# Heavy quarkonium and quarkonium–like states at Belle and BaBar

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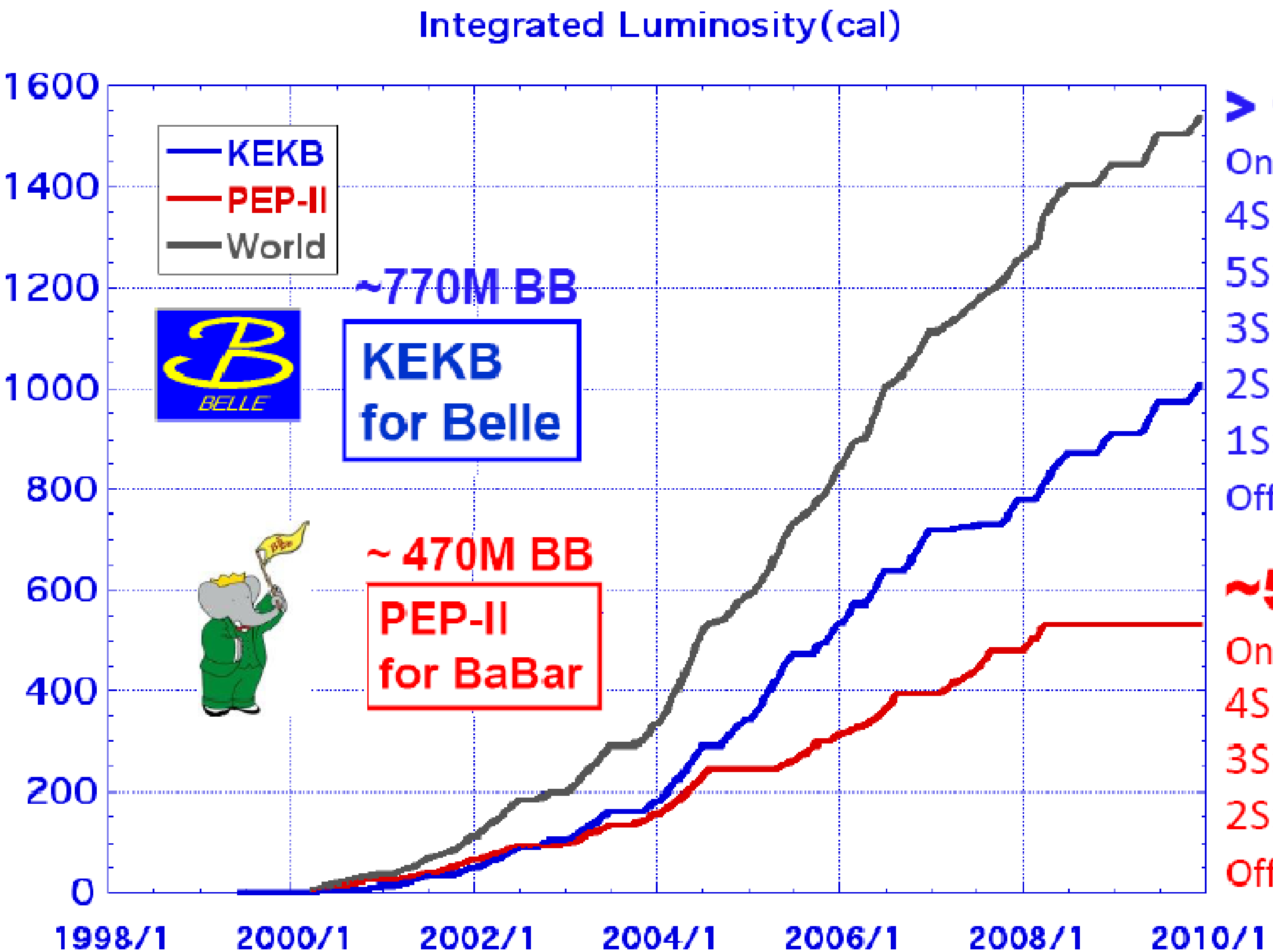
**Outline:**

- -Quarkonium production at B-factories
- -X(3872)
- -X,Y,Z(3940)
- -Charged Z states
- -Quarkonium in ISR
- -Upsilon scan results
- -Summary

# Luminosity at B factories




**> 1.0 $ab^{-1}$**

On-resonance samples:

4S: 711 $fb^{-1}$

5S: 121 $fb^{-1}$

3S: 3.0 $fb^{-1}$

2S: 24 $fb^{-1}$

1S: 5.7 $fb^{-1}$

Off-resonance: 87 $fb^{-1}$

**~553 $fb^{-1}$**

On-resonance samples:

4S: 433 $fb^{-1}$

3S: 30 $fb^{-1}$

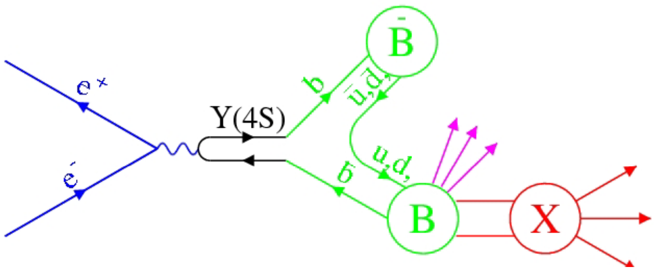
2S: 14 $fb^{-1}$

Off-resonance: 54 $fb^{-1}$

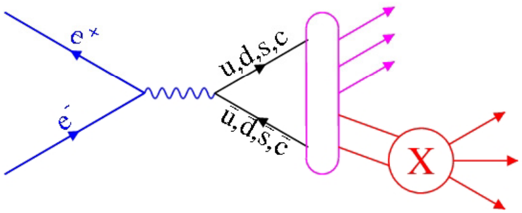
# Quarkonium production at B factories

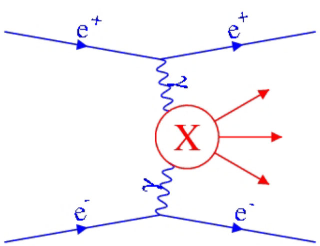
- **Energy scan and Y(nS) transitions**

- **Production from B decay**



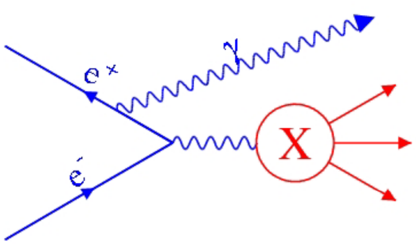

- **Production from continuum**
  **Double charmonium production**



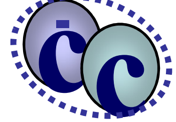



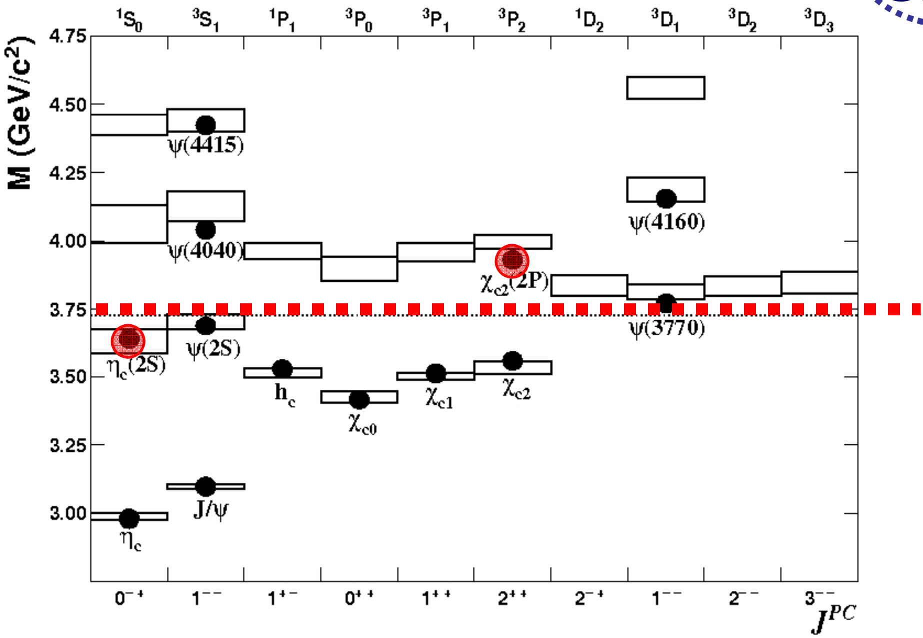

- **Two-photon production**

- **Initial state radiation**



# Conventional charmonium




**Discovered at B-factories**

$\eta(2S)$, $Z(3930)=\chi_{c2}(2P)$

**Exotic charmonium-like states**

**Double charmonium:**

**X(3940), X(4160)**

**Decays with $\psi(\psi')$:**

**X(3872), Y(3940), Y(4008), Y(4260), Y(4360), Y(4630),Y(4660)….**

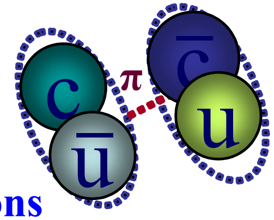
**Charged charmonium:**

**Z(4430), $Z_1(4058)$, $Z_2(4258)$**

# Exotic charmonium-like states

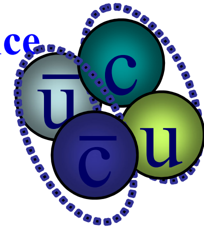
- **Multiquark states**
  - *Molecular state*

    two loosely bound charm mesons
    - quark/color exchange at short distances
    - pion exchange at large distance



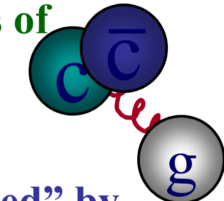

  - *Tetraquark*

    tightly bound four-quark state

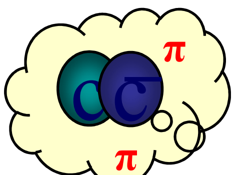



- **Charmonium hybrids**

  - States with excited gluonic degrees of freedom




- **Hadro-charmonium**
  - Specific charmonium state “coated” by excited light-hadron matter



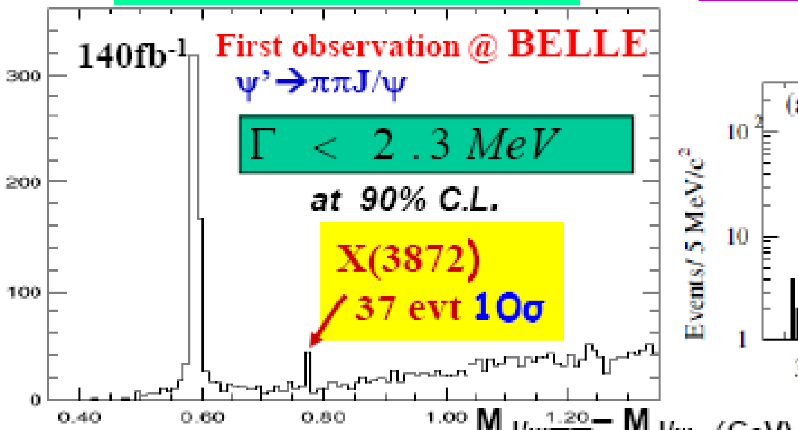

- **Threshold effects**
  - Virtual states at thresholds
  - Charmonium states with masses shifted by nearby $D_{(s)}^{(*)}D_{(s)}^{(*)}$ thresholds

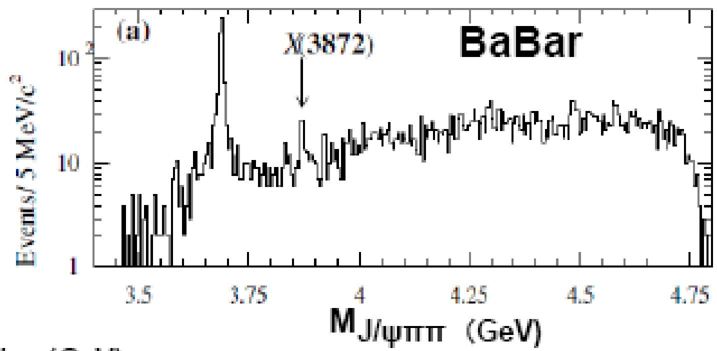
# X(3872)

# Discovery of X(3872)

- X(3872) was discovered by Belle at 2003 in $\pi\pi J/\psi$ mass distribution and confirmed by BaBar, CDF and D0.
- First exotic charmonium

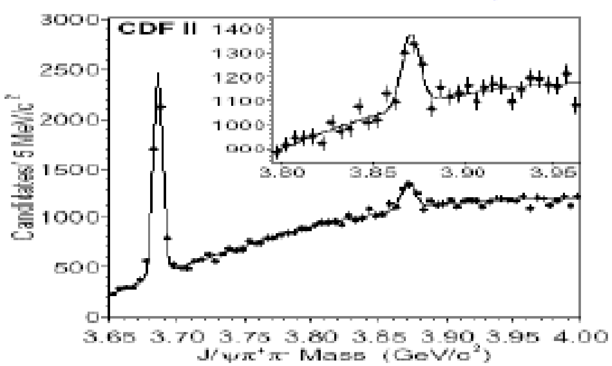
Belle PRL 91, 262001 (2003)

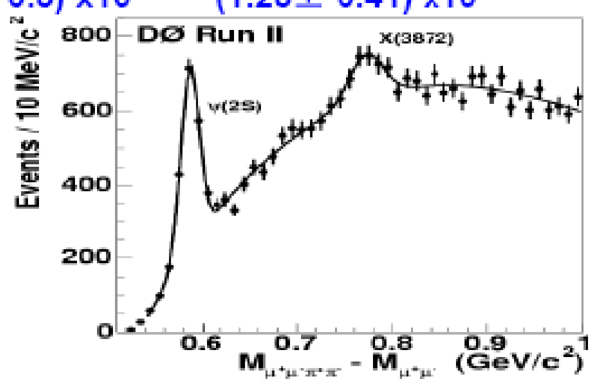



$M_X$ = 3872.0 ± 0.6 ± 0.5 MeV    3873.4 ± 0.14 MeV

Br($B^- \to XK^-$) × Br($X \to J/\psi\pi\pi$) = (1.3 ± 0.3) $\times 10^{-5}$    (1.28 ± 0.41) $\times 10^{-5}$



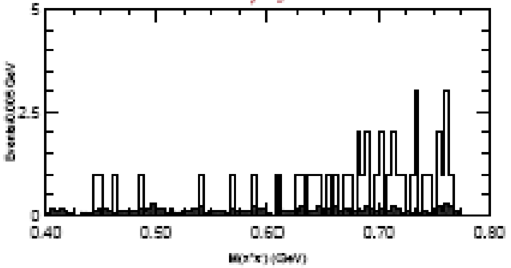

$M_X$ = 3871.3 ± 0.7 ± 0.4 MeV    $M_{J/\psi\pi\pi} - M_{J/\psi}$ = 774.9 ± 3.1 ± 3.0 MeV

hep-ex/0505037(2005)

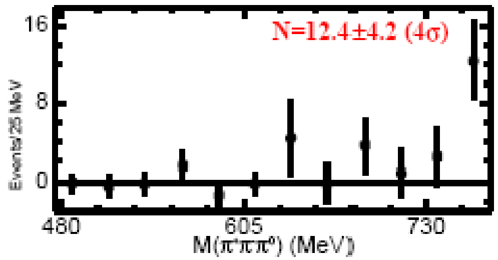
# X(3872) properties

253 $fb^{-1}$

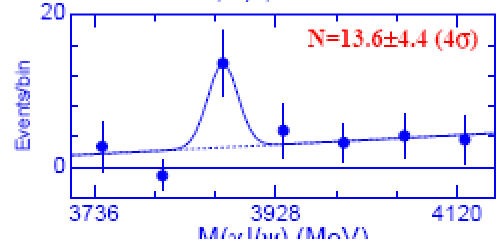
$B \to K\pi^+\pi^- J/\psi$



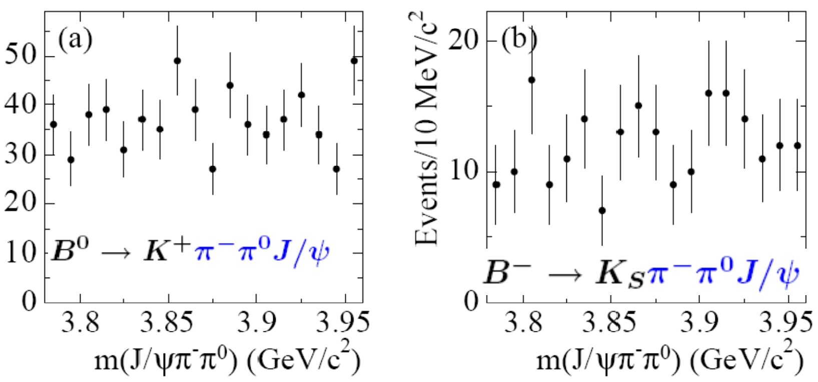
$B \to K\pi^+\pi^-\pi^0(\omega) J/\psi$

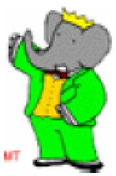



$B \to K\gamma J/\psi$

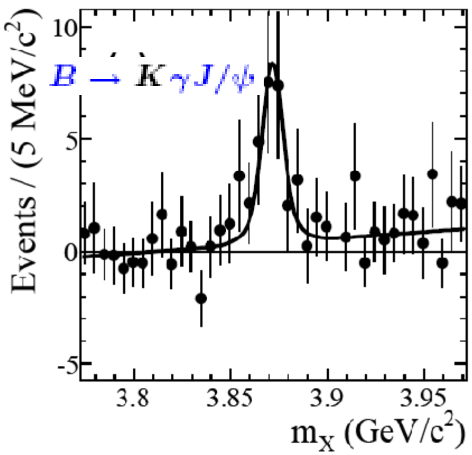



BaBar PRD 71, 031501(2005)



BaBar PRL 102, 182002(2009)




- $M_{\pi^+\pi^-} \approx M_\rho$ (violates isospin)
- Decays to $J/\psi\gamma$, $\psi(2S)\gamma \Rightarrow C = +1$
- Spin-parity analysis $\Rightarrow J^{PC} = 1^{++}, 2^{-+}$
- Doesn't decay to $\chi_{c1}\gamma$, $D\bar{D}$, $\gamma\gamma$, $e^+e^-$
- No charged partner, not an isovector

# Search for other decay modes with X(3872)

Measurement $B^{\pm} \to X(3872)K^{\pm}$ and $B^0 \to X(3872)K_S$

Doublet X?

BaBar PRD 77, 111101(R)(2008)

413 $fb^{-1}$

$$\frac{\mathcal{B}(B^0 \to XK^0)}{\mathcal{B}(B^{\pm} \to XK^{\pm})} = 0.41 \pm 0.24 \pm 0.05$$

Belle Arxiv:0909.1224

605 $fb^{-1}$

$$\frac{\mathcal{B}(B^0 \to XK^0)}{\mathcal{B}(B^{\pm} \to XK^{\pm})} = 0.82 \pm 0.22 \pm 0.05$$

(<0.1 for a molecule, 1 for $c\bar{c}$, $c\bar{c}g$, $gg$)

$$\Delta M = 2.7 \pm 1.6 \pm 0.4\ MeV/c^2$$

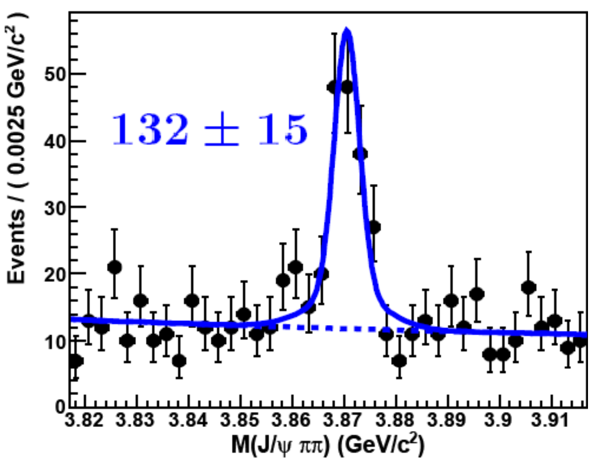
$$\Delta M = 0.18 \pm 0.89 \pm 0.26\ MeV/c^2$$

$$M_X = 3871.46 \pm 0.37 \pm 0.07 MeV/c^2$$

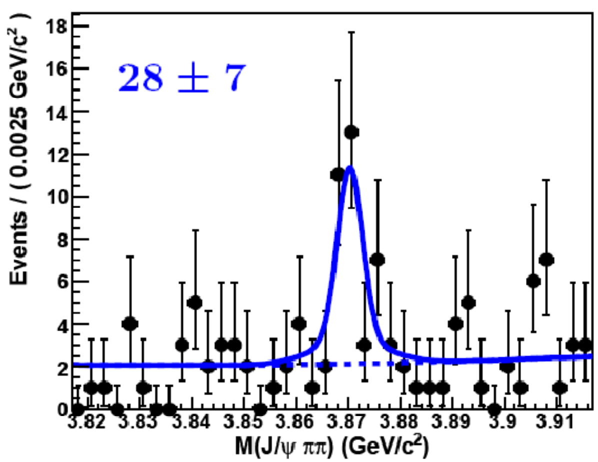
CDF PRL 103, 152001(2009)

$$M_X = 3871.61 \pm 0.16 \pm 0.19 MeV/c^2$$

$B^+ \to X(3872)K^+$



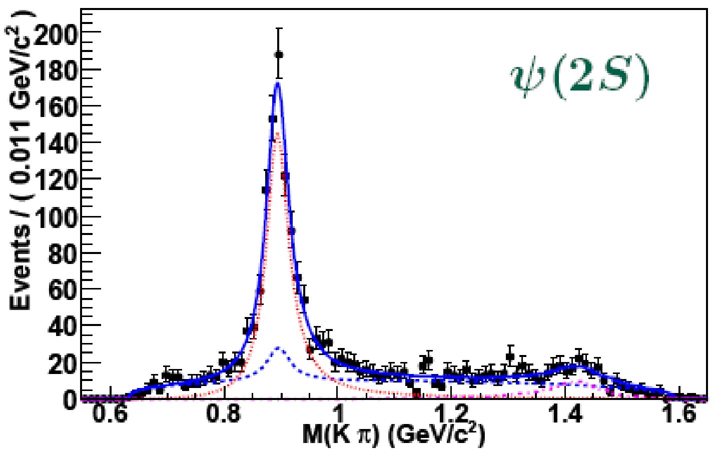

$B^0 \to X(3872)K_S$

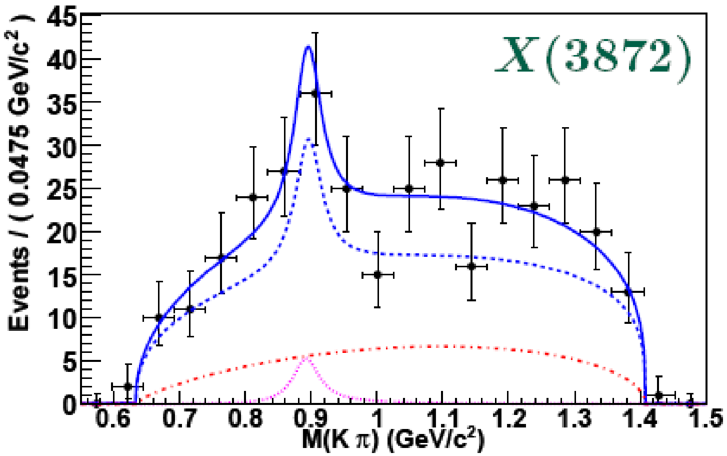


# X(3872) new production mode

Belle ArXiv:0809.1224(2008)

- $B^0 \to X(3872)(K^+\pi^-)_{NR}$ observed
- $\mathcal{B}(B^0 \to X(K^+\pi^-)_{NR})\mathcal{B}(X \to J/\psi\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$
- $\mathcal{B}(B^0 \to XK^{*0}(892))\mathcal{B}(X \to J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$
- $K^*$ fraction is small unlike to $c\bar{c}$

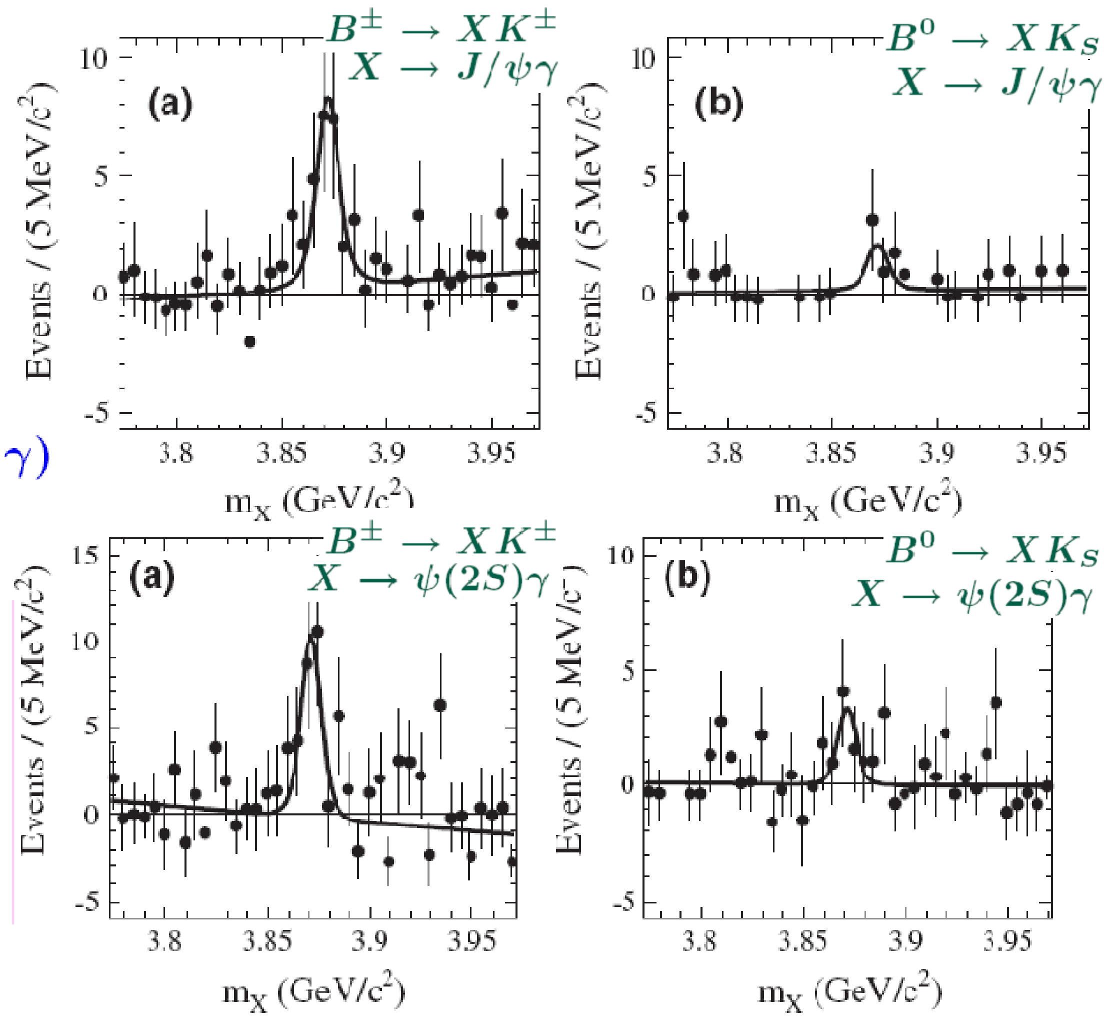


# Measurement $B \to X(3872)K$. $X \to J/\psi\gamma, X \to \psi(2S)\gamma$

**BaBar PRL 102, 132001(2009)**

$424\ \mathrm{fb}^{-1}$




**new decay mode**

$$\mathcal{B}(B^\pm \to XK^\pm) \times \mathcal{B}(X \to \psi(2S)\gamma)$$
$$= (9.5 \pm 2.7 \pm 0.6) \times 10^{-6}$$
$$\frac{\mathcal{B}(\psi(2S)\gamma)}{\mathcal{B}(J/\psi\gamma)} = 3.4 \pm 1.4$$

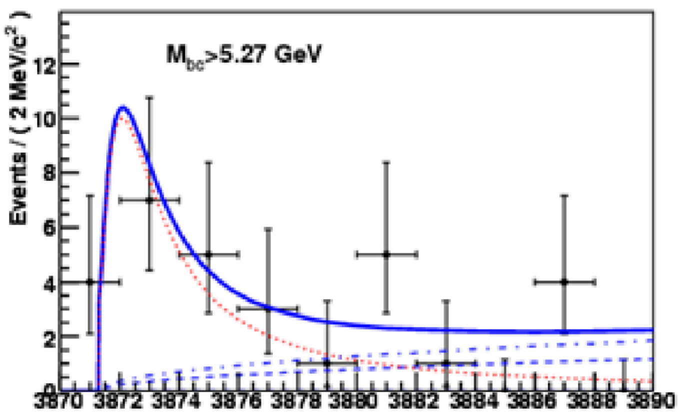
**Disfavor to $D\bar{D}^*$ molecule**

# Study of $B \to X(3872)(D^{*0}\bar{D}^0)K$

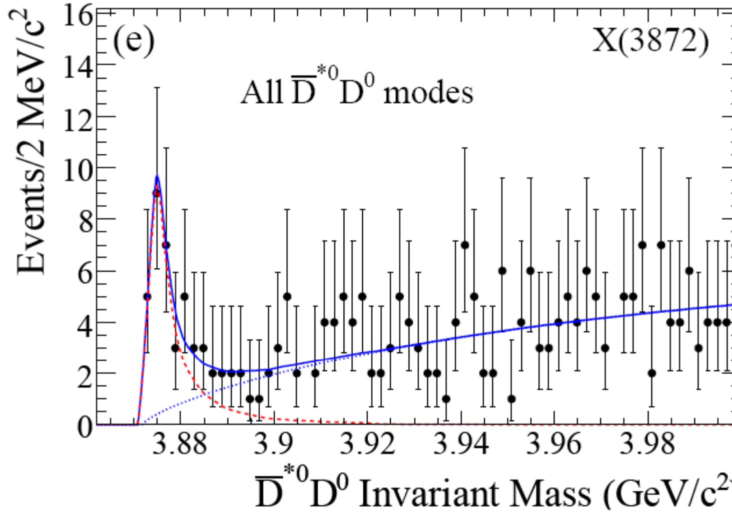
$D^{*0} \to D^0\pi^0$

$D^{*0} \to D^0\gamma$

Belle PRD 81, 031103(2010)




BaBar PRD 77, 011102(2008)




- $M = 3872.6^{+0.5}_{-0.4} \pm 0.4\ MeV/c^2$; $\Gamma = 3.9^{+2.5+0.8}_{-1.3-0.3}\ MeV$
- No significant mass difference from $X \to J/\psi\pi^+\pi^-$
- $\mathcal{B}(B^0 \to XK)\mathcal{B}(X \to \bar{D}^0 D^{*0}) = (0.73 \pm 0.17 \pm 0.09)$ $M = 3875.1^{+0.7}_{-0.5} \pm 0.5 MeV/c^2$

Still there is no clear understanding of X(3872)

**More data is necessary**

# X(3940), Y(3940), Z(3930)

# X(3940), Y(3940), Z(3930)

Belle PRL 98, 082001(2007)

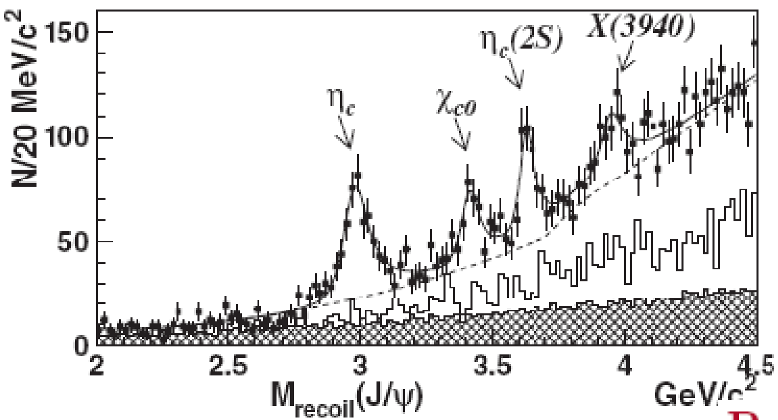
Belle PRL 100, 202001(2008)

$357\ fb^{-1}$

Reconstruction $J/\psi \to l^+l^-$

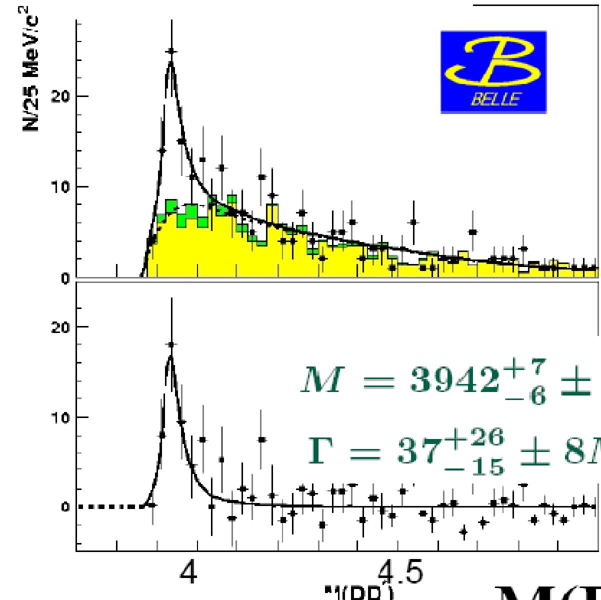
Observation in $J/\psi$ recoil mass:

$$M_{rec} = \sqrt{(E_{CM} - E^*_{J/\psi})^2 - p^{*\,2}_{J/\psi}}$$




$\eta_c(3S)$?

$e^+e^- \to J/\psi D D^*$ $693\ fb^{-1}$




$M = 3942^{+7}_{-6} \pm 6 MeV/c^2$

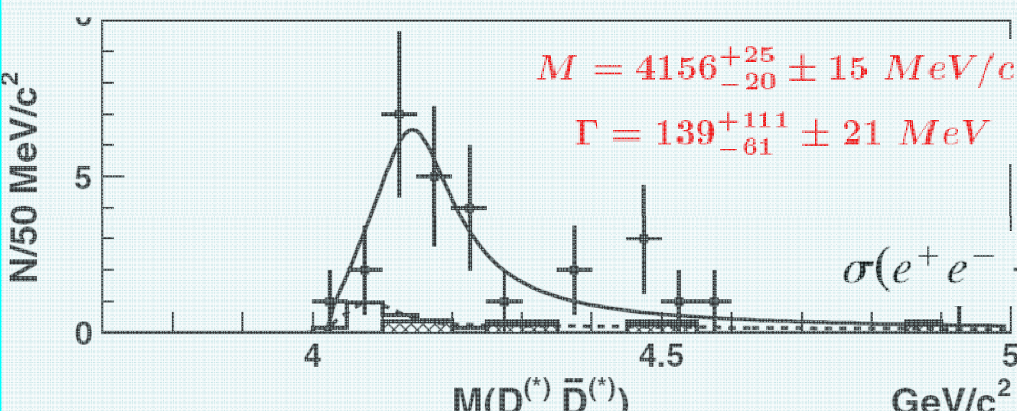
$\Gamma = 37^{+26}_{-15} \pm 8 MeV$

$M(D\bar{D}^*)$

Potential models predict mass of $\eta(3S) \sim 100\ MeV$ higher

$e^+e^- \to J/\psi D^* \bar{D}^*$

$N = 23.8^{+12.3}_{-8.0}$ **(5.5σ)**




$M = 4156^{+25}_{-20} \pm 15\ MeV/c^2$

$\Gamma = 139^{+111}_{-61} \pm 21\ MeV$

expected contribution of $\psi(4160)$ $0.5 \pm 0.3$

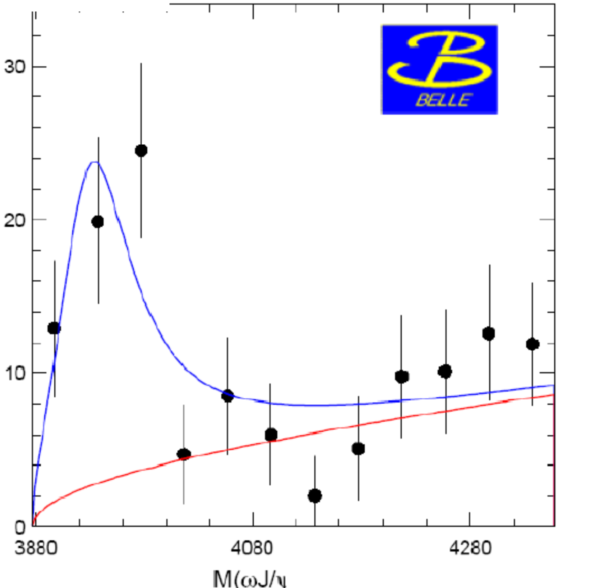
**New state**

$$\sigma(e^+e^- \to J/\psi X(4160))\mathcal{B}_{D^*\bar{D}^*} = (24.2^{+12.8}_{-8.3} \pm 5.0)\ fb$$

# X(3940), Y(3940), Z(3930)

Belle PRL 94, 182002(2005)

253 $\text{fb}^{-1}$




**M(ωJ/ψ)**

$N = 58 \pm 11 (> 8\sigma)$

$M_Y = 3943 \pm 11 \pm 13$ MeV

$\Gamma_Y = 87 \pm 22 \pm 26$ MeV

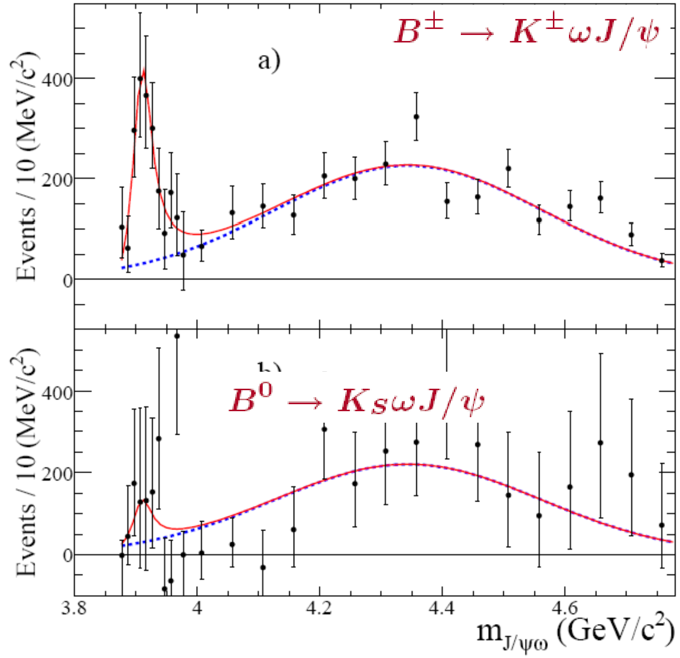
$\text{B}(\text{B} \to KY)\mathcal{B}(Y \to \omega J/\psi) =$
$(7.1 \pm 1.3 \pm 3.1) \times 10^{-5}$

$$\frac{\mathcal{B}(X(3940) \to \omega J/\psi)}{\mathcal{B}(X(3940) \to D^{*0}\bar{D})} < 0.58$$

$$\frac{\mathcal{B}(Y(3940) \to \omega J/\psi)}{\mathcal{B}(Y(3940) \to D^{*0}\bar{D})} > 0.71$$

BaBar PRL 101, 082001(2008)

350 $\text{fb}^{-1}$




$M_Y = 3914^{+3.8}_{-3.4} \pm 2$ MeV

$\Gamma_Y = 34^{+12}_{-8} \pm 5$ MeV

Some discrepancy in M & Γ

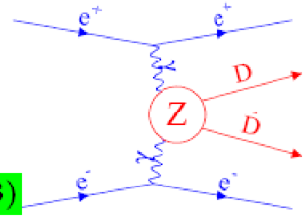
General features agree

- Radially excited $c\bar{c}$?
  - Large $Br(Y \to \omega J/\psi)$
    $D^{(*)}\bar{D}^{(*)}$ decay modes expected to be dominated
- $c\bar{c}$-gluon hybrid?
  - $D^{(*)}\bar{D}^{(*)}$ suppression
  - predicted masses 4.3 – 4.5 GeV

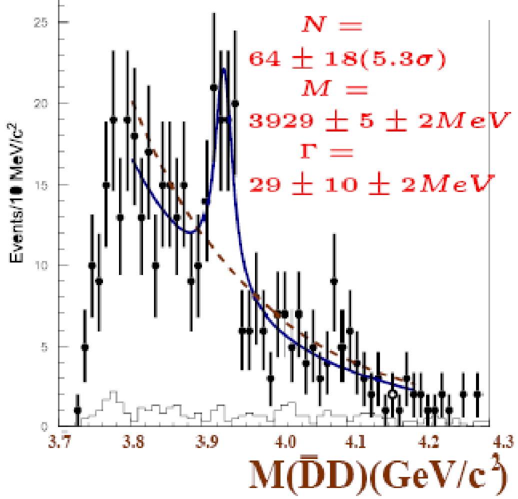
No evidence $X(3940) \to J/\psi\omega$

$X(3940) \neq Y(3940)$

# X(3940), Y(3940), Z(3930)




Belle PRL 96, 082003(2006)

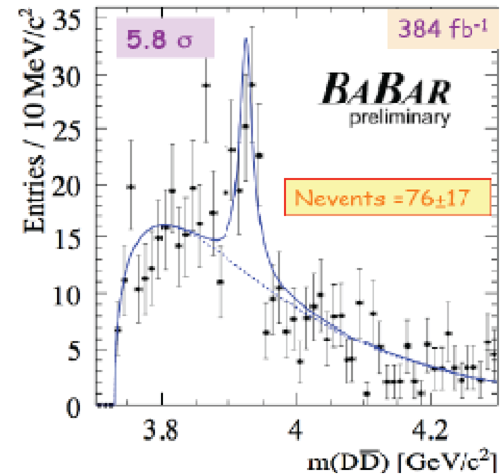


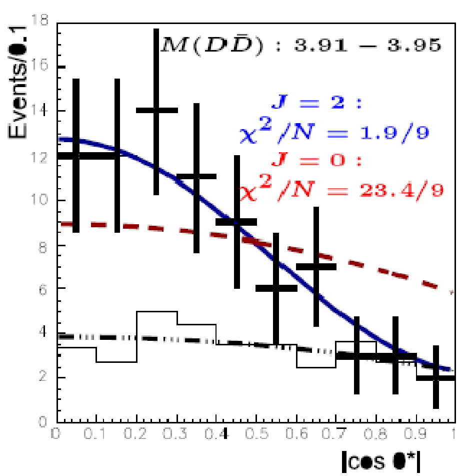

$$M = 3929 \pm 5 \pm 2\ MeV/c^2$$

$$\Gamma = 29 \pm 10 \pm 2\ MeV$$

$$\Gamma_{\gamma\gamma}\mathcal{B}(Z \to D\bar{D}) = 0.18 \pm 0.05 \pm 0.03\ keV$$

BaBar arXiv:1002.0281(2010)

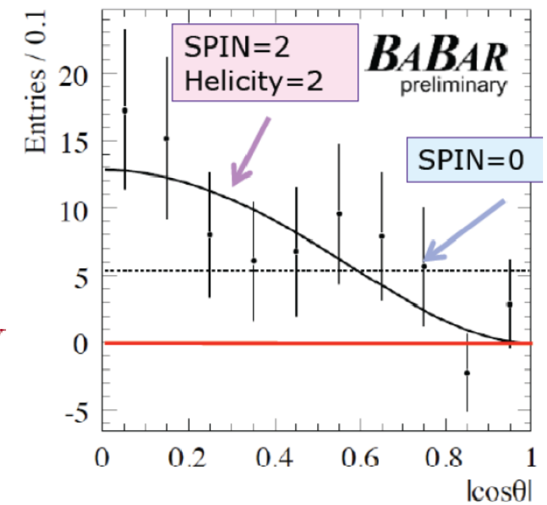



$$M = 3926.7 \pm 2.7 \pm 1.1\ MeV/c^2$$

$$\Gamma = 21.3 \pm 6.8 \pm 3.6\ MeV$$

$$\Gamma_{\gamma\gamma}\mathcal{B}(Z \to D\bar{D}) = 0.241 \pm 0.054 \pm 0.043\ keV$$

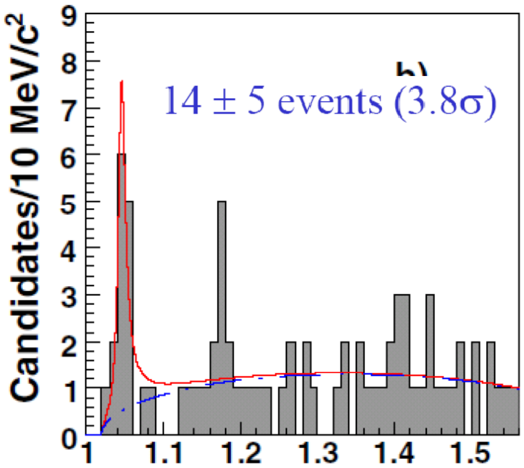



Belle and BaBar results are consistent with each other and $\chi_{c2}(2P)$

# X(4140)

CDF observed new charmonium like state in $B^+ \to \phi J/\psi K^+$

CDF, PRL 102, 242002 (2009)




ΔM (GeV/c²) =M(μμKK)-M(μμ)

$$M = 4143.0 \pm 2.9 \pm 1.2\ MeV/c^2$$

$$\Gamma = 11.7^{+8.3}_{-5.3} \pm 3.7\ MeV$$

$c\bar{c}s\bar{s}$ tetraquark $D_s^* \bar{D}_s^*$ melecule ?

Belle has not seen the Y(4140) in B decays:

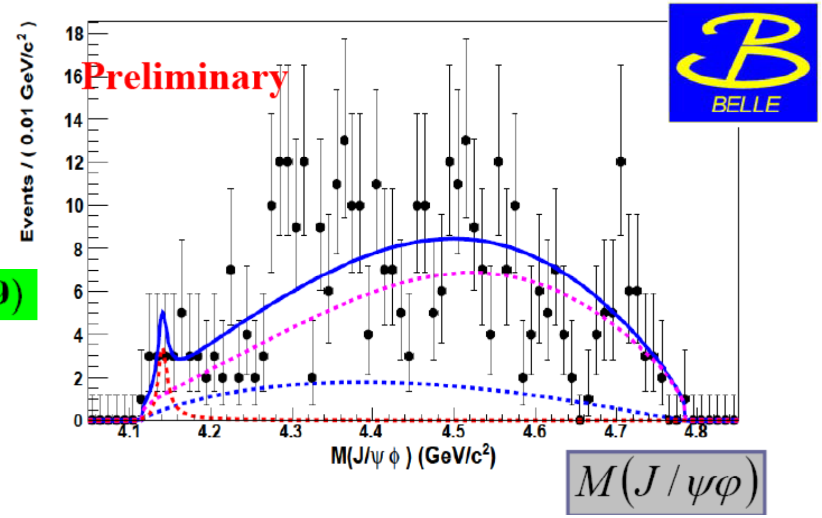
$$\mathcal{B}(B^\pm \to Y K^\pm) \times \mathcal{B}(Y \to J/\psi\phi) < 6 \times 10^{-6} (90\% CL)$$

or in two-photon

Belle PRL 104, 112004(2009)

$$\Gamma_{\gamma\gamma}\mathcal{B}(Y \to \phi J/\psi) < \ 36\ eV \text{ for } J^P = 0^+$$

$$5.3\ eV \text{ for } J^P = 2^+$$

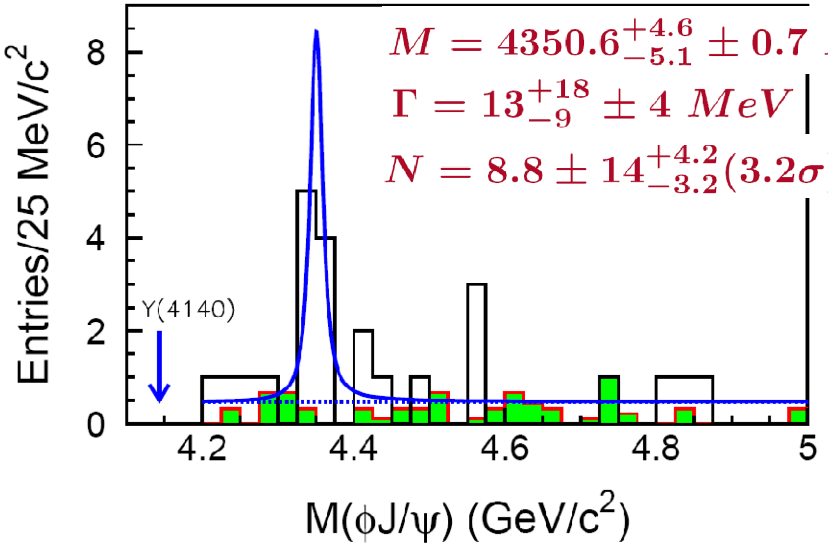


# New states from two-photon study

Belle PRL 104, 112004(2009)

## New peak in $\gamma\gamma \to \phi J/\psi$

$J/\psi \to l^+l^-$ $\omega \to \pi^+\pi^-\pi^0$




$M = 4350.6^{+4.6}_{-5.1} \pm 0.7\ MeV/c^2$

$\Gamma = 13^{+18}_{-9} \pm 4\ MeV$

$N = 8.8 \pm 14^{+4.2}_{-3.2} (3.2\sigma)$

$\Gamma_{\gamma\gamma}\mathcal{B}(Y \to \phi J/\psi) =$

$6.7^{+3.2}_{-2.4} \pm 1.1\ eV$ for $J^P = 0^+$

$1.5^{+0.7}_{-0.6} \pm 0.3\ eV$ for $J^P = 2^+$

$c\bar{c}s\bar{s}$ tetraquark $2^{++}$ ?

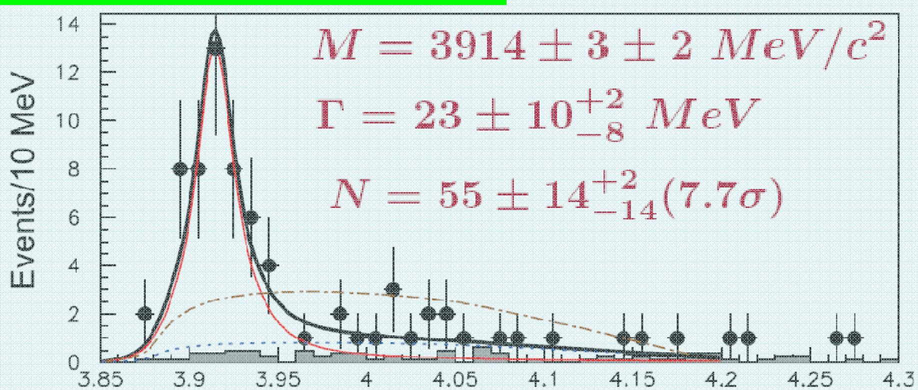
$D_s^{*+}D_{s0}^{*-}$ melecule ?

$\chi''_{c2}$ ?

## New peak in $\gamma\gamma \to \omega J/\psi$

$J/\psi \to l^+l^-$ $\omega \to \pi^+\pi^-\pi^0$

Belle PRL 104, 092001(2010) 694 $fb^{-1}$




$M = 3914 \pm 3 \pm 2\ MeV/c^2$

$\Gamma = 23 \pm 10^{+2}_{-8}\ MeV$

$N = 55 \pm 14^{+2}_{-14} (7.7\sigma)$

$$\Gamma_{\gamma\gamma}(X(3915))\mathcal{B}(X(3915) \to \omega J/\psi) = \begin{cases} (61 \pm 17 \pm 8)\ \text{eV} & \text{for } J^P = 0^+ \\ (18 \pm 5 \pm 2)\ \text{eV} & \text{for } J^P = 2^+,\ \text{helicity-2} \end{cases}$$

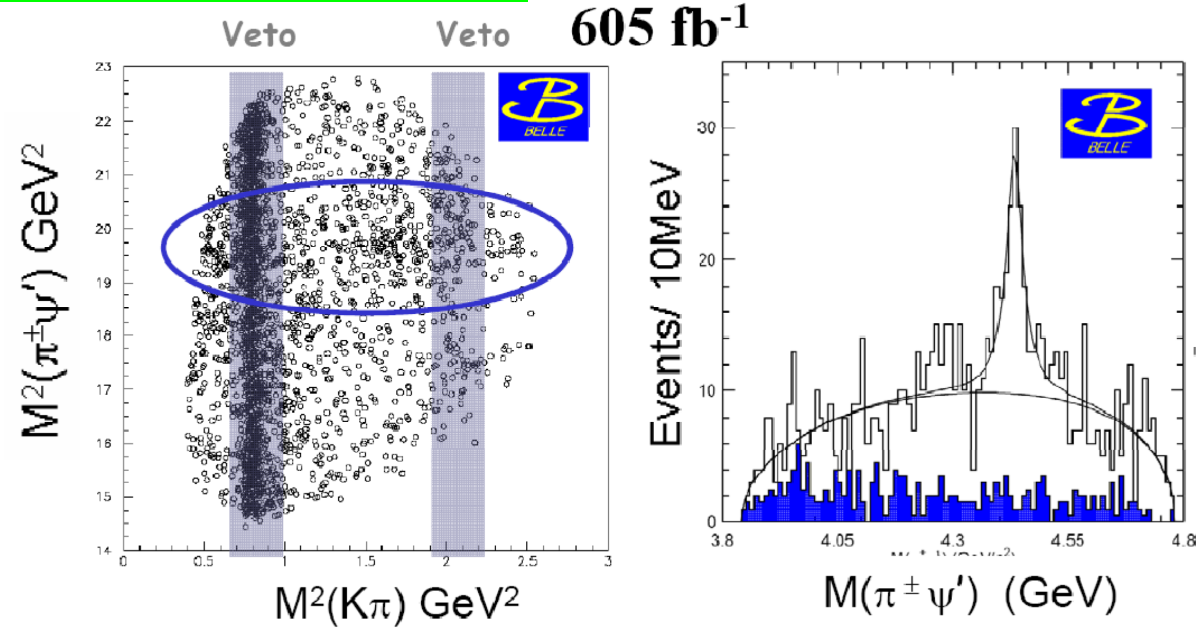
Two photon production of Y(3940)?

New decay mode of Z(3930)?

# Charged charmonia

# Z(4430)$^+$ observation by Belle

Belle PRL 100, 142001(2008)




$B \to \psi(2S)\pi^\pm K$

$\psi(2S) \to l^+l^-,\ J/\psi\pi^+\pi^-$

Veto the $K\pi$ regions of $K^*(892),\ K^*(1430)$

Enhancement at $M(\pi\psi') \sim 4.43\ GeV$

$N_{sig} = 121 \pm 30\ \chi^2/N_{dof} = 80.2/94.0\ 6.5\ \sigma$

$M = 4433 \pm 4 \pm 2\ MeV/c^2;\quad \Gamma = 45^{+18+30}_{-13-33}\ MeV$

$\mathcal{B}(\bar{B}^0 \to Z^+K)\mathcal{B}(Z^+ \to \psi(2S)\pi^+) = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

Tetraquark $(c\bar{c}u\bar{d})$, $D\bar{D}$ molecule?

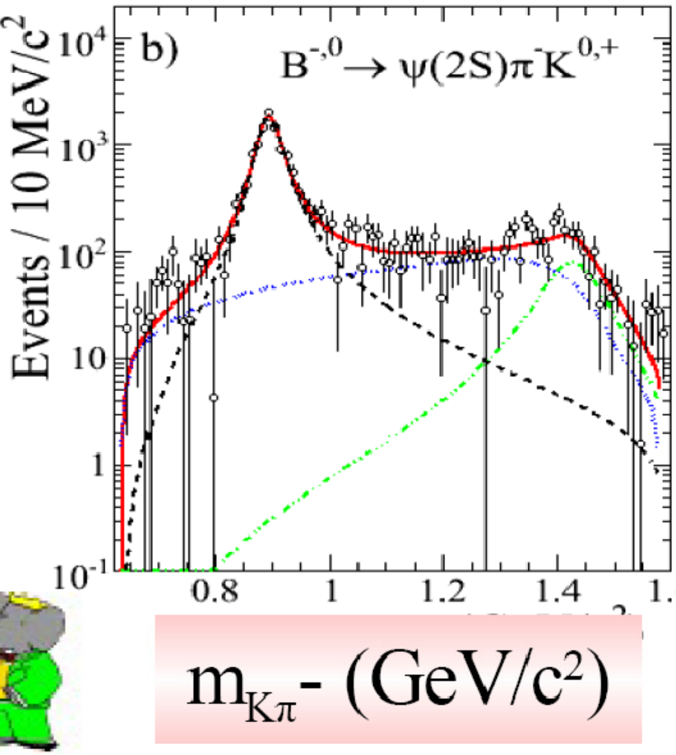
# Search Z(4430) by BaBar

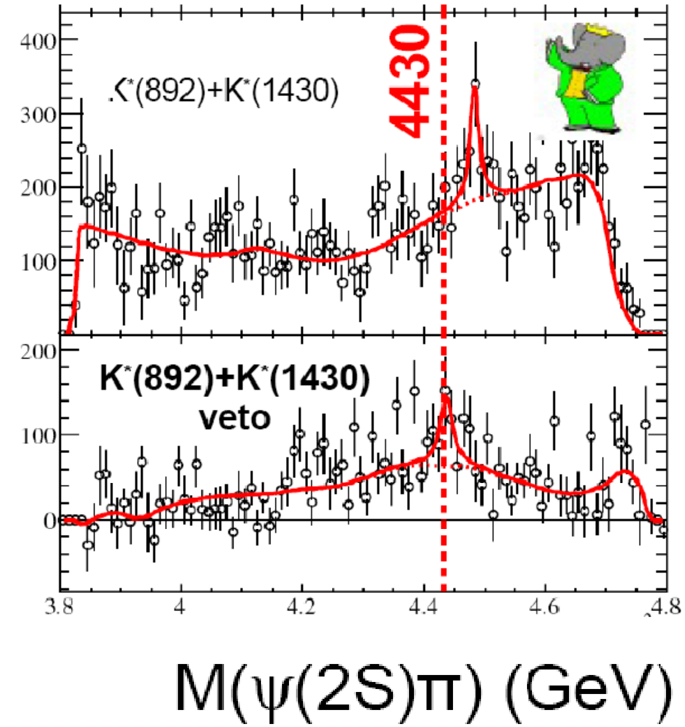
Detailed study of $K\pi$ system

$B \to \psi(2S)\pi^{\pm}K$

$B \to J/\psi\pi^{\pm}K$

BaBar PRD 79, 012001(2009)




$\mathcal{B}(\bar{B}^0 \to Z^+K)\mathcal{B}(Z^+ \to \psi(2S)\pi^+) < (3.1) \times 10^{-5}$

BaBar and Belle values differ by 1.7 $\sigma$ (without systematic)

No conclusive evidence of $Z(4430)^+$

# Z(4430) Dalitz analysis by Belle

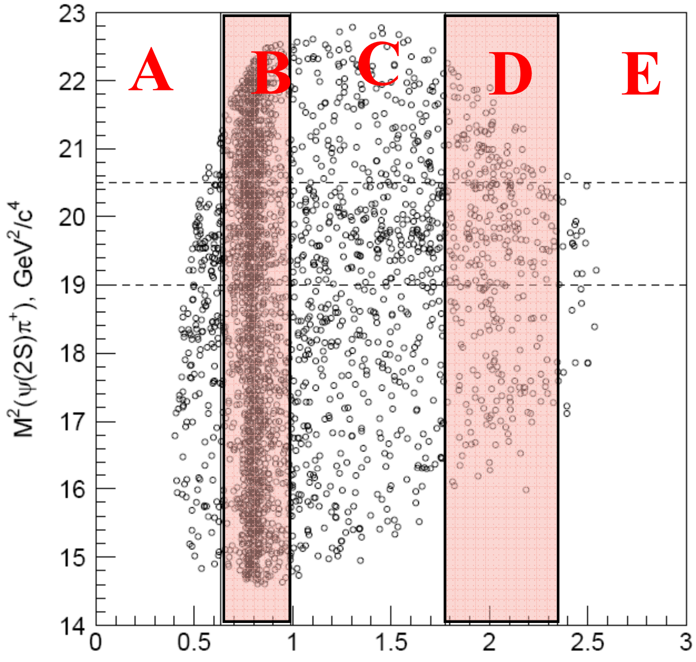
**Belle PRD 80, 031104(2009)**

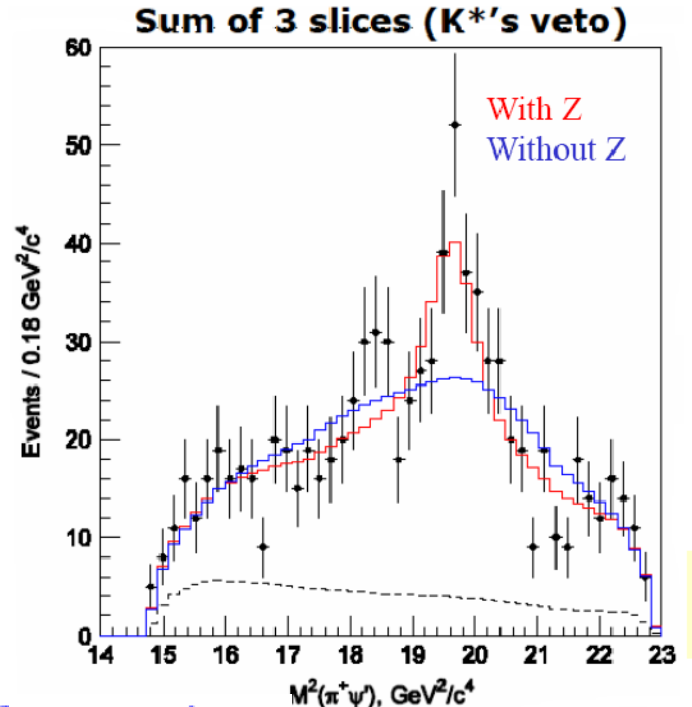
Integration over $\psi$ decay angles

Dalitz plot analysis:

$K\pi$ bound states:

$\kappa$, $K^*(892)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$




Belle confirms the previous result of Z(4430)

$$M = 4443^{+15+17}_{-12-13}\ MeV/c^2$$

$$\Gamma = 109^{+86+57}_{-43-52}\ MeV$$

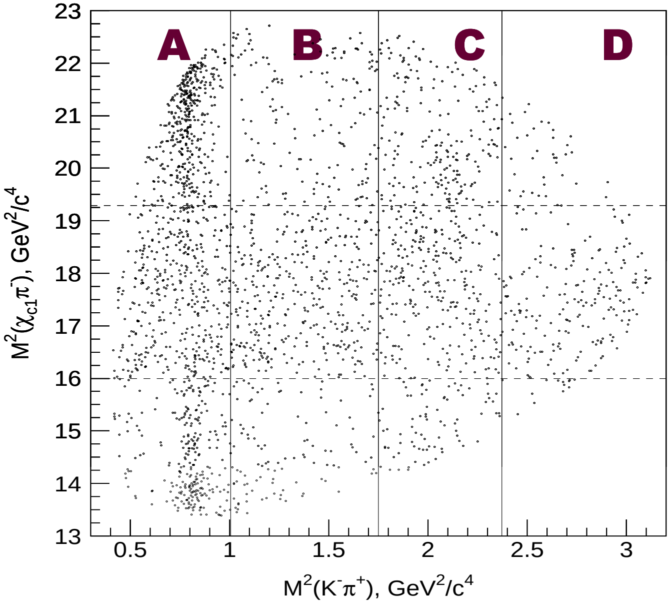
$$\mathcal{B}(\bar{B}^0 \to Z^+K)\mathcal{B}(Z^+ \to \psi(2S)\pi^+) = (3.2^{+1.8+5.3}_{-0.9-1.6}) \times 10^{-5}$$

Fit with/without $Z(4430)^+$ 36%/0.1%

Belle PRD 78, 072004(2008)

# New charged Z's decaying into $\pi^+\chi_{c1}$

## $B \to K^- \pi^+ \chi_{c1}$




Integration over $\psi$ decay angles

Dalitz plot analysis:

$K\pi$ bound states:

$\kappa$, $K^*(892)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$

**No discrimination between J=0 or 1**

$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}/c^2,$$

$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV},$$

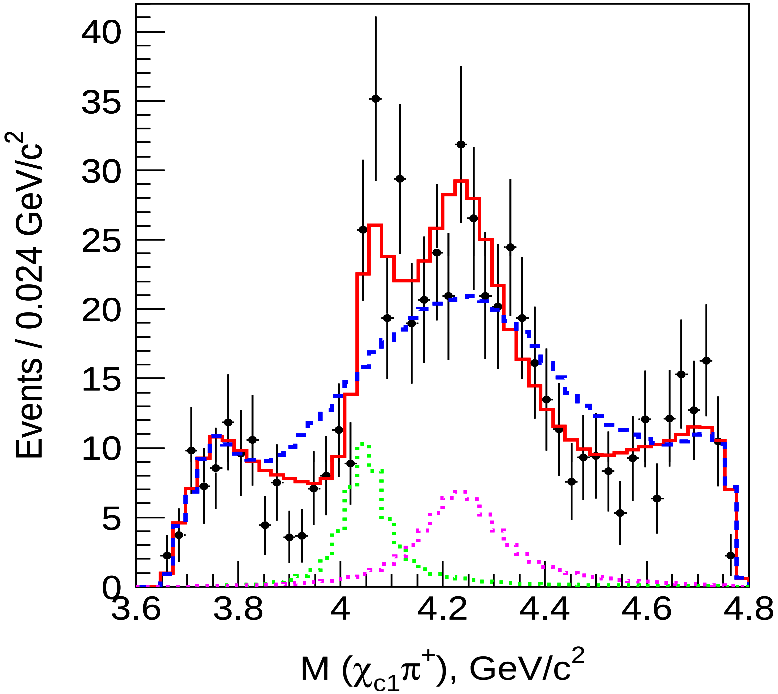
$$M_2 = (4248^{+44+180}_{-29-35})\ \mathrm{MeV}/c^2,$$

$$\Gamma_2 = (177^{+54+316}_{-39-61})\ \mathrm{MeV},$$

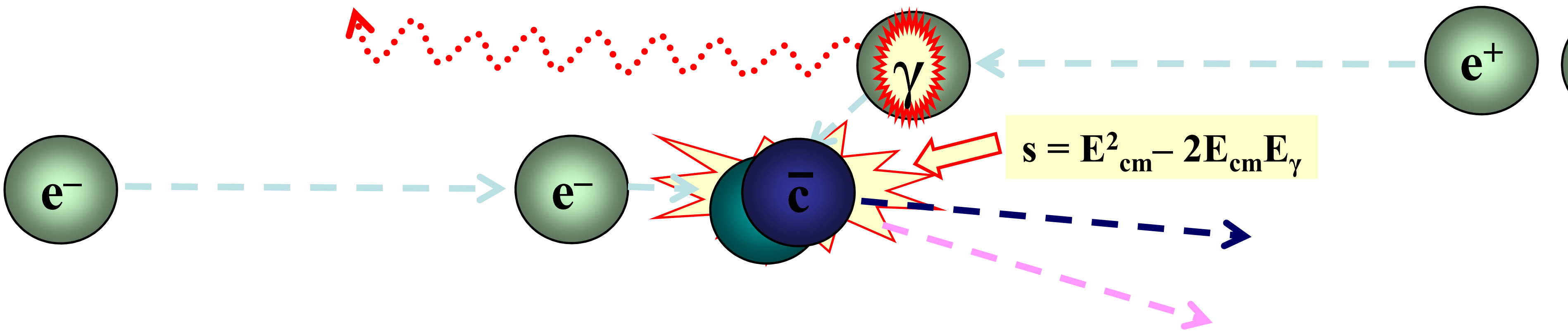
with the product branching fractions of

$$\mathcal{B}(\bar{B}^0 \to K^- Z_1^+) \times \mathcal{B}(Z_1^+ \to \pi^+ \chi_{c1}) = (3.0^{+1.5+3.7}_{-0.8-1.6}) \times 10^{-5},$$

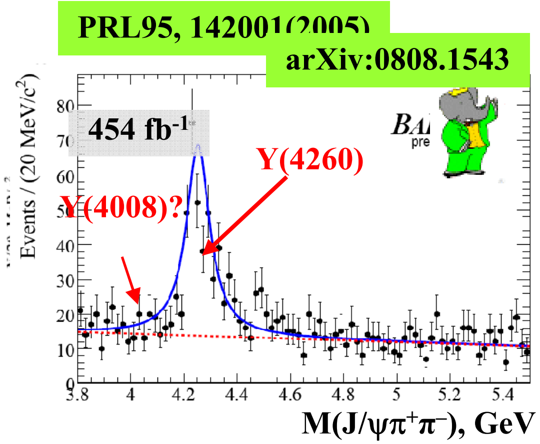
$$\mathcal{B}(\bar{B}^0 \to K^- Z_2^+) \times \mathcal{B}(Z_2^+ \to \pi^+ \chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-0.5}) \times 10^{-5}.$$

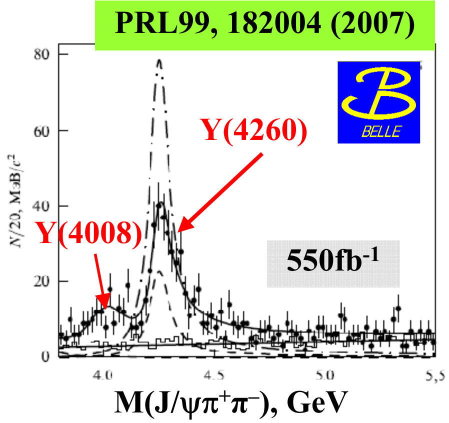


# ISR at B factories




- **Quantum numbers of final states are fixed $J^{PC} = 1^{--}$**
- **Continuous ISR spectrum:**
  - **access to the whole energy range**
  - **$\alpha_{em}$ suppression compensated by huge luminosity**
  - **comparable sensitivity to energy scan (CLEO-c, BES)**



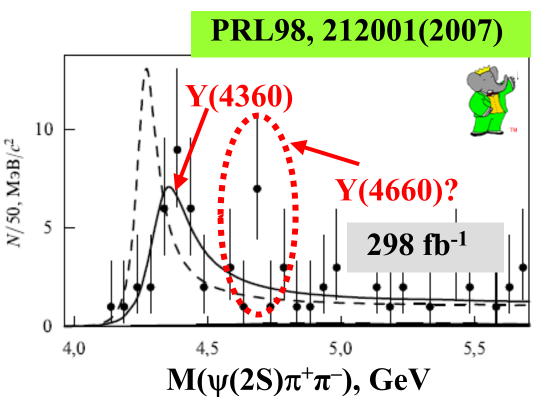

# $e^+e^- \to J/\psi\pi^+\pi^-\gamma_{ISR}$
# Y(4260)... Y(4008)?

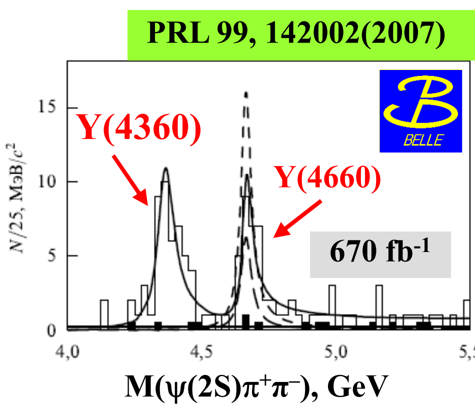
| State | M, $MeV/c^2$ | $\Gamma_{tot}$, MeV |
|---|---|---|
| Y(4008) | $4008 \pm 40^{+114}_{-28}$ | $226 \pm 44 \pm 87$ |
| Y(4260) | $4259 \pm 8^{+2}_{-6}$ | $88 \pm 23^{+6}_{-4}$ |
| Y(4260) | $4252 \pm 6^{+2}_{-3}$ | $105 \pm 18^{+4}_{-6}$ |
| Y(4260) | $4284^{+17}_{-16} \pm 4$ | $73^{+39}_{-25} \pm 5$ |
| Y(4260) | $4247 \pm 12^{+17}_{-32}$ | $108 \pm 19 \pm 10$ |

***$e^+e^- \to J/\psi\, \pi^0\pi^0\gamma_{ISR}$ is on the way***

- 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 ...

*are inconsistent with conventional charmonium*



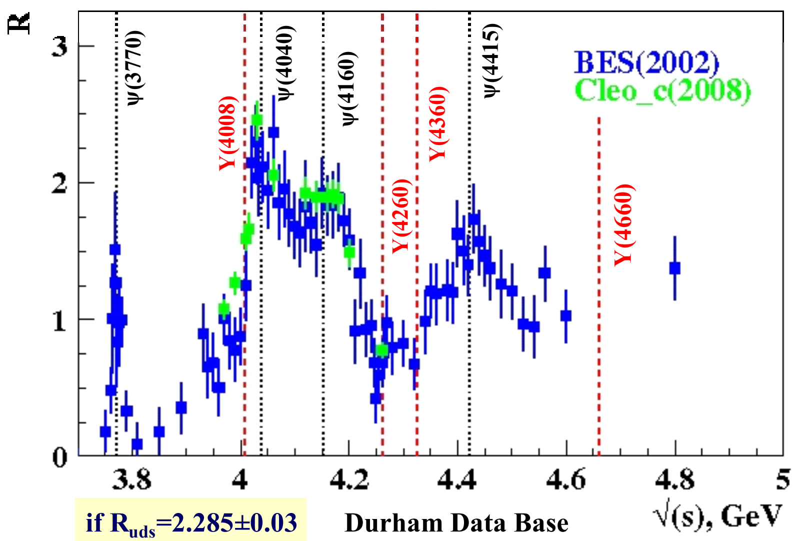



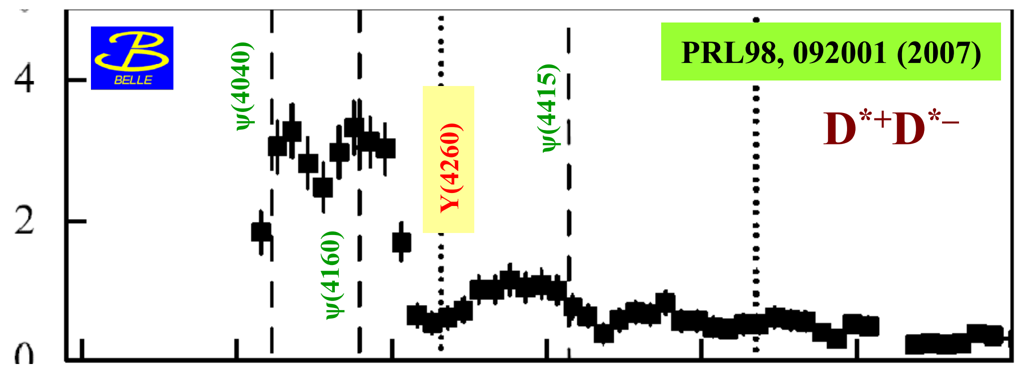

# $e^+e^- \to \psi(2S)\pi^+\pi^-\gamma_{ISR}$
# Y(4360), Y(4660) ...

| State | M, $[MeV/c^2]$ | $\Gamma_{tot}$, [MeV] |
|---|---|---|
| Y(4360) | $4324 \pm 24$ | $172 \pm 33$ |
| Y(4360) | $4361 \pm 9 \pm 9$ | $74 \pm 15 \pm 10$ |
| Y(4360) | $4355^{+9}_{-10} \pm 9$ | $103^{+17}_{-15} \pm 11$ |
| Y(4660) | $4664 \pm 11 \pm 5$ | $48 \pm 15 \pm 3$ |
| Y(4660) | $4661^{+9}_{-8} \pm 6$ | $42^{+17}_{-12} \pm 6$ |

# Y states vs inclusive & exclusive cross sections $e^+e^- \to hadrons$

$R(s) = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-) - R_{uds}$

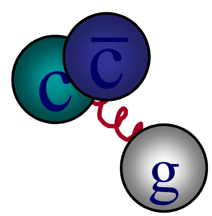


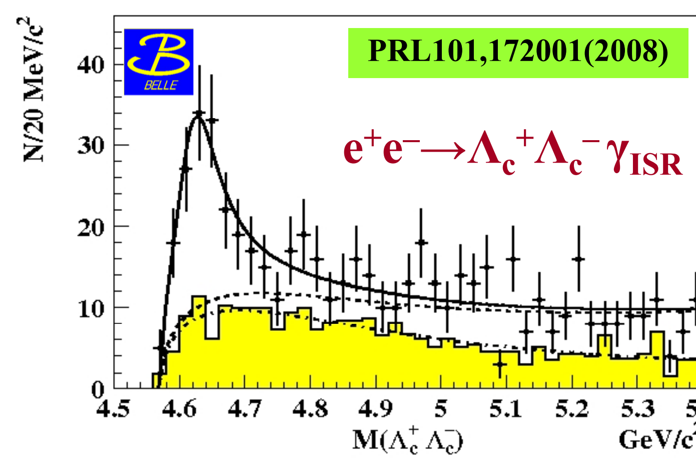




- Peak positions for M(J/ψππ) and M(ψ(2S)ππ) are significantly different
- Y(4260) mass corresponds to dip in inclusive and $D^*D^*$ cross sections
- Y(4660) mass is close to $\Lambda_c^+\Lambda_c^-$ peak

**Interpretations of Y states**

- Conventional charmonia with shifted masses
- Charmonium hybrids
  - The lightest hybrid is expected by LQCD around 4.2 GeV
  - The dominant decays $Y(4260) \to D^{(*)}D^{(*)}\pi$, via virtual $D^{**}$
- Hadro-charmonium
- Multiquark states
- S-wave charm meson thresholds



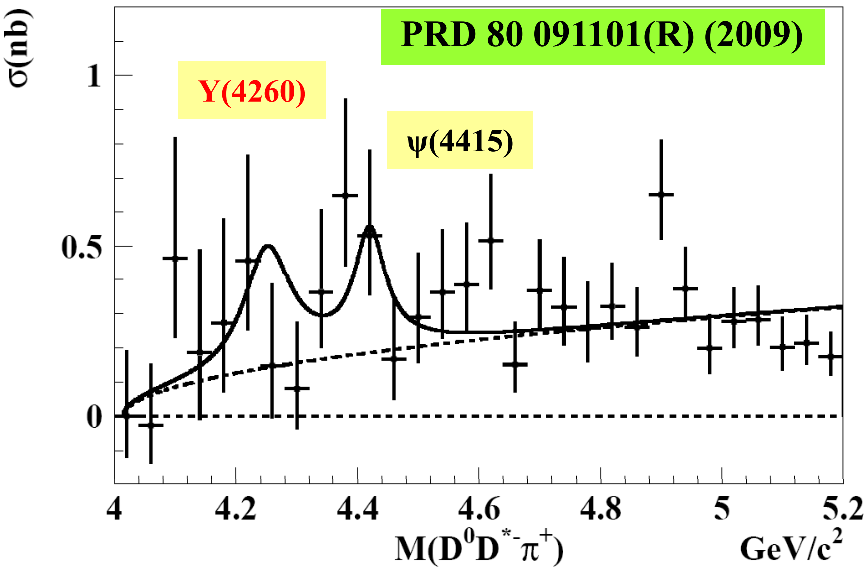




$$\frac{\mathcal{B}(Y(4260) \to D^*\overline{D})}{\mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-)} < 34$$

$$\frac{\mathcal{B}(Y(4260) \to D^*\overline{D}^*)}{\mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-)} < 40$$

PRD 79, 092001 (2009)

# Exclusive $e^+e^- \to D^0D^{*-}\pi^+$ cross-section via ISR




- **No evident structures: only UL's**
- **Baseline fit:**
  - **RBW for $\psi(4415)$ & threshold function for non-resonant contribution without interference between amplitudes**
- **To obtain limits on $X \to D^0D^{*-}\pi^+$,**
  **X=Y(4260), Y(4360), Y(4660), X(4630) perform four fits each with one of the X states, $\psi(4415)$ and non-resonant contribution**

**disfavor hybrid interpretation for Y(4260)**

**$\sigma(e^+e^- \to \psi(4415)) \times Br(\psi(4415) \to D^0D^{*-}\pi^+) < 0.76$ nb at 90% CL**
**$Br(\psi(4415) \to D^0D^{*-}\pi^+) < 10.6$ % at 90% CL**

| UL at 90% CL | $Y(4260)$ | $Y(4350)$ | $Y(4660)$ | $X(4630)$ |
|---|---|---|---|---|
| $\sigma(e^+e^- \to X) \times \mathcal{B}(X \to D^0D^{*-}\pi^+)$, [nb] | 0.36 | 0.55 | 0.25 | 0.45 |
| $\mathcal{B}_{ee} \times \mathcal{B}(X \to D^0D^{*-}\pi^+)$, [$\times 10^{-6}$] | 0.42 | 0.72 | 0.37 | 0.66 |
| $\mathcal{B}(X \to D^0D^{*-}\pi^+)/\mathcal{B}(X \to \pi^+\pi^- J/\psi)$ | 9 | | | |
| $\mathcal{B}(X \to D^0D^{*-}\pi^+)/\mathcal{B}(X \to \pi^+\pi^- \psi(2S))$ | | 8 | 10 | |

# Heavy quarkonia discovered at B-factories

| State | M (MeV) | Γ(MeV) | $J^{PC}$ | Process (mode) | Experiment |
|---|---|---|---|---|---|
| | | | B-decays | | |
| $\eta_c(2S)$ | $3637 \pm 4$ | $14\pm7$ | $0^{-+}$ | $K(K_S^0 K^- \pi^+)$ | Belle(2002), BaBar, CLEO |
| $X(3872)$ | $3871.52\pm0.20$ | $1.3\pm0.6$ | $1^{++}$ | $K(\pi^+\pi^- J/\psi)$<br>$K(D^{*0}\bar{D}^0), \ldots$ | Belle(2003), BaBar,CDF,D0 |
| $Y(3940)$ | $3915.7 \pm 4.2$ | $41\pm12$ | $0/2^{?+}$ | $K(\omega J/\psi)$ | Belle(2004), BaBar |
| $Z_1(4050)^+$ | $4051^{+24}_{-43}$ | $82^{+51}_{-55}$ | ? | $K(\pi^+\chi_{c1}(1P))$ | Belle (2008) |
| $Z_2(4250)^+$ | $4248^{+185}_{-45}$ | $177^{+321}_{-72}$ | ? | $K(\pi^+\chi_{c1}(1P))$ | Belle (2008) |
| $Z(4430)^+$ | $4443^{+24}_{-18}$ | $107^{+113}_{-71}$ | ? | $K(\pi^+\psi(2S))$ | Belle (2007) |
| | | | Double charmonium | | |
| $X(3940)$ | $3942^{+9}_{-8}$ | $37^{+27}_{-17}$ | $?^{?+}$ | $J/\psi(D\bar{D}^*)$ | Belle (2007) |
| $X(4160)$ | $4156^{+29}_{-25}$ | $139^{+113}_{-65}$ | $?^{?+}$ | $J/\psi(D^*\bar{D}^*)$ | Belle (2007) |
| | | | ISR | | |
| $Y(4008)$ | $4008^{+121}_{-49}$ | $226\pm97$ | $1^{--}$ | $(\pi^+\pi^- J/\psi)$ | Belle (2007) |
| $Y(4260)$ | $4263 \pm 5$ | $108\pm14$ | $1^{--}$ | $(\pi^+\pi^- J/\psi)$ | BaBar (2005), Belle, CLEO |
| $Y(4360)$ | $4353 \pm 11$ | $96\pm42$ | $1^{--}$ | $(\pi^+\pi^- \psi(2S))$ | BaBar (2007), Belle |
| $X(4630)$ | $4634^{+9}_{-11}$ | $92^{+41}_{-32}$ | $1^{--}$ | $(\Lambda_c\Lambda_c)$ | Belle (2007) |
| $Y(4660)$ | $4664\pm12$ | $48\pm15$ | $1^{--}$ | $(\pi^+\pi^- \psi(2S))$ | Belle (2007) |
| | | | Two photons | | |
| $\chi_{c2}(2P)$ | $3927.2 \pm 2.6$ | $24.1\pm6.1$ | $2^{++}$ | $(D\bar{D})$ | Belle(2005), BaBar |
| $X(3915)$ | $3914 \pm 4$ | $23^{+10}_{-13}$ | $0, 2^{++}$ | $(\omega J/\psi)$ | Belle(2009) |
| $X(4350)$ | $4350.6^{+4.6}_{-5.1}$ | $13.3^{+18.4}_{-10.0}$ | $0,2^{++}$ | $(\phi J/\psi)$ | Belle(2009) |
| | | | Energy scan and Υ transitions | | |
| $\eta_b(1S)$ | $9390.7 \pm 2.9$ | ? | $0^{-+}$ | $\gamma + (\ldots)$ | BaBar(2008), CLEO |
| $Y_b$ | $10889.6 \pm 2.3$ | $54.7^{+8.9}_{-7.6}$ | $1^{--}$ | $\pi^+\pi^-\Upsilon(nS)$ | Belle (2008) |

# Summary

- **In the experiments at B-factories more than 15 new quarkonia have been discovered (both predicted conventional states and many new exotic quarkonium-like states).**
- **Recent topics:**

**-Charged charmonia**

**-X(4160) in D*D***

**-New narrow peaks observed in two-photon events $J/\psi\omega$ and $J/\psi\phi$**

**-Belle has not confirmed CDF Y(4140)**

**Analysis of B-factories data is still going on…**

# Backup slides

# Υ(5s) scan

Belle arXiv:0808.2445(2008)

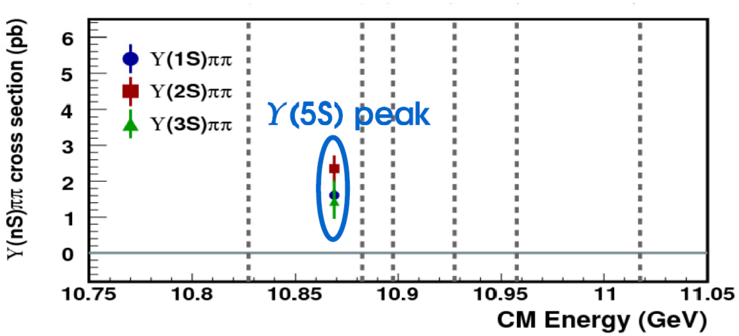
Suprisingly high $\Gamma(\Upsilon(5S) \to \pi\pi\Upsilon(nS))$ were measured

$\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-) = (0.53 \pm 0.03 \pm 0.05)\%$

$\mathcal{B}(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-) = (0.78 \pm 0.06 \pm 0.11)\%$

PRL 100,112001 (2008)

In December 2007 scan at 6 $\sqrt{s}$ between 10.8 11.0 GeV



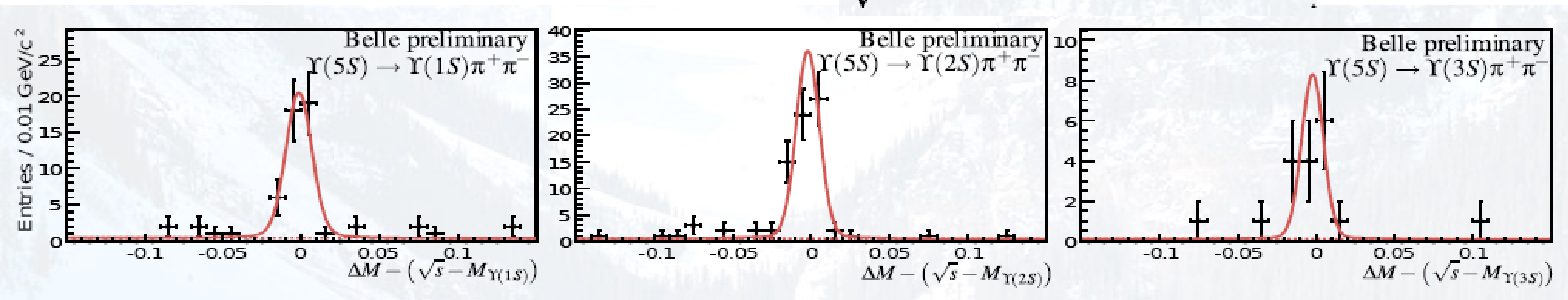

Reconstruction of $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$,

$\Upsilon(nS) \to \mu^+\mu^-$

$\Delta M = M_{(\mu^+\mu^-)\pi^+\pi^-} - M_{(\mu^+\mu^-)}$

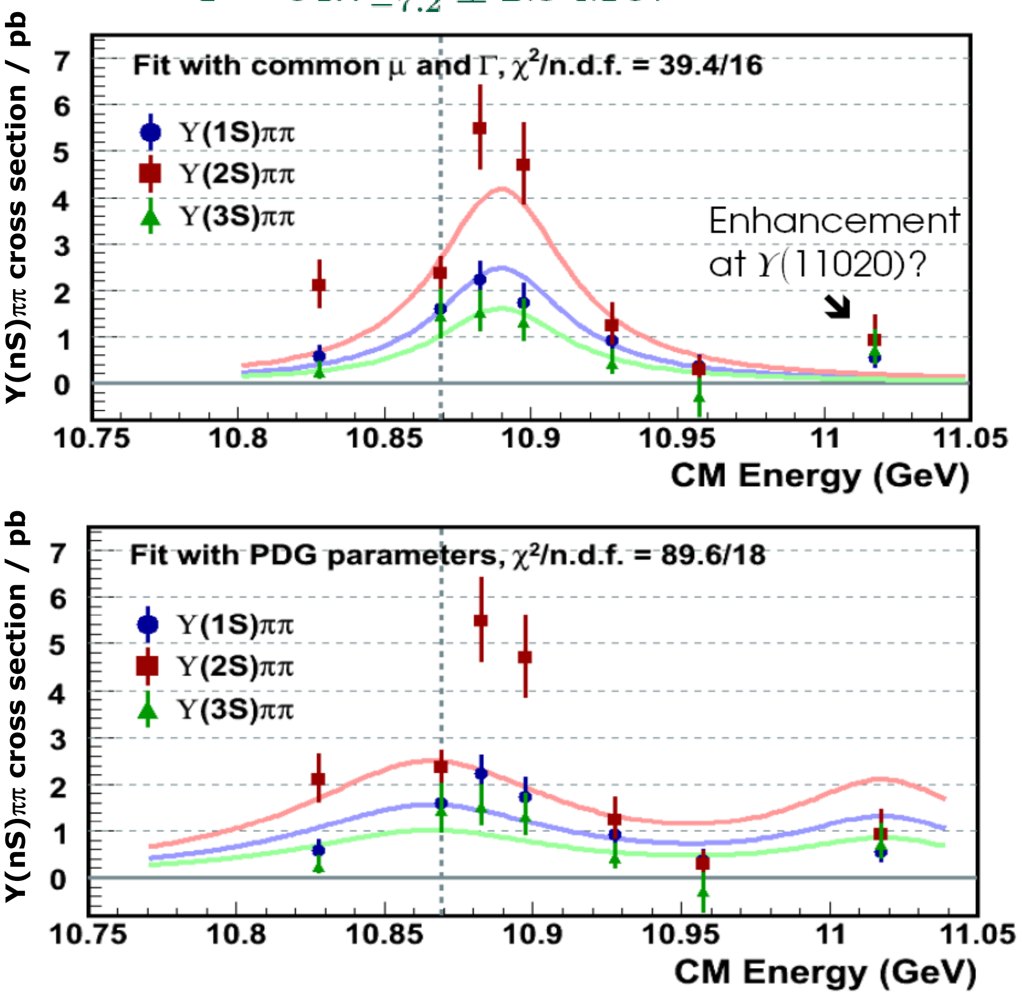
Yields extracted from simultaneous fit

$\sqrt{s} = 10.8825$ GeV



# The $\Upsilon_b(10889)$

$$M = 10889.6 \pm 1.8 \pm 1.5\ MeV/c^2$$
$$\Gamma = 54.7^{+8.5}_{-7.2} \pm 2.5\ MeV$$




- **Fit with 1 Breit-Wigner (floated mean and width) with 3 floated normalizations (for 1S, 2S and 3S)**
- **Comparison $\Upsilon_b$ vs. Υ(5S): mean ~20 MeV higher width around ½**
- **Fit with 2 Breit-Wigners fixed to Υ(10860) = Υ(5S) Υ(11020) = Υ(6S) PDG parameters**
- **Final state interaction or a new state?**

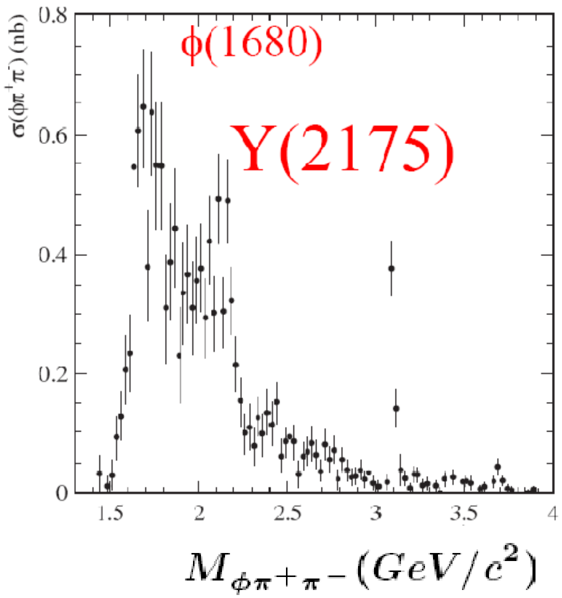
# Y(2175) $e^+e^- \to \phi\pi^+\pi^- \gamma_{ISR}$

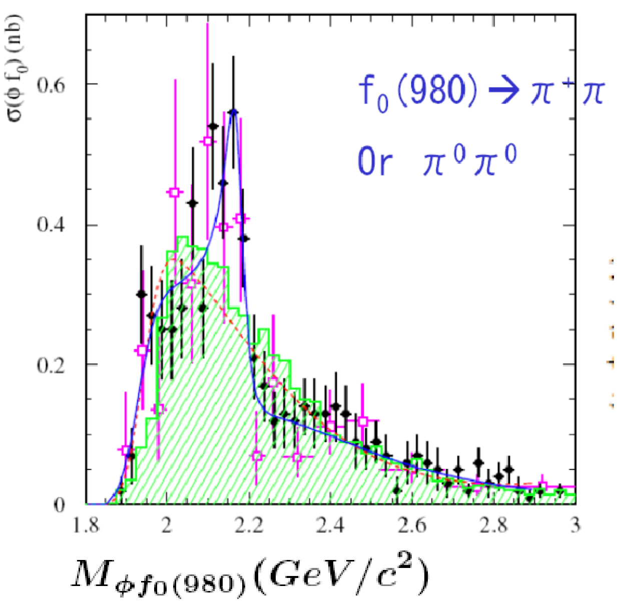
**BaBar PRD 76, 012008(2007)**

BaBar found clear structure above

$\phi(1680) - Y(2175)$ $M = 2175 \pm 10 \pm 15\ MeV/c^2$

$\Gamma = 58 \pm 16 \pm 20\ MeV$

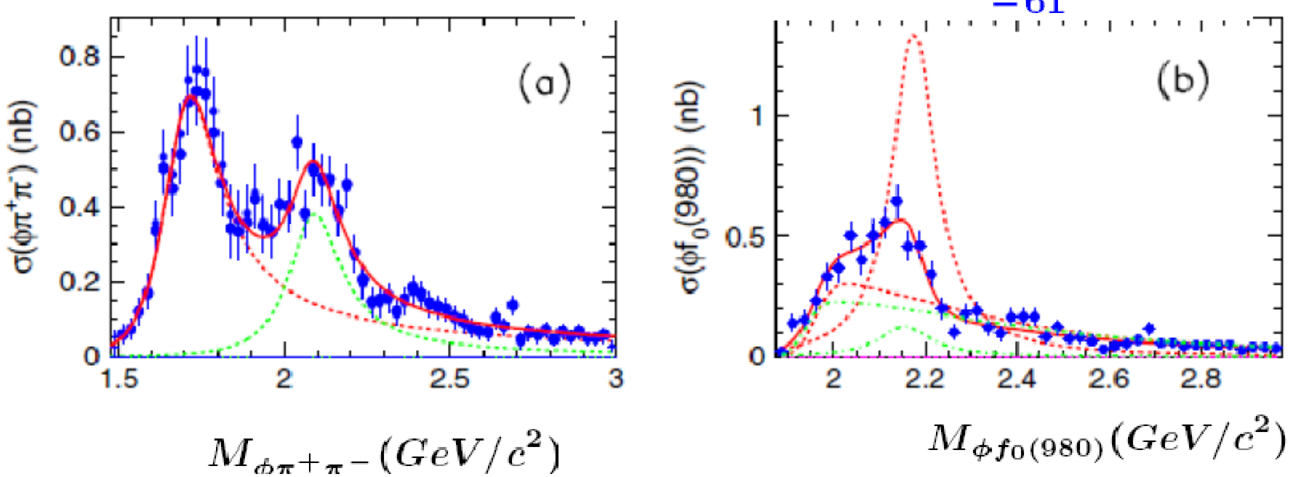



**Belle PRD 80, 031101(R)(2009)**

$M = 2079 \pm 13^{+79}_{-28}\ MeV/c^2$

$\Gamma = 192 \pm 0.023^{+25}_{-61}\ MeV$




***Interpretations:***

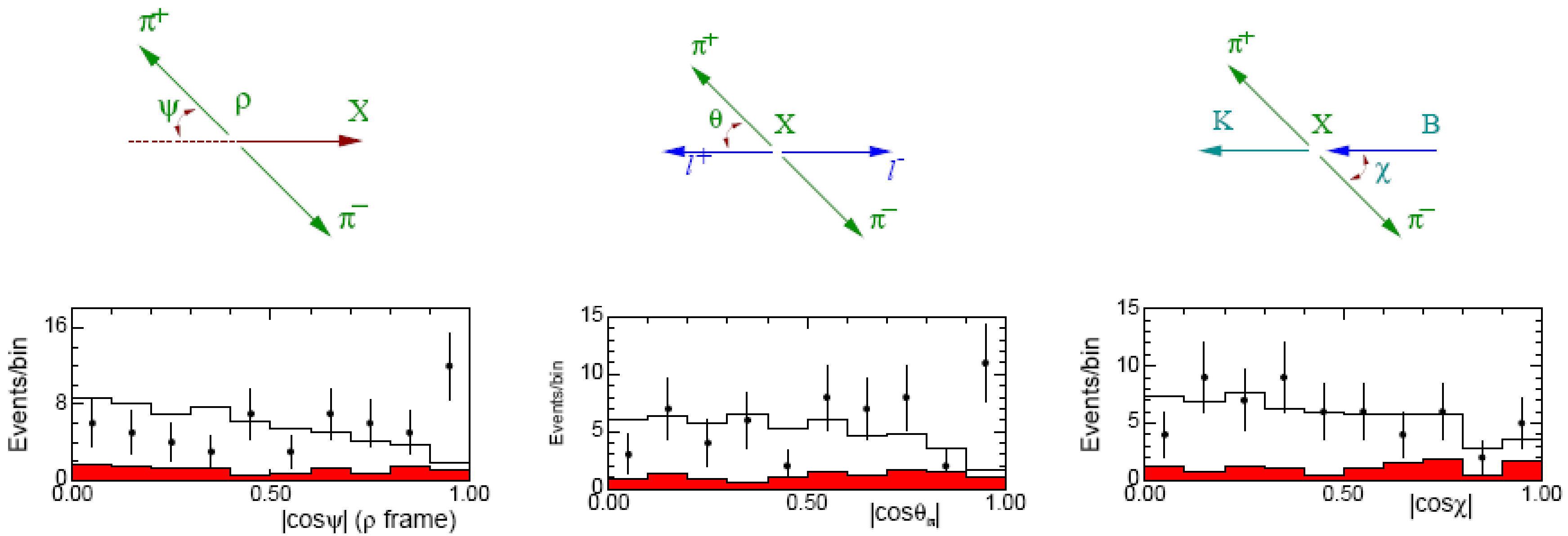
**PDG 09:Y(2170) $3^3S_1$ ss state? but predicted width ~380MeV!**

**hybrid similar to Y(4260)? tetraquark? ....**

***Other decay channels to be measured to clarify the nature of Y(2175)***

# $X(3872)$ angular distributions

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



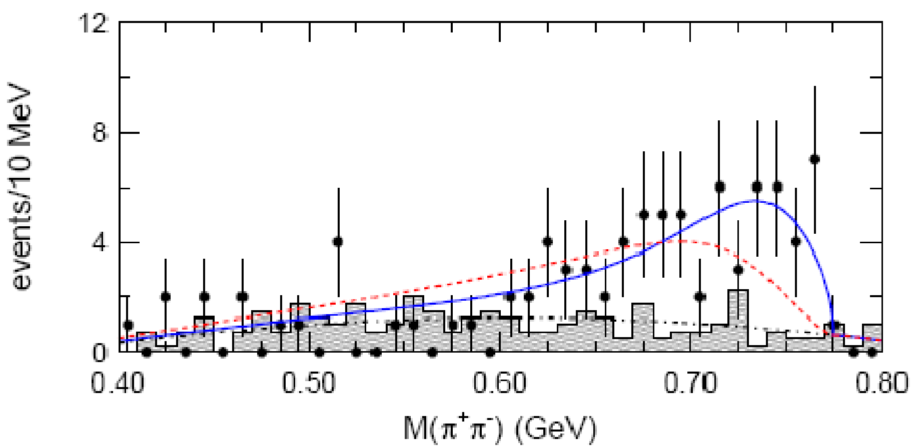

| $0^{-+}$ P-wave | $0^{++}$ S(D) wave | $1^{++}$ S(D) wave |
|---|---|---|
| $\propto \sin^2\theta \sin^2\psi$ | $\propto \sin^2\theta_{l\pi}$ | $\propto \sin^2\theta_l \sin^2\chi$ |
| $\chi^2/Ndf = 34.2/9$ | $\chi^2/Ndf = 31/9$ | $\chi^2/Ndf = 5/9$ |

$0^{-+}$, $0^{++}$ - quantum numbers are disfavored

# $X(3872)$ quantum numbers

$$X \to \rho^0 J/\psi \to \pi^+\pi^- J/\psi$$

Even parity: S-wave; Odd parity: P-wave




$\pi\pi$ spectrum is more consistent with S-wave

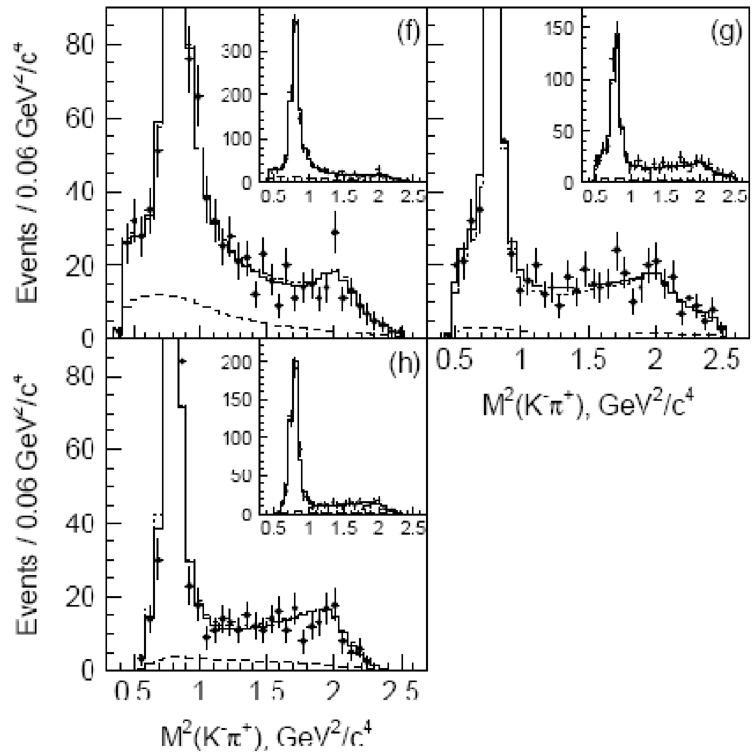
S-wave $\chi^2/Ndf = 43/39$

P-wave $\chi^2/Ndf = 71/39$

$1^{++}$ is strongly favored over $1^{-+}$

# Z(4430) Dalitz analysis by Belle

| Contribution | Fit fraction (%) | Significance |
|---|---|---|
| $Z(4430)^+$ | $5.7^{+3.1}_{-1.6}$ | $6.4\,\sigma$ |
| $\kappa$ | $4.1^{+3.4}_{-1.1}$ | $1.5\,\sigma$ |
| $K^*(892)$ | $64.8^{+3.8}_{-3.5}$ | huge |
| $K^*(1410)$ | $5.5^{+8.8}_{-1.5}$ | $0.5\,\sigma$ |
| $K_0^*(1430)$ | $5.3 \pm 2.6$ | $1.3\,\sigma$ |
| $K_2^*(1430)$ | $5.5^{+1.6}_{-1.4}$ | $3.1\,\sigma$ |
| $K^*(1680)$ | $2.8^{+5.8}_{-1.0}$ | $1.2\,\sigma$ |

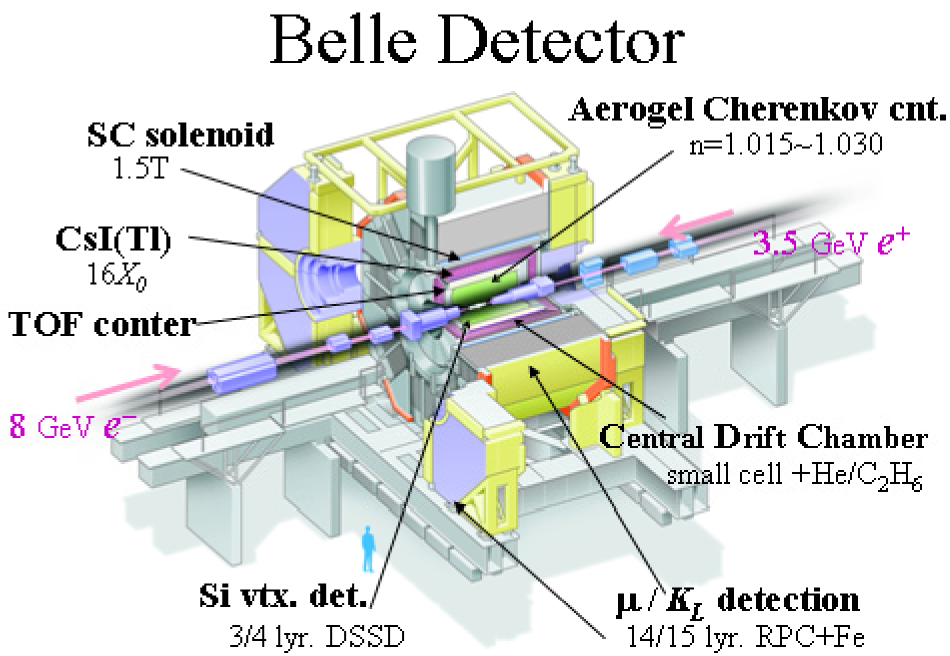


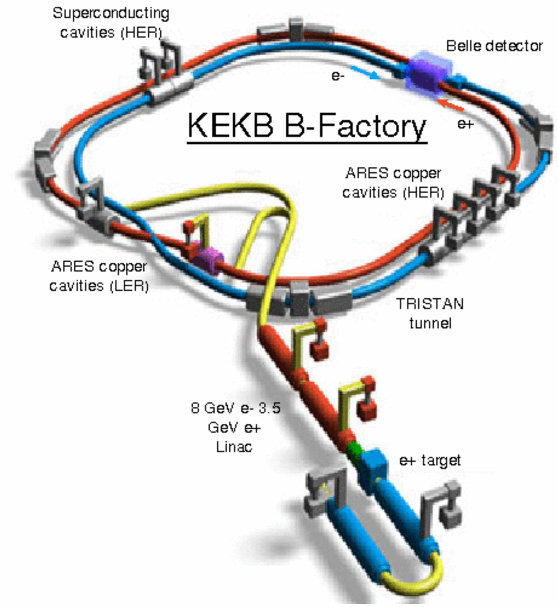

**Significance $Z(4430)^+ \;=\; 6.4\sigma$**

**Add $K_3^*(1780)$, significance $4.7\sigma$**

**But fit fraction of $K_3^*(1780)$ =6.6%(too large)**

**( $\mathcal{B}(K_3^*(1780) \to K\pi) = 18.8\%,\ B \to K_3^*\psi' \Rightarrow L \geq 2$)**




- $3.5\ \text{GeV}\ e^+ \times 8.0\ \text{GeV}\ e^-$.
- $\mathcal{L}_{\max} = 2.1 \times 10^{34} cm^{-2} s^{-1}$
- Continuous injection
  $\rightarrow 1.1\,\text{fb}^{-1}/\text{day}$.
- $\int \mathcal{L} dt \approx 1\, ab^{-1}$