Recent results on Charmonium(like) at Belle

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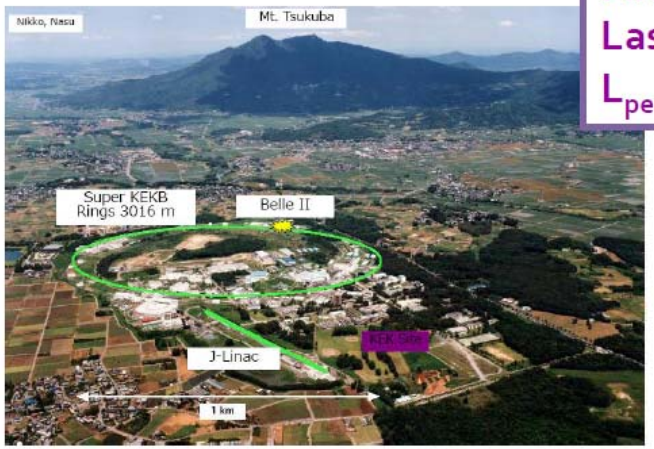
for Belle Collaboration

Outline

- Update $e^+e^- \to K^+K^- J/\psi$ and search for $Z_{cs}^{\pm} \to K^{\pm} J/\psi$
- Observation of a new charged charmoniumlike state Zc(4200) in $B \to K \pi J/\psi$
- Update $e^+e^- \to \pi^+\pi^- \psi(2S)$: Y(4360) and Y(4660)
- Search for X(3872) like states decays to η_c modes

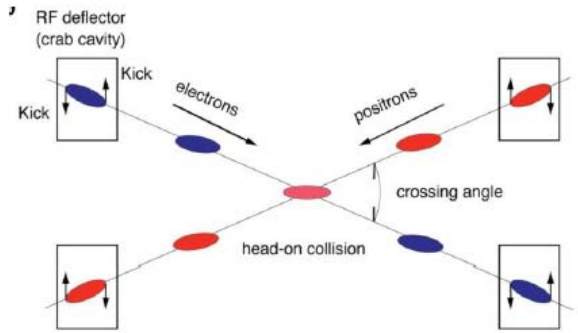
KEKB/Belle

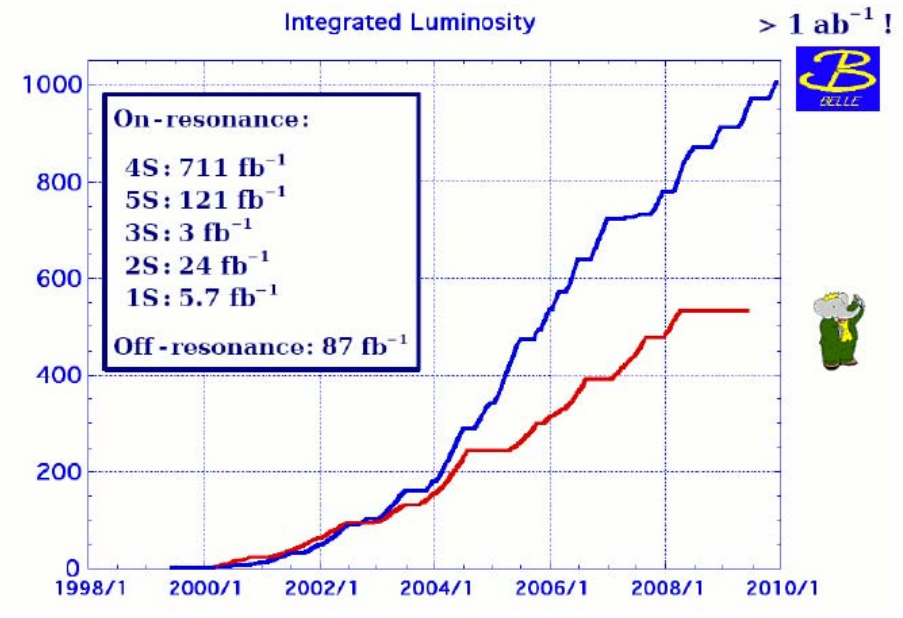
World maximum luminosity



First physics run on June 2, 1999
Last physics run on June 30, 2010
L_{peak} = 2.1x10^{34}/cm^2/s Ltot > 1ab^{-1}

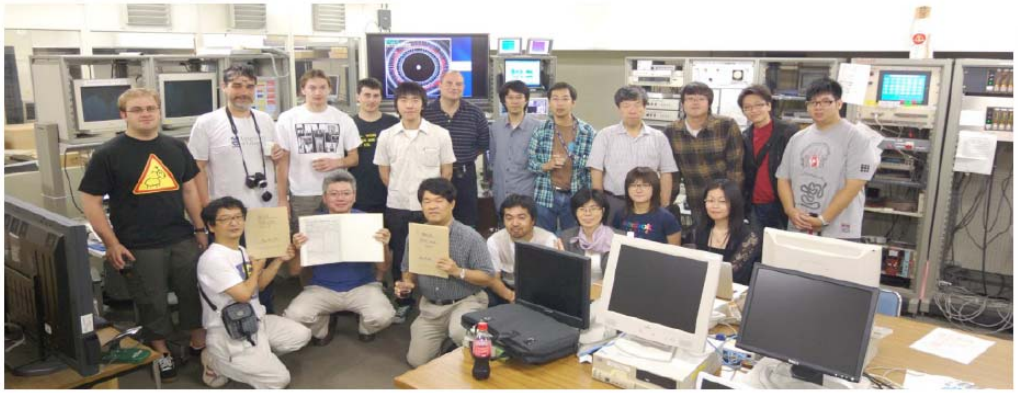
KEKB:
HER: 8.0 GeV
LER: 3.5 GeV
crossing: 22 mrad
E_{CMS}=M(U(4S))





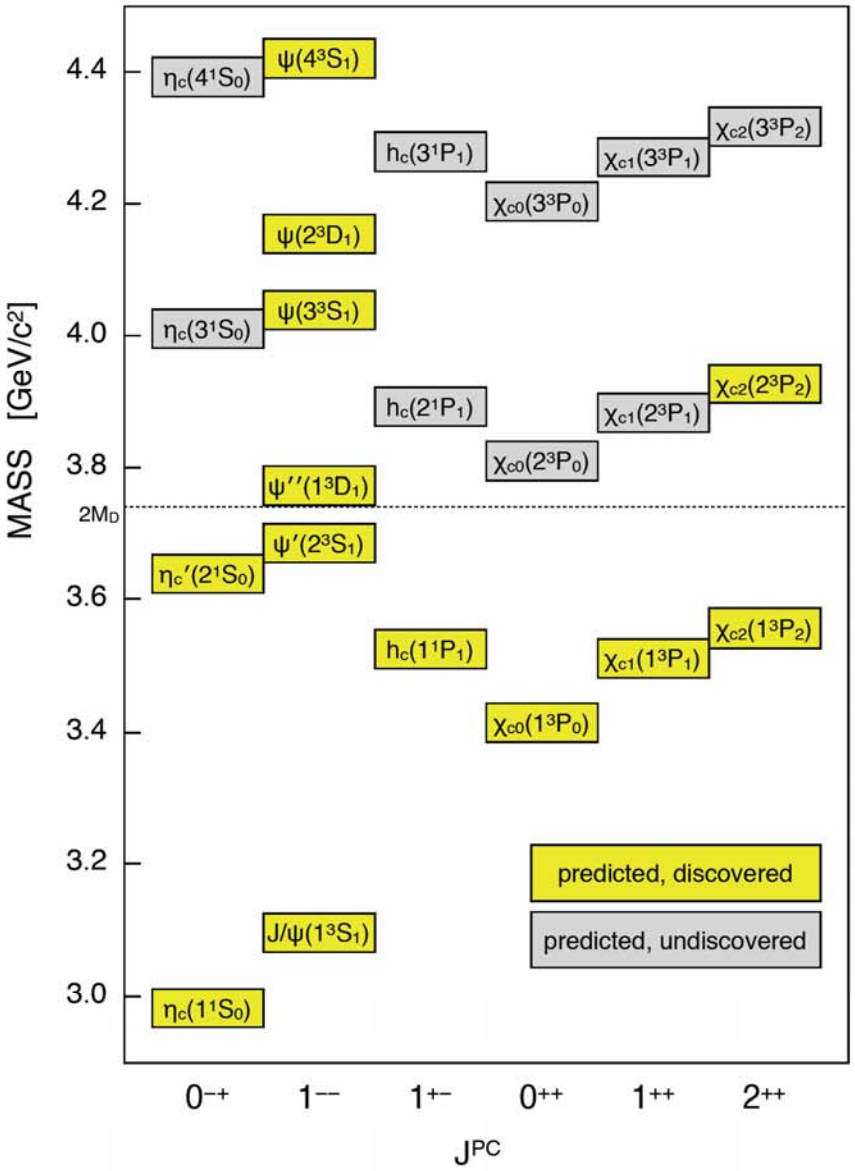
Peak lumi record at KEKB: L=2.1 x 10^{34}/cm^2/sec with crab cavities

The last beam abort of KEKB on June 30, 2010



First physics run on June 2, 1999
Last physics run on June 30, 2010
L_{peak} = 2.1x10^{34}/cm^2/s
L > 1ab^{-1}

Charmonium states



(I) The quark model describes most of charmonium remarkably well. $(c\bar{c})$

Example potential from Barnes, Godfrey, Swanson:

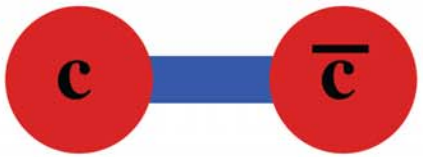
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

(Coulomb + Confinement + Contact)

$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

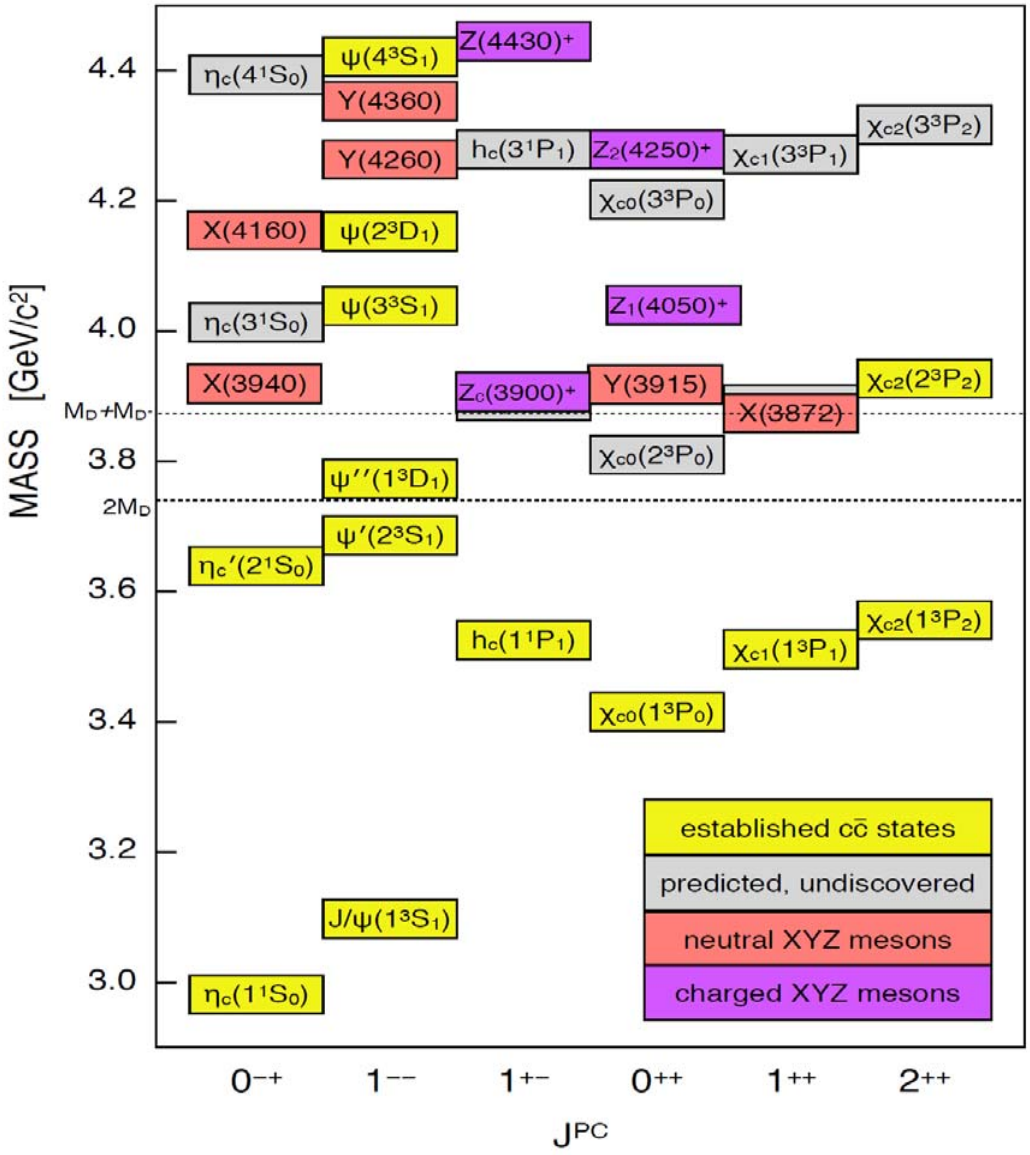
(Spin-Orbit + Tensor)

PRD72, 054026 (2005)



CHARMONIUM

Charmoniumlike states



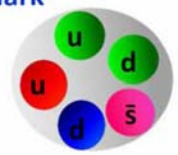
The quark model describes most of charmonium remarkably well. $(c\bar{c})$

But the *"XYZ"* states point beyond the quark model. $(c\bar{c}g, c\bar{q}q\bar{c}, (c\bar{q})(q\bar{c}), c\bar{c}\pi\pi)$

Most of the XYZ states were discovered by Belle and BaBar.

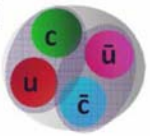
Pentaquark

S= +1 Baryon



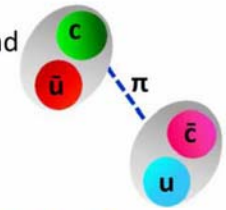
Tetraquark

Tightly bound diquark & anti-diquark



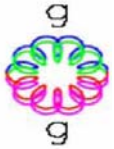
Molecule

loosely bound meson-antimeson "molecule"

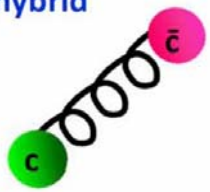


Glueball

Color-singlet multi-gluon bound state

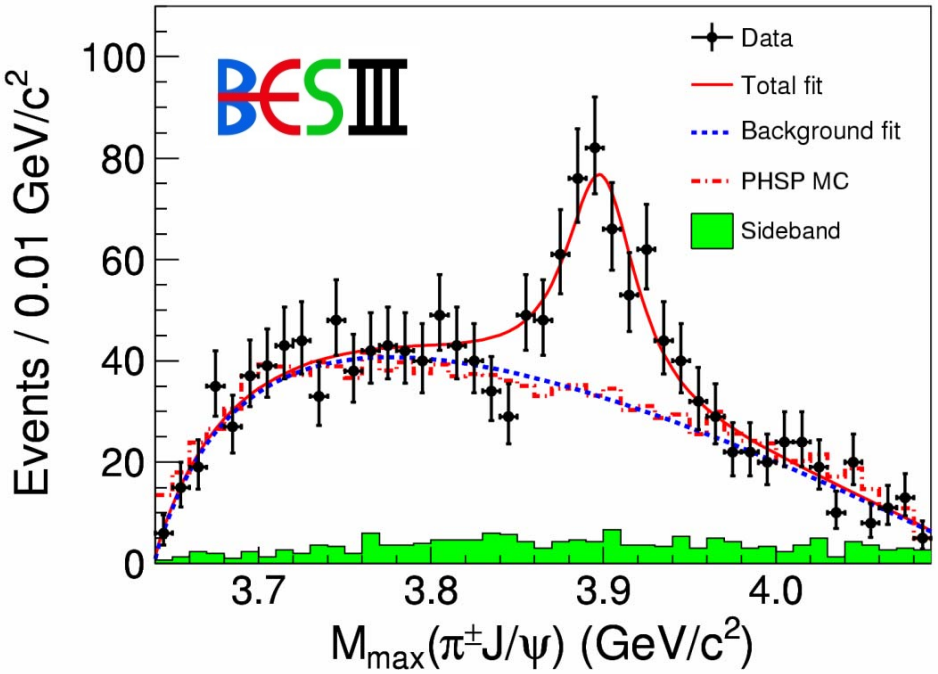


qq̄ -gluon hybrid mesons



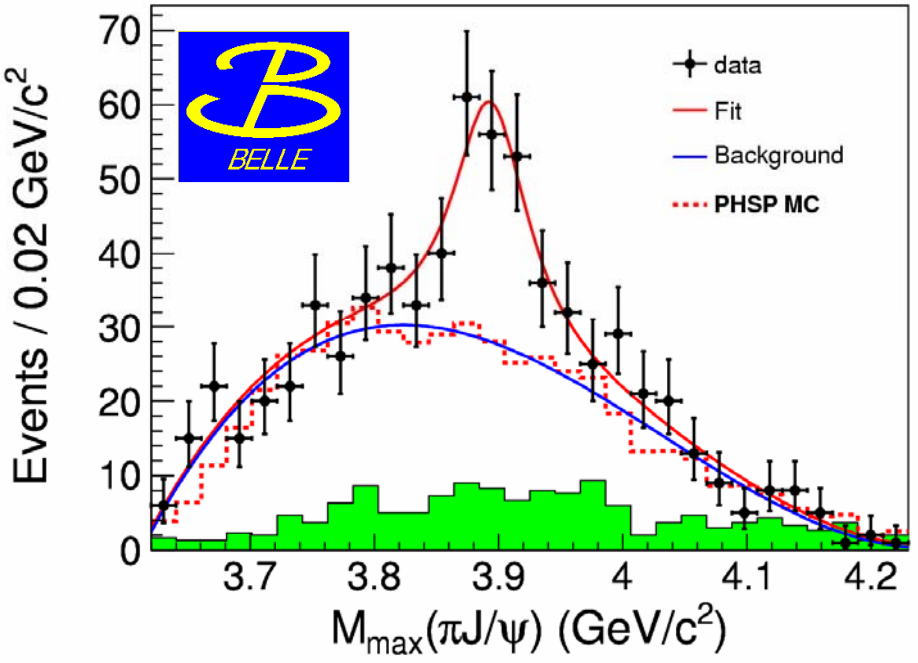
$Z_c(3900)$ observed in two experiments!

BES3 at 4.26 GeV: PRL110,252001



- M = 3899.0±3.6±4.9 MeV
- Γ = 46±10±20 MeV
- 307 ± 48 events
- >8σ

Belle with ISR: PRL110, 252002

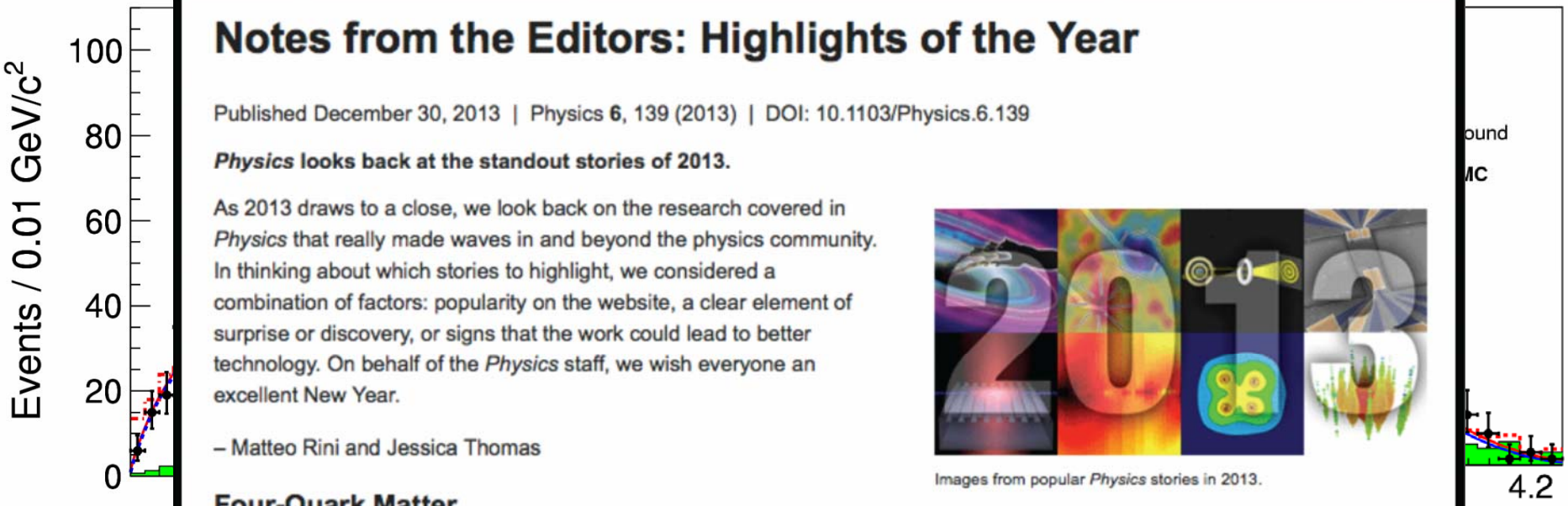


- M = 3894.5±6.6±4.5 MeV
- Γ = 63±24±26 MeV
- 159 ± 49 events
- >5.2σ

$Z_c(3900)$ observed in two experiments!

BES3 at 4.26 GeV: PRL110,252001

Belle with ISR: PRL110, 252002



Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics 6, 139 (2013) | DOI: 10.1103/Physics.6.139

***Physics* looks back at the standout stories of 2013.**

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas

Images from popular *Physics* stories in 2013.

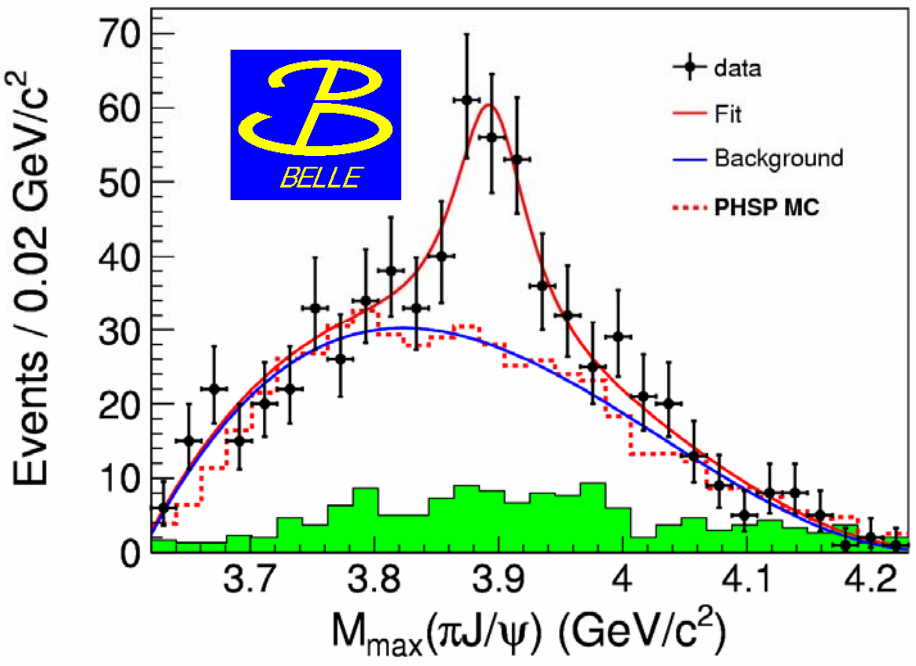
Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

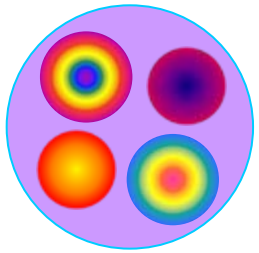
- M
- Γ =
- 307 ± 48 events
- >8σ

- 159 ± 49 events
- >5.2σ

What is $Z_c(3900)$?



- Couples to $\bar{c}c$
- Has electric charge
- At least 4-quarks
- What is its nature?



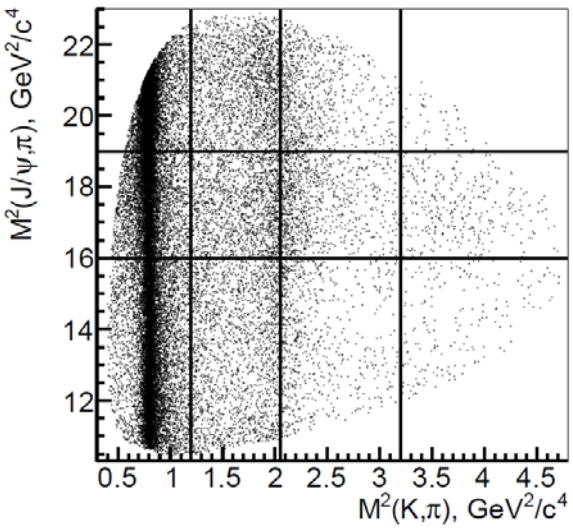
- $\bar{D}D^*$ molecule?
- Tetraquark state?
- Cusp?
- Threshold effect?
- …

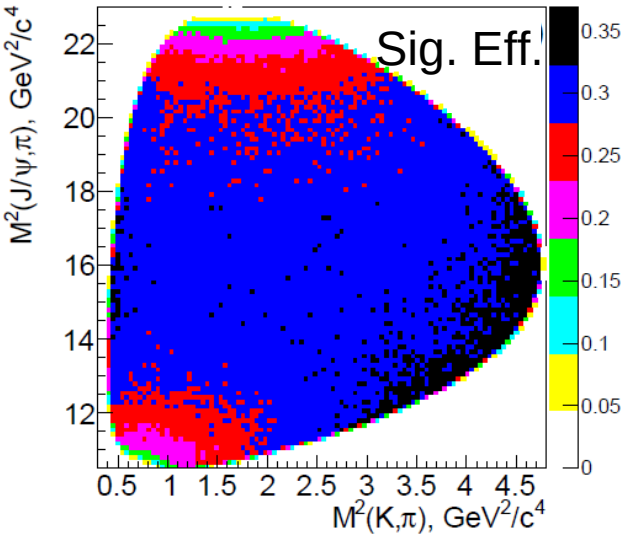
Predictions and more experimental information will be essential to understand its nature.

➔ A partner Z_c in B decays ?

Amplitude analysis of $B \to J/\psi K\pi$ arXiv:1408.6457

- 4-dimensional amplitude analysis similar to $Z_c(4430)^+$ quantum number measurement. $\Phi = (M^2_{K\pi}, M^2_{J/\psi\pi}, \theta_{J/\psi}, \varphi)$.
- Resonances: all K^* (10 resonances) and $Z_c(4430)^+$.
- Search for additional Z_c^+ is performed.





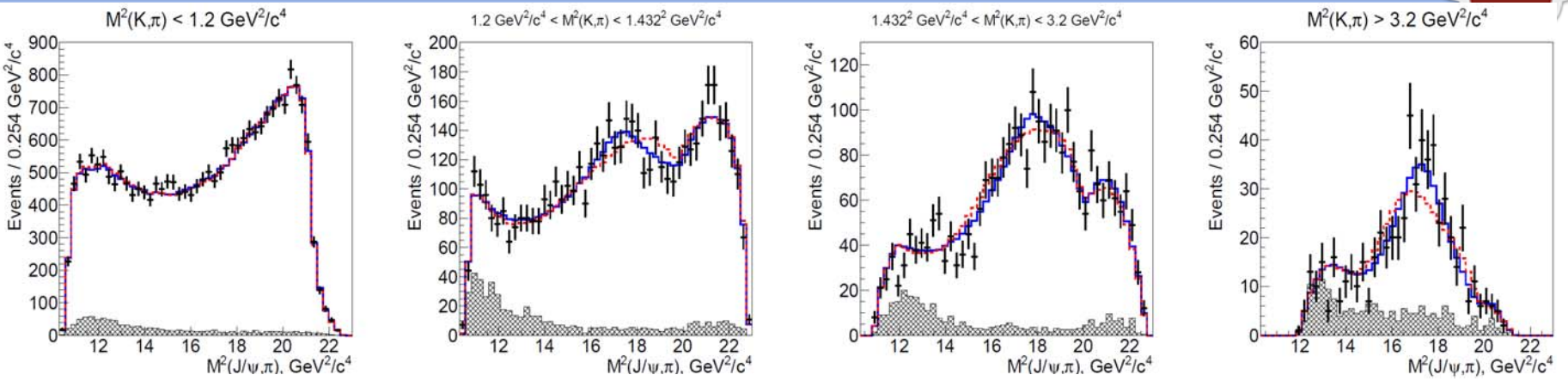
Resonance	Fit fraction	Significance (local)
$K_0^*(800)$	$(7.1^{+0.7}_{-0.5})\%$	22.5σ
$K^*(892)$	$(69.0^{+0.6}_{-0.5})\%$	166.4σ
$K^*(1410)$	$(0.3^{+0.2}_{-0.1})\%$	4.1σ
$K_0^*(1430)$	$(5.9^{+0.6}_{-0.4})\%$	22.0σ
$K_2^*(1430)$	$(6.3^{+0.3}_{-0.4})\%$	23.5σ
$K^*(1680)$	$(0.3^{+0.2}_{-0.1})\%$	2.7σ
$K_3^*(1780)$	$(0.2^{+0.1}_{-0.1})\%$	3.8σ
$K_0^*(1950)$	$(0.1^{+0.1}_{-0.1})\%$	1.2σ
$K_2^*(1980)$	$(0.4^{+0.1}_{-0.1})\%$	5.3σ
$K_4^*(2045)$	$(0.2^{+0.1}_{-0.1})\%$	3.8σ
$Z_c(4430)^+$	$(0.5^{+0.4}_{-0.1})\%$	5.1σ
$Z_c(4200)^+$	$(1.9^{+0.7}_{-0.5})\%$	8.2σ

Zc(4200) !

TABLE I. Fit results in the default model. Errors are statistical only.

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4318 ± 48	4315 ± 40	4196^{+31}_{-29}	4209 ± 14	4203 ± 24
Width, MeV	720 ± 254	220 ± 80	370 ± 70	64 ± 18	121 ± 53
Significance (Wilks)	3.9σ	2.3σ	8.2σ	3.9σ	1.9σ

Projections of fit results



- New Z_c^+ is found ($J^P = 1^+$) [$Z_c(4200)^+, 6.2\sigma$ with syst. error].

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

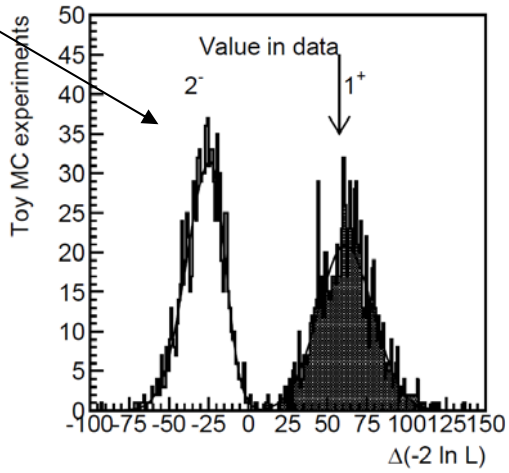
Additional Zc

Z(4430) only

- Exclusion levels ($J^P = 0^-$, 1^-, 2^-, 2^+): 6.1σ, 7.4σ, 4.4σ 7.0σ.
- The $Z_c(4430)^+$ is significant (4.0σ, evidence for new decay mode).

Zc(3900) is also tried to add:

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	3889.8 ± 3.3	3890.3 ± 3.1	3890.6 ± 3.3	3891.1 ± 3.2	3891.5 ± 3.3
Width, MeV	43.2 ± 6.5	37.8 ± 7.9	39.2 ± 8.1	39.4 ± 8.5	41.2 ± 7.7
Significance	2.4σ	1.1σ	0.1σ	$< 0.1\sigma$	0.2σ

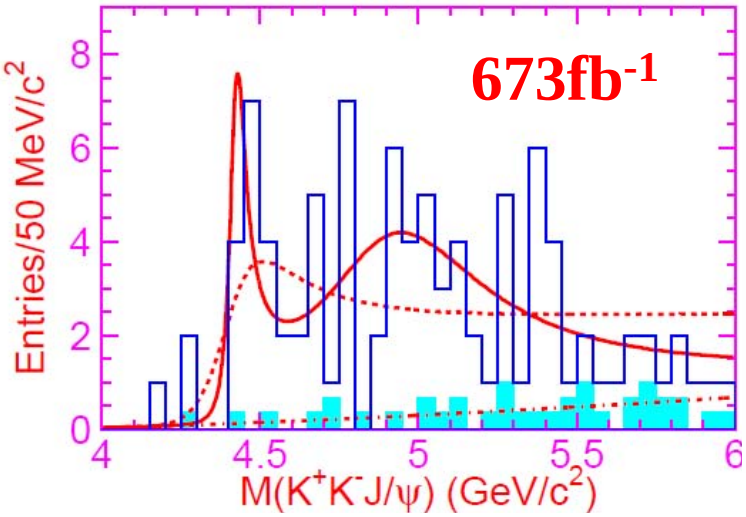


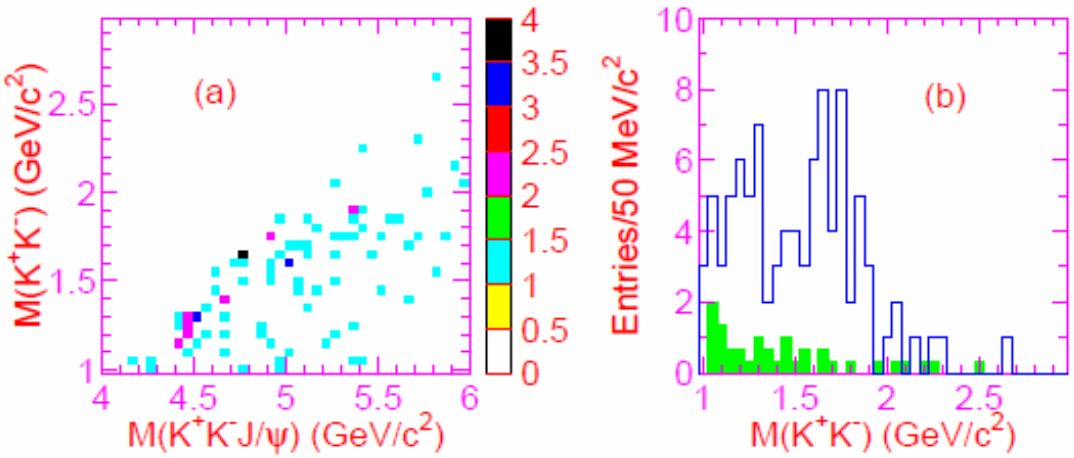
Zc(3900) is not needed !

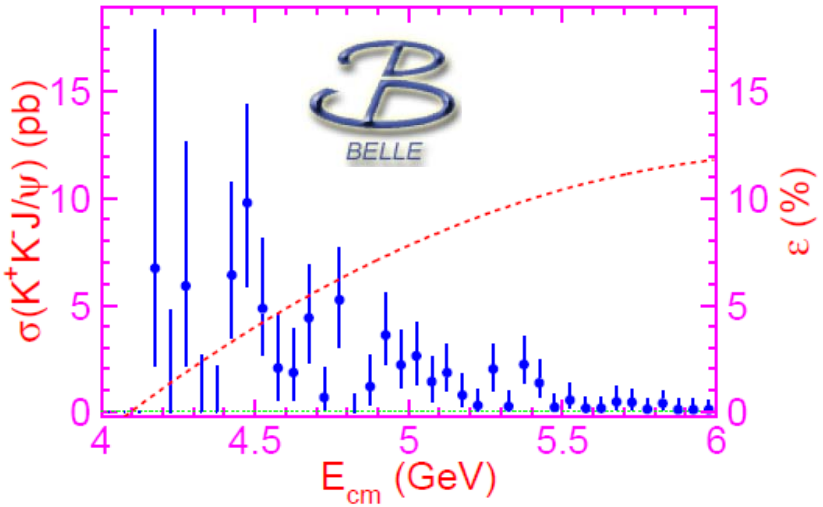
➔ A partner with s quark Zcs?

Zcs? History: previous published results

Phys. Rev. D 77, 011105(R) (2008)







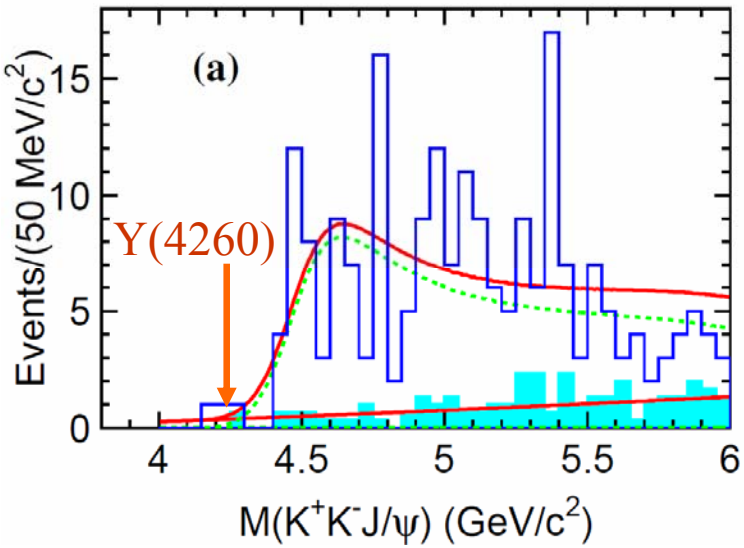
1. cross section is measured between 4-6 GeV.
2. There is one very broad structure;
3. Two events near the Y (4260) mass
4. We did not show Dalitz Plot before !

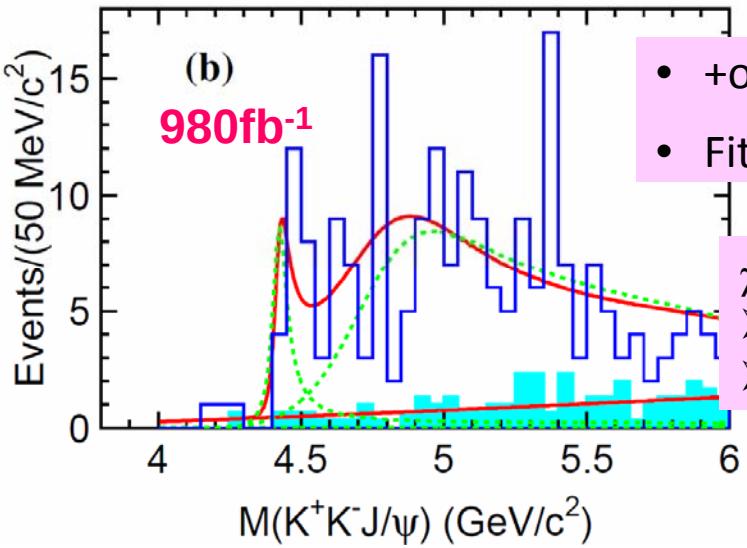
Updated $e^+e^- \to K^+K^-J/\psi$

PRD 89,072015(2014)

Event selections are almost the same as in Phys. Rev. D 77, 011105(R) (2008)

Shaded hist.: J/ψ mass sidebands



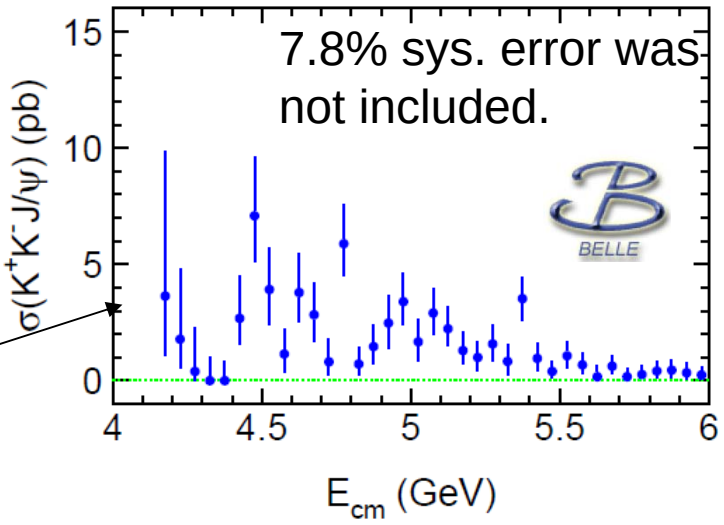


- +one resonance.
- Fit with ψ(4415)

χ^2/ndf=30/11
- M=4747±117MeV
- Γ=671±86 MeV

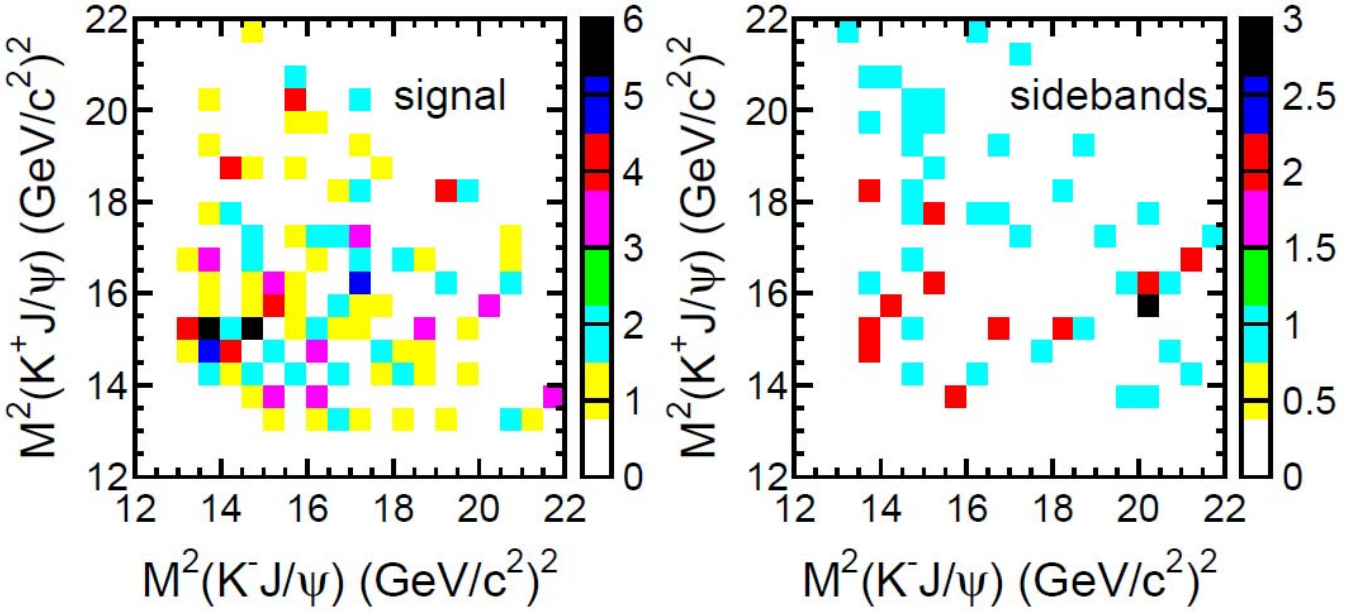
4-6 GeV: 213 events
35 bkg, 178±16 signal

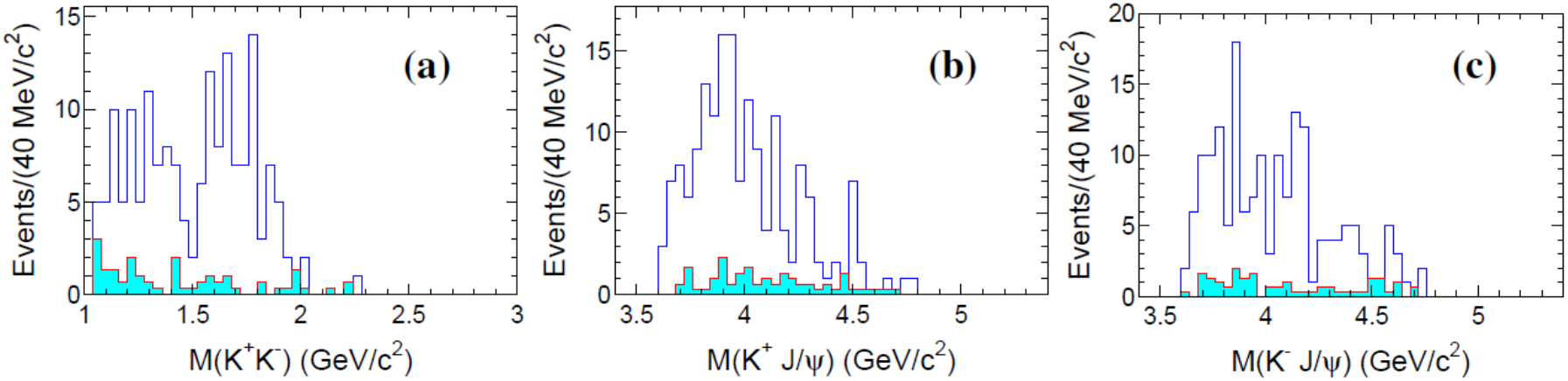
$$\sigma_i = \frac{n_i^{\rm obs} - f \times n_i^{\rm bkg}}{\mathcal{L}_i \cdot \epsilon_i \cdot \mathcal{B}(J/\psi \to \ell^+\ell^-)}$$



Search for Z_{cs}→KJ/ψ states

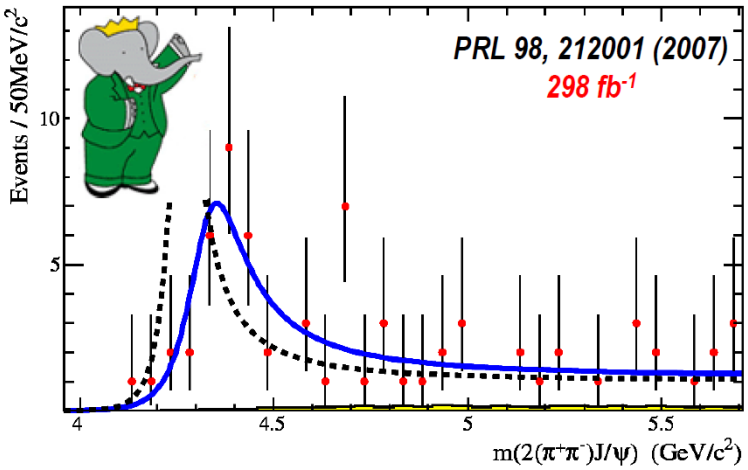
PRD 89,072015(2014)

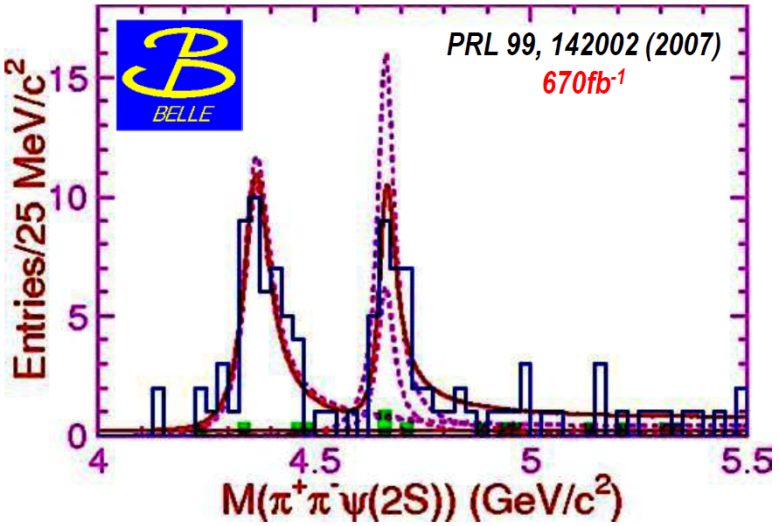




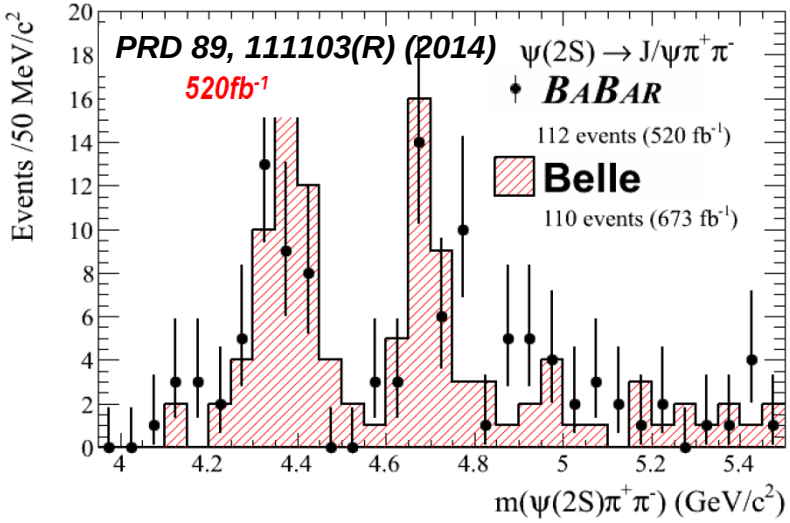
No evident structure in $K^{+-}J/\psi$ mass distribution under current statistics

$e^+e^- \to \pi^+\pi^-\psi(2S)$: history





$e^+e^- \to \gamma_{ISR}\psi'\pi^+\pi^-$



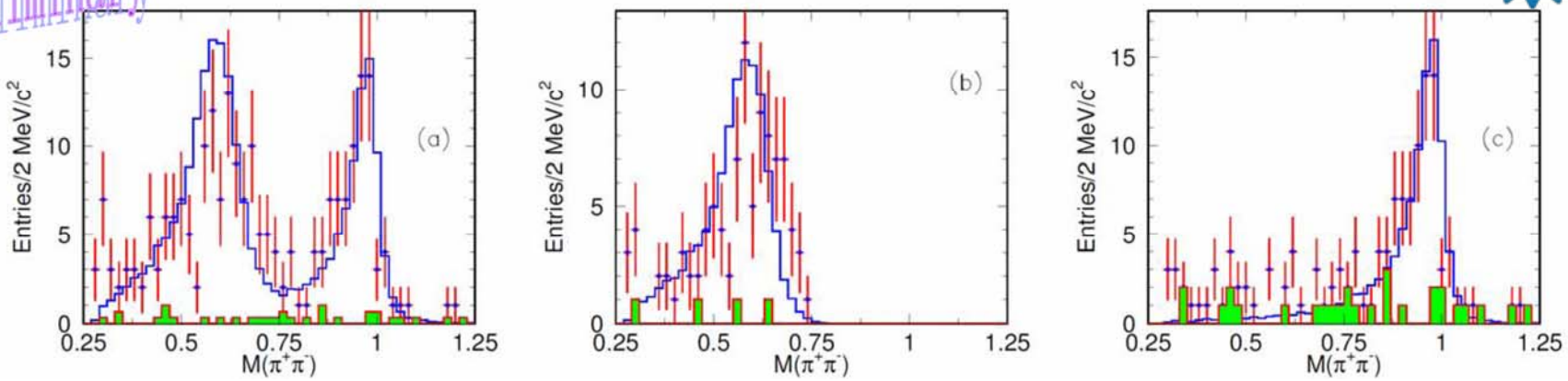
- BaBar and Belle observed Y(4360)
- Belle observed additional Y(4660)
- Babar updated results in good agreement with Belle

Y(4660) confirmed

Updated $e^+e^- \to \pi^+\pi^-\psi(2S)$

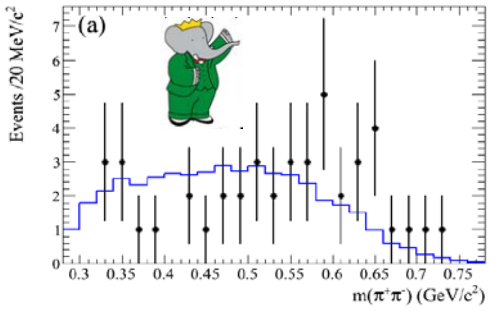
NEW

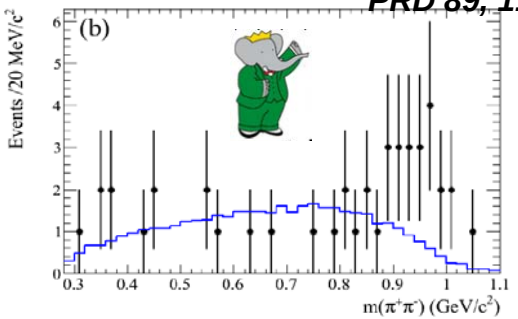
Preliminary



- Dots: data; Blank hist: MC simulations; Shaded hist: bkg from $\psi(2S)$ sidebands.
- Left: with $4.0 < M_{\pi^+\pi^-\psi(2S)} < 5.5\ \mathrm{GeV}/c^2$.
- Middle: from Y(4360), $4.0 < M_{\pi^+\pi^-\psi(2S)} < 4.5\ \mathrm{GeV}/c^2$, looks like $f_0(600)$
- Right: from Y(4660), $4.5 < M_{\pi^+\pi^-\psi(2S)} < 4.9\ \mathrm{GeV}/c^2$, should be $f_0(980)$, confirmed in BaBar update.

PRD 89, 111103(R) (2014)





(a) $4.0 < M_{\pi^+\pi^-\psi(2S)} < 4.5\ \mathrm{GeV}/c^2$

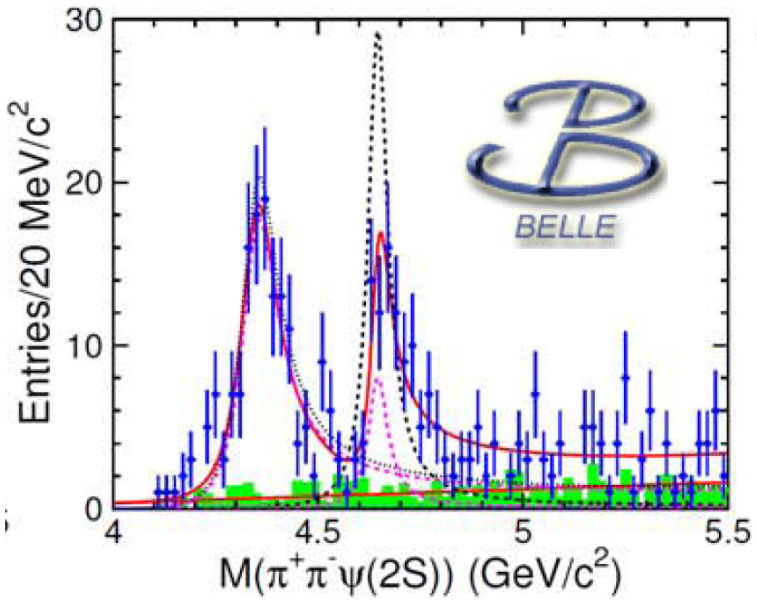
(b) $4.5 < M_{\pi^+\pi^-\psi(2S)} < 4.9\ \mathrm{GeV}/c^2$

Fit M($\pi^+\pi^-\psi(2S)$) with two resonances

NEW

Unbinned simultaneous maximum likelihood fit for $Y(4360)$ and $Y(4660)$.

$Amp = BW_1 + e^{i\phi} \cdot BW_2$ $\quad \pi^+\pi^- J/\psi + \mu^+\mu^-$

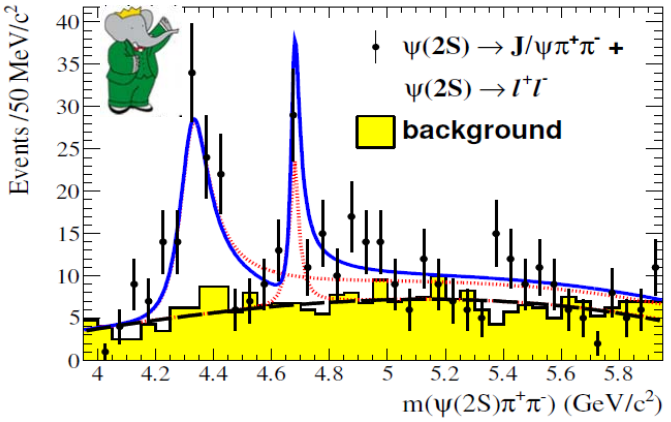


Comparing to previous measurement:

- $M_{Y(4360)}$ and $M_{Y(4660)}$ are smaller.
  Previous measurement:
  $M_{Y(4360)} = 4361 \pm 9 \pm 9\,\mathrm{MeV}/c^2$,
  $M_{Y(4660)} = 4664 \pm 11 \pm 5\,\mathrm{MeV}/c^2$.
- No obvious signal above $Y(4660)$.
- Some events accumulate at $Y(4260)$, especially the $\pi^+\pi^- J/\psi$ mode.
- If $Y(4260)$ is included in the fit, ...???

Parameters	Solution I	Solution II
$M_{Y(4360)}$ (MeV/c^2)	$4346 \pm 6 \pm 2$	
$\Gamma_{Y(4360)}$ (MeV)	$111 \pm 10 \pm 7$	
$\mathcal{B} \cdot \Gamma^{Y(4360)}_{e^+e^-}$ (eV)	$10.6 \pm 0.6 \pm 0.7$	$9.2 \pm 0.8 \pm 0.7$
$M_{Y(4660)}$ (MeV/c^2)	$4644 \pm 12 \pm 8$	
$\Gamma_{Y(4660)}$ (MeV)	$59 \pm 12 \pm 2$	
$\mathcal{B} \cdot \Gamma^{Y(4660)}_{e^+e^-}$ (eV)	$6.8 \pm 1.6 \pm 0.7$	$1.8 \pm 0.3 \pm 0.1$
ϕ (°)	$278 \pm 11 \pm 8$	$19 \pm 24 \pm 20$

$\chi^2/ndf = 27.6/21$ $(p = 1.6 \times 10^{-9})$.



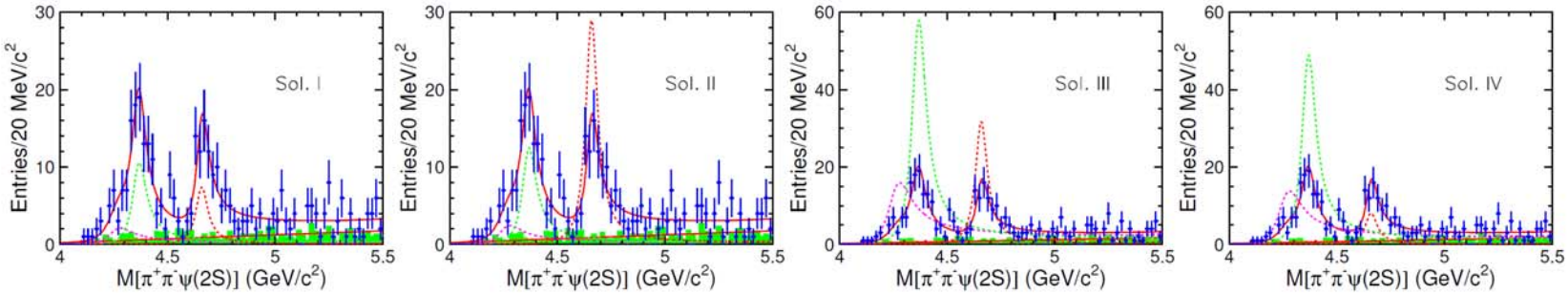
Fit $M(\pi^+\pi^-\psi(2S))$ with three resonances

NEW

Unbinned simultaneous maximum likelihood fit for $Y(4260)$, $Y(4360)$ and $Y(4660)$.

$Amp = BW_1 + e^{i\phi_1} \cdot BW_2 + e^{\phi_2} \cdot BW_3$.

Preliminary



Preliminary results:

Parameters	Solution I	Solution II	Solution III	Solution IV
$M_{Y(4260)}$ (MeV/c^2)		4259(fix)		
$\Gamma_{Y(4260)}$ (MeV)		134(fix)		
$\mathcal{B} \cdot \Gamma^{Y(4260)}_{e^+e^-}$ (eV)	1.4 ± 0.6	1.6 ± 0.7	10.7 ± 1.4	9.3 ± 1.3
$M_{Y(4360)}$ (MeV/c^2)		4363 ± 8		
$\Gamma_{Y(4360)}$ (MeV)		80 ± 16		
$\mathcal{B} \cdot \Gamma^{Y(4360)}_{e^+e^-}$ eV	3.9 ± 1.0	4.6 ± 1.3	21.5 ± 3.7	18.2 ± 2.9
$M_{Y(4660)}$ (MeV/c^2)		4657 ± 9		
$\Gamma_{Y(4660)}$ (MeV)		68 ± 11		
$\mathcal{B} \cdot \Gamma^{Y(4660)}_{e^+e^-}$ (eV)	2.0 ± 0.4	7.7 ± 0.9	8.4 ± 1.1	2.1 ± 0.4
ϕ_1 (°)	309 ± 26	300 ± 28	131 ± 5	140 ± 5
ϕ_2 (°)	25 ± 22	243 ± 14	329 ± 9	111 ± 26

The significance of $Y(4260)$ is 2.1σ. Not significant, but effect is large.

FOUR solutions with equally good fit quality, which is $\chi^2/ndf = 24.8/19$ $(p = 3.2 \times 10^{-9})$.

Search for X(3872) decays to η_c modes

Motivation:

- X(3872) was first observed by Belle in $B \to K(J/\psi\pi^+\pi^-)$. Angular analysis of this mode performed by LHCb determined all quantum numbers: 1^{++}.
- If X(3872) is a $D^0\overline{D}^{*0}$ molecule, there may be other «X-like» particles with different quantum numbers, that are also bound states of $D^{(*)}$ mesons.
  - X(3872): $(D^0\overline{D}^{*0} - \overline{D}^0D^{*0})$ combination: $J^{PC}=1^{+-}$, decays $X\to\eta_c\omega$, $X\to\eta_c\rho$
  - X(3730): $(D^0\overline{D}^0 + \overline{D}^0D^0)$ combination: $J^{PC}=0^{++}$, decays $X\to\eta_c\eta$, $X\to\eta_c\pi^0$
  - X(4014): $(D^{*0}\overline{D}^{*0} + \overline{D}^{*0}D^{*0})$ combination: $J^{PC}=0^{++}$, decays $X\to\eta_c\eta$, $X\to\eta_c\pi^0$

Analysis features:

- X is produced in charged B decays: $B^\pm \to K^\pm X$
- $\eta_c \to K_S K\pi$, $K_S \to \pi^+\pi^-$
- combined fit of 2 decay modes of η ($\gamma\gamma$ and $\pi^+\pi^-\pi^0$)
- test mode $B^\pm \to K^\pm\psi(2S)$, $\psi(2S) \to J/\psi\pi^+\pi^-$ gives results consistent with PDG
- $B^\pm$ decays into the same final states, but without intermediate X are studied

Search for X(3872) decays to η_c modes

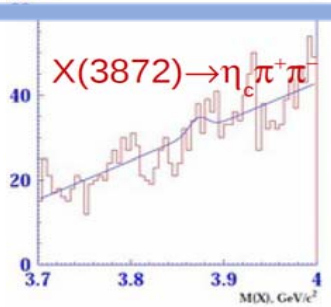
$B^{\pm} \to K^{\pm} X$

X(3872)

- $\to \eta_c \pi^+\pi^-$
- $\to \eta_c \omega,\ \omega \to \pi^+\pi^-\pi^0,\ \pi^0 \to \gamma\gamma$
- $\to \eta_c \eta$
  - $\to \gamma\gamma$
  - $\to \pi^+\pi^-\pi^0,\ \pi^0 \to \gamma\gamma$

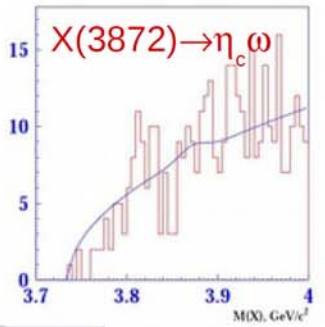
X(3730), X(4014)

- $\to \eta_c \pi^0,\ \pi^0 \to \gamma\gamma$

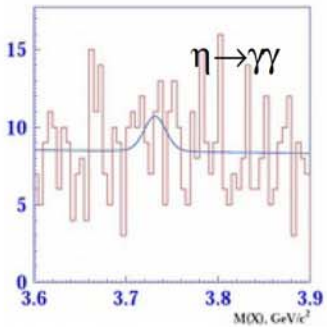


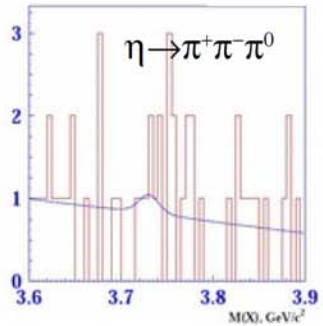
Preliminary results

New

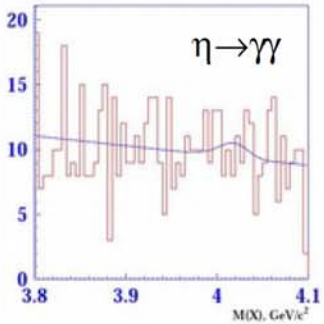


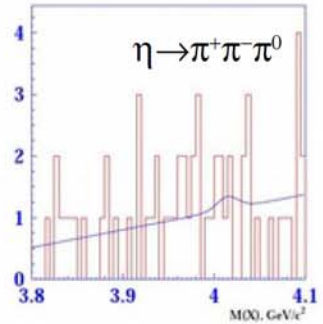
X(3730)→η_c η

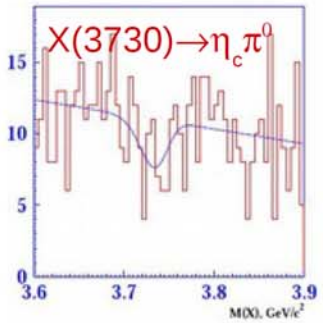


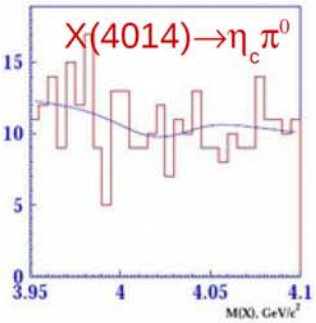


X(4014)→η_c η









Search for X(3872) decays to η_c modes

Preliminary results

X mass, MeV/c^2	Decay mode $B^\pm \to K^\pm X$	Yield	U (90% C.L.)
3872	$X \to \eta_c \pi^+\pi^-$	17.9 ± 16.5	3.0×10^{-5}
	$X \to \eta_c \omega$	6.0 ± 12.5	6.9×10^{-5}
3730	$X \to \eta_c \eta$,		
	$\eta \to \gamma\gamma$	13.8 ± 9.9	4.6×10^{-5}
	$\eta \to \pi^+\pi^-\pi^0$	1.4 ± 1.0	
	$X \to \eta_c \pi^0$	-25.6 ± 10.4	5.7×10^{-6}
4014	$X \to \eta_c \eta$,		
	$\eta \to \gamma\gamma$	8.9 ± 11.0	3.9×10^{-5}
	$\eta \to \pi^+\pi^-\pi^0$	1.3 ± 1.6	
	$X \to \eta_c \pi^0$	-8.1 ± 13.2	1.2×10^{-5}

Upper limits on the
$\mathcal{B}(B^\pm \to K^\pm X)\cdot\mathcal{B}(X \to \eta_c h)$
for $h = \pi^+\pi^-, \omega, \eta, \pi^0$

Upper limits on the
$\mathcal{B}(B^\pm \to K^\pm \eta_c h)$
for $h = \pi^+\pi^-, \omega, \eta, \pi^0$

Decay mode	Yield	U (90% C.L.)
$B^\pm \to K^\pm \eta_c \pi^+\pi^-$	155 ± 72	3.9×10^{-4}
$B^\pm \to K^\pm \eta_c \omega$	-41 ± 27	5.3×10^{-4}
$B^\pm \to K^\pm \eta_c \eta$,		
$\eta \to \gamma\gamma$	-14.1 ± 26.1	2.2×10^{-4}
$\eta \to \pi^+\pi^-\pi^0$	-1.8 ± 3.4	
$B^\pm \to K^\pm \eta_c \pi^0$	-1.9 ± 12.1	6.2×10^{-5}

Summary

- The $e^+e^- \to K^+K^-J/\psi$ cross sections are updated. There are clear K^+K^-J/ψ signal events.
- No clear structure Zcs is observed in the $K^{\pm}J/\psi$.
- The $e^+e^- \to \pi^+\pi^-\psi(2S)$ cross sections and Y(4360), Y(4660) parameters are updated.
- The Y(4260) was tried in the fit. The significance is $<3\sigma$, but it has significant effect on Y(4360) and Y(4660) parameters.
- 4D amplitude analysis of $B^0 \to J/\psi K^- \pi^+$ decays has been performed. A new charged charmoniumlike state $Zc(4200)^+ \to J/\psi\pi^+$ is observed (6.2σ, $J^P = 1^+$).
- Evidence for a new decay channel $Zc(4430)^+ \to J/\psi\pi^+$
- We study $B^{\pm} \to K^{\pm}X$ with X decays: $\eta_c\pi^+\pi^-$, $\eta_c\omega$, $\eta_c\eta$, $\eta_c\pi^0$. No signal was observed in any of the studied decay channels.

Thanks!