Exotic charmonia at Belle

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QWG 2013

2013/04/24

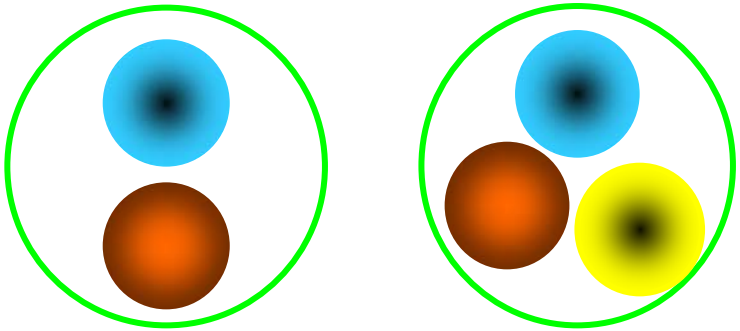
Outline

1. Conventional & exotic hadrons
2. First evidence of X(3823) ($\psi_2(1D)$)
3. Measurement of $Z(4430)^+$ quantum numbers
4. Updated analysis of ISR $e^+e^- \rightarrow \pi^+\pi^- J/\psi$
5. Updated results of Y(4008) and Y(4260)
6. Observation of a charged charmonium-like state $Z(3895)^\pm$ in $Z^\pm \rightarrow \pi^\pm J/\psi$
7. Summary

Hadrons：normal & exotic

- Hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks

Quark model



- QCD allows hadrons with $N_{quarks} \neq 2, 3$
  - glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - hybrid : $N_{quarks} = 2$ + gluon
  - multiquark state : $N_{quarks} > 3$
  - molecule : bound state of more than 2 hadrons

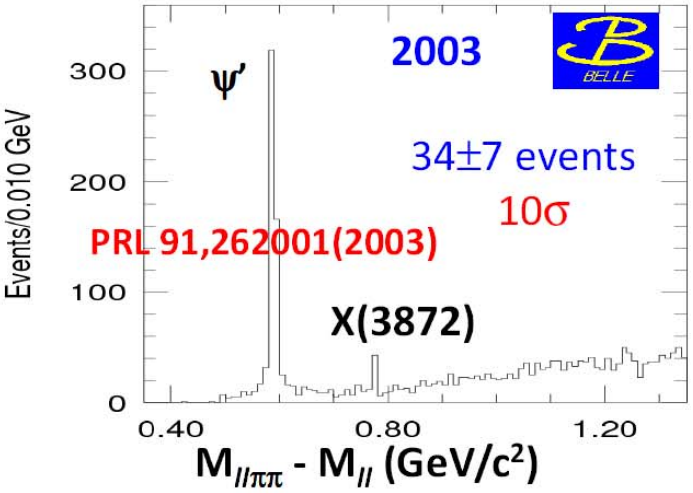
A bit history on exotics hunting

- "The absence of exotics is one of the most obvious features of QCD" – R. L. Jaffe, 2005
- Deuteron ➔ H state, $\Omega^-\Omega^-$ bound state, …
- No solid signature of glueballs
- Pentaquark state appeared and disappeared

  ("The story of pentaquark shows how poorly we understand QCD" – F. Wilczek, 2005)
- There are lots of new states from low to high mass in various experiments! Are they normal or exotic?

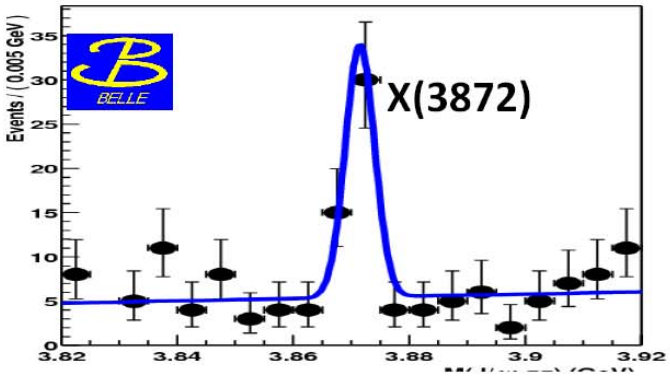
X(3872) Most famous $c\bar{c}$ (-like) state

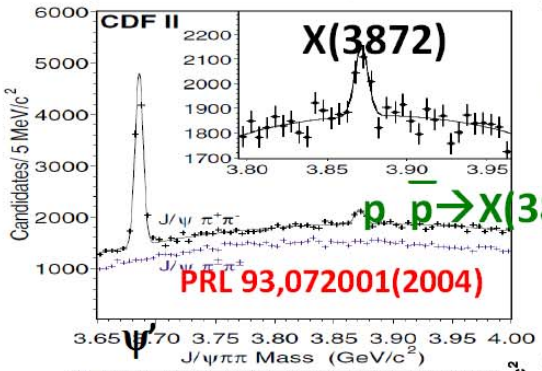
Discovered by Belle in $J/\psi\pi\pi$ decay mode

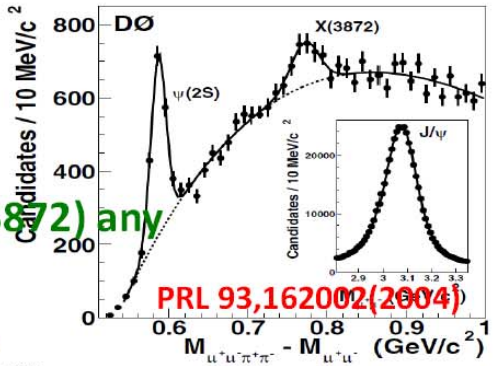


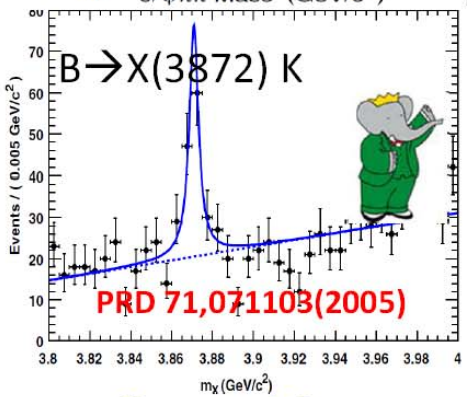
$B^+ \rightarrow X(3872) K^+$, $X(3872) \rightarrow J/\psi\pi^+\pi^-$

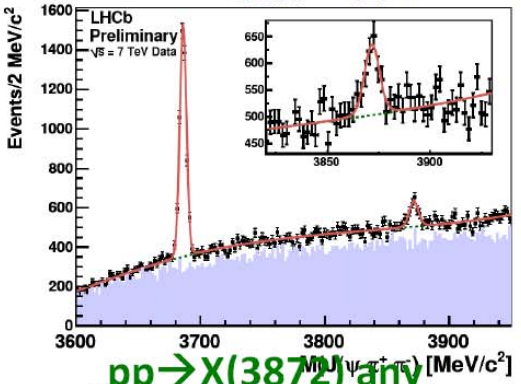
Γ<2.5 MeV (90%CL)



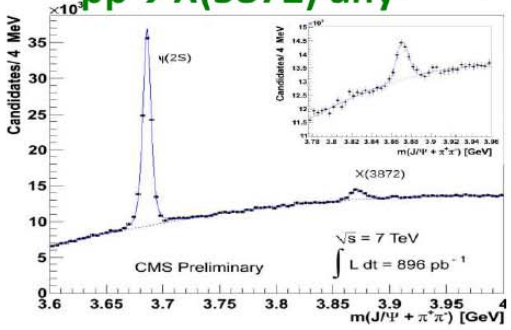








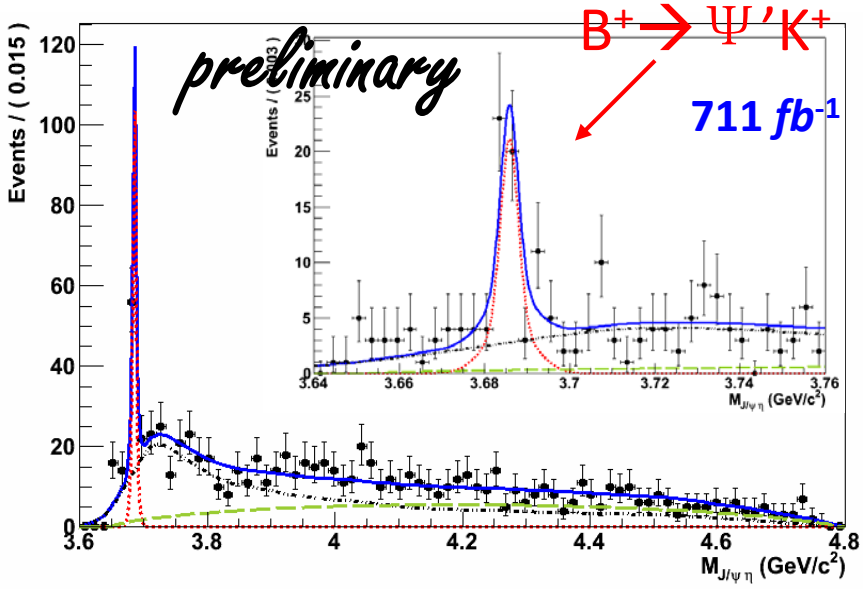
Confirmed by CDF, DO, BaBar, CMS and LHCb.



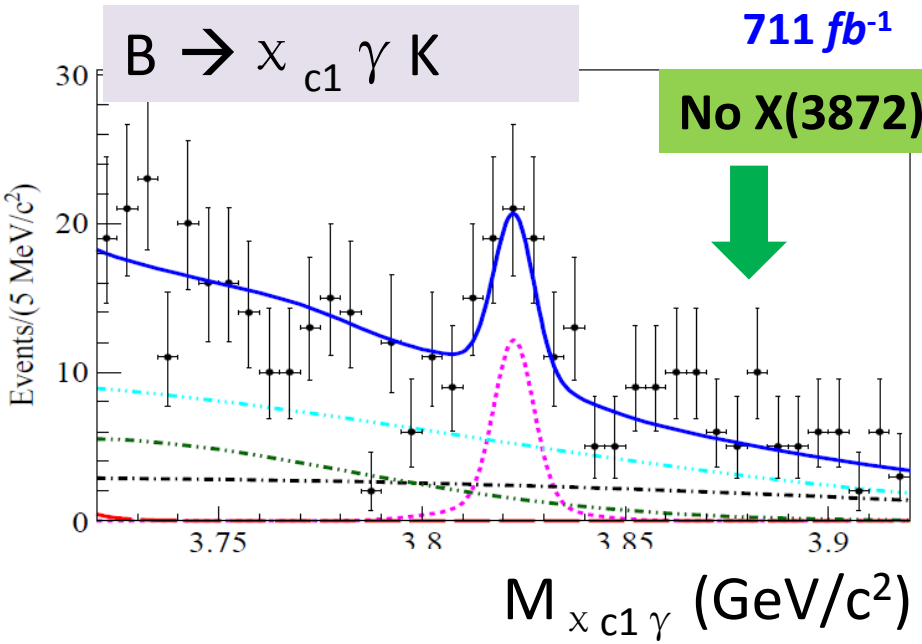
Difficult to place as conventional charmonium state.

Search for C-odd partner of X(3872)

If X(3872) is tetraquark, then X(3872) has C-odd partner which can dominantly decay into $J/\Psi\eta$ and $\chi_{c1}\gamma$



arXiv:1304.3975 (submitted to PRL)



No X(3872) signal in $J/\Psi\eta$ mass spectrum in $B \rightarrow J/\Psi\,\eta\,K$

For details, please see Bhardwaj 's report.

Clear evidence (3.8 σ) of signal at 3823 MeV/c^2 .
The measured mass and width are consistent with the missing Ψ_2(1D) state

How to identify an exotic meson easily?

- Decays to charmonium thus has a $\bar{c}c$ pair!
- With electric charge thus has two more light quarks!

$$\rightarrow N_{quark} \geq 4 \text{ !}$$

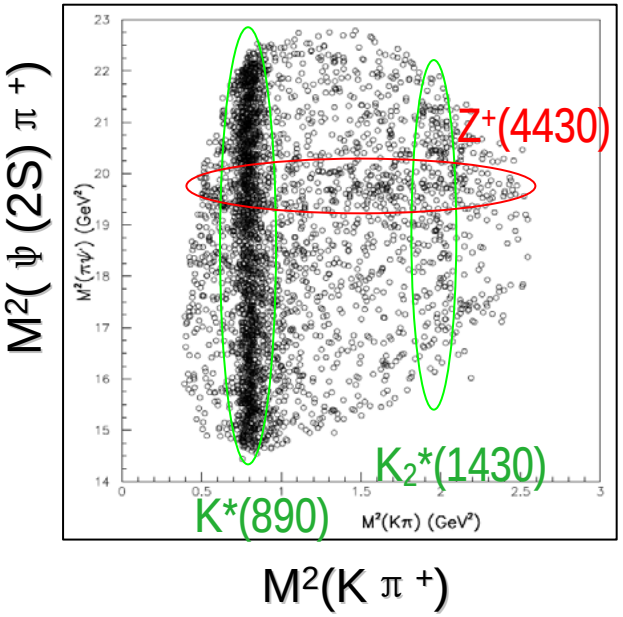
- Do searches in $\pi^{\pm} J/\psi$, $\pi^{\pm}\psi(2S)$, $\pi^{\pm}\chi_{cJ}$, …

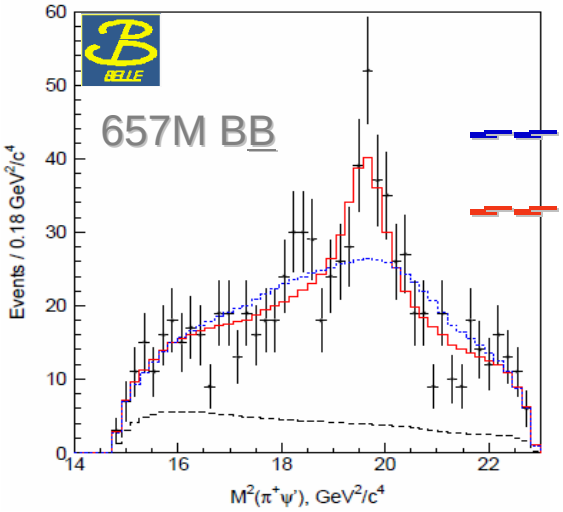
Belle observed $Z(4430)^{\pm}\to\psi(2S)\pi^{\pm}$

PRL100, 142001 (2008)

- Found in $\psi(2S)\pi^+$ from $B\to\psi(2S)\pi^+K$. Z parameters from fit to $M(\psi(2S)\pi^+)$
- Confirmed through Dalitz-plot analysis of $B\to\psi(2S)\pi^+K$
- $B\to\psi(2S)\pi^+K$ amplitude: coherent sum of Breit-Wigner contributions
- Models: all known $K^*\to K\pi^+$ resonances only

  all known $K^*\to K\pi^+$ and $Z^+\to\psi(2S)\pi^+$ ⇨ favored by data





M²(ψ (2S) π +) after K* veto

Significance: 6.4 σ

fit for model with K*'s only

fit for model with K*'s and Z

$$M = 4433\,^{+15\,+19}_{-12\,-13}\ \text{MeV}$$

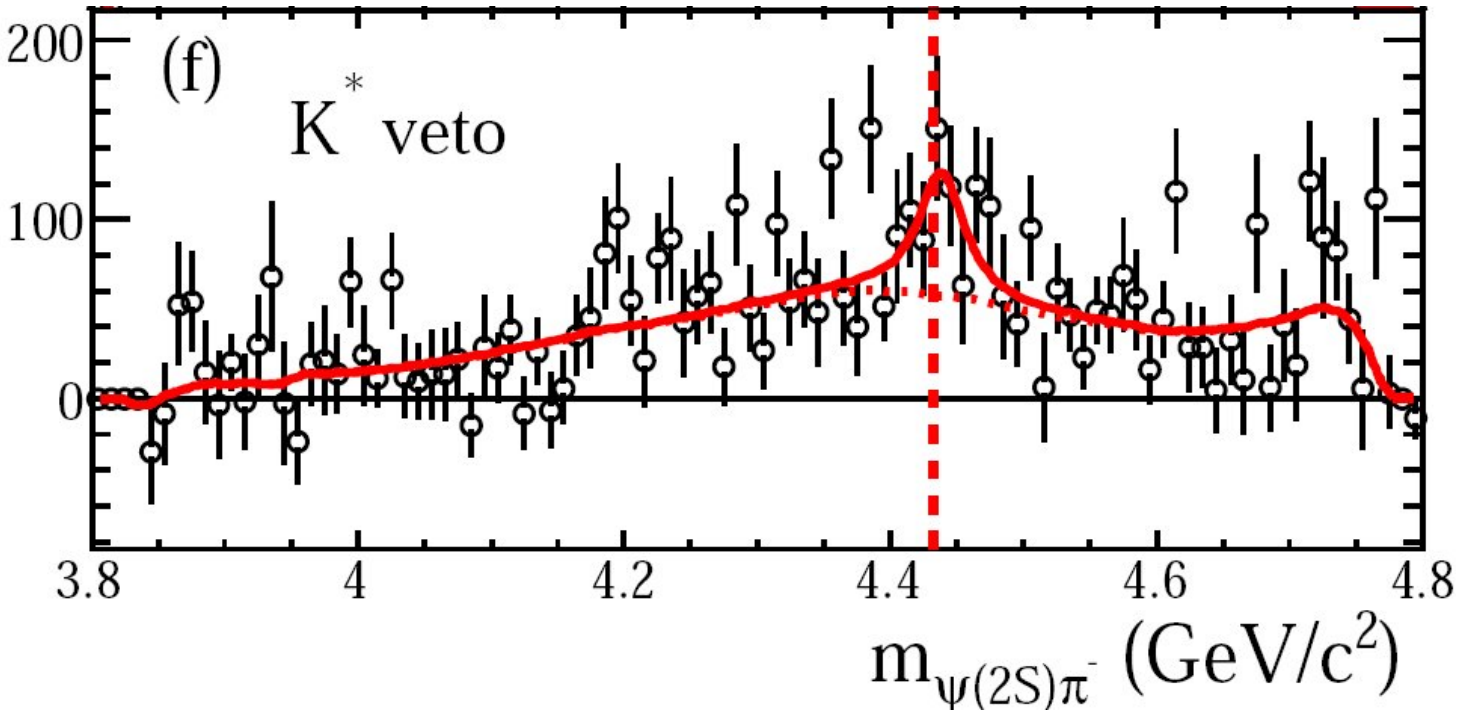
$$\Gamma = 107\,^{+86\,+74}_{-43\,-53}\ \text{MeV}$$

PRD80, 031104 (2009)

- [cu][$\underline{\text{cd}}$] tetraquark? neutral partner in $\psi'\pi^0$ expected
- $D^*\underline{D}_1(2420)$ molecule? should decay to $D^*\underline{D}^*\pi$

BaBar doesn't see a significant Z(4430)$^+$

PRD79, 112001 (2009)



"For the fit … equivalent to the Belle analysis…we obtain mass & width values that are consistent with theirs,… but only ~1.9σ from zero; fixing mass and width increases this to only ~3.1σ."

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

Belle PRL: $(4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

Measurement of $Z(4430)^+$ quantum numbers

NEW

★ Amplitude analysis in 4D phase:

$(M^2_{K\pi}, M^2_{\psi'\pi}, \phi_{\psi' K^*}, \theta_{\psi'})$.

$\phi_{\psi' K^*}$: angle between Ψ' and K* decay planes

$\theta_{\psi'}$: Ψ' helicity angle

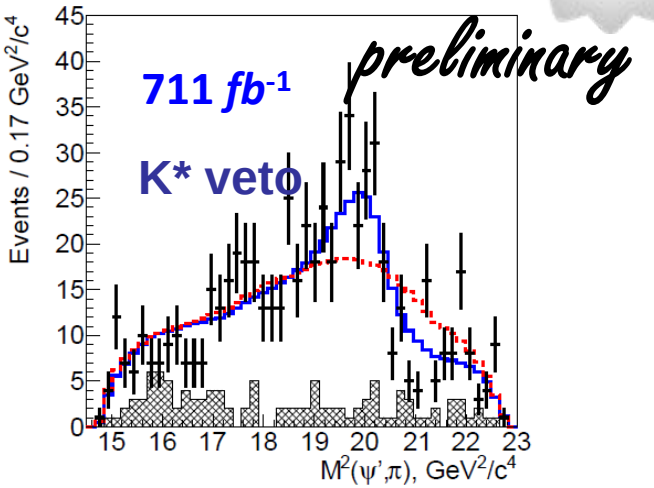
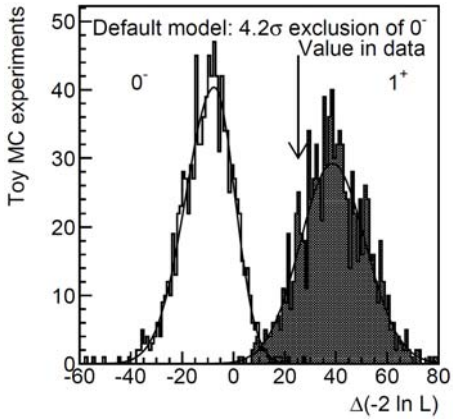


TABLE I: Fit results: $Z^+ \to \psi'\pi^+$.

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV	4470 ± 20	4482 ± 4	4500 ± 12	4545 ± 2	4367 ± 2
Width, MeV	139 ± 36	10.9 ± 0.3	126 ± 20	11.2 ± 0.6	9.1 ± 0.6
Significance	4.4σ	1.2σ	6.1σ	2.3σ	2.6σ



★ **The 1^+ hypothesis is preferred**

★ Exclusion levels are calculated from toy MC

★ 0^- is not excluded; significance of 1^+ over 0^- is 2.9σ. 1^-,2^- and 2^+ are excluded at levels of 5.5σ, 4.3σ,and 5.4σ

★ **We also calculated some Brs:**

$$\mathcal{B}(\bar{B}^0 \to \psi' K^- \pi^+) = (5.50 \pm 0.15 \pm 0.42) \times 10^{-4},$$
$$\mathcal{B}(\bar{B}^0 \to \psi' K^*(892)) = (4.93^{+0.30+1.40}_{-0.23-0.43}) \times 10^{-4},$$

$$\mathcal{B}(\bar{B}^0 \to Z(4430)^+ K^-) \times \mathcal{B}(Z(4430)^+ \to \psi'\pi^+) =$$
$$(3.4^{+1.1+0.4}_{-0.7-1.3}) \times 10^{-5} \quad \text{for } J^P = 1^+ \text{ or}$$
$$(1.4^{+0.8+0.6}_{-0.7-0.2}) \times 10^{-5} \quad \text{for } J^P = 0^-.$$

Belle observed Two $Z^{\pm}\to\chi_{c1}\pi^{\pm}$

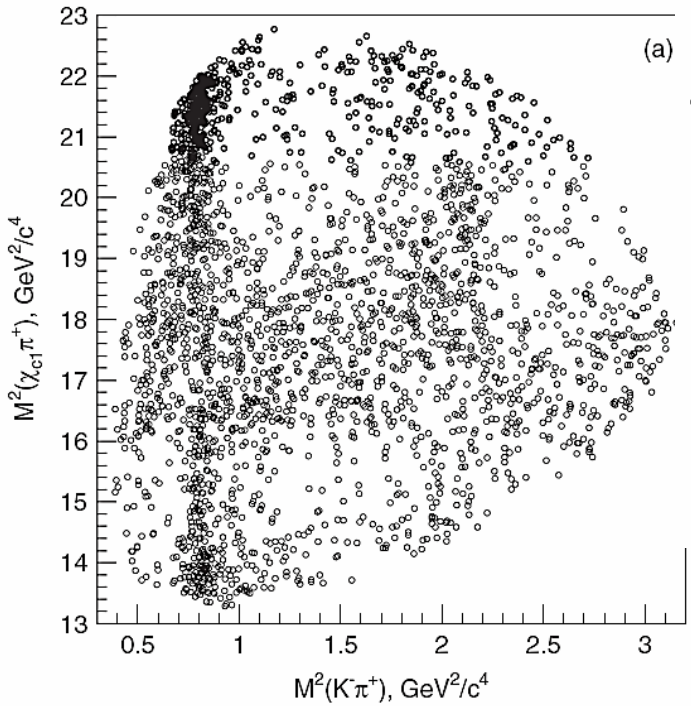
- Dalitz-plot analysis of $\underline{B^0}\to\chi_{c1}\pi^+K^-$ $\chi_{c1}\to J/\psi\gamma$ with 657M $B\underline{B}$
- Dalitz plot models: known $K^*\to K\pi$ only

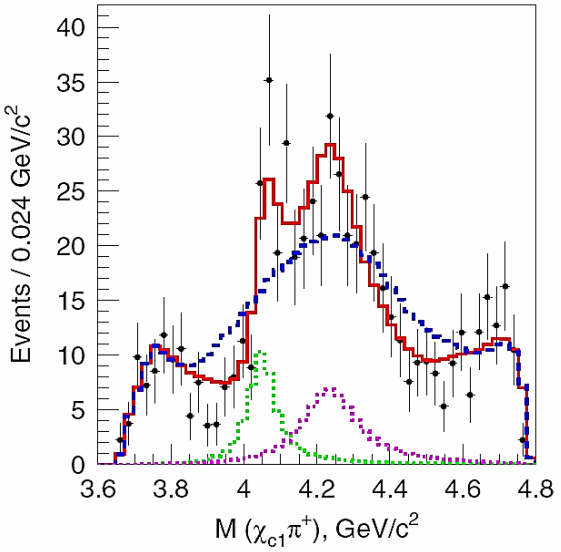
  K^*'s + one $Z\to\chi_{c1}\pi^{\pm}$

  K^*'s + two $Z^{\pm}$ states ⇨ favored by data

PRD 78, 072004 (2008)

Significance: 5.7σ





M($\chi_{c1}\pi^+$)
for $1<M^2(K^-\pi^+)<1.75$GeV^2

fit for model with K*'s

fit for double Z model

Z_1 contribution

Z_2 contribution

$$M_{Z_1} = 4051 \pm 14\,^{+20}_{-41}\ \text{MeV}$$

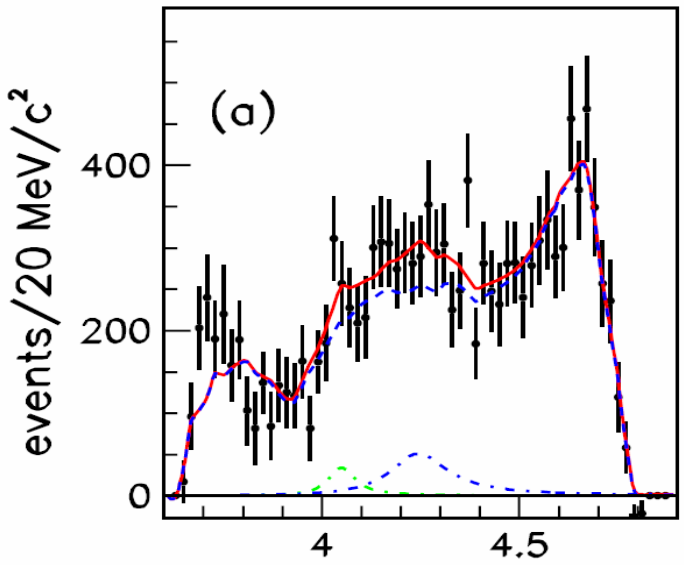
$$\Gamma_{Z_1} = 82\,^{+21\,+47}_{-17\,-22}\ \text{MeV}$$

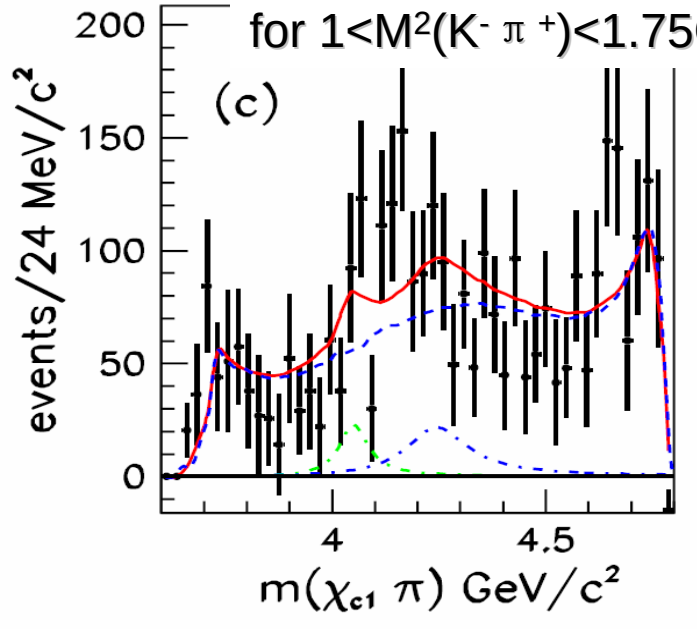
$$M_{Z_2} = 4248\,^{+44\,+180}_{-29\,-35}\ \text{MeV}$$

$$\Gamma_{Z_2} = 177\,^{+54\,+316}_{-39\,-61}\ \text{MeV}$$

BaBar doesn't see significant $Z^{\pm} \to \chi_{c1}\pi^{\pm}$

PRD85, 052003 (2012)





$$\mathcal{B}(\bar{B}^0 \to Z_1(4050)^+ K^-) \times \mathcal{B}(Z_1(4050)^+ \to \chi_{c1}\pi^+) < 1.8 \times 10^{-5},$$

Belle: $(3.0^{+1.5}_{-0.8}{}^{+3.7}_{-1.6})\times10^{-5}$

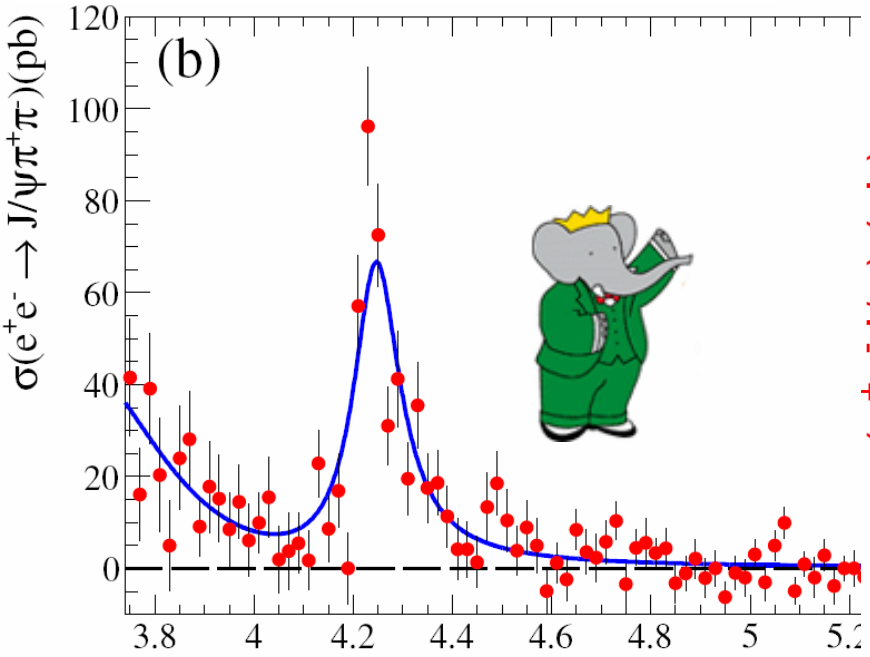
$$\mathcal{B}(\bar{B}^0 \to Z_2(4250)^+ K^-) \times \mathcal{B}(Z_2(4250)^+ \to \chi_{c1}\pi^+) < 4.0 \times 10^{-5},$$

Belle: $(4.0^{+2.3}_{-0.9}{}^{+19.7}_{-0.5})\times10^{-5}$

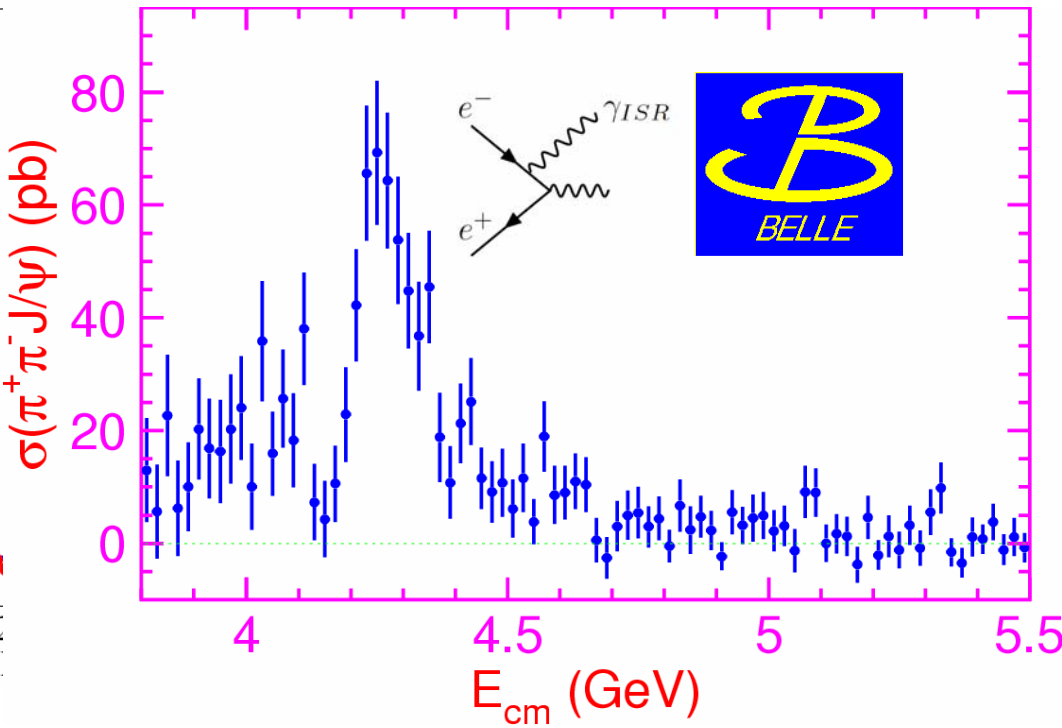
"We find that it is possible to obtain a good description of our data without the need for additional resonances in the $\chi_{c1}\pi$ system."

We may search for such state if it decays into $\pi^{\pm}J/\psi$!

BaBar: PRD86, 051102 (2012)



Belle: PRL99, 182004 (2007)



- $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ reaches maximum at ~4.26 GeV

1. "Charmonium-like" states: Y(4008) & Y(4260) are observed via ISR method by Belle.
2. BaBar's recent results do not confirm Y(4008).

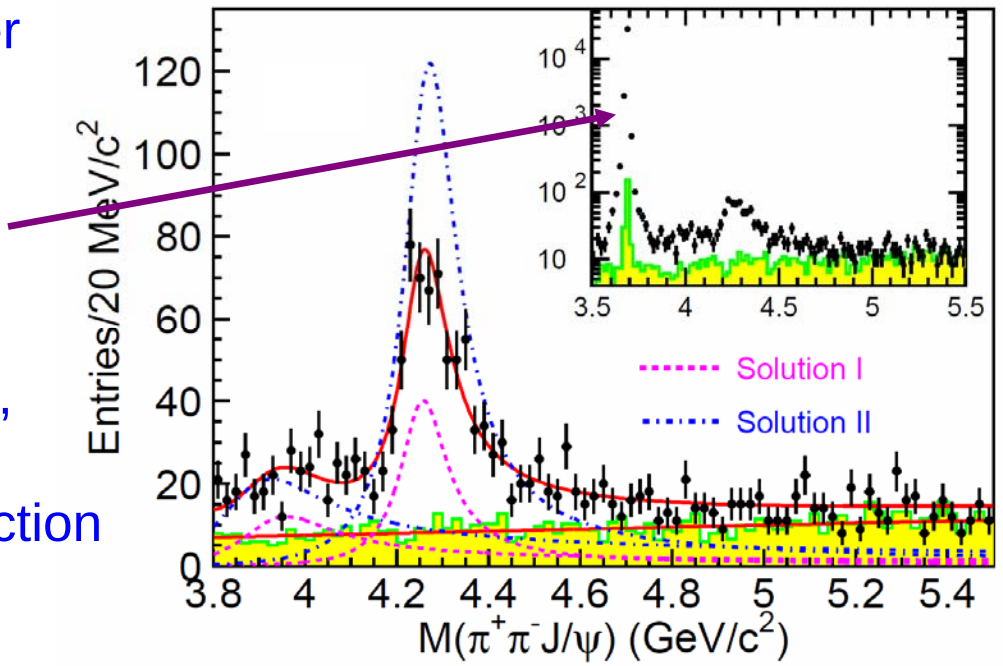
Update ISR $\pi^+\pi^-J/\psi$ analysis

NEW

Lum: 967.02fb^{-1}

Event selections are almost the same as in previous Belle published paper **PRL99, 182004 (2007)**

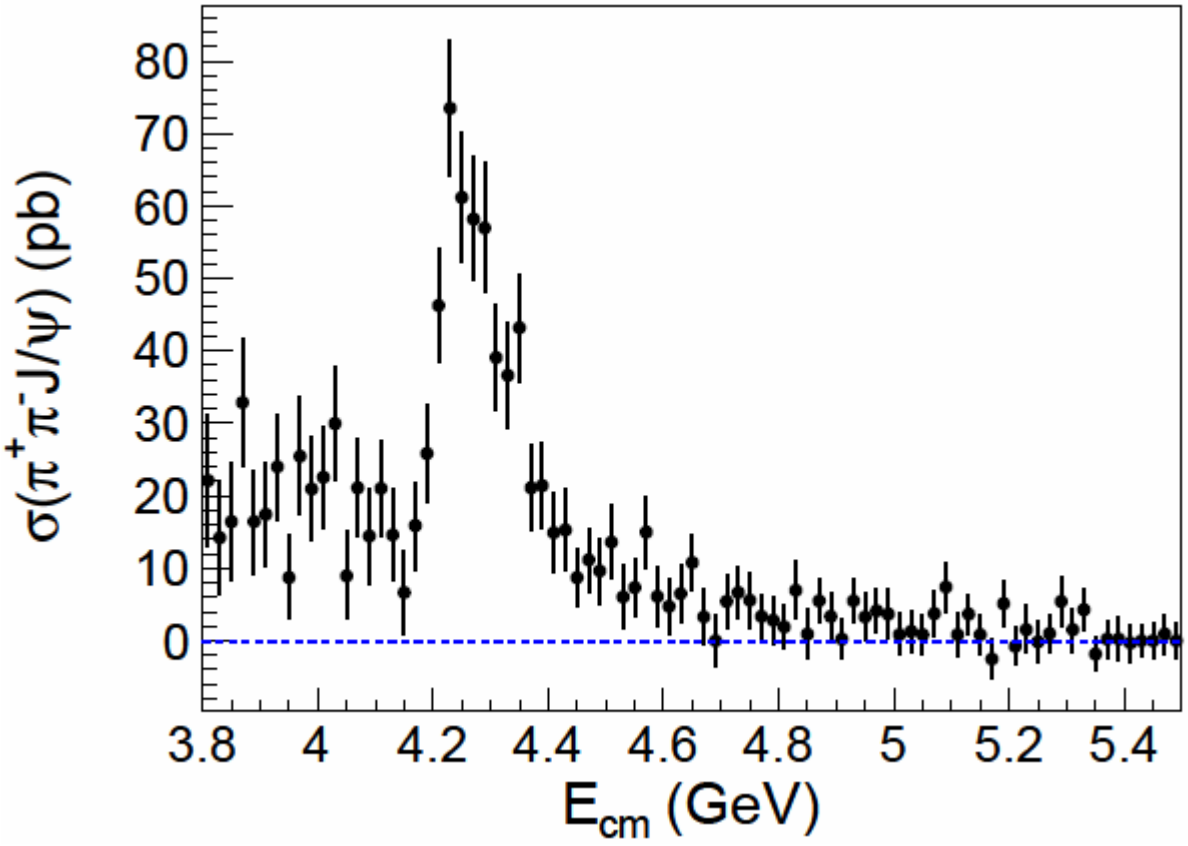
- Clean $\psi(2S)$ signal events are obtained, purity>99%.
- Fit data with double Gaussian yields M($\psi(2S)$)=(3686.1$\pm$0.2)MeV, σ=4.8MeV
- We calculated ISR $\Psi(2S)$ production cross section:



	e^+e^-	$\mu^+\mu^-$	QED
$\sigma(\Upsilon(4S))$	$(14.12 \pm 0.18 \pm 0.85)$ pb	$(15.09 \pm 0.11 \pm 0.79)$ pb	(14.25 ± 0.26) pb
$\sigma(\Upsilon(5S))$	$(13.79 \pm 0.44 \pm 0.83)$ pb	$(13.33 \pm 0.25 \pm 0.70)$ pb	(13.42 ± 0.25) pb
$\sigma(\Upsilon(2S))$	$(16.75 \pm 0.85 \pm 1.01)$ pb	$(16.63 \pm 0.54 \pm 0.87)$ pb	(16.03 ± 0.29) pb

We also found a few $\psi(3770)\rightarrow\pi^+\pi^-J/\psi$ (N=54$\pm$20, 2.8σ)
Br($\psi(3770)\rightarrow\pi^+\pi^-J/\psi$)=(5.5$\pm$2.1)$\times10^{-3}$, PDG(1.28 $\times10^{-3}$)

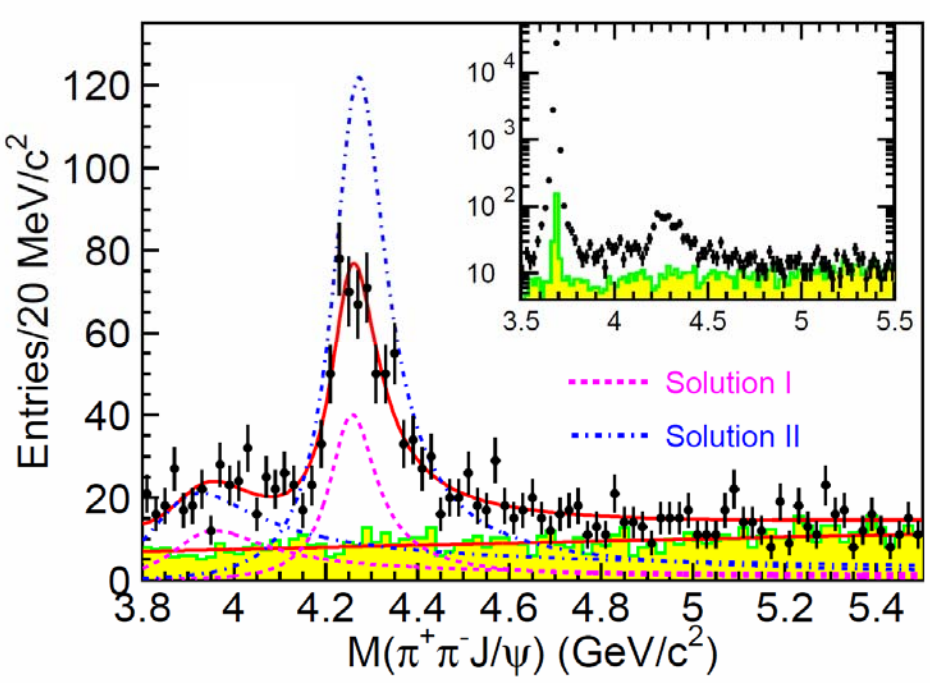
$e^+e^-\rightarrow\pi^+\pi^-J/\psi$ cross section



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

1. $e^+e^-\rightarrow\pi^+\pi^-J/\psi$ cross section measurement above 3.8 GeV.
2. Sideband background events have been subtracted.
3. Essential measurement. ~7% systematic error not shown.

Two resonances fit



We still observed two resonances, Y(4008) and Y(4260) , which agrees with Belle's previous results.

R_1=Y(4008)
R_2=Y(4260)

Parameters	Solution I	Solution II
$M(R_1)$	$3890.8 \pm 40.5 \pm 11.5$	
$\Gamma_{\rm tot}(R_1)$	$254.5 \pm 39.5 \pm 13.6$	
$\Gamma_{ee}\mathcal{B}(R_1 \to \pi^+\pi^- J/\psi)$	$(3.8 \pm 0.6 \pm 0.4)$	$(8.4 \pm 1.2 \pm 1.1)$
$M(R_2)$	$4258.6 \pm 8.3 \pm 12.1$	
$\Gamma_{\rm tot}(R_2)$	$134.1 \pm 16.4 \pm 5.5$	
$\Gamma_{ee}\mathcal{B}(R_2 \to \pi^+\pi^- J/\psi)$	$(6.4 \pm 0.8 \pm 0.6)$	$(20.5 \pm 1.4 \pm 2.0)$
ϕ	$59 \pm 17 \pm 11$	$-116 \pm 6 \pm 11$

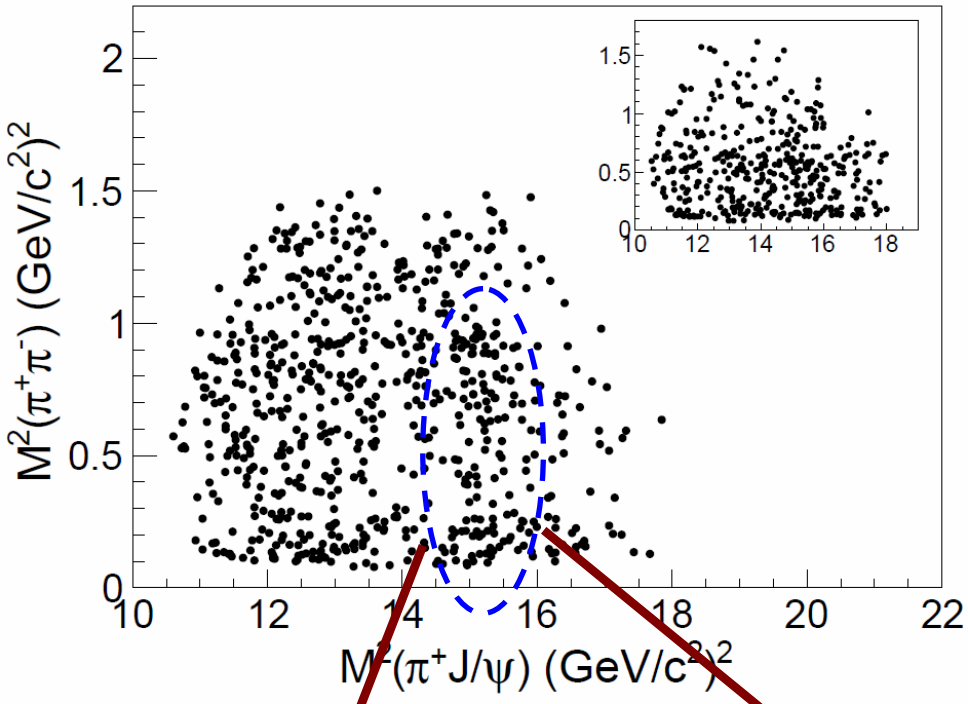
1. Fit with two coherent resonance $|BW_1+BW_2*\exp(i\phi)|^2$+bkg.
2. Mass of Y(4008) is smaller than 4008 MeV
3. Fit quality: χ^2/ndf=101/84, confidence level of 9.3%

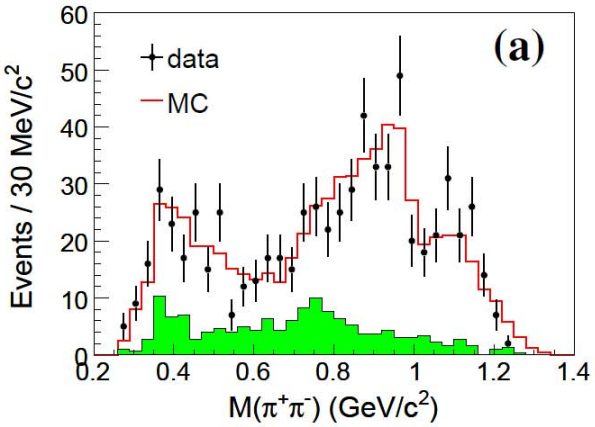
Search for $Z^{\pm} \rightarrow \pi^{\pm} J/\psi$

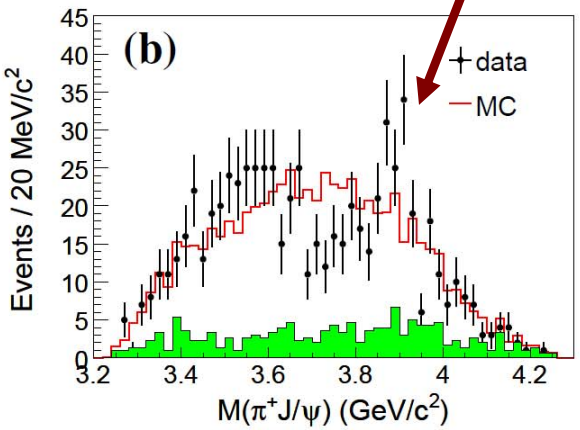
Dalitz plots & 1D projections

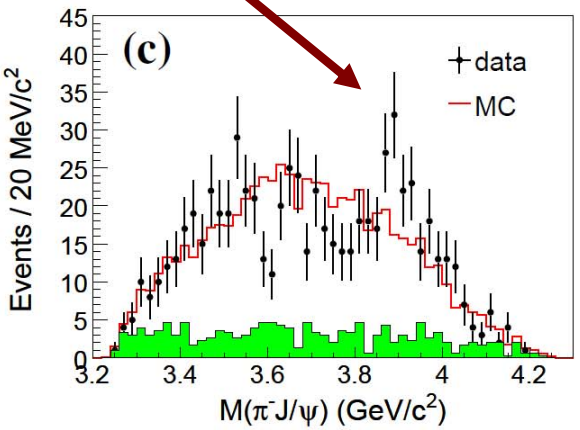
Belle: arXiv:1304.0121

1. Dalitz plot of $M^2(\pi\pi)$ vs $M^2(\pi J/\psi)$ for $4.15<M(\pi\pi J/\psi)<4.45$ GeV
2. (inset) Background events in J/ψ-mas sidebands
3. Structures both in $\pi\pi$ and $\pi J/\psi$ systems





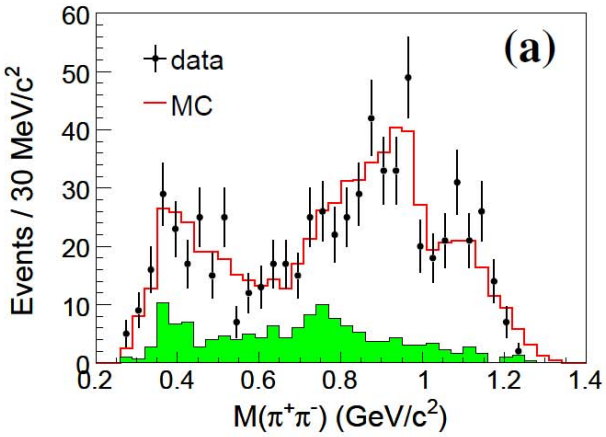


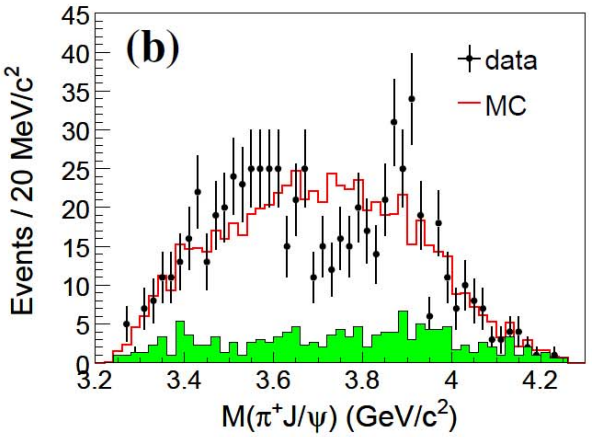


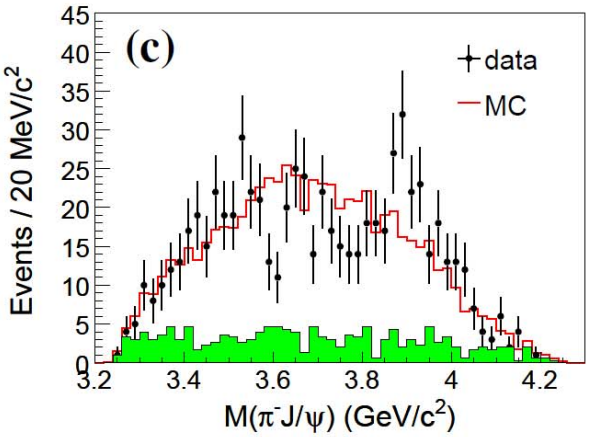
Is it a real signal?

- Is it due to $\pi^+\pi^-$ S-wave states, like σ, $f_0(980)$, …? N
- Is it due to $\pi^+\pi^-$ D-wave states, like $f_2(1270)$, …?

  We did not see clear D-wave state contribution N
- Are there two states, one at 3.4, the other 3.9 GeV? N
- Exist in both e^+e^- & $\mu^+\mu^-$ samples? Y
- Exist in both $\pi^+\pi^-$ low mass and high mass samples? Y
- Background fluctuation? (see next page) N





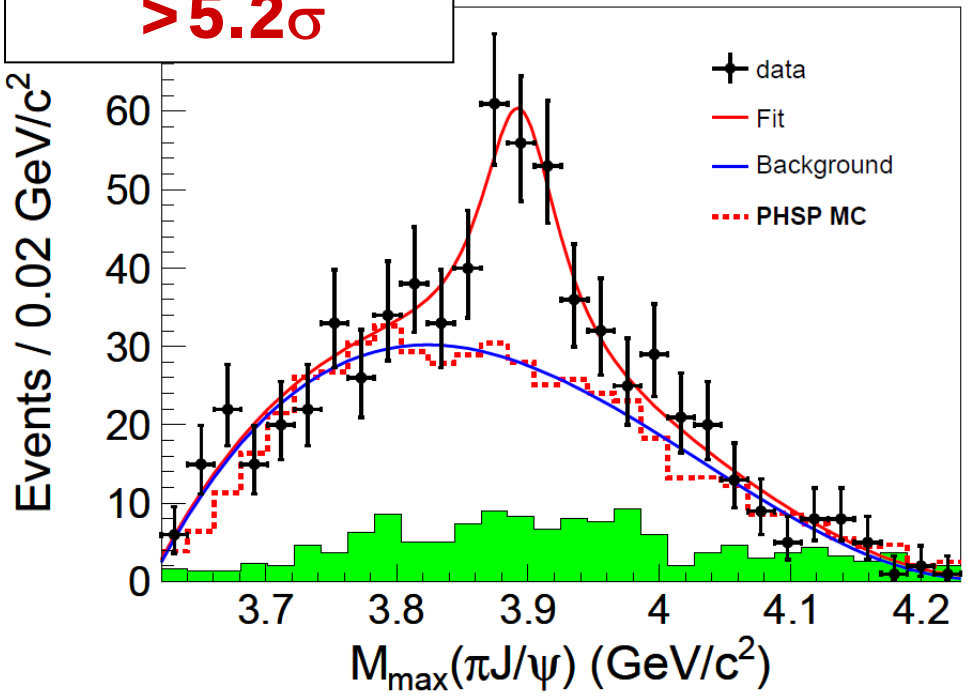


There are $f_0(980)$, $f_0(500)$ and non-resonant S-wave in $\pi^+\pi^-$. They cannot reproduce the structure at 3.9GeV in $\pi J/\Psi$ (histogram).

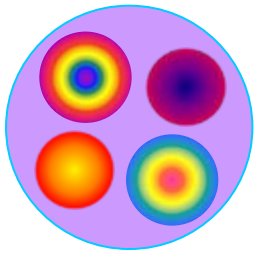
The Z(3895) signal

Significance >5.2σ

Belle: arXiv:1304.0121



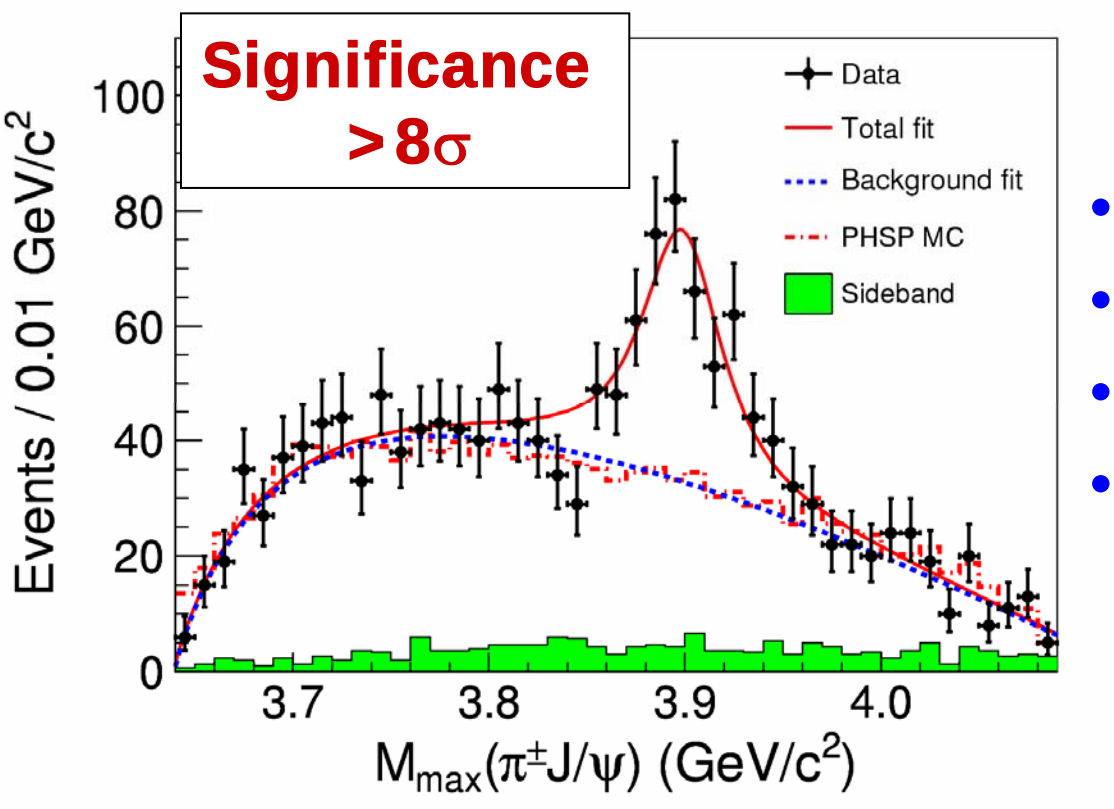
- Couples to $c\bar{c}$
- Has electric charge
- At least 4-quarks
- What is its nature?



- S-wave Breit-Wigner convolved with a Gaussian (7.4 MeV); background: a cubic polynomial
- Mass = (3894.5±6.6±4.5) MeV
- Width = (63±24±26) MeV
- Fraction = (29.0±8.9)% (stat. error only)

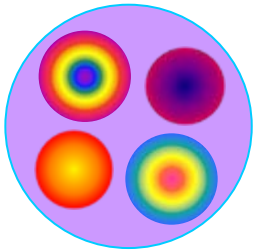
- **Similar to Zb state observed in $\pi\Upsilon$(nS) and πh_b ?**
- **For Zb details, please see Roman's talk.**

The $Z_c(3900)$ signal



BESIII: arXiv:1303.5949
At a fixed energy point

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



- S-wave Breit-Wigner with efficiency correction
- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

For details, please see Zhiqing's report.

Various theoretical explanation

After BESIII and Belle papers were released, there have been a few theoretical explanations:

- D*D molecule: arXiv:1303.6355, 1303.6608, 1303.6842 , 1304.1850, 1304.2882
- Tetraquark and molecule possibilities: arXiv:1303.6857
- Hadro-charmonium state: arXiv:1304.1301
- Molecule or hadron-charmonium as possible: arXiv:1304.0380
- Doubly heavy tetraquark and baryonic state : arXiv:1304.0345

Previously, there were also a few theoretical Papers on it, like:

- Initial single pion emission mechanism predicted a structure near D*D threshold: PRD 84, 034032 (2011)
- Tetraquark prediction: PRD 85, 054011 (2012)

Summary

- Evidence (4.2 σ) is seen in $\chi_{c1}\gamma$ mass spectrum at 3823 MeV. Probably it is Ψ_2 state: the missing piece of $c\bar{c}$ spectrum.
- Y(4008) is confirmed with full of Belle data sample. Y(4008) and Y(4260) parameters are updated.
- We measured of $Z(4430)^+$ quantum numbers: the 1^+ hypothesis is preferred
- We observed a charged charmoniumlike structure, Z(3895), in its $\pi^\pm J/\psi$ decays
- $Z(3895)^\pm$ is not a charmonium. The nature is yet unknown.