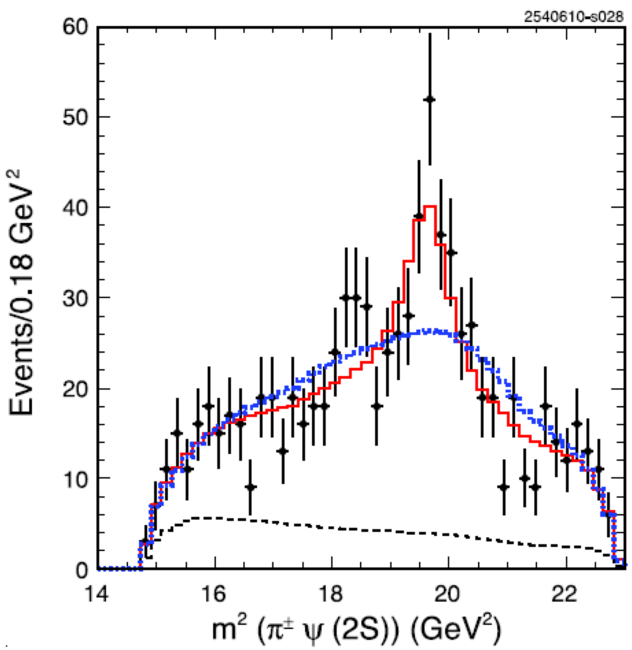
EPJ C71, 1534(2011)

Charged charmonium-like states $Z_c^{\pm}(4430)$, $Z_c^{\pm}(4050)$, $Z_c^{\pm}(4250)$

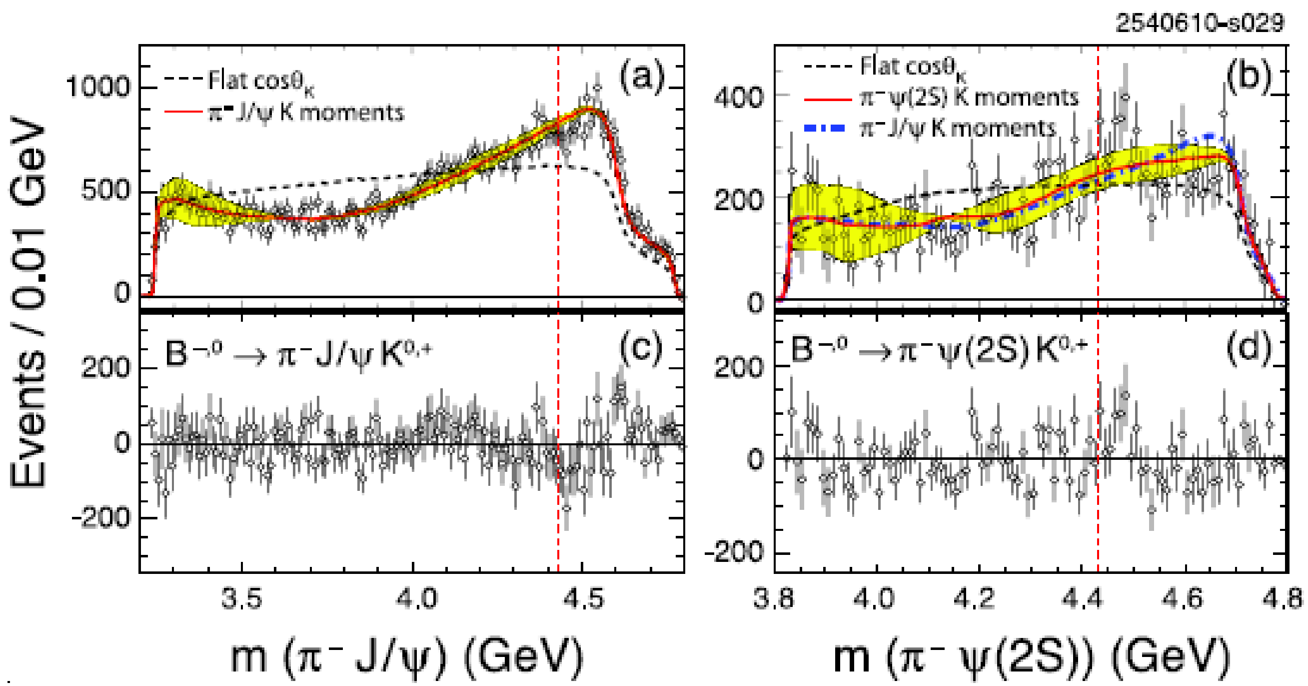
Observed by BELLE in $B \to K\pi\psi(2S)$, $B \to K\pi\chi_{c1}$

Not observed by BaBar in very similar conditions

BELLE

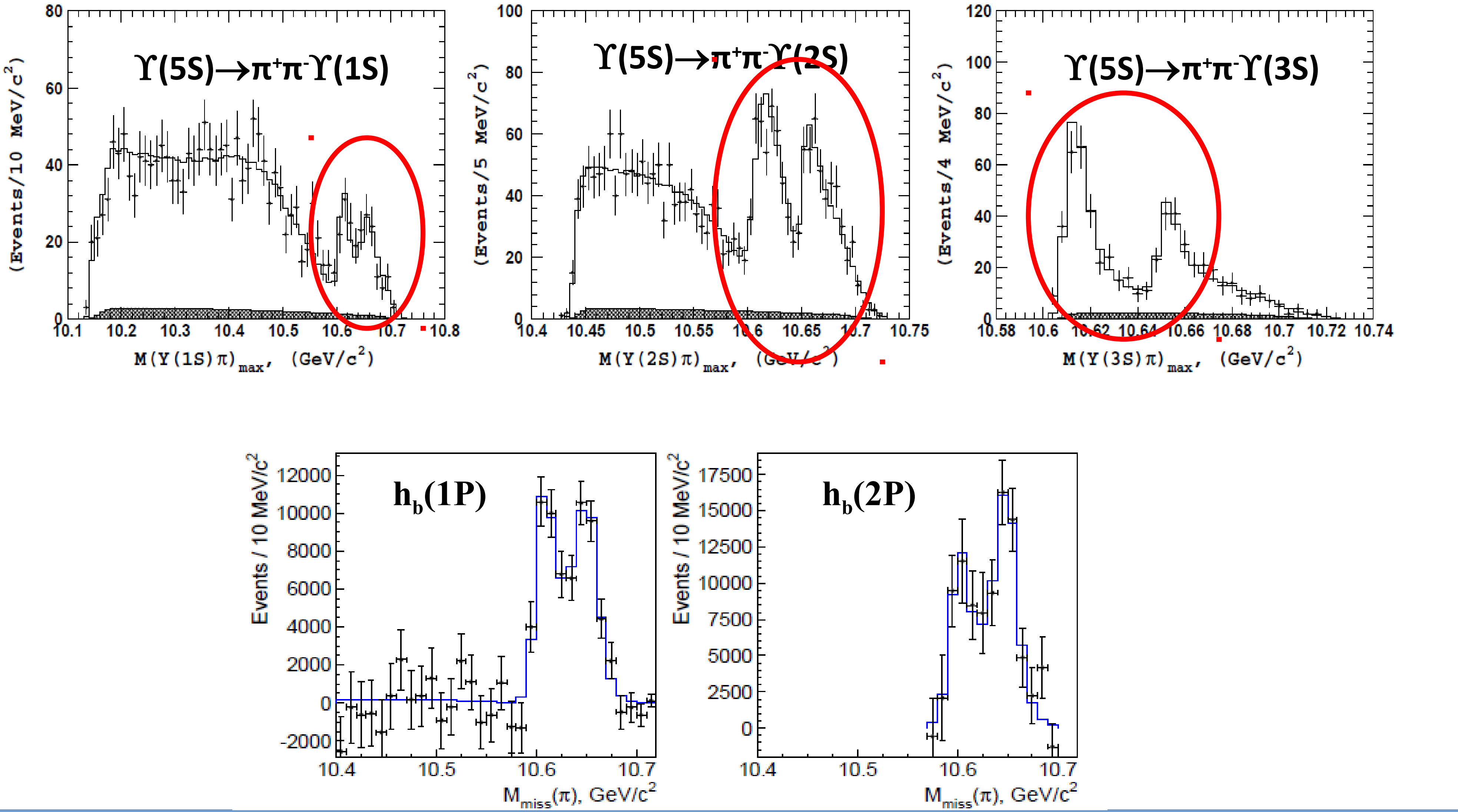


BaBar



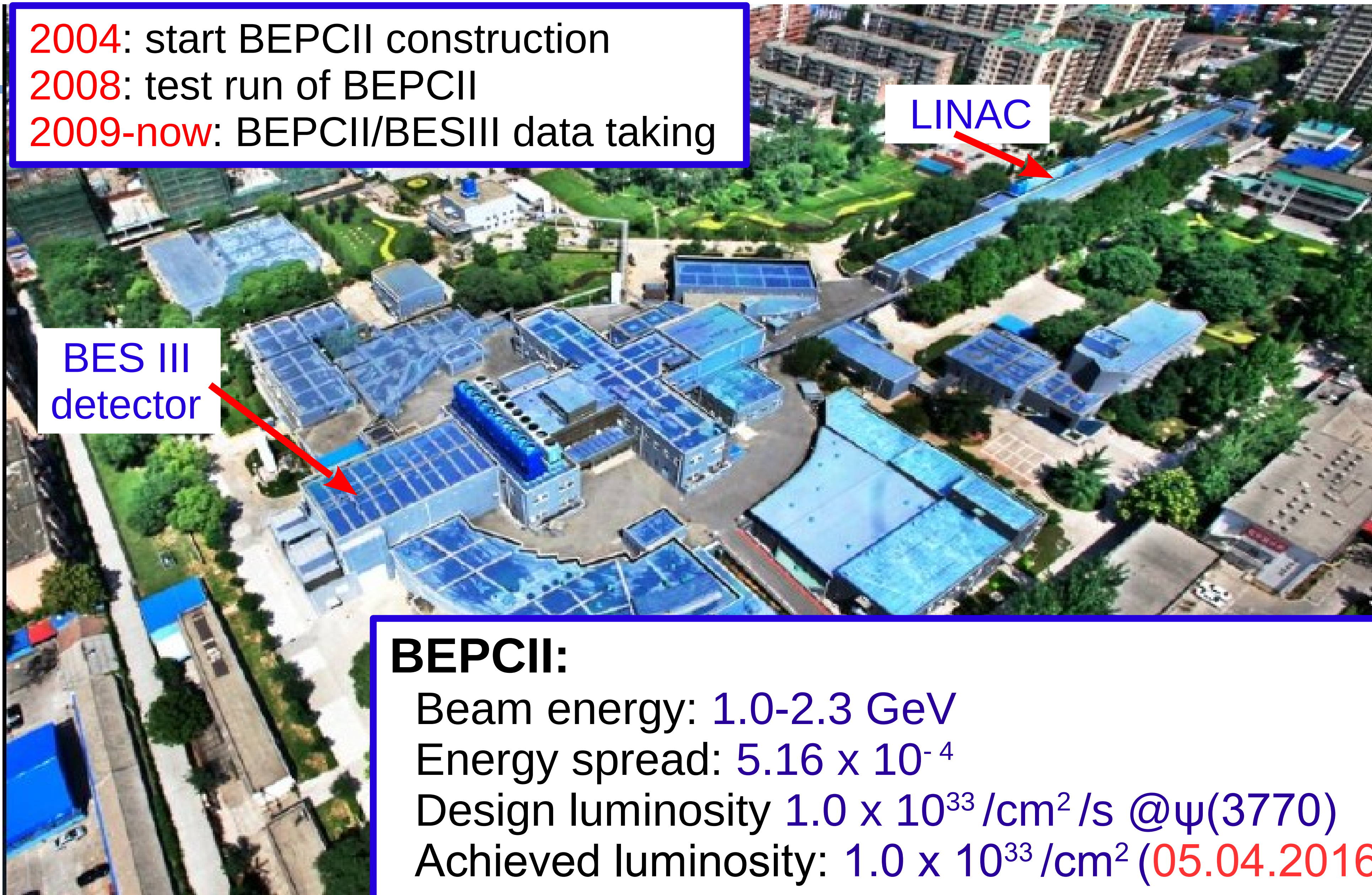
Observation of charged bottomonium-like state Z_b(10610) and Z_b(10650)

$\Upsilon(5S)\to\pi^+\pi^-\Upsilon(nS)$, $\pi^+\pi^- h_b(nP)$ **BELLE, PRL 108, 122001 (2012)**



The BESIII experiment

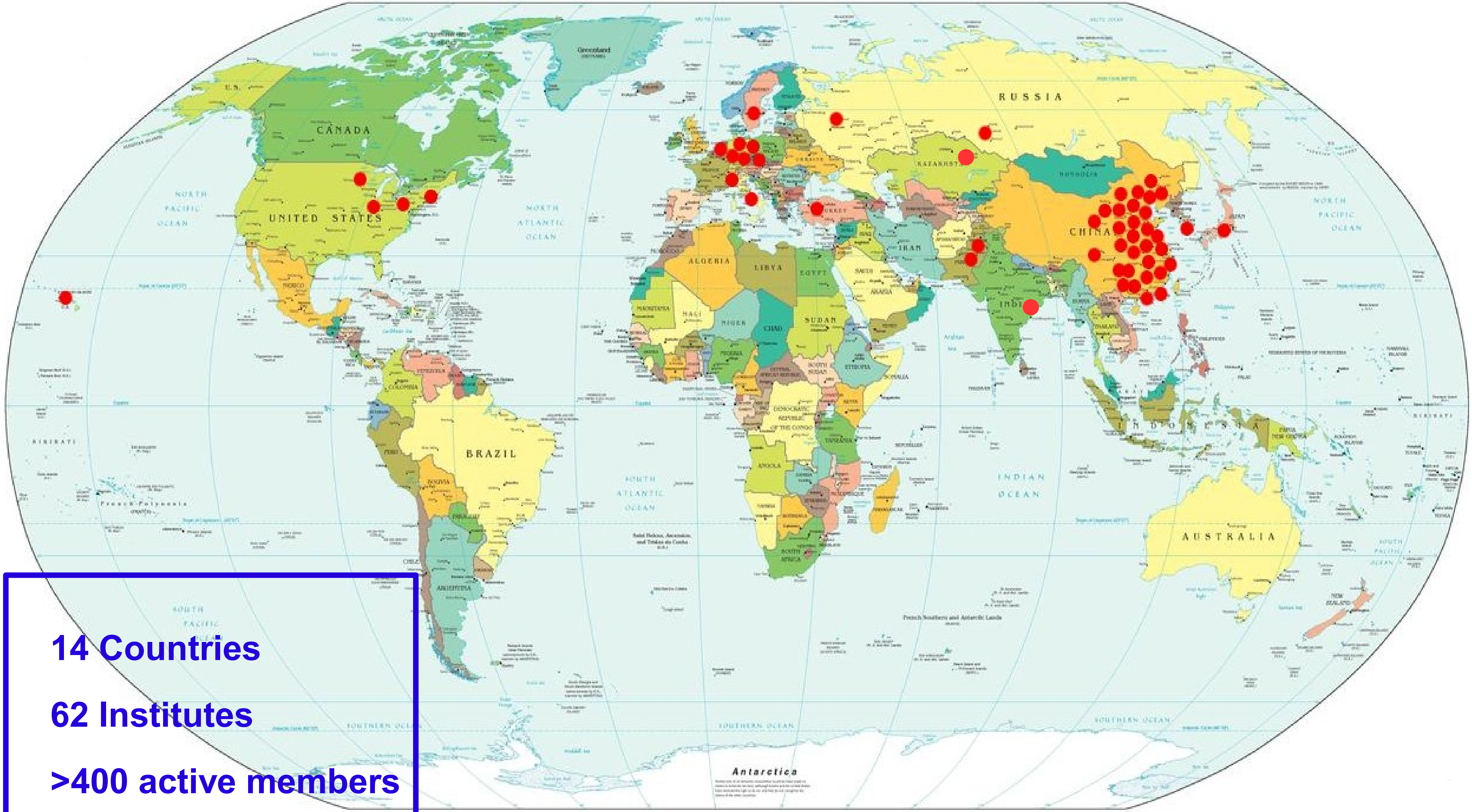
2004: start BEPCII construction
2008: test run of BEPCII
2009-now: BEPCII/BESIII data taking



BEPCII:

Beam energy: 1.0-2.3 GeV
Energy spread: 5.16×10^{-4}
Design luminosity 1.0×10^{33} /cm^2 /s @$\psi(3770)$
Achieved luminosity: 1.0×10^{33} /cm^2 (05.04.2016)

The BES-III collaboration



14 Countries

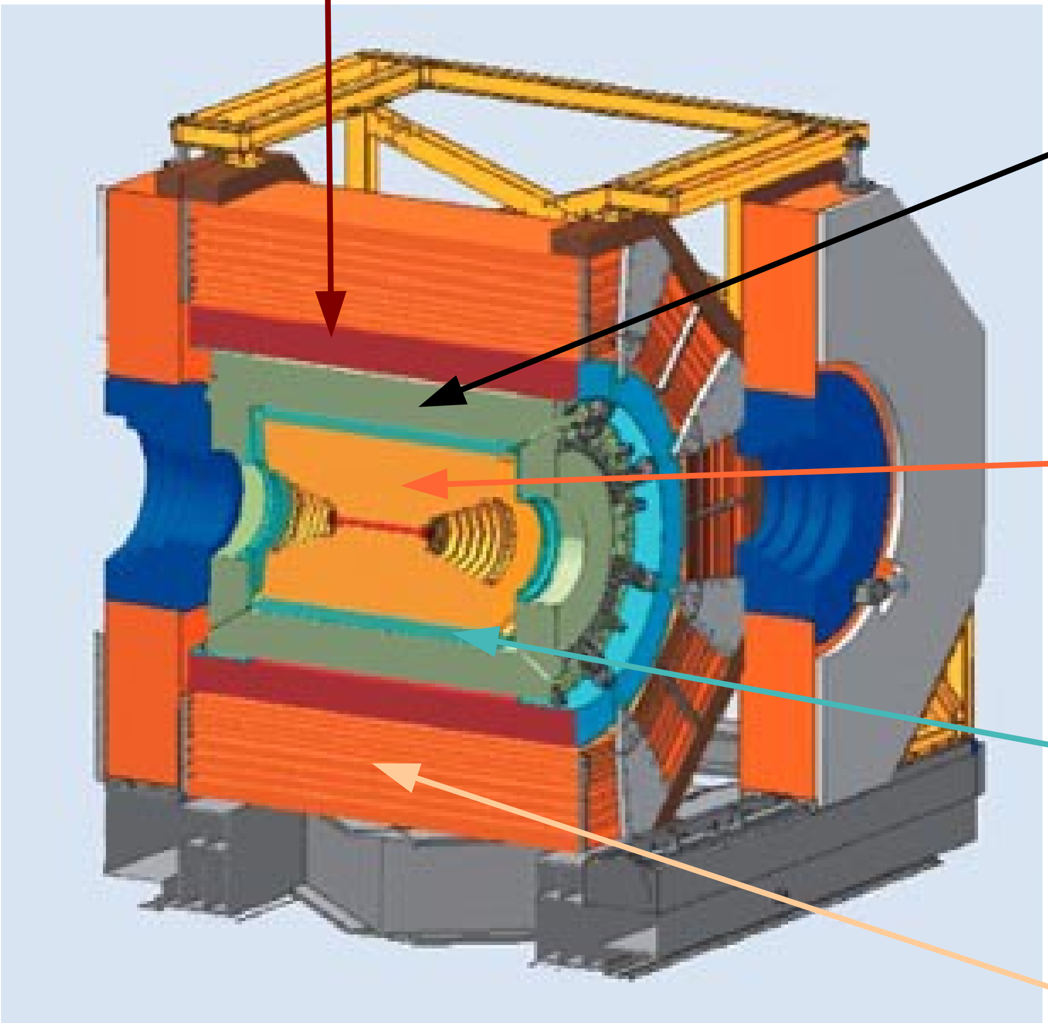
62 Institutes

>400 active members

The BES-III detector

NIM A614, 345(2010)

Super conducting magnet: 1 T

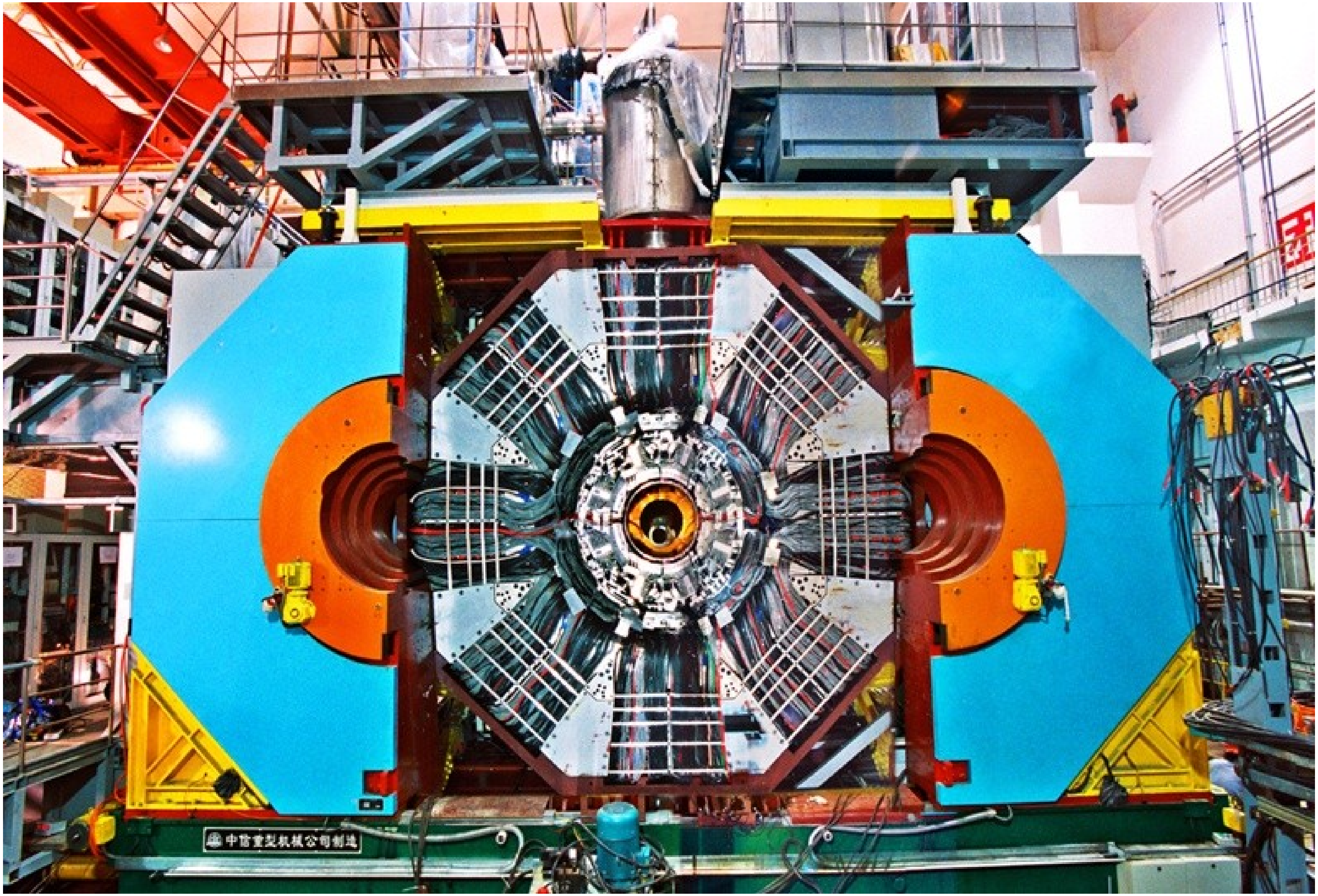


EMC: CsI cristal
- Energy resolution: **2.5% @1GeV**
- Spatial resolution: **6mm**

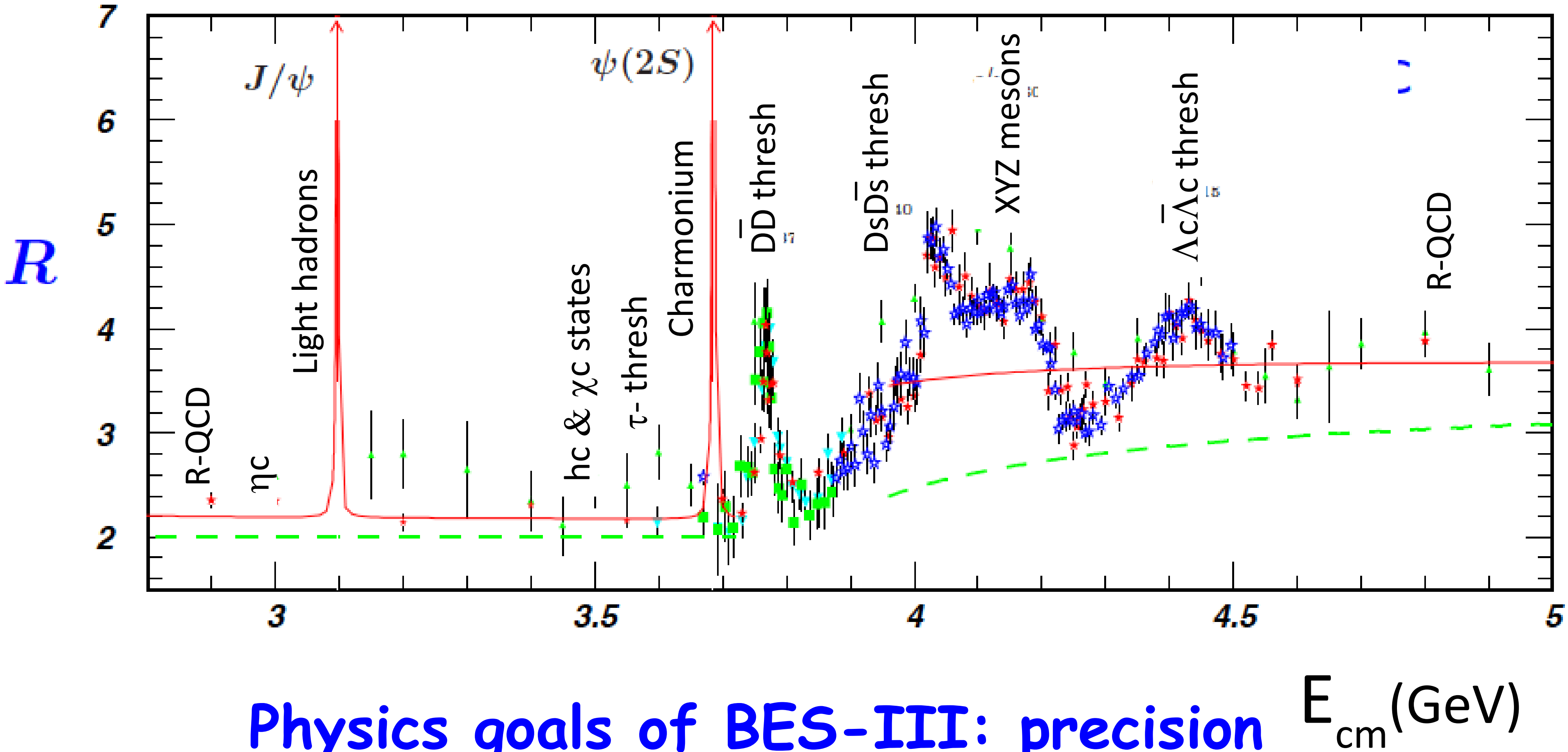
MDC:
- Spatial resolution: **σ_{xy}= 120μm**
- Momentum resolution:**0.5%** @ **1GeV**
- **dE/dx** resolution: 6%

TOF (double layer scitiliator, mRPC):
Time resolution: **100ps** (barrel)
110ps (endcaps)

Muon ID:
9 layers RPC (8 for endcaps) in the flux-return yoke

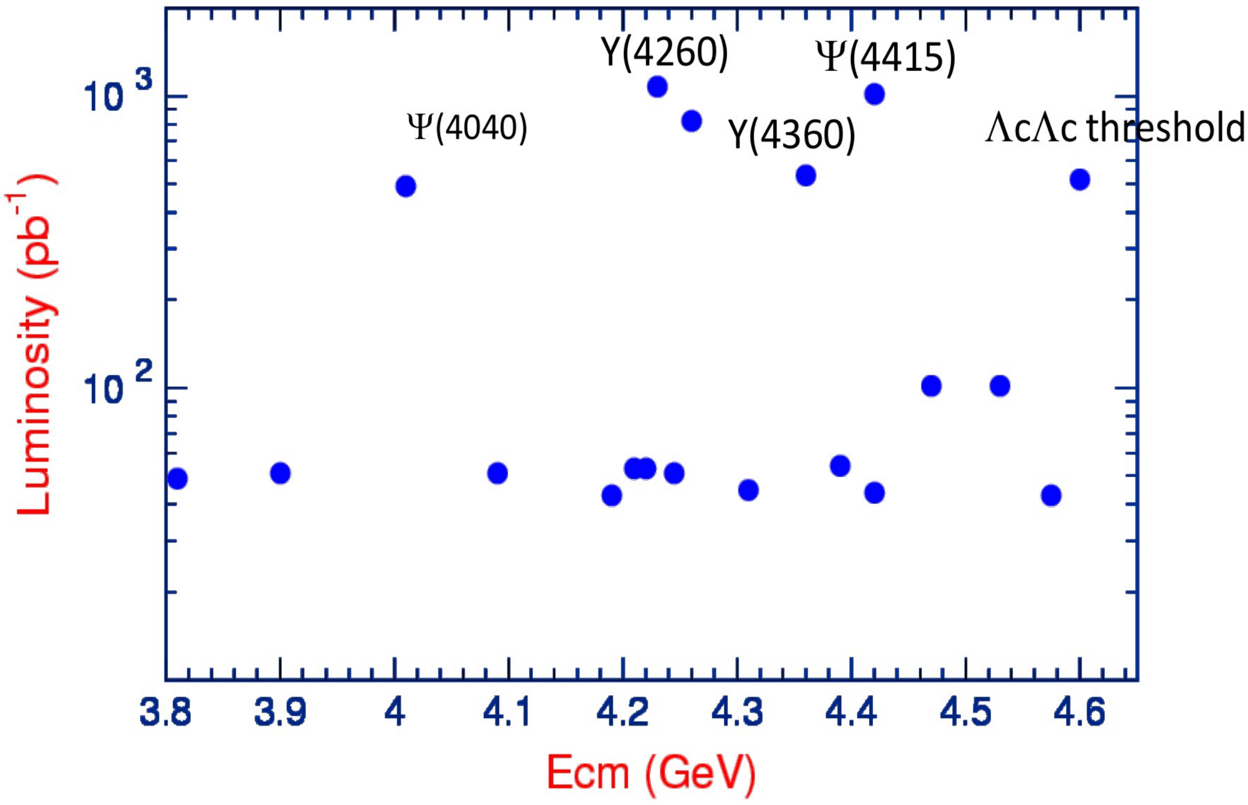


e^+e^- annihilation at $\sqrt{s}$ = 2.0 – 4.6 GeV



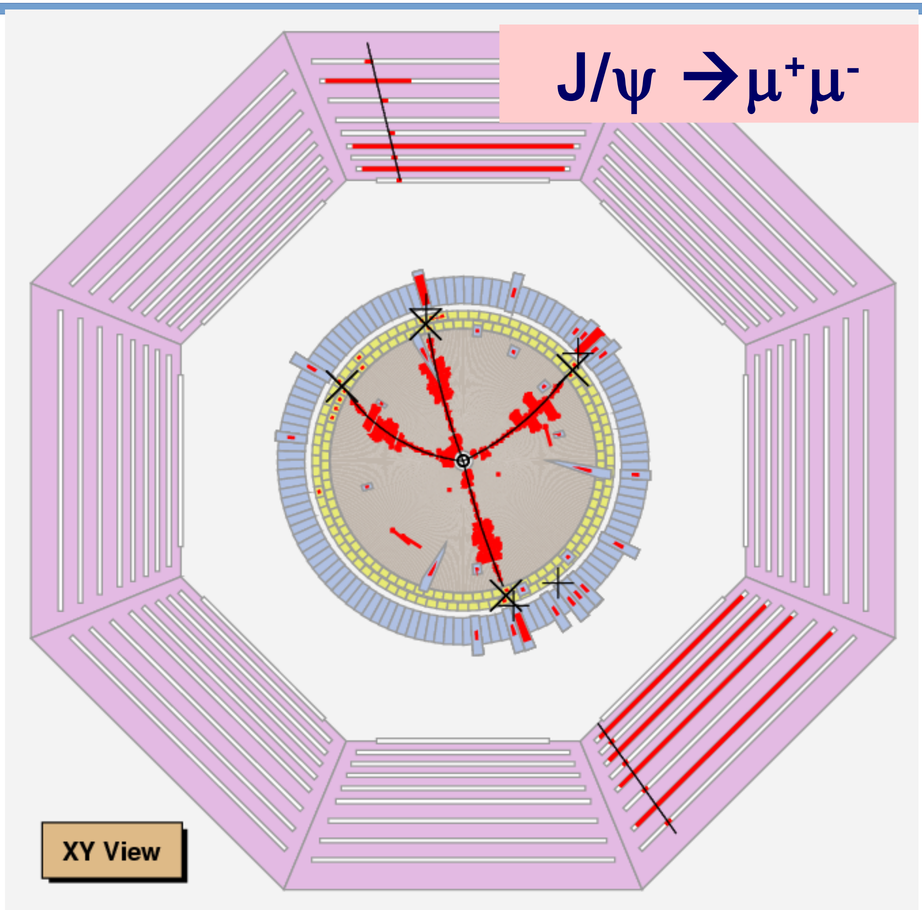
Physics goals of BES-III: precision measurements in τ-charm domain

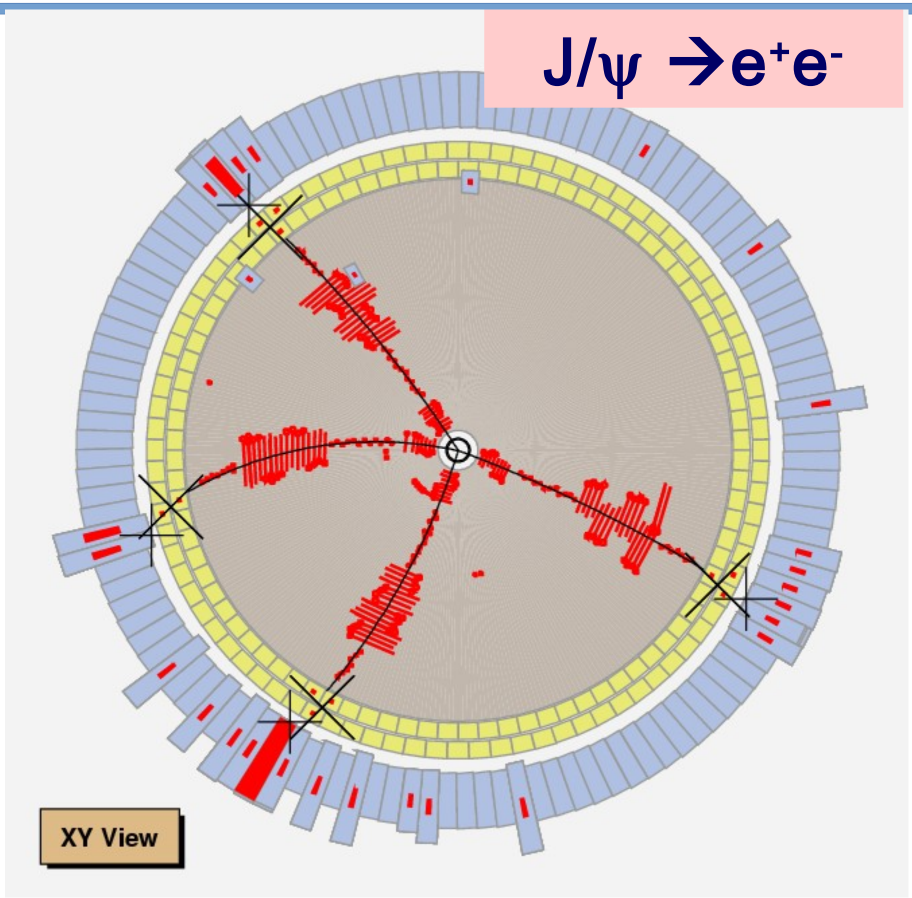
Data samples



CM energy (GeV)	L (pb^{-1})
3.810	50.54±0.03
3.900	52.61±0.03
4.009	481.96±0.01
4.090	52.63±0.03
4.190	43.09±0.03
4.210	54.55±0.03
4.220	54.13±0.03
4.230[1]	44.40±0.03
4.230[2]	1047.34±0.14
4.245	55.59±0.04
4.260[1]	523.74±0.10
4.260[2]	301.93±0.08
4.310	44.90±0.03
4.360	539.84±0.10
4.390	55.18±0.04
4.420[1]	44.67±0.03
4.420[2]	1028.89±0.13
4.470	109.94±0.04
4.530	109.98±0.04
4.575	47.67±0.03
4.600	566.93±0.11

$e^+e^- \to \pi^+\pi^- J/\psi$ events @ BESIII

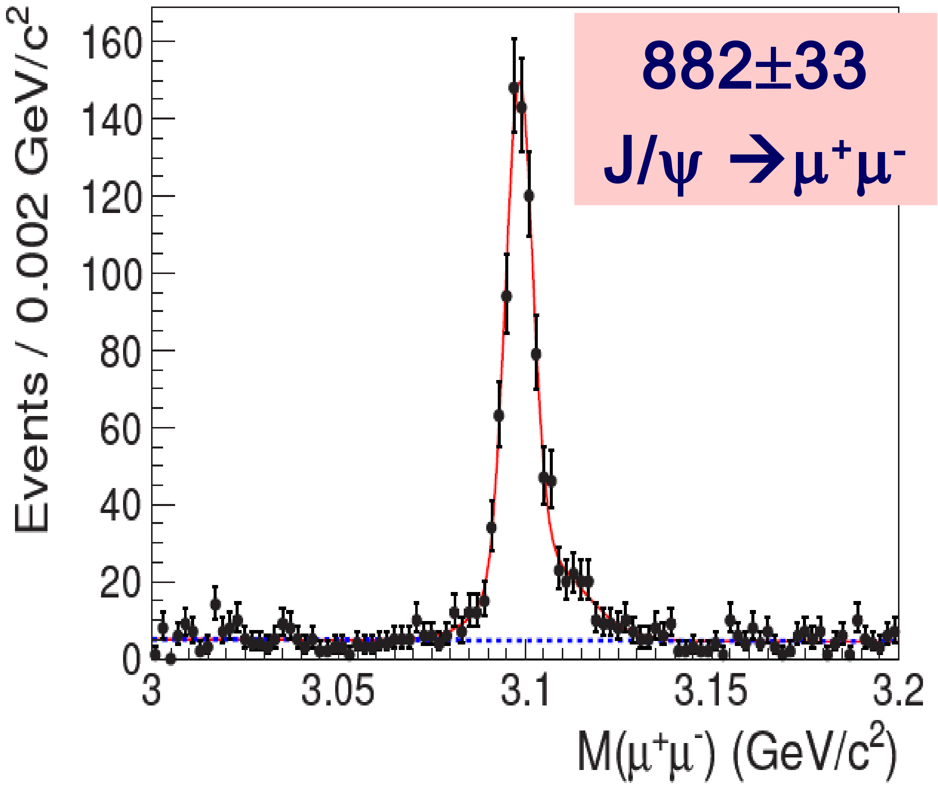


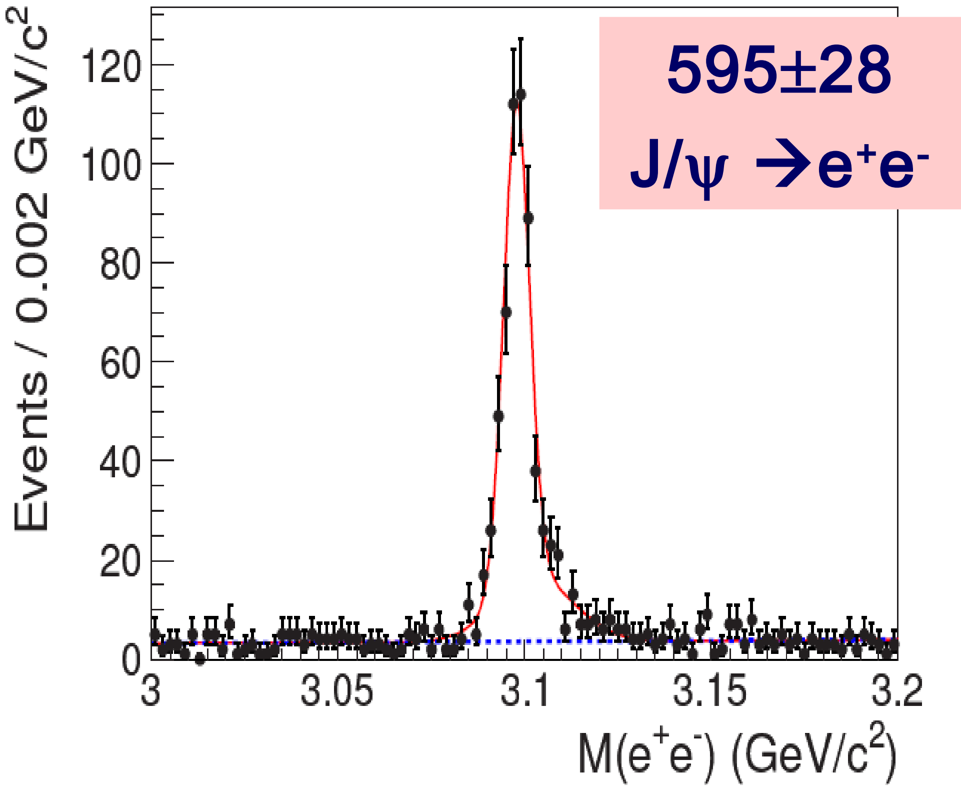


- Select 4 charged tracks and reconstruct J/ψ with lepton pair.
- Very clean sample, very high efficiency.

The J/ψ signals @ BESIII

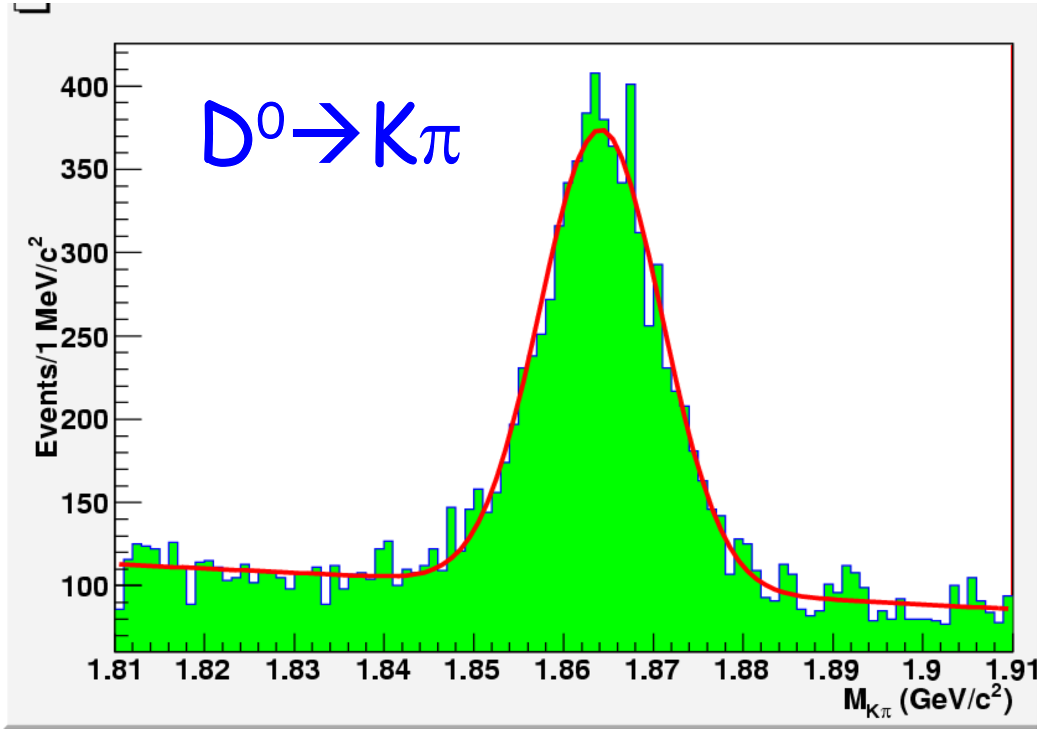
BESIII: arXiv:1303.5949

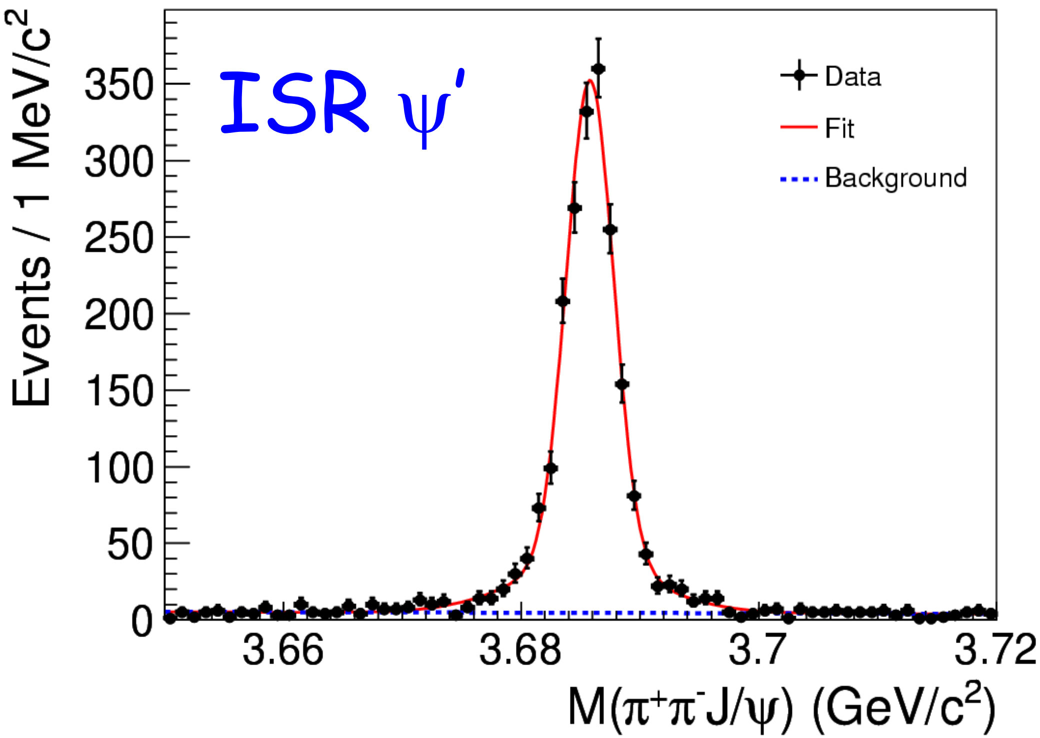




- Dominant background $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$
- J/ψ signal: [3.08,3.12] GeV
- J/ψ sideband: [3.0,3.06] GeV or [3.14,3.20] GeV

Data quality check





$\Delta M_D = 0.5 \pm 0.2$ MeV

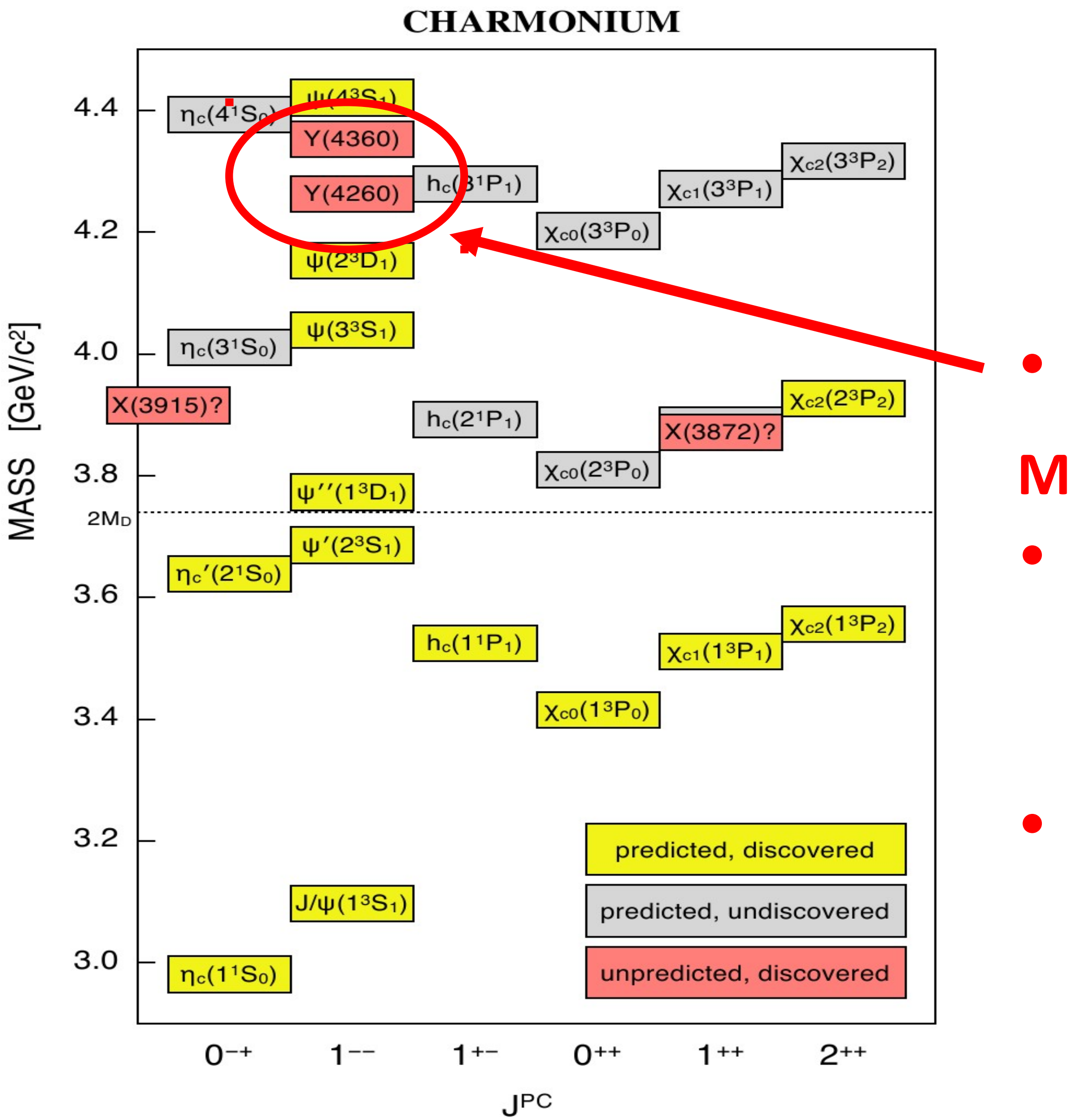
$\sigma M_D = 6.0 \pm 0.1$ MeV

$\Delta M_{\psi'} = 0.2 \pm 0.1$ MeV

$\sigma M_{\psi'} = 2.0 \pm 0.1$ MeV

- Reconstruction was cross-checked using known resonances

Y(4260) and Y(4360)



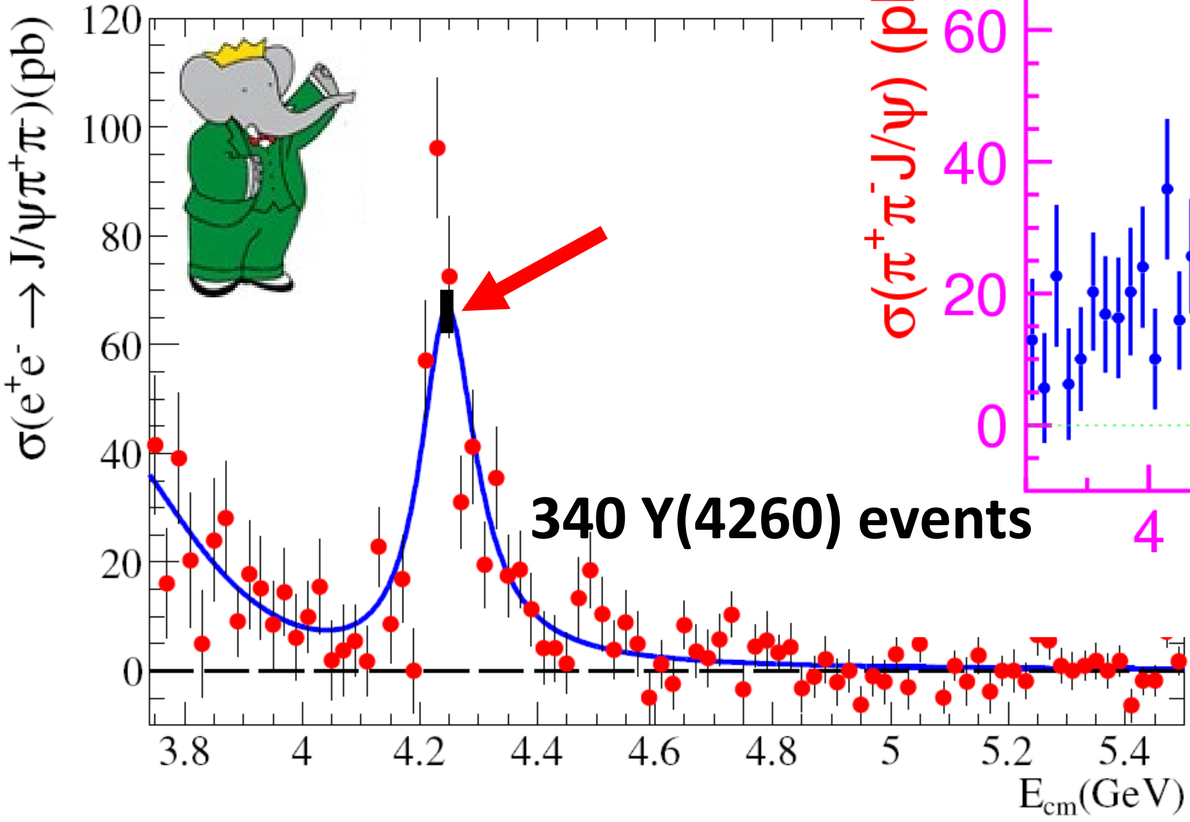
- 1^{--}

May be produced in e^+e^- collision

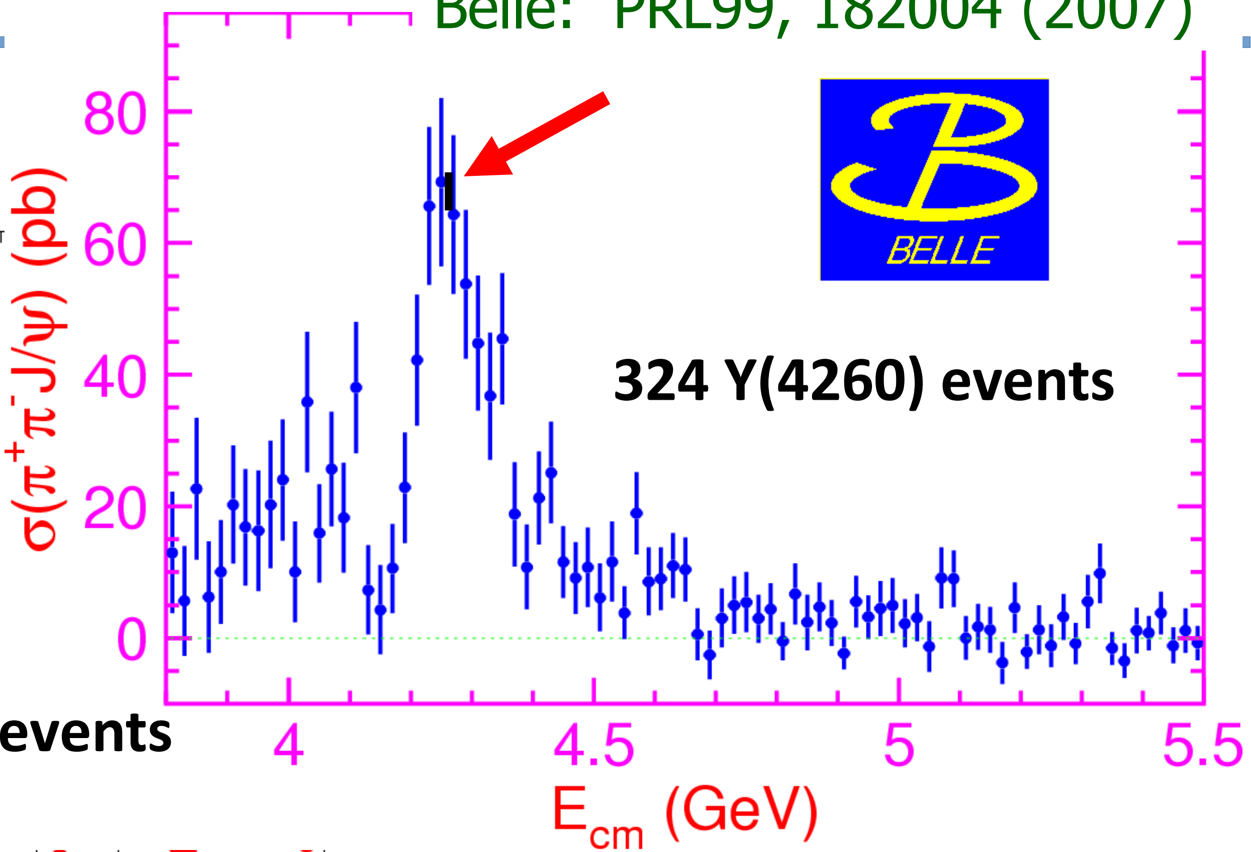
- Very high rate of charmonium transition, but not visible in inclusive spectrum
- Extra vector states

$e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$

BaBar: PRD86, 051102 (2012)



Belle: PRL99, 182004 (2007)



BESIII: arXiv:1303.5949

$\sigma(e+e- \to \pi+\pi- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb

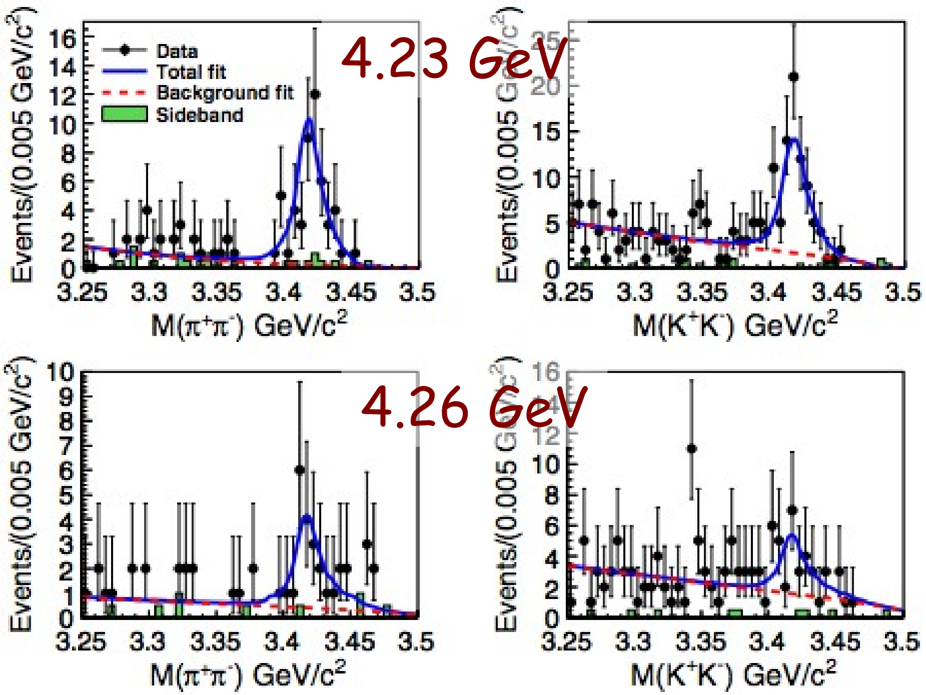
Y(4230)

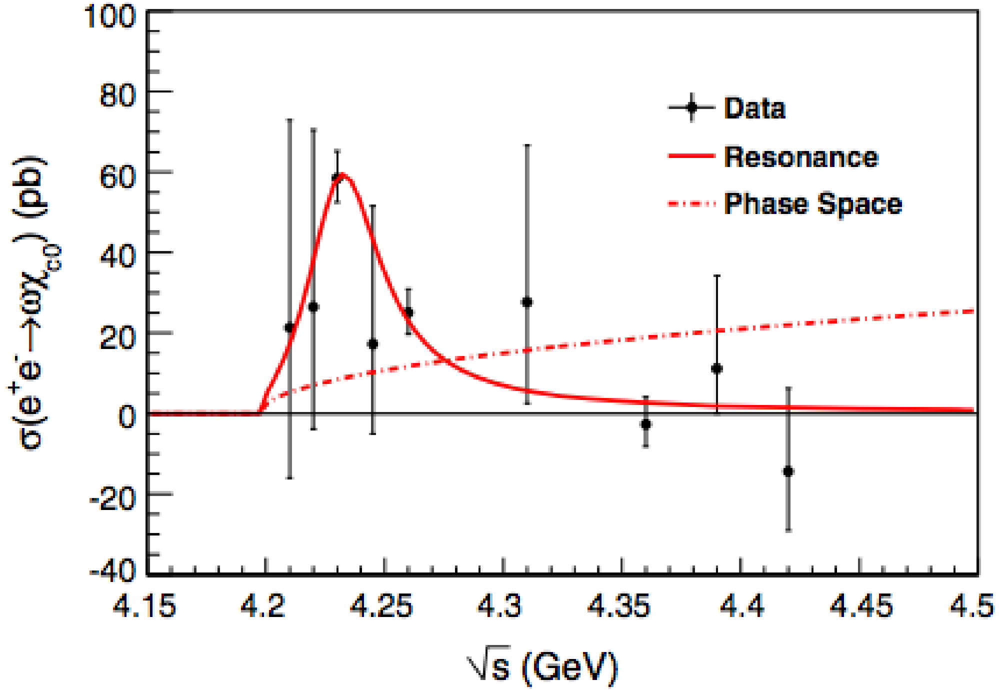
$e^+e^- \to \omega\chi_{c0}$

PRL114, 092003 (2015)

4.23 GeV

4.26 GeV



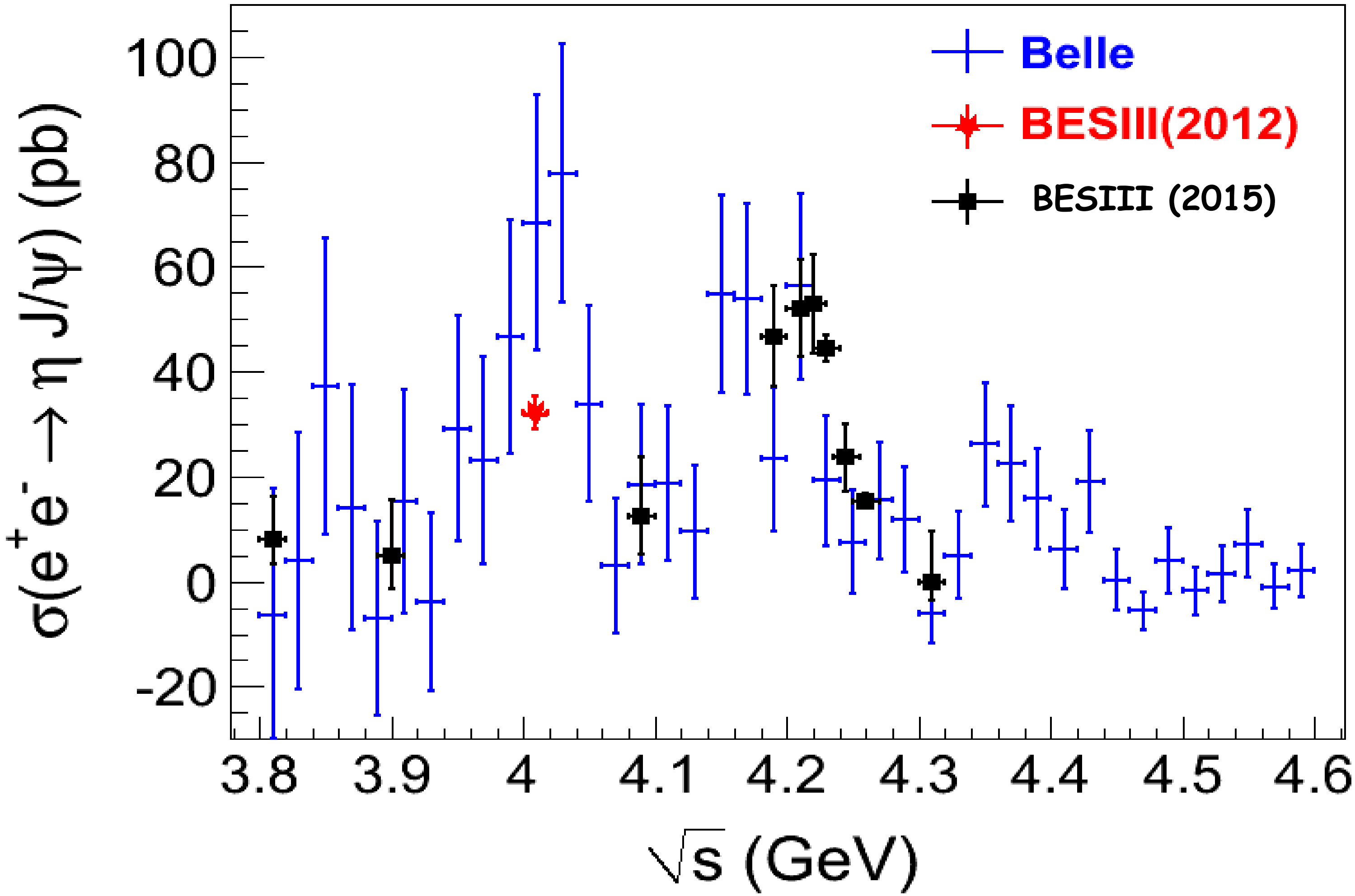


- Cross section peak near 4.23 GeV, fit with BW yields Mass=(4230±8±6) MeV, Width=(38±12±2) MeV.

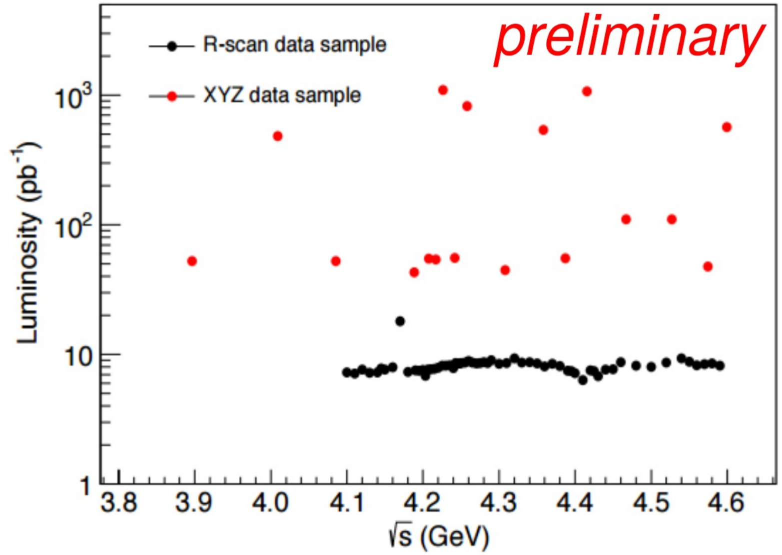
22

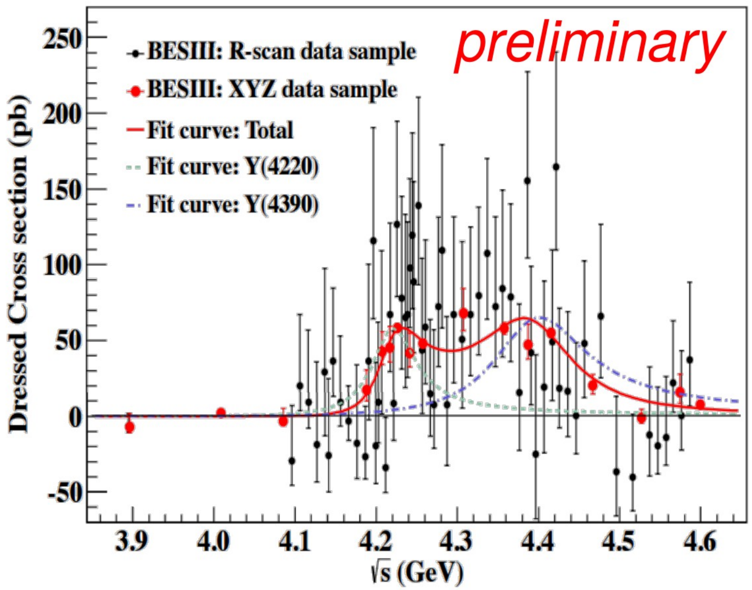
Observation of $e^+e^- \rightarrow \eta J/\psi$

Phys.Rev. D91 (2015) 11, 112005



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





- Data samples:

XYZ sample: 17 energy points from 3896 MeV to 4600 MeV

total luminosity: 5.26 fb-1

- R-scan data sample:

62 energy points from 4097 MeV to 4587 MeV

total luminosity: 0.51 fb-1

$e^+e^- \rightarrow \pi^+\pi^-h_c, h_c \rightarrow \gamma\eta_c$

$\eta_c \rightarrow X_i$, X_i signifies 16 hadronic decay modes

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

B_i (m): constant width Breit-Wigner function

P(m): 3-body phase space factor

phi: relative phase between two resonances

significance of two structures assumption over one structure > 10σ

	M (MeV)	Γ_{tot} (MeV)	Γ_{ee}•Br (eV)	ϕ (rad)
Y(4220)	4218.4±4.0±0.9	66.0±9.0±0.4	4.6±4.1±0.8	--
Y(4390)	4391.6±6.3±1.0	139.5±16.1±0.6	11.8±9.7±1.9	3.1±1.5±0.2

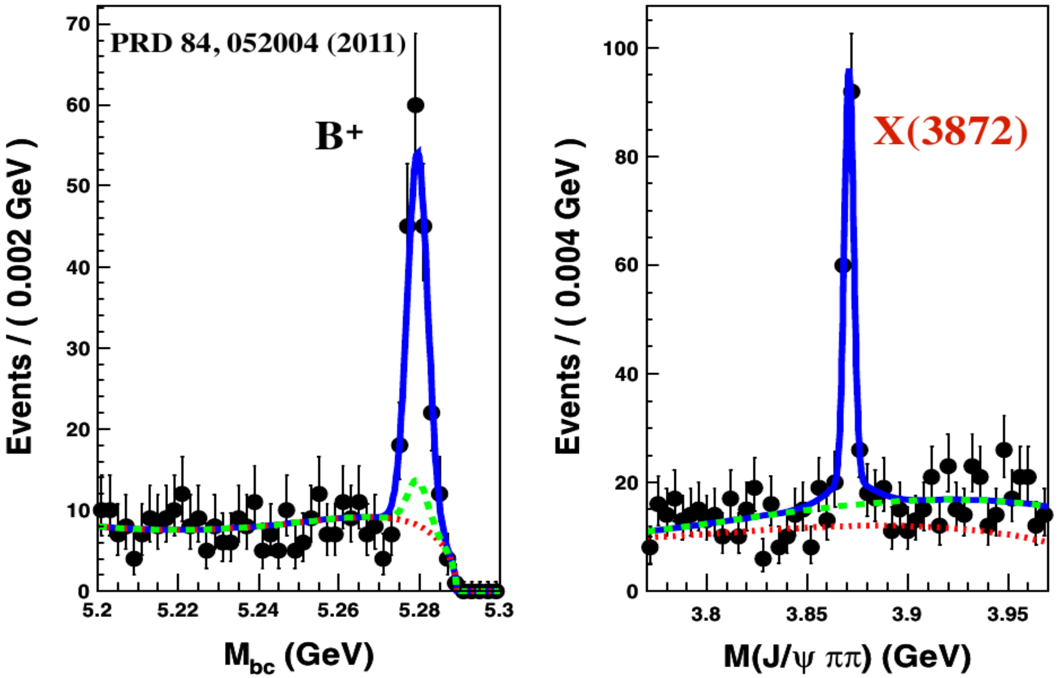
X(3872)

Observation and study of X(3872)

The oldest, the most studied and the most intriguing XYZ -state

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$
				$B \to K(\omega J/\psi)$
				$B \to K(D^{*0}\bar{D}^0)$
				$B \to K(\gamma J/\psi)$
				$B \to K(\gamma\psi(2S))$

$B^+ \to K^+(\pi^+\pi^- J/\psi)$ at Belle



|M-M(D*D)|<1 MeV

Decay rate to $\omega J/\psi$ and $\rho J/\psi$ is approximately the same

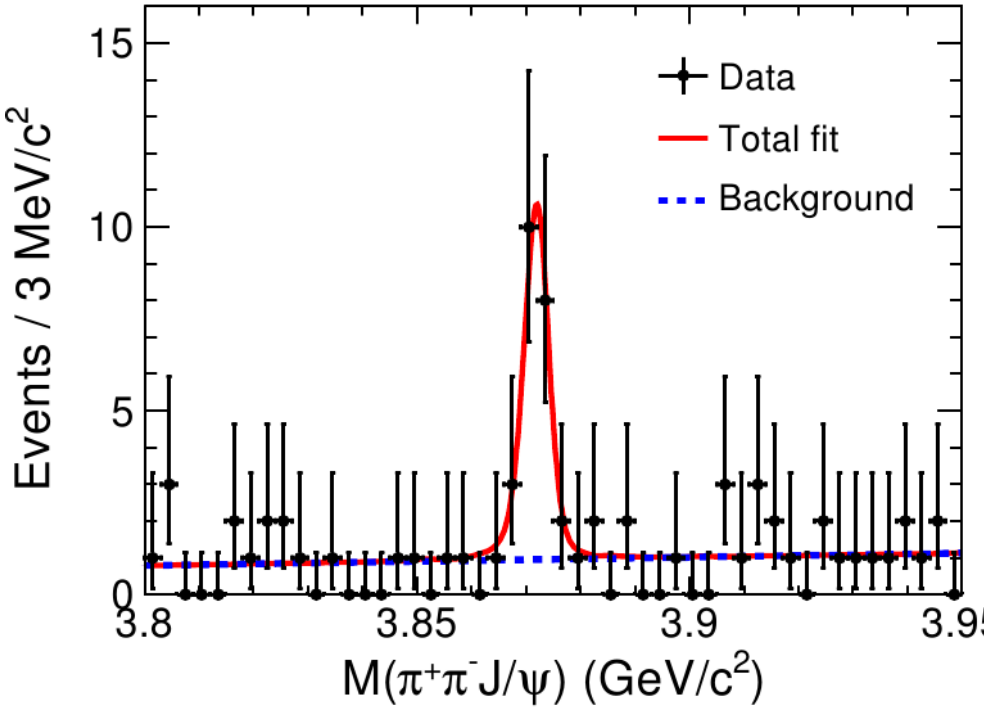
Comparable decay rate to D*D and $\gamma\psi(2S)$- Not a D^*D bound state

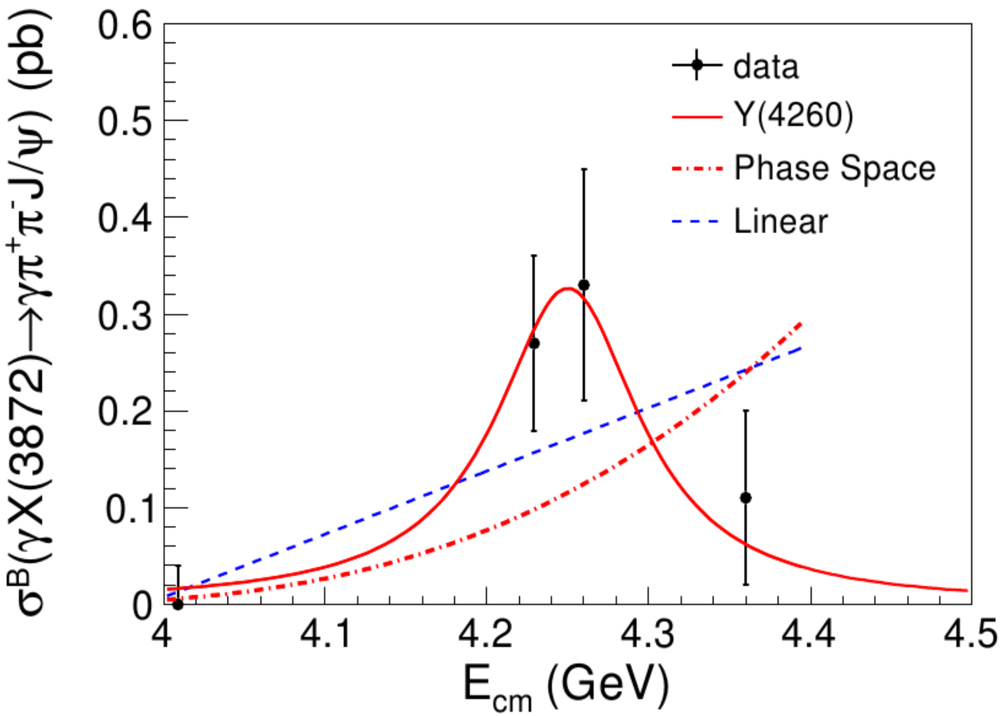
1^{++} (LHCb PRL 110, 222001 (2013))

Charged partner is not found - Not a di(quark-antiquark)

$e^+e^- \to \gamma X(3872)$

Phys. Rev. Lett. 112, 092001 (2014)



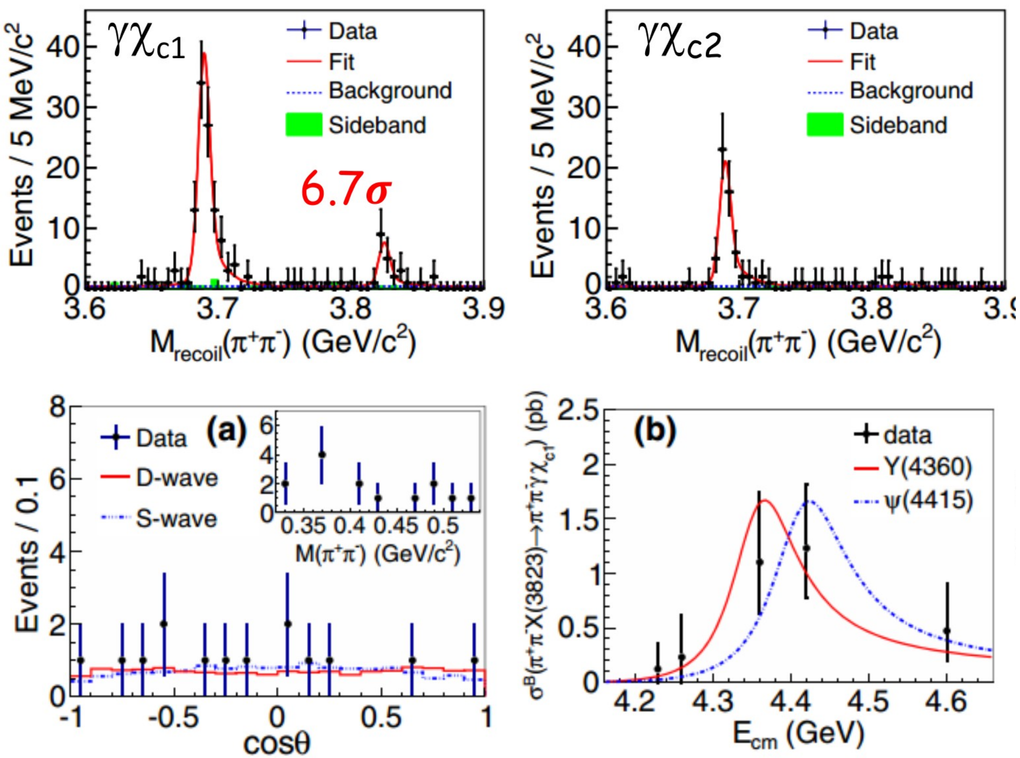


Data: 4.009 – 4.420 GeV
The first observation of $e^+e^- \to \gamma X(3872)$, stat. sign. 6.3σ.

$Y(4260) \to \gamma X(3872)$?

X(3823)

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



$\psi(1^3D_2)$?

$\psi(1^1D_2)\to\gamma\chi_{c1}$ forbidden (C-parity)

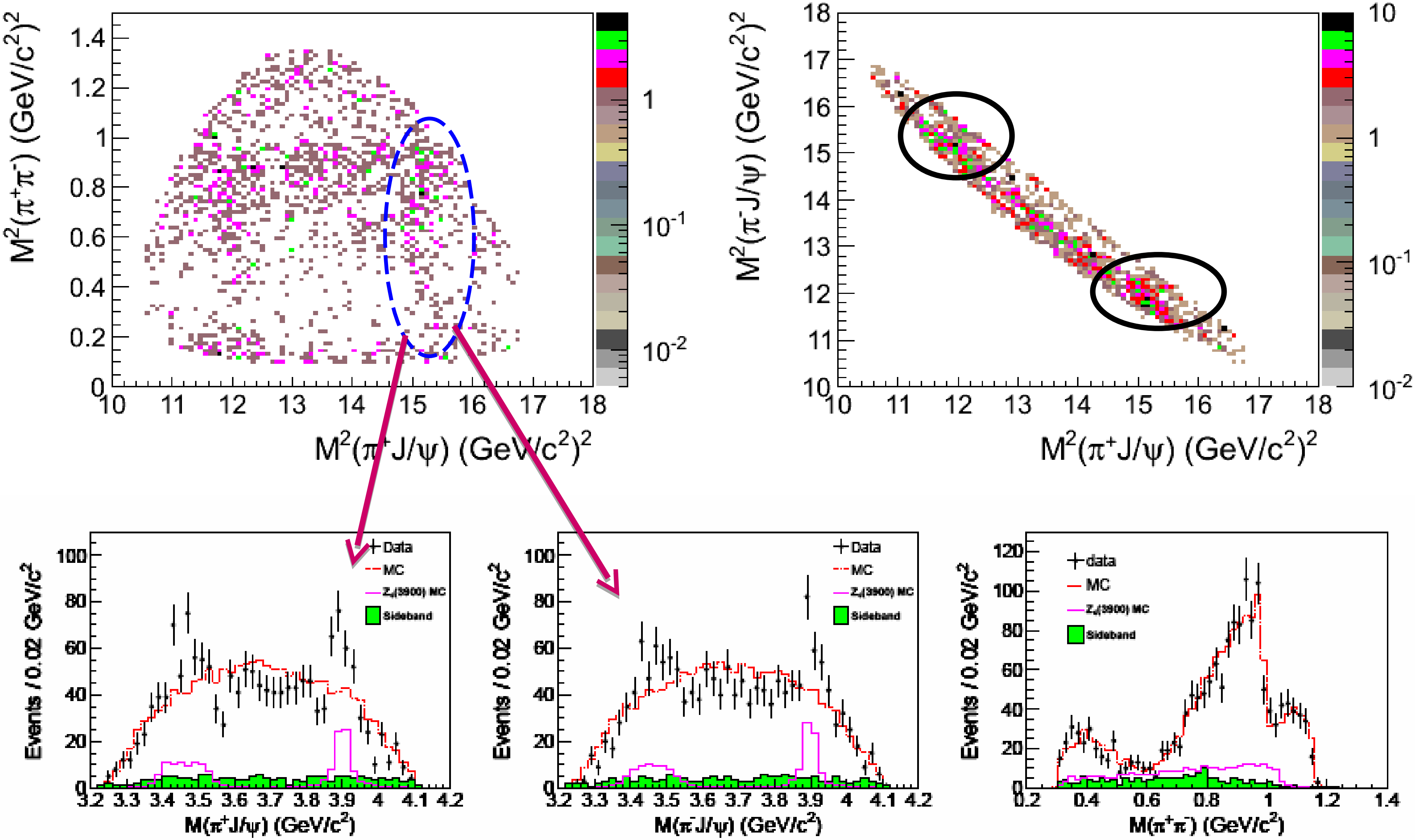
$\psi(1^3D_3)\to\gamma\chi_{c1}$ – amplitude is small

(PRD72,054026)

- M=(3821.7±1.3(stat.)±0.7(syst.))MeV/c²
- Narrow width Γ<16 MeV @ 90% C.L. **consistent with Belle's result.** (Phys.Rev.Lett. **111**, 032001 (2013))
- $R=\frac{B(X(3823)\to\gamma\chi_{c2})}{B(X(3823)\to\gamma\chi_{c1})}$<0.43 @ 90% C.L. **agree with R~0.2 prediction.**

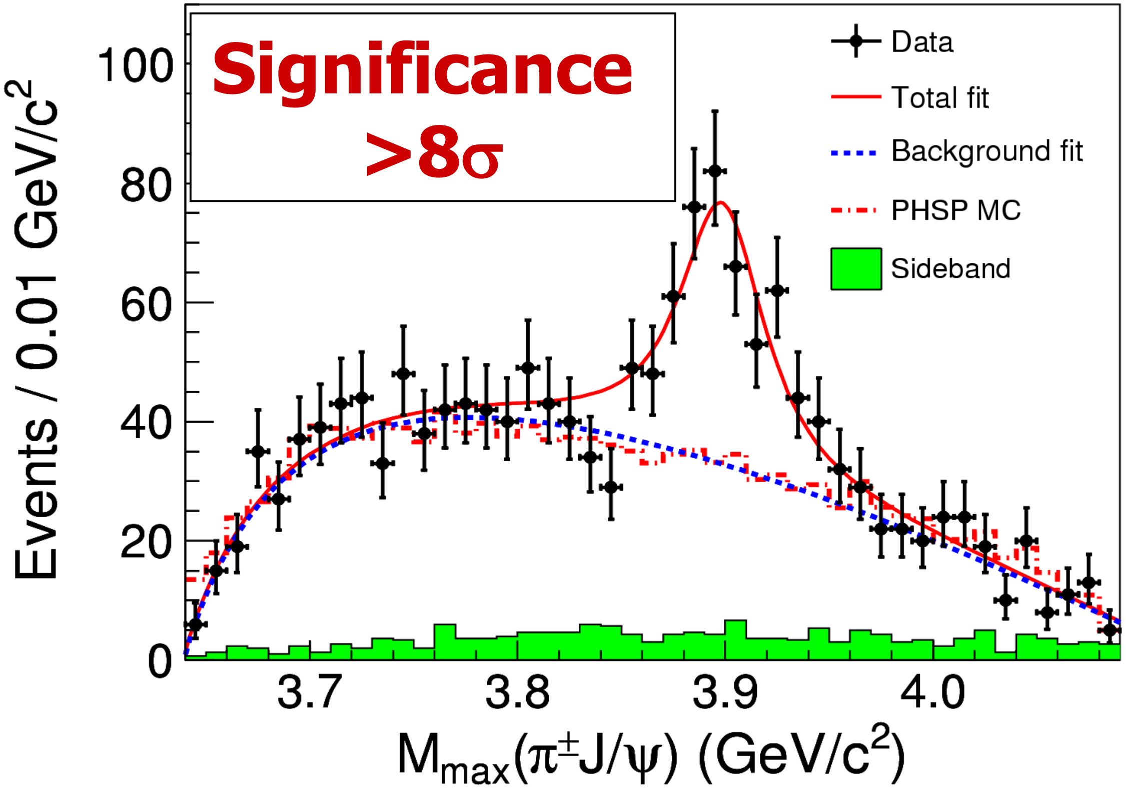
Z^+_c states

$e^+e^- \to \pi^+\pi^- J/\psi$ @ Y(4260)



The $Z_c^{\pm}(3900)$ observaton @BESII

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at $\sqrt{s}$=4260 MeV



BESIII: arXiv:1303.5949
Phys. Rev. Lett (2013) 252001

Plot maximimum of $M(\pi^+ J/\Psi)$ and $M(\pi^- J/\Psi)$ for each event. Neglect interference with background, but several test was done to ensure that bump is not reflection of $\pi^+ \pi^-$ resonance

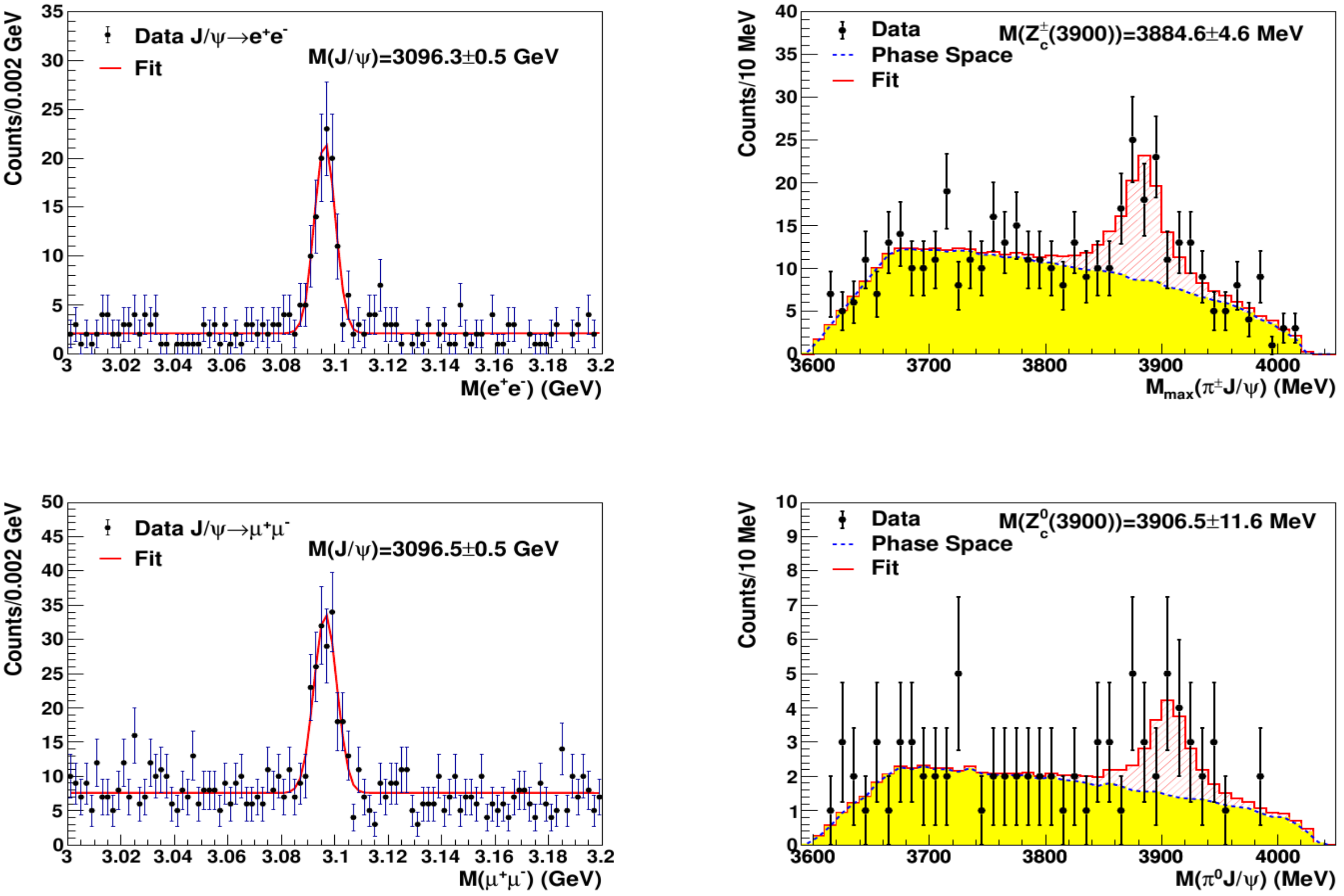
- **Mass = (3899.0±3.6±4.9) MeV**
- **Width = (46±10±20) MeV**
- **Fraction = (21.5±3.3±7.5)%**

Structure has charge and couples to charmonium. Suggestive of a state with minimal $c\bar{c}u\bar{d}$ ($c\bar{c}d\bar{u}$) quark content.

Confirmation by CLEO-c

$e^+e^- \to \psi(4160) \to \pi^+\pi^- J/\psi$

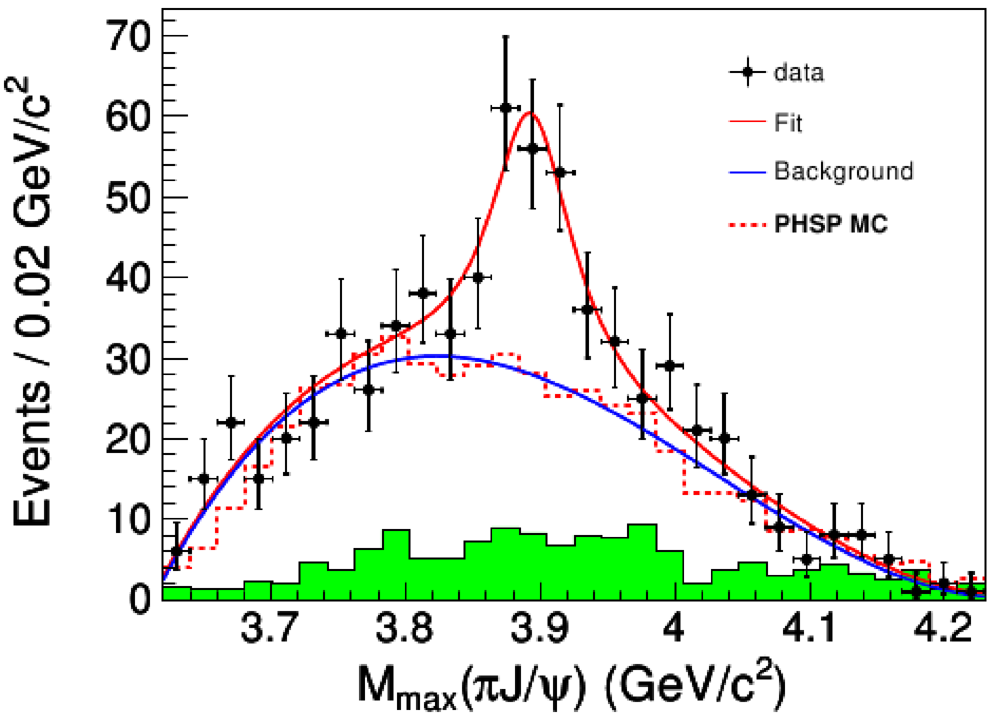
arXiv:1304.3036

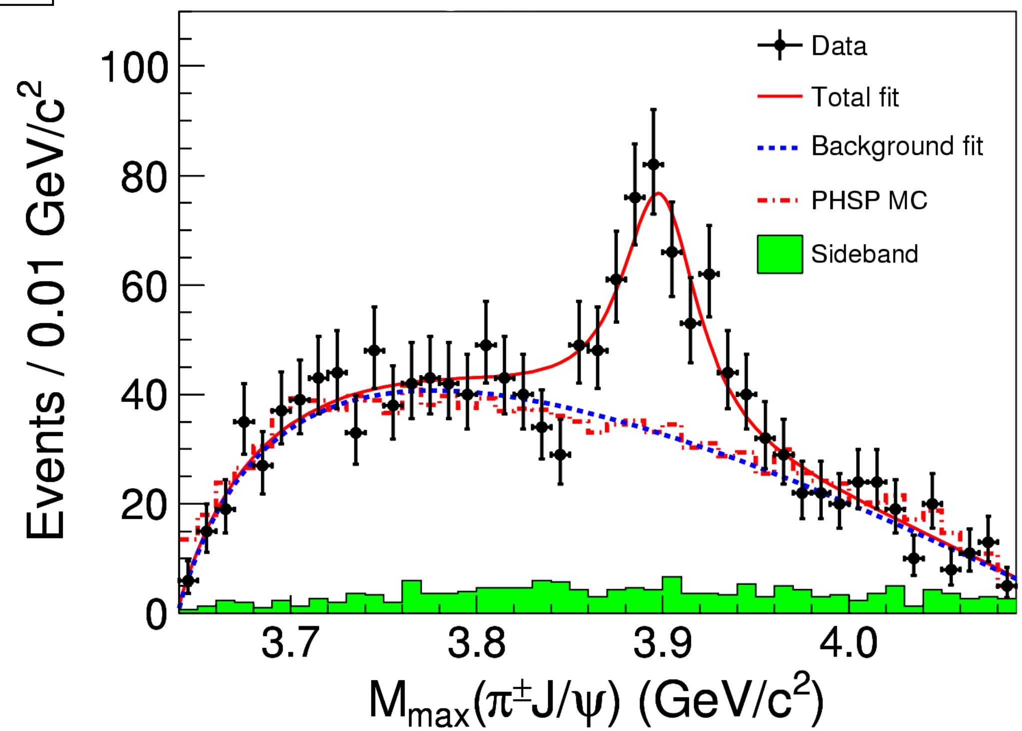


Confirmation by BELLE

$e^+e^-(\gamma) \to \pi^+\pi^- J/\psi$ around $m(\pi^+\pi^- J/\psi$ =4260 MeV

arXiv:1304.0121





M=3894±6.6±4.5MeV

Γ=63±26±26MeV

M = 3899.0±3.6±4.9 MeV

Γ = 46±10±20 MeV

$Z_c(3900)^0$

Observation of neutral $Z(3900)^0$

Phys. Rev. Lett. 115, 112003 (2015)

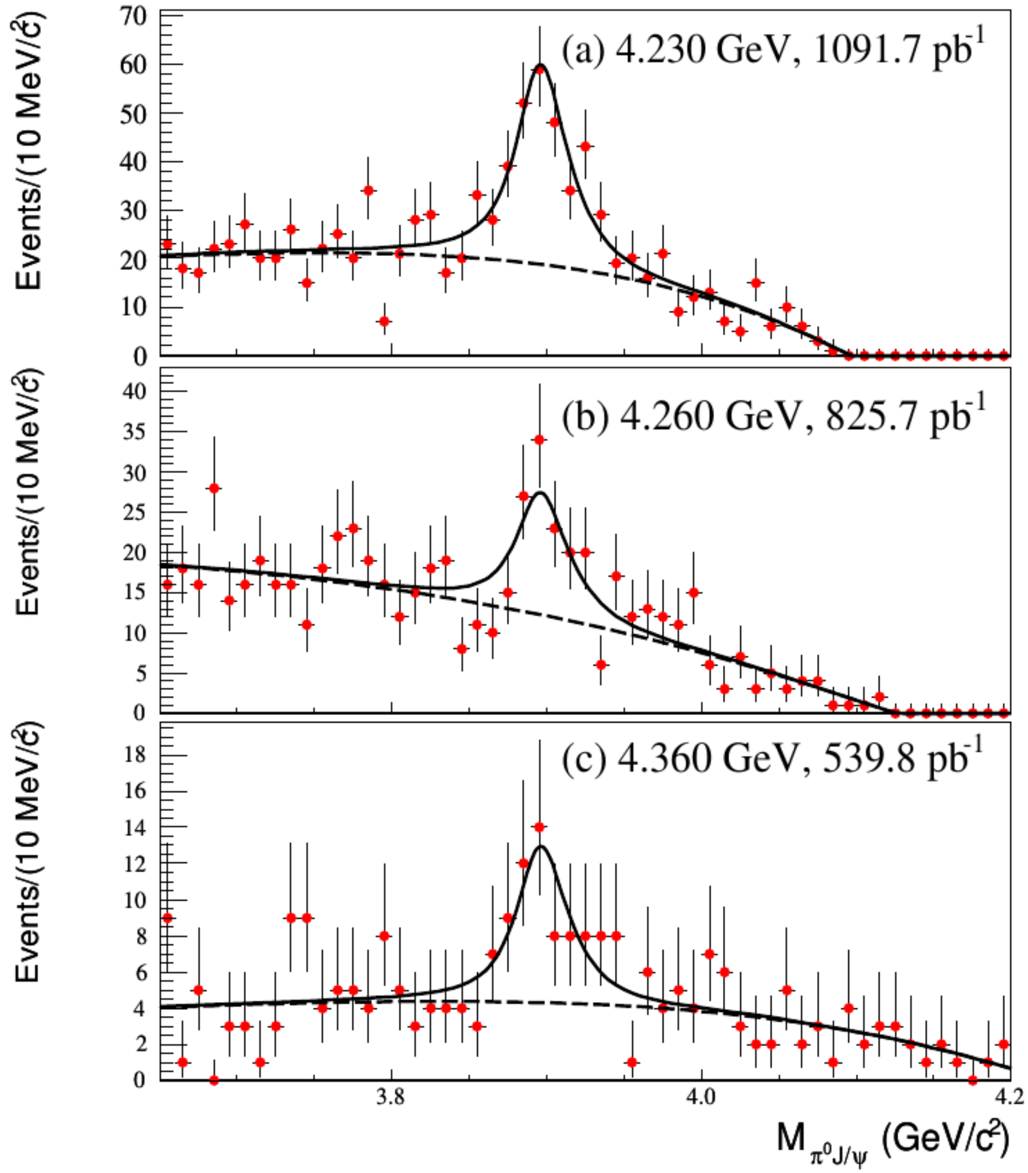
Process: e+e- → $\pi^0\pi^0 J/\psi$
@4.23 GeV (1 fb^{-1})
@4.26 GeV (0.8 fb^{-1})
@4.36 GeV (0.5fb^{-1})
+ 7 small samples 4.19 – 4.42 GeV

M = 3894.8 ± 2.3 ± 3.2 MeV/c^2
Γ = 29.6 ± 8.2 ± 8.2 MeV

Statistical significance: 10.4σ

Born cross section consistent with isosping expectation.

Interpreted as isospin partner of $Z(3900)^{\pm}$



$Z_c(3900)$ quantum numbers

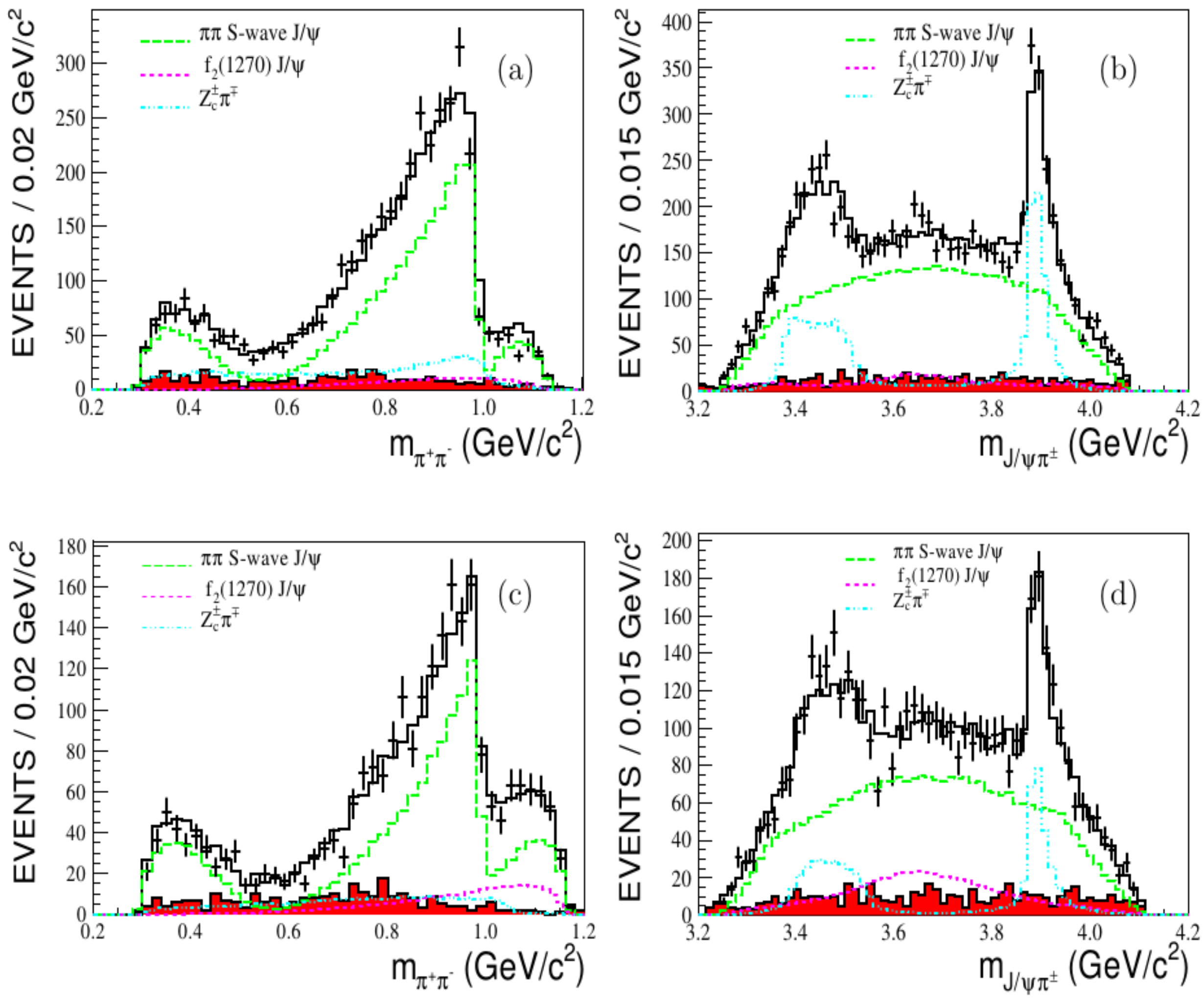
BESIII preliminary

$J^p=1^+$

Hypothesis	$\Delta(-2\ln L)$	significance
1^+ over 0^-	89.0	7.3σ
1^+ over 1^-	214.0	$> 8.0\sigma$
1^+ over 2^-	103.6	$> 8.0\sigma$
1^+ over 2^+	387.0	$> 8.0\sigma$

4.23 GeV

4.26 GeV



$Z_c(3885)^{\pm}$

Phys. Rev. Lett. 112, 022001 (2014)

$Z_c(3900)$ lies ~20 MeV above $D\bar{D}^*$ mass threshold.

Process: $e^+e^- \to (D^0D^{*-})\pi^+ + (D^+\bar{D}^{*0})\pi^-$ @4.26 (0.5 fb^{-1})

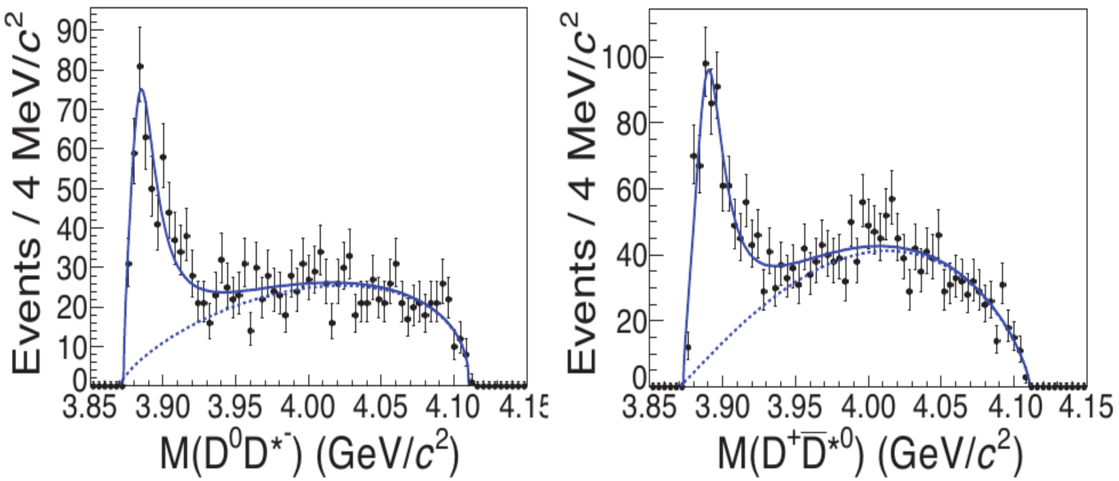
Partial reconstruction technique

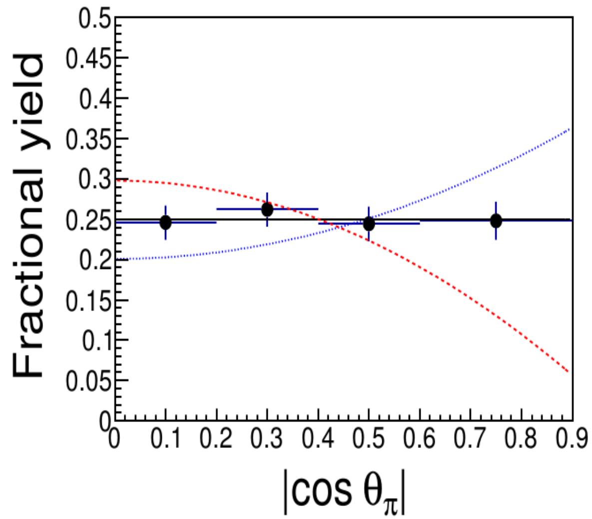
	$Z_c(3885) \to D\bar{D}^*$	$Z_c(3900) \to \pi J/\psi$
Mass (MeV/c^2)	$3883.9 \pm 1.5 \pm 4.2$	$3899 \pm 3.6 \pm 4.9$
Γ (MeV)	$24.8 \pm 3.3 \pm 11.0$	$46 \pm 10 \pm 20$
$\sigma \times \mathcal{B}$ (pb)	$83.5 \pm 6.6 \pm 22.0$	$13.5 \pm 2.1 \pm 4.8$

Assuming $Z_c(3885)$ and $Z_c(3900)$ are one state

$$\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

$$\frac{\mathcal{B}(\psi(3770) \to D\bar{D})}{\mathcal{B}(\psi(3770) \to J/\psi\pi^+\pi^-)} = 482 \pm 84$$





Black: 1^+
Red: 0^-
Blue: 1^-

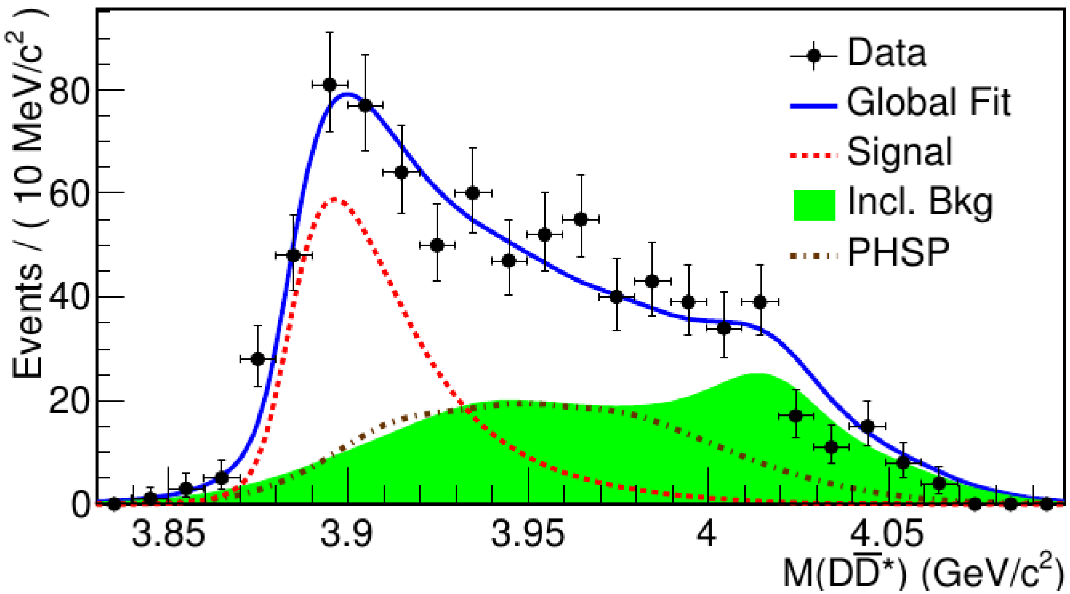
$Z_c(3885)^0$

Phys. Rev. Lett. 115, 222002 (2015)

Process: $e^+e^- \rightarrow (D^+D^{*-})^0\pi^0 + (D^0\bar{D}^{*0})^0\pi^0$
@4.23 ($1.1\ fb^{-1}$)
@4.26 ($0.8\ fb^{-1}$)

$$M = 3885.7^{+4.3}_{-5.7} \pm 8.4\ MeV/c^2$$
$$\Gamma = 47 \pm 9 \pm 10\ MeV$$

Born cross section consistent for
$e^+e^- \rightarrow Z_c\pi^0 \rightarrow (D\bar{D}^*)^0\pi^0$ + c.c.
is consistent with half of
$e^+e^- \rightarrow Z_c^+\pi^- \rightarrow (D\bar{D}^*)^+\pi^-$ + c.c.



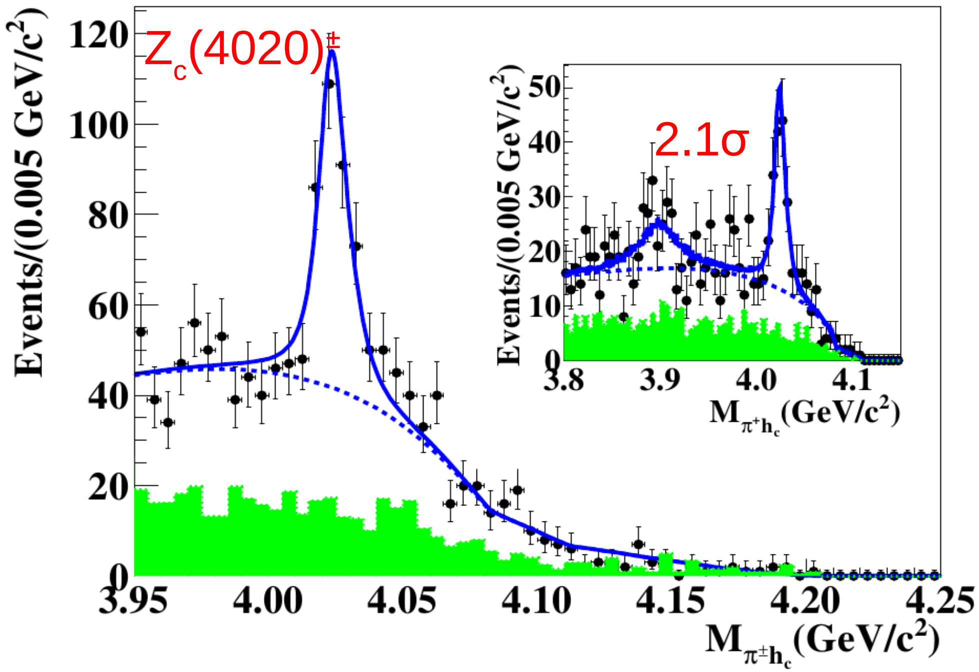
$Z_c(4020)^{\pm}$ and $Z_c(4020)^0$

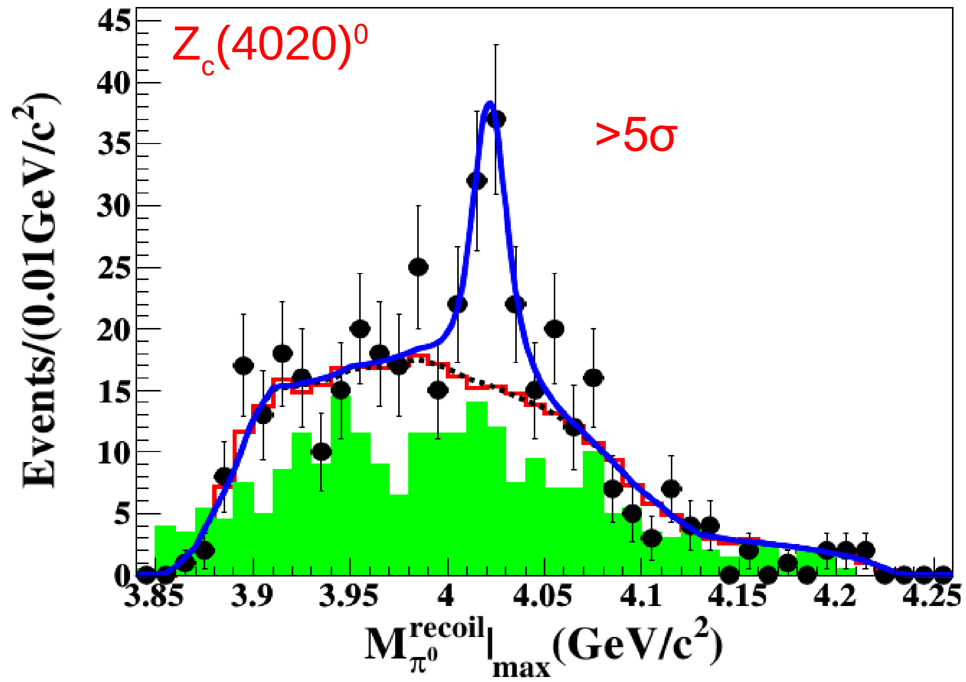
BESIII

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

h_c reconstructed through E1 transition $h_c \rightarrow \gamma\eta_c$, reconstructed from 16 exclusive hadronic modes.

$$\sqrt{s} = 4.23,\ 4.26,\ \text{and}\ 4.36\ \text{GeV}$$





Phys.Rev.Lett.111, 242001 (2013)

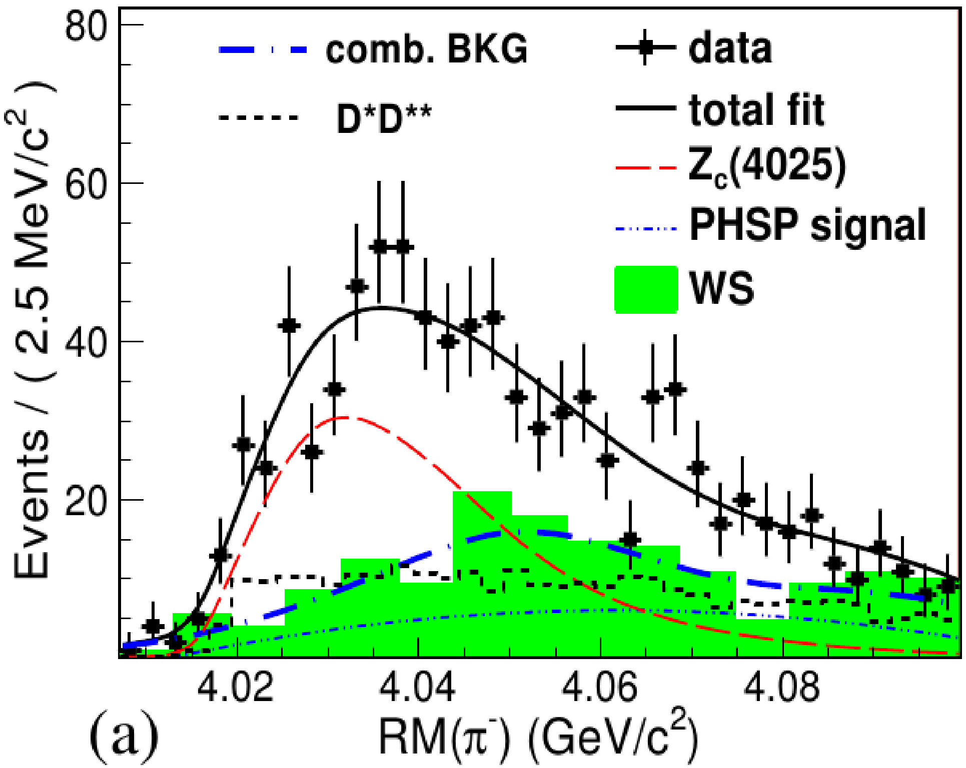
Phys.Rev.Lett.113.212002(2014)

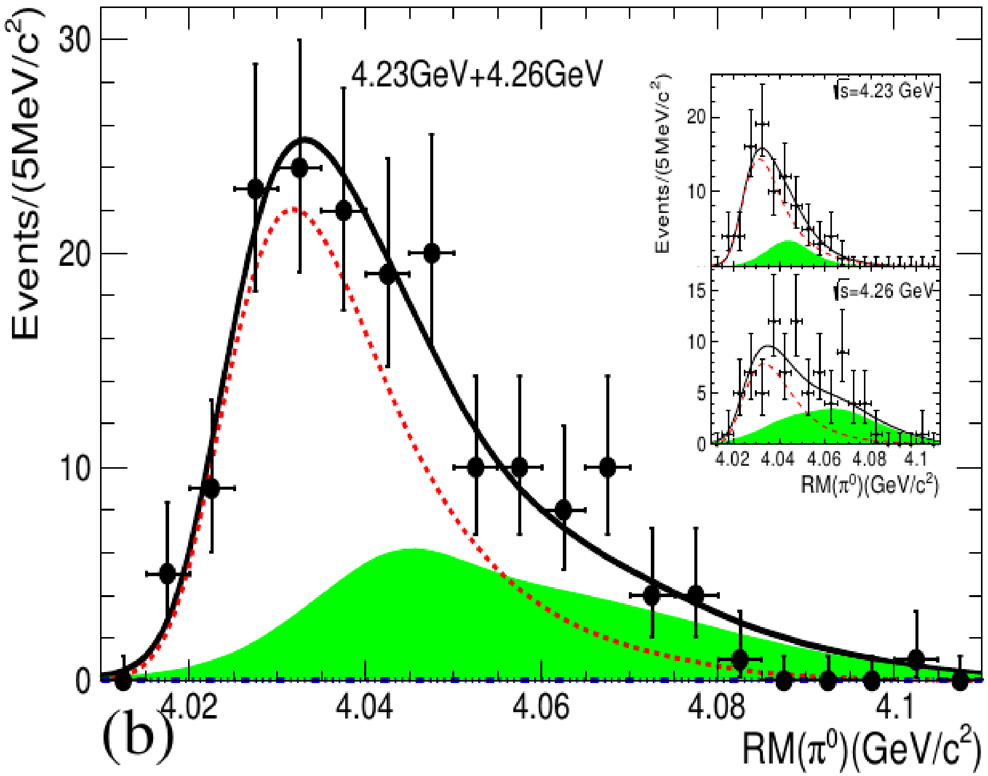
M=4022.9 ± 0.8 ± 2.7 MeV/c²
Γ = 7.9 ± 2.7 ± 2.6 MeV

M=4023.9 ± 2.2 ± 3.8 MeV/c²
Fixed Γ

Close to $D^*\bar{D}^*$ threshold

$Z_c(4025)^{\pm}$ and $Z_c(4025)^0$





Phys. Rev. Lett. 112, 132001 (2014)

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

0.8 fb^{-1} @ 4.26 GeV

Partial reconstruction technique

M = 4026.3 ± 2.6 ± 3.7 MeV/c^2

Γ = 24.8 ± 5.6 ± 7.7 MeV

Phys. Rev. Lett. 115, 182002 (2015)

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

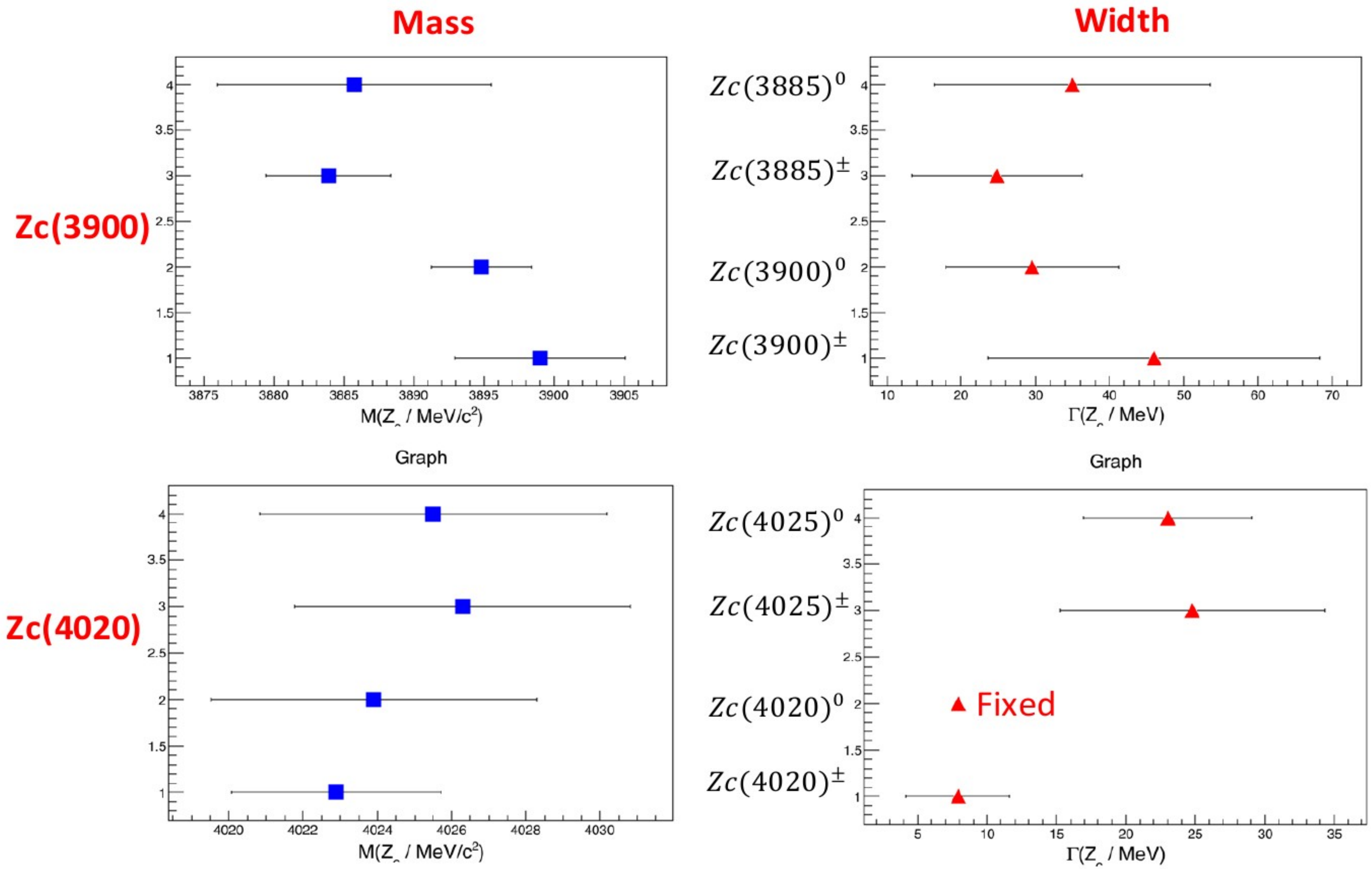
1.1 fb^{-1} @ 4.23 and 0.8 fb^{-1} @ 4.26 GeV

Partial reconstruction technique

M = $(4025.5^{+2.0}_{-4.7} \pm 3.1)\ \mathrm{MeV}/c^2$

Γ = $(23.0 \pm 6.0 \pm 1.0)\ \mathrm{MeV}$

Summary on Z_c



Interpretation

Theoretical Ideas on Y(4260), Y(4360)

DD* bound states ($Y(4360) = D_sD_s^*$)

(NPA815, 53 (2009))

$J/\psi f_0$ bound state (with $KK \to \pi\pi$)

(PRD80, 094012 (2009))

Tetraquarks (or two diquarks)

(PRD72, 031502(R) (2005))

Hadrocharmonium

(PLB666, 344 (2008))

Hybrid Charmonium

(PLB628, 215 (2005), PRD78, 094504 (2008))

Theoretical ideas on Zc(3900), Zc(4020)

Tetraquark state

(Phys. Rev. D87,125018(2013); Phys. Rev. D88, 074506(2013), Phys. Rev. D89,054019(2014); Phys. Rev. D90,054009(2014))

$D^{(*)}$□$D^{(*)}$ molecule state

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

FSI? Kinematical effect?

Open questions and immediate goals

- Are X(3872) and Zc coming from resonance decay or continuum production?
- Can X(3915), X(4140), X(4350), X (3940) be produced in the same way?
- Is the Y(4260) a single resonance? What is the structure of lineshape of $e^+e^- \rightarrow \pi^+\pi^- h_c$?
- Are Y(4660) and Y(4630) identical? Is Y(4008) a real resonance?
- Is there a Zcs state?
- ….

Summary

- A number of new unpredicted quarkoniumlike particles have been discovered during last decade by B-factories, BES-III and LHCb.
- Charged charmoniumlike particles observed by BES-III provided a strong evidence that unconventional hadrons do exist.
- The properties of these particles doesn't contradict QCD, however interpretation of their composition and properties is not yet established.
- It’s time to move from the search of exotic states to the detailed study of their features.

Further reading

- H.X. Chen, W. Chen, X. Liu, S.L. Zhu,

  The hidden-charm pentaquark and tetraquark states // arXiv:1601.02092
- C.Z.Yuan, Study of the XYZ states at the BESIII // Frontiers of Physics vol. 10 issue 6, 101401 (2015)