

LATEST XYZ RESULTS FROM e^+e^- COLLIDERS



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BESIII

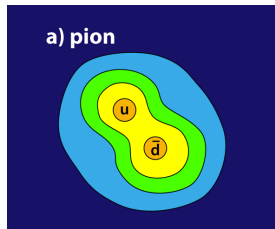
MESON2014, 29th May – 3rd June 2014

Kraków, Poland

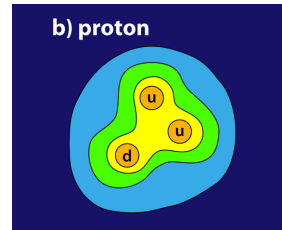
Hadrons

- Quark model:

Mesons

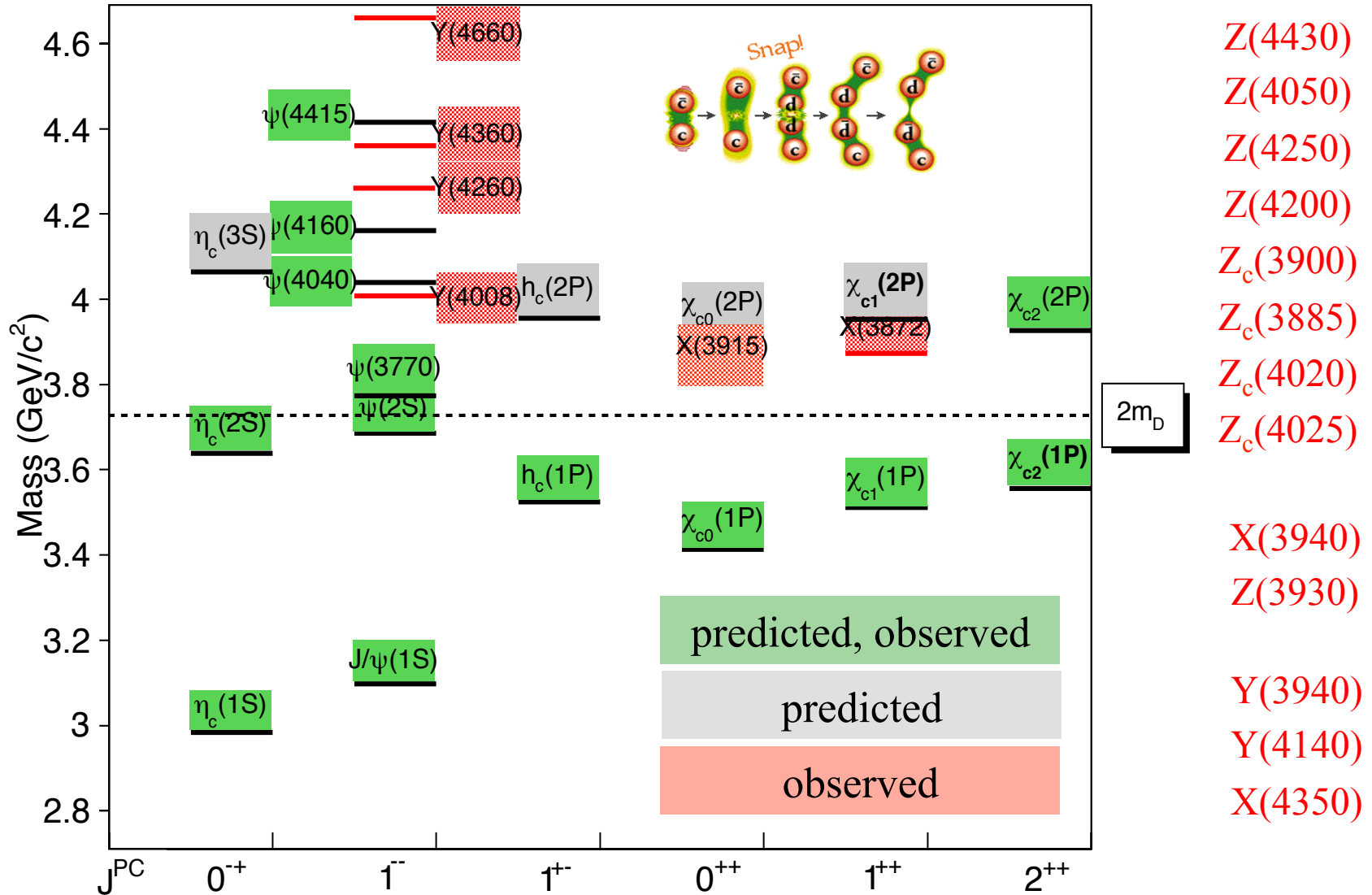


Baryons



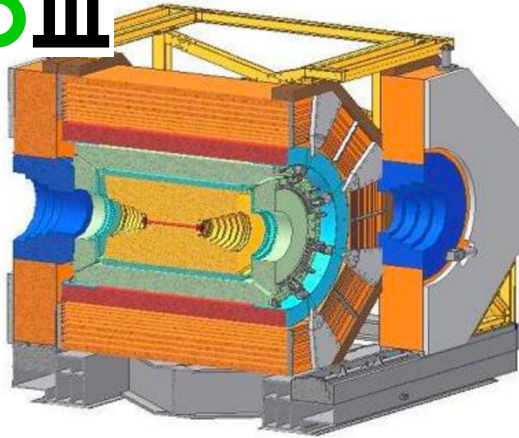
- Hadrons with other configurations not excluded:
 - Glueball: (gg, ggg, ...)
 - Hybrid: ($q\bar{q}g$, ...)
 - Multiquark state: ($qq\bar{q}\bar{q}$, $qqqq\bar{q}$, ...)
 - Molecule: bound state of two hadrons

Charmonium spectroscopy

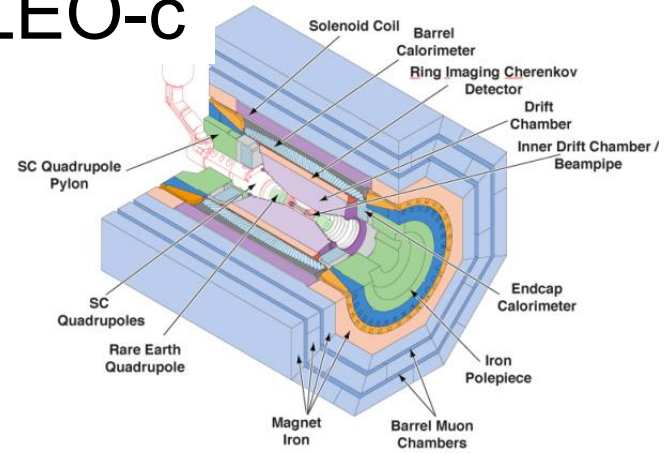


Experiments

BES III



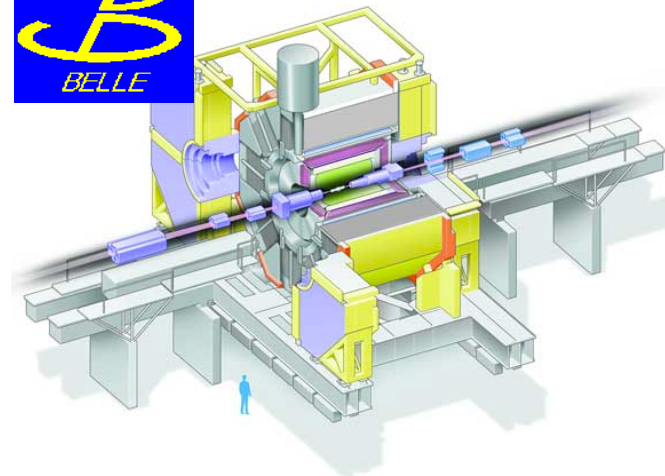
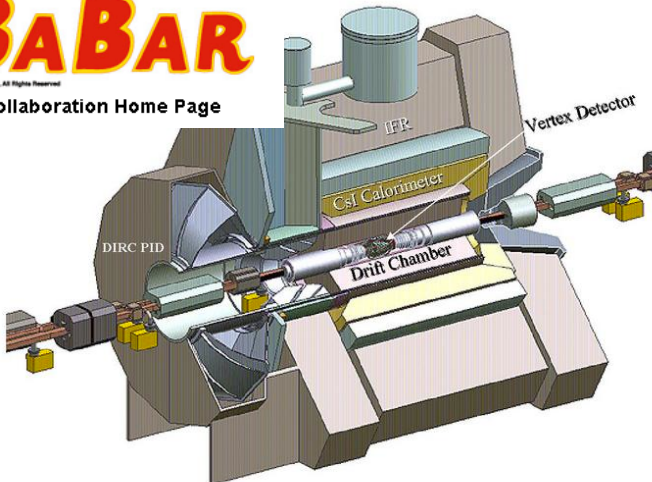
CLEO-c



BABAR

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Collaboration Home Page



LHCb, D0, CDF...

Data samples

Experiment	\sqrt{s}	Luminosity (fb^{-1})
BaBar	$\Upsilon(2S)$	14
	$\Upsilon(3S)$	30
	$\Upsilon(4S)$	433
	Off resonance	54
Belle	$\Upsilon(1S)$	6
	$\Upsilon(2S)$	25
	$\Upsilon(3S)$	3
	$\Upsilon(4S)$	711
	$\Upsilon(5S)$	121
	Off resonance/scan	100
BESIII	$\psi(4040)\text{@}4.009$	0.5
	$\Upsilon(4260)$	1.1+0.8
	$\Upsilon(4360)$	0.5
	$\psi(4415)\text{@}4.420$	1.0
	$\Upsilon(4660)\text{@}4.600$	0.6
	scan	1.6
CLEO-c	$\psi(4160)$	0.6

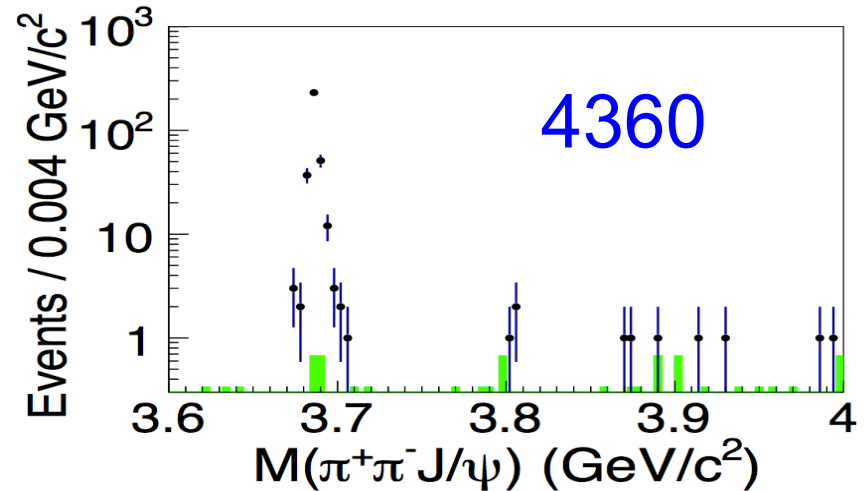
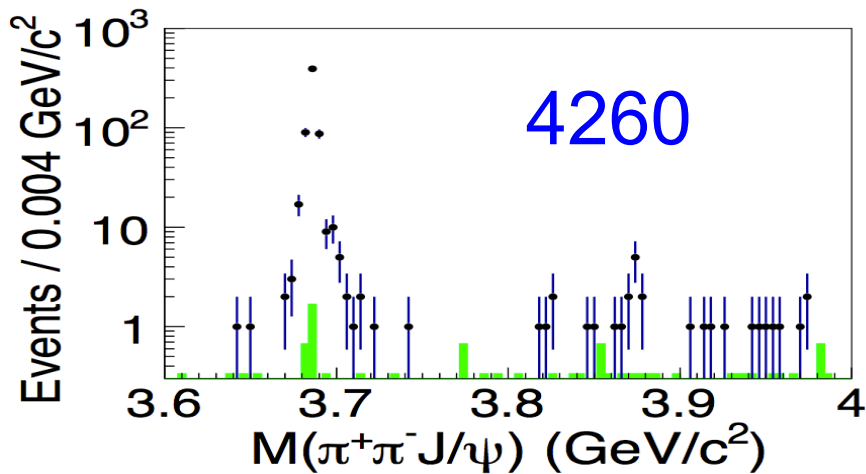
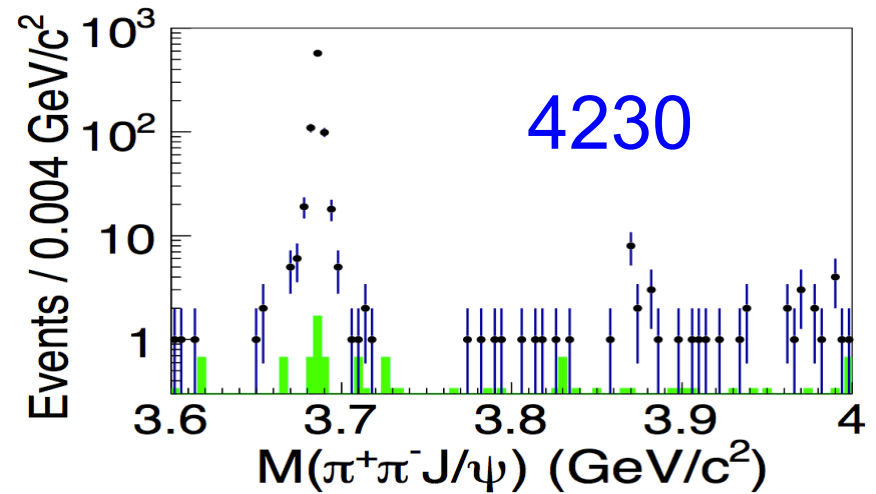
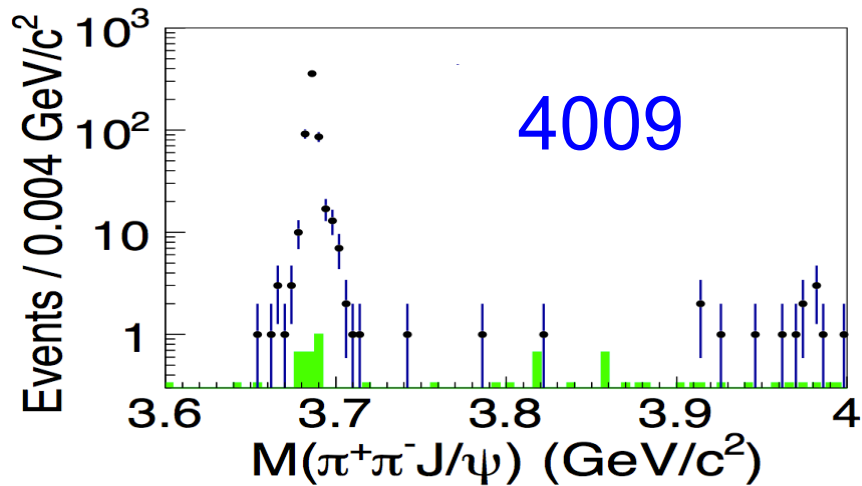
X(3872)

- Observed by Belle in $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ [PRL91,262001(2003)]
- Close to $D^0 \bar{D}^{*0}$ mass threshold, narrow peak
- $J^{PC}=1^{++}$ [CDF (PRL98,132002) $1^{++}/2^{-+}$; LHCb (EPJC72,1972) 1^{++}]
- Nature unclear:
 - $D^0 \bar{D}^{*0}$ bound state?
 - Mixture of $\chi_{c1}(2P)$ and $D^0 \bar{D}^{*0}$ bound state?
 - Conventional charmonium $\chi_{c1}(2P)$? tetraquark? hybrid?...
- Production
 - pp collision; B decays;
 - $Y(4260) \rightarrow \gamma X(3872)$ [BESIII, PRL112, 092001 (2014)]
- Decay: $\pi^+ \pi^- J/\psi$, $\pi^+ \pi^- \pi^0 J/\psi$, $D^0 \bar{D}^0 \pi^0$, $D^0 \bar{D}^{*0}$, $\gamma J/\psi$, $\gamma \psi'$

Observation of

$$e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma \pi^+ \pi^- J/\psi$$

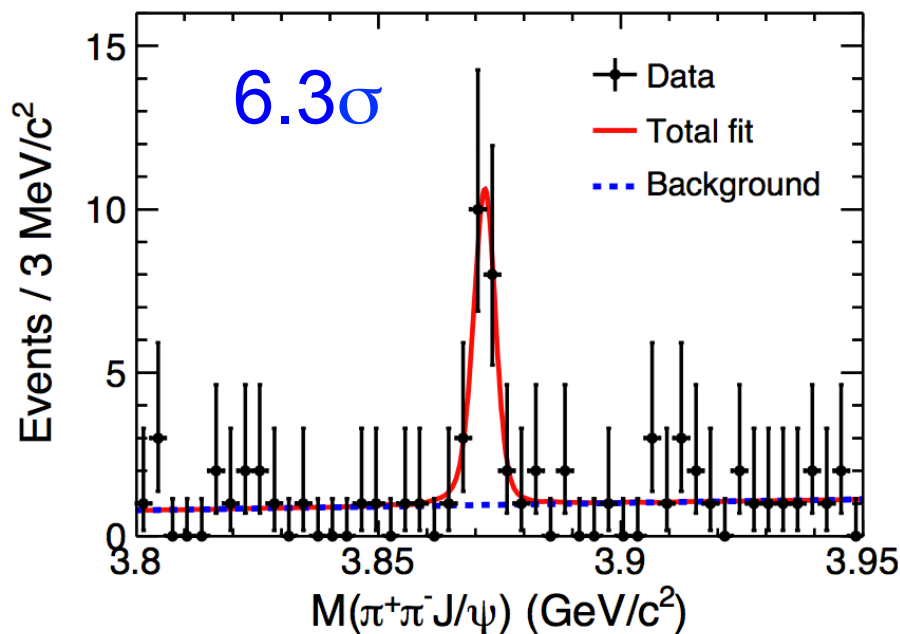
BESIII



Clear ISR ψ' signal for data validation; X(3872) signal at around 4.23-4.26 GeV

$e^+e^- \rightarrow \gamma X(3872)$, observation

[PRL 112, 092001 (2014)]

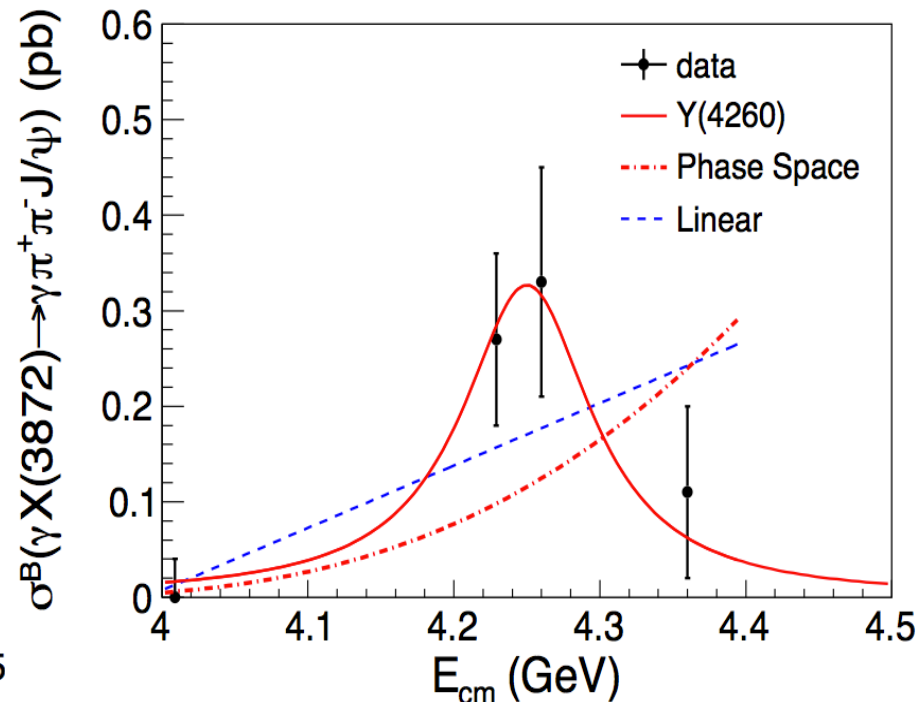


Obvious $X(3872)$ signal through radiative decay

$$N = 20.1 \pm 4.5;$$

$$M = 3871.9 \pm 0.7 \pm 0.2 \text{ MeV}$$

[PDG = $3871.68 \pm 0.17 \text{ MeV}$]



- Seems from $Y(4260)$ decays
- $\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7) \text{ pb}$;
 $B(X(3872) \rightarrow \pi^+\pi^- J/\psi) = 5\%$

$$\frac{\sigma(e^+e^- \rightarrow \gamma X(3872))}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} \sim 11\%$$

X(3872) radiative decays

- Radiative decays of X(3872) help to understand its nature
 - $X(3872) \rightarrow \gamma J/\psi$ determines its C-parity
 - Ratio (R) of $X(3872) \rightarrow \gamma \psi'$ to $\gamma J/\psi$:
 - Theoretical predictions:
 - $\overline{D}D^*$ molecule: $(3-4) \times 10^{-3}$
 - Charmonium: 1.2-15
 - Mixture: 0.5-5
 - Experimental measurements:
 - BaBar: 3.4 ± 1.4 , 3.5σ [PRL102, 132001 (2009)]
 - Belle: < 2.1 @ 90% C.L [PRL107, 091803 (2011)]
 - LHCb: $2.46 \pm 0.64 \pm 0.29$, 4.4σ arXiv:1404.0275

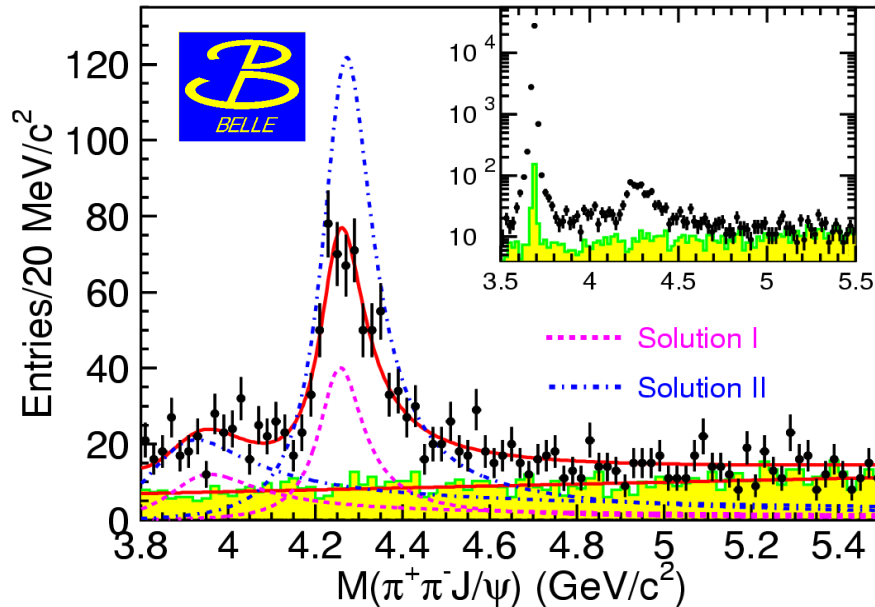
see Michal Kreps's talk this afternoon

Y states

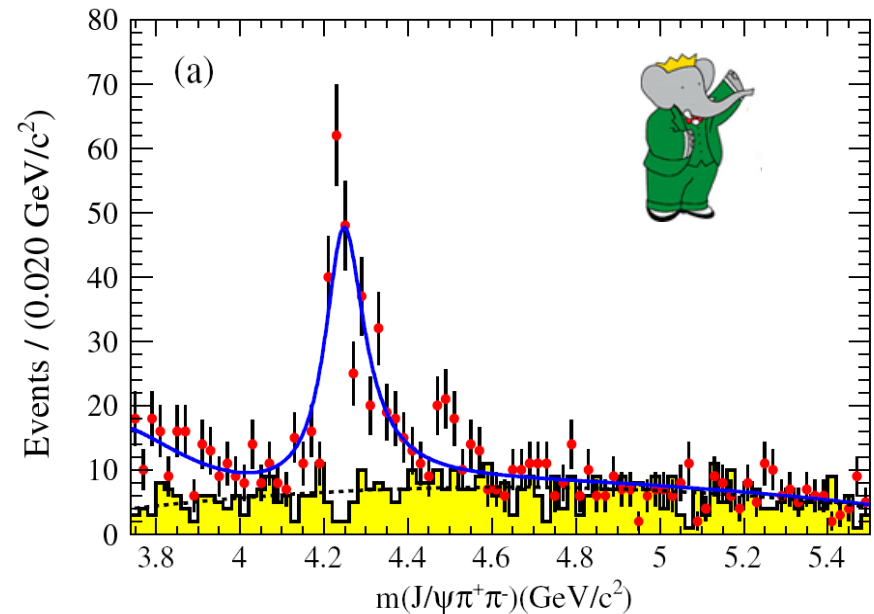
- Mainly from B factories through ISR processes
 - $Y(4260): e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi$
 - Observed by BaBar, confirmed by CLEO and Belle
 - $Y(4008): e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-J/\psi$ [PRL95,142001(2005)], 273 fb⁻¹
[PRD74,091104(R)(2006)], 13.3 fb⁻¹
[PRL99,182004(2007)], 548 fb⁻¹
 - Only in Belle data
 - $Y(4360): e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-\psi(2S)$
 - Observed by BaBar, confirmed by Belle
 - $Y(4660): e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-\psi(2S)$
 - Observed by Belle, confirmed by BaBar updated analysis
[PRL98,212001(2007)], 298 fb⁻¹
[PRL99,142002(2007)], 670 fb⁻¹
 - $Y(4630): e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$
 - Observed by Belle [PRL101,172001(2008)], 695 fb⁻¹

Y(4260) and Y(4008)

[PRL110,252002 (2013)], 967 fb⁻¹



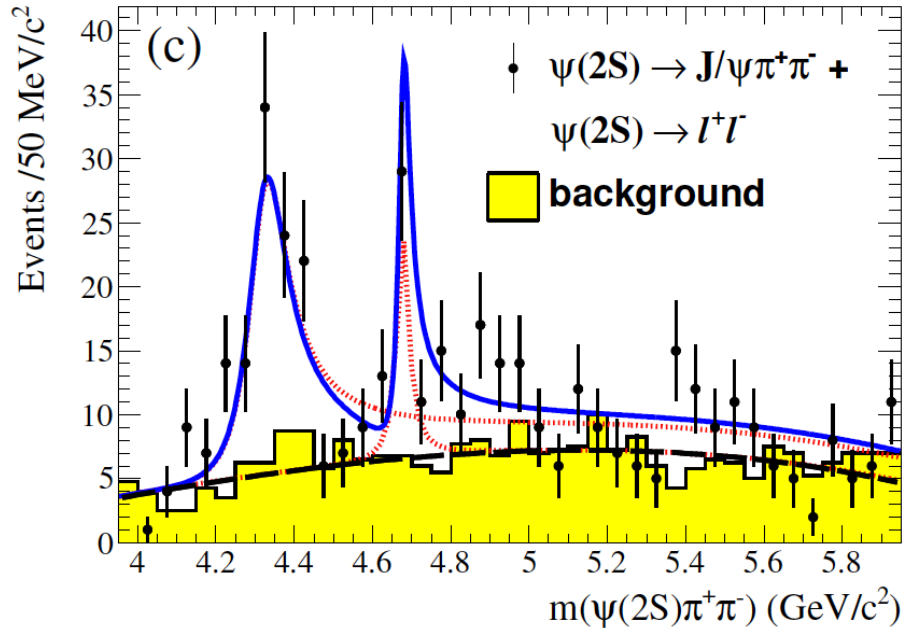
[PRD86,051102 (2012)], 454 fb⁻¹



- Both Belle and Babar updated results, consistent with previous measurements
- Discrepancy between two experiments still exist
- Fit formula different, two coherent resonances in Belle fit, exponential function explain tail of ψ' in BaBar fit

BESIII data could clarify

Confirmation of the $Y(4660)$

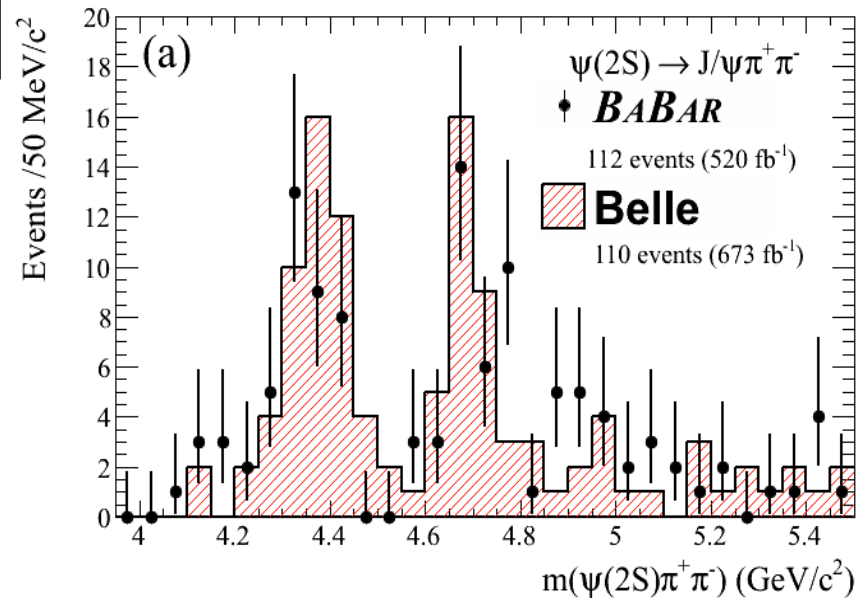


Result in good agreement
with Belle measurement

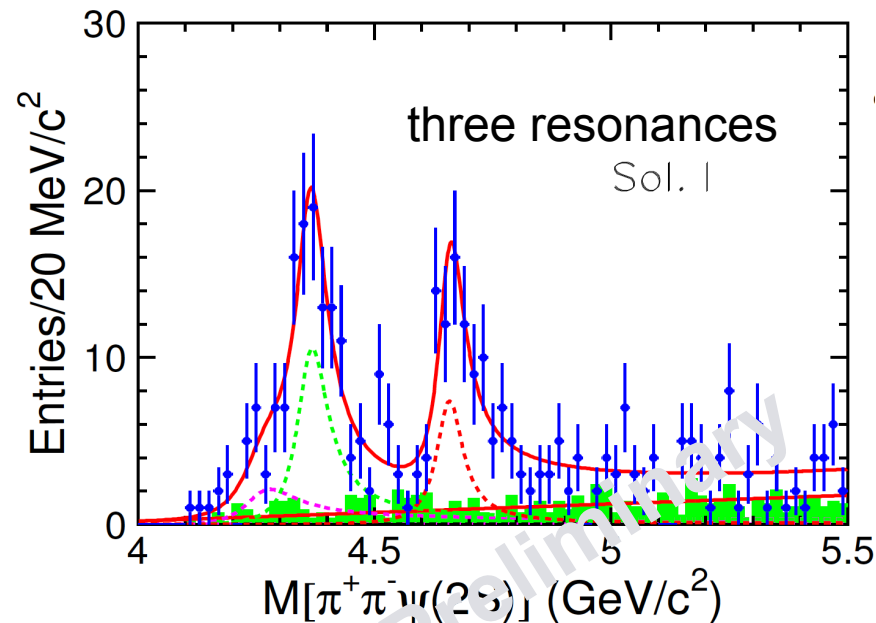
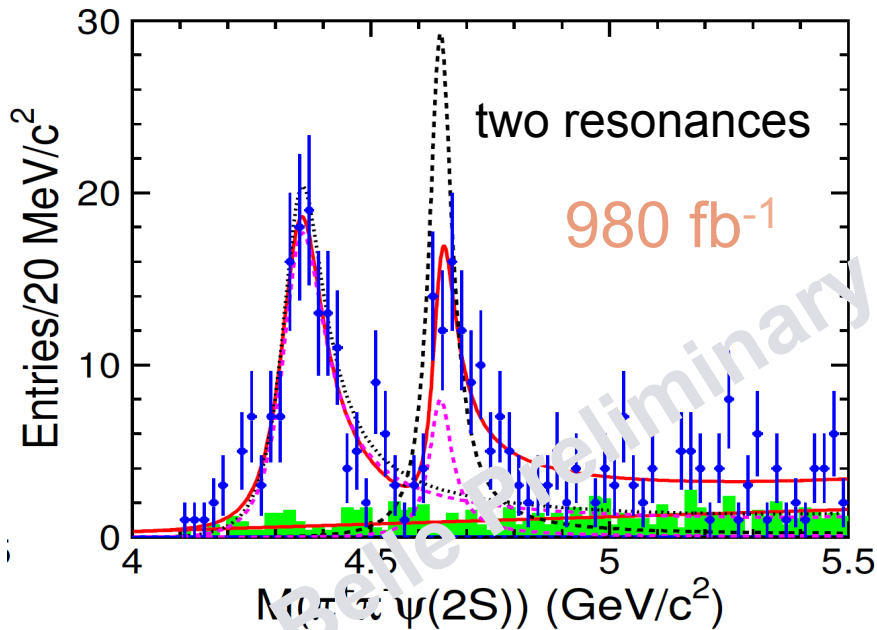
$Y(4660)$ confirmed!

arXiv1211.6271, 520 fb⁻¹

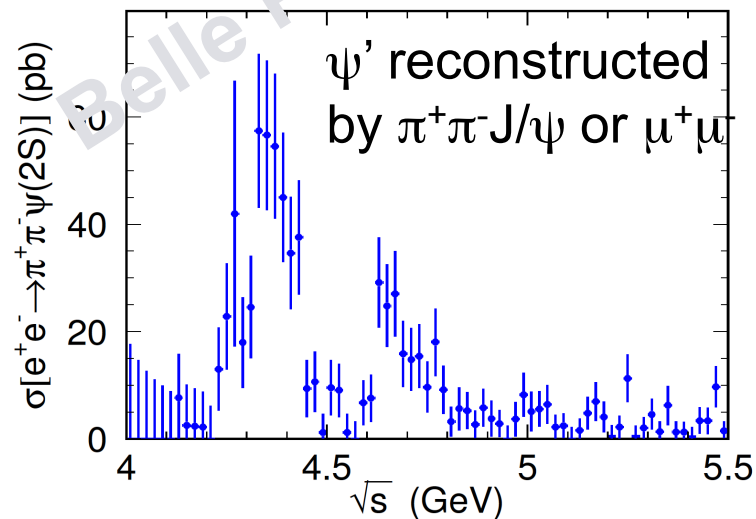
- ψ' reconstructed by $\pi^+ \pi^- J/\psi$ (dominate) or $\mu^+ \mu^-$
- Two resonances observed



Update of $\pi^+\pi^-\psi'$ at Belle



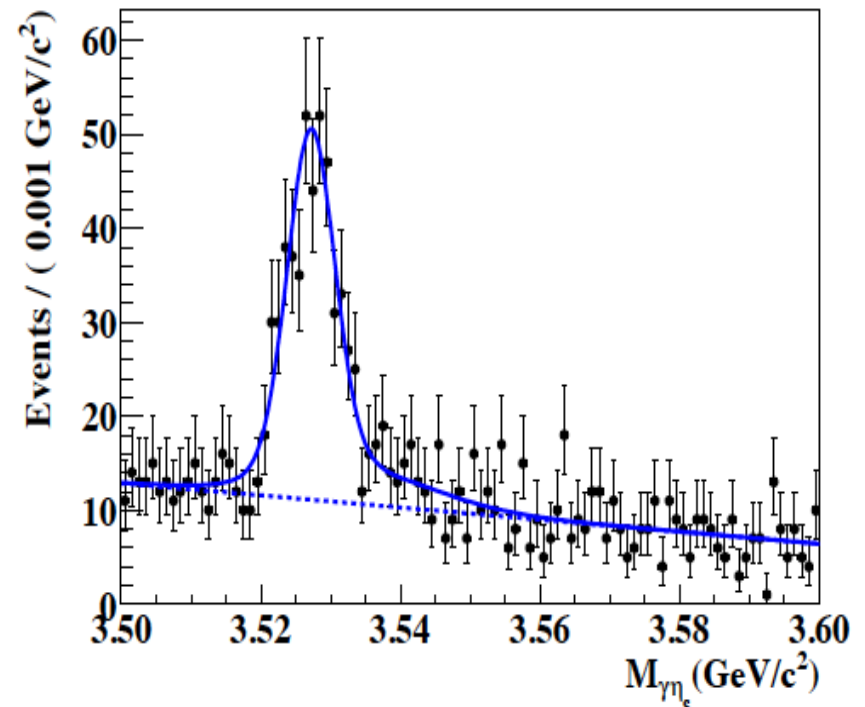
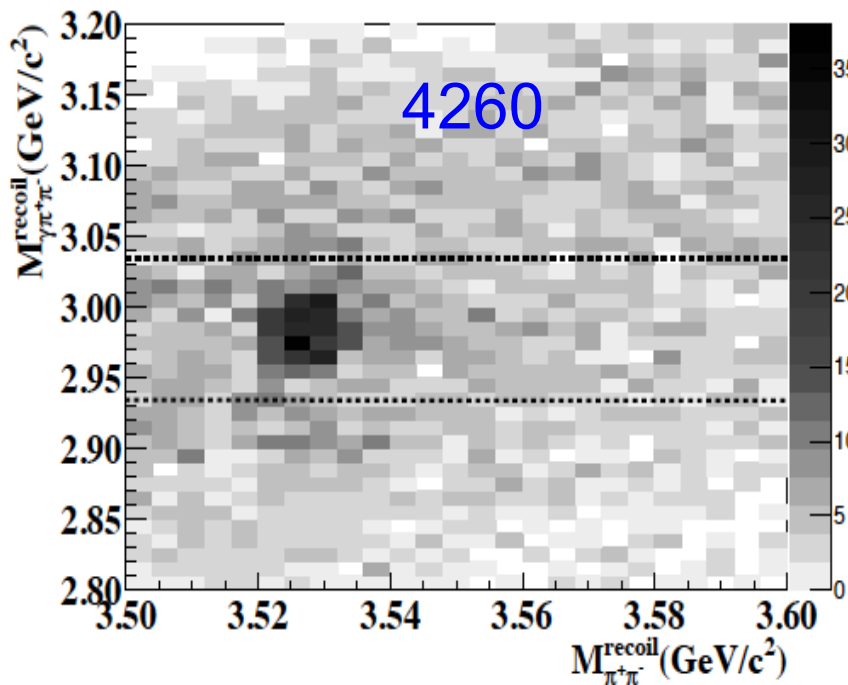
- Fit with two coherent resonances, mass of Y(4360) and Y(4660) smaller than previous results
- Add Y(4260) in the fit, significance 2.1 σ , change parameters of Y(4360) and Y(4660) obviously



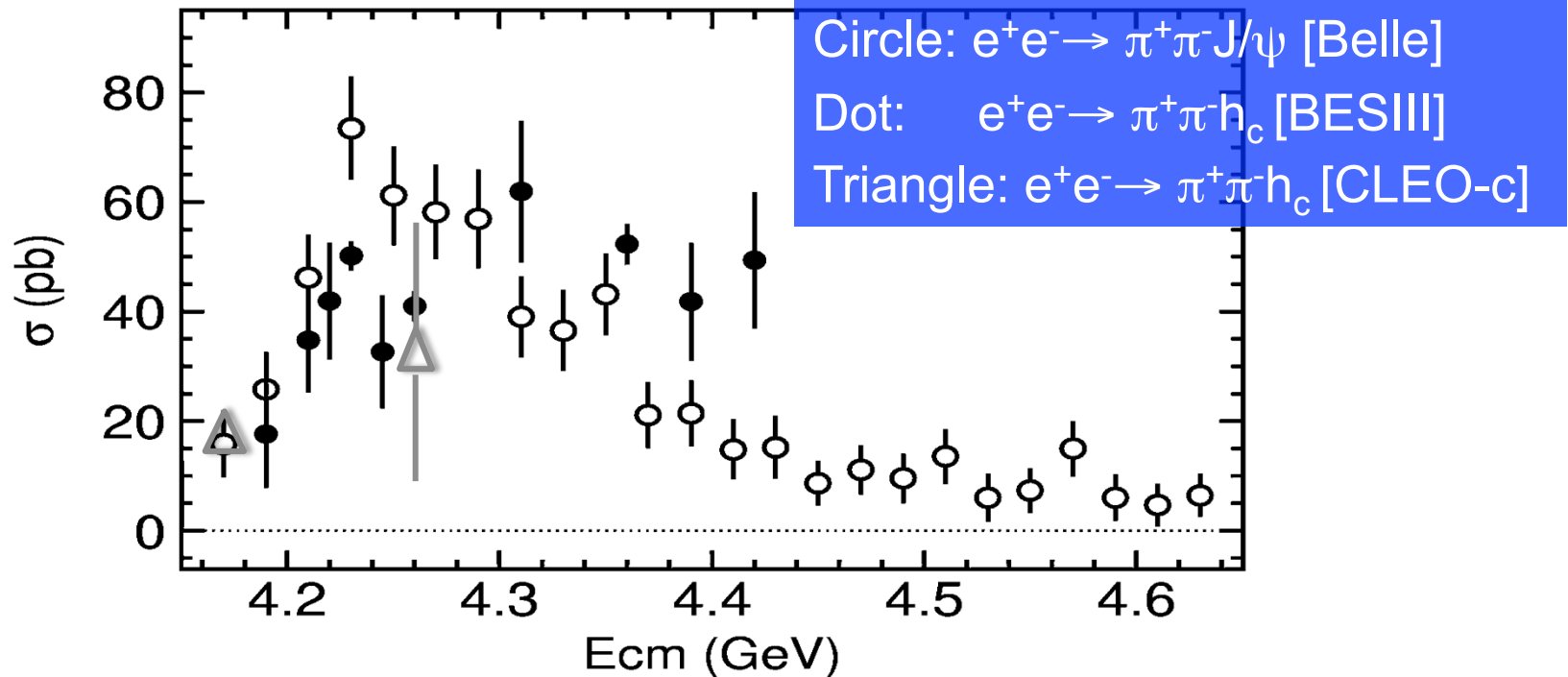
Cross section of $e^+e^- \rightarrow \pi^+\pi^-h_c$ BESIII

- 3.3 fb⁻¹ data at 13 energy points from 3900 MeV to 4420 MeV
 - $h_c \rightarrow \gamma\eta_c$, $\eta_c \rightarrow \text{hadrons}$
- [16 exclusive decay modes, ~35% of the η_c decays]

[PRL111,242001 (2013)]

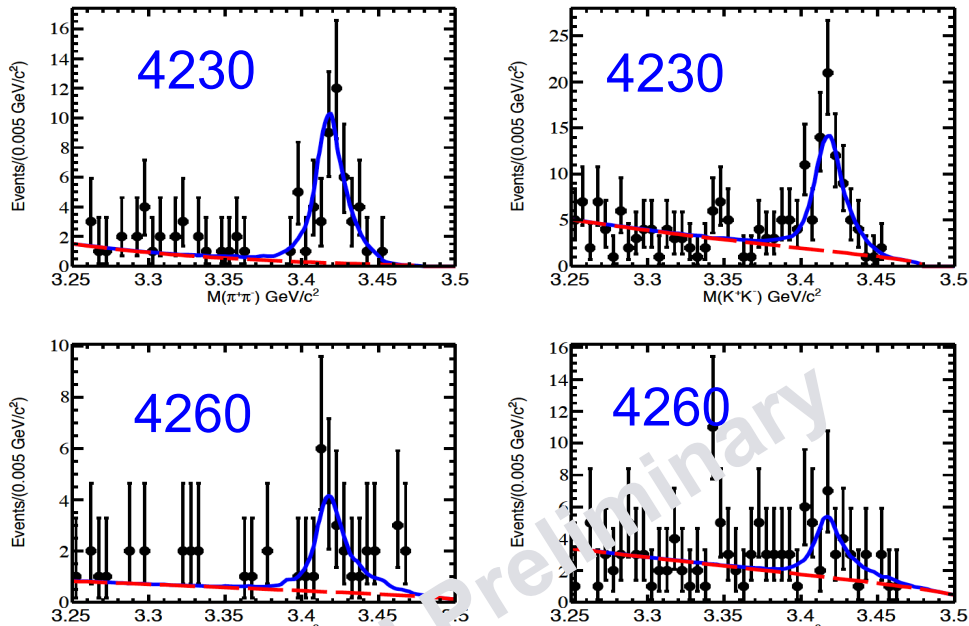


Comparison of $e^+e^- \rightarrow \pi^+\pi^-h_c$ and $\pi^+\pi^-J/\psi$

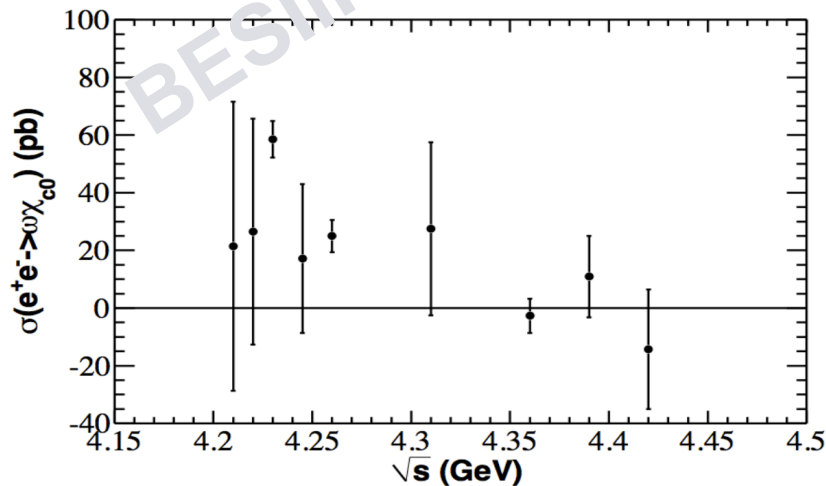


- $\sigma(e^+e^- \rightarrow \pi^+\pi^-h_c) \sim \sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi)$ but line shape different
- Local maximum ~ 4.23 GeV, broad structure at ~ 4.4 GeV?
- Hint for a vector $c\bar{c}g$ hybrid? [PRD78, 056003 (Guo); 094504 (Dudek)]

Cross section of $e^+e^- \rightarrow \omega\chi_{c0}$



- Data samples at 9 energy points from 4210 MeV to 4420 MeV
- $\omega \rightarrow \pi^+\pi^-\pi^0$;
- $\chi_{c0} \rightarrow \pi^+\pi^-/K^+K^-$
- Signal observed at 4230 MeV and 4260 MeV
- Simultaneous fit performed



Cross section peaks around 4230

Summary of Y states

- Above charm threshold, 5 states expected from potential model, but 7 observed in experiment
- $Y(4260)$, $Y(4360)$, and $Y(4660)$ have similar properties
 - narrow structure above charm threshold
 - not peak at $D^{(*)}\bar{D}^{(*)}$ cross section
- $e^+e^- \rightarrow \pi^+\pi^-h_c$ and $\omega\chi_{c0}$ (preliminary) cross section measured by BESIII
 - different line shape observed at $\pi^+\pi^-h_c$ process, makes situation complicate
- Molecule? Threshold effect? Hybrid?
→ Nature need to be understood

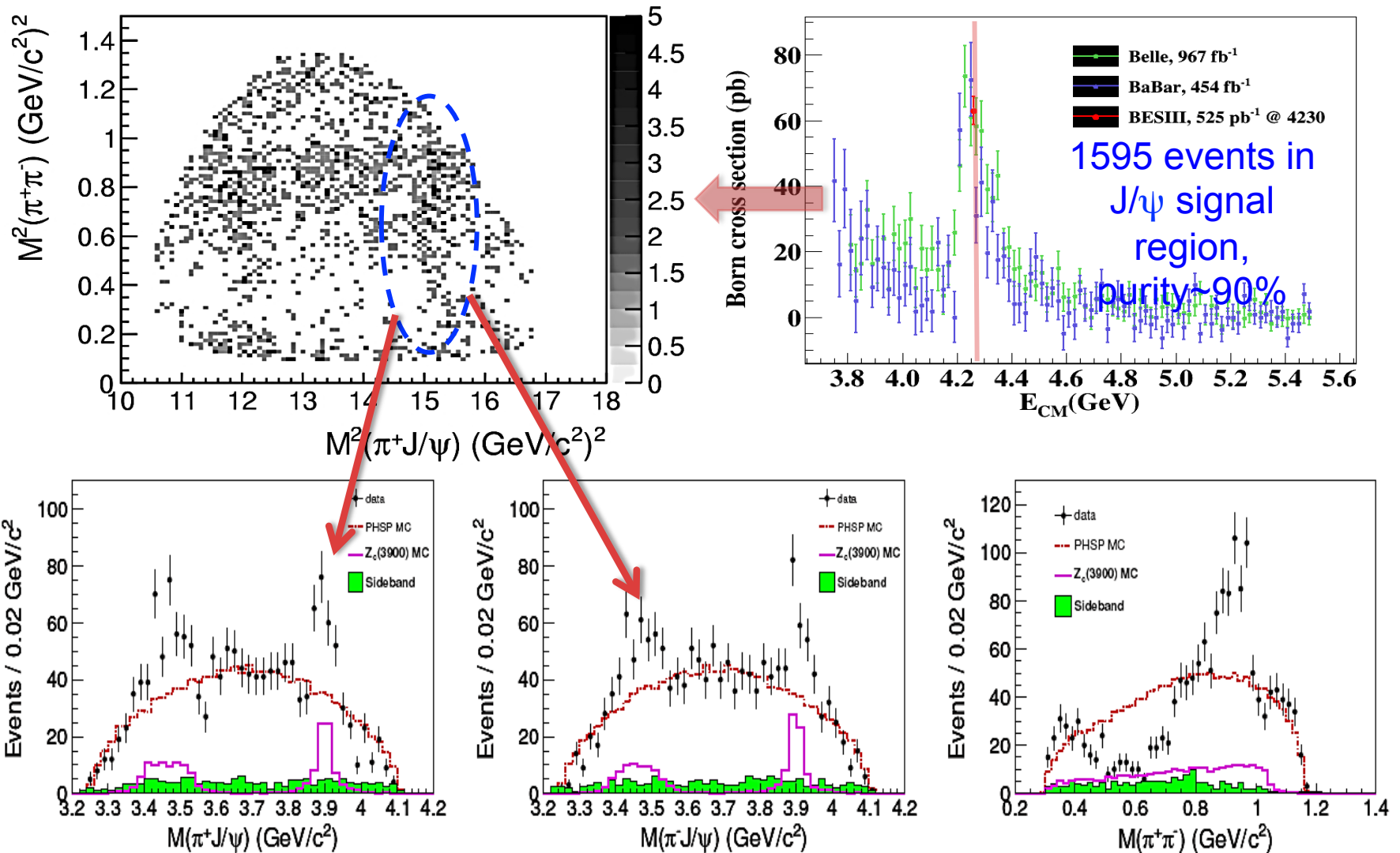
Charged charmonium-like states

- Decay into a charmonium, thus contains $c\bar{c}$
- Have electric charge, thus has two more light quarks
- Could exist in $\pi^\pm J/\psi$, $\pi^\pm \psi(2S)$, $\pi^\pm h_c$, $\pi^\pm \chi_{cJ}, \dots$
- Experimental search:
 - BESIII/CLEO-c: $e^+e^- \rightarrow \pi^\pm$ exotics, ...
 - Belle/BaBar: $e^+e^- \rightarrow (\gamma_{\text{ISR}})\pi^\pm$ exotics, ...
 - Belle/BaBar/LHCb: $B \rightarrow K$ exotics, ...

$e^+e^- \rightarrow \pi^+\pi^-J/\psi$ at BESIII

[PRL 110, 252001(2013)]

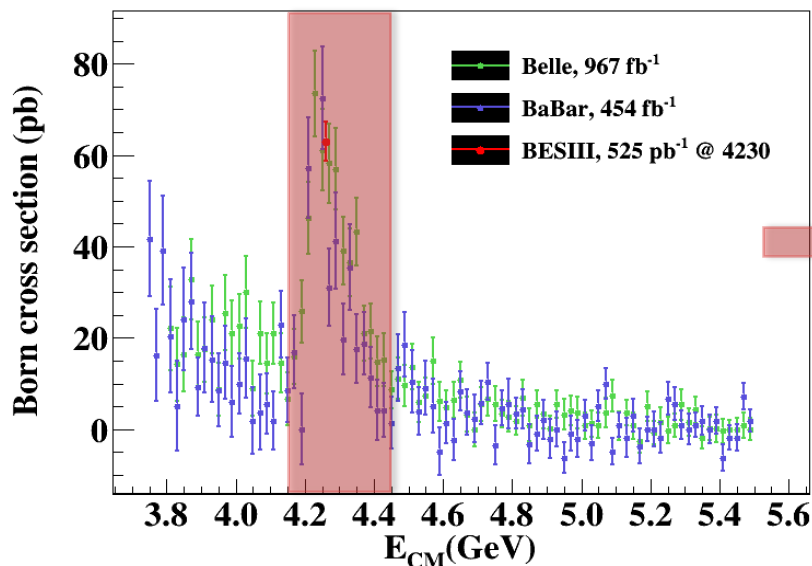
525 pb⁻¹ data at 4.260 GeV



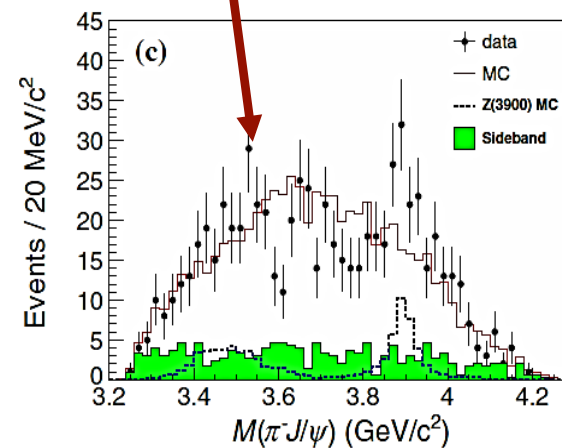
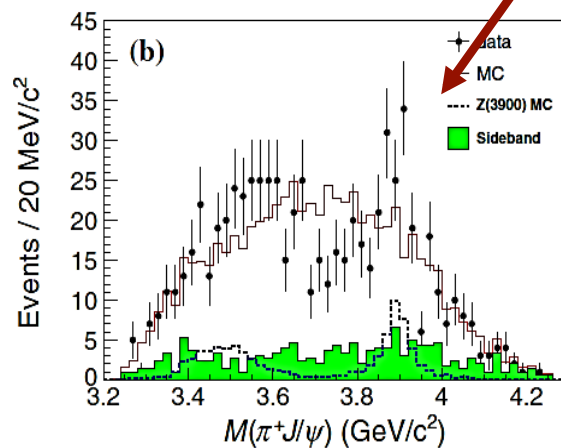
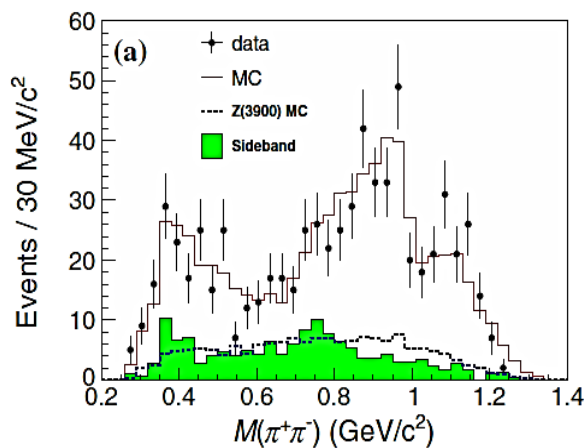
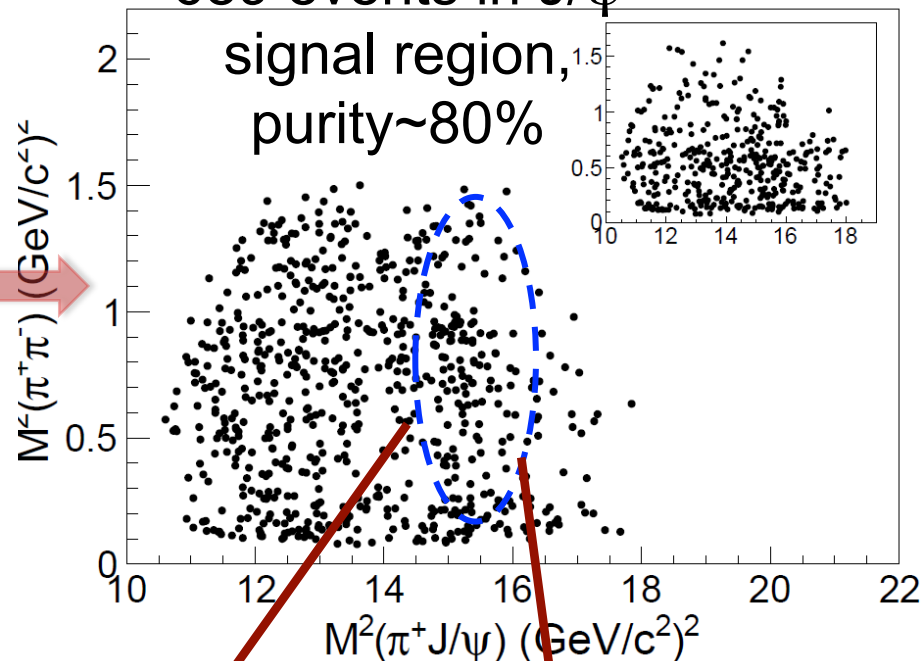
$e^+e^- \rightarrow \pi^+\pi^-J/\psi$ from ISR



[PRL 110, 252002 (2013)]

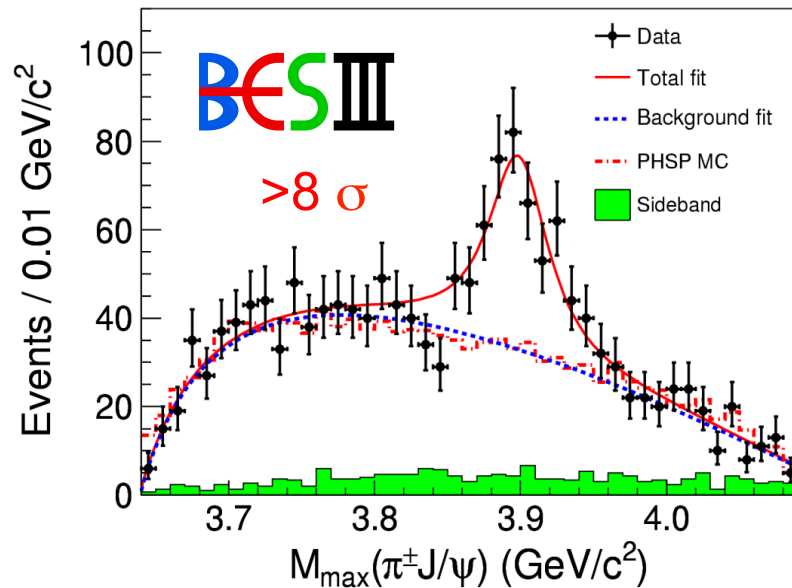


689 events in J/ψ



Observation of $Z_c(3900)$

BESIII: [PRL110, 252001(2013)]



$$M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}$$

$$\Gamma = 46 \pm 10 \pm 20 \text{ MeV}$$

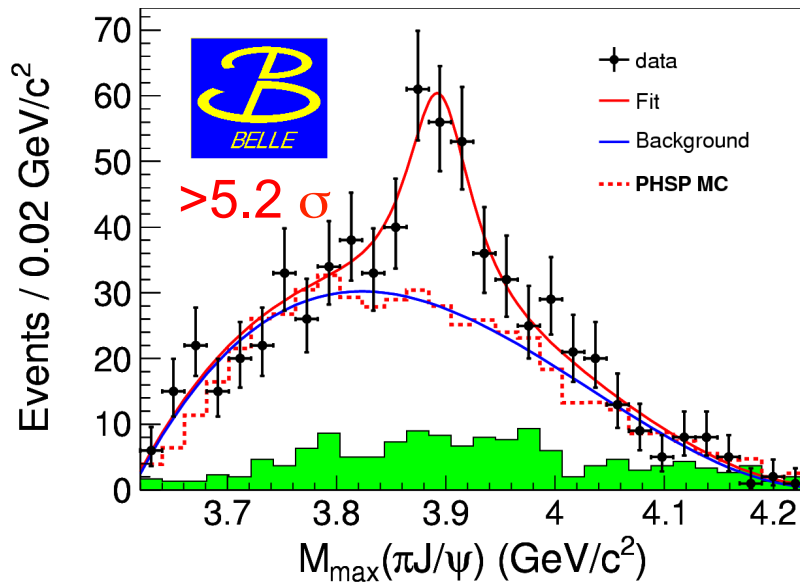
$$307 \pm 48 \text{ events}$$

BELLE: [PRL110, 252002 (2013)]

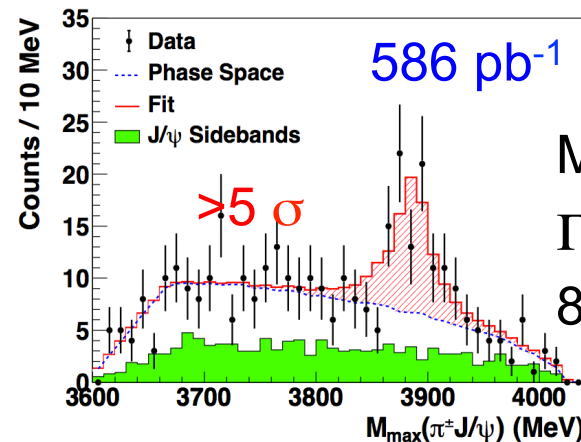
$$M = 3894.5 \pm 6.6 \pm 4.5 \text{ MeV}$$

$$\Gamma = 63 \pm 24 \pm 26 \text{ MeV}$$

$$159 \pm 49 \text{ events}$$



[PLB727, 366-370(2013)]



586 pb⁻¹ data at 4.170 GeV

$$M = 3886 \pm 4 \pm 2 \text{ MeV}$$

$$\Gamma = 37 \pm 4 \pm 8 \text{ MeV}$$

$$81 \pm 16 \text{ events}$$

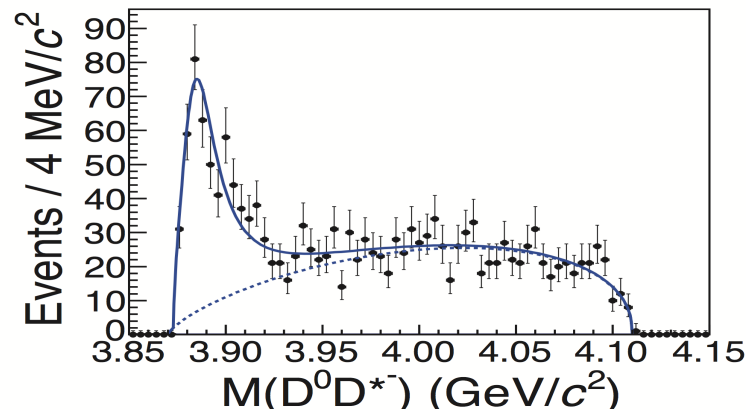
$e^+e^- \rightarrow \pi^- (D^* \bar{D})^+ + c.c.$

525 pb⁻¹ data at 4.260 GeV

[PRL112, 022001 (2014)]

Strategy:

- reconstruct $D^0 \rightarrow K^- \pi^+ / D^+ \rightarrow K^- \pi^+ \pi^+$; reconstruct “bachelor” π ; require D^* in the missing mass using kinematic fit; look at the recoil side of π



$$M = 3883.9 \pm 1.5 \pm 4.2 \text{ MeV}$$

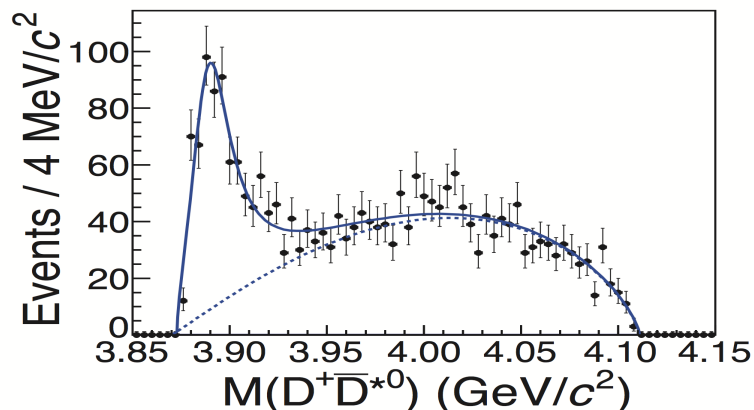
$$\Gamma = 24.8 \pm 3.3 \pm 11.0 \text{ MeV}$$

$$\sigma \times B = 85.3 \pm 6.6 \pm 22.0 \text{ pb}$$

Assuming $Z_c(3885)$ is $Z_c(3900)$

$$\frac{\Gamma(Z_c(3885) \rightarrow D \bar{D}^*)}{\Gamma(Z_c(3900) \rightarrow \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

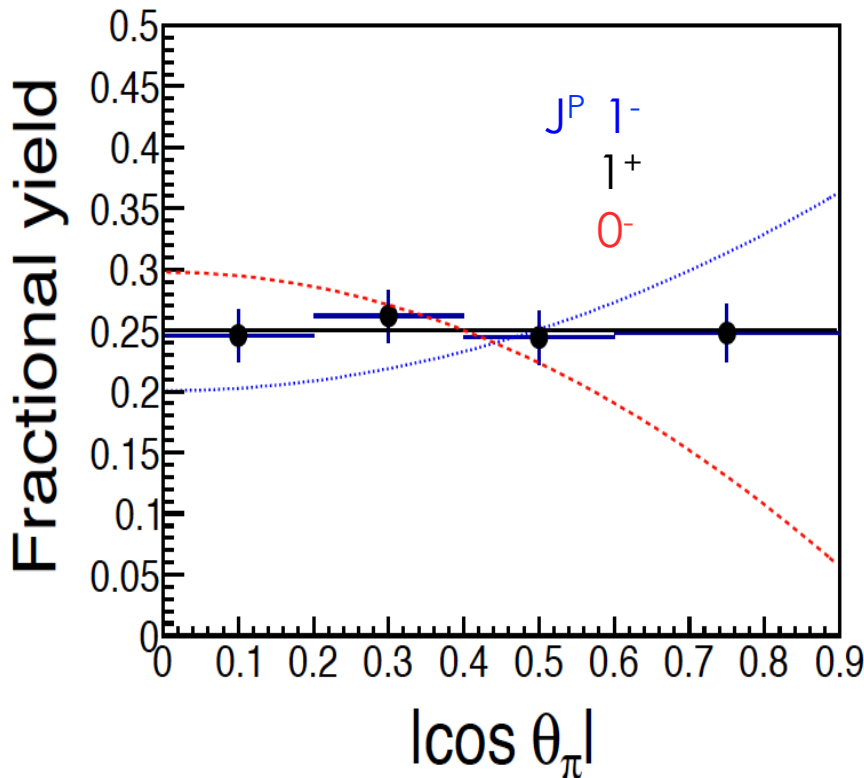
Large non- $D \bar{D}$ coupling



$e^+e^- \rightarrow \pi^- (D^* \bar{D})^+ + \text{c.c.}$

[PRL112, 022001 (2014)]

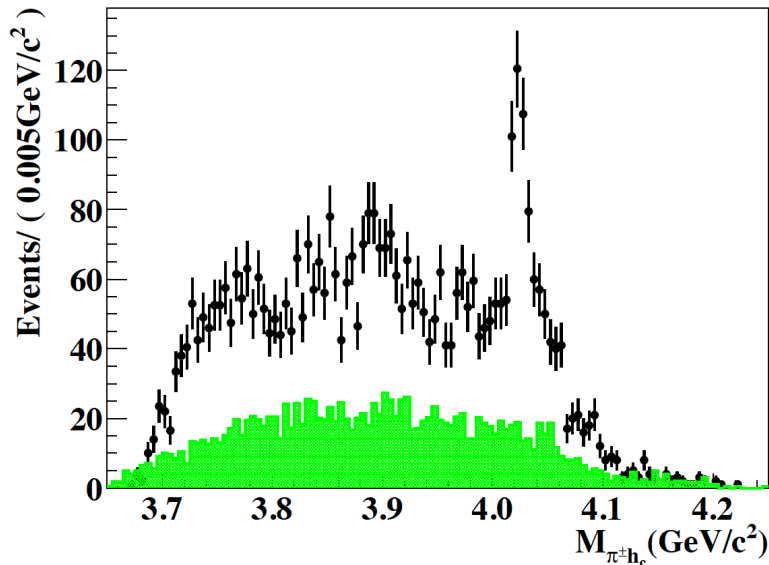
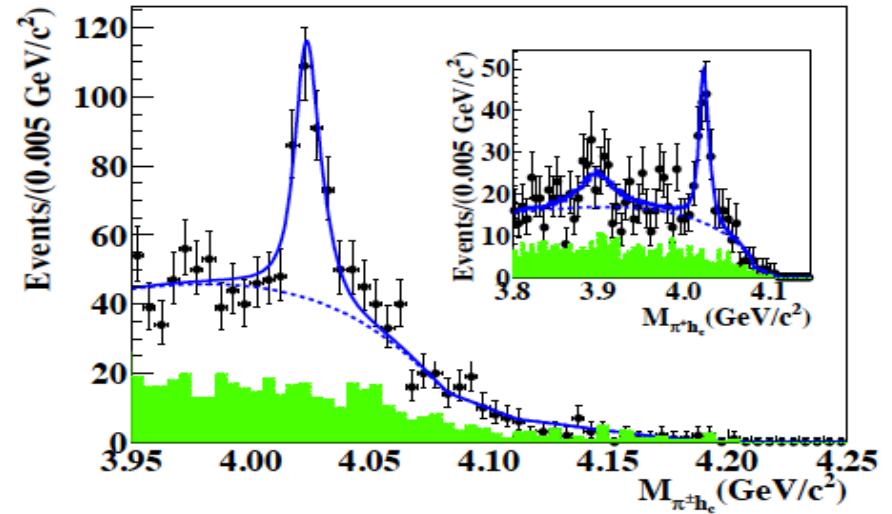
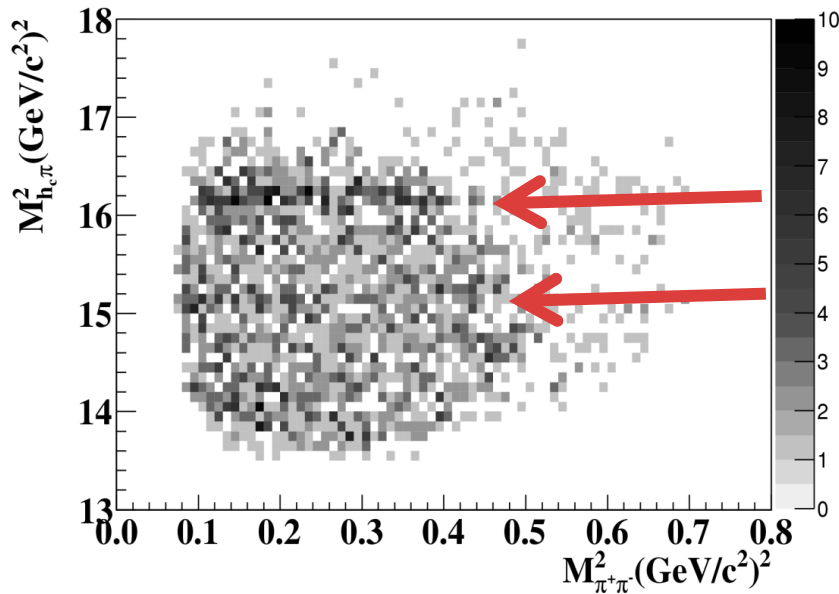
- $\cos\theta_\pi$:
 - bachelor pion's pole angle (relative to beam direction) in the CMS



- 0^- : P-wave, with $J_z = \pm 1$
 $\rightarrow \sin^2\theta_\pi$
- 0^+ : parity conservation
- 1^- : P-wave, $1 + \cos^2\theta_\pi$
- 1^+ : S-wave/D-wave, D-wave small contribution
 \rightarrow flat distribution
fits favor 1^+ assumption

Observation of $Z_c(4020)$

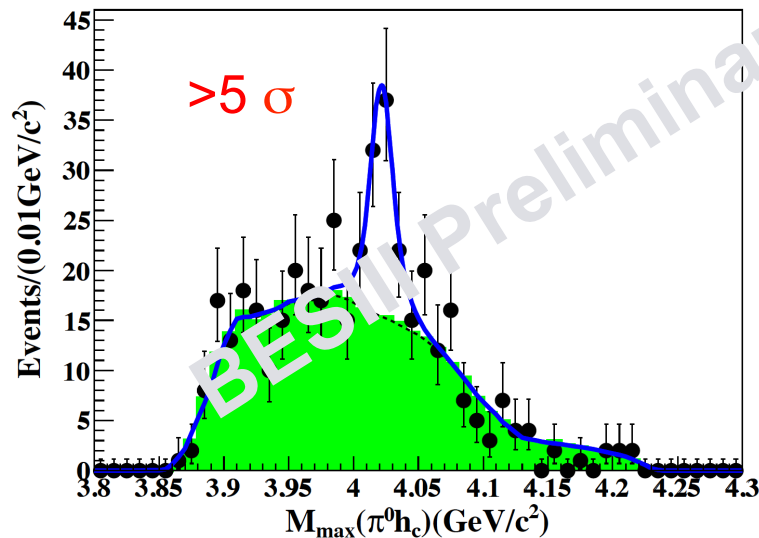
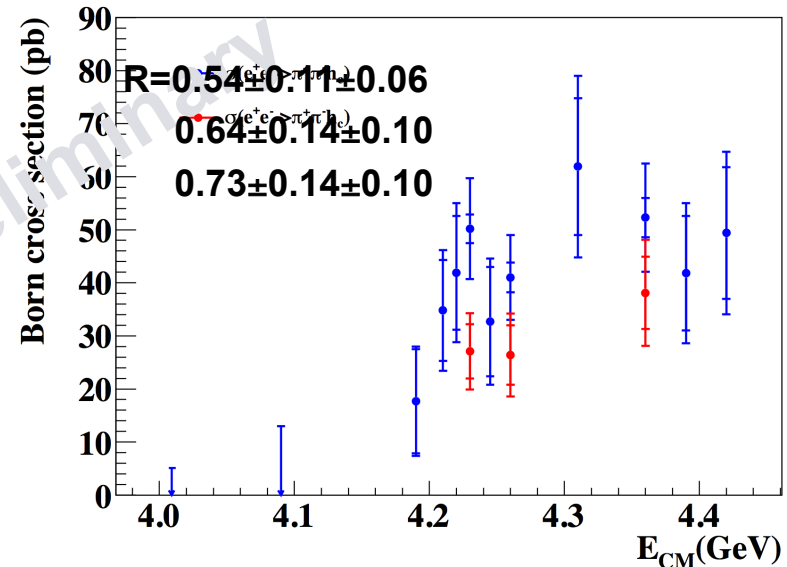
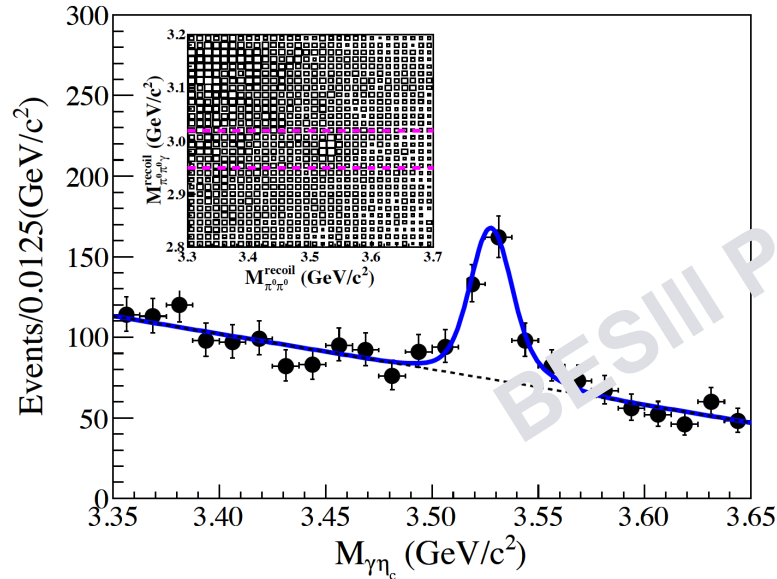
[PRL111, 242001 (2013)]



- Simultaneous fit to 4.23 /4.26/ 4.36 GeV data
- $M = 4022.9 \pm 0.8 \pm 2.7$ MeV;
- $\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV

$Z_c(4020)$: 8.9σ ; $Z_c(3900)$: 2.1σ

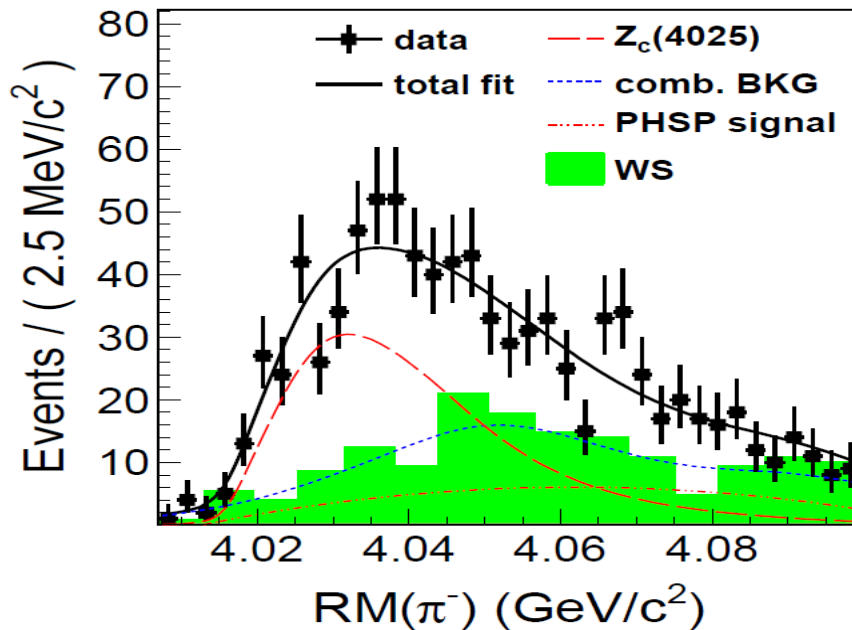
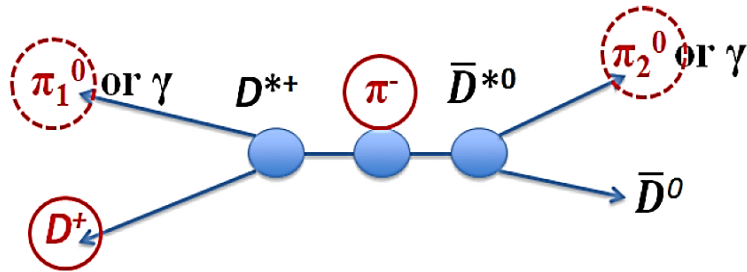
Neutral partner of $Z_c(4020)$



- Simultaneous fit to 4.23 /4.26/ 4.36 GeV data
- Width fixed to charged $Z_c(4020)$
- Interference neglect
- $M= 4023.6\pm2.2\pm3.9$ MeV;
 $[M= 4022.9\pm0.8\pm2.7$ MeV]

$Z_c(4025)$ in $D^* \bar{D}^*$

Strategy:



827 pb^{-1} data at 4.260 GeV

[PRL112, 132001 (2014)]

- Look at π^\pm recoil mass
- Events excess phase space, could be described by a state decay into $D^* \bar{D}^*$
- $N = 401 \pm 47$
- $M = 4026.3 \pm 2.6 \pm 3.7 \text{ MeV}$;
 $\Gamma = 24.8 \pm 5.6 \pm 7.7 \text{ MeV}$

Assuming $Z_c(4025)$ is $Z_c(4020)$

$$\frac{\Gamma(Z_c(4025) \rightarrow D^* \bar{D}^*)}{\Gamma(Z_c(4020) \rightarrow \pi h_c)} = 12 \pm 5$$

Z(4430)

- First observation: [PRL100, 142001 (2008)]
 - Belle, $B \rightarrow K\pi^\pm\psi(2S)$, 605 fb⁻¹ data at Y(4S)
 - Fit to the mass spectrum of $\pi^\pm\psi(2S)$, 6.5 σ
- Not confirmed by BaBar, found data can be explained by K* reflections: [PRD79, 112001 (2009)]
 - 413 fb⁻¹ data at Y(4S), two dimensional analysis
- Updated Belle results:
 - Two dimensional analysis using 605 fb⁻¹ data at Y(4S)
 - Four dimensional amplitude analysis with 711 fb⁻¹ data at Y(4S), Z(4430) favor 1⁺ over 0⁻, 1⁻, 2⁻, 2⁺ at level of 3.4 σ , 3.7 σ , 4.7 σ , 5.1 σ
 - Both confirmed previous Z(4430), measured a larger width

[PRD80, 031104(R) (2009)]

[PRD88, 074026 (2013)]

Updated Belle results



[PRD88, 074026 (2013)]

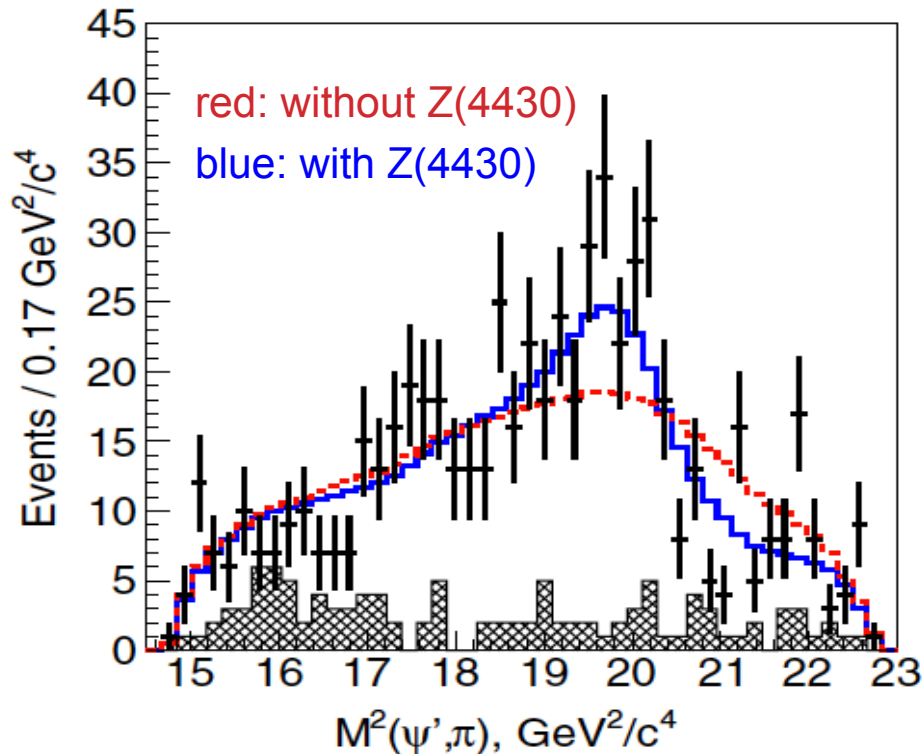
711 fb⁻¹ data

722 × 10⁶ BBbar pair

$B^0 \rightarrow \psi' K^+ \pi^-$, $\psi' \rightarrow l^+ l^-$

Four dimensional analysis:

$\Phi = (M_{K\pi}^2, M_{\psi'\pi}^2, \theta_{\psi'}, \varphi)$



$M = 4485 \pm 22^{+28}_{-11}$ MeV; $\Gamma = 200^{+41}_{-46} {}^{+26}_{-35}$ MeV

Mass a little bit higher, width much larger

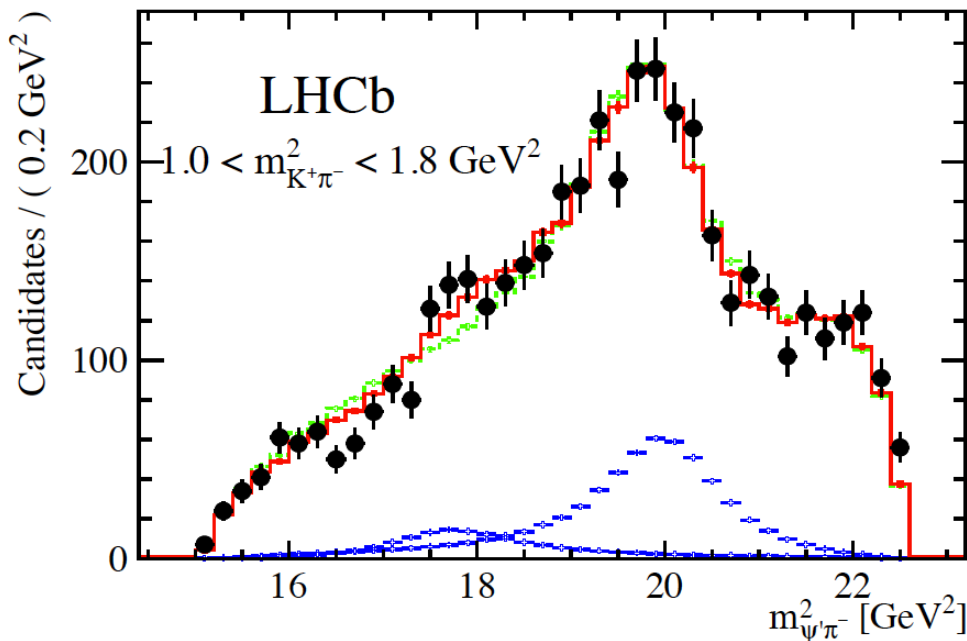
Favor 1⁺ over other assumptions with 3.4σ

Observation of $Z(4430)$ at LHCb



$25176 \pm 174 B^0 \rightarrow \psi' K^+ \pi^-, \psi' \rightarrow \mu^+ \mu^-$

arXiv1404.1903, 3 fb⁻¹



Four dimensional analysis:
 $\Phi = (M_{K\pi}^2, M_{\psi'\pi}^2, \theta_{\psi'}, \varphi)$

Significance: $> 13.9\sigma$

$M = 4475 \pm 7^{+15}_{-25} \text{ MeV}; \quad \Gamma = 172 \pm 13^{+37}_{-34} \text{ MeV}$

Mass and width consistent with Belle latest result

$J^{PC} = 1^+$

Summary of the Z states

State	Mass (MeV/c ²)	Width (MeV)	Note
$Z_c(3900)^\pm$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	BESIII
	$3894.5 \pm 6.6 \pm 4.5$	$63 \pm 24 \pm 26$	Belle
	$3886 \pm 4 \pm 2$	$37 \pm 4 \pm 8$	CLEO-c*
	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$	BESIII
	<u>3888.7 ± 2.7</u>	<u>34.7 ± 6.6</u>	<u>Average</u>
$Z_c(4020)^{\pm,0}$ BESIII	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$\pi^\pm h_c$
	$4026.3 \pm 2.6 \pm 2.7$	$24.8 \pm 5.6 \pm 7.7$	$D^* D^*$
	$4023.6 \pm 2.3 \pm 3.9$	-	$\pi^0 h_c$
	<u>4023.8 ± 2.1</u>	<u>10.2 ± 3.5</u>	<u>Average</u>
$Z(4430)^-$	$4485 \pm 22^{+28}_{-11}$	$200^{+41}_{-46} {}^{+26}_{-35}$	Belle
	$4475 \pm 7^{+15}_{-25}$	$172 \pm 13^{+37}_{-34}$	LHCb
	<u>4478 ± 21</u>	<u>181 ± 33</u>	<u>Average</u>

At least
4-quarks;
Charged;
Near
threshold;

Summary

- Lots of progress in XYZ studies from different experiment
- X(3872):
 - $J^{PC}=1^{++}$; Observed in $Y(4260)\rightarrow\gamma X(3872)$
 - Ratio of $X(3872)\rightarrow\gamma\psi'$ to $X(3872)\rightarrow\gamma J/\psi$ disfavor molecule explanation
- 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 at BESIII; observstion of $\omega\chi_{c0}$ at BESIII
- Charged Z states:
 - Confirmed exotic state with at least four quarks, $Z_c(3900)$, at BESIII & Belle
 - Observation of charged and neutral Z_c' at BESIII
 - Z(4430) confirmed by LHCb, quantum number favor 1^+
- More results will come soon

THANKS FOR THE ATTENTION!

BACKUP

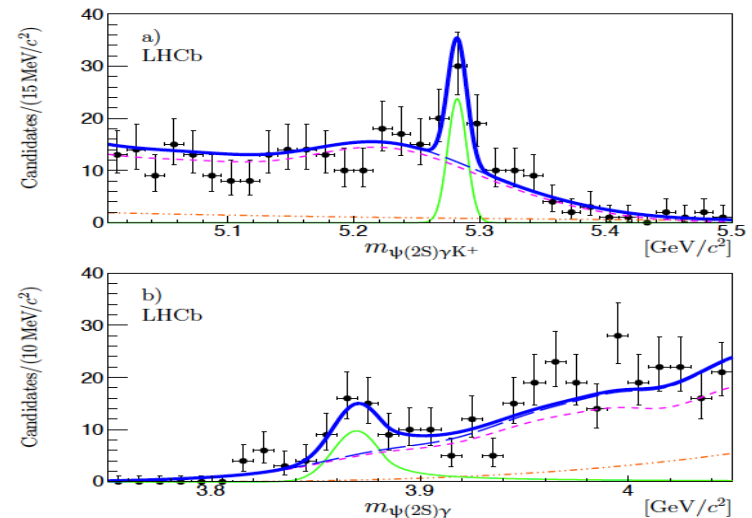
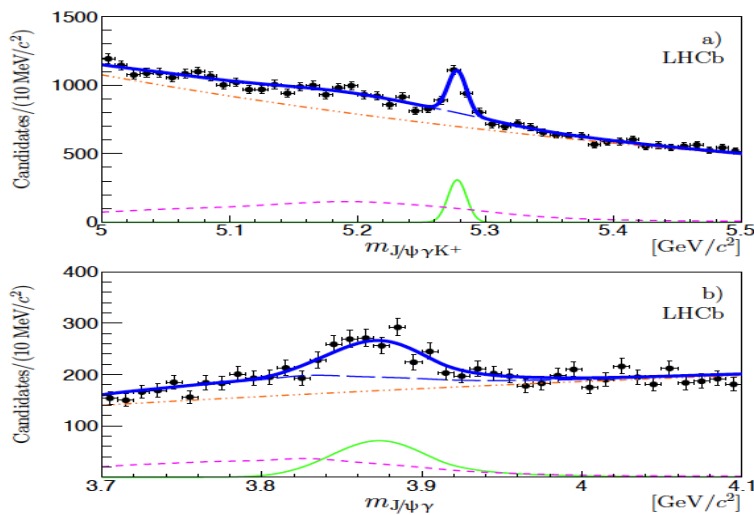
Evidence of $X(3872) \rightarrow \gamma\psi'$

see Michal Kreps's talk this afternoon

arXiv:1404.0275

- $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow \gamma\psi$, $\psi \rightarrow \mu^+\mu^-$
- Two dimensional fit to the $K^+\gamma\psi$ and $\gamma\psi$ mass spectrum

$$N_{X(3872)} = 591 \pm 48 \text{ in } J/\psi \quad N_{X(3872)} = 36.4 \pm 9.0 \text{ in } \psi'$$



$$R = 2.46 \pm 0.64 \pm 0.29 \quad 4.4\sigma$$

not in the range of molecule assumption

Update of $\pi^+\pi^-\psi'$ at Belle



Parameters	Solution I	Solution II
$M_{Y(4360)}$ (MeV/ c^2)	$4346 \pm 6 \pm 2$	
$\Gamma_{Y(4360)}$ (MeV)	$111 \pm 10 \pm 7$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}^{Y(4360)}$ (eV)	$10.6 \pm 0.6 \pm 0.7$	$9.2 \pm 0.8 \pm 0.7$
$M_{Y(4660)}$ (MeV/ c^2)	$4644 \pm 12 \pm 6$	
$\Gamma_{Y(4660)}$ (MeV)	$59 \pm 12 \pm 2$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}^{Y(4660)}$ (eV)	$6.8 \pm 1.6 \pm 0.7$	$1.8 \pm 0.3 \pm 0.1$
ϕ ($^\circ$)	$278 \pm 1 \pm 8$	$19 \pm 24 \pm 20$

Previous measurement:

$$M_{Y(4360)} = 4361 \pm 9 \pm 9 \text{ MeV}/c^2,$$

$$M_{Y(4660)} = 4664 \pm 11 \pm 5 \text{ MeV}/c^2.$$

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

Parameters	Solution I	Solution II	Solution III	Solution IV
$M_{Y(4260)}$ (MeV/ c^2)		4259(fix)		
$\Gamma_{Y(4260)}$ (MeV)		134(fix)		
$\mathcal{B} \cdot \Gamma_{e^+e^-}^{Y(4260)}$ (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		
$\mathcal{B} \cdot \Gamma_{e^+e^-}^{Y(4360)}$ (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		
$\mathcal{B} \cdot \Gamma_{e^+e^-}^{Y(4660)}$ (eV)	2.0 ± 0.4	7.7 ± 0.9	8.4 ± 1.1	2.1 ± 0.4
ϕ_1 ($^\circ$)	309 ± 26	300 ± 28	131 ± 5	140 ± 5
ϕ_2 ($^\circ$)	25 ± 22	243 ± 14	329 ± 9	111 ± 26