Observation of the $Z_c(3900)$

— a charged charmoniumlike structure —

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(for the BESIII Collaboration)

March 27, 2013

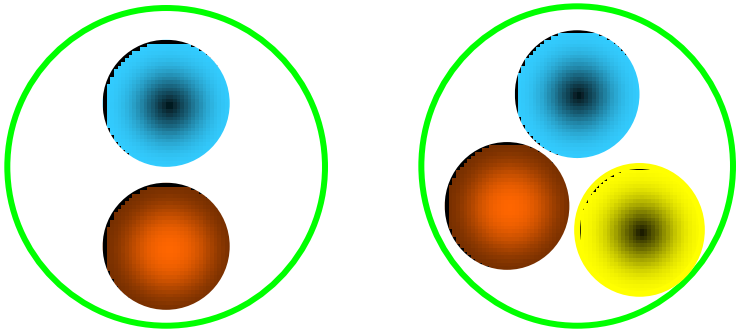
Outline

- Conventional & exotic hadrons
- How to study exotic hadrons
- BESIII analysis & results
- Summary & perspectives

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 : $N_{quarks} = 2$ + excited 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?

Why hard to identify exotic state?

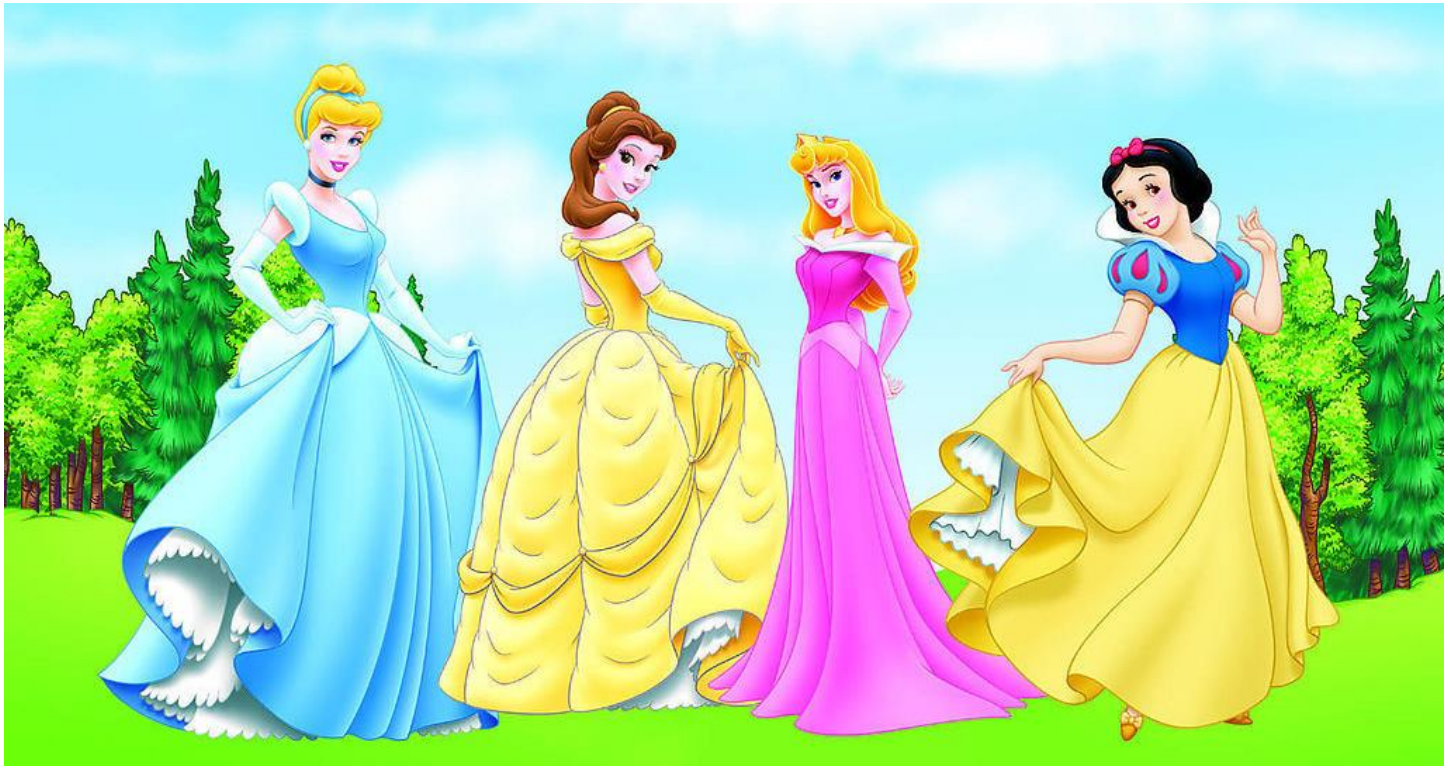
- Which dwarf was named “Happy”?

- I donot know …

No solid signature!

Why hard to identify exotic state?

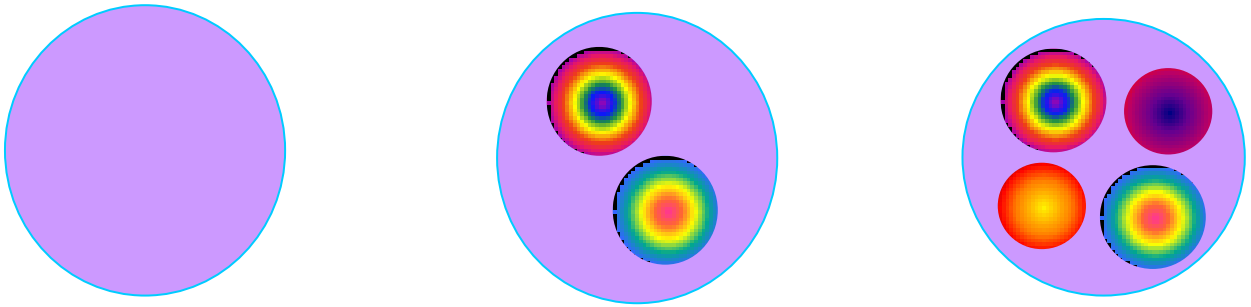
- Which beauty is “Snow White”?



- Yes, I know! “Hair black as ebony [乌木，黑檀]”.
- Very clear signature!

How to identify an exotic meson?

- Find a clear signature for exotic state!



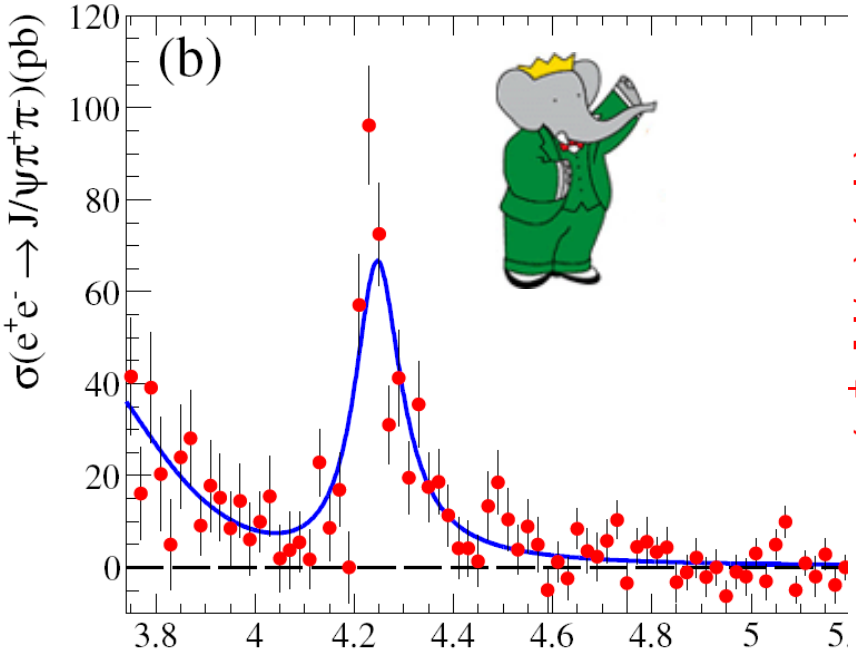
- Decays to charmonium thus has a $\bar{c}c$ pair!
- With electric charge thus has two more light quarks!

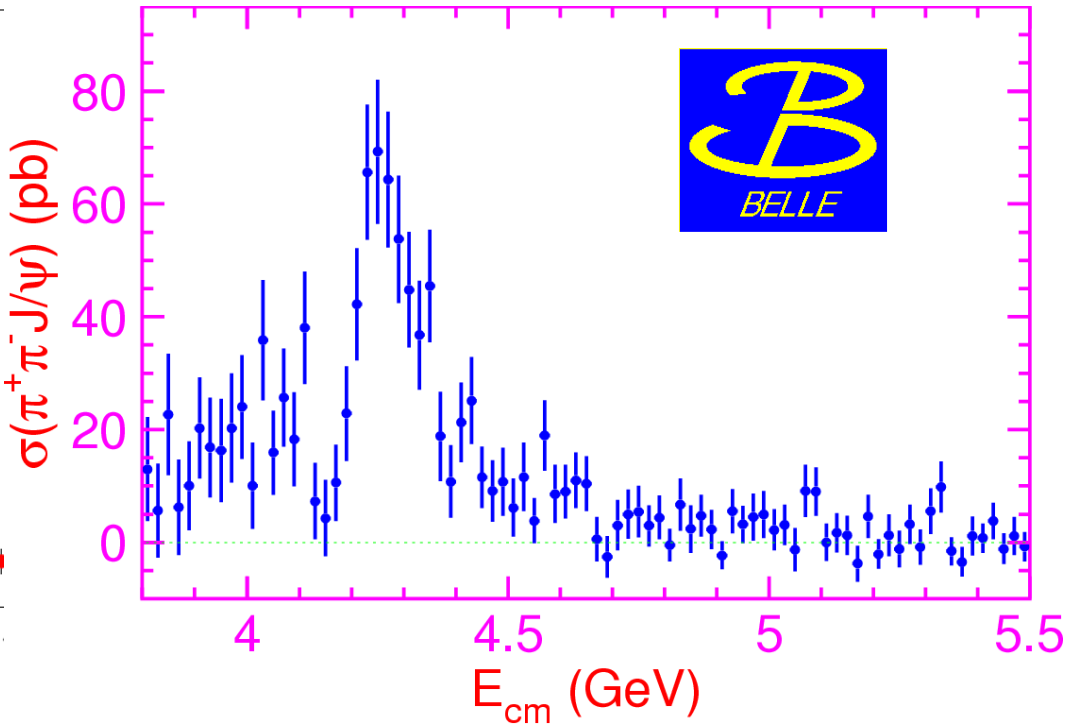
➔ $N_{quark} \geq 4$!

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

What do we do at BESIII

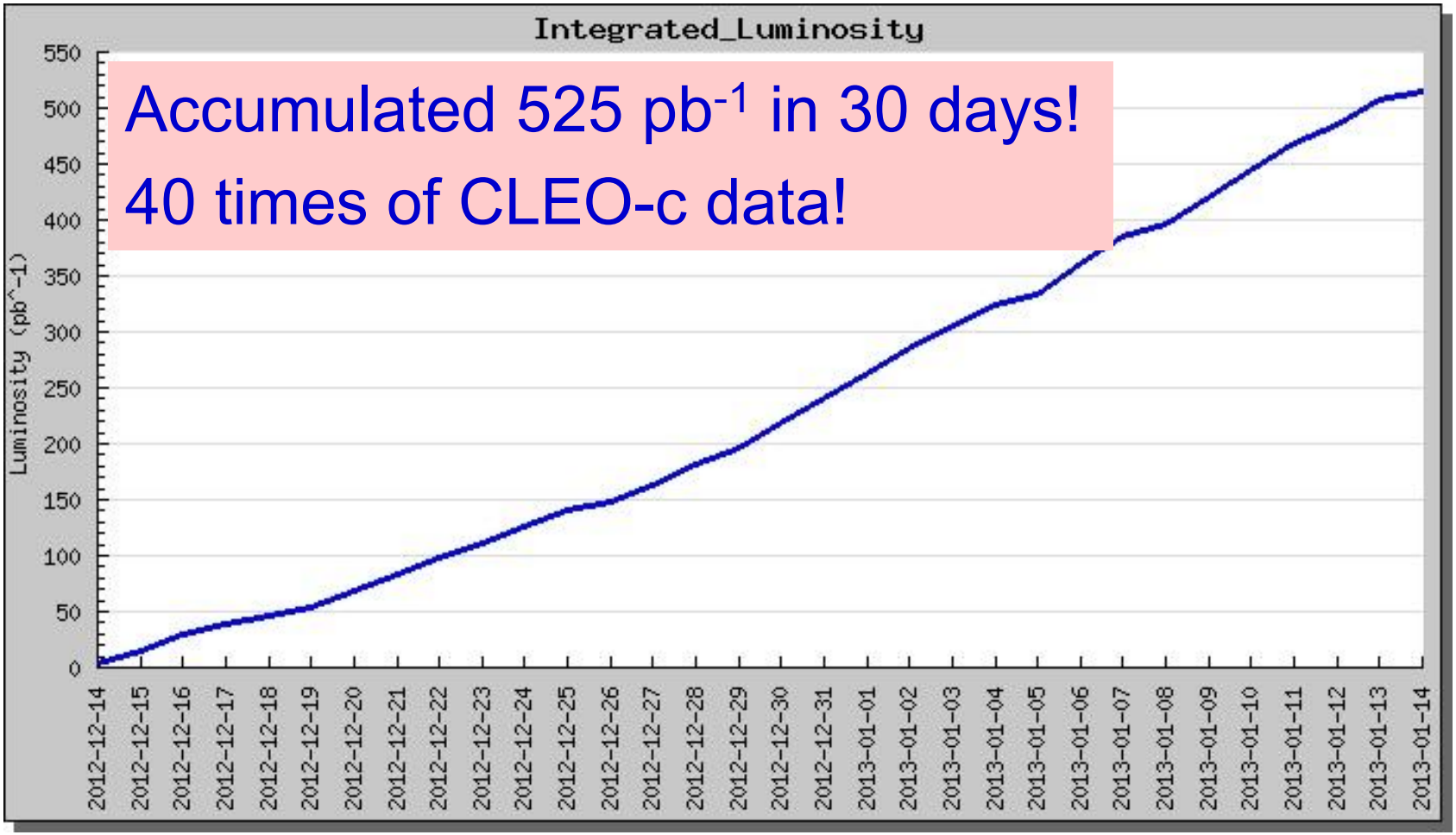
We may search for such state if it decays into $\pi^{\pm}J/\psi$!





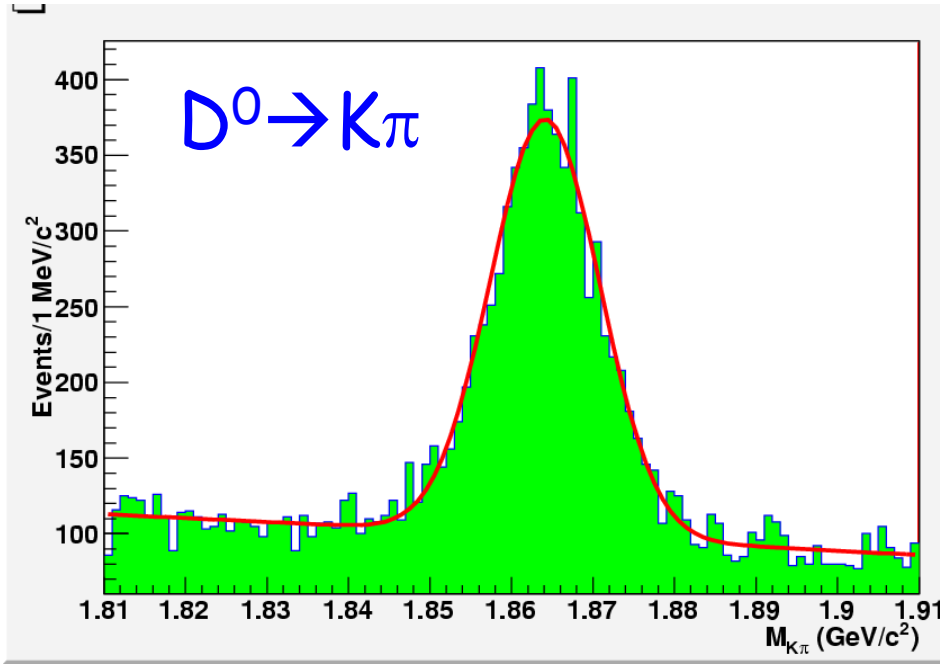
- $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ reaches maximum at ~4.26 GeV
- We proposed a 45 days' data taking for 500 pb^{-1} data at peak
- ~1500 reconstructed events are expected [3xB-factories]

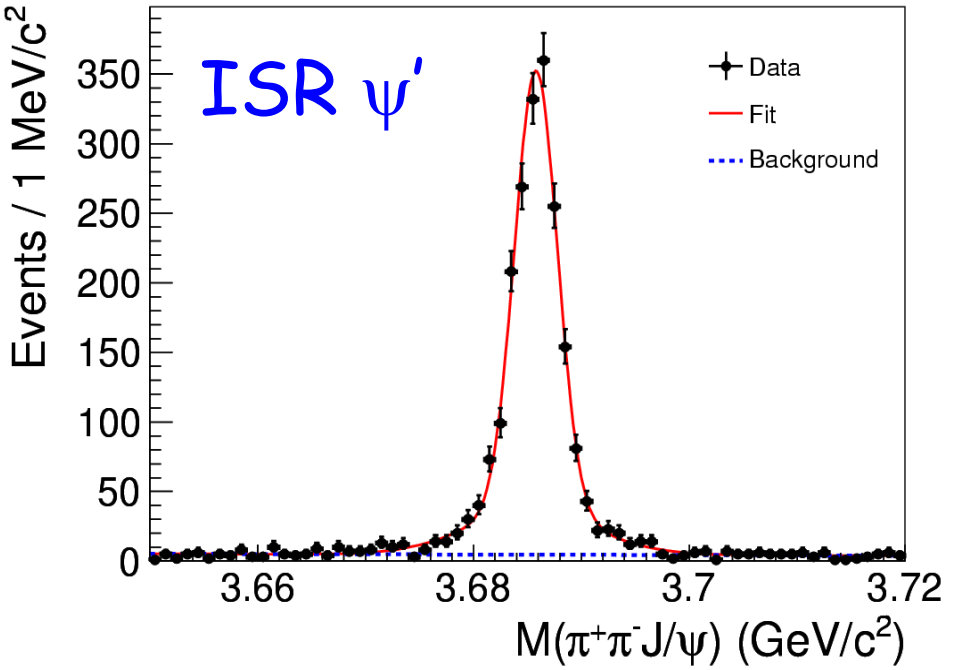
Data taking at BESIII



- Highest energy BEPCII ever reach, L_{peak} ~ 5.3x10^{32}/cm^2/s !
- BEMS measures Ecm at 1 MeV level !
- Low background, low noise, all sub-detectors excellent !

Data quality is excellent





$\Delta M_D = 0.5 \pm 0.2$ MeV

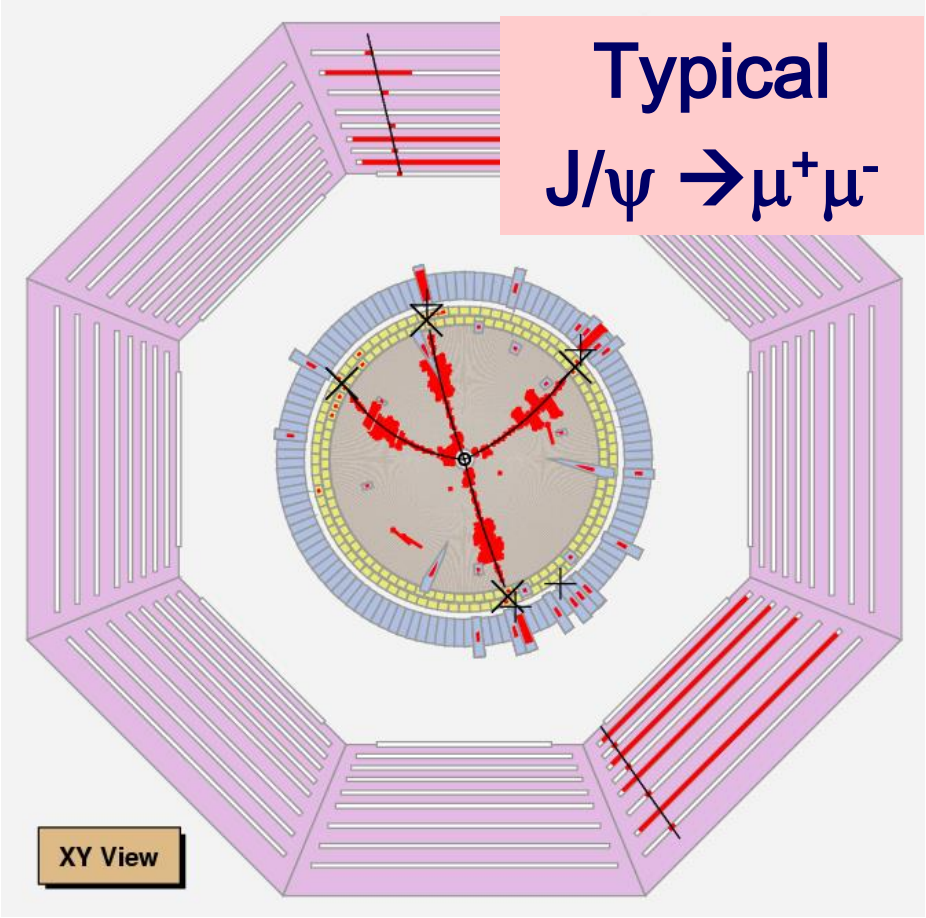
$\sigma M_D = 6.0 \pm 0.1$ MeV

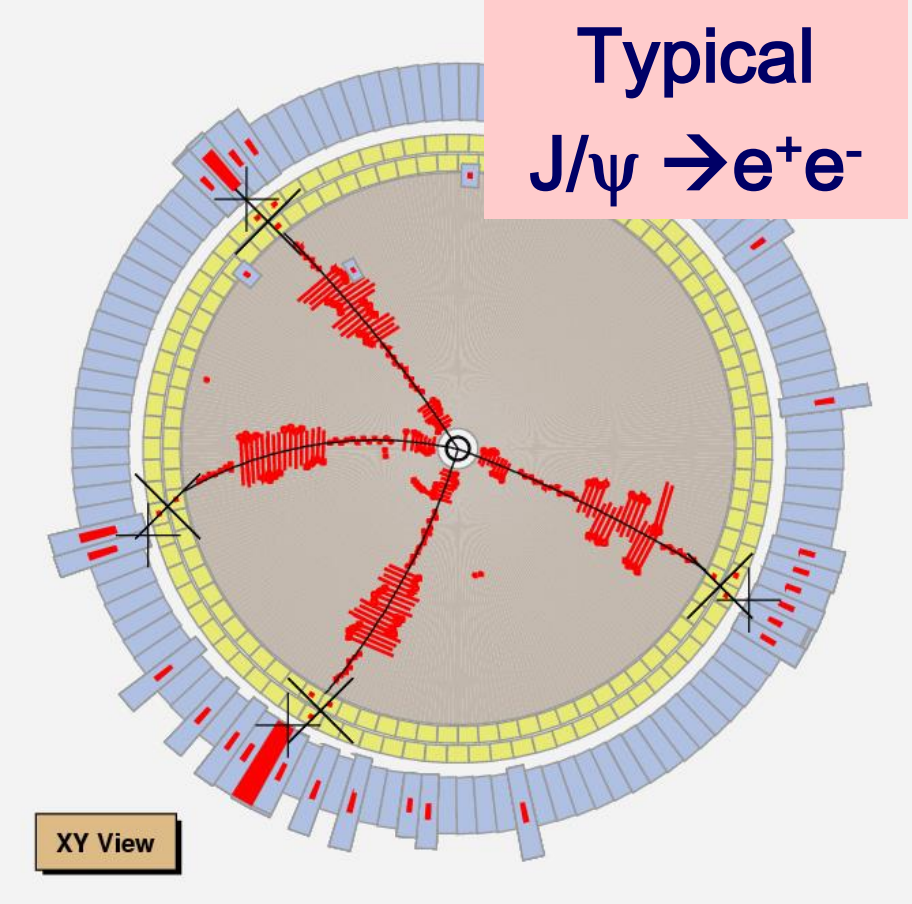
$\Delta M_{\psi'} = 0.2 \pm 0.1$ MeV

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

- Data calibration, reconstruction, MC simulation were finished shortly after the data taking …
- Production version was ready earlier March …

Select $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ events

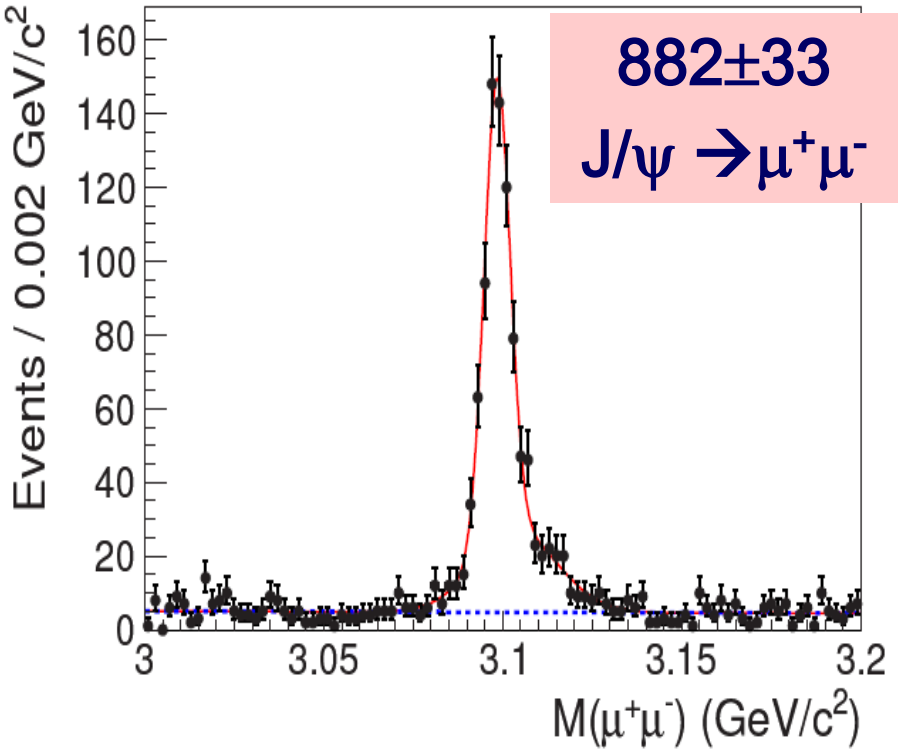


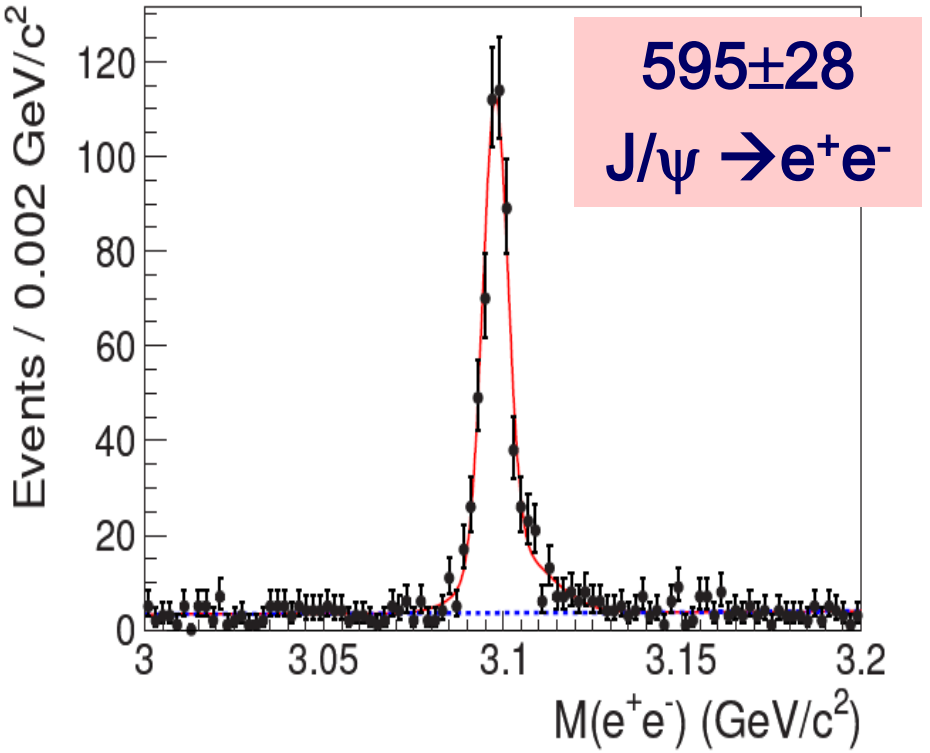


- Select 4 charged tracks and reconstruct J/ψ with lepton pair.
- Very clean sample, very high efficiency. Use kinematic fit.
- Only use MDC & EMC information, MC simulation reliable.

The J/ψ signals

BESIII: arXiv:1303.5949

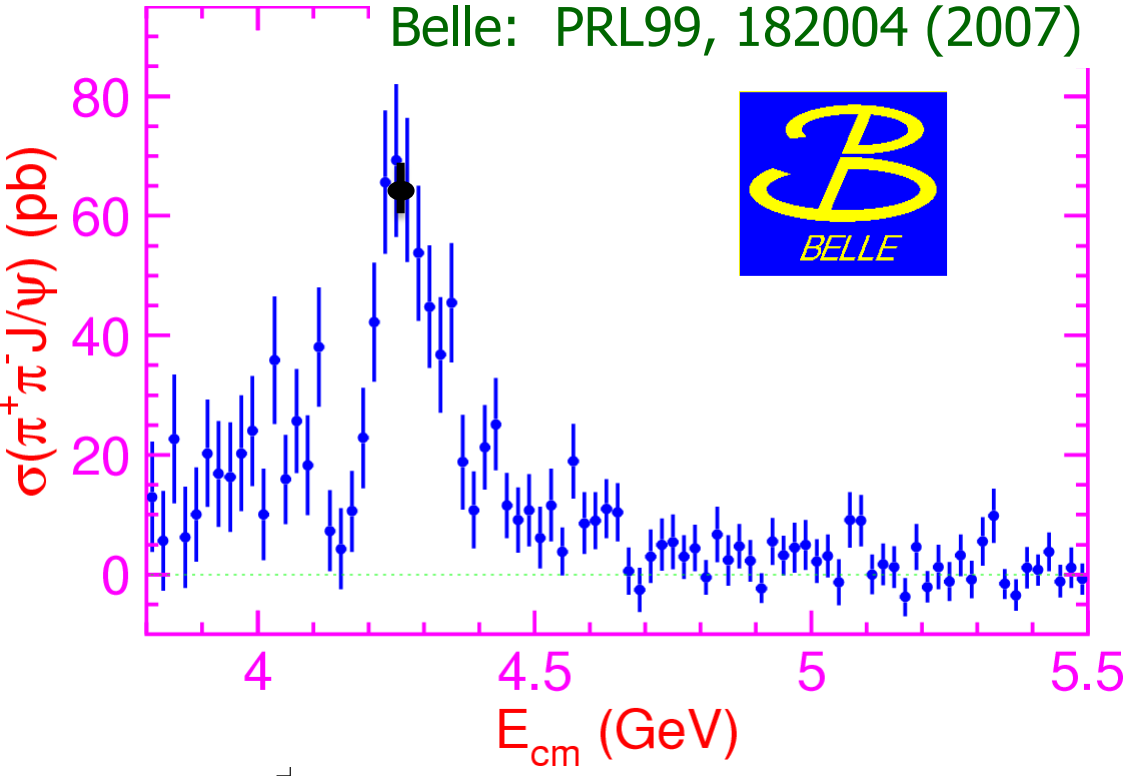




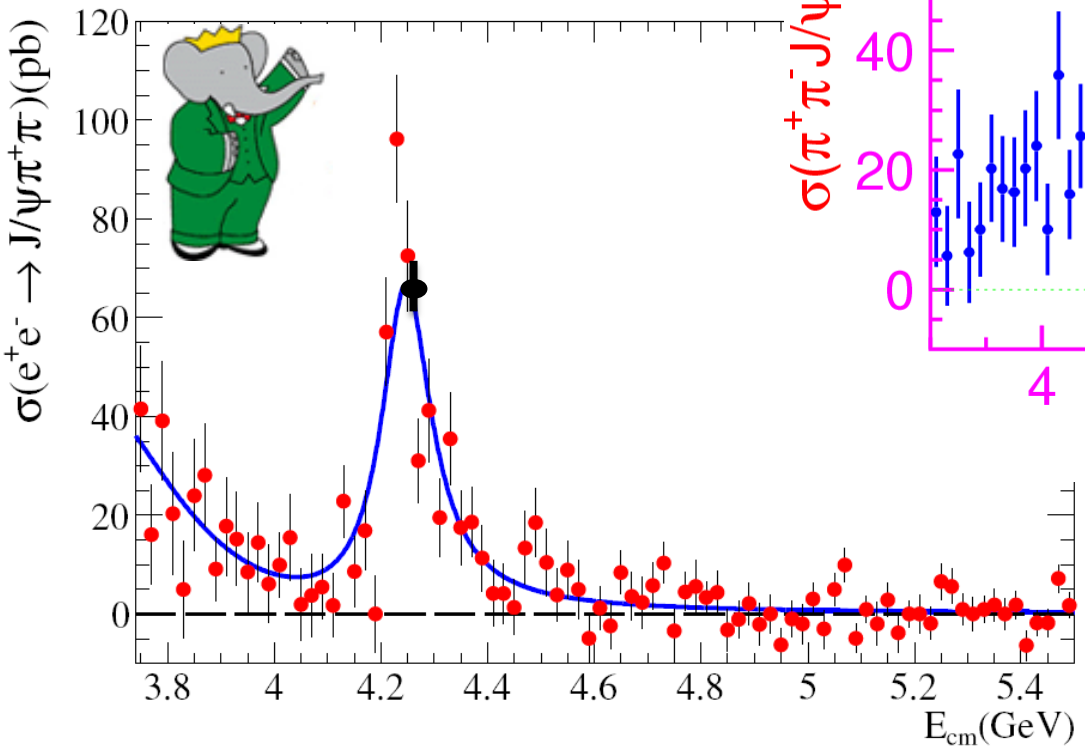
- Dominant background $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$
- J/ψ signal: [3.08,3.12] GeV
- J/ψ sideband: [3.0,3.06] GeV or [3.14,3.20] GeV, 3xsignal
- At least 4 independent analyses, all get similar results !

Cross section of $e^+e^- \to \pi^+\pi^- J/\psi$

Belle: PRL99, 182004 (2007)



BaBar: PRD86, 051102 (2012)



BESIII: $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ = (62.9±1.9±3.7) pb

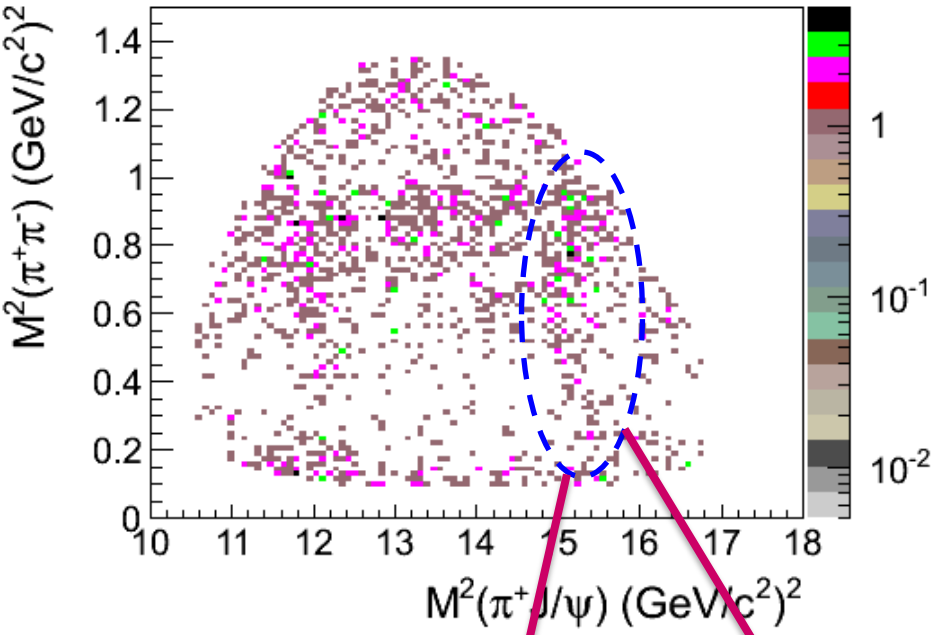
Agree with BaBar & Belle!

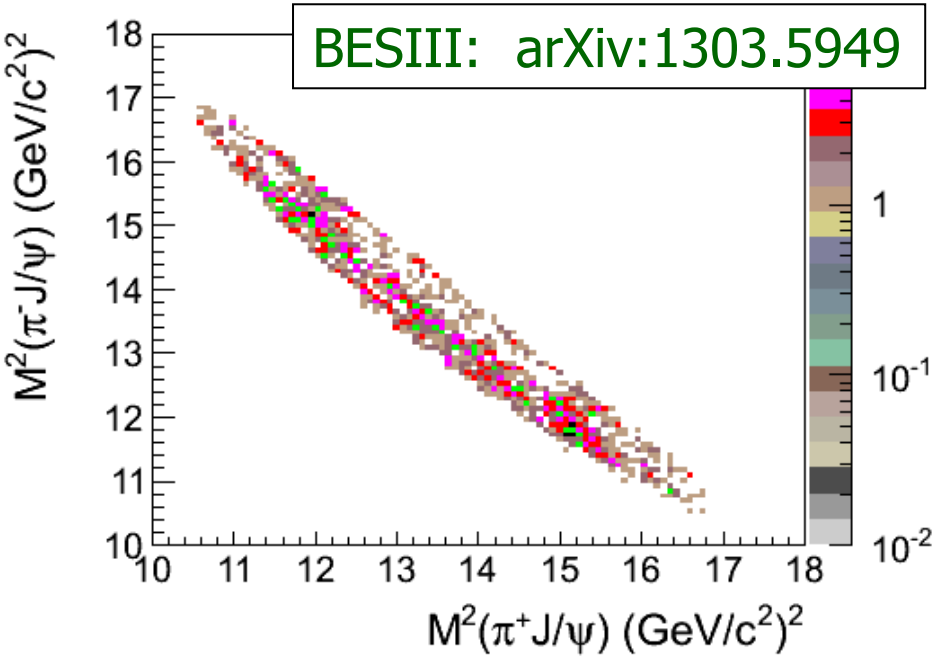
Best precision!

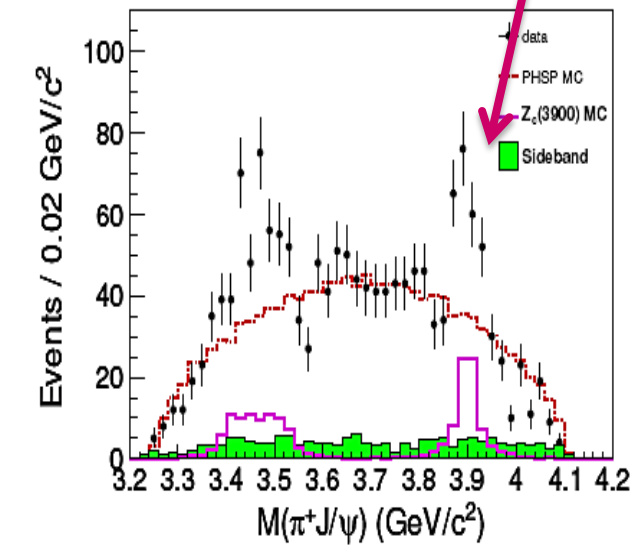
BESIII: arXiv:1303.5949

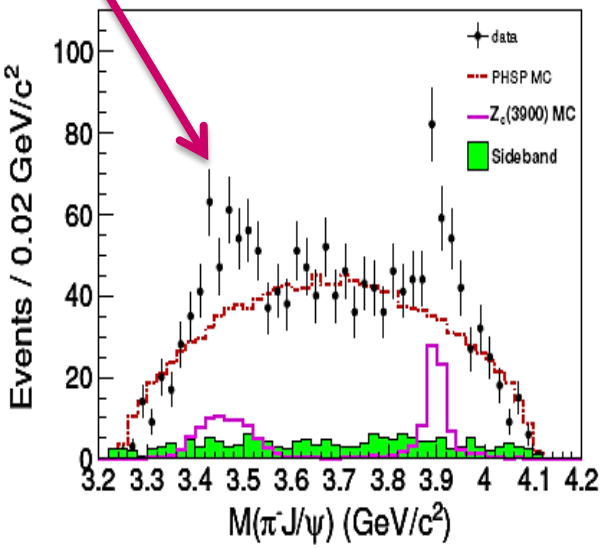
Dalitz plots & 1D projections

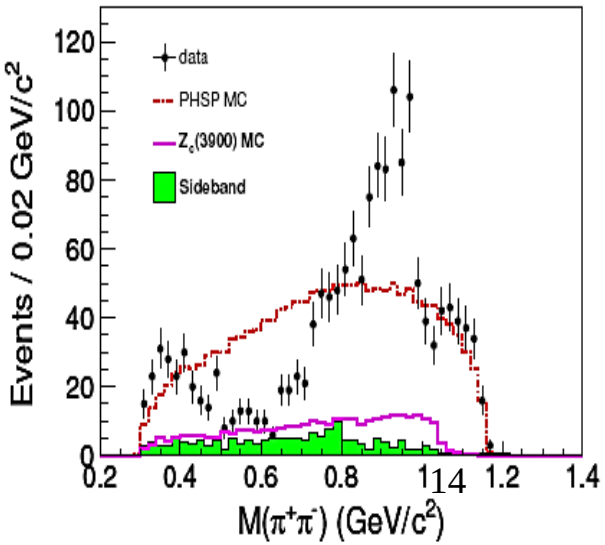
BESIII: arXiv:1303.5949





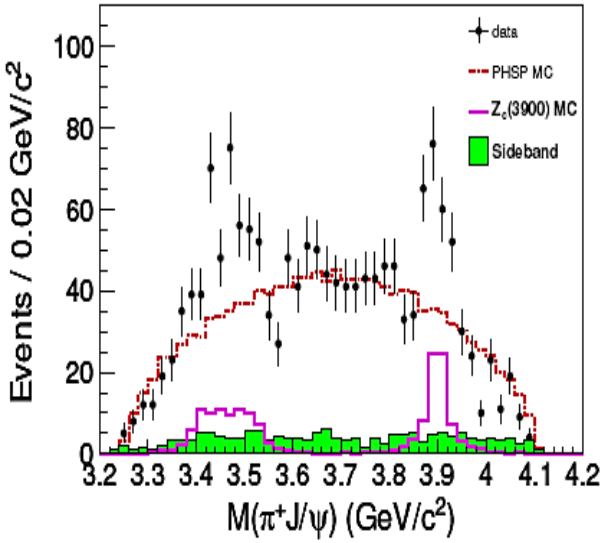


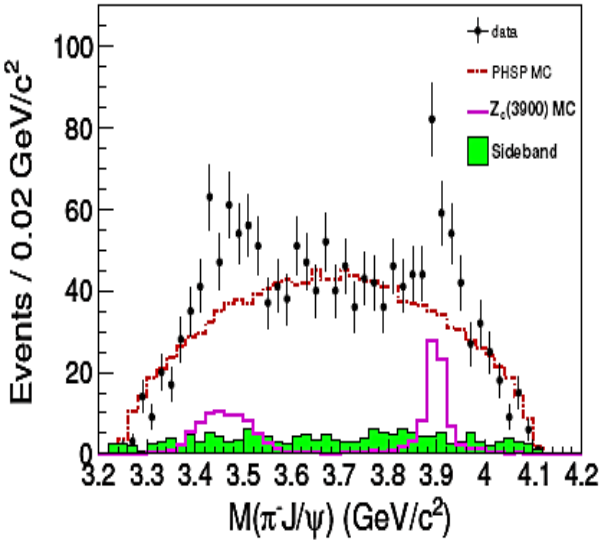


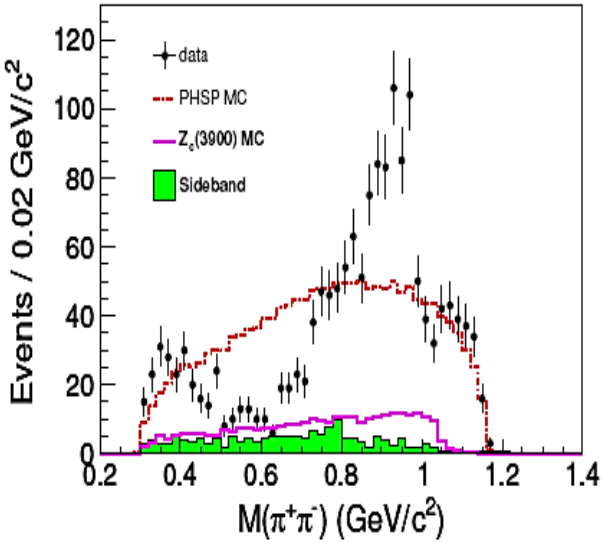


Is it a real signal?

- 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 $f_2(1270)$, …? 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? N

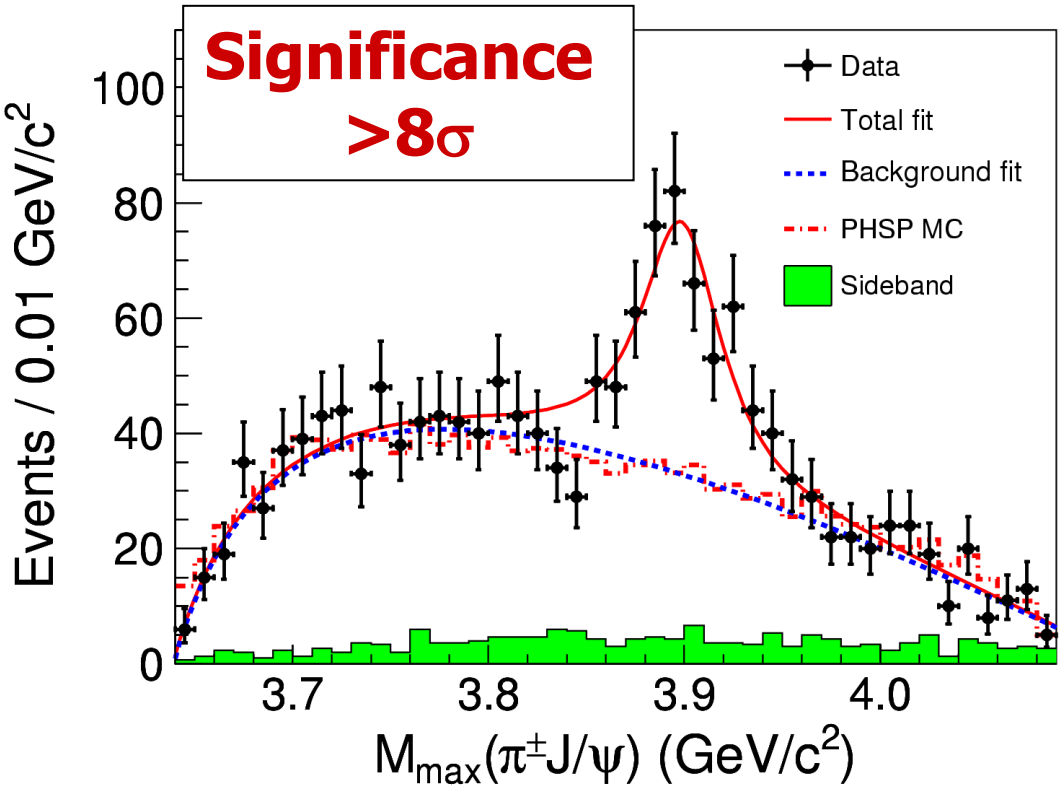




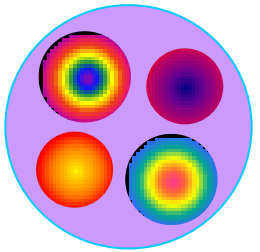


The $Z_c(3900)$ signal

BESIII: arXiv:1303.5949



- 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)%

What next?

- We are accumulating 3x more data
- Precise resonant parameters
- Spin-parity [PWA on going]
- More decay modes
- Production mechanisms, production rate
- Test various theoretical models
- Neutral partner of Z_c
- Other Z_c states? Z_c' states?
- …

XYZ group expanding rapidly since Jan., but more are welcome

B424 (40.96 m^2)➔ B410 (95.04 m^2)

Everyone is working excitedly and passionately!

Summary

- We observed a charged charmoniumlike structure, $Z_c(3900)$, in its $\pi^{\pm}J/\psi$ decays
- It is not a charmonium
- The nature is yet unknown
- We are working very hard to understand it better …

We thank the staff of BEPCII and the computing center, thank the funding agencies, and all the friends of BES!

Thanks a lot!

Thanks a lot!

Table 1: Results on the cross section of $e^+e^- \to \pi^+\pi^- J/\psi$.

CM energy	(4.260 ± 0.001) GeV
Integrated luminosity	$525(1 \pm 1\%)$ pb^{-1}
Radiative correction factor	0.818
Number of $J/\psi \to e^+e^-$	595 ± 28
Efficiency of $J/\psi \to e^+e^-$	38.4%
Cross section from $J/\psi \to e^+e^-$	(60.7 ± 2.9) pb
Number of $J/\psi \to \mu^+\mu^-$	882 ± 33
Efficiency of $J/\psi \to \mu^+\mu^-$	53.8%
Cross section from $J/\psi \to \mu^+\mu^-$	(64.4 ± 2.4) pb
Cross section from combined e^+e^- and $\mu^+\mu^-$	$(62.9 \pm 1.9 \pm 3.7)$ pb

Source	$\mu^+\mu^-$	e^+e^-
Luminosity	1.0	1.0
MC Statistics	0.5	0.7
Tracking	4.0	4.0
Background shape	0.5	3.4
$Y(4260)$ line-shape	0.6	0.6
Kinematic fit	2.2	2.3
Branching ratios	1.0	1.0
Decay model	3.1	3.1
Others	1.0	1.0
Total	5.9	6.8
e^+e^- & $\mu^+\mu^-$ combined	5.9	

Table 3: Results on the $Z_c(3900)$.

Number of signal events	307 ± 48
Significance	$> 8\sigma$
Mass	$(3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2
Width	$(46 \pm 10 \pm 20)$ MeV
$R = \frac{\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)}$	$(21.5 \pm 3.3 \pm 7.5)\%$

Table 4: Summary of the systematic errors for $Z_c(3900)$ resonant parameters.

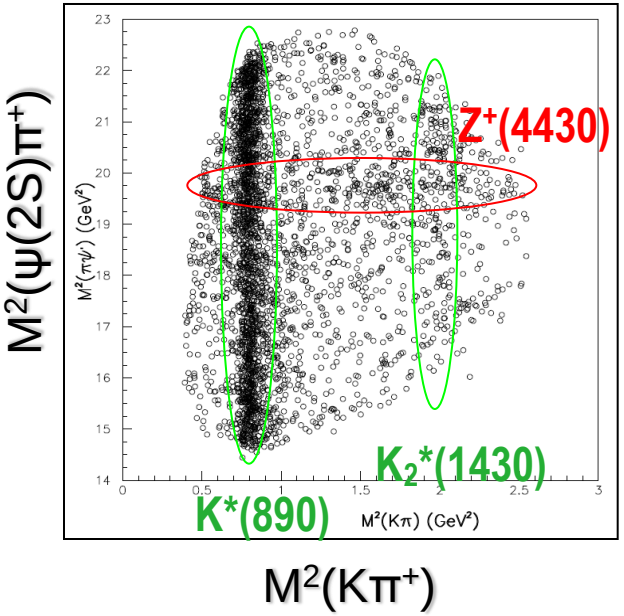
Source	Mass (MeV)	Width (MeV)	Ratio (%)
Absolute mass scale	1.8	-	-
S/P-wave	2.1	3.7	2.6
Flatté	2.1	15.4	0.0
Background shape	3.5	12.1	7.1
Resolution	-	1.0	0.2
Total	4.9	20.0	7.5

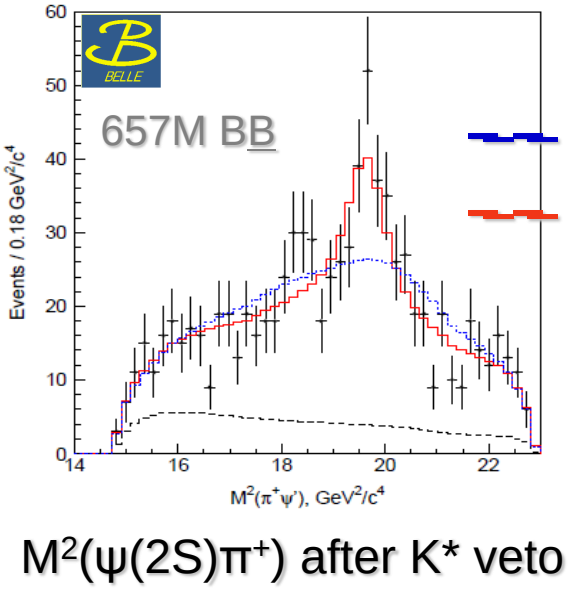
Belle observed $Z(4430)^{\pm}\to\psi(2S)\pi^{\pm}$

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





Significance: 6.4σ

fit for model with K*'s only

fit for model with K*'s and Z

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

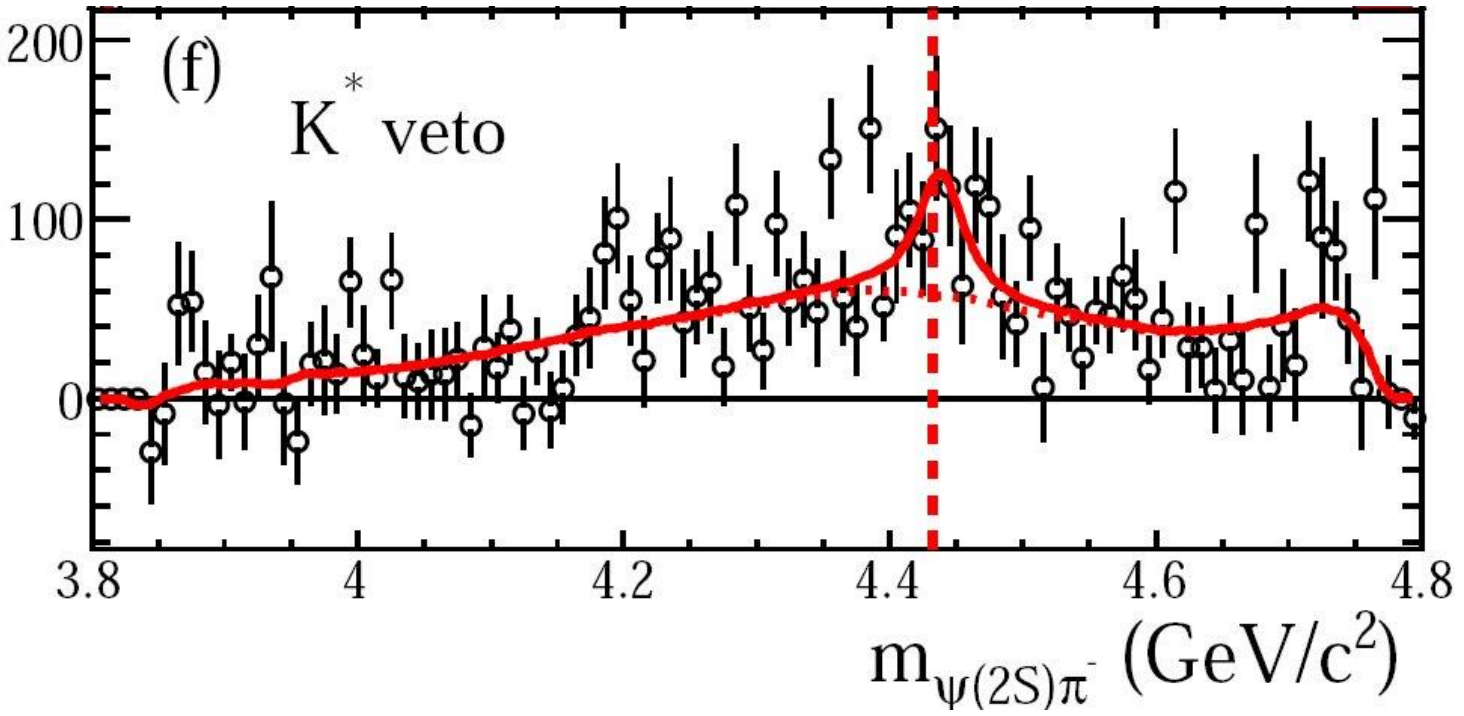
$$\Gamma = 107\ ^{+86+74}_{-43-53}\ \text{MeV}$$

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

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

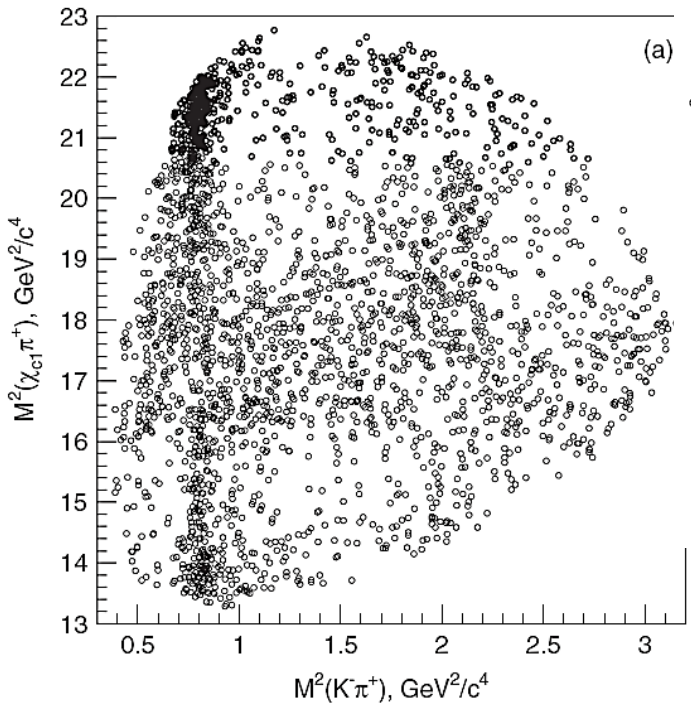
- Dalitz-plot analysis of $\underline{B^0}\to\chi_{c1}\pi^+K^-$ $\chi_{c1}\to J/\psi\gamma$ with 657M $B\underline{B}$
- Dalitz plot models: known $K^*\to K\pi$ only

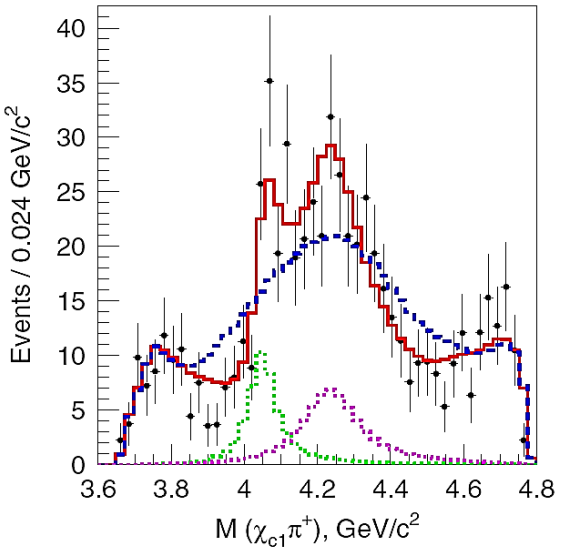
  K^*'s + one $Z\to\chi_{c1}\pi^{\pm}$

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

PRD 78, 072004 (2008)

Significance: 5.7σ





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

fit for model with K*'s

fit for double Z model

Z_1 contribution

Z_2 contribution

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

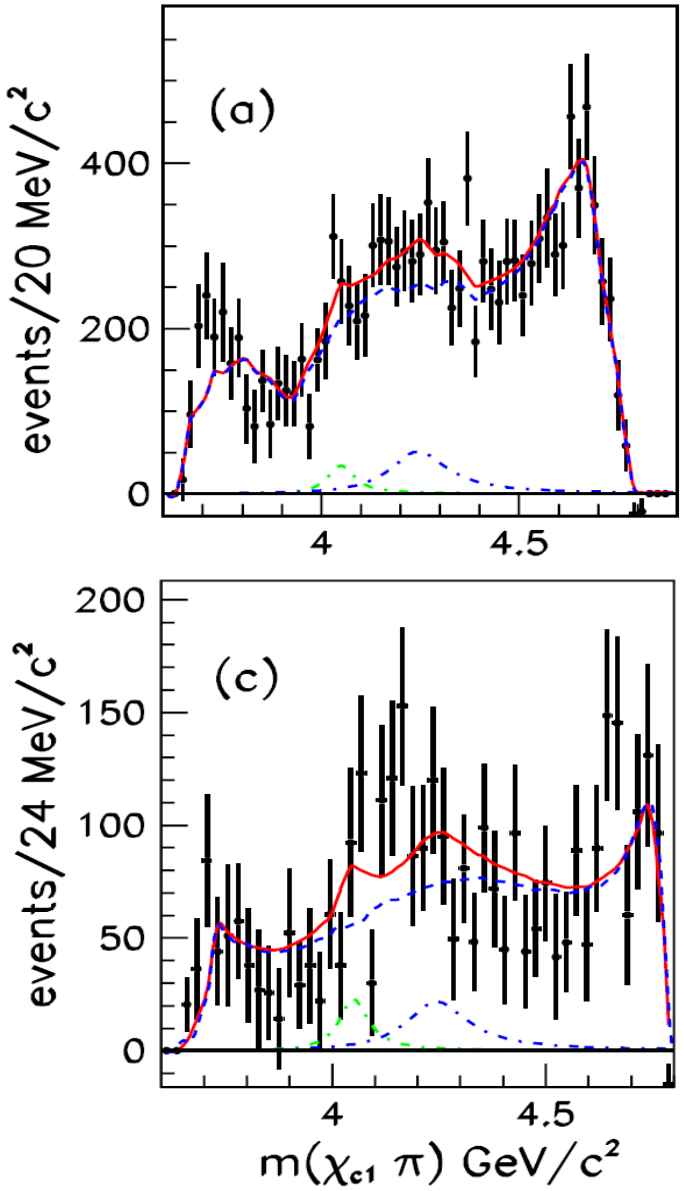
$$\Gamma_{Z_1} = 82\,^{+21\,+47}_{-17\,-22}\ \text{MeV}$$

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

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

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."

M(ππJ/ψ)∈[4.2, 4.4] GeV via ISR

550/fb at 10.58 GeV
Peaks at 12 & 15 GeV^2?
Shown at QWG'2011