Charmonium & charmoniumlike exotics

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Hadrons： normal & exotic

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

Quark model
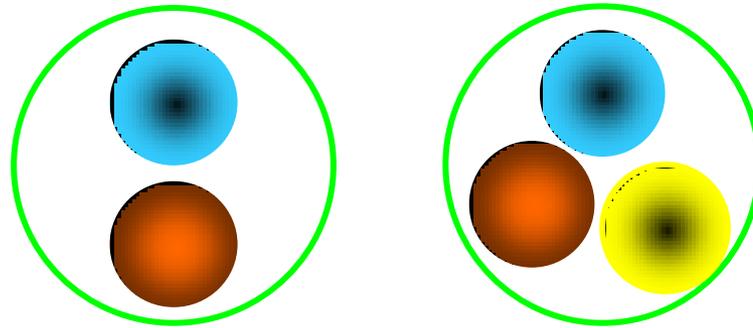
- QCD doesnot forbid hadrons with other configurations
  - glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - multiquark state : $N_{quarks} > 3$
  - molecule :   bound state of more than 2 hadrons
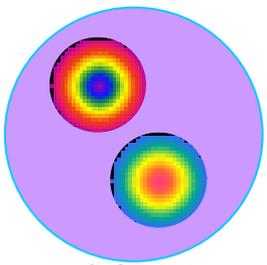
Charmonium spectroscopy

States below charm threshold are all observed now, still many missing states above charm threshold.

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

n radial quantum number

S total spin of c & c-bar

L orbital angular momentum

L = 0, 1, 2 ... correspond to S, P, D, …

J = S + L

P = $(-1)^{L+1}$ parity

C = $(-1)^{L+S}$ charge conj.
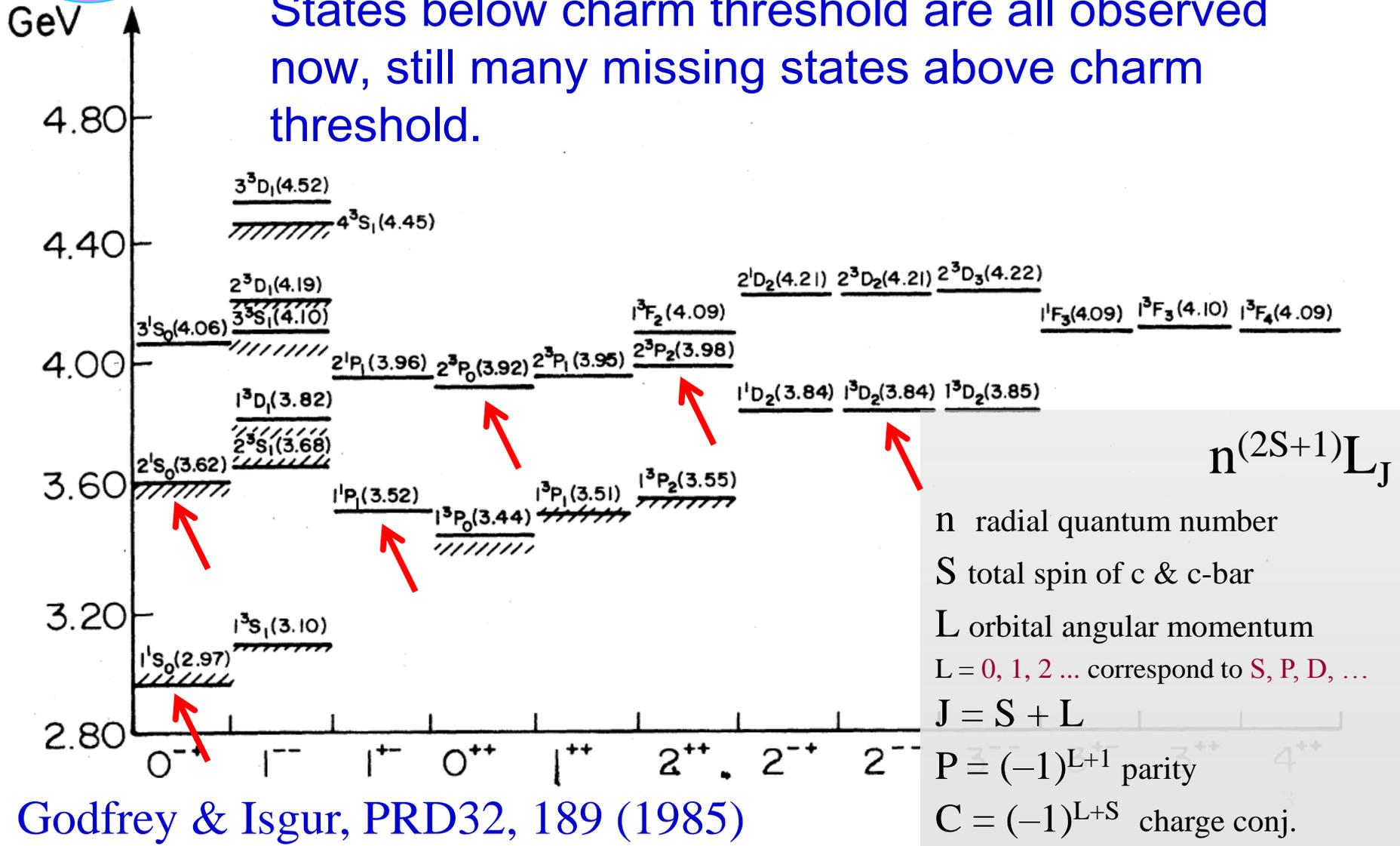
Godfrey & Isgur, PRD32, 189 (1985)

There are lots of XYZ states

Charmonium in the final state, but not an obvious charmonium state (charmoniumlike or XYZ)
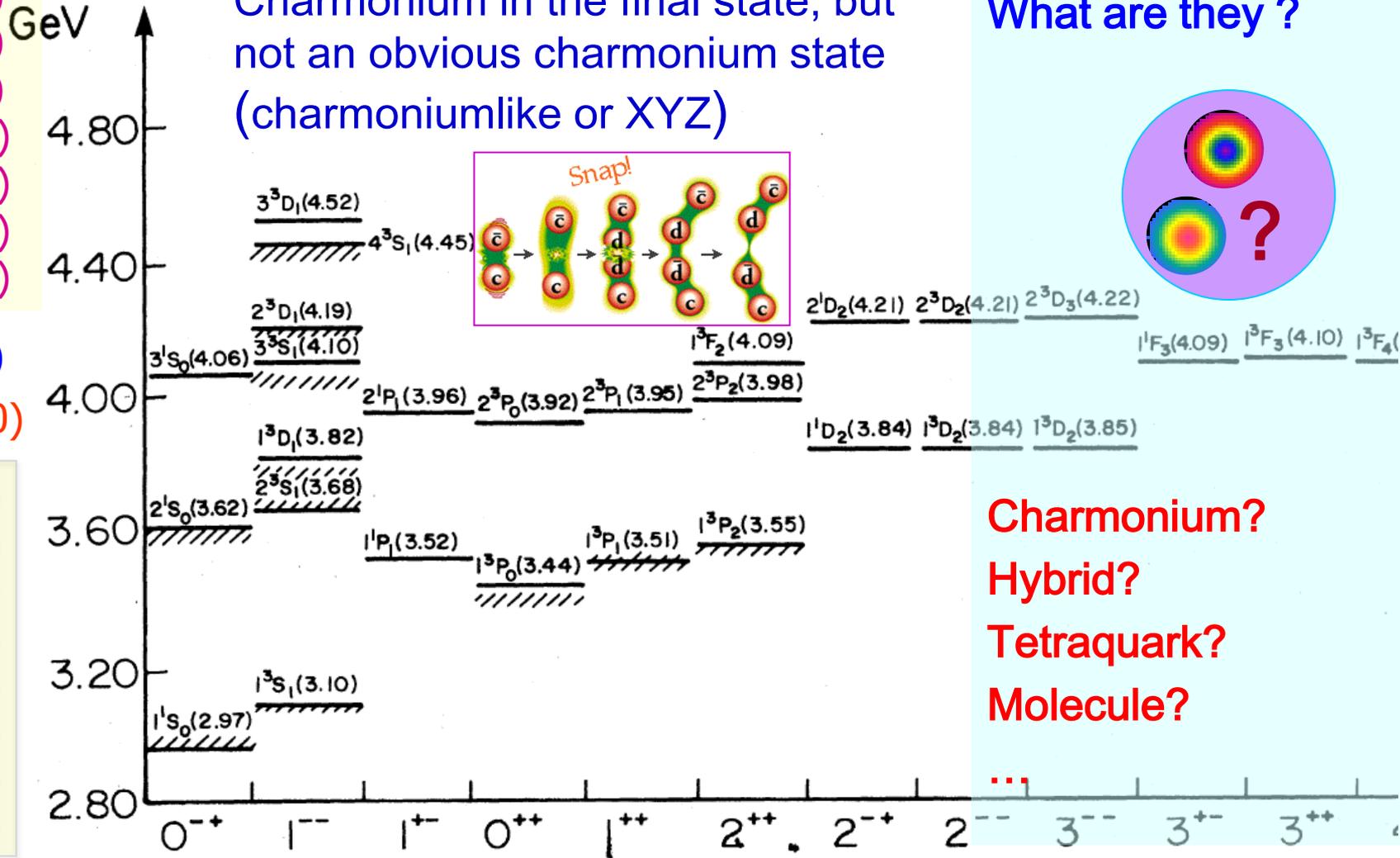
What are they ?

Charmonium?
Hybrid?
Tetraquark?
Molecule?
...

Not all of them are charmonia!

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Outline

- The experiments

- New results on charmonium [spin-singlets +]

- New information on the X(3872)

- Update ISR Y-family analyses and more …

- $Z_c(3900)^+$, $Z_c(4020)^+$

- Summary & Outlook

Detailed results from BESIII by Zhiqing on Friday!

Results are from these experiments

BESIII

BELLE

LHCb

Tracking system
Track reconstruction

Muon chambers
µ trigger + ID

Magnet

ECAL HCAL
SPD/PS

RICH2 M1

M3 M4 M5

M2

T3
T2
T1

RICH1

TT

Vertex
Locator

Interaction point

RICH system
Hadron ID

CALO systems
Trigger + γ/e energy and ID

JINST 3
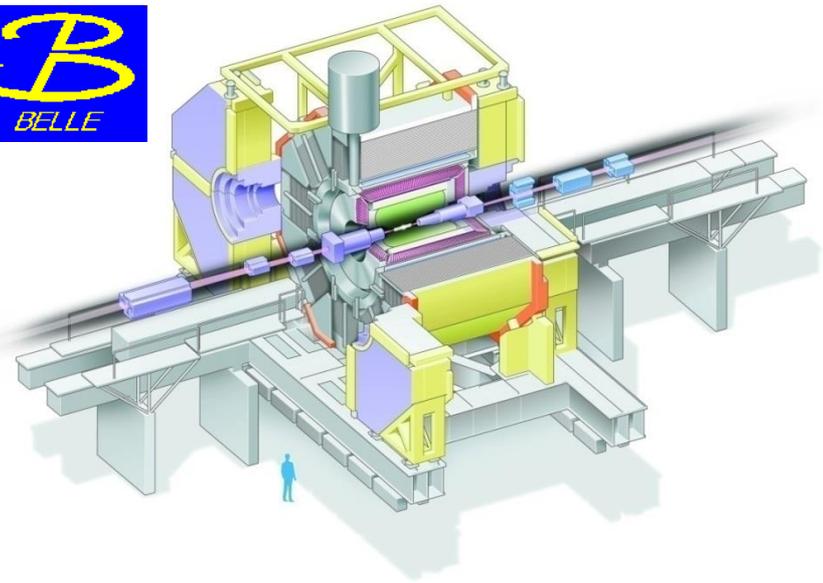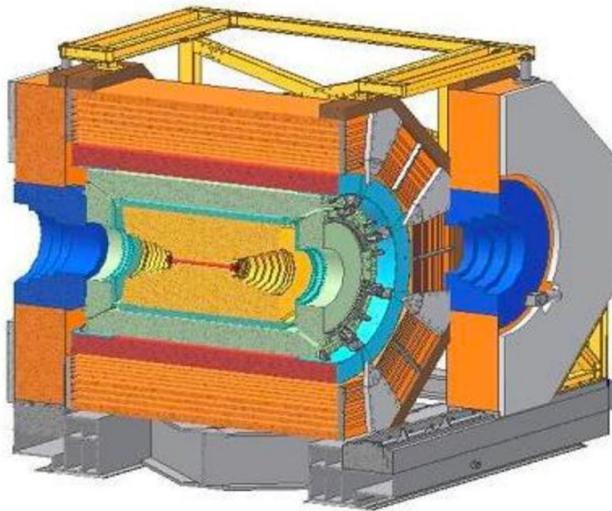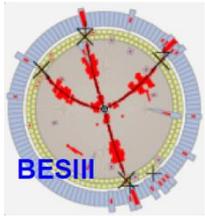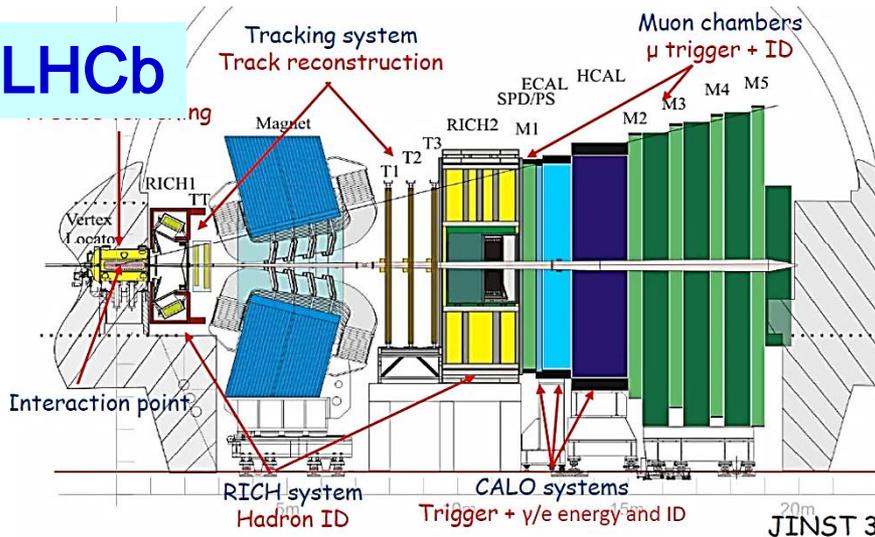
BaBar
Collaboration Home Page

IFR

Vertex Detector

CsI Calorimeter

Drift Chamber

DIRC PID
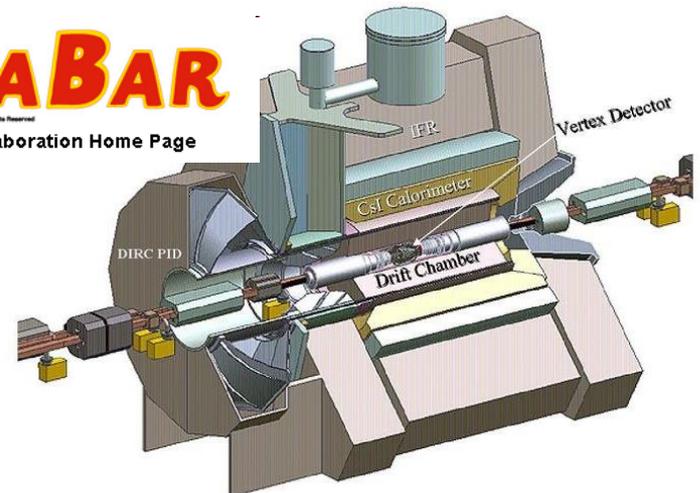
+ CLEOc, CDF, D0, ATLAS, CMS … 6
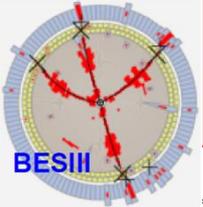
$\psi' \rightarrow \pi^0 h_c$ transition [106M ψ' evts]
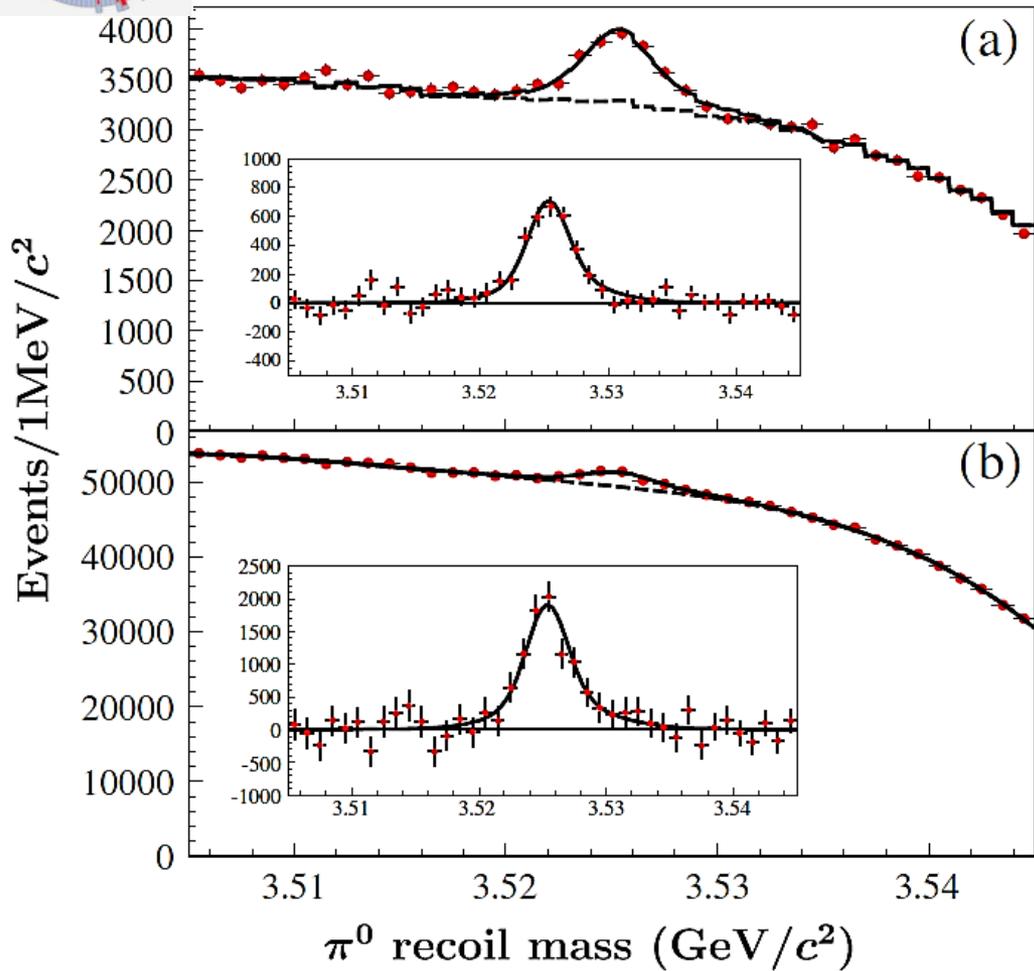
BESIII: PRL 104, 132002 (2010)

Mass: 3525.40±0.13±0.18 MeV

Width: 0.73±0.45±0.28 MeV

(<1.44 MeV @ 90% C.L.)

CLEOc: PRL101, 182003 (2008)

Mass: 3525.28±0.19±0.12 MeV

Width: fixed to 0.9 MeV

ΔM_{hf}= <M(^3P_J)>-M($^1P_1$)

Agrees with zero within ~0.5 MeV

Information on spin-spin interaction.

Combined inclusive and E1-photon-tagged spectrum (First measurements)

$B(\psi' \rightarrow \pi^0 h_c)$ = [8.4±1.3(stat.) ±1.0(syst.)]×10^{-4}

$B(h_c \rightarrow \gamma\eta_c)$ = [54.3±6.7(stat.) ±5.2(syst.)] %

Agree with predictions of Kuang, Godfrey, Dudek, et al.

h_c via $\psi' \rightarrow \pi^0 h_c \rightarrow \pi^0 \gamma \eta_c$ transition

106M ψ' evts
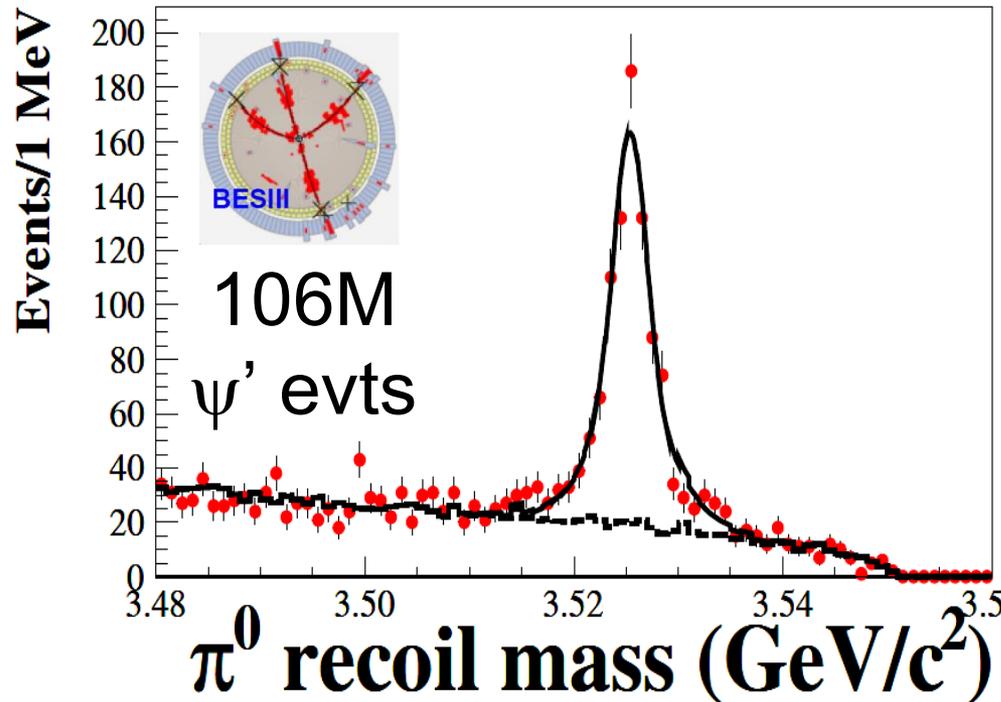
16 modes, 832 events
Mass: 3525.31±0.11±0.15 MeV
Width: 0.70±0.28±0.25 MeV

CLEOc: PRL101, 182003 (2008)
Mass: 3525.28±0.19±0.12 MeV
Width: fixed to 0.9 MeV

π^0 recoil mass (GeV/c²)

Dominant errors in mass and width measurements are from photon energy calibration, resolution calibration, and kinematic fit.

Can be improved with more data!

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η$_c$ parameters from ψ'→γη$_c$

106M ψ' evts
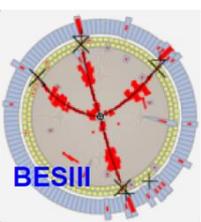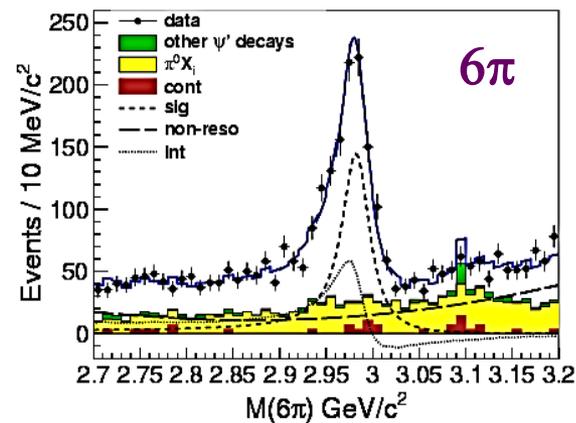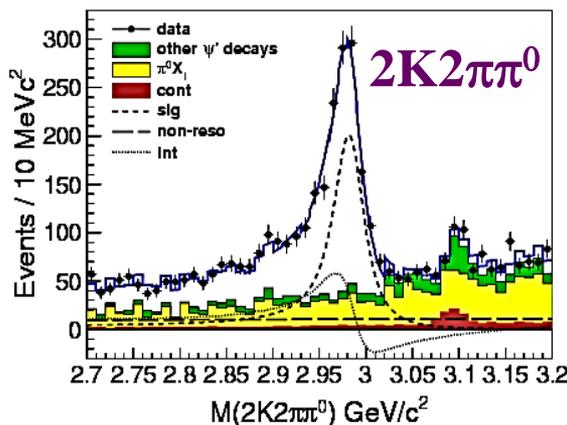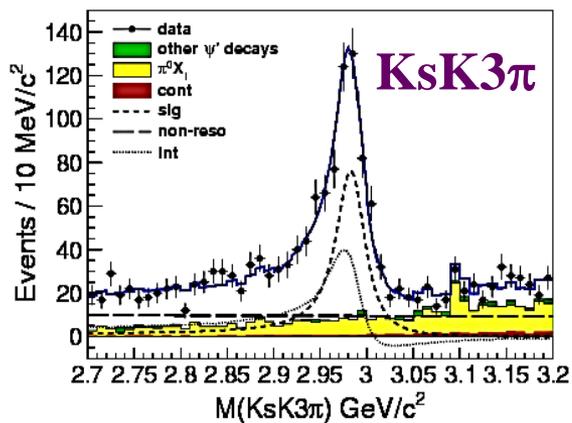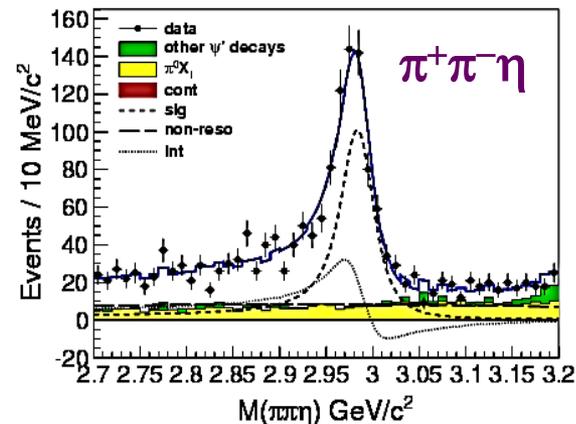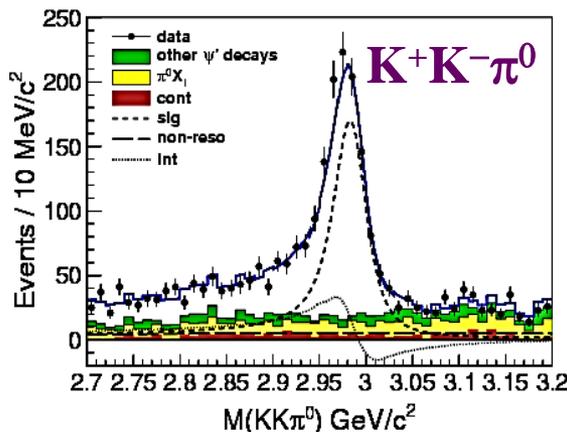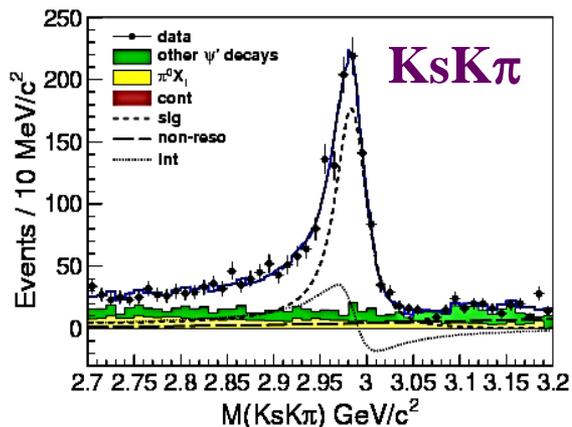
Simultaneous fit with modified Breit-Wigner (hindered *M1*) by considering possible **interference** between η$_c$ and non-η$_c$ decays

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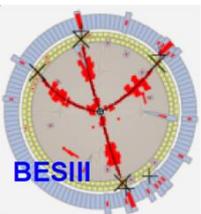
Mass and width of η_c

Mass = $2984.3 \pm 0.6 \pm 0.6$ MeV/c^2 **[LQCD found a higher mass!]**

Width = $32.0 \pm 1.2 \pm 1.0$ MeV

$\phi = 2.40 \pm 0.07 \pm 0.08$ **rad** or $4.19 \pm 0.03 \pm 0.09$ **rad**

(two solutions of the interference)

World average in PDG2012 uses earlier measurements.
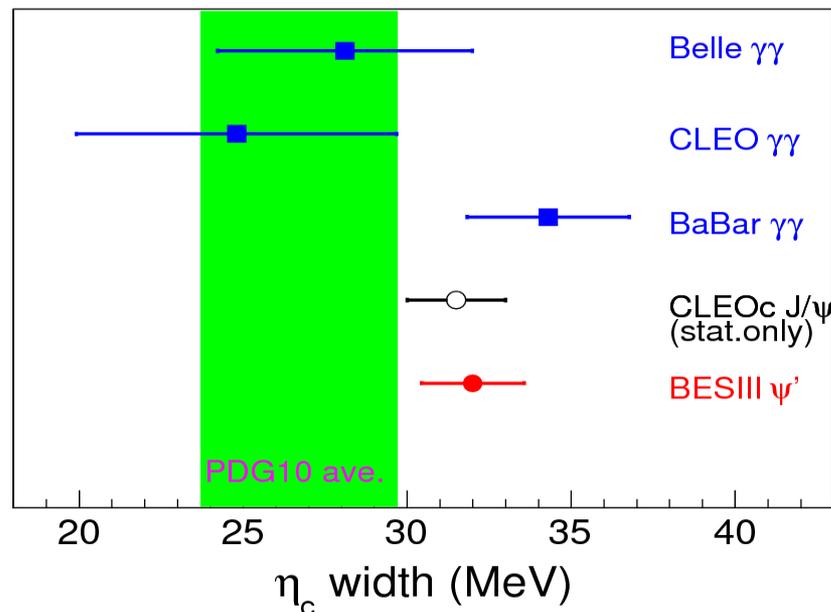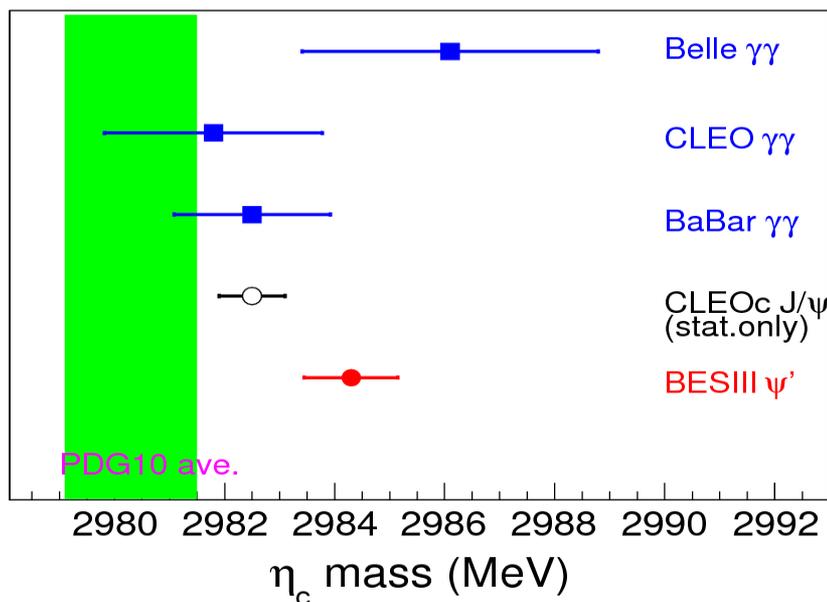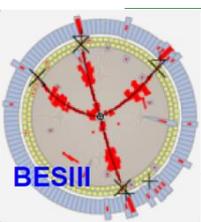
η_c properties from $h_c \rightarrow \gamma \eta_c$

106M ψ' evts
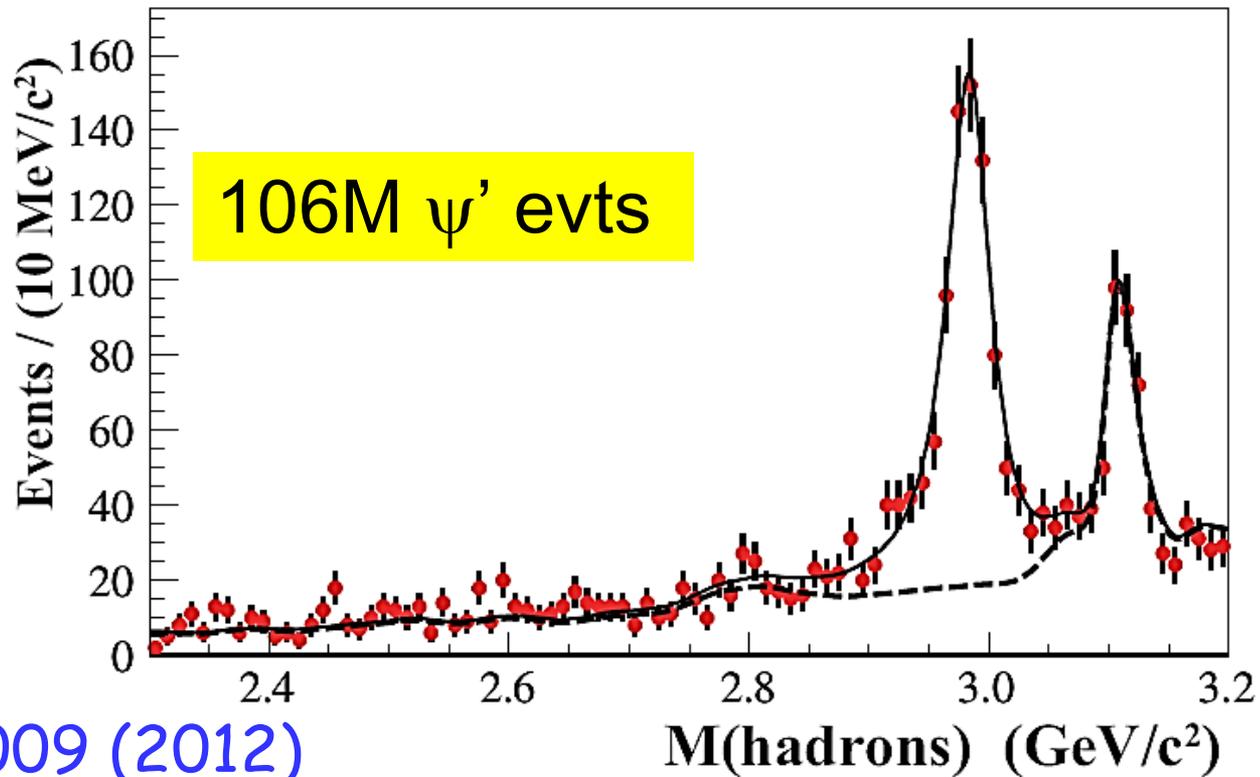
PRD86，092009 (2012)

M(η_c) [MeV]	$\Gamma(\eta_c)$ [MeV]	N(η_c)
2984.49±1.16±0.52	36.4±3.2±1.7	1035

E1 transition! Eγ suppression less severe than in M1 transition!

Irreducible non-η_c background is smaller than in ψ' decays!

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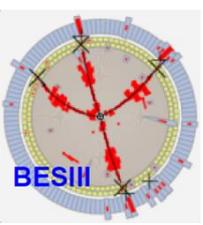
First observation of ψ′→γη$_c$′

106M ψ' evts   **arXiv:1205.5103, PRL109, 042003 (2012)**
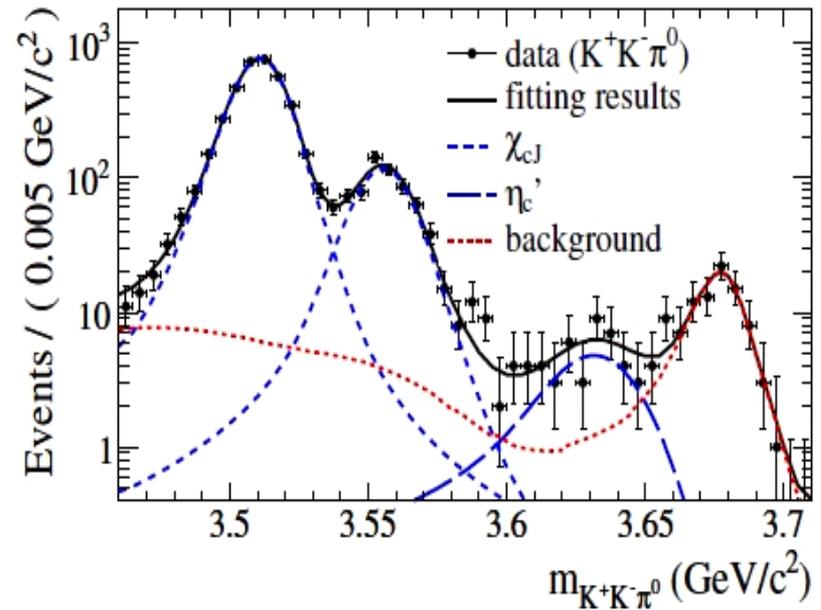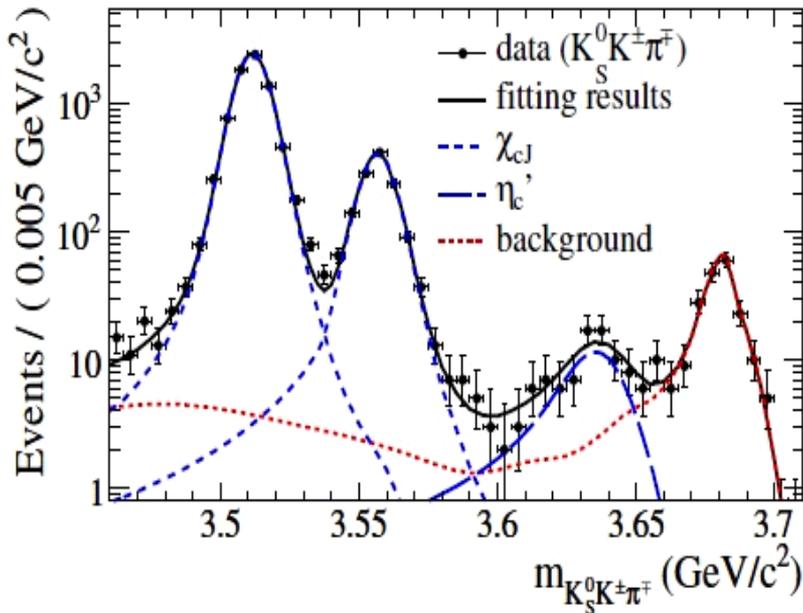
Statistical significance > 10σ

- Simultaneous fit with:

  - η$_c$' signal: modified BW (*M1*) (Resolution extrapolated from χ$_{cJ}$)

  - χ$_{cJ}$ signal: MC shape smeared with Gaussian

  - BGs from $e^+ e^- \to KK\pi$ (ISR), $\psi' \to KK\pi$ (FSR), $\psi' \to \pi^0 KK\pi$: are measured from data

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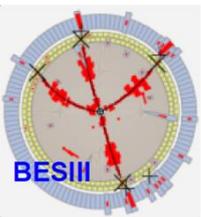
First observation of $\psi' \to \gamma \eta_c'$

18 years' work!

3 generation physicists

- $M(\eta_c') = 3637.6 \pm 2.9 \pm 1.6$ MeV/c^2

- $\Gamma(\eta_c') = 16.9 \pm 6.4 \pm 4.8$ MeV

- $Br(\psi' \to \gamma \eta_c' \to \gamma KK\pi) = (1.30 \pm 0.20 \pm 0.30) \times 10^{-5}$

$Br(\eta_c' \to KK\pi) = (1.9 \pm 0.4 \pm 1.1)\%$ from BaBar
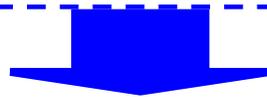
$Br(\psi' \to \gamma \eta_c') = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}$

CLEO-c: $<7.6 \times 10^{-4}$ *(PRD81,052002(2010))*

Potential model: $(0.1-6.2) \times 10^{-4}$ *(PRL89,162002(2002))*

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Evidence for the X(3823)

BELLE

arXiv:1304.3975 (PRL111, 032001 (2013))

711 fb^{-1}   B $\rightarrow \chi_{c1}\gamma K$

3.8σ
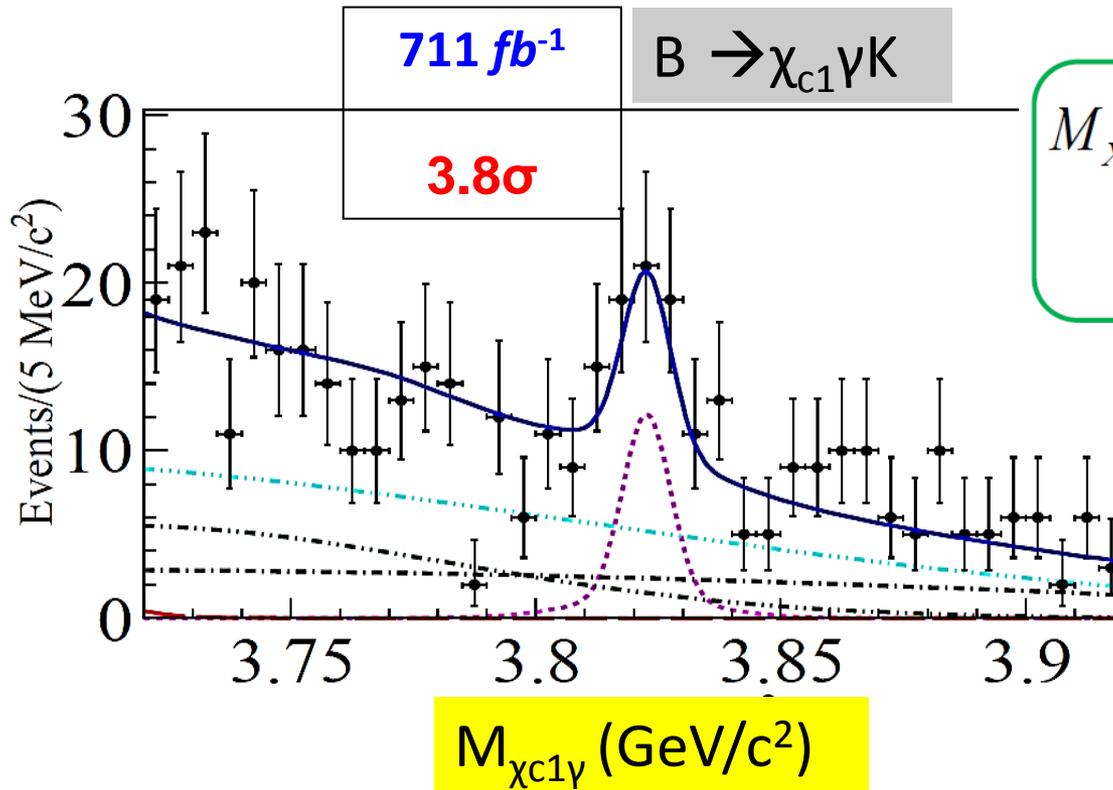
$$M_{X(3823)} = M^{meas}_{X(3823)} - M^{meas}_{\psi'} + M^{PDG}_{\psi'}$$
$$= 3823.1 \pm 1.8 \pm 0.7\, MeV$$

$M_{\chi c1 \gamma}$ (GeV/c²)

FIG. 4: 2D UML fit projection of $M_{\chi_{c1}\gamma}$ distribution for the simultaneous fit of $B^{\pm} \rightarrow (\chi_{c1}\gamma)K^{\pm}$ and $B^0 \rightarrow (\chi_{c1}\gamma)K^0_S$ decays for $M_{bc} > 5.27$ GeV/c^2. The curves used in the fits are described in [31].

The measured mass and width are consistent with the missing Ψ₂(1D) state

BESIII may search for it!

What is the X(3872)?

- Mass: Very close to $\bar{D}^0 D^{*0}$ threshold
- Width: Very narrow, < 1.2 MeV
- $J^{PC}=1^{++}$ [LHCb, talk by Thomas Latham]
- Production
  - in $\bar{p}p$/pp collison – rate similar to charmonia
  - In B decays – KX similar to $c\bar{c}$, K*X smaller than $c\bar{c}$
  - Y(4260)$\rightarrow\gamma$+X(3872) [BESIII, more by Zhiqing on Friday]
- Decay BR: open charm ~ 50%, charmonium~O(%)
- Nature   (very likely exotic)
  - Loosely $\bar{D}^0 D^{*0}$ bound state (like deuteron?)?
  - Mixture of excited χ_{c1} and $\bar{D}^0 D^{*0}$ bound state?
  - Many other possibilities   (if it is not χ'_{c1}, where is χ'_{c1}?)

Belle, 2003
140/fb

$M(\pi\pi J/\psi) - M(J/\psi)$ [GeV]
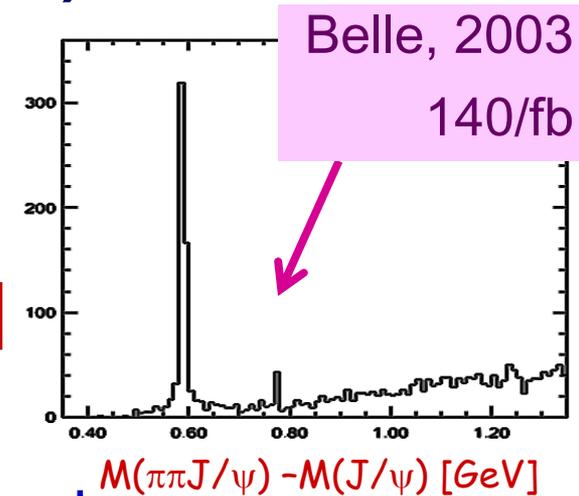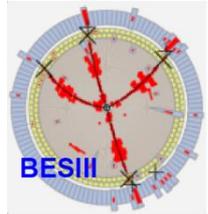
Observation of $e^+e^- \to \gamma X(3872)$
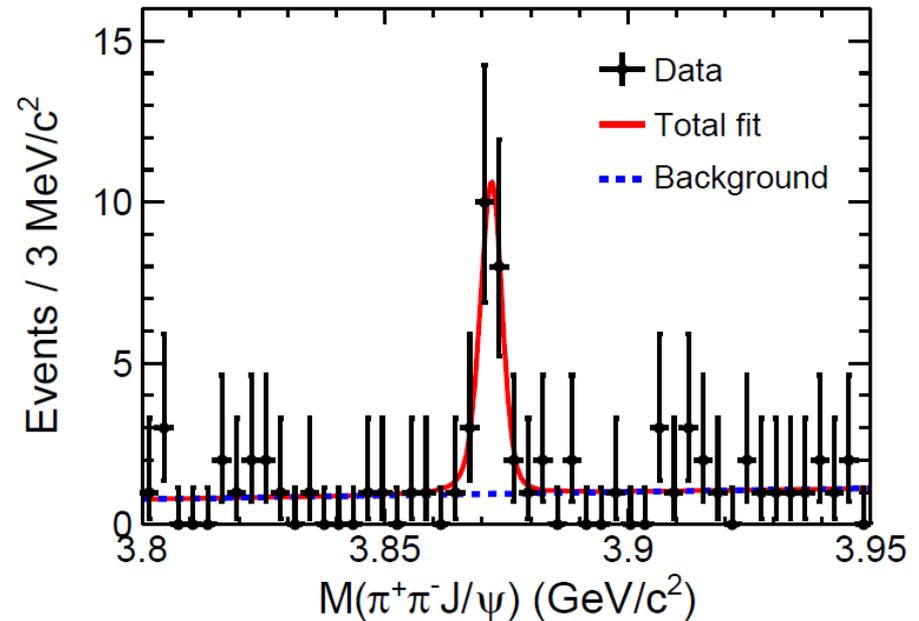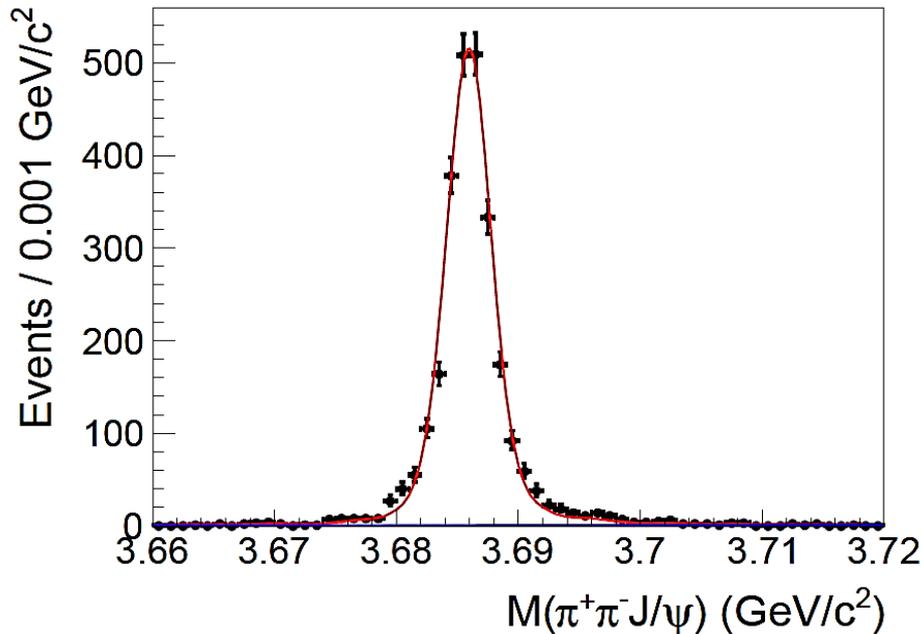
ISR ψ' signal is used for mass, and mass resolution calibration.

N=1818; ΔM=0.34±0.04 MeV; $\Delta\sigma_M$=1.14 ±0.07 MeV

N(X(3872)) = 20.1±4.5   **6.3σ**

M(X(3872)) = 3871.9±0.7±0.2 MeV   [PDG: 3871.68 ±0.17 MeV]
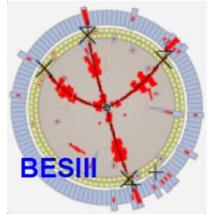
Observation of **Y(4260)**→γX(3872)
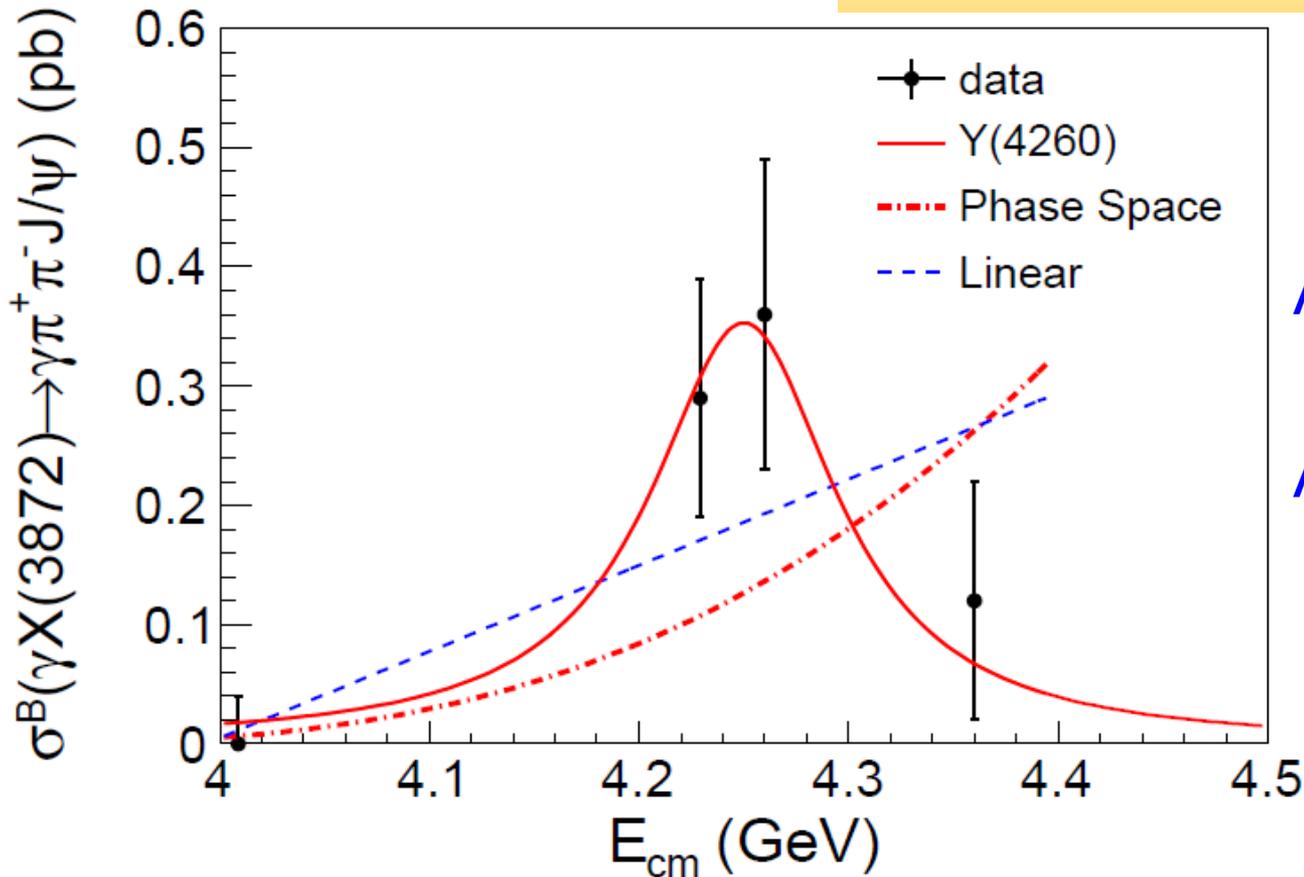
A new Y(4260)
decay mode

A new X(3872)
production mode

If we take $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) \sim 5\%$, ($>2.6\%$ in PDG)

$$\frac{\sigma(e^+e^- \to \gamma X(3872))}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} \sim 10\% \quad \text{Large transition ratio !}$$

Y-family states

(vectors observed in Initial State Radiation)

+ $e^+e^- \rightarrow \pi^+\pi^- h_c$ from BESIII

The Y states

PRL99,142002
670/fb

PRL99,182004
548/fb

PRL98,212001
298/fb

PRL95,142001
273/fb
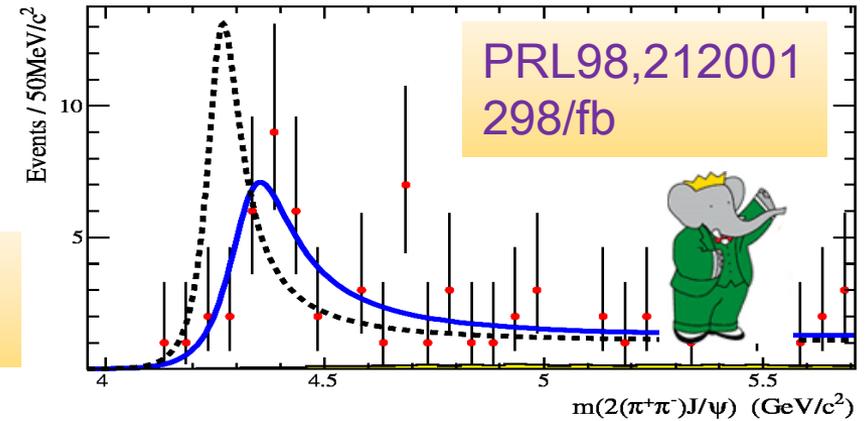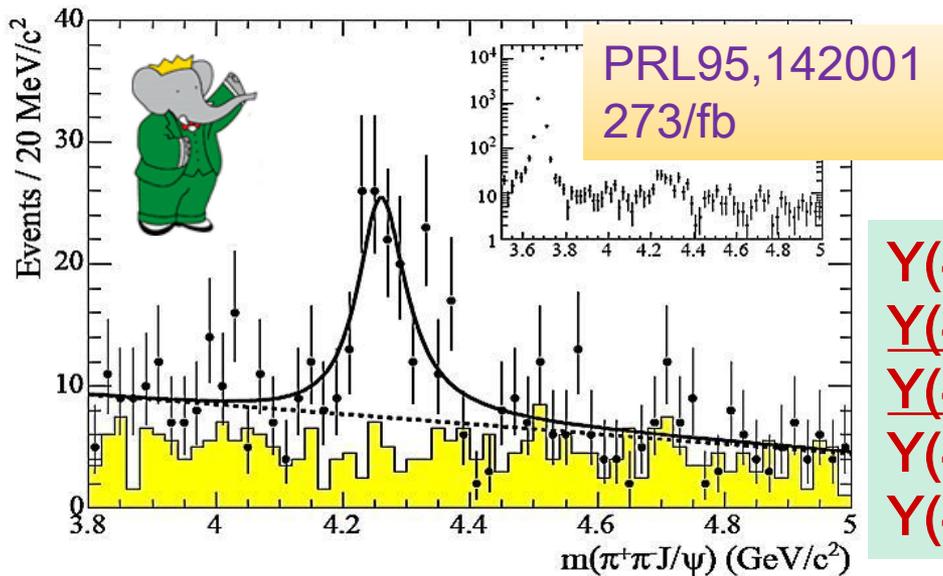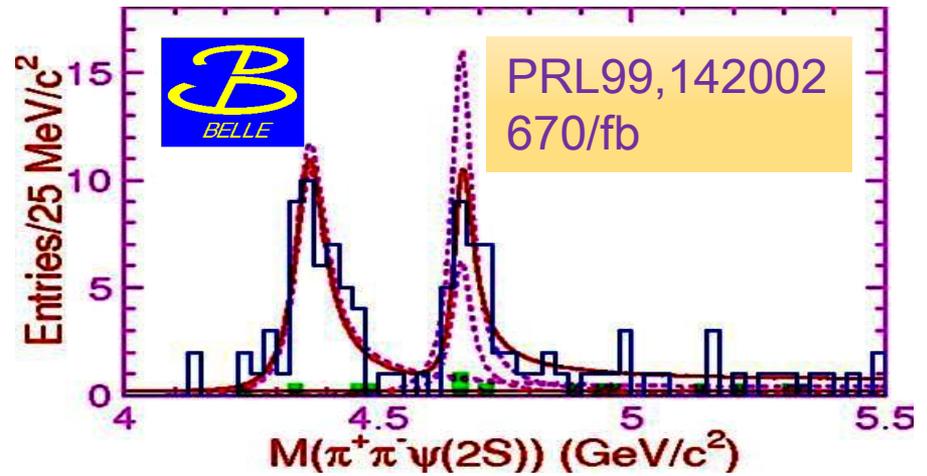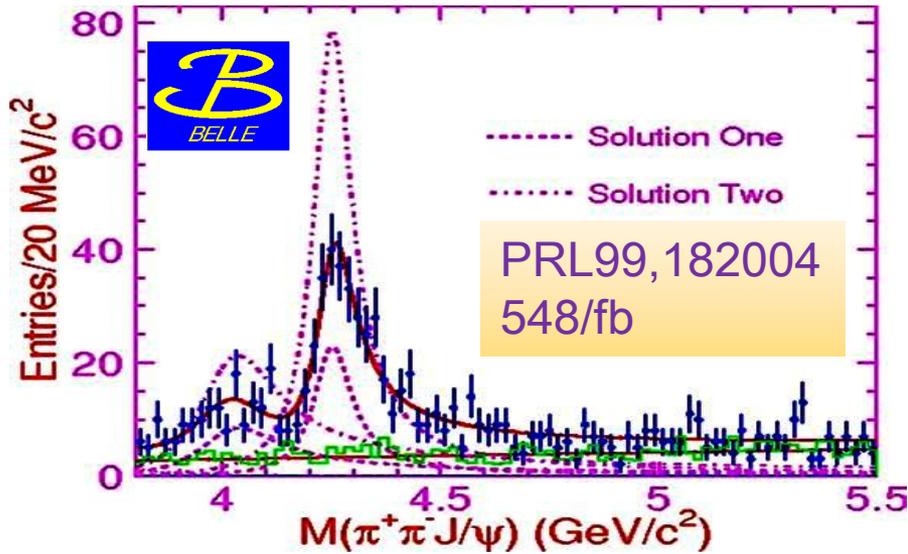
Y(4008)
Y(4260)
Y(4360)
Y(4660)
Y(4630)

PRL101,172001
695/fb

$M(\Lambda_c^+ \Lambda_c^-)$
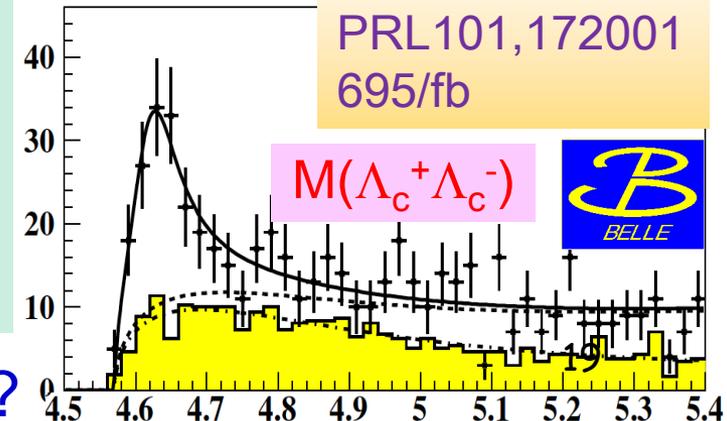
Above $\bar{D}D$ thres., decay to open charm?

The Y states

PRL110,252002
967/fb
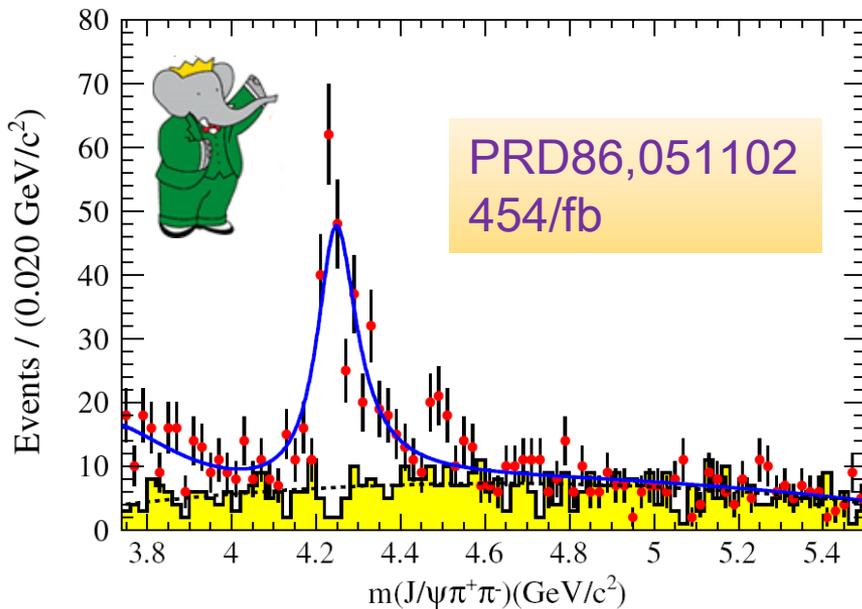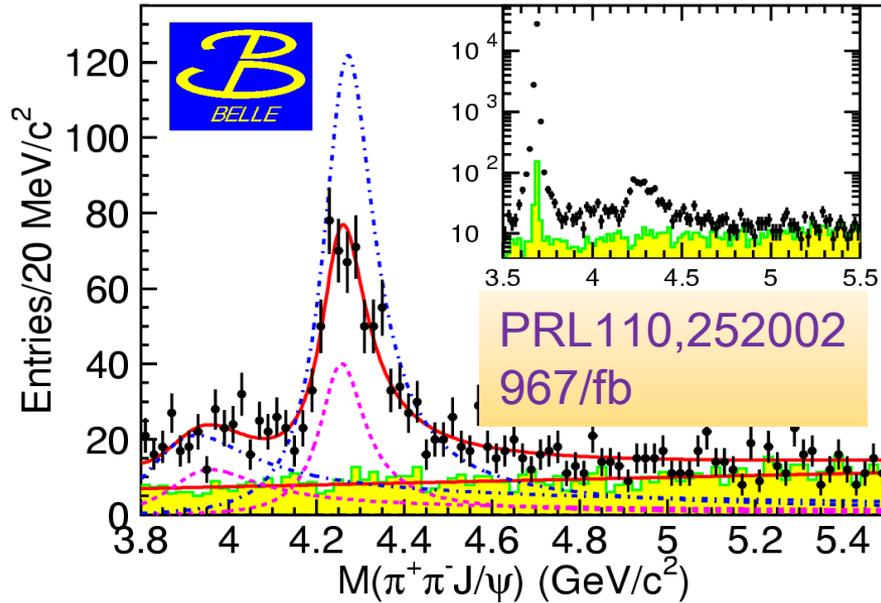
PRD86,051102
454/fb
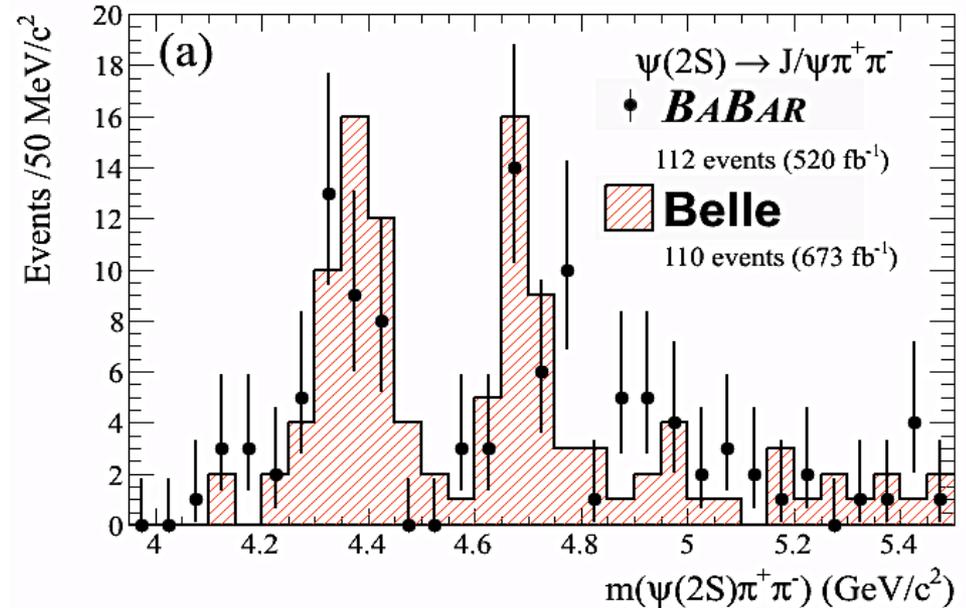
Y(4008): confirmed by Belle with more data; events observed at BaBar, fit with exponential

Wait for BESIII

Y(4660): confirmed by BaBar

Y(4630): no data, a bit beyond

BEPCII/BESIII limit

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Two-resonance fit

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

R₁=Y(4008)
R₂=Y(4260)
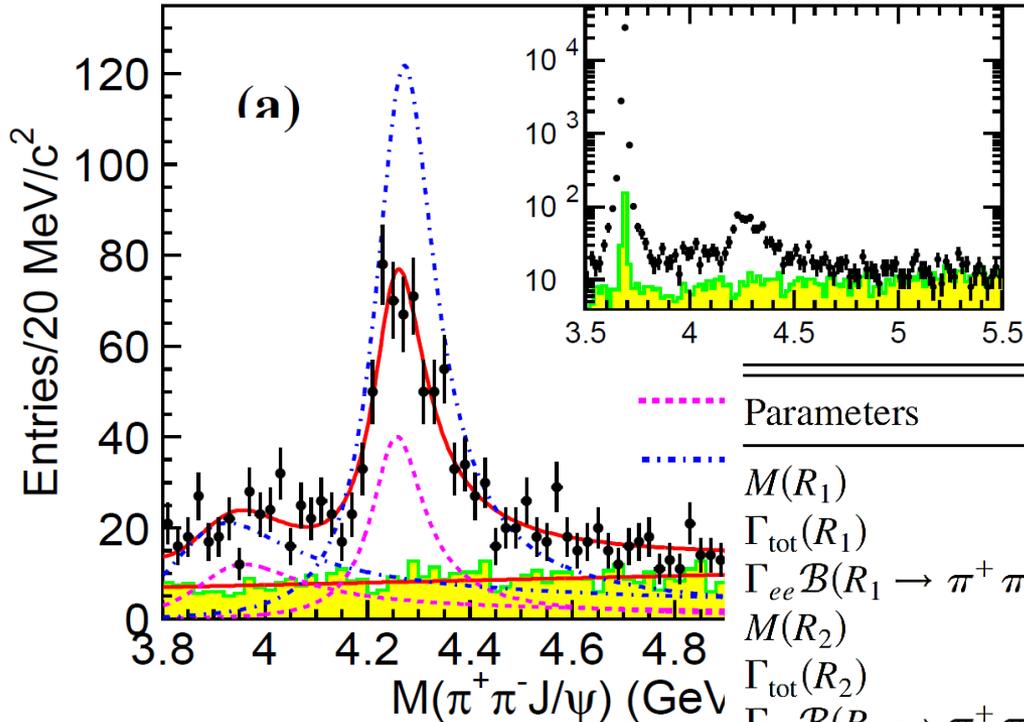
Parameters	Solution I	Solution II
$M(R_1)$	3890.8 $\pm$ 40.5 $\pm$ 11.5	
$\Gamma_{tot}(R_1)$	254.5 $\pm$ 39.5 $\pm$ 13.6	
$\Gamma_{ee}\mathcal{B}(R_1 \to \pi^+\pi^-J/\psi)$	(3.8 $\pm$ 0.6 $\pm$ 0.4)	(8.4 $\pm$ 1.2 $\pm$ 1.1)
$M(R_2)$	4258.6 $\pm$ 8.3 $\pm$ 12.1	
$\Gamma_{tot}(R_2)$	134.1 $\pm$ 16.4 $\pm$ 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 resonances $|BW_1+BW_2*\exp(i\phi)|^2+bkg$.
2. Mass of Y(4008) is lower than before
3. Fit quality: $\chi^2/ndf=101/84$, confidence level is 9.3%

Select e⁺e⁻→ π⁺π⁻J/ψ at 4.26 GeV

882±33
J/ψ →μ⁺μ⁻

595±28
J/ψ →e⁺e⁻
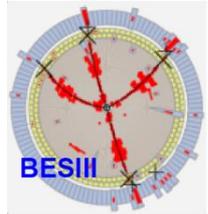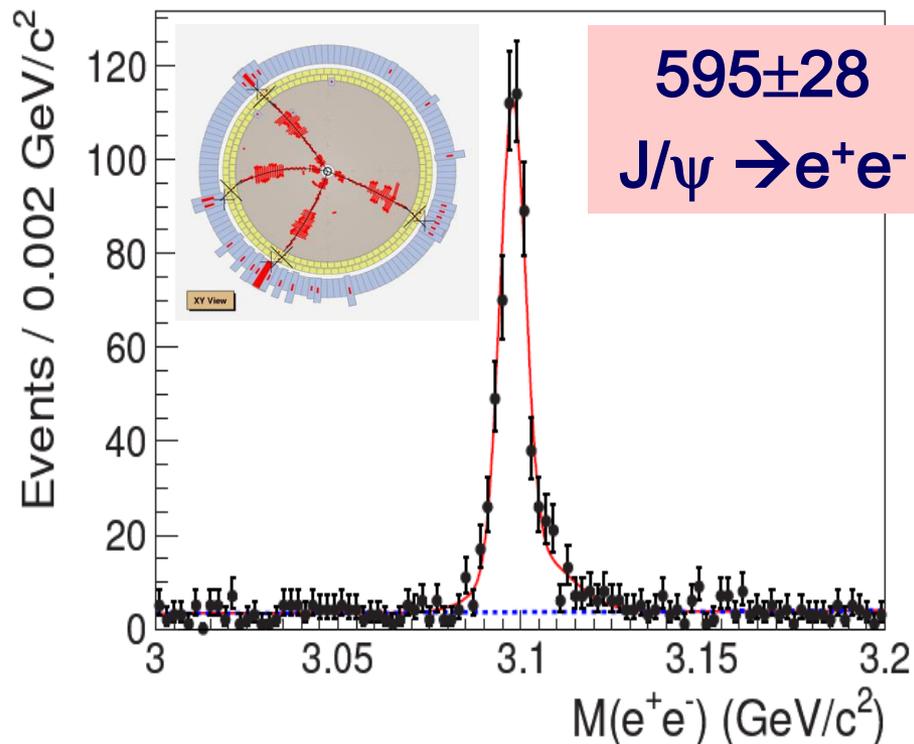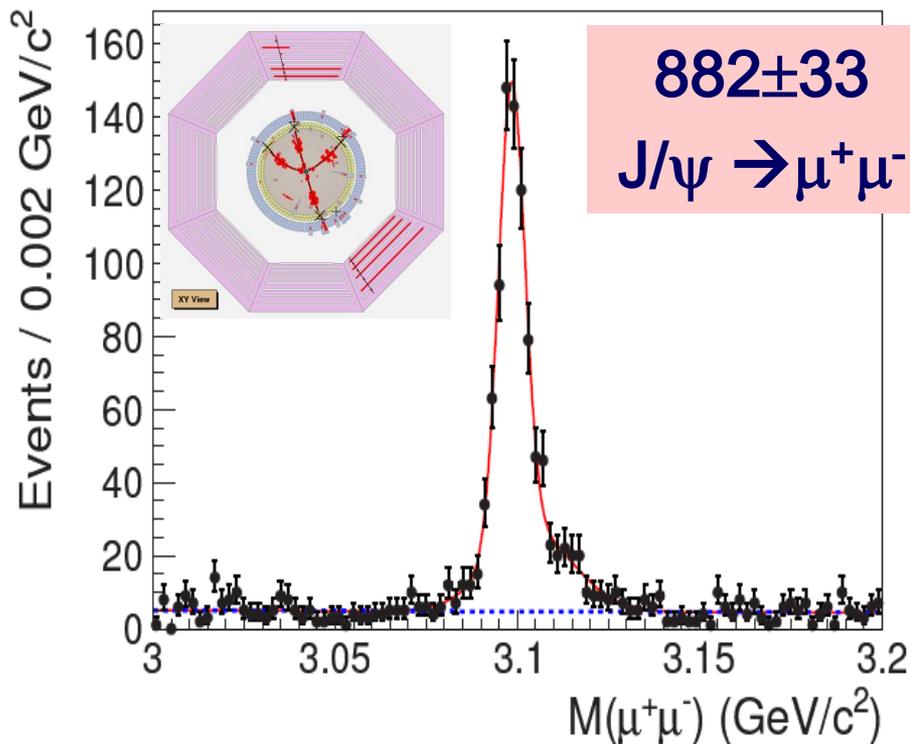
- Select 4 charged tracks and reconstruct J/ψ with lepton pair.
- Very clean sample, very high efficiency (~45%).
- $\sigma(e^+e^- \to \pi^+\pi^-J/\psi)$= (62.9±1.9±3.7) pb
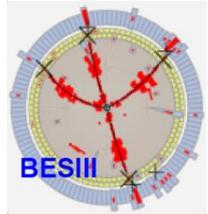
Cross section of e⁺e⁻→ π⁺π⁻J/ψ

BaBar: PRD86,051102
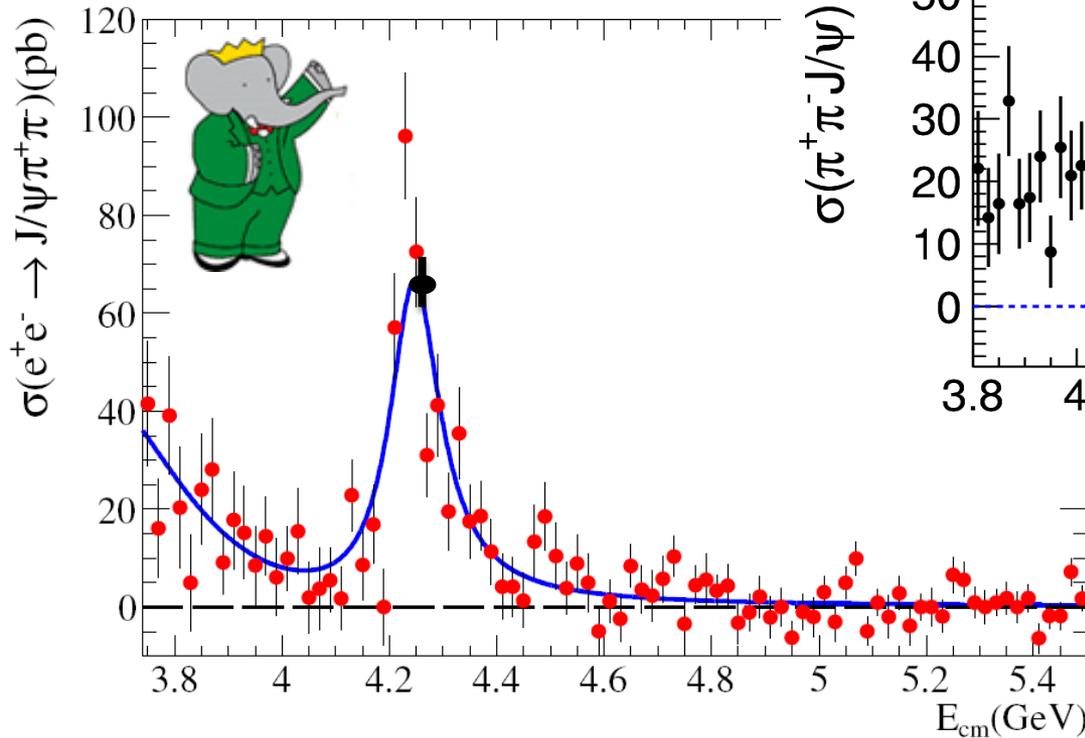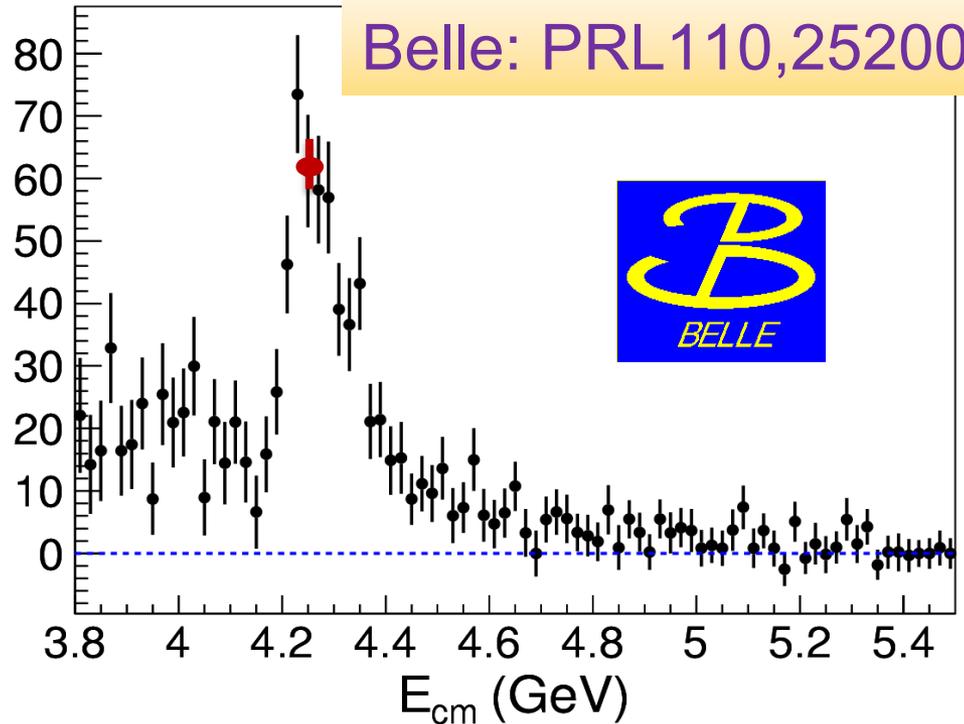
Belle: PRL110,252002

BESIII: PRL110,252001

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

Agree with BaBar & Belle!

Best precision!

BESIII is measuring cross sections at more energy points, and will take more data!

23
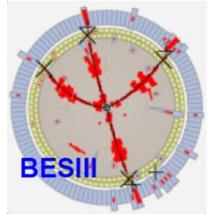
$e^+e^- \rightarrow \pi^+\pi^- h_c(1P)$ at BESIII

- $h_c \rightarrow \gamma \eta_c$, $\eta_c \rightarrow$ hadrons [16 exclusive decay modes]
  - $p\bar{p}$, $\pi^+\pi^- K^+K^-$, $\pi^+\pi^- p\bar{p}$, $2(K^+K^-)$, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$
  - $2(\pi^+\pi^-)K^+K^-$, $K_S^0 K^+\pi^-$+c.c., $K_S^0 K^+\pi^-\pi^+\pi^-$+c.c., $K^+K^-\pi^0$
  - $p\bar{p}\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)\eta$, $2(\pi^+\pi^-\pi^0)$

BESIII: arXiv:1309.1896, PRL111, 242001

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Observation of $e^+e^- \to \pi^+\pi^- h_c(1P)$

E_{cm}=4.26 GeV

E_{cm}=4.36 GeV
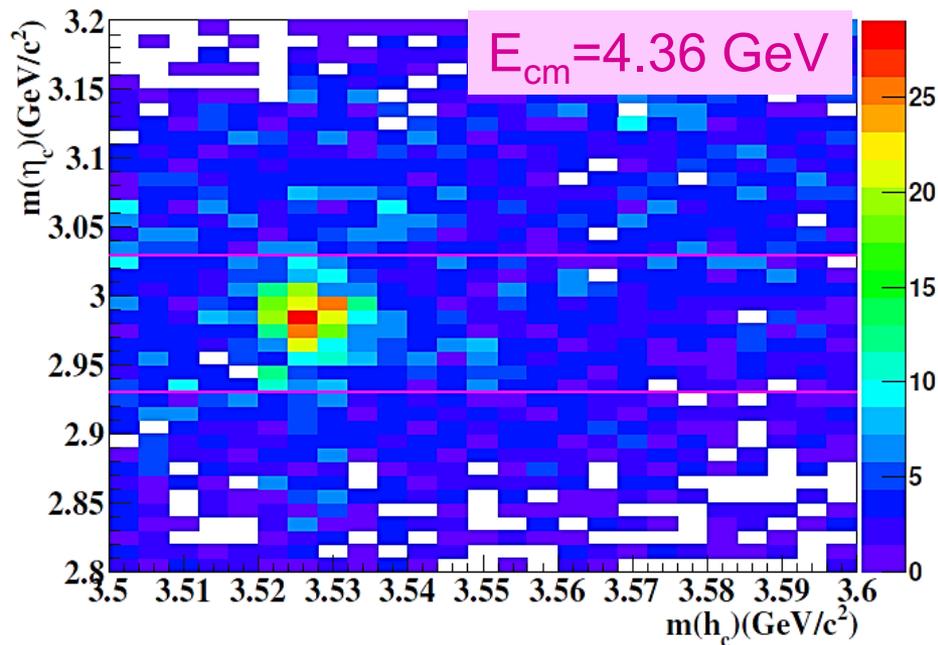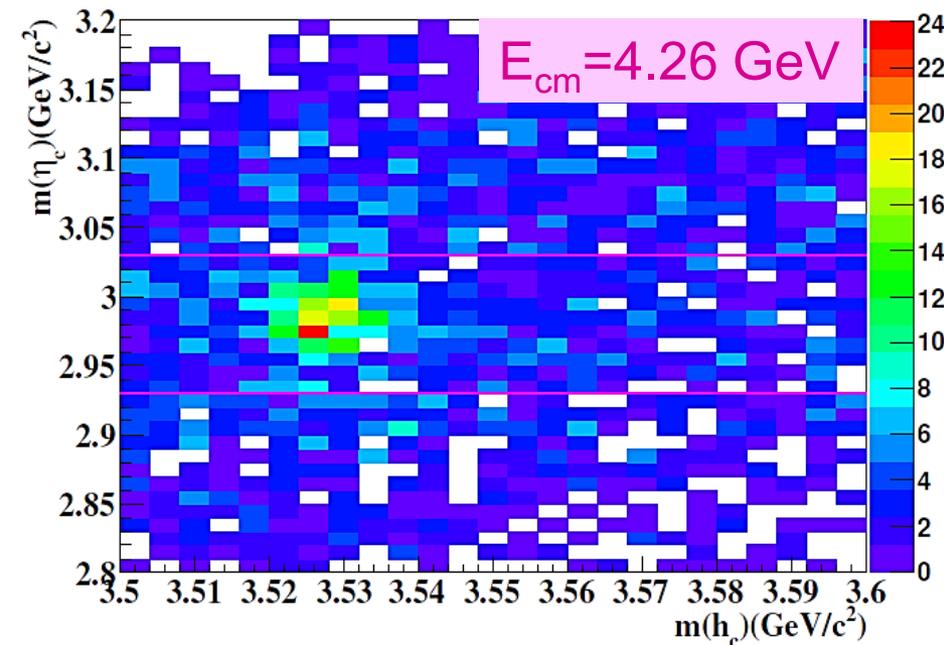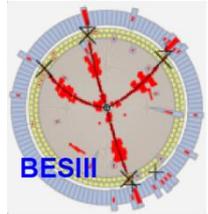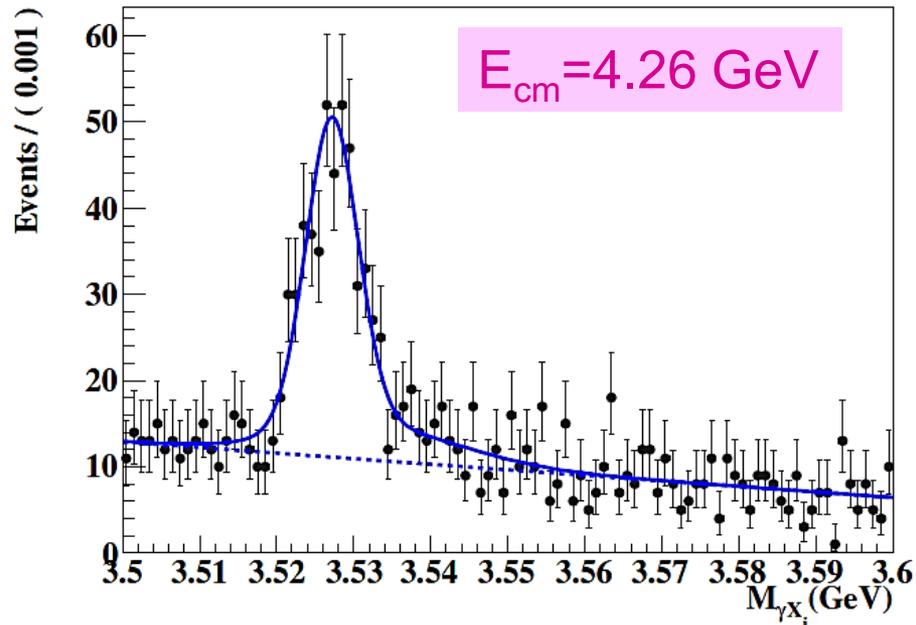
$N(h_c)$=416$\pm$28

Lum=827/pb

σ^B= 41.0$\pm$2.8$\pm$7.4 pb

$N(h_c)$=357$\pm$25

Lum=544/pb

σ^B= 52.3$\pm$3.7$\pm$9.2 pb

BESIII: arXiv:1309.1896, PRL111, 242001
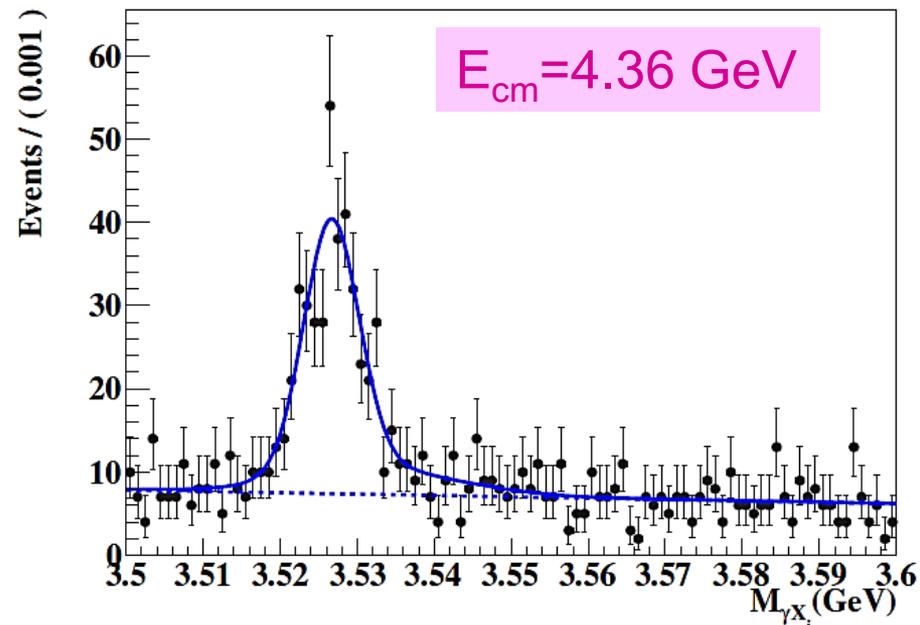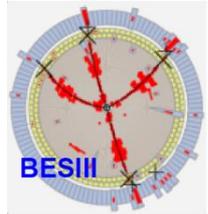
Observation of $e^+e^- \rightarrow \pi^+\pi^-h_c(1P)$
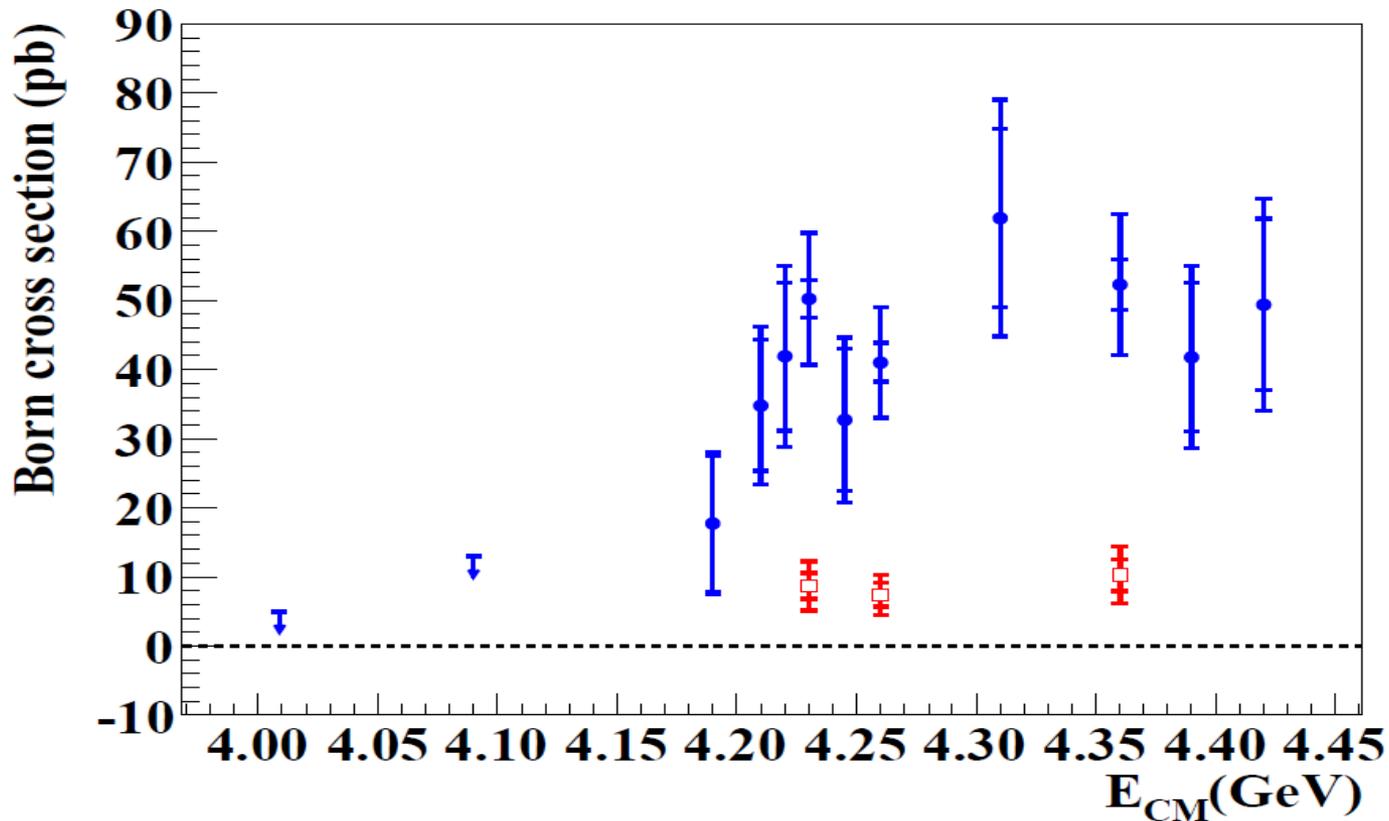
- $\sigma(e^+e^- \rightarrow \pi^+\pi^-h_c) \sim \sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi)$ but line shape different

- Local maximum ~ 4.23 GeV

- Hint for a vector $\bar{c}cg$ hybrid? [PRD78, 056003 (Guo); 094504 (Dudek): cc in spin-singlet in hybrids!]

Comparison of $e^+e^- \to \pi^+\pi^-h_c$ and $\pi^+\pi^-J/\psi$

Open circles: Belle $e^+e^- \to \pi^+\pi^-J/\psi$
Solid dots: BESIII $e^+e^- \to \pi^+\pi^-h_c$

σ (pb)

Ecm (GeV)
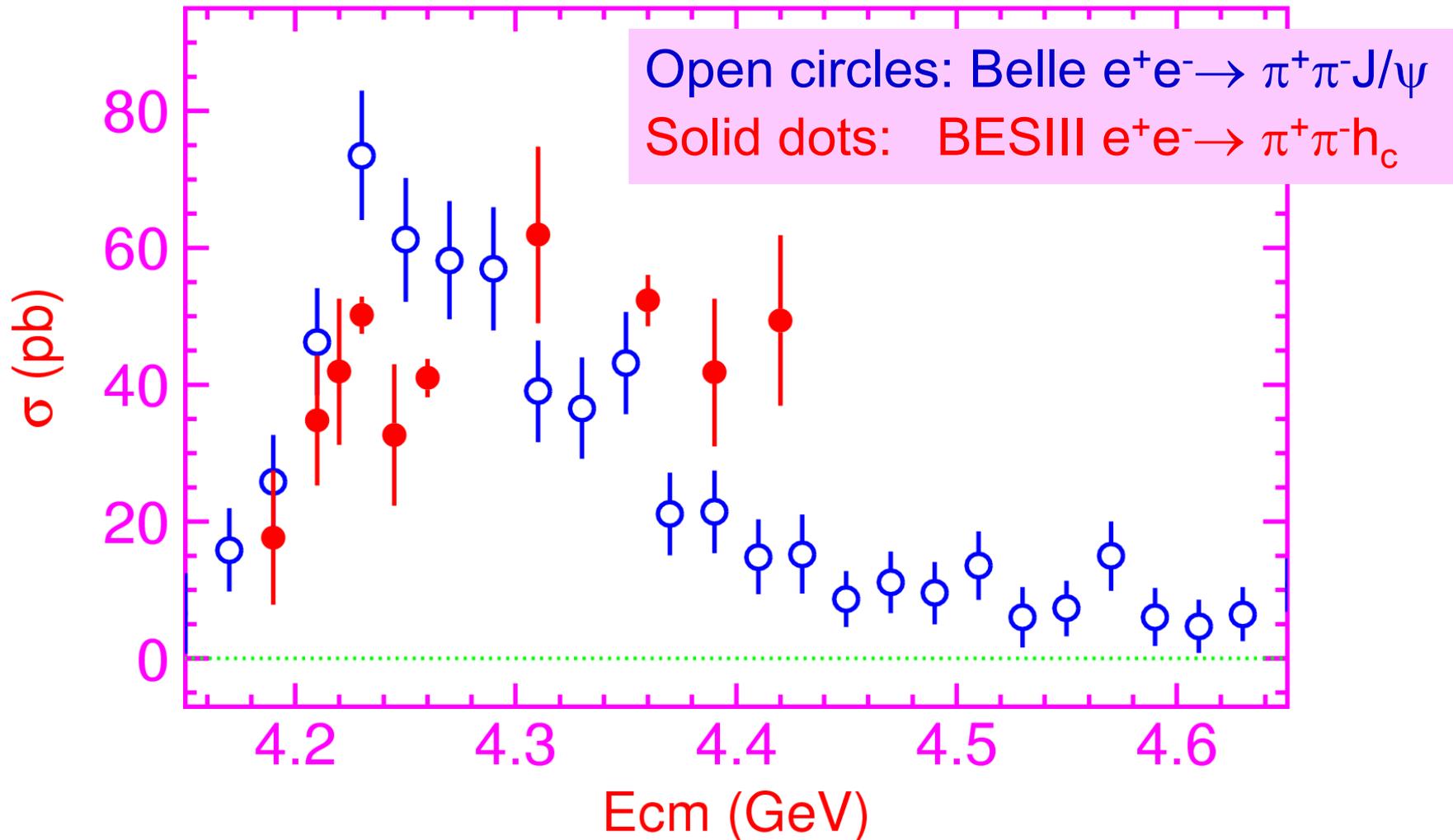
Broad structure at high energy region? Need more data at high energies to complete the line shape measurement.

Structure in $e^+e^- \to \pi^+\pi^- h_c$?

PS+Y(4220): 7.1σ

Y(4290)+Y(4220): 4.5σ
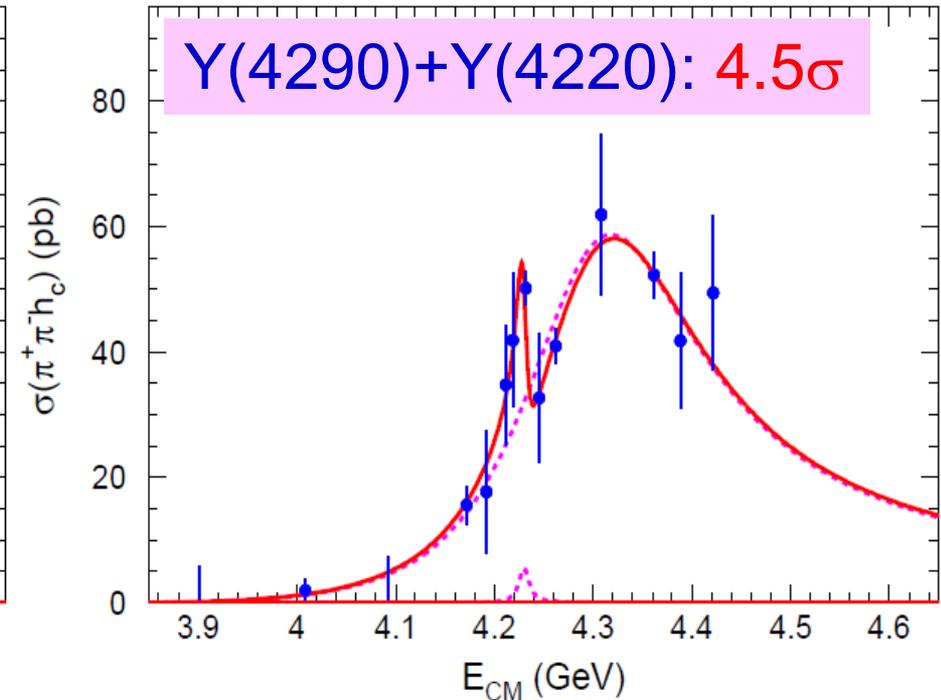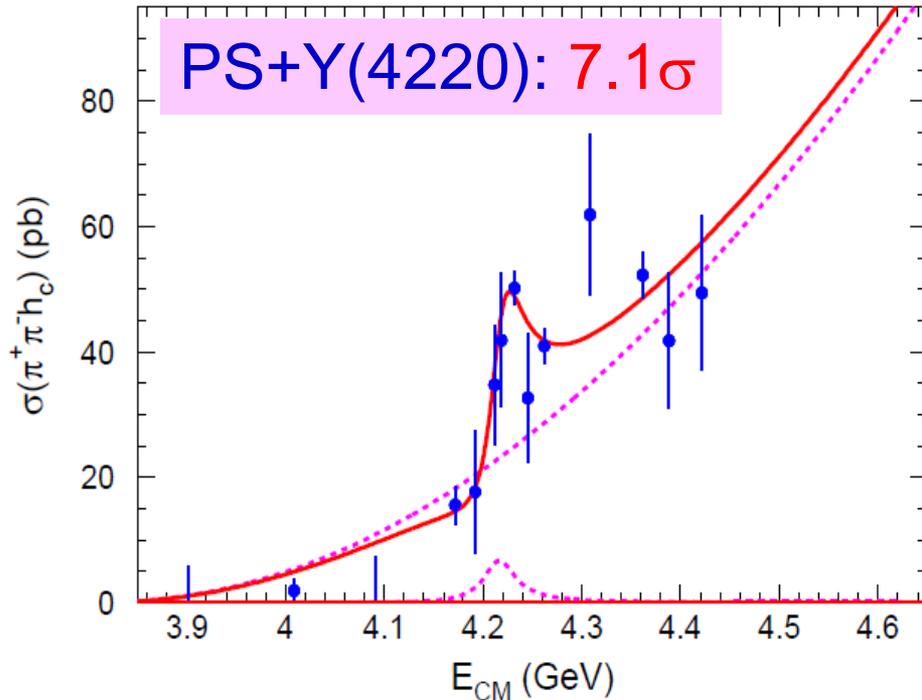
Common sys. errors not included in these fits!   (cf. arXiv:1310.2190)

Narrow structure at 4.22 GeV?   More data at around 4.22 GeV!

Broad structure at 4.29 GeV?   More data at above 4.4 GeV!

CZY: arXiv:1312.6399: fit to BESIII and CLEOc data

What are the Y states?
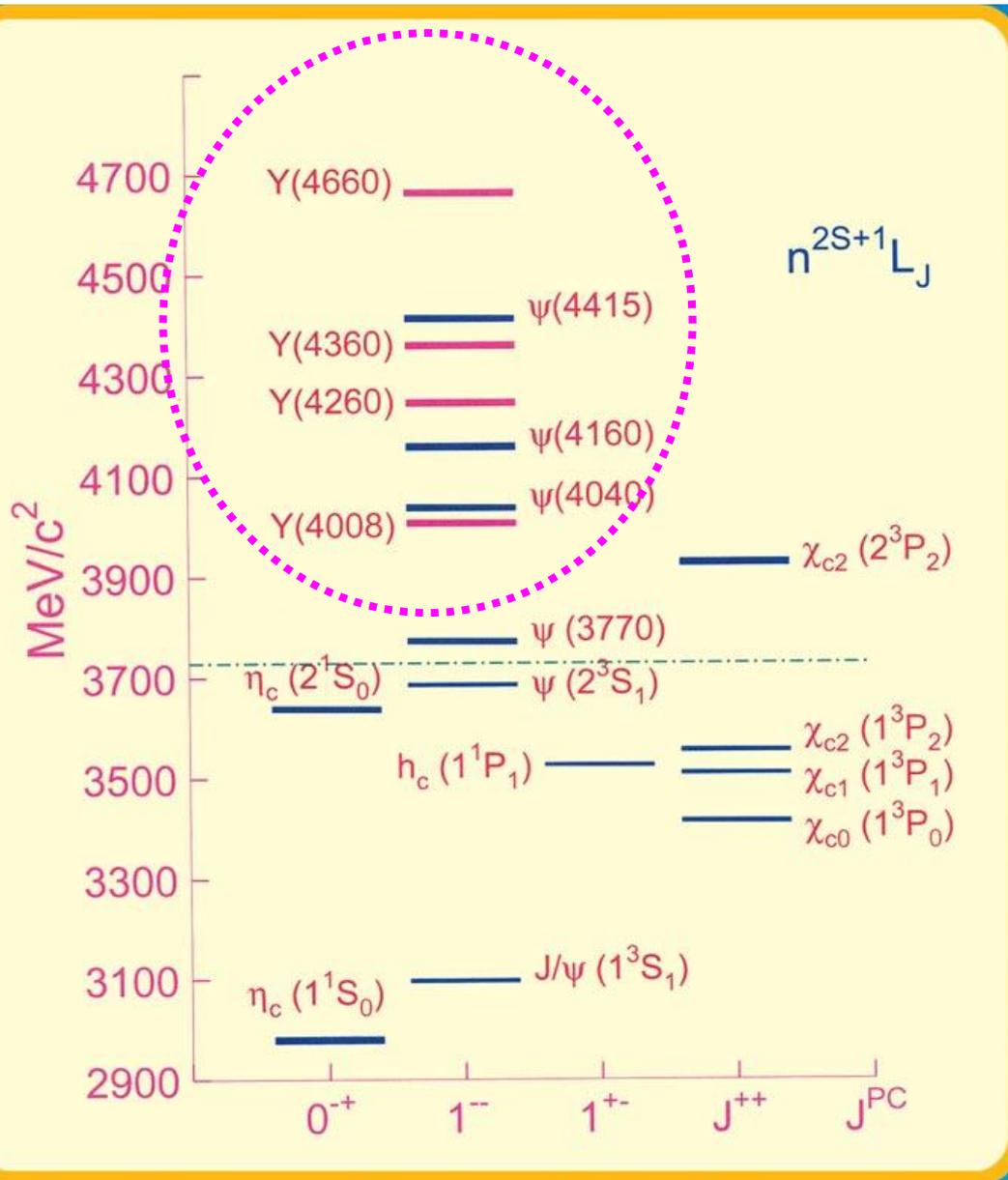
- Between 4 and 4.7 GeV, at most 5 states expected (3S, 2D, 4S, 3D, 5S), 7 observed
- Hybrids are expected in this mass region
- Molecular states?
- Cannot rule out threshold effect/FSI/…
- Y(4260), Y(4360), Y(4660) are all narrow and similar
- $\pi^+\pi^-h_c$ add complexity

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Z_c: charged charmoniumlike states

- Find a clear signature for exotic state!
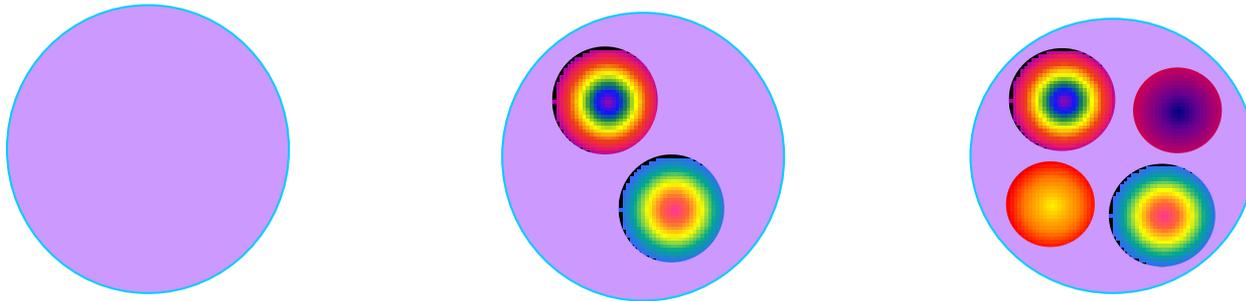
- Decays to charmonium thus has a $\bar{c}c$ pair!

- With electric charge thus has two more light quarks!

$$\Rightarrow N_{quark} \geq 4 \,!$$

- Do searches in $\pi^{\pm}J/\psi$, $\pi^{\pm}h_c(1P)$, $\pi^{\pm}\psi(2S)$, $\pi^{\pm}\chi_{cJ}$, …

- BESIII: $e^+e^- \Rightarrow \pi^{\pm}$+exotics, $\rho^{\pm}$+exotics, …
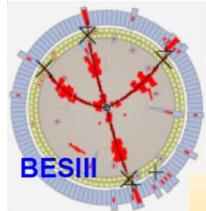
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at E_{cm}=4.26 GeV

BESIII: PRL110,252001

525 pb^{-1} data at 4.260 GeV

1595 events in J/ψ signal region, purity~90%

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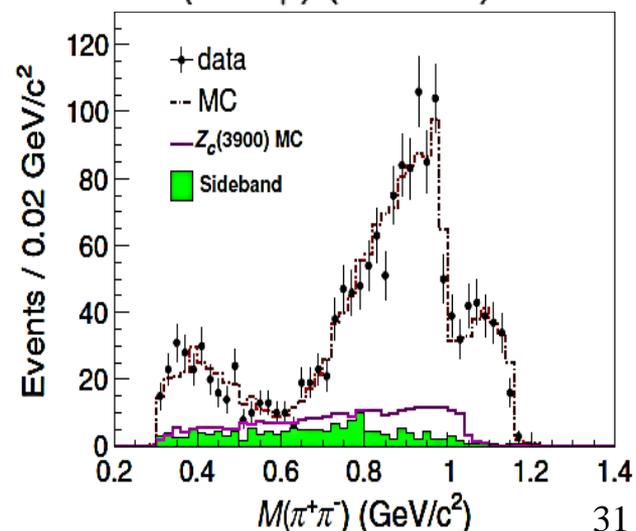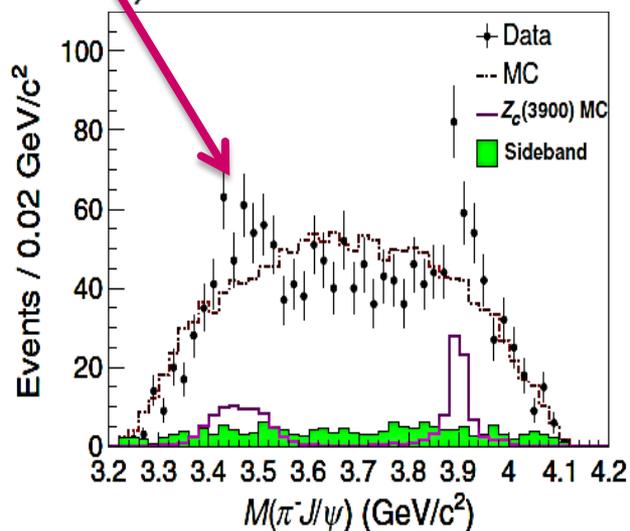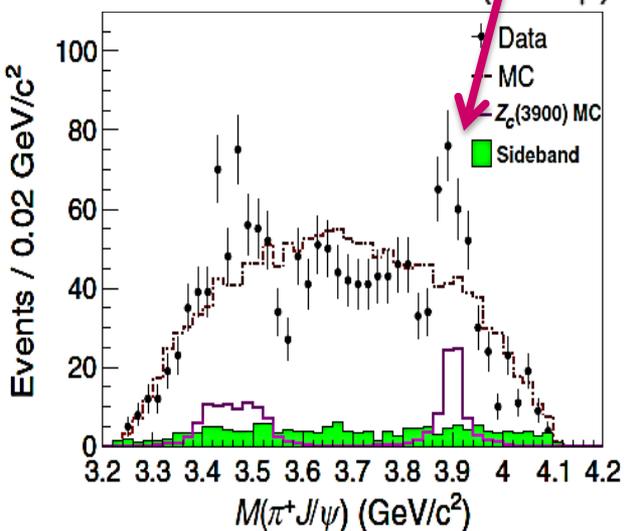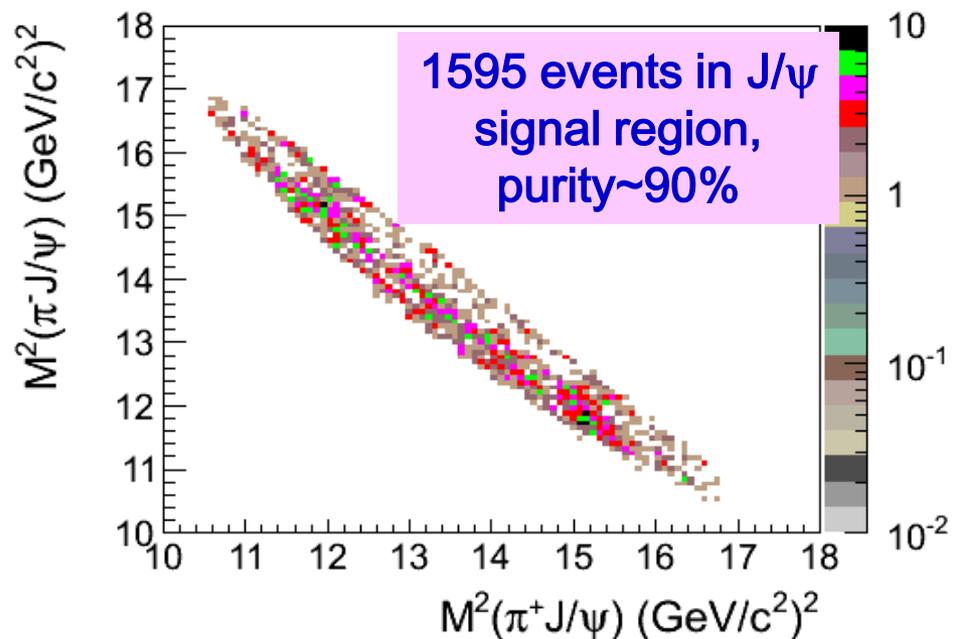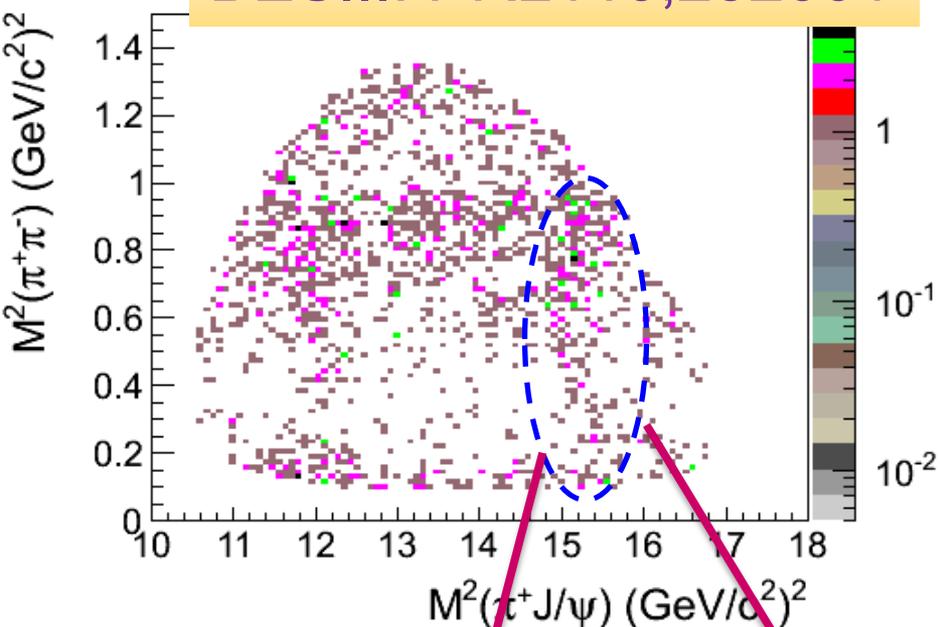
e⁺e⁻→ π⁺π⁻J/ψ from ISR

Belle: PRL110,252002

- $M^2(\pi\pi)$ vs. $M^2(\pi J/\psi)$ for $4.15 < M(\pi\pi J/\psi) < 4.45$ GeV

- (inset) Background events in J/ψ-mass sidebands

- Structures both in $\pi\pi$ and $\pi J/\psi$ systems

- **689 events in J/ψ signal region, purity~80%**
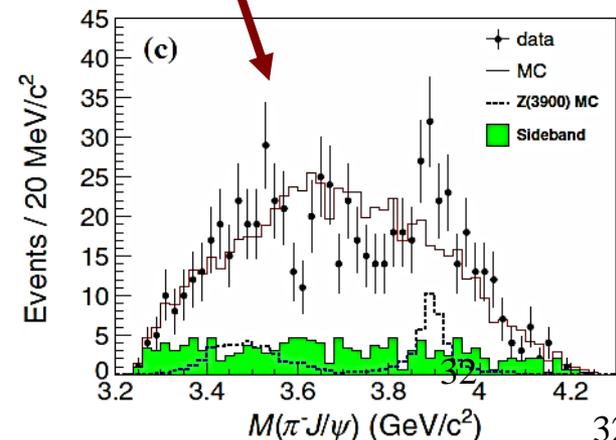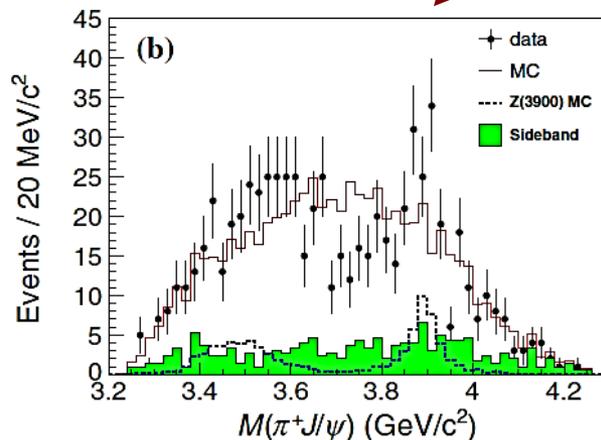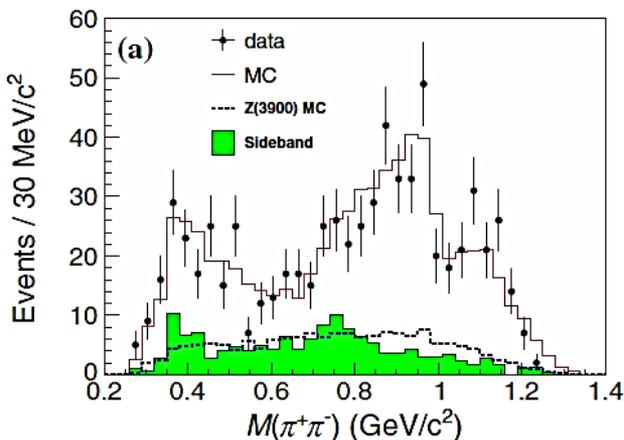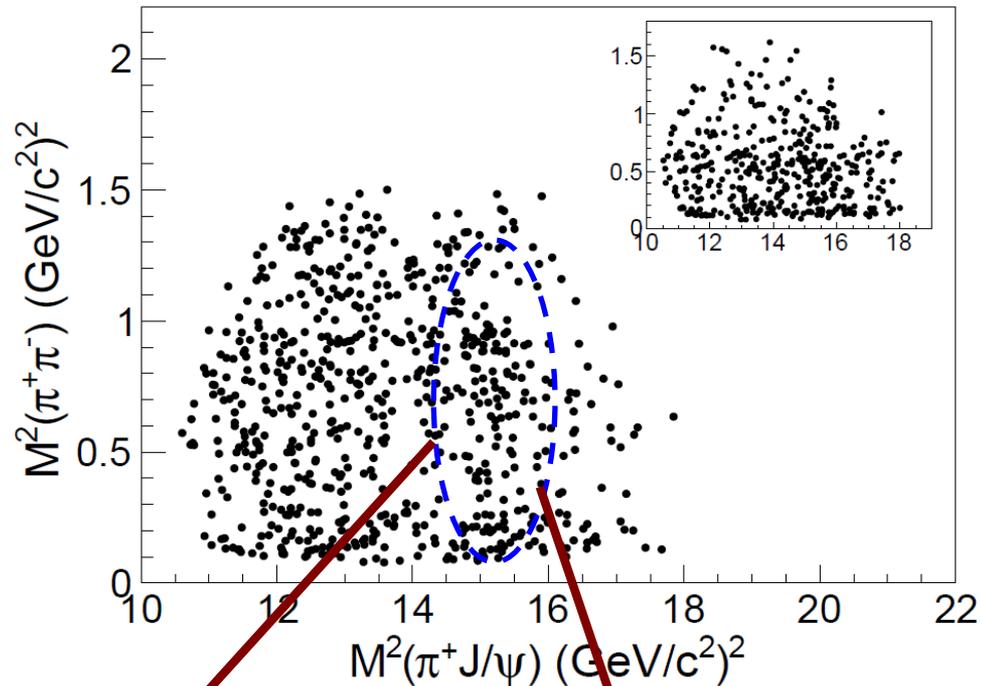
$Z_c(3900)$ observed in two experiments!
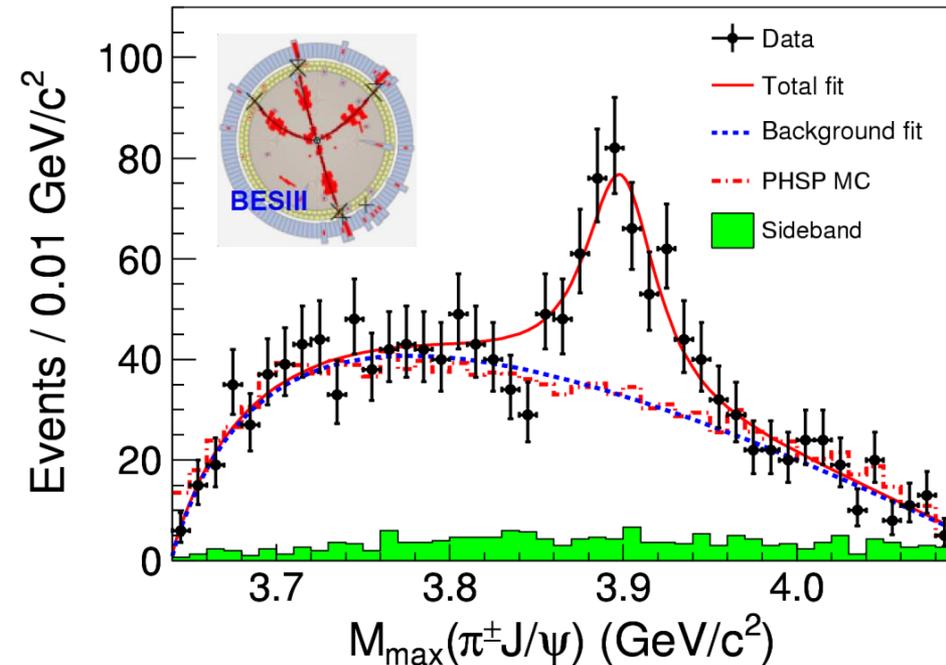
- M = 3899.0$\pm$3.6$\pm$4.9 MeV

- Γ = 46$\pm$10$\pm$20 MeV

- 307 $\pm$ 48 events

- >8σ
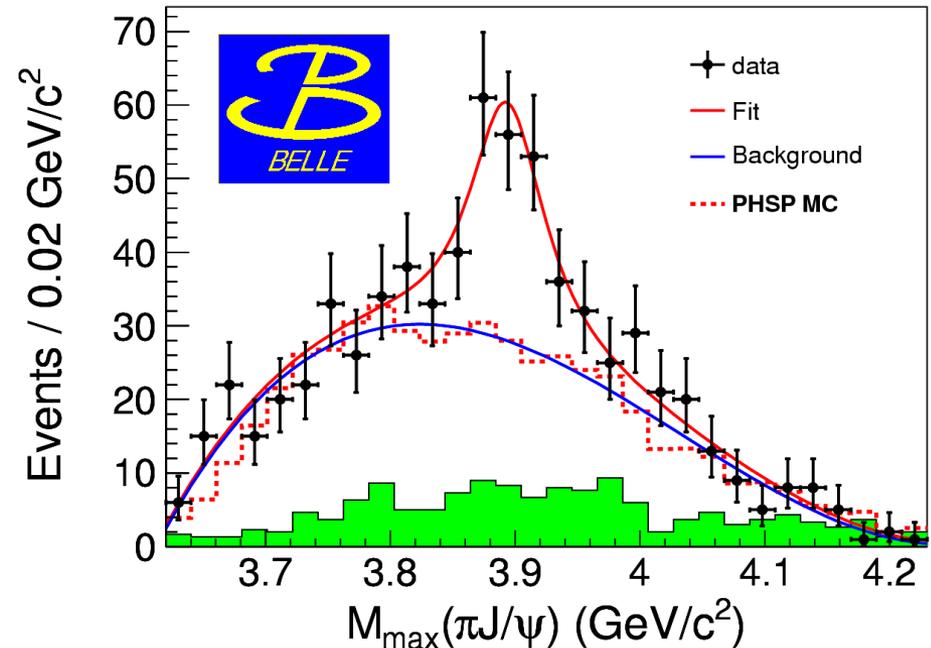
- M = 3894.5$\pm$6.6$\pm$4.5 MeV

- Γ = 63$\pm$24$\pm$26 MeV

- 159 $\pm$ 49 events

- >5.2σ

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Confirmed with CLEOc data!

CLEOc data at 4.17 GeV:
arXiv:1304.3036, PLB727, 366 (2013)
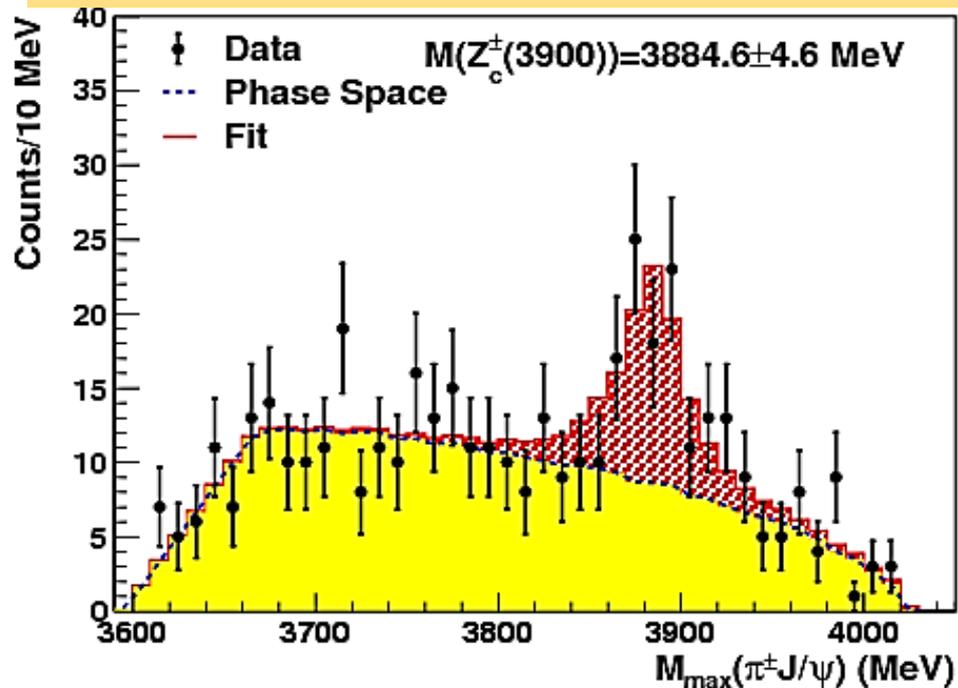
- M = 3885±5±1 MeV
- Γ = 34±12±4 MeV
- 81 ± 20 events   6.1σ
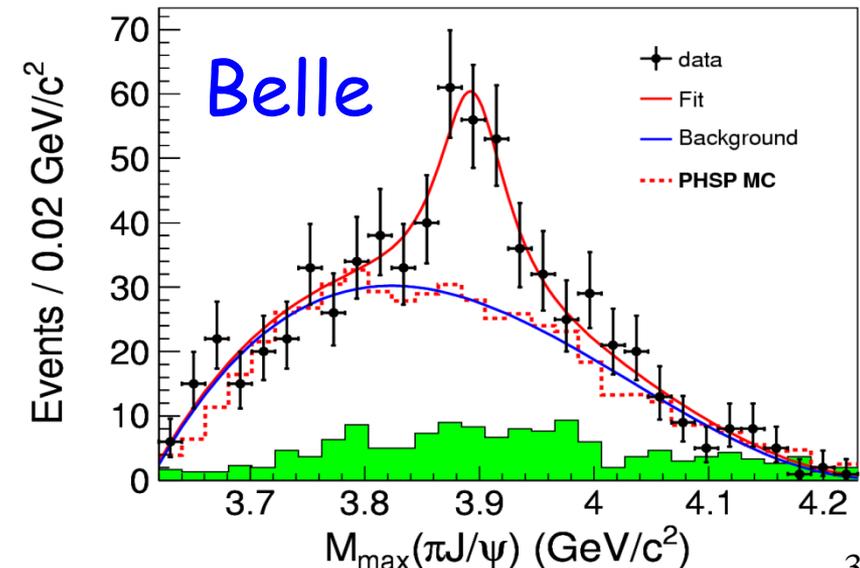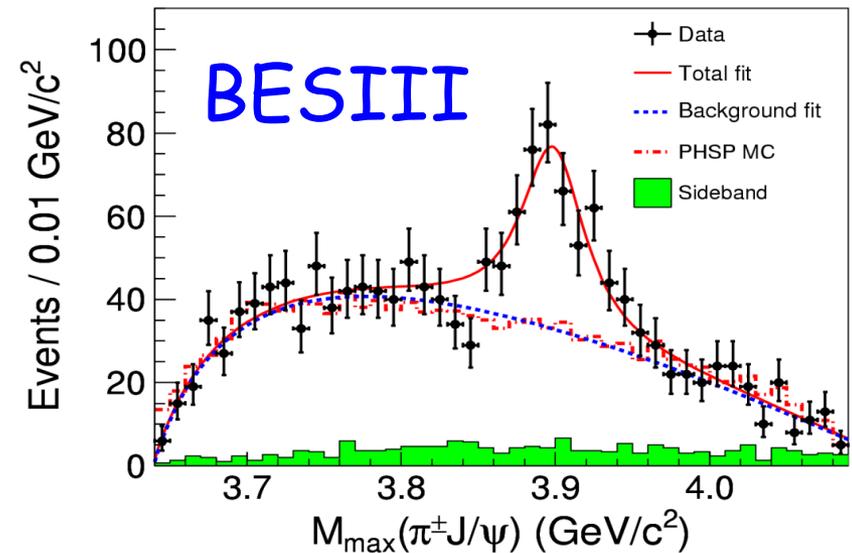
What is $Z_c(3900)$?
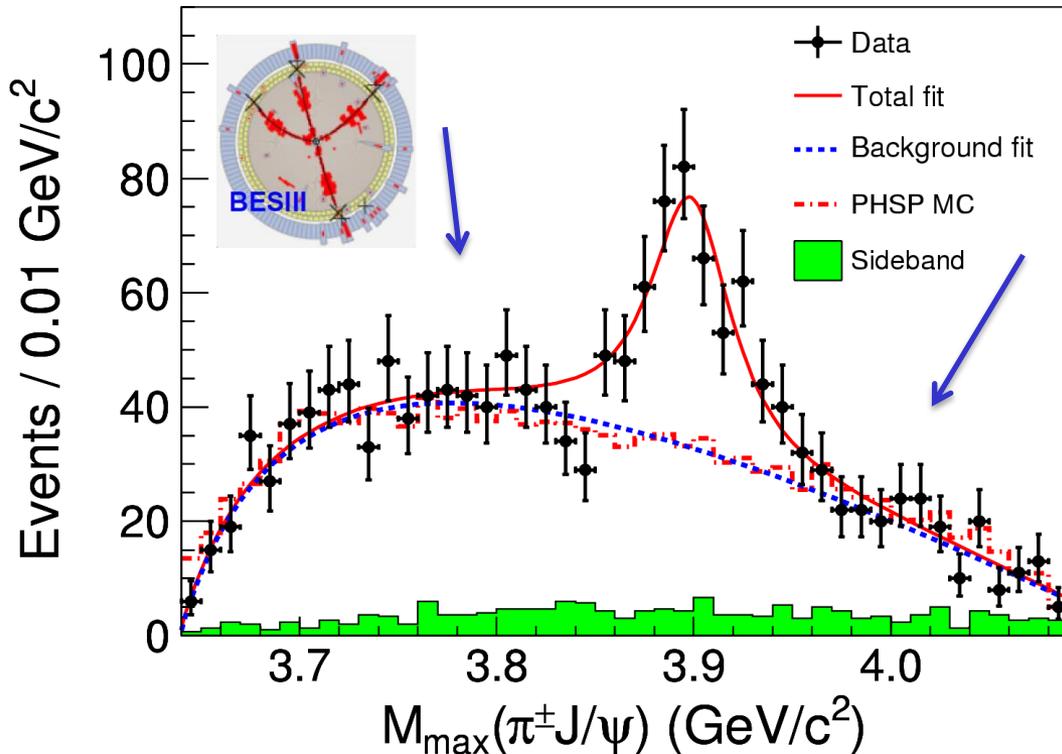
- Couples to $\bar{c}c$
- Has electric charge
- At least 4-quarks
- What is its nature?
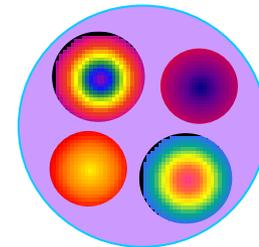
- $\bar{D}D^*$ molecule?
- Tetraquark state?
- Threshold effect?
- …

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

➜ A partner below/above Z_c?
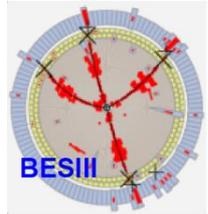
Dalitz plot of $e^+e^- \to \pi^+\pi^- h_c(1P)$
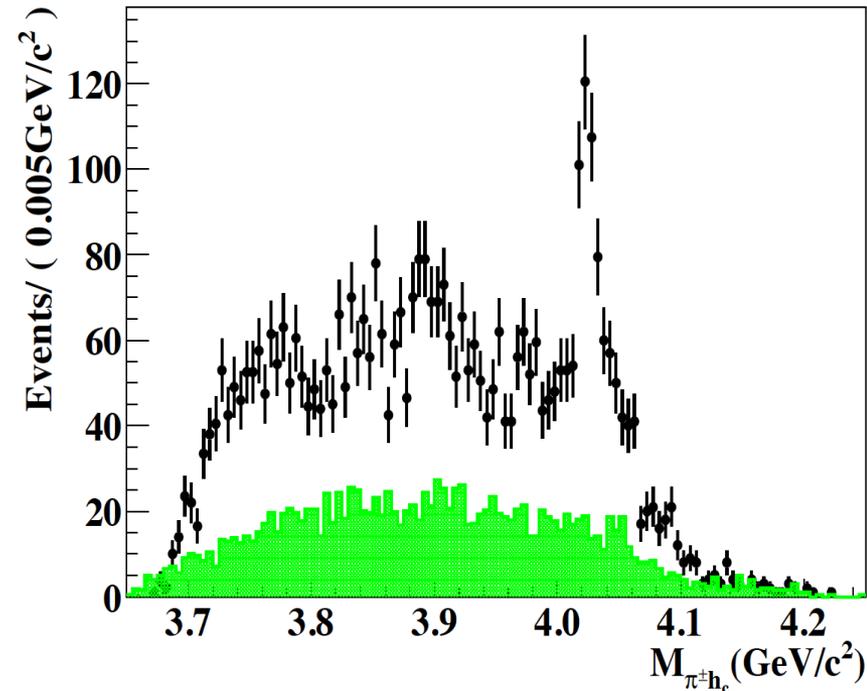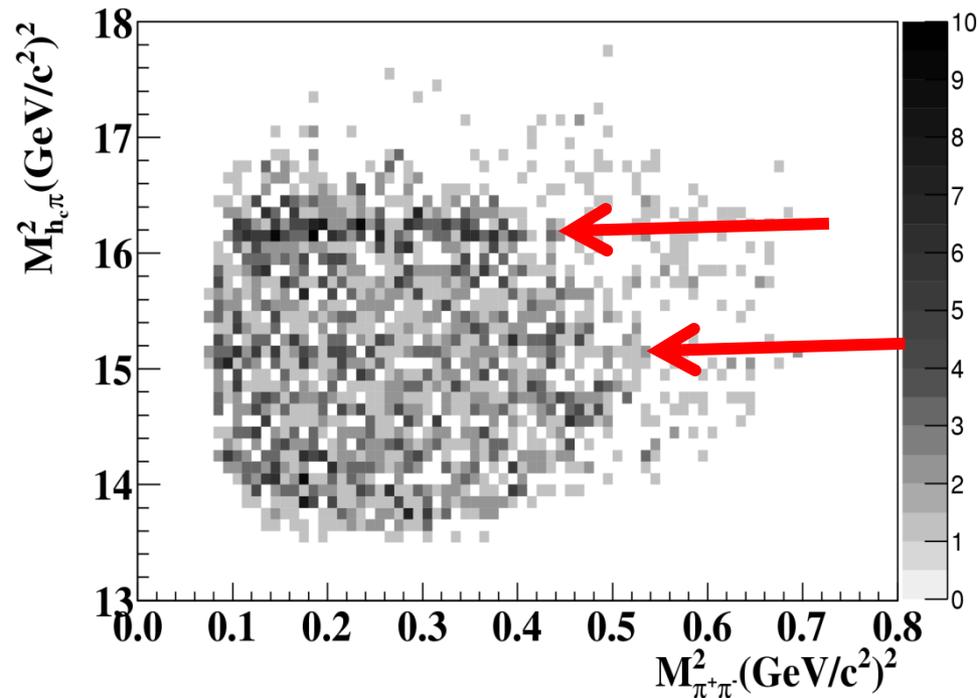
- **Obvious structure around 4.02 GeV**
- **Hints of $Z_c(3900)$**   BESIII: PRL111, 242001
- ~1500 events in h_c signal region at 4.230, 4.260 and 4.360 GeV, purity about 65%

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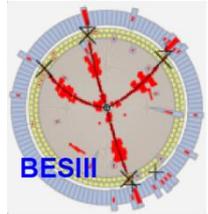
$e^+e^- \rightarrow \pi Z_c(4020) \rightarrow \pi^+\pi^- h_c(1P)$

Simultaneous fit to 4.23/4.26/4.36 GeV data, 16 η_c decay modes. 8.9σ

$M(Z_c(4020)) =$

4022.9$\pm$0.8$\pm$2.7 MeV;

$\Gamma(Z_c(4020)) =$

7.9$\pm$2.7$\pm$2.6 MeV

Close to $\bar{D}^*D^*$ threshold

Significance: 8.9σ [$Z_c(4020)$]

No significant $Z_c(3900)$ (2.1σ)
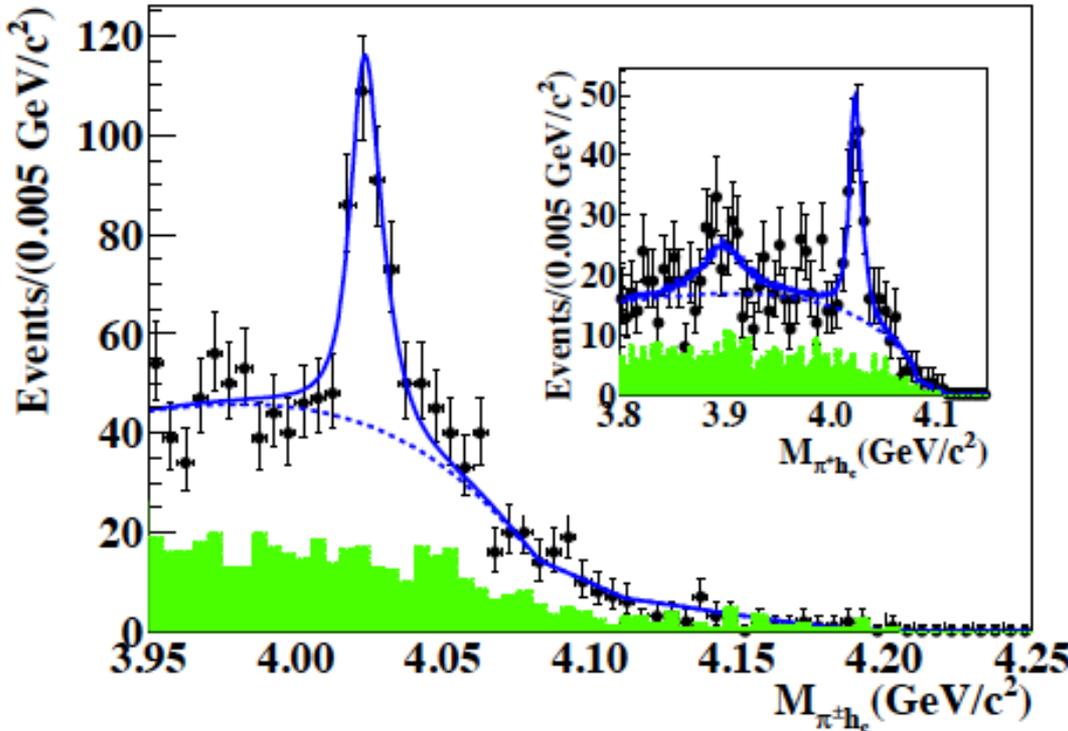
$\sigma(e^+e^- \rightarrow \pi Z_c \rightarrow \pi^+\pi^- h_c)$:

8.7$\pm$1.9$\pm$2.8$\pm$1.4 pb @ 4.230 GeV

7.4$\pm$1.7$\pm$2.1$\pm$1.2 pb @ 4.260 GeV

10.3$\pm$2.3$\pm$3.1$\pm$1.6 pb @ 4.360 GeV

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X、Y、Z particles are correlated!

What are they? Are they all molecules?

Y(4260)

X(3872) **?** Z_c(3900)
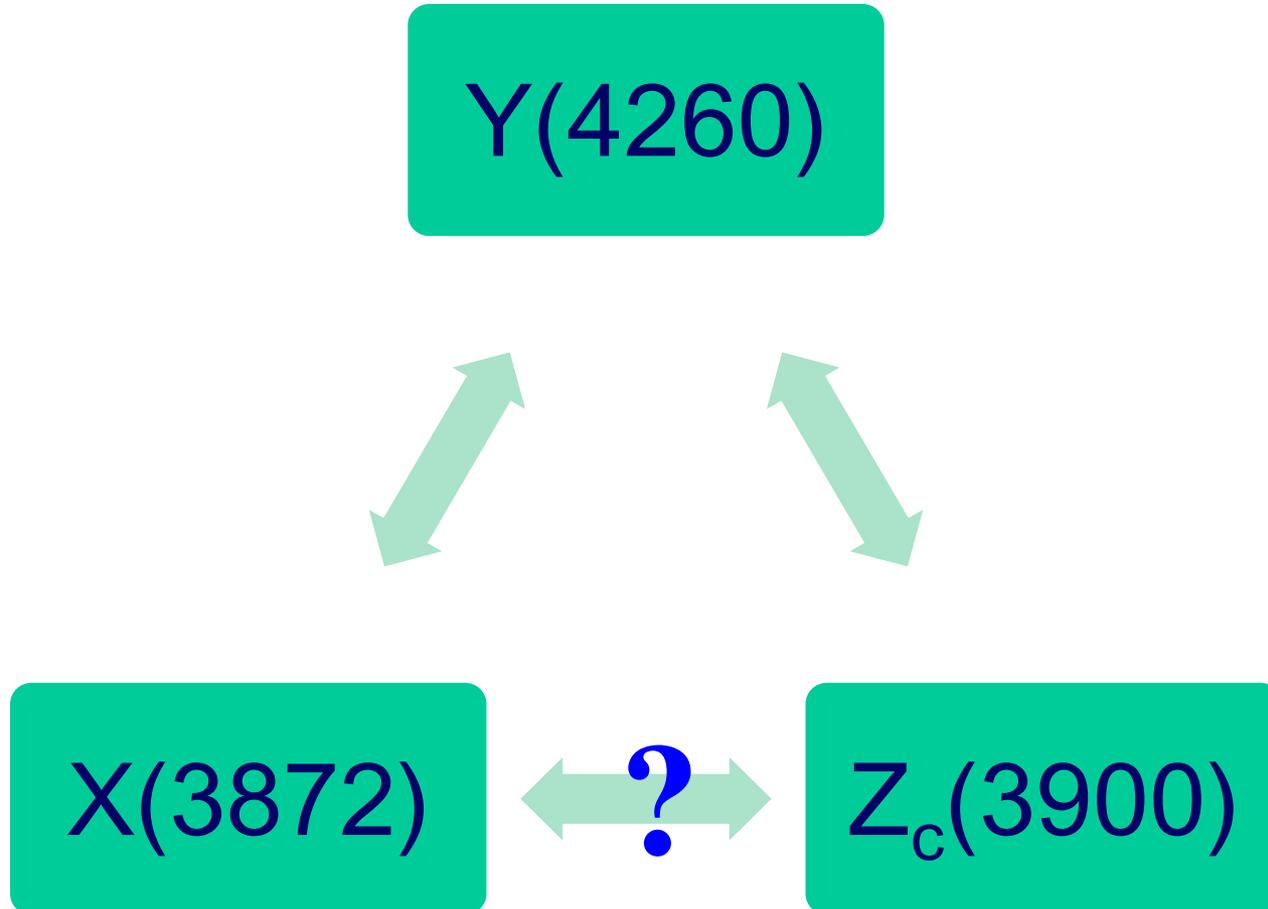
Summary

- There were lots of progress in charmonium and charmoniumlike studies recently

- BESIII started study of the XYZ particles

- Observation of $Y(4260) \rightarrow \gamma X(3872)$

- New information on the Y's from BaBar and Belle. Y(4660) confirmed, Y(4008) not confirmed; large $\pi^+\pi^- h_c$ production rate above 4.2 GeV

- First confirmed exotic state with at least four quarks, $Z_c(3900)^+$, at BESIII & Belle [close to M(DD*)]

- Observation of the Z_c' at BESIII [close to M(D*D*)]

- More study from BESIII, BelleII, Panda?

Thanks a lot!

谢谢！

Vielen Dank!

Who can answer?

"Where Do They Come From?
What Are They?
Where Are They Going?"

Belle observed Z(4430)±→ψ(2S)π±

- Found in ψ(2S)π+ from B→ψ(2S)π+K. Z parameters from fit to M(ψ(2S)π+)
- Confirmed through Dalitz-plot analysis of B→ψ(2S)π+K
- B→ψ(2S)π+K amplitude: coherent sum of Breit-Wigner contributions

- **Models: all known K*→Kπ+ resonances only**

  all known K*→Kπ+ and Z+→ψ(2S)π+ ⇨ favored by data

M²(ψ(2S)π+) (vertical axis), M²(Kπ+) (horizontal axis)

K₂*(1430), K*(890), Z+(4430)

Significance: 6.4σ

657M B$\underline{B}$
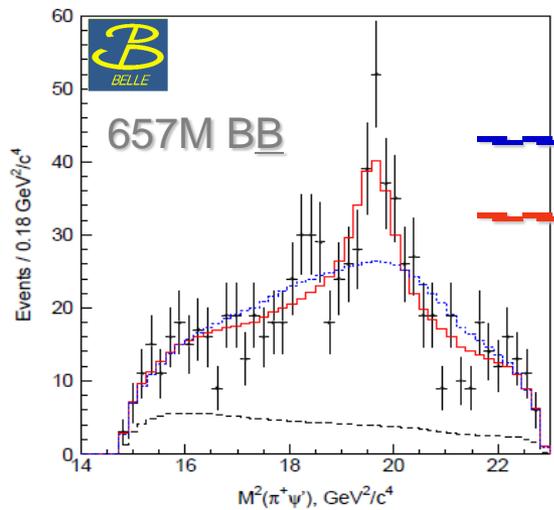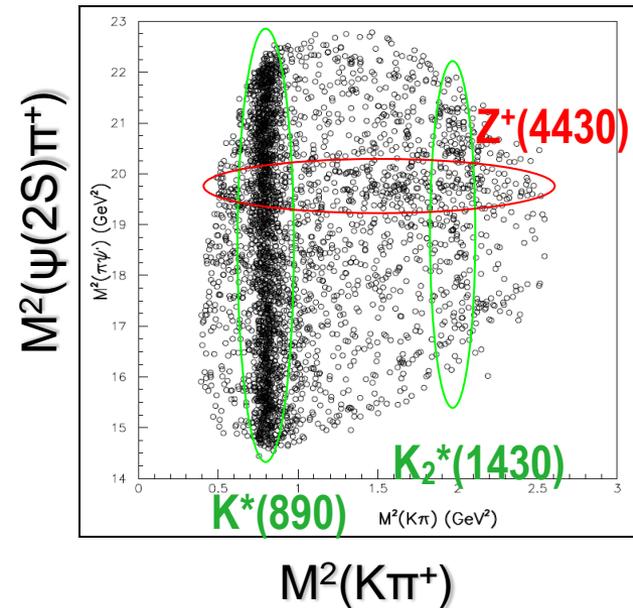
— fit for model with K*'s only
— fit for model with K*'s and Z

M²(ψ(2S)π+) after K* veto

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

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

- **[cu][cd] tetraquark? neutral partner in ψ'π⁰ expected**
- **D*D₁(2420) molecule? should decay to D*D*π**

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Spin-parity of the Z(4430)±

- B→ψ(2S)π+K amplitude: coherent sum of Breit-Wigner contributions

$$J^P = 1^+ \qquad M = 4500\,^{+14\,+16}_{-13\,-9}\;\text{MeV} \qquad \Gamma = 126\,^{+30\,+3}_{-26\,-26}\;\text{MeV}$$
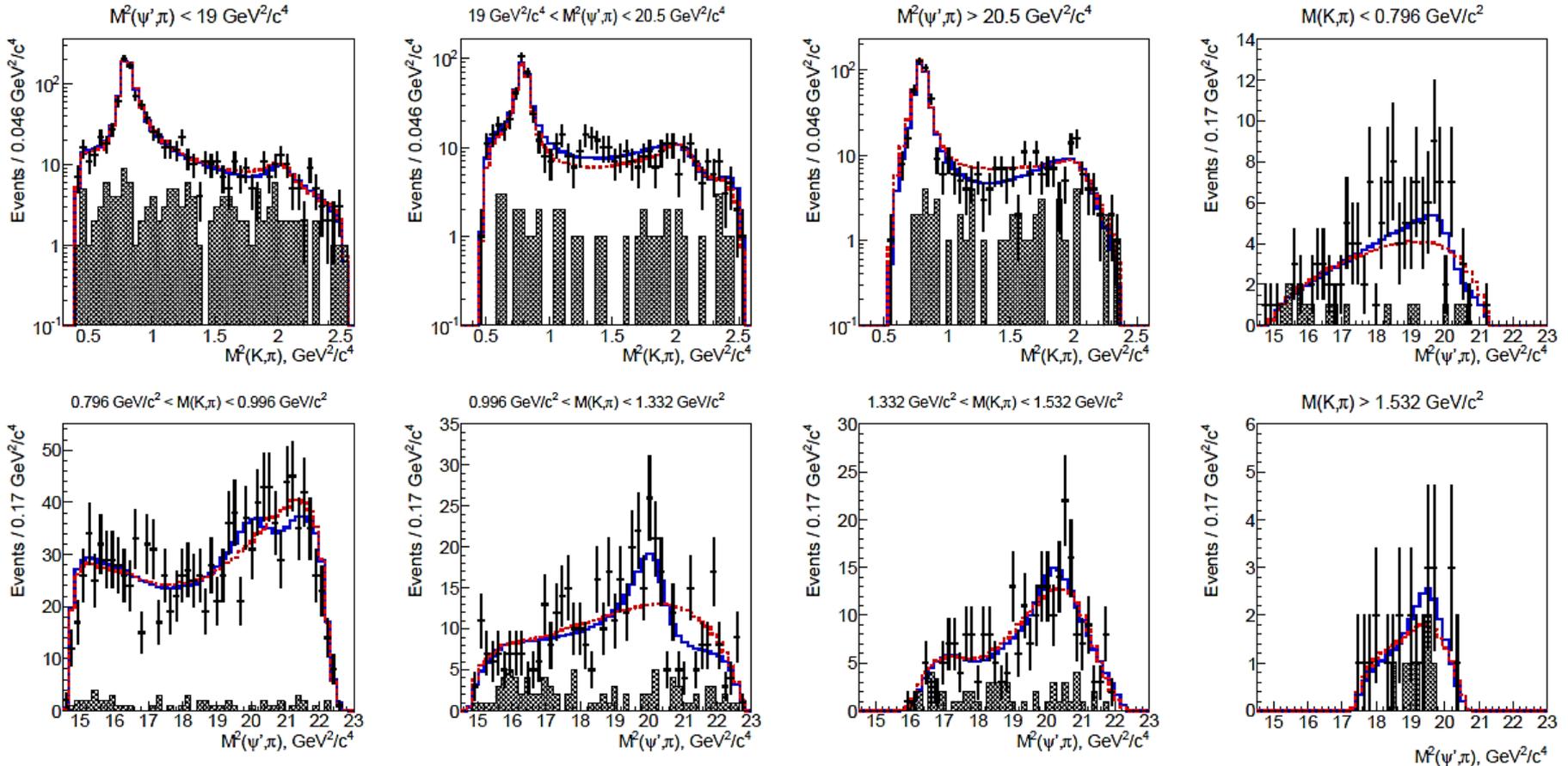
$$J^P = 0^- \qquad M = 4470\,^{+26\,+83}_{-30\,-23}\;\text{MeV} \qquad \Gamma = 139\,^{+52\,+17}_{-39\,-32}\;\text{MeV}$$

BaBar doesn't see a significant Z(4430)$^+$
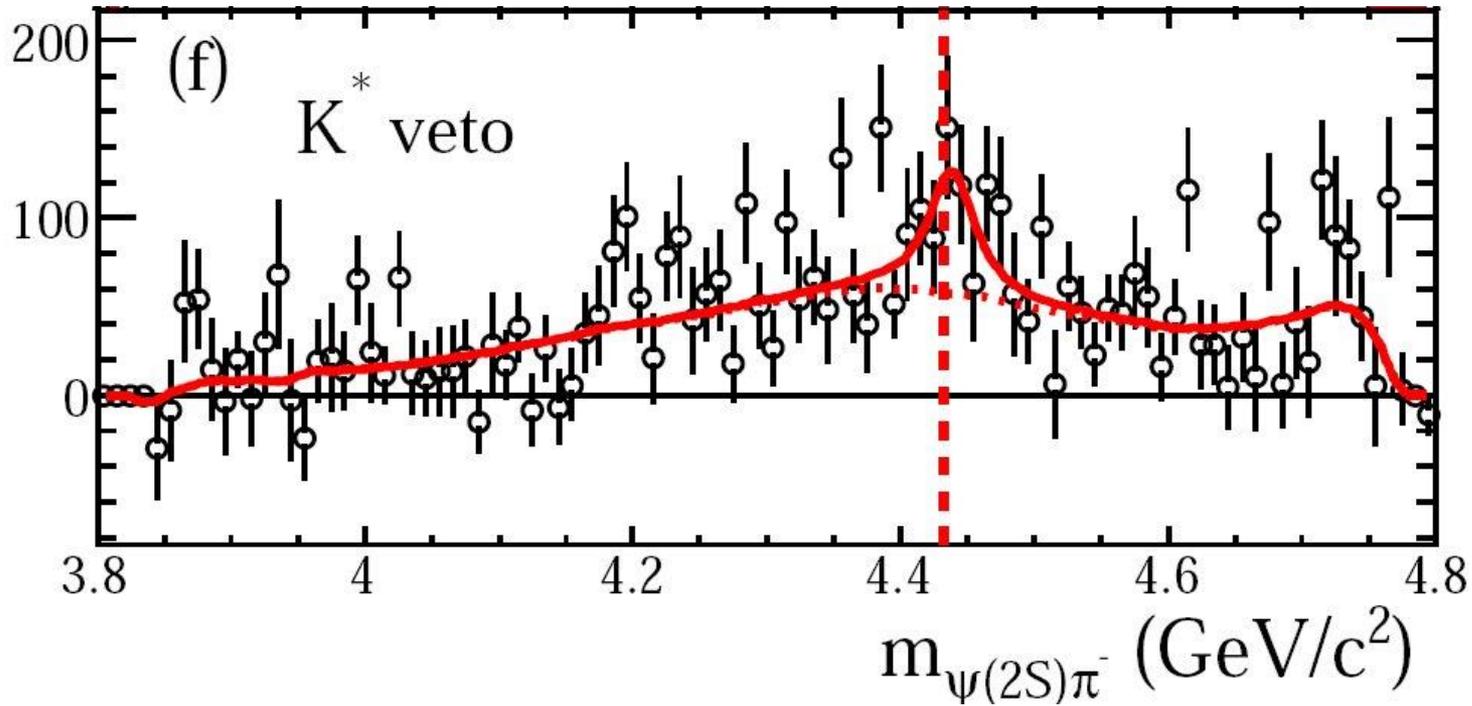
"For the fit … equivalent to the Belle analysis…we obtain mass & width values that are consistent with theirs,… but only ~1.9σ from zero; fixing mass and width increases this to only ~3.1σ."

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

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

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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 $Z \to \chi_{c1}\pi^{\pm}$

PRD 78, 072004 (2008)

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

Significance: 5.7σ
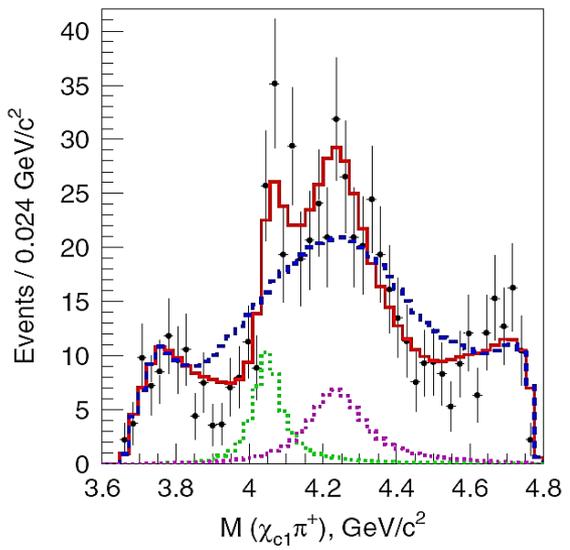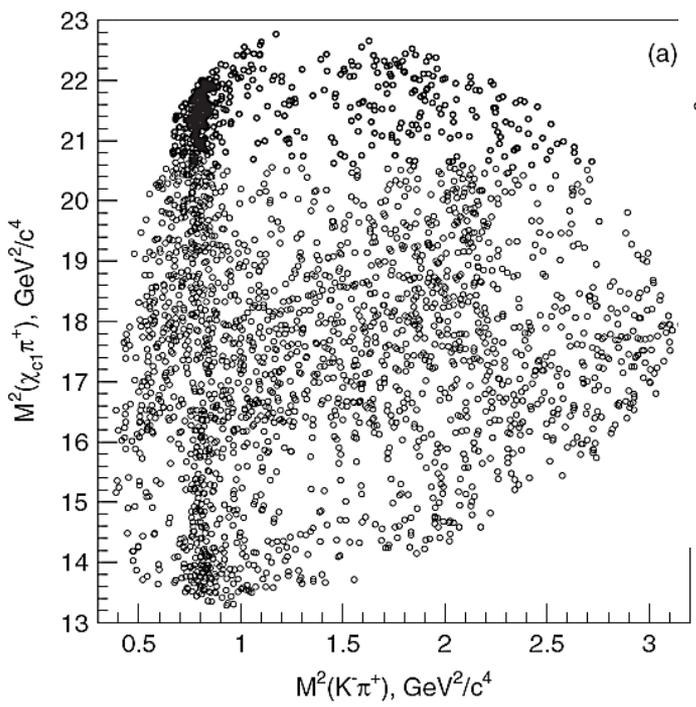
fit for model with K*'s
fit for double Z model
Z_1 contribution
Z_2 contribution

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

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

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

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

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

BaBar doesn't see significant $Z^{\pm} \to \chi_{c1}\pi^{\pm}$
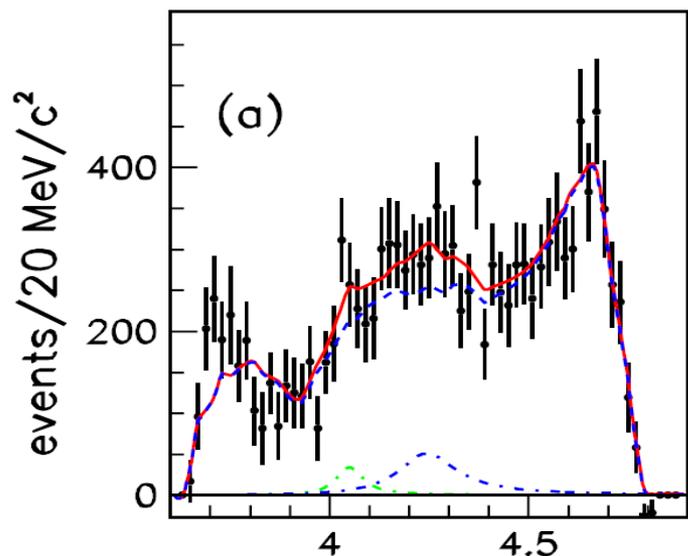
$$\mathcal{B}(\bar{B}^0 \to Z_1(4050)^+ K^-) \times \mathcal{B}(Z_1(4050)^+$$
$$\to \chi_{c1}\pi^+) < 1.8 \times 10^{-5},$$

Belle: $(3.0^{+1.5}_{-0.8}{}^{+3.7}_{-1.6}) \times 10^{-5}$

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

Belle: $(4.0^{+2.3}_{-0.9}{}^{+19.7}_{-0.5}) \times 10^{-5}$
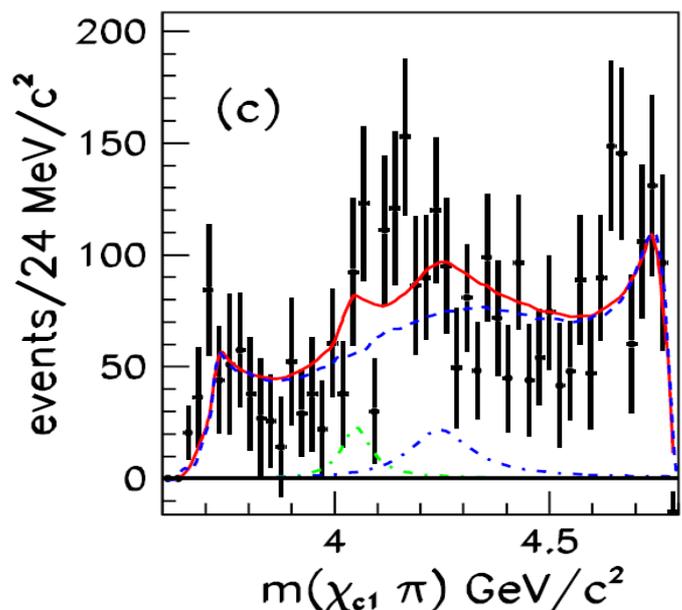
"We find that it is possible to obtain a good description of our data without the need for additional resonances in the $\chi_{c1}\pi$ system."

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M($\pi\pi$J/ψ)$\in$[4.2, 4.4] GeV via ISR

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

2007/02/14   16

M^2 -- π^+J/ψ or π^-J/ψ