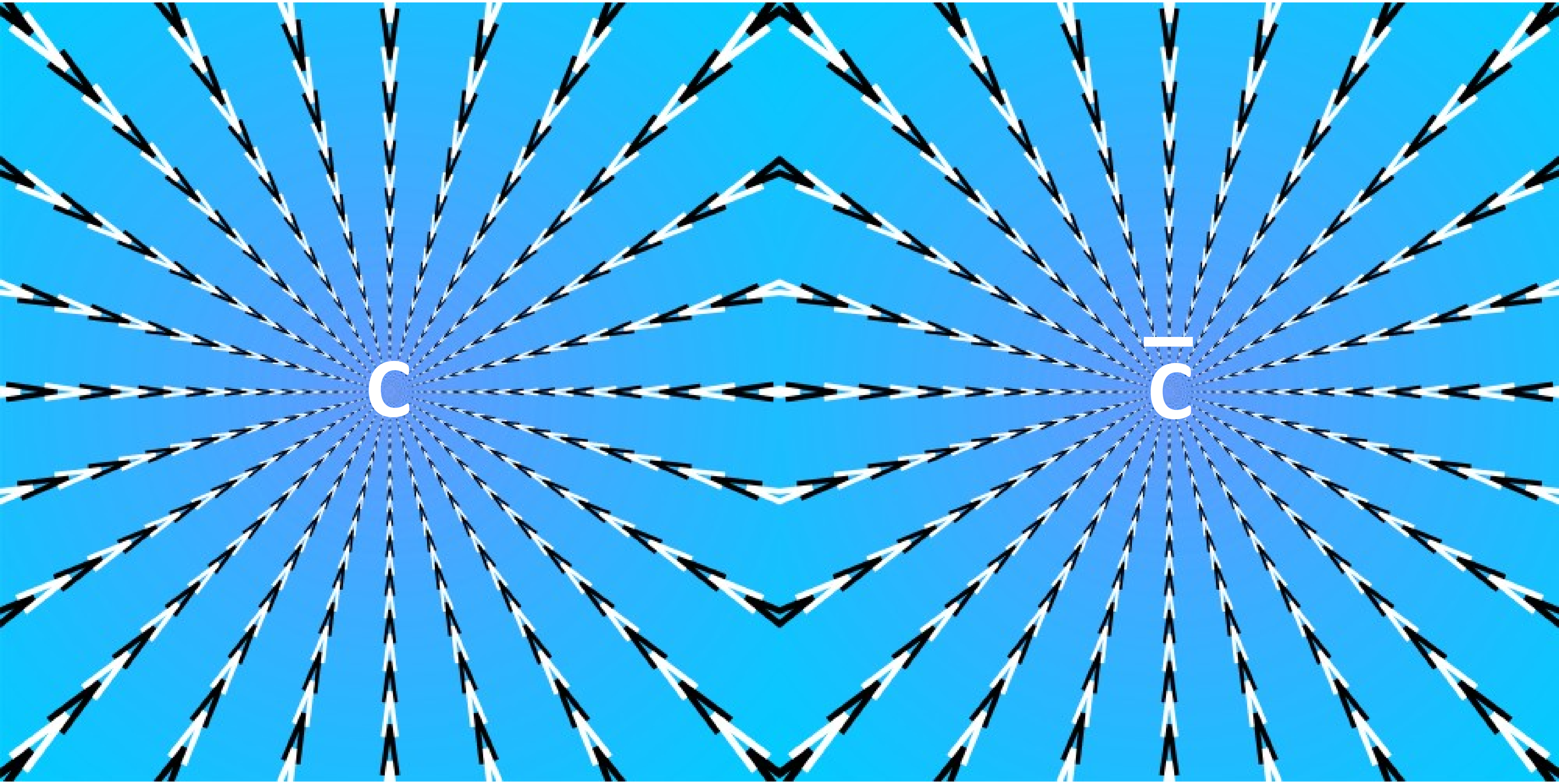
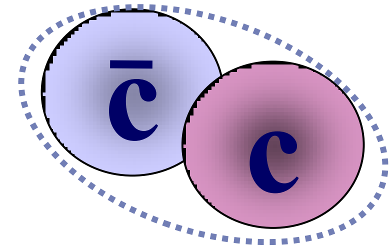
GALINA PAKHLOVA,
LPI RAS, MEPHI, MIPT

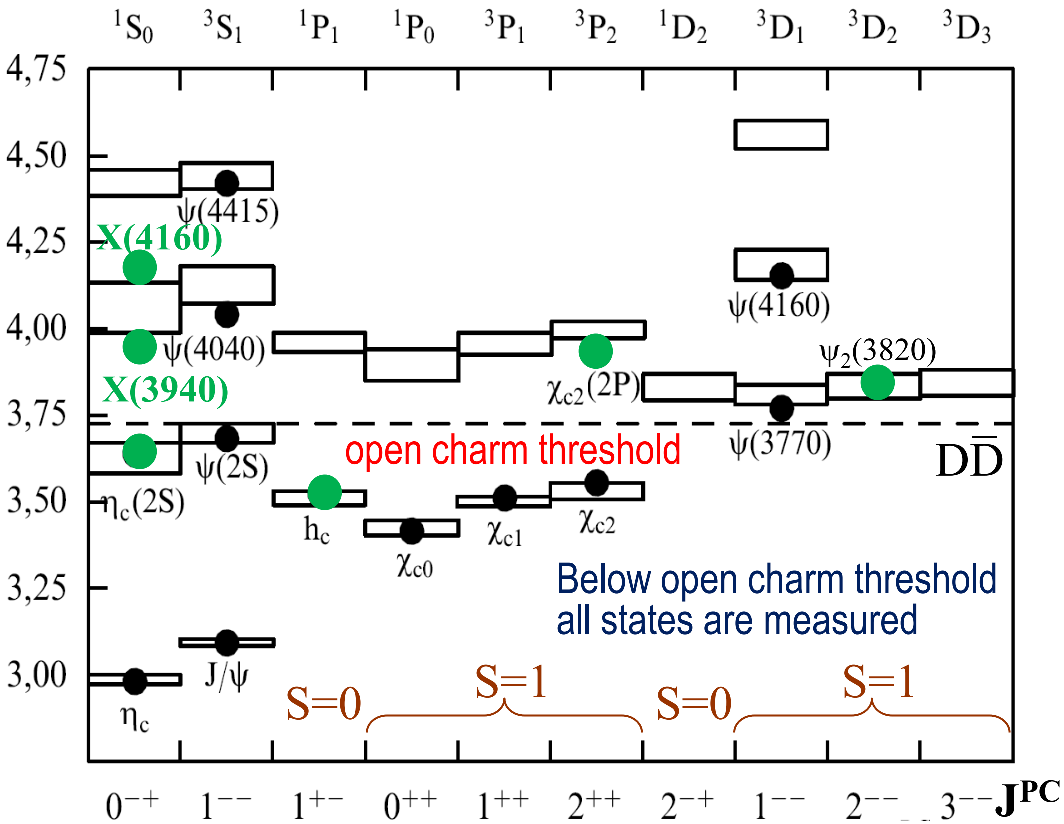



# CHARMONIUM: PRESENT AND FUTURE

ICPPA, October, 10, 2016, Moscow

# Charmonium in standard quark model




$$(n+1)^{(2S+1)}L_J$$

- n radial quantum number
- S total spin of quark-antiquark
- L relative orbital ang. mom.
  - L = 0, 1, 2 ... corresponds to S, P, D...
- J = S + L
- $P = (-1)^{L+1}$ parity
- $C = (-1)^{L+S}$ charge conj.

**1974 -1980** Discovery of **10 standard charmonium states**

**1980-2002** … nothing

**2002-2013** Discovery of **6 standard charmonium states**

# Charm factories

**BESIII**
**Symmetric $e^+e^-$ collider**
$e^+e^- \to J/\psi$, $\psi(2S)$, $\psi(3770)$, etc
scan 2.0 - 4.6 GeV
$L \sim 10^{33}/cm^2/s$

# LHC

**pp collider**

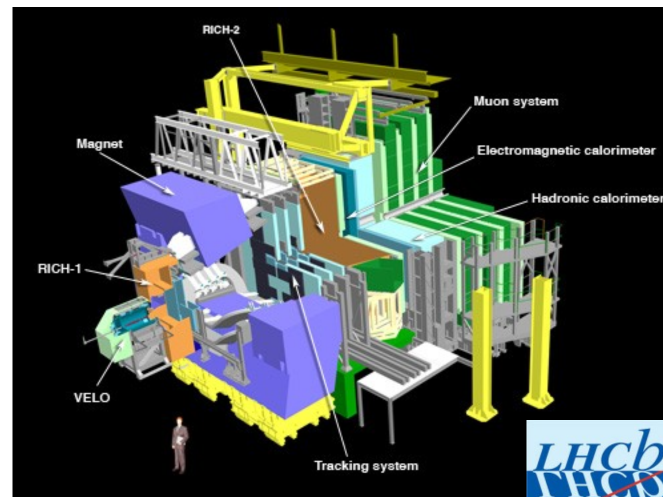
E ~ 7 TeV: $L \sim 5 fb^{-1}$ per experiment
E ~ 8 TeV: $L \sim 20 fb^{-1}$ per experiment

**LHCb** E ~ 7-8 TeV: $L \sim 3\ fb^{-1}$

# Tevatron

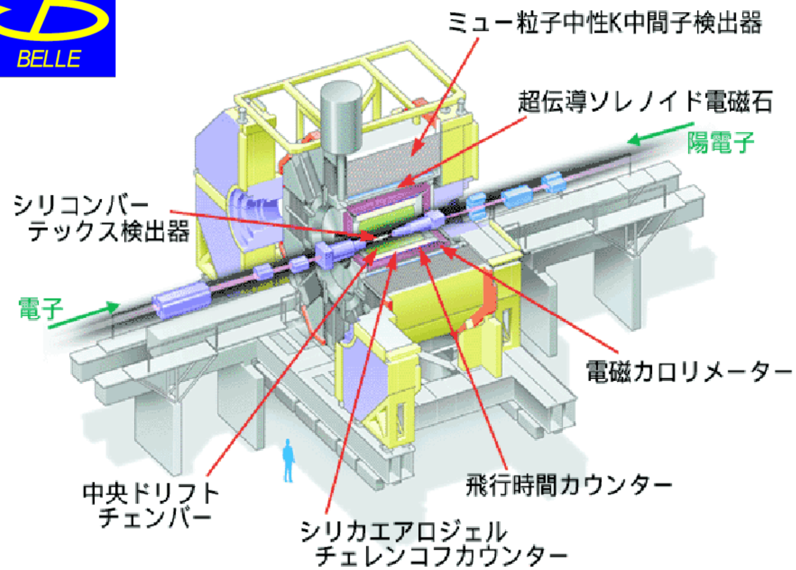
**pp collider**
E ~ 1.8 TeV: $L \sim 4 fb^{-1}$ per experiment

Charmonium
Prompt production
B meson decays




Charmonium
Prompt production
Beauty hadrons decays

# B factories

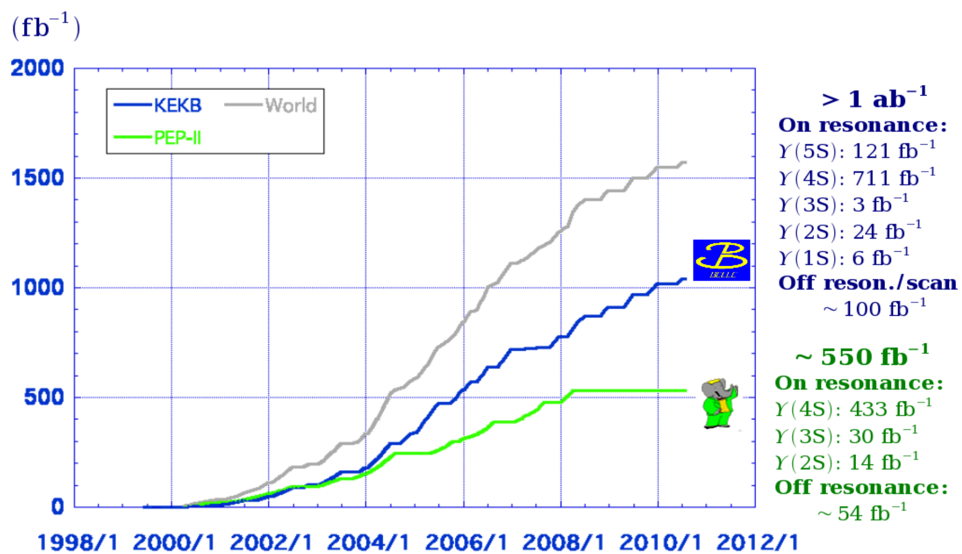


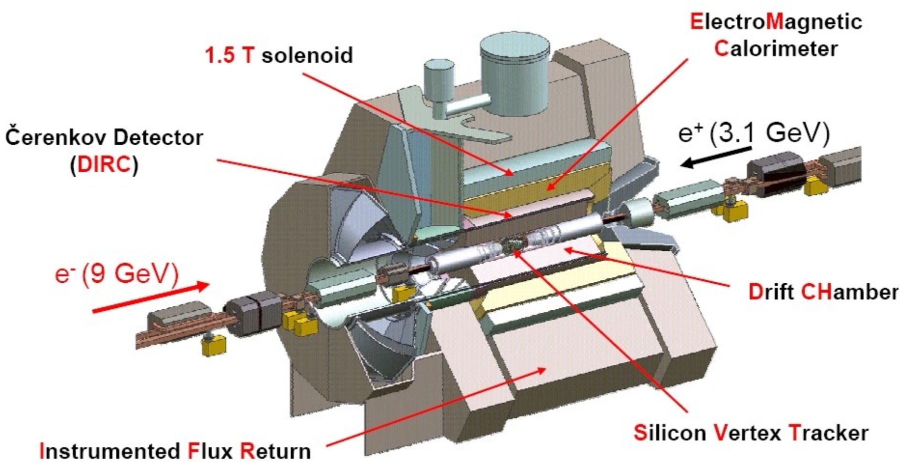

**Belle**: 8 GeV ($e^-$) × 3.5 GeV ($e^+$)

designed luminosity: $10.0\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

achieved $21.2\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (>2 times larger!)

## Luminosity at B factories

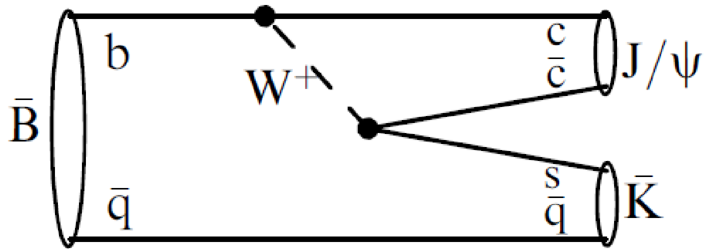



Belle completed data taking in 2010
to start SuperKEKB/Belle II upgrade

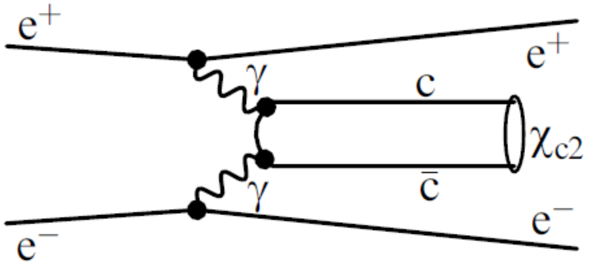
# Charmonium (+like) production at B factories

## B decays



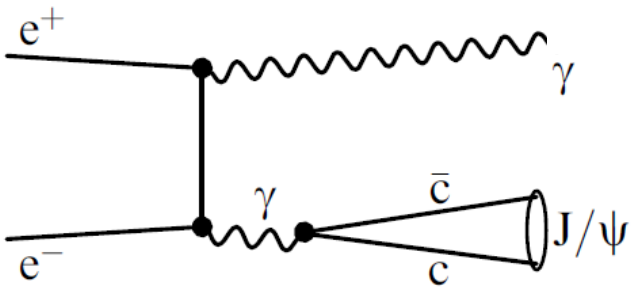

Any quantum numbers are possible, can be measured in angular analysis (Dalitz plot)

## γγ fusion



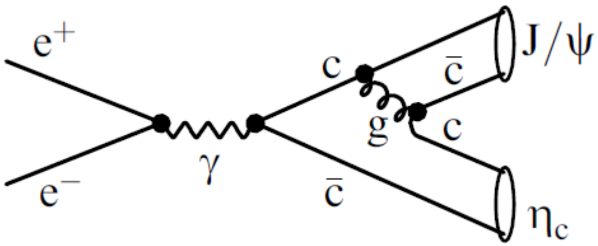

$J^{PC} = 0^{\pm+}, 2^{\pm+}$

## e+e− annihilation with ISR




$J^{PC} = 1^{--}$

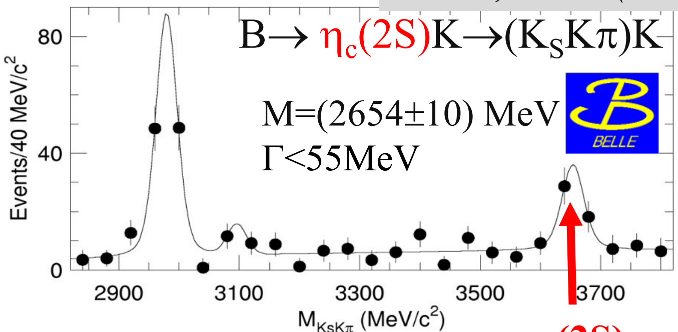
## double charmonium production



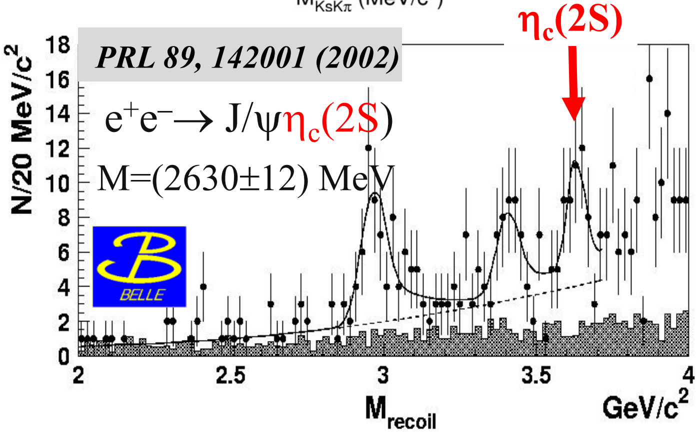

in association with J/ψ only $J^{PC} = 0^{\pm+}$ seen

# Observation of $\eta_c(2S)$ and $h_c$

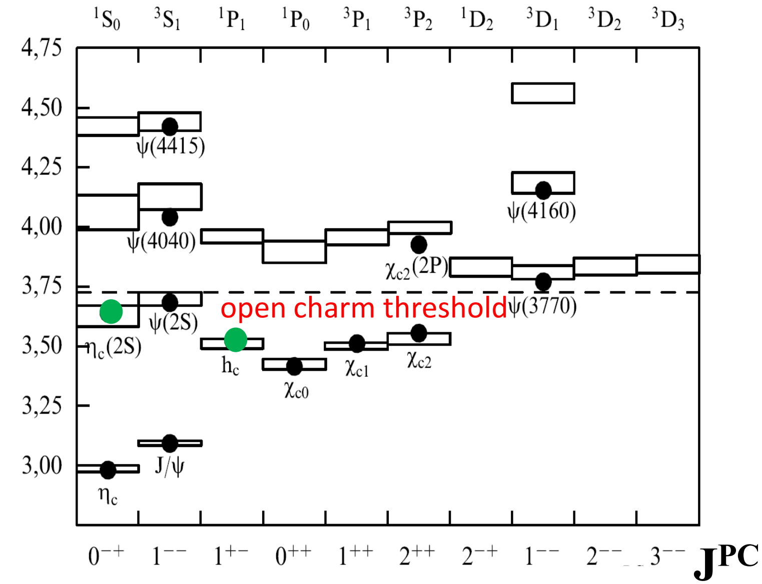
*PRL 89, 102001 (2002)*




*PRL 89, 142001 (2002)*



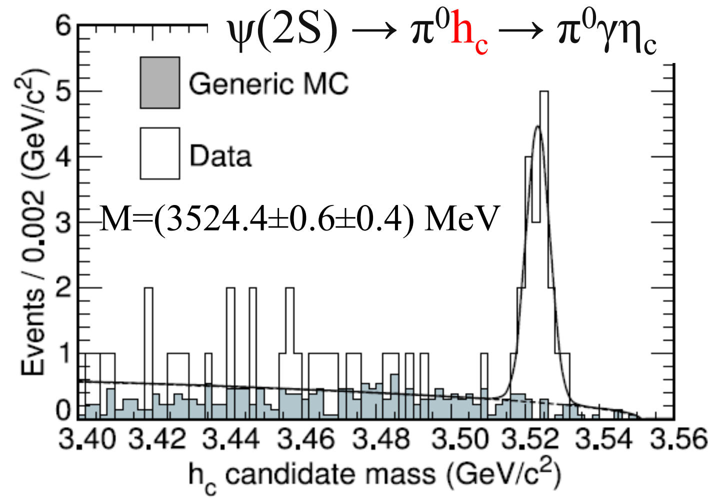

- $\eta_c(2S)$ confirmed by CLEO, BaBar&Belle in $\gamma\gamma$
- $h_c$ first observed by CLEO




*$\eta_c(2S)$ and $h_c$: mass, total width, decays modes, $\gamma\gamma$-width are in good agreement with the potential model expectations*

***Charmonium table below DD threshold is completed!***

*PRL 95, 102003 (2005)*

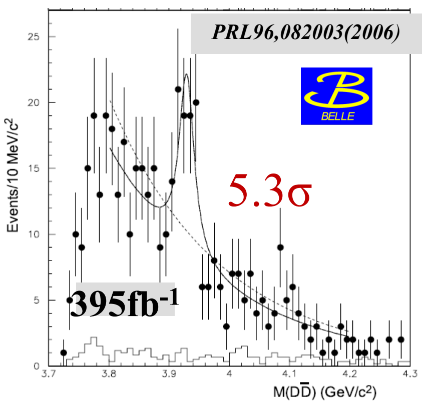


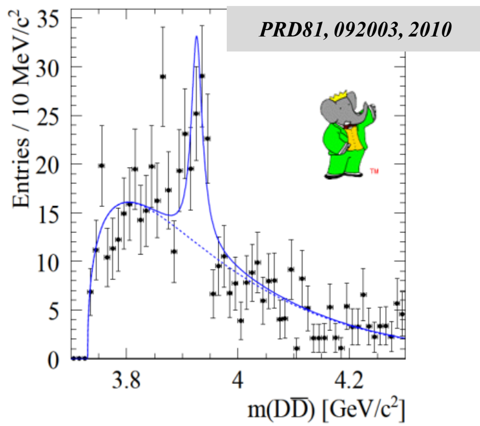

**Future**

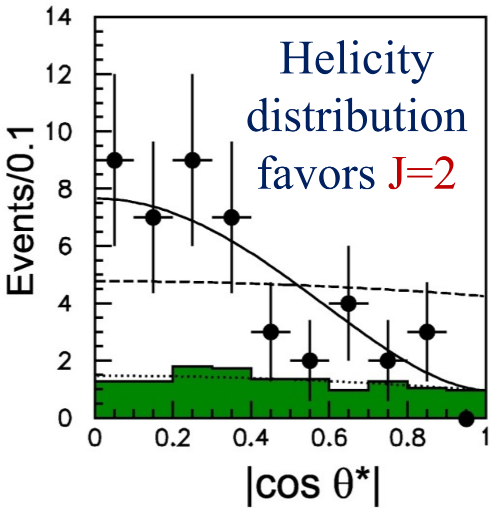
**$\eta_c$ :** new decay modes, absolute BR measurements, improve mass, total width and $\Gamma_{\gamma\gamma}$

**$h_c$ :** search in three body B decays: $B \to h_c K\pi$…

# $\gamma\gamma \rightarrow Z(3940) = \chi_{c2}(2P)$

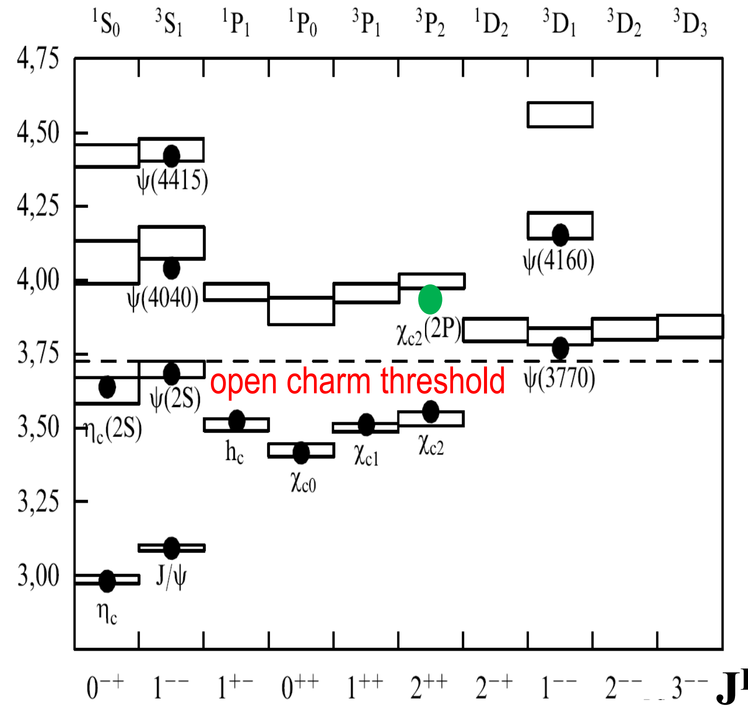



Decay mode, helicity distribution, $\Gamma_{\gamma\gamma}$ width prove out:

$Z(3940) = \chi_{c2}(2P) = 2^3P_2$



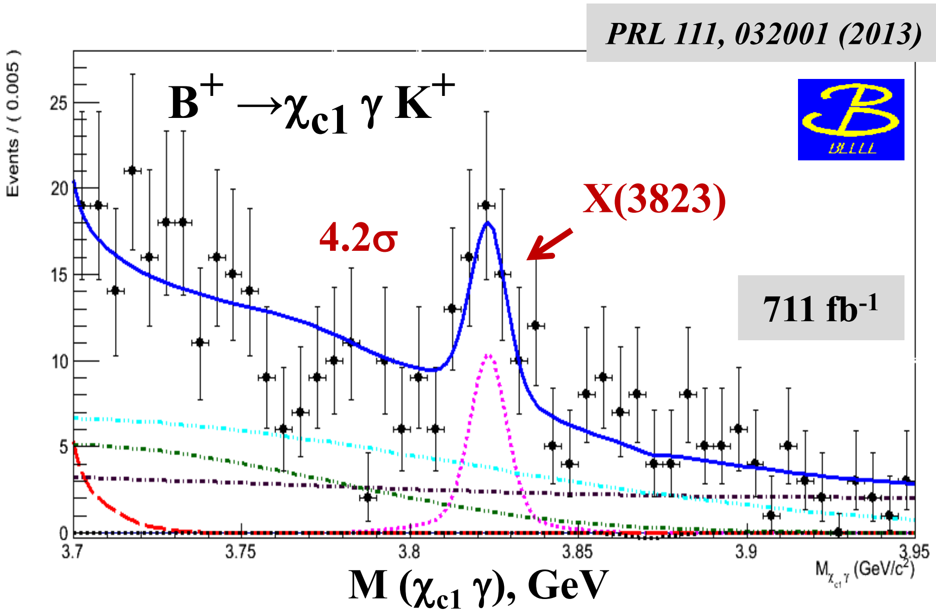

*Mass is ~50-100 MэВ/c² lighter than expected*

**Future**

Improve parameters, search in multi-body B decays

| Exp. | Process | Luminosity $(\mathrm{fb}^{-1})$ | Mass $(\mathrm{MeV}/c^2)$ | Width $(\mathrm{MeV})$ | Spin $J^{PC}$ | $\Gamma_{\gamma\gamma}(\chi_{c2}(2P))\times \mathcal{B}(\chi_{c2}(2P)\to D\bar{D})$ $(\mathrm{keV})$ |
|---|---|---|---|---|---|---|
| Belle | $\gamma\gamma\to D\bar{D}$ | 395 | $3929\pm5\pm2$ | $29\pm10\pm2$ | $2^{++}$ | $0.18\pm0.05\pm0.03$ |
| BaBar | $\gamma\gamma\to D\bar{D}$ | 384 | $3926.7\pm2.7\pm1.1$ | $21.3\pm6.8\pm3.6$ | $2^{++}$ | $0.24\pm0.05\pm0.04$ |

# $X(3823) = \psi(1^3D_2)$




Confirmed by BESIII, 6.2σ
*PRL115,011803(2015)*

$M = 3823.5 \pm 2.8$ MeV
$\Gamma = 4 \pm 6$ MeV, $< 14$ MeV @90%CL

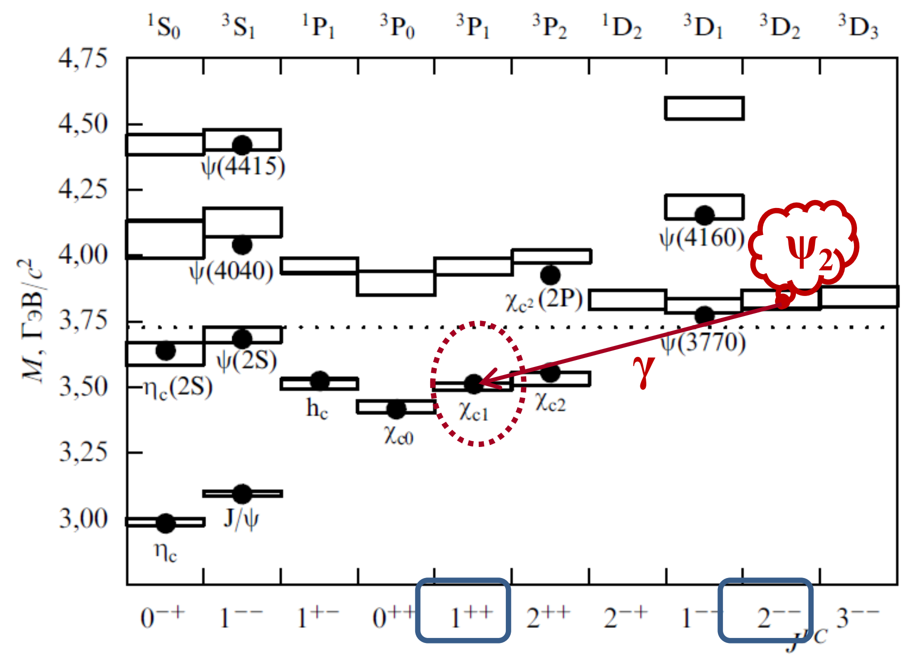
$X(3823) \to \chi_{c1}\gamma \implies C = -$

| $1^{--}$ | $1^{+-}$ | $2^{--}$ | $3^{--}$ |
|---|---|---|---|
| Ψ(3770) | $h_c(2P)$ | $\psi_2$ | $\psi_3 \to DD$ |

decay to DD is forbidden due to unnatural spin-parity → small Γ

decay to $\chi_{c1}\gamma$ should be prominent (E1)

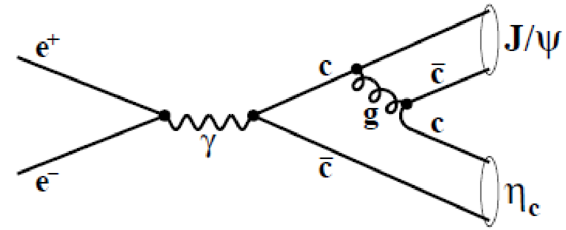
$\Gamma(\chi_{c1}\gamma) \sim O(10 KeV)$ is typical for charmonium




## Future

- Critical prove at Belle II
- To measure X(3823) decays to $J/\psi\pi^+\pi^-$ and $\chi_{c2}\gamma$ final states and to compare with theoretical predictions for $\psi(1^3D_2)$

# X(3940) & X(4160) in $e^+e^- \to J/\psi\, D^*D^{(*)}$

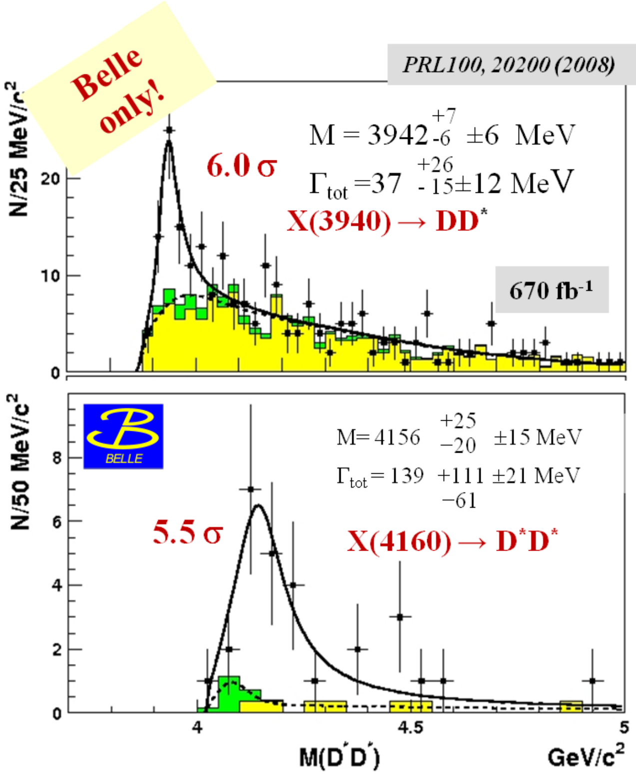



$J^{PC}=0^{-+}$

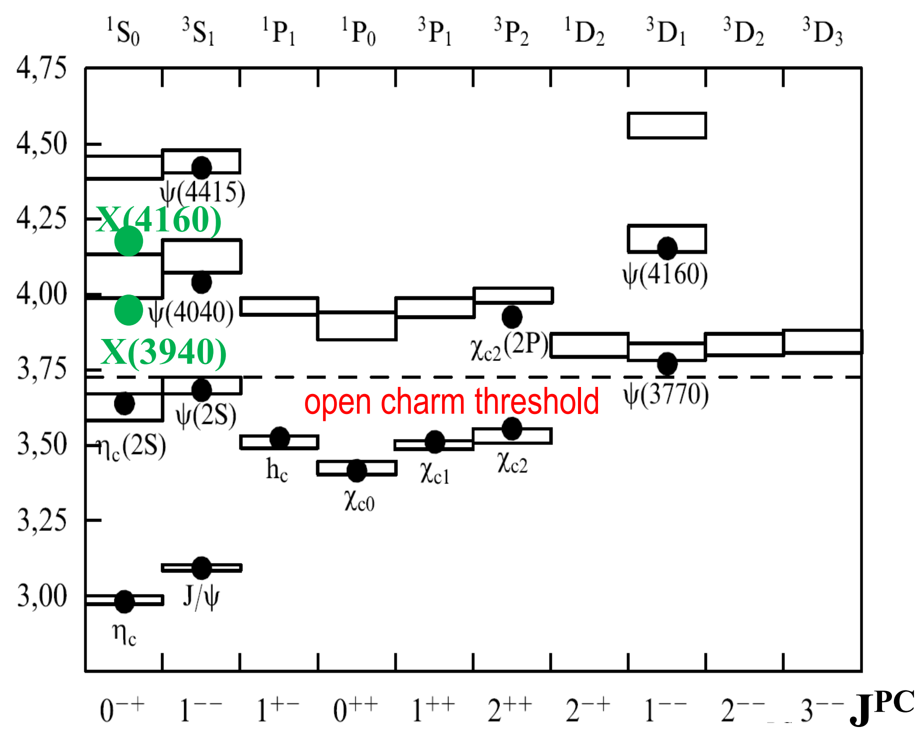
$X(3940) = 3^1S_0 = \eta_c(3S)$

$X(4160) = 4^1S_0 = \eta_c(4S)$

Decays to open charm like standard charmonium



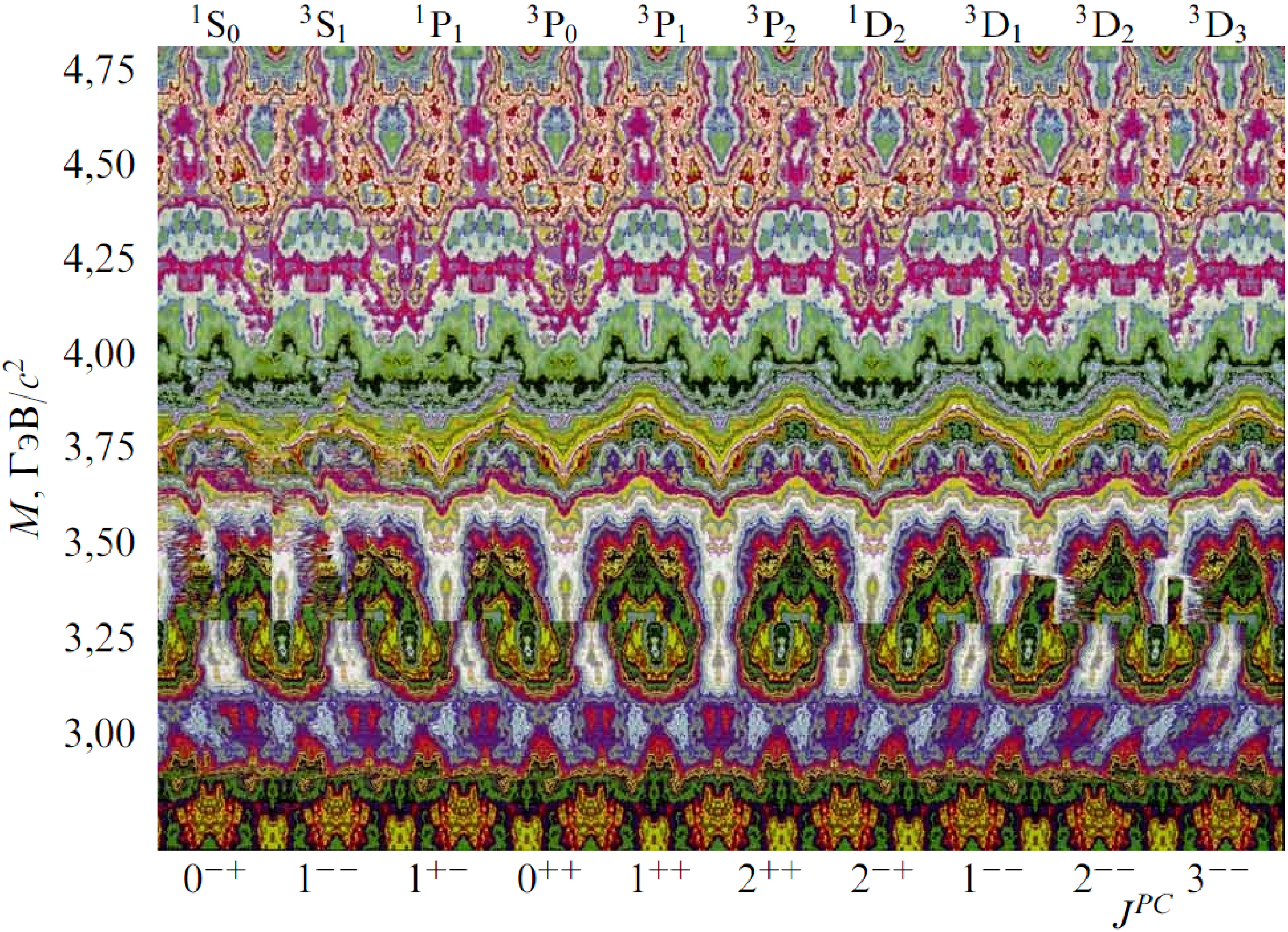

*X(3940)&X(4160): masses are ~100-150 (250-300)MeV lower than the masses predicted by the potential models*



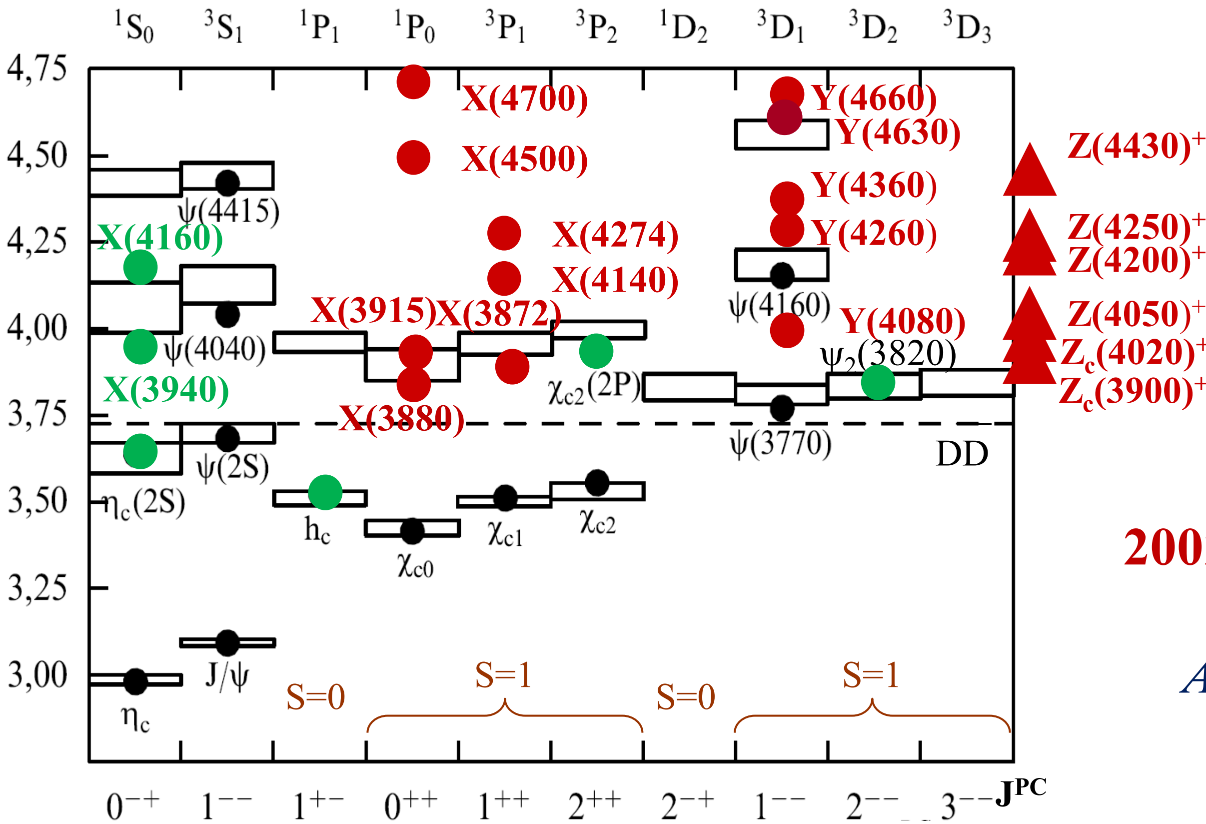

## Future

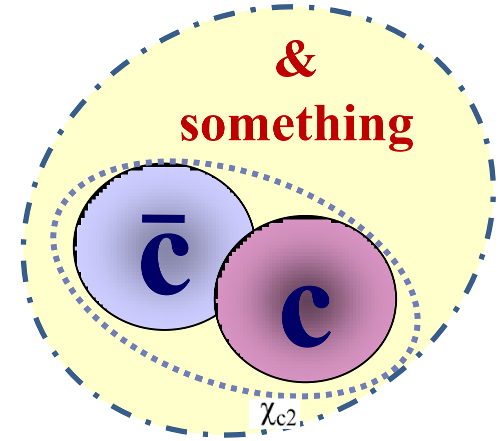
- Angular analysis for solid identification
- Search in B decays

# New charmoniumlike spectroscopy



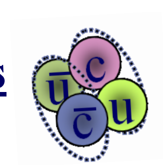
# Charmonium & Charmoniumlike states



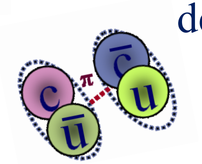

**2002-2016** Discovery of **18 (+4?)**
**exotic charmonium states**
***All of them above open charm threshold***

**Multiquark states**



Tetraquark

tightly bound four-quark state

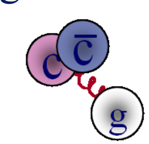


Molecular state

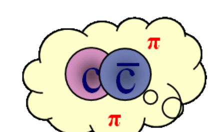
two loosely bound charm mesons

**Charmonium hybrids**

States with excited gluonic degrees of freedom

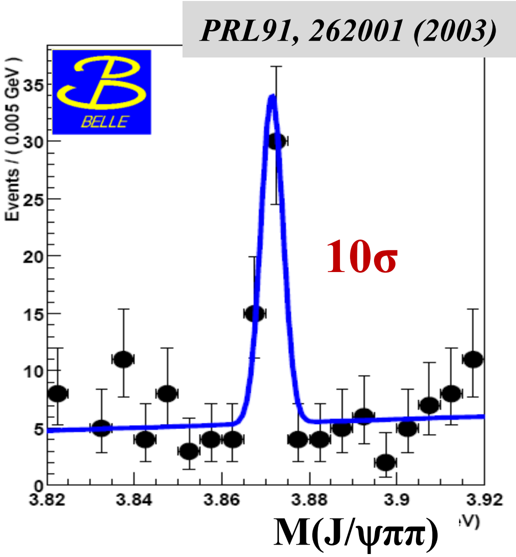


**Hadro-charmonium**



Specific charmonium state "coated" by excited light-hadron matter

# X(3872)




$M_X$ close to $D^0D^{*0}$ threshold

$M = 3871.68 \pm 0.17$ MeV

not clear below or above:

$\Delta m = -0.11 \pm 0.22$ MeV

surprisingly narrow:

$\Gamma_{tot} < 1.2$ MeV at 90% CL

**$J^{PC} = 1^{++}$**

finally established

**Belle topcited: 1200+**

First observed by Belle in

**$B \to K\, J/\psi\pi^+\pi^-$**

Confirmed:

BaBar, LHCb, CMS, ATLAS, CDF

*<u>Hadronic collisions</u>: produced mostly promptly; only 0.263±0.023±0.016 from B-decays (CMS)*

| Known decays | BR relative to $J/\psi\rho$ mode | Comments |
|---|---|---|
| $J/\psi\rho$ | 1 | isospin violation |
| $J/\psi\omega$ | $0.8 \pm 0.3$ | isospin violation |
| $J/\psi\gamma$ | $0.21 \pm 0.06$ | Belle&Babar good agreement |
| $\psi(2S)\gamma$ | $0.50 \pm 0.15$ | Belle&Babar disagreement LHCb confirms BaBar |
| $D^0D^{*0}$ | ~10 | dominant mode |

# X(3872) interpretations

**Conventional charmonium $\chi_{c1}$ (2P) ($J^{PC}=1^{++}$)**

Problems:

- $\Gamma(\chi_{c1}(2P)\rightarrow J/\psi\gamma)/\Gamma(\chi_{c1}(2P)\rightarrow J/\psi\pi\pi) \sim 30$, **measured < 0.2**
- ~ 100MeV heavier then expected

**Tetraquark (cq)(cq):**

**+ 3 states (cu)(cu), (cd)(cu), (cd)(cd) with a few MeV mass splitting**

Problems:

no evidence of neither neutral doublet nor charged partner yet

**$D^0D^{*0}$ molecular state: (the most popular)**

- $M_X \sim M_{D0} + M_{D^{*0}}$ is not accidental
- $J^{PC}=1^{++}$ ($D^0D^{*0}$ in S-wave)
- $DD^*$ decay
- Small rate for decay into $J/\psi\gamma$ is expected

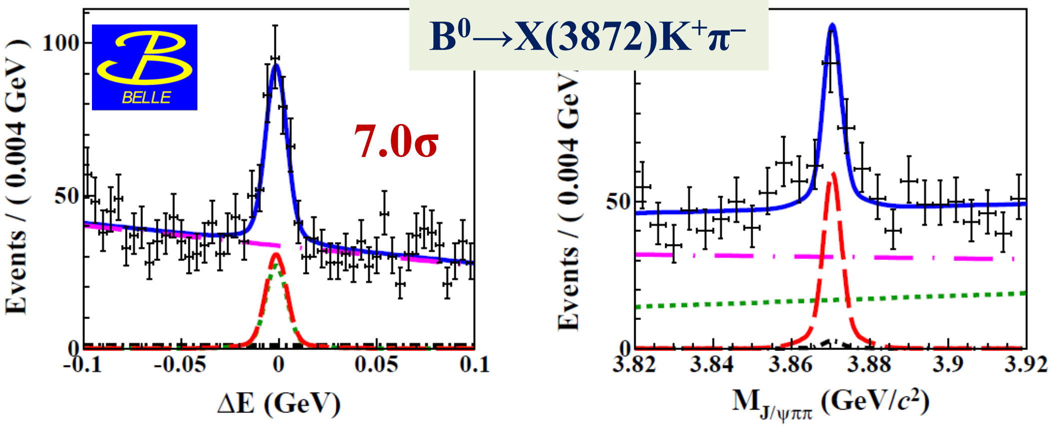
Problems:

- too large $X(3872) \rightarrow \psi(2S)\gamma$
- too small binding energy: $D^0$ and $D^{*0}$ too far in space to be produced in high energy pp collisions

**Possible solution:**

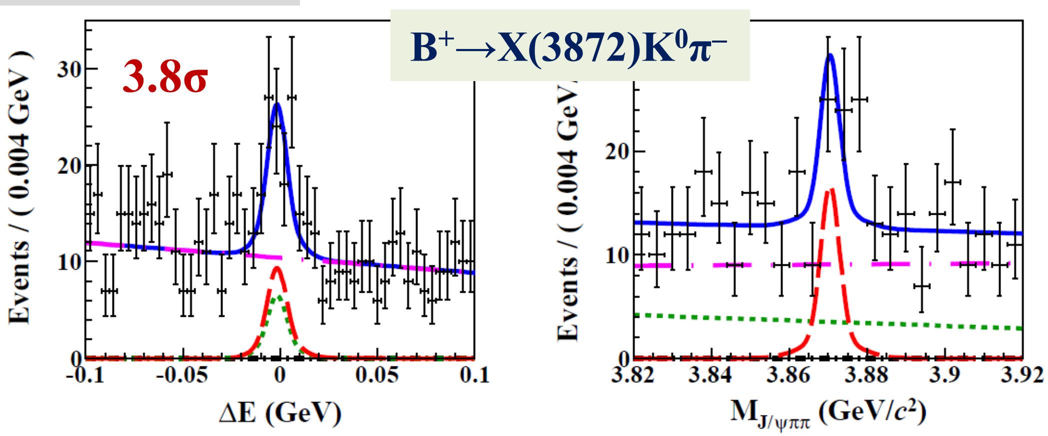
**Mixture of P-wave charmonium level $\chi_{c1}(2P)$ and S-wave $DD^{*0}$ molecule**

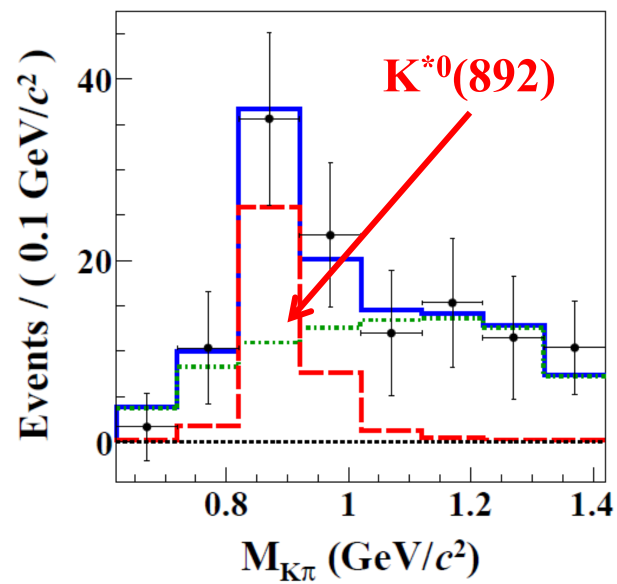
# Observation of X(3872) in B→X(3872)Kπ




| Decay mode | Y | $\epsilon$ (%) | $\Sigma$ ($\sigma$) | $\mathcal{B}(B \to X(3872)K\pi) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ |
|---|---|---|---|---|
| $B^0 \to X(3872)K^+\pi^-$ | $116 \pm 19$ | 15.99 | 7.0 | $(7.9 \pm 1.3 \pm 0.4) \times 10^{-6}$ |
| $B^+ \to X(3872)K^0\pi^+$ | $35 \pm 10$ | 10.31 | 3.7 | $(10.6 \pm 3.0 \pm 0.9) \times 10^{-6}$ |

PRD91, 051101 (2015)

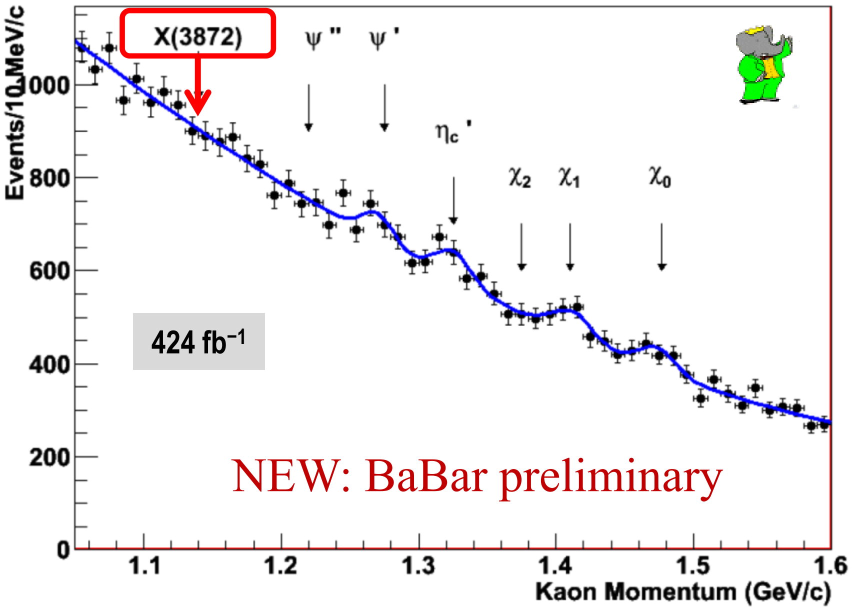



$$\frac{\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(K^*(892)^0 \to K^+\pi^-)}{\mathcal{B}(B^0 \to X(3872)K^+\pi^-)}$$
$$= 0.34 \pm 0.09(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

⇒ Contrast to ψ(2S) case

# Measurements of absolute Br of B →KX(3872)




$\Upsilon(4S) \rightarrow B B_{tag}$ → $D\pi$, … full reconstruction

$B \rightarrow KX$

Looking for recoil mass to $(B_{tag}K)$

**BaBar 2006:** $Br(B \rightarrow KX(3872)) < 3.2\cdot10^{-4}$ at 90% C.L

**Low limit on $Br(X(3872) \rightarrow J/\psi\, \pi^+\pi^-) > 4.2\%$**

| Particle | Yield | Peak Position | Width | BF($10^{-4}$) |
|---|---|---|---|---|
| $J/\psi$ | 516±67 | | | 9.6±1.2(sta)±0.8(sys) |
| $\eta_c$ | 655±77 | 2982±5 | <43 | 13.3±1.8(stat)±0.4(sys)±0.3(ref) |
| $\chi_{c0}$ | 218±76 | | | 4.4±0.9 |
| $\chi_{c1}$ | 192±35 | | | 7.0±1.3(stat)±1.0(sys) |
| $\chi_{c2}$ | 0±32 | | | <1.2 |
| $\eta_c$ (2S) | 283±94 | 3632±0.007 | <33 | 6.0±2.1(stat)±0.4(sys) |
| $\psi'$ | 293±90 | | | 6.2±2(stat)±0.6(sys) |
| $\psi(3770)$ | 0±49 | | | <2.0 |
| X(3872) | 75±81 | | | 1.4±1.5 or < 4.4 |

BaBar preliminary

# X(3872): future

| Search for X(3872) partners decays | Comments |
|---|---|
| $\chi_{c1}\,\gamma$<br>$\chi_{c2}\,\gamma$ | Forbidden by C-parity conservation<br>C-odd partners: tetraquark, molecule<br>UL : $< 1/4$ from $J/\psi\ \pi^+\pi^-$ |
| $J/\psi\ \eta$ | C-odd partners: tetraquark<br>UL : $< 1/2$ from $J/\psi\ \pi^+\pi^-$ |
| $\eta_c\,\eta$<br>$\eta_c\,\pi^0$<br>$\eta_c\,\pi^+\pi^-$<br>$\eta_c\,\omega$ | Search for other X-like molecular states<br>UL : $\sim J/\psi\ \pi^+\pi$ |

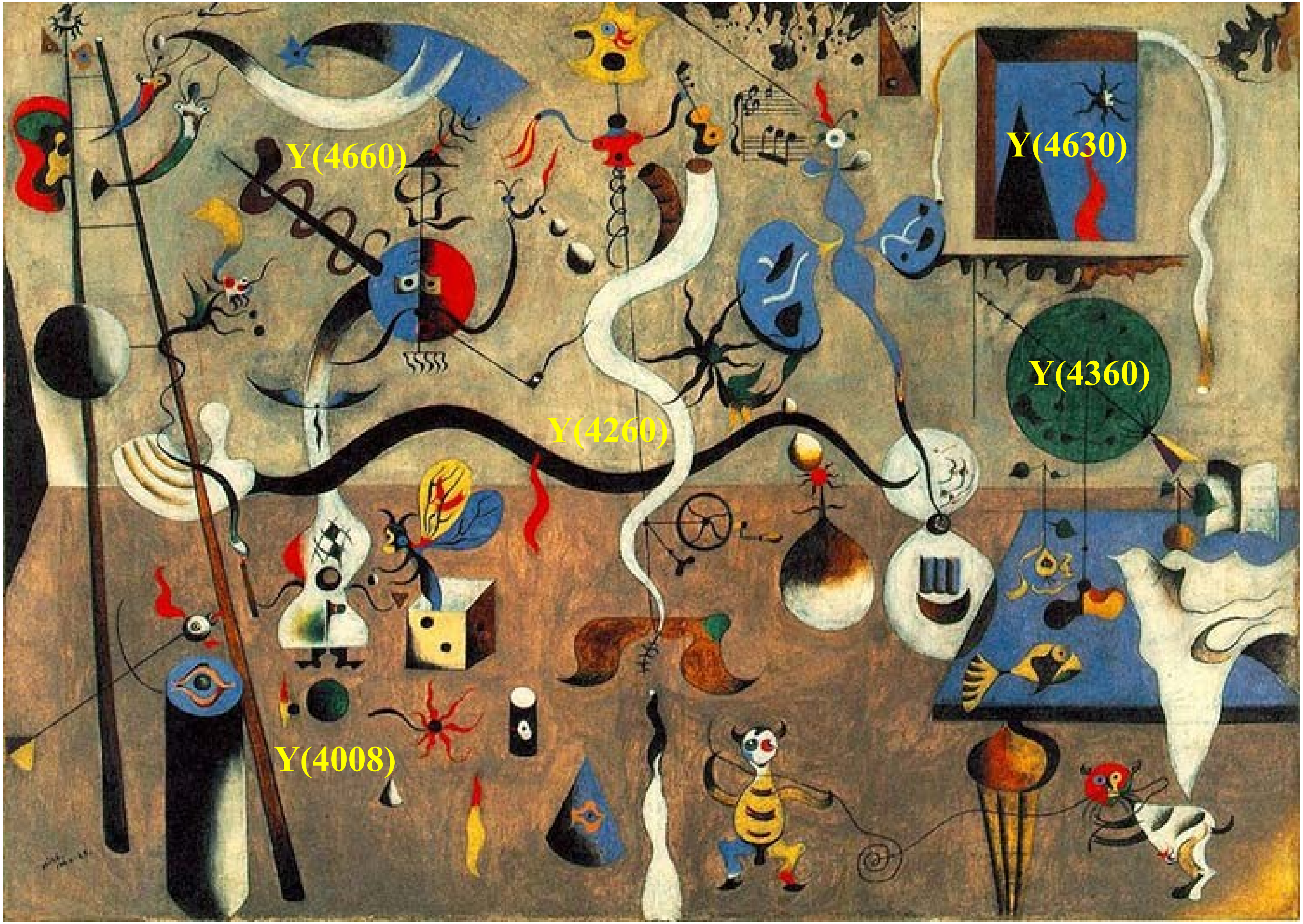
- Detailed pattern of X(3872) to charmonium transitions (radiative and hadronic) with significantly improved accuracy

- Search for partners of X(3872)
  molecules with $J^{PC} = 0^{++}, 1^{+-}, 2^{++}\ldots$

- Measurements of absolute BR of $B \to KX(3872)$ with improved accuracy

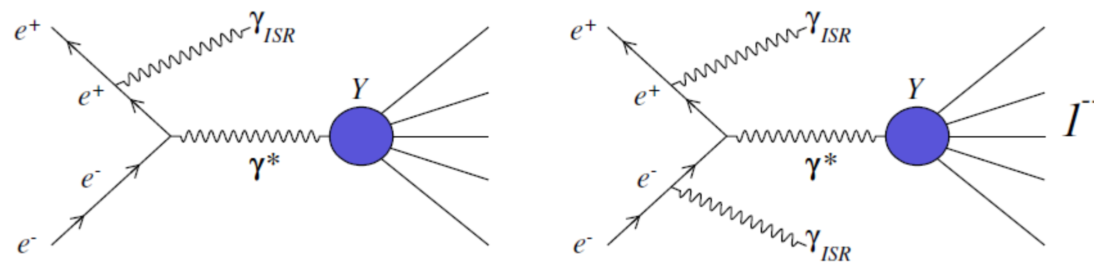
- Measurements of line shape of X(3872) decaying to $DD^*$ at threshold and to $J/\psi\pi^+\pi^-$ to clarify nature of X(3872): virtual or bound state

- Measurements of the total width of X(3872)



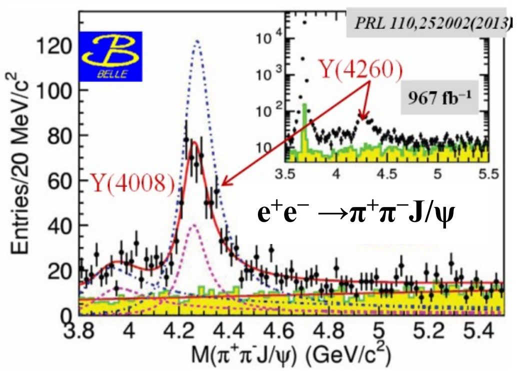

# Exotic vector states

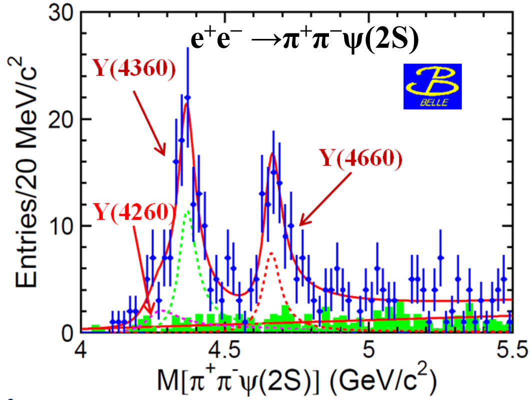
# ISR measurements at B factories

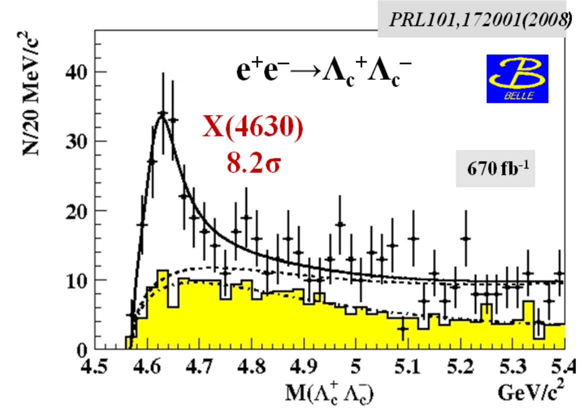



- Fixed quantum numbers of final state $J^{PC} = 1^{--}$
- Study of charmonium(+like) final states from threshold in wide energy region
- Huge accumulated luminosity at B factories
- *Limited statistics*
- *strong electromagnetic suppression*
- *typical events topology: fast photon with small $p_t$*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $Y(4008)$ | $3891 \pm 42$ | $255 \pm 42$ | $1^{--}$ | $e^+e^- \to (\pi^+\pi^- J/\psi)$ | Belle [1046, 1094] (7.4) | 2007 | NC! |
| $Y(4260)$ | $4250 \pm 9$ | $108 \pm 12$ | $1^{--}$ | $e^+e^- \to (\pi\pi J/\psi)$ | BaBar [1104, 1105] (8), CLEO [1106, 1107] (11) Belle [1046, 1094] (15), BES III [1045] (np) | 2005 | Ok |
| | | | | $e^+e^- \to (f_0(980) J/\psi)$ | BaBar [1105] (np), Belle [1046] (np) | 2012 | Ok |
| | | | | $e^+e^- \to (\pi^- Z_c(3900)^+)$ | BES III [1045] (8), Belle [1046] (5.2) | 2013 | Ok |
| | | | | $e^+e^- \to (\gamma X(3872))$ | BES III [1108] (5.3) | 2013 | NC! |
| $Y(4360)$ | $4354 \pm 11$ | $78 \pm 16$ | $1^{--}$ | $e^+e^- \to (\pi^+\pi^- \psi(2S))$ | Belle [1110] (8), BaBar [1111] (np) | 2007 | Ok |
| $X(4630)$ | $4634^{+9}_{-11}$ | $92^{+41}_{-32}$ | $1^{--}$ | $e^+e^- \to (\Lambda_c^+ \bar{\Lambda}_c^-)$ | Belle [1116] (8.2) | 2007 | NC! |
| $Y(4660)$ | $4665 \pm 10$ | $53 \pm 14$ | $1^{--}$ | $e^+e^- \to (\pi^+\pi^- \psi(2S))$ | Belle [1110] (5.8), BaBar [1111] (5) | 2007 | Ok |




## *Unlike conventional charmonium*

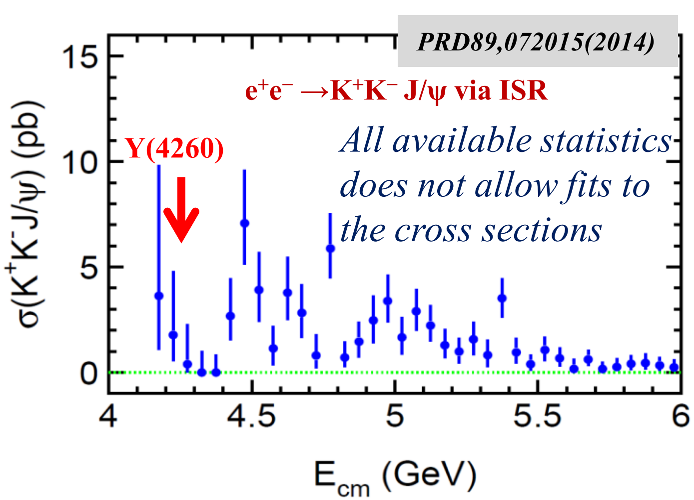
- No room for Y states among $1^{--}$ charmonium

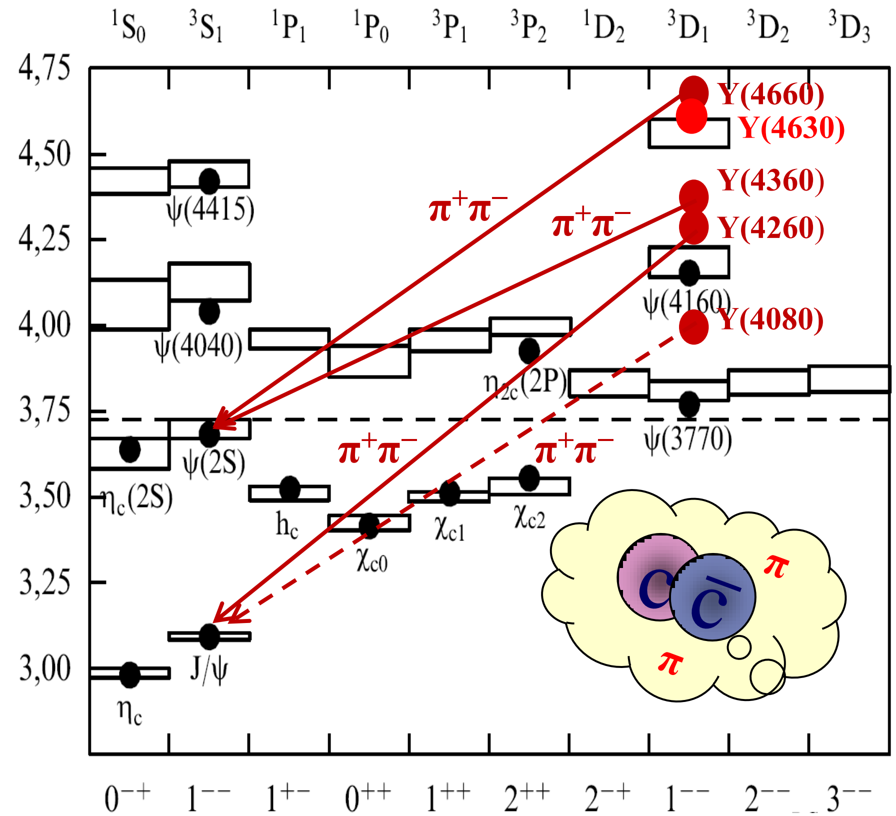
$3^3S_1 = \psi(4040)$; $2^3D_1 = \psi(4160)$ ; $4^3S_1 = \psi(4415)$; masses of predicted $3^3D_1$ (4520); $5^3S_1$ (4760); $4^3D_1$(4810) are higher (lower)

- Absence of open charm production
- Anomalous large partial width

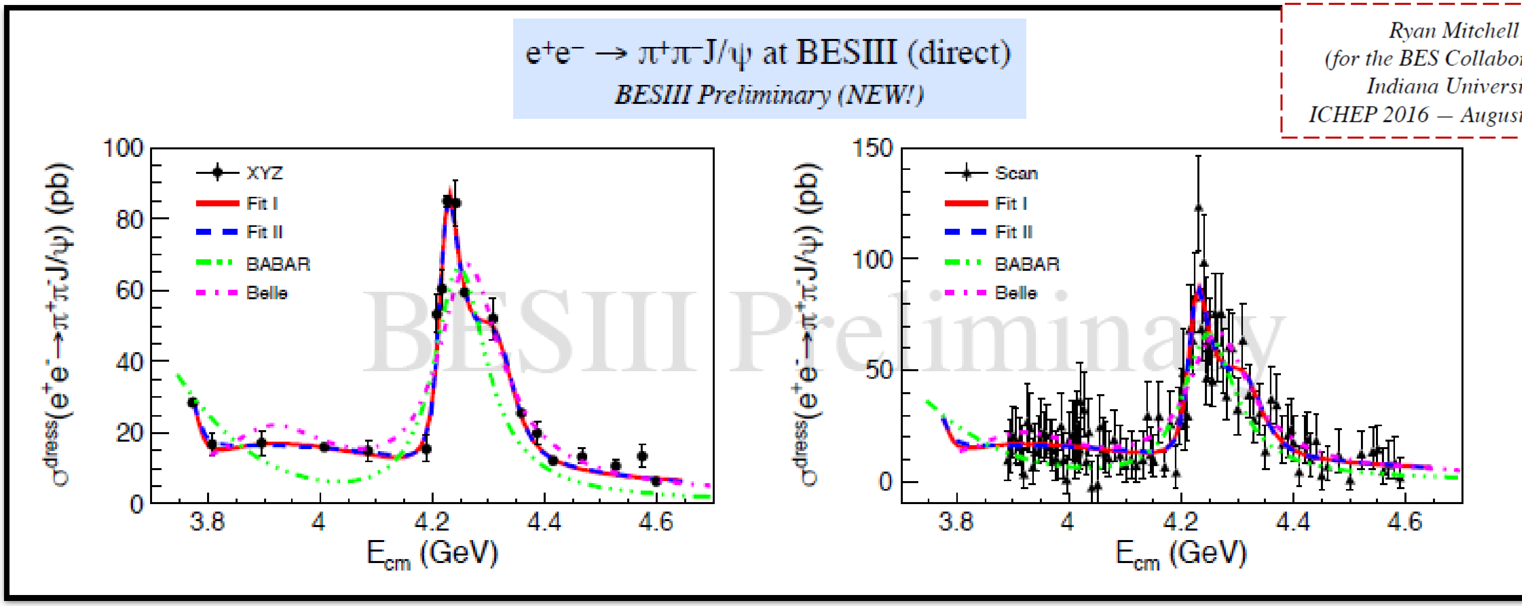
  $\Gamma(Y \to J/\psi\ \pi\pi) > 1$ MeV
- Only one decay channel per one Y state:

  light charmonium + ππ



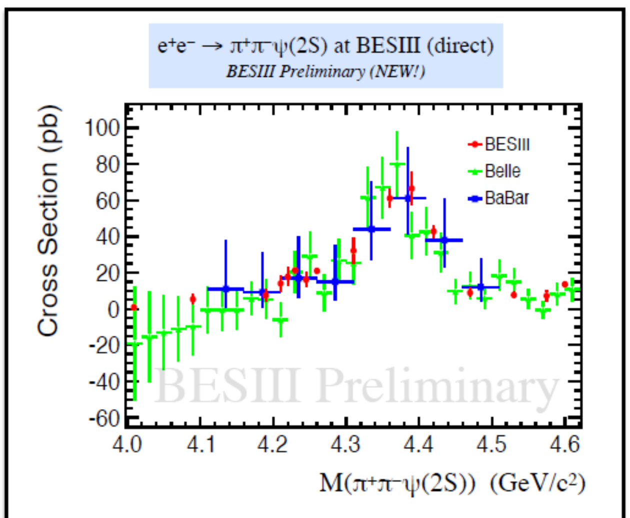
*Ryan Mitchell*
*(for the BES Collaboration)*
*Indiana University*
*ICHEP 2016 — August 4, 2016*



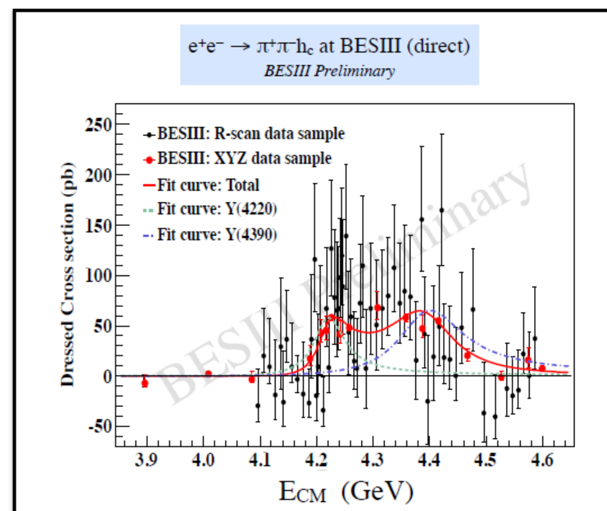

$e^+e^- \to \pi^+\pi^- J/\psi$ cross section is inconsistent with a single pick of Y(4260)

*Two peaks are favored over one peak by 7σ*

Y(4008) is not needed to describe BESIII data

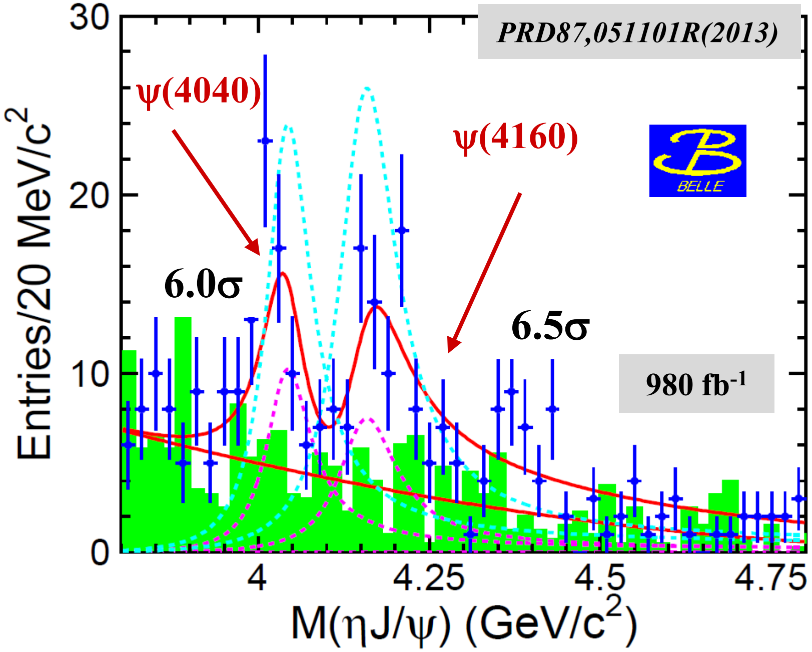



BESIII confirms lineshape of Y(4360) in $e^+e^-\to\pi^+\pi^-\psi(2S)$ cross section



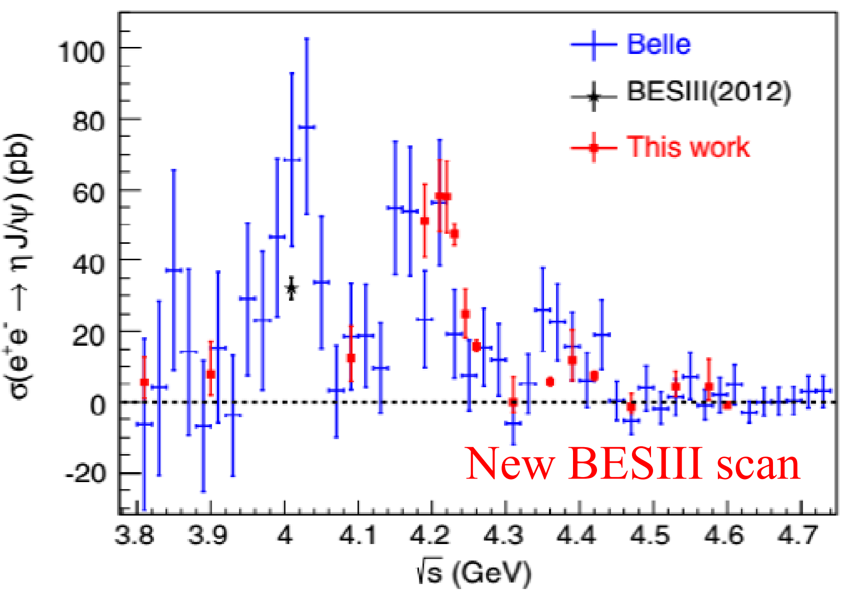

The $\pi^+\pi^-h_c$ shape is clearly different from $\pi^+\pi^-J/\psi$

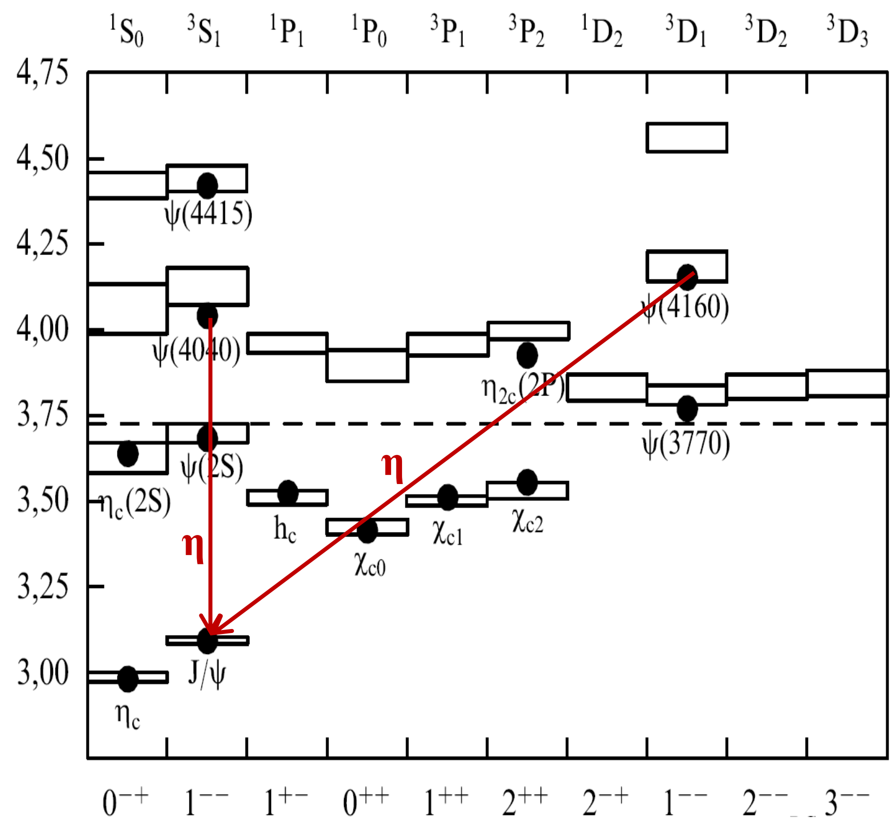
# $e^+e^- \to J/\psi\eta$




- Peaks of $\psi(4040)$ and $\psi(4160)$
- No sign of any Y state
- $\Gamma$ ($\psi(4040,4160) \to J/\psi\eta$) ~ 1 MeV
  - Anomalous transitions: common feature of all $1^{--}$ states above threshold ?

BESIII is in agreement with Belle:
$\psi(4160) \to J/\psi\eta$ structure

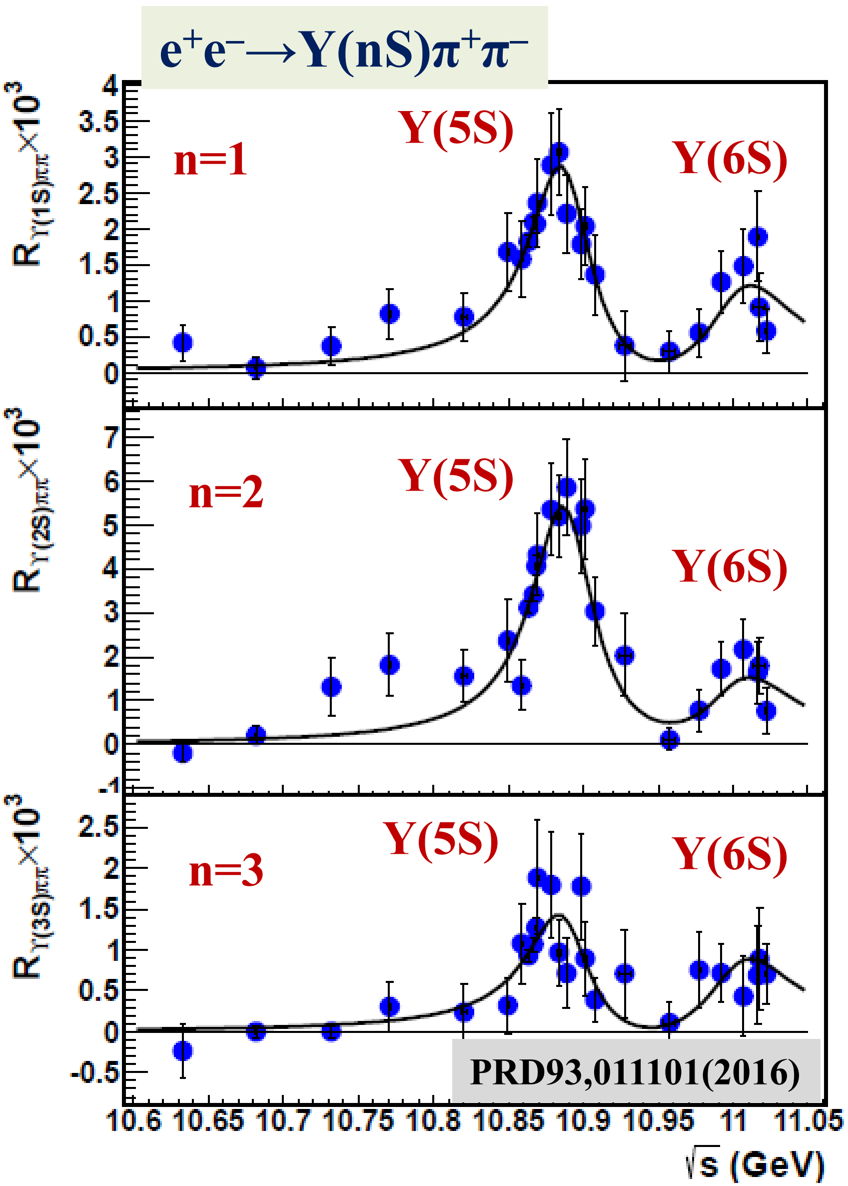


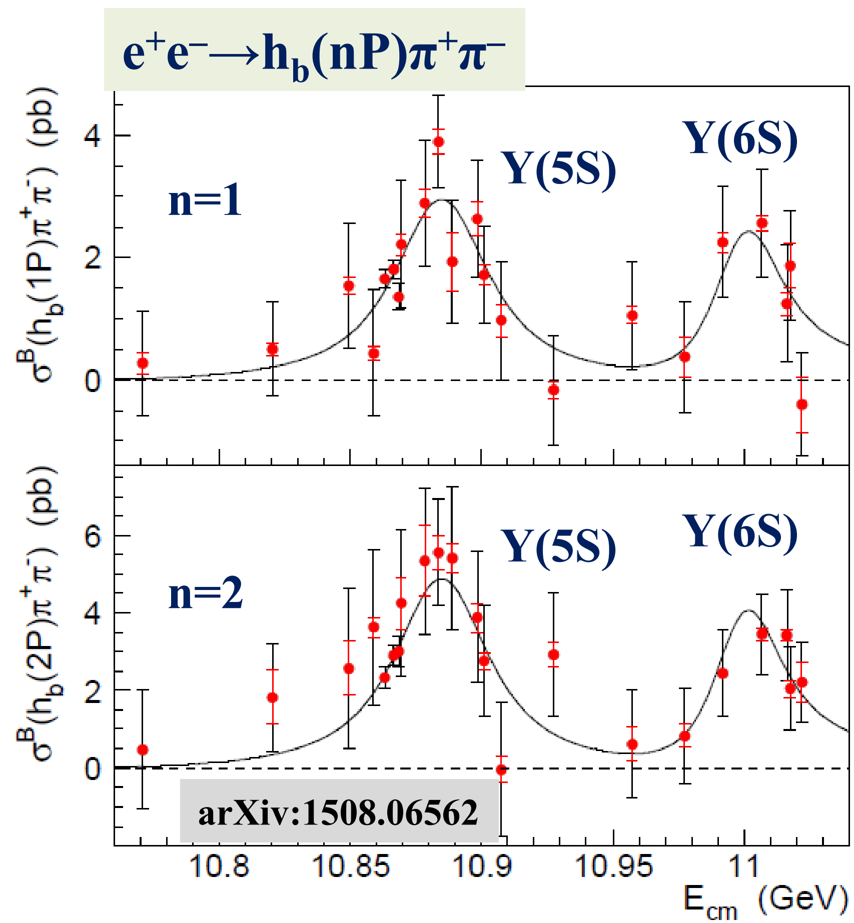



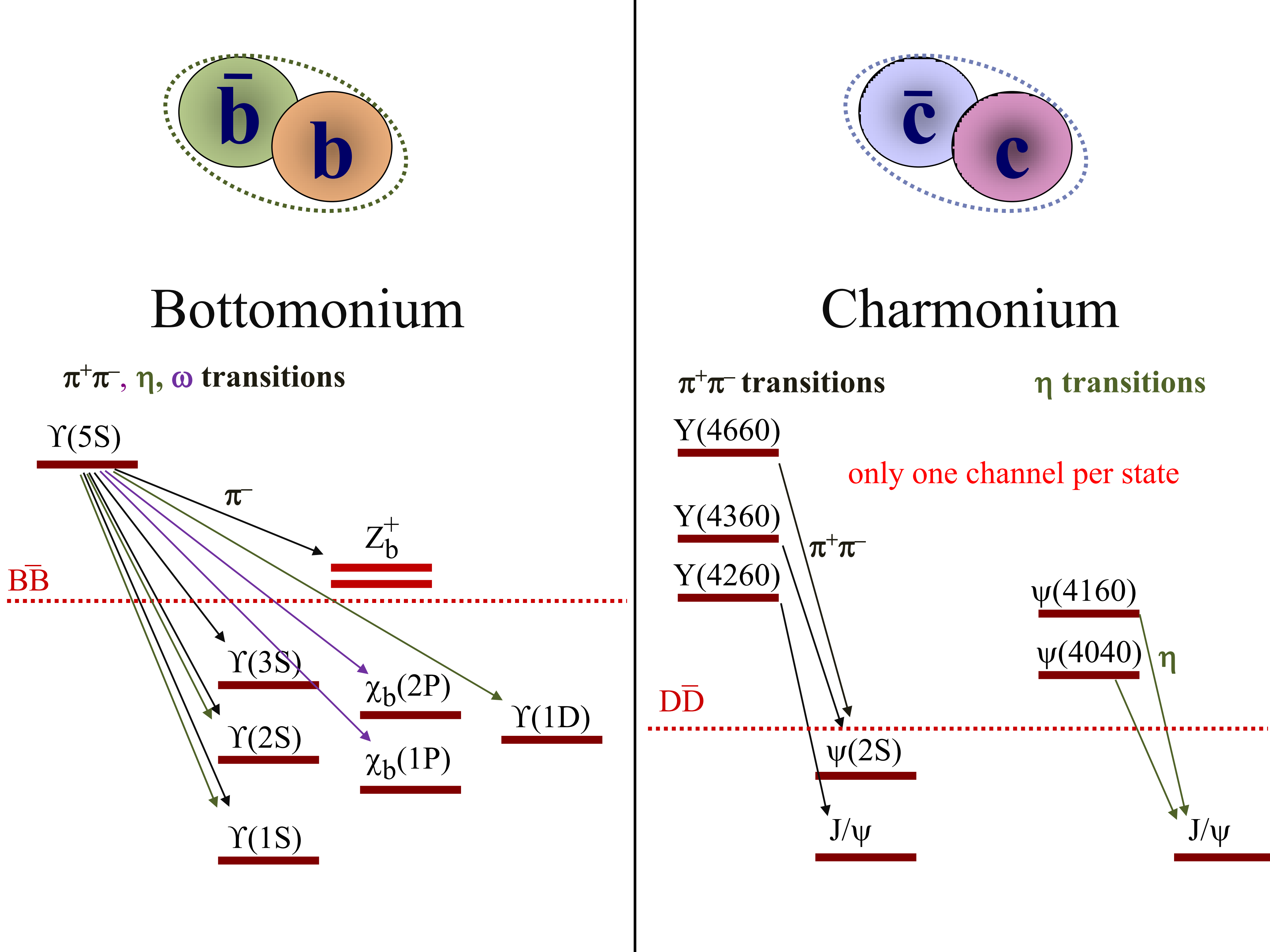
# Bottomonium cross sections

**Only Υ(5S) and Υ(6S) peaks in all cross sections**

**While for any charmoniumlike state only one decay mode**





b̄
b
Bottomonium
π⁺π⁻, η, ω transitions
ϒ(5S)
π⁻
Z_b^+
BB̄
ϒ(3S)
ϒ(2S)
ϒ(1S)
χb(2P)
χb(1P)
ϒ(1D)
c̄
c
Charmonium
π⁺π⁻ transitions
η transitions
Y(4660)
only one channel per state
Y(4360)
π⁺π⁻
Y(4260)
ψ(4160)
ψ(4040)
η
DD̄
ψ(2S)
J/ψ
J/ψ

# 13 years after Y(4260) discovery nature of Y family remains unclear

**More data more open questions:**

- Confirmation of Y(4008) found by Belle only
- Confirmation of X(4630) found by Belle only
- Absence of clear understanding of X(4630) nature
  - *X(4630) quantum numbers, mass and width are in agreement with Y(4660), too different decay modes: does not mean that X(4630) ≡ Y(4660)*
  - *Lots of interpretations*
- Anomalous large transitions: common feature of all $1^{--}$ states above threshold ?
- Search for other final states: $\chi_{c1}$ , $\chi_{c2}$ , $\eta_c$, X(3872) + and/or other light hadrons
  - *Up to now only* $J/\psi$, $\psi(2S) + \pi\pi$, $\eta$
- **Charmonium via Bottomonium puzzle!**
- Nature of Y states?
  - *Molecule, diquark-antidiquark, hadrocharmonium…*

# Charged charmoniumlike states

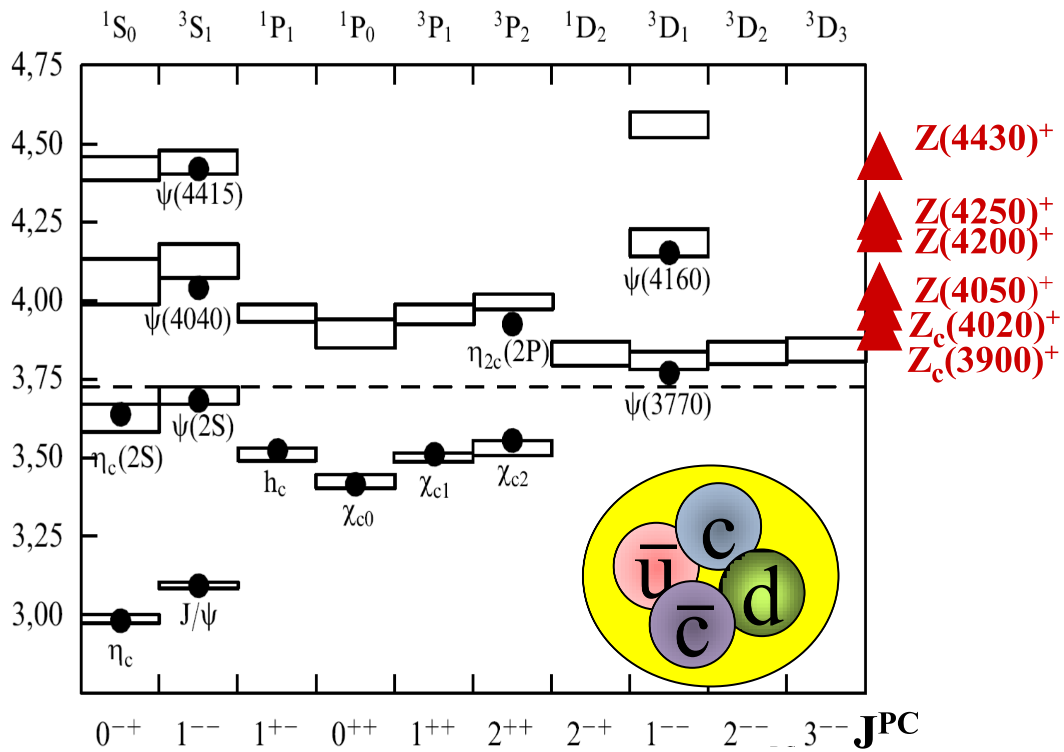
## Charged $Z_c^+$ states cannot be conventional charmonium or hybrid

### In B decays

- Four states found by Belle
  - *only $Z(4430)^+$ is confirmed by LHCb*

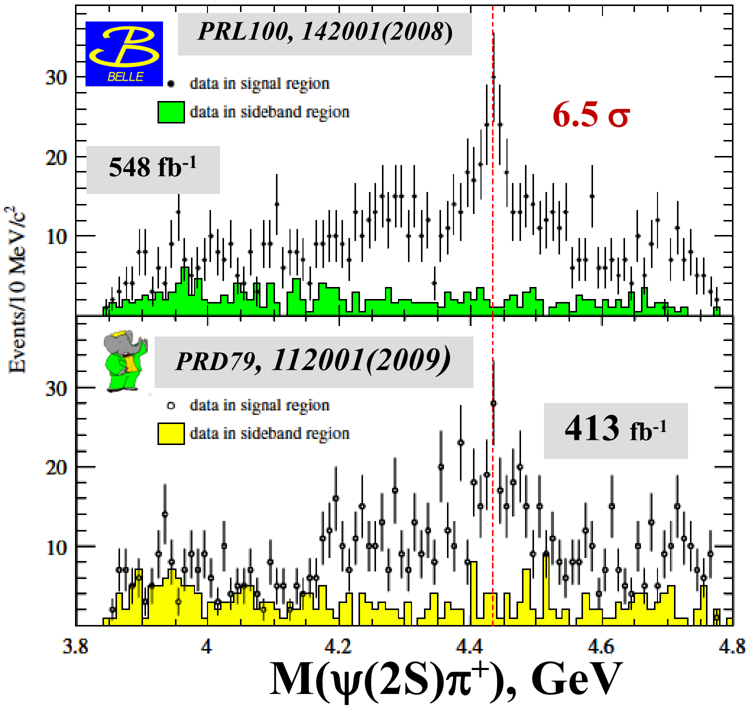
### In $e^+e^-$ annihilation

- Two states are found by Belle
- $Z_c$ family with eight members charged and neutral is found by BESIII




| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $Z(4430)^+$ | $4458 \pm 15$ | $166^{+37}_{-32}$ | $1^{+-}$ | $B^0 \to K^-(\pi^+\psi(2S))$ | Belle [1112, 1113] (6.4), BaBar [1114] (2.4) LHCb [1115] (13.9) | 2007 | Ok |
| | | | | $\bar{B}^0 \to K^-(\pi^+J/\psi)$ | Belle [1103] (4.0) | 2014 | NC! |
| $Z(4050)^+$ | $4051^{+24}_{-43}$ | $82^{+51}_{-55}$ | $??^+$ | $\bar{B}^0 \to K^-(\pi^+\chi_{c1})$ | Belle [1096] (5.0), BaBar [1097] (1.1) | 2008 | NC! |
| $Z(4200)^+$ | $4196^{+35}_{-30}$ | $370^{+99}_{-110}$ | $1^{+-}$ | $\bar{B}^0 \to K^-(\pi^+J/\psi)$ | Belle [1103] (7.2) | 2014 | NC! |
| $Z(4250)^+$ | $4248^{+185}_{-45}$ | $177^{+321}_{-72}$ | $??^+$ | $\bar{B}^0 \to K^-(\pi^+\chi_{c1})$ | Belle [1096] (5.0), BaBar [1097] (2.0) | 2008 | NC! |

# $B \to Z^+_c K^-$

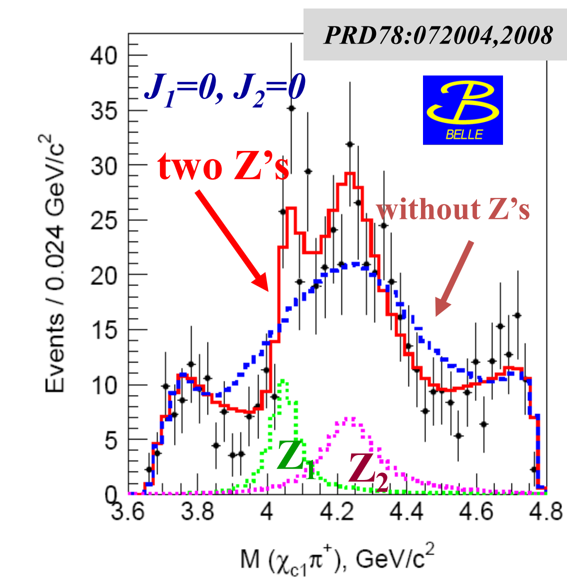



**$Z(4430)^+$ : three different analysis, $J^P = 1^+$**

- Fit to $M(\psi(2S)\pi^+)$ with $K^*(890)$&$K^*(1430)$ veto
- Dalitz analysis
- Full amplitude analysis to obtain spin-parity

*Mass values are the same, width depends on method*

**$Z(4250)^+$ & $Z(4050)^+$**
in $\chi_{c1}\pi^+$ final state
- Daliz analysis

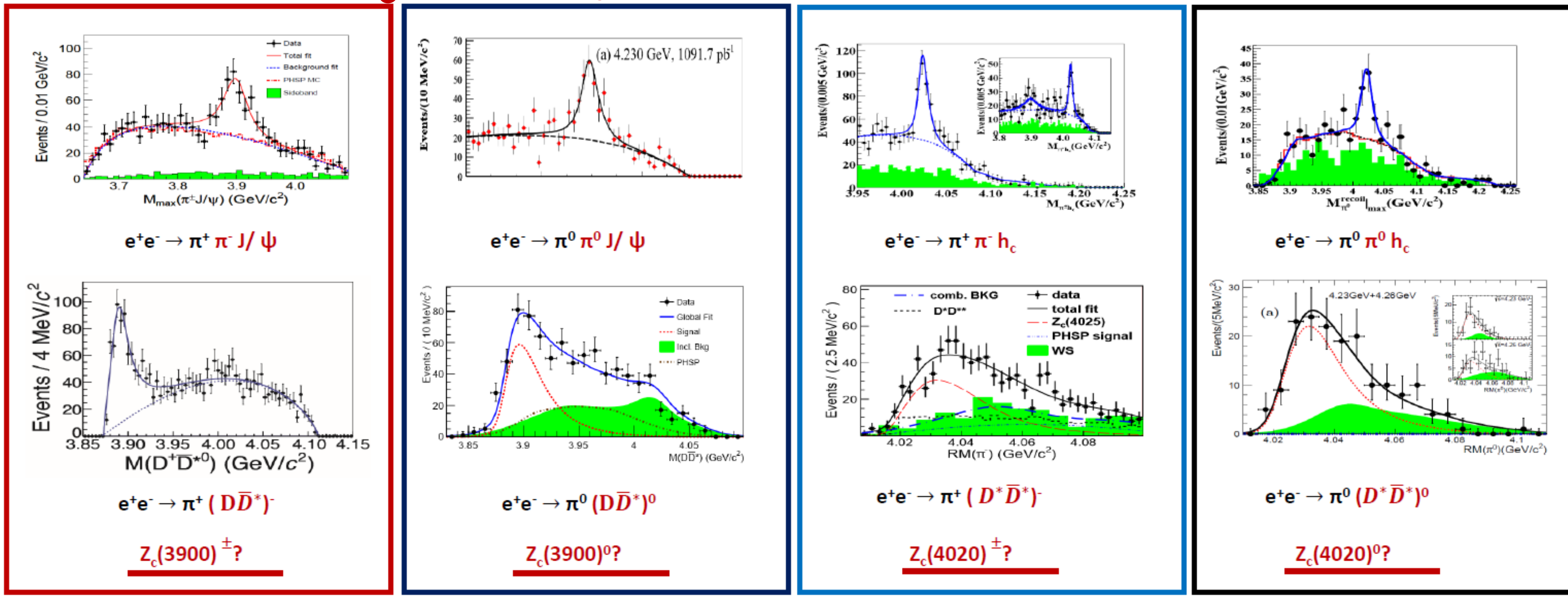



**$Z_c(4200)^+$ in $J/\psi\ \pi^+$ final state, $J^P=1^+$**

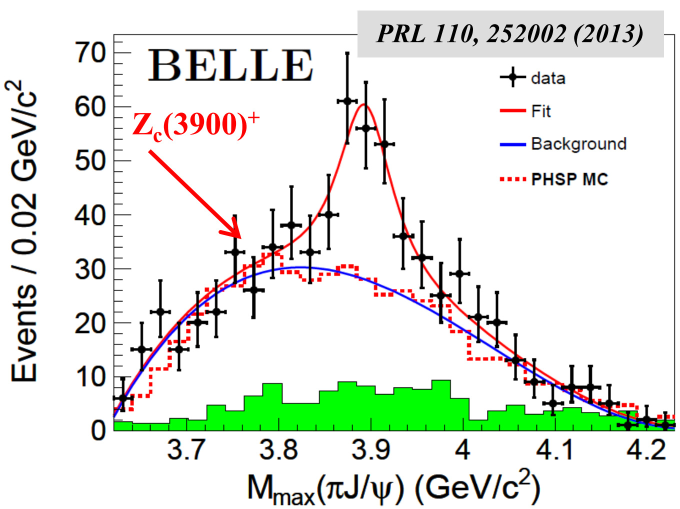
- 4D-fit: Dalitz + angular variables
- New decay mode $Z_c(4430)^+ \to J/\psi\ \pi$
  - order of magnitude suppressed (to $\psi(2S)\pi$) despite larger phase space

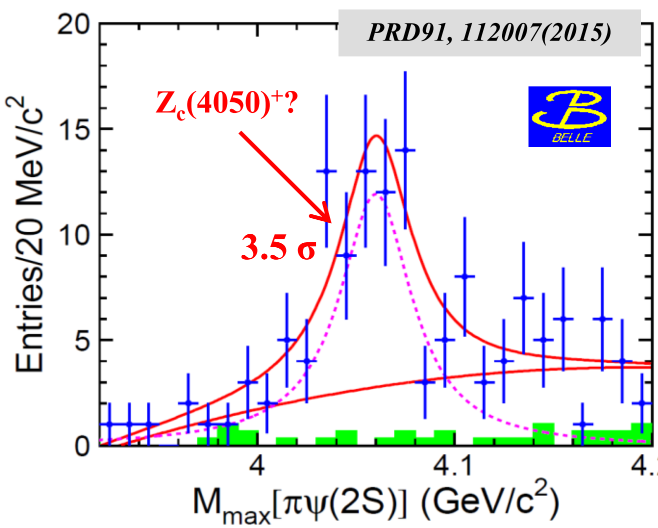
BaBar does not confirm Belle, but also does not rule it out!

# $Z_c$ family in $e^+e^-$ annihilation




- If these structures are real QCD states, charged $Z_c$ decays into $\pi^{+/-} J/\psi$ ($\pi^{+/-} h_c$) → at least four valence quarks to satisfy charge=±1 and strong couplings to ccbar components.




**New signal in**
**$Y(4360) \to \pi^- Z(4050)^+$**
$M = 4054 \pm 3 \pm 1$ MeV/$c^2$
$\Gamma = 45 \pm 11 \pm 6$ MeV
***No signal is found for Y(4660)***

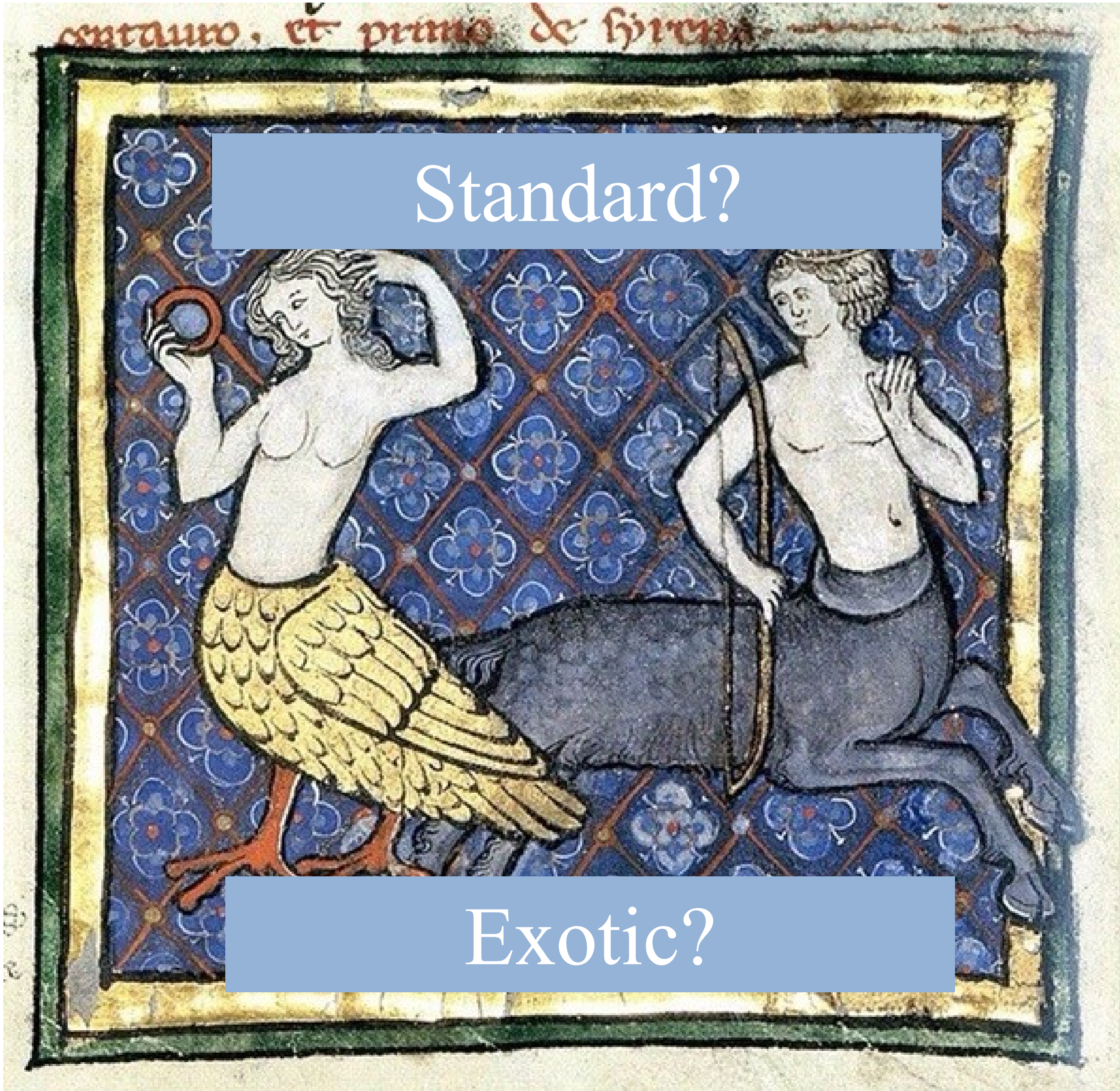
# BESIII: a summary of $Z_c$ observations

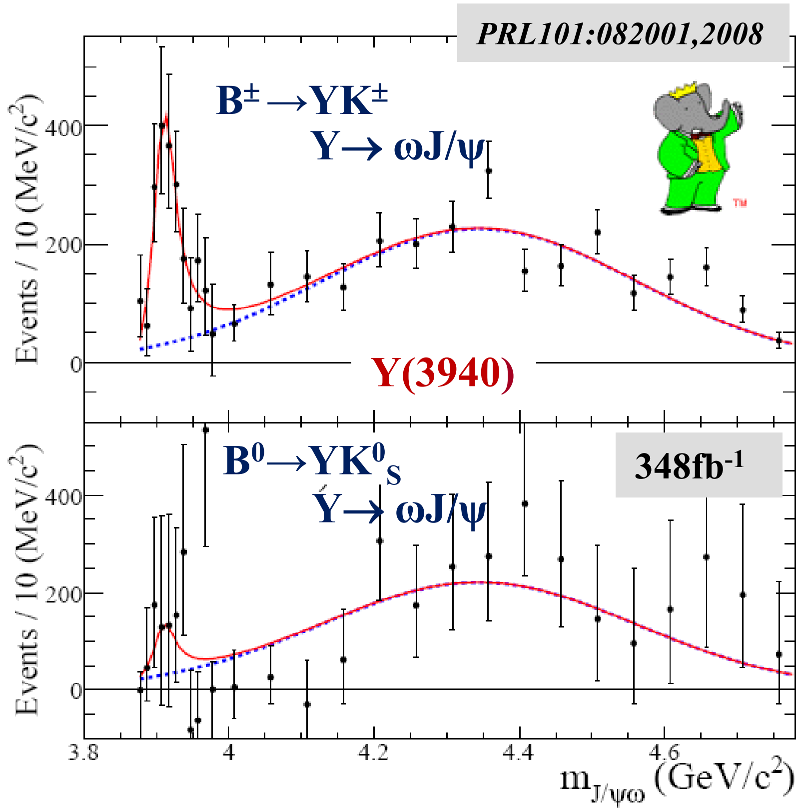
| Zc | Mass (MeV/c²) | Width (MeV) | Decay | Process | [Ref] |
|---|---|---|---|---|---|
| $Z_c(3900)^\pm$ | 3899.0±3.6±4.9 | 46±10±20 | $\pi^\pm J/\psi$ | $e^+e^- \to \pi^+\pi^- J/\psi$ | [1] |
| $Z_c(3900)^0$ | 3894.8±2.3±2.7 | 29.6±8.2±8.2 | $\pi^0 J/\psi$ | $e^+e^- \to \pi^0\pi^0 J/\psi$ | [2] |
| $Z_c(3885)^\pm$ | 3883.9±1.5±4.2 Single D tag | 24.8±3.3±11.0 Single D tag | $(D\bar{D}^*)^\pm$ | $e^+e^- \to (D\bar{D}^*)^\pm\pi^\mp$ | [3] |
| | 3881.7±1.6±2.1 Double D tag | 26.6±2.0±2.3 Double D tag | $(D\bar{D}^*)^\pm$ | $e^+e^- \to (D\bar{D}^*)^\pm\pi^\mp$ | [4] |
| $Z_c(3885)^0$ | $3885.7^{+4.3}_{-5.7}\pm8.4$ | $35^{+11}_{-12}\pm15$ | $(D\bar{D}^*)^0$ | $e^+e^- \to (D\bar{D}^*)^0\pi^0$ | [5] |
| | | | | | |
| $Z_c(4020)^\pm$ | 4022.9±0.8±2.7 | 7.9±2.7±2.6 | $\pi^\pm h_c$ | $e^+e^- \to \pi^+\pi^- h_c$ | [6] |
| $Z_c(4020)^0$ | 4023.9±2.2±3.8 | fixed | $\pi^0 h_c$ | $e^+e^- \to \pi^0\pi^0 h_c$ | [7] |
| $Z_c(4025)^\pm$ | 4026.3±2.6±3.7 | 24.8±5.6±7.7 | $D^*\bar{D}^*$ | $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$ | [8] |
| $Z_c(4025)^0$ | $4025.5^{+2.0}_{-4.7}\pm3.1$ | 23.0±6.0±1.0 | $D^*\bar{D}^*$ | $e^+e^- \to (D^*\bar{D}^*)^0\pi^0$ | [9] |


[1] PRL 110,252001; [2] PRL 115, 112003; [3] PRL 112, 022001; [4] PRD 92, 092006
[5] PRL 115, 222002; [6] PRL110, 252001; [7] PRL 113,212002; [8] PRL 112, 132001
[9] PRL 115, 182002


- Charged and neutral $Z_c$'s are consistent with isospin triplets expectations.
- Mass and widths of $Z_c(3900)$ and $Z_c(3885)$ (also $Z_c(4020)$ and $Z_c(4025)$ ) are consistent within 2σ → the same states?

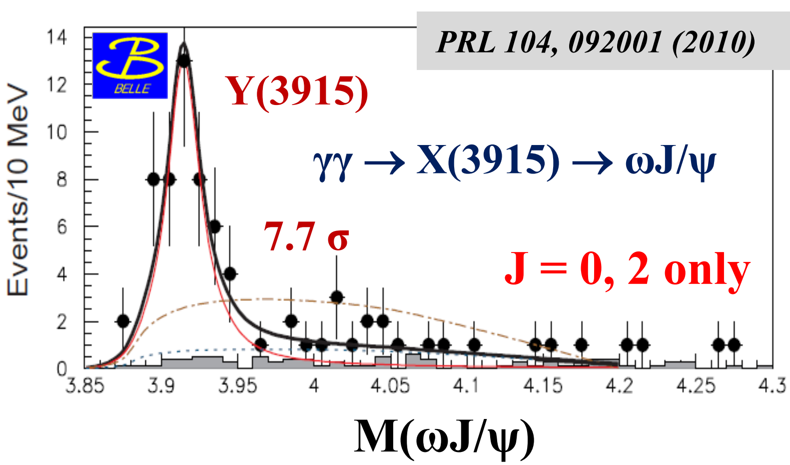

Shan JIN
*Institute of High Energy Physics*
On Behalf of the BESIII Collaboration

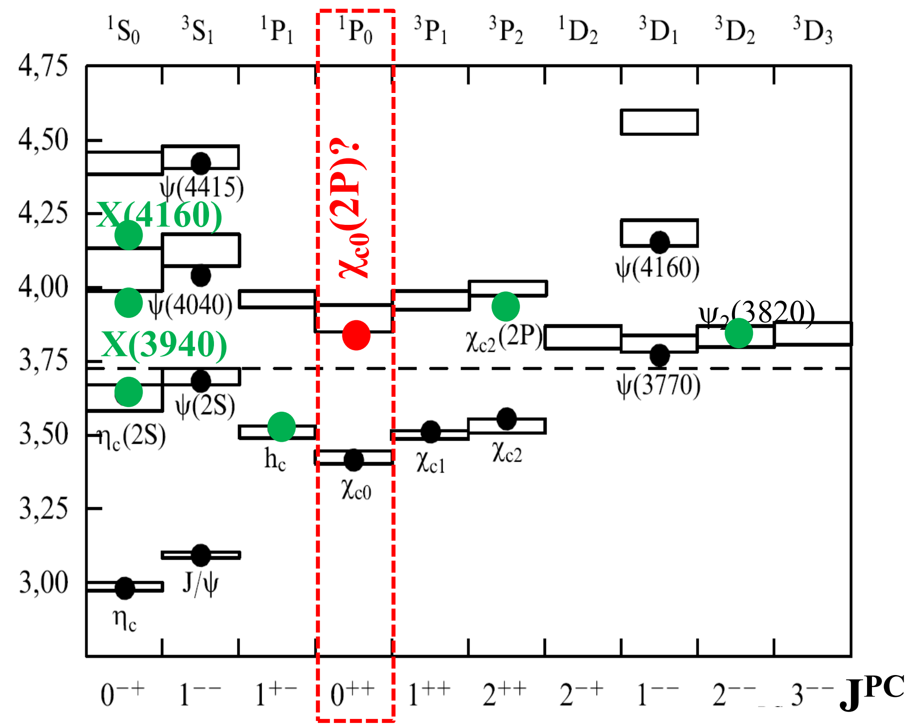

Standard?
Exotic?




# Y(3940) ≡ X (3915)

- same decay mode
- similar masses and widths
- *different production mechanisms*
- confirmed by Belle & BaBar

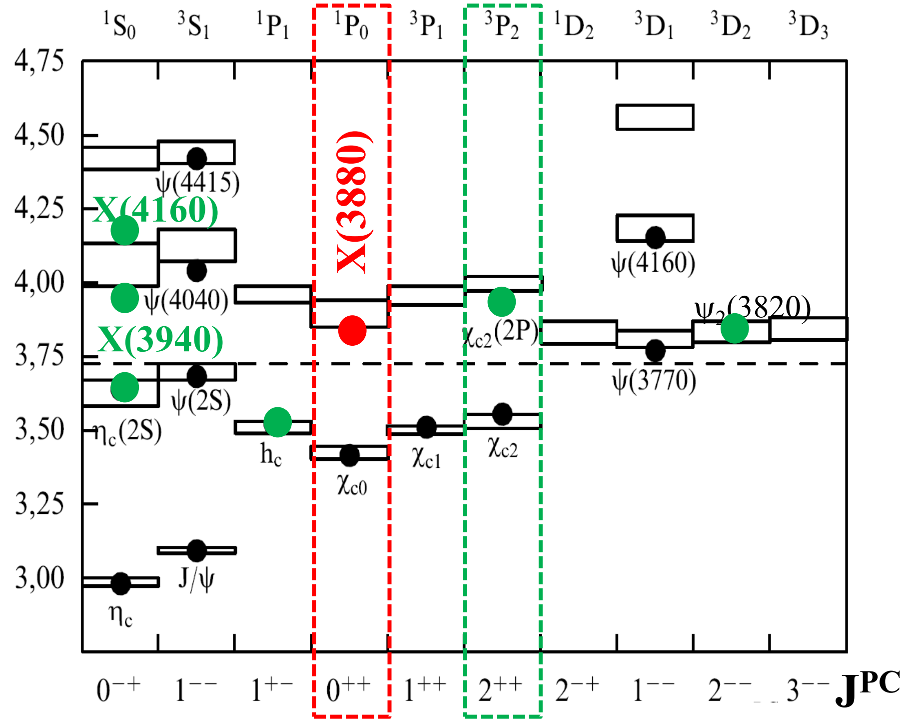



Confirmed by BaBar, **prefer $J^P=0^+$**

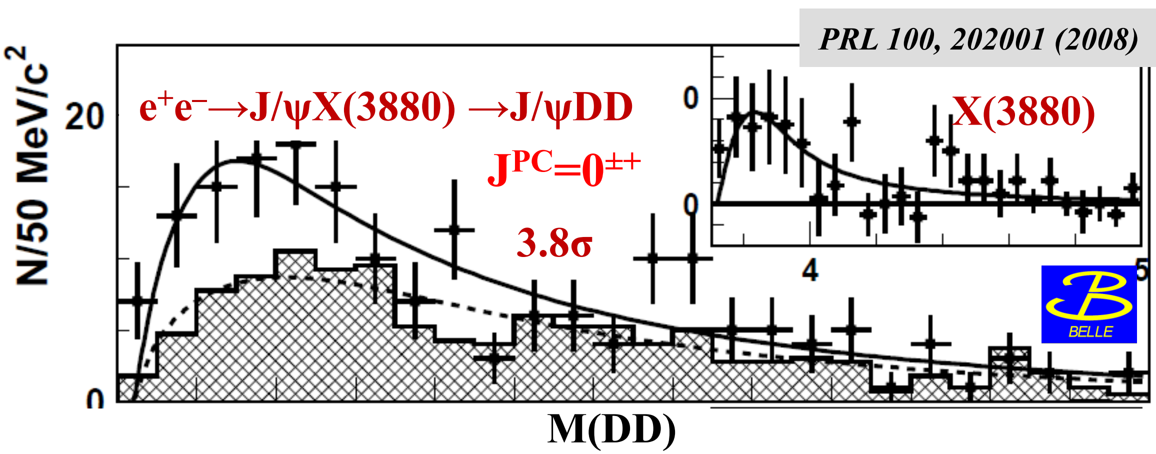
# X(3915) puzzle

**Partilce Data Group**
**Y(3940) = X(3915)= $\chi_{c0}$(2P)**




**Theory**

- $\chi_{c0}$(2P) production in two body B decays is suppressed
- $\chi_{c0}$(2P) → DD should be dominant
- a better candidate for $\chi_{c0}$(2P) seen in **X(3880)**→ DD




**New ideas:**

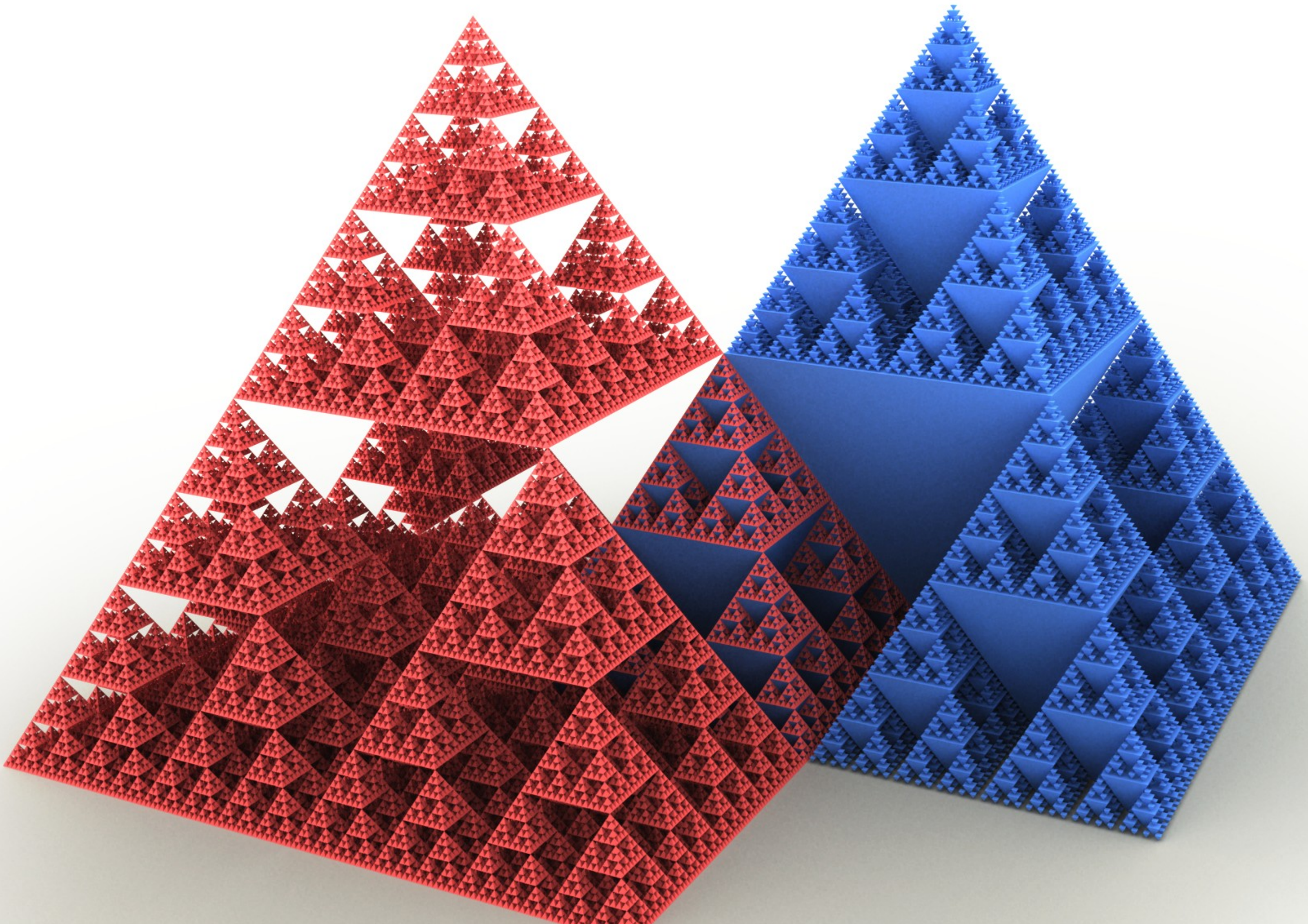
- Y(3940) = Y(3915) is **$\chi_{c2}$(2P)**
- $\chi_{c2}$(2P)≠ Z(3940)

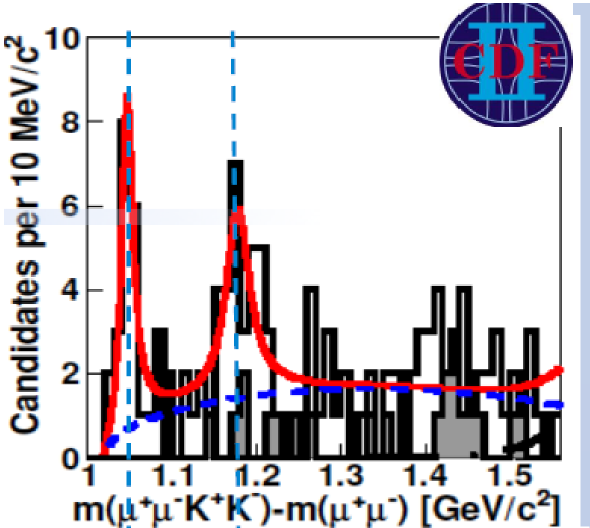
Z(3940) =Y(3940) = Y(3915) is **$\chi_{c0}$(2P)**

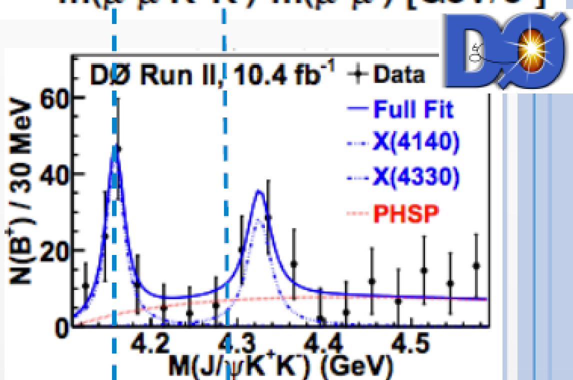
**Future**

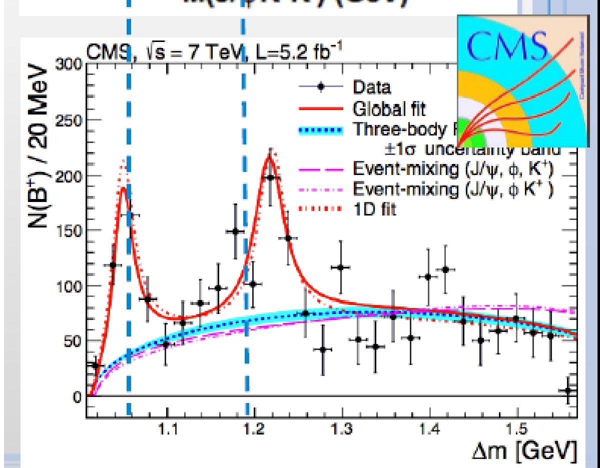
More data for new angular analysis to confirm quantum numbers

# Search for tetraquarks

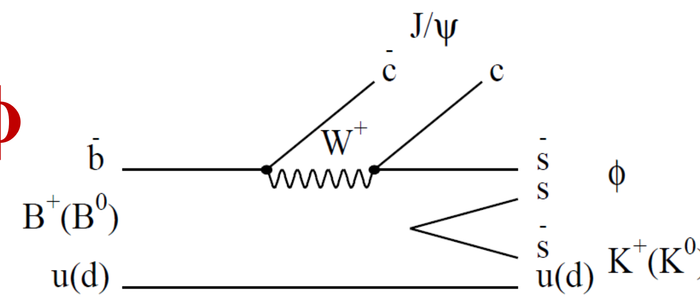




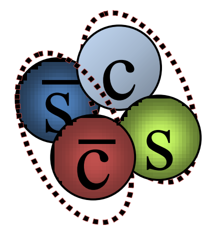



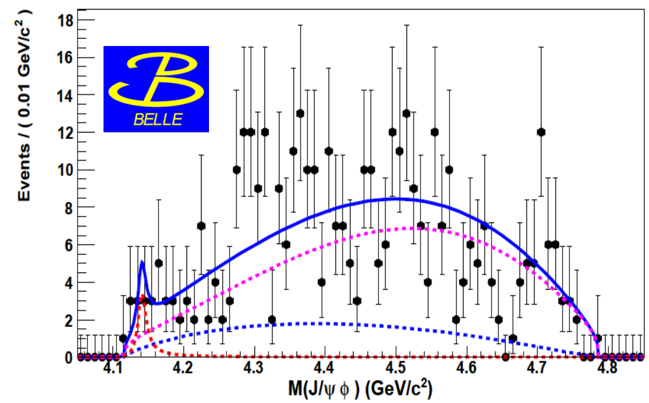




# $B^+ \to J/\psi \phi K^+$
# $Y(4140) \to J/\psi \phi$



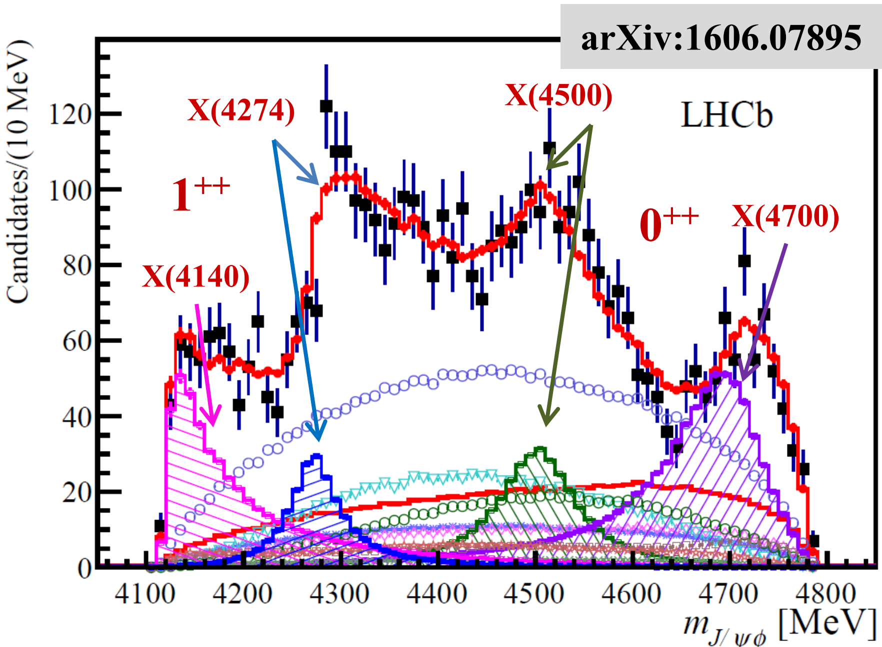

Y(4140) & Y(4274)
narrow peak at threshold
and one more nearby

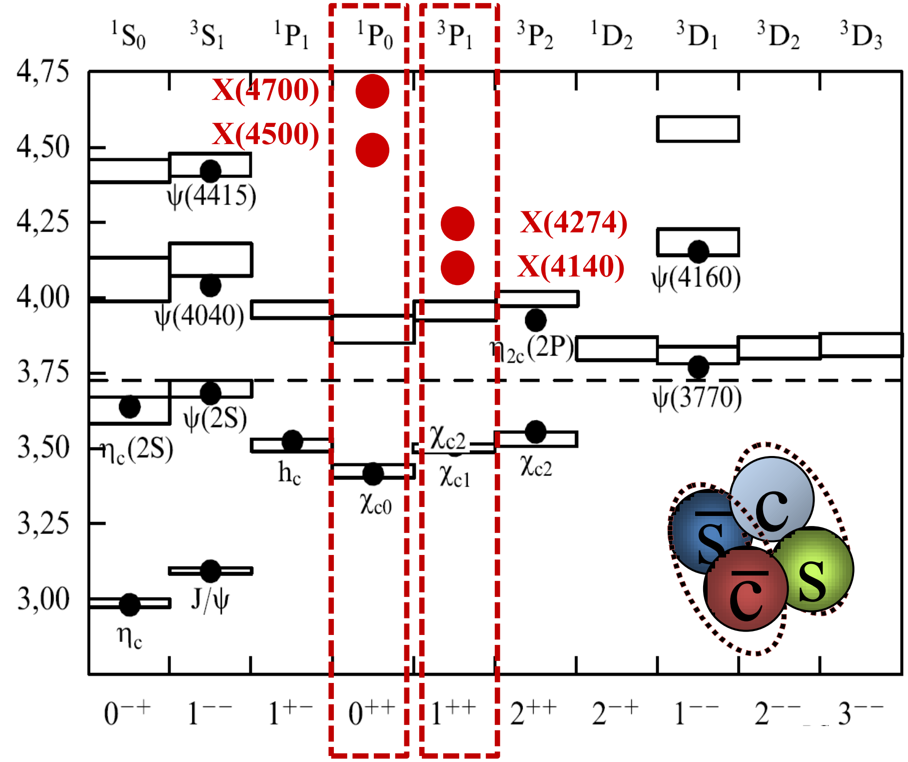



| Exp. | $N_B$ | Mass [MeV ] | Width [MeV ] | $\sigma$ | Frac. [%] |
|---|---|---|---|---|---|
| CDF [1] | 58 | 4143.0±2.9±1.2 | $11.7^{+8.3}_{-5.0}$±3.7 | 3.8 | |
| *Belle* [19] | *325* | *4143.0 fixed* | *11.7 fixed* | *1.9* | |
| *CDF* [26] | *115* | *$4143.4^{+2.9}_{-3.0}$±0.6* | *$15.3^{+10.4}_{-6.1}$±2.5* | *5.0* | *15±4±2* |
| LHCb [21] | 346 | 4143.4 fixed | 15.3 fixed | 1.4 | < 7 |
| CMS [23] | 2480 | 4148.0±2.4±6.3 | $28^{+15}_{-11}$ ± 19 | 5.0 | 10±3 |
| D0 [24] | 215 | 4159.0±4.3±6.6 | 19.9±12.6 $^{+1.0}_{-8.0}$ | 3.1 | 21±8±4 |
| BaBar [22] | 189 | 4143.4 fixed | 15.3 fixed | 1.6 | < 13 |
| D0 [25] | – | 4152.5±1.7 $^{+6.2}_{-5.4}$ | 16.3±5.6±11.4 | 4.7–5.7 | – |
| Average | | 4143.4±1.9 | 15.7±6.3 | | |

# $B^+ \to J/\psi\phi K^+$ at LHCb




Full amplitude analysis to obtain spin-parity

**FOUR NEW STATES!!!**

Theory:

X(4140) $D_sD_s^*$ cusp? tetraquark?

X(4274) tetraquark?

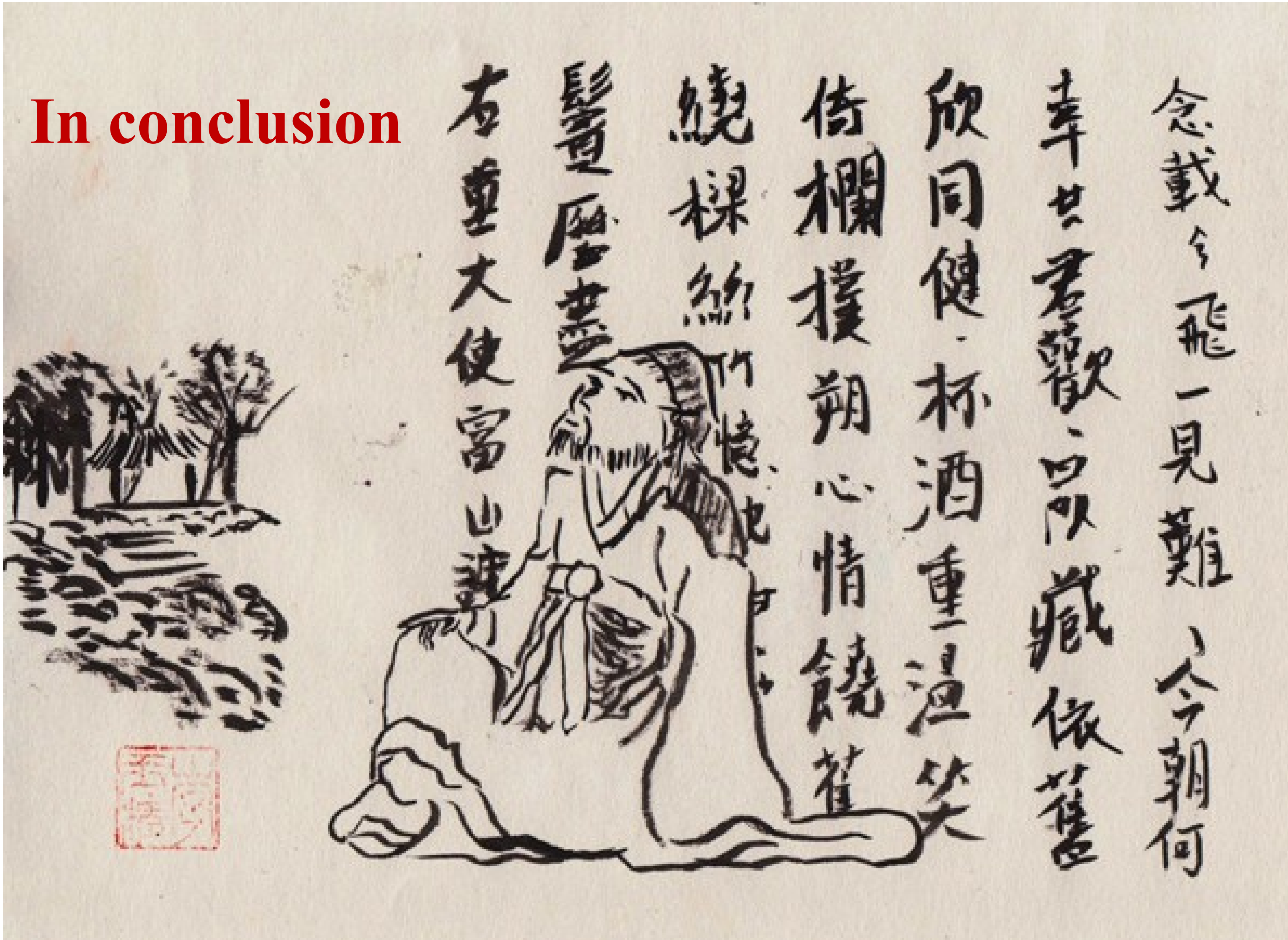
X(4500) $D_s^*D_s^*$ cusp?

X(4700)?

| | | | | |
|---|---|---|---|---|
| All $X(1^+)$ | | | | $16\pm3\ {}^{+\ 6}_{-\ 2}$ |
| $X(4140)$ | $8.4\sigma$ | $4146.5\pm4.5\ {}^{+4.6}_{-2.8}$ | $83\pm21\ {}^{+21}_{-14}$ | $13\pm3.2\ {}^{+4.7}_{-2.0}$ |
| ave. | Table 1 | $4143.4\pm1.9$ | $15.7\pm6.3$ | |
| $X(4274)$ | $6.0\sigma$ | $4273.3\pm8.3\ {}^{+17.2}_{-\ 3.6}$ | $56\pm11\ {}^{+\ 8}_{-11}$ | $7.1\pm2.5\ {}^{+3.5}_{-2.4}$ |
| CDF | [26] | $4274.4\ {}^{+8.4}_{-6.7}\pm1.9$ | $32\ {}^{+22}_{-15}\pm8$ | |
| CMS | [23] | $4313.8\pm5.3\pm7.3$ | $38\ {}^{+30}_{-15}\pm16$ | |
| All $X(0^+)$ | | | | $28\pm\ 5\pm\ 7$ |
| $\mathrm{NR}_{J/\psi\phi}$ | $6.4\sigma$ | | | $46\pm11\ {}^{+11}_{-21}$ |
| $X(4500)$ | $6.1\sigma$ | $4506\pm11\ {}^{+12}_{-15}$ | $92\pm21\ {}^{+21}_{-20}$ | $6.6\pm2.4\ {}^{+3.5}_{-2.3}$ |
| $X(4700)$ | $5.6\sigma$ | $4704\pm10\ {}^{+14}_{-24}$ | $120\pm31\ {}^{+42}_{-33}$ | $12\pm\ 5\ {}^{+\ 9}_{-\ 5}$ |

?

# In conclusion



# Conclusion

- Since 2002 six standard charmonium states were discovered. ***Charmonium table below DD threshold is completed now.***

- About two dozens of charmoniumlike states were found recently and this list continues to increase. ***All of them are above open charm threshold.***

- Nature of the most of XYZ states is open question yet.

- ***Precise measurements of known charmonium(+like) states and search for new charmonium(+like) states above open charm threshold are needed.***