Status of X, Y, Z States

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(For Belle, BaBar, CDF Collaborations)

Outline

1. X
2. Y
3. Z
4. Search for exotics in $\Upsilon(1S)$ decays
5. Conclusions

Introduction

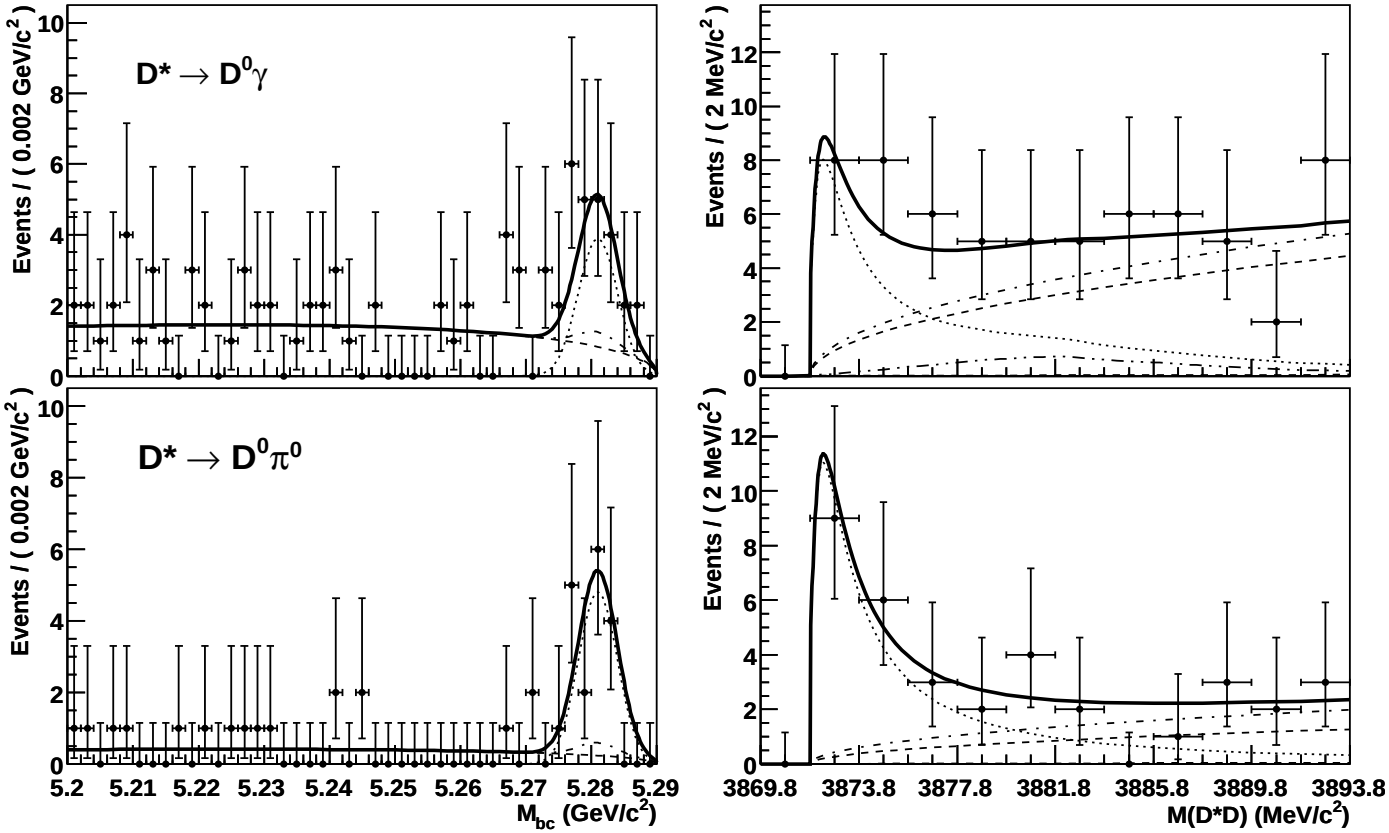
- Conventional states – C. Patrignani, theory – R. Springer
- The era of X, Y, Z (charmonium-like) states started in 2003 when Belle discovered $X(3872)$
- These states have mass above the open charm threshold, but mysteriously open charm decay modes are suppressed
- About 20 states belong to this family and usually do not find a place in the charmonium model
- Many models: tetraquark, hybrid, molecules, hadrocharmonium or, alternatively, effects of close thresholds, coupled channels and rescattering
- Very important: readily accepted by PRL and have hundreds of citations (more than to CP violation)

$X(3872)$ General

- A narrow state discovered by Belle in $B^+ \to J/\psi\pi^+\pi^- K^+$, S.-K.Choi et al.,PRL 91, 262001 (2003)
- Confirmed by BaBar, B.Aubert et al., PRL 93, 041801 (2004); at Tevatron: CDF, D.Acosta et al., PRL 93, 072001 (2004) and D0, V.M.Abazov et al., PRL 93, 162002 (2004)
- Charged partner not found by BaBar, B.Aubert et al., PRD 71, 031501 (2005)
- Helicity analysis of CDF in $X \to J/\psi\pi^+\pi^-$ gives $J^{PC} = 1^{++}, 2^{-+}$, A.Abulencia et al., PRL 98, 132002 (2007)
- Study of the 3π invariant mass spectrum in $X \to J/\psi\omega$ slightly favors $J^{PC} = 2^{-+}$, BaBar, P.del Amo Sanchez et al., PRD 82, 132002 (2010)
- Mass in $D^0\bar{D}^{*0}$ higher than in $J/\psi\pi^+\pi^-$ – 2 states? Belle, G.Gokhroo et al., PRL 97, 162002 (2006), BaBar, B.Aubert et al., PRD 77, 011102 (2008)

Study of $X(3872) \to D^{*0}\bar{D}^0$ – I

Belle used 657×10^6 $B\bar{B}$ to study $X(3872) \to D^{*0}\bar{D}^0$



T. Aushev et al., Phys. Rev. D81, 031103 (2010)

Study of $X(3872) \to D^{*0}\bar{D}^0$ – II

Group	$\int \mathcal{L}dt$, fb^{-1}	Mass, MeV
Belle–2006	414	$3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$
BaBar–2008	347	$3875.1^{+0.7}_{-0.5} \pm 0.5$
Belle–2010	605	$3872.9^{+0.6+0.4}_{-0.4-0.5}$

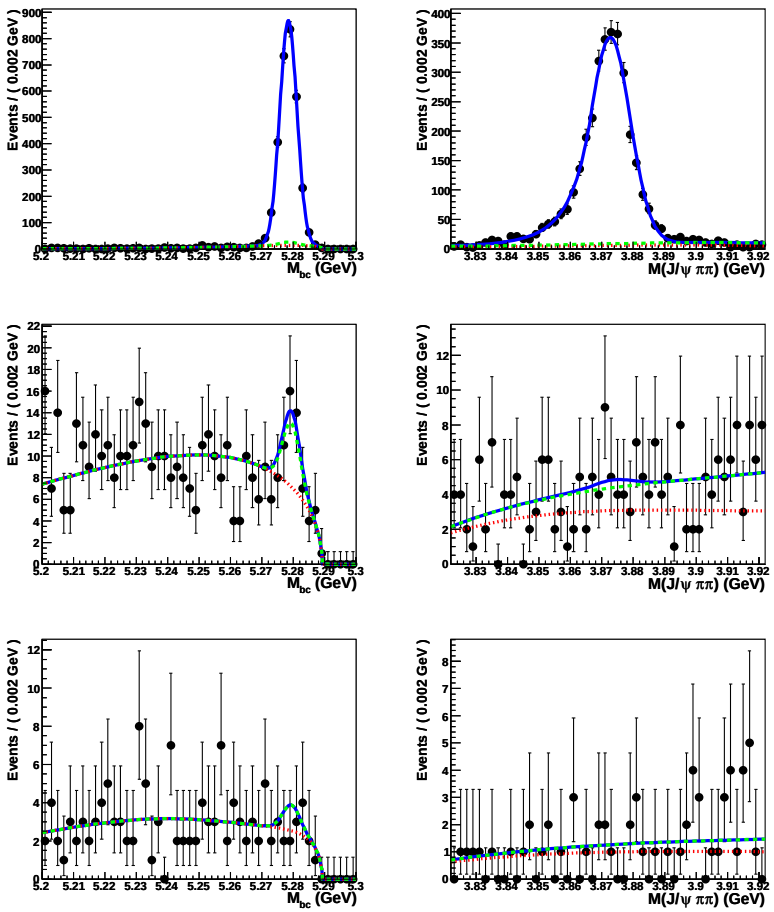
- A 6.4σ signal is observed in $D^{*0} \to D^0\pi^0,\ D^0\gamma$
- $M_X - M_{D^0\bar{D}^{*0}} = (1.1^{+0.6+0.1}_{-0.4-0.3})$ MeV
- The fitted M_X is 2.3σ lower than that of BaBar

Study of $X(3872) \to \pi\pi J/\psi$ – I

Belle used 772×10^6 $B\bar{B}$ to study $X(3872) \to \pi\pi J/\psi$

- After selection 151 ± 15 events of $B^+ \to K^+ X$ and 21.0 ± 5.7 events of $B^+ \to K^0 X$
- Separate fits show very close mass values with
  $\Delta M = (-0.69 \pm 0.97 \pm 0.13)$ MeV - Belle
  $\Delta M = (2.7 \pm 1.6 \pm 0.4)$ MeV – BaBar
- $M = (3871.84 \pm 0.27 \pm 0.19)$ MeV – Belle
  $M = (3871.61 \pm 0.16 \pm 0.19)$ MeV – CDF

Study of $X(3872) \to \pi\pi J/\psi$ – II

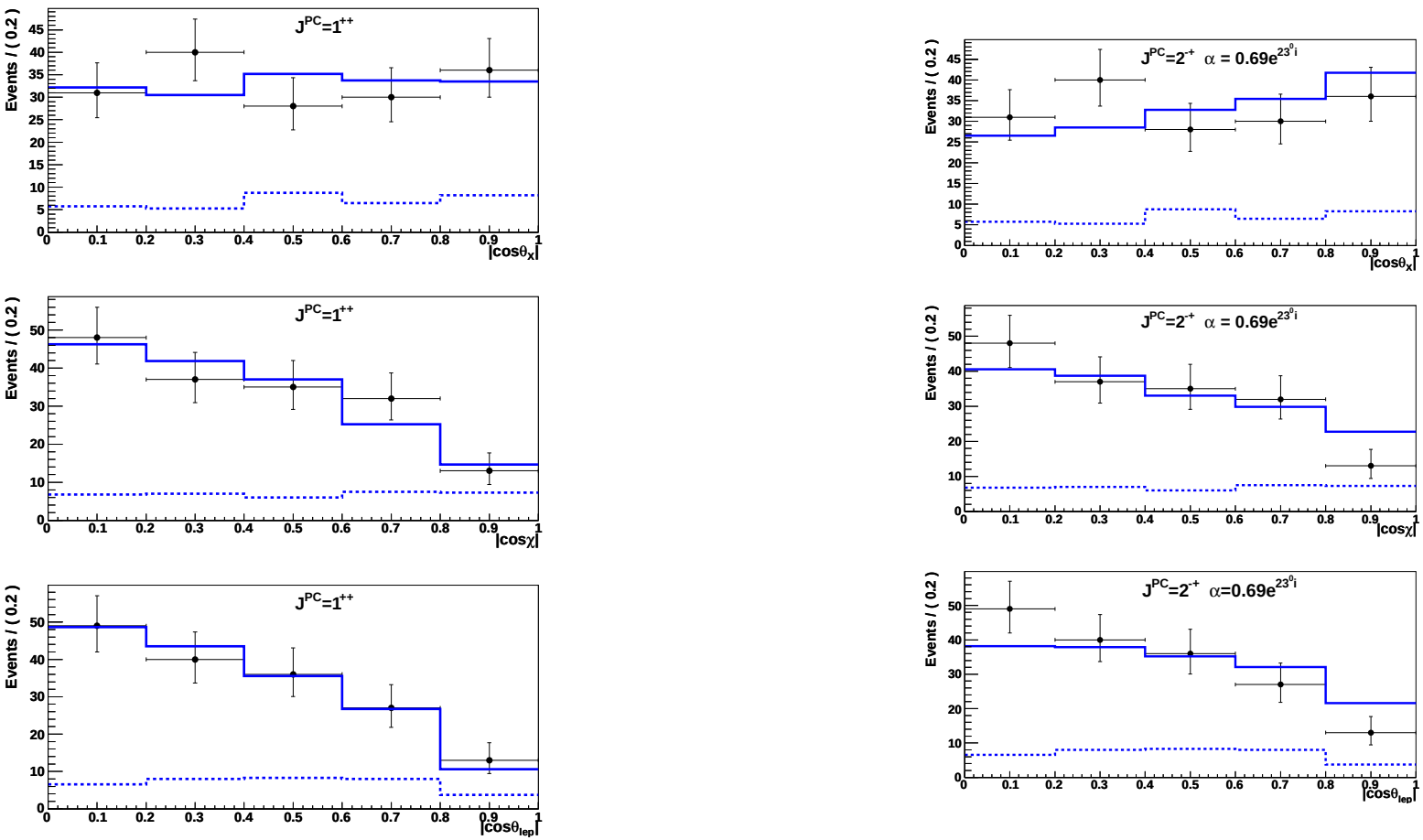


$\mathcal{B}(\bar{B}^0 \to K^- X^+) \cdot \mathcal{B}(X^+ \to \rho^+ J/\psi) < 3.9(5.4) \cdot 10^{-6}$

$\mathcal{B}(B^+ \to K^0 X^+) \cdot \mathcal{B}(X^+ \to \rho^+ J/\psi) < 4.5(22) \cdot 10^{-6}$

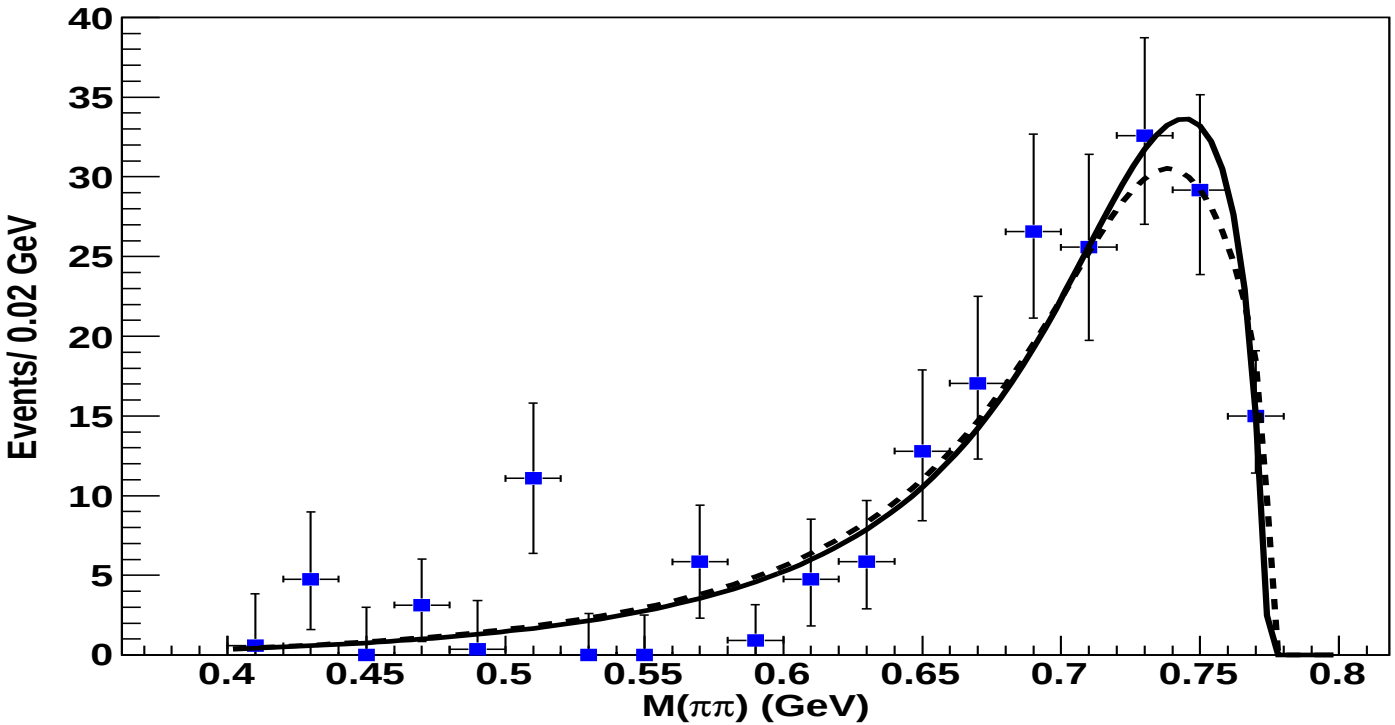
disfavoring $X^+(3872) \Rightarrow \; I = 0$

Study of $X(3872) \to \pi\pi J/\psi$ – III



Both $J^{PC} = 1^{++}$ and 2^{-+} are possible

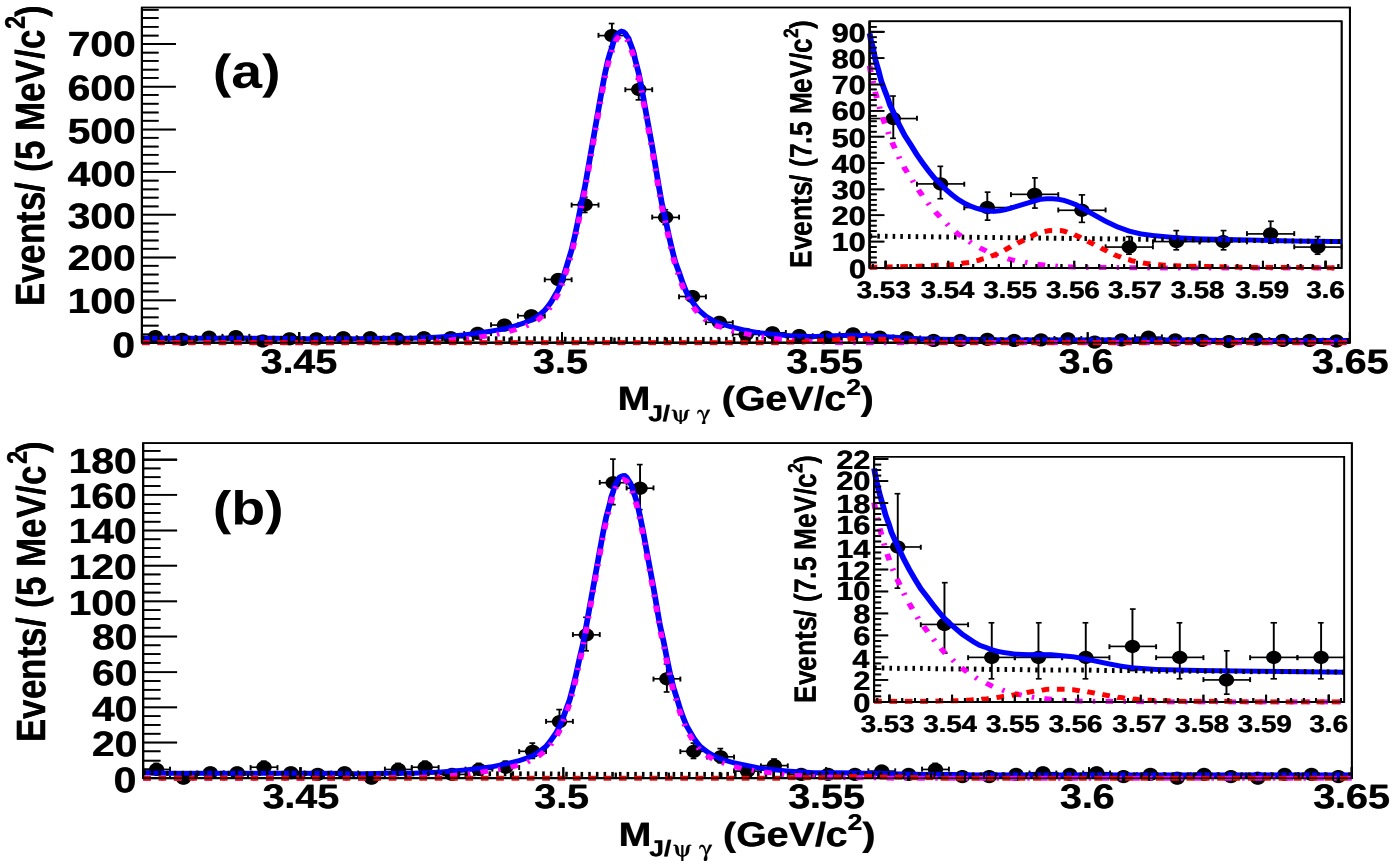
Study of $X(3872) \to \pi\pi J/\psi$ – IV



$\rho - \omega$ interference is important

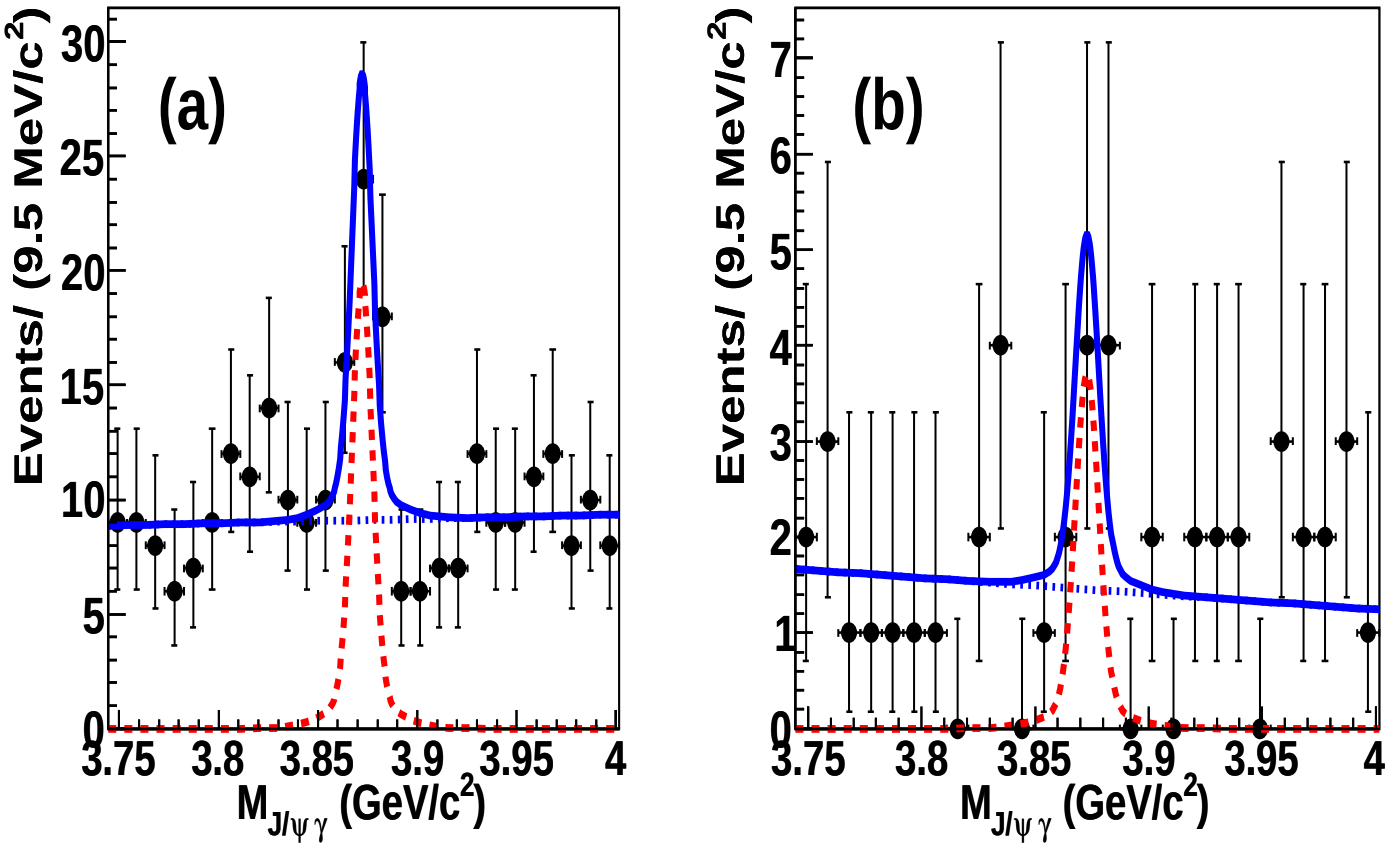
Study of $X(3872) \to J/\psi\gamma$ and Search for $X(3872) \to \psi'\gamma$ – I

Belle used 657×10^6 $B\bar{B}$ to study $X(3872) \to J/\psi(\psi')\gamma$



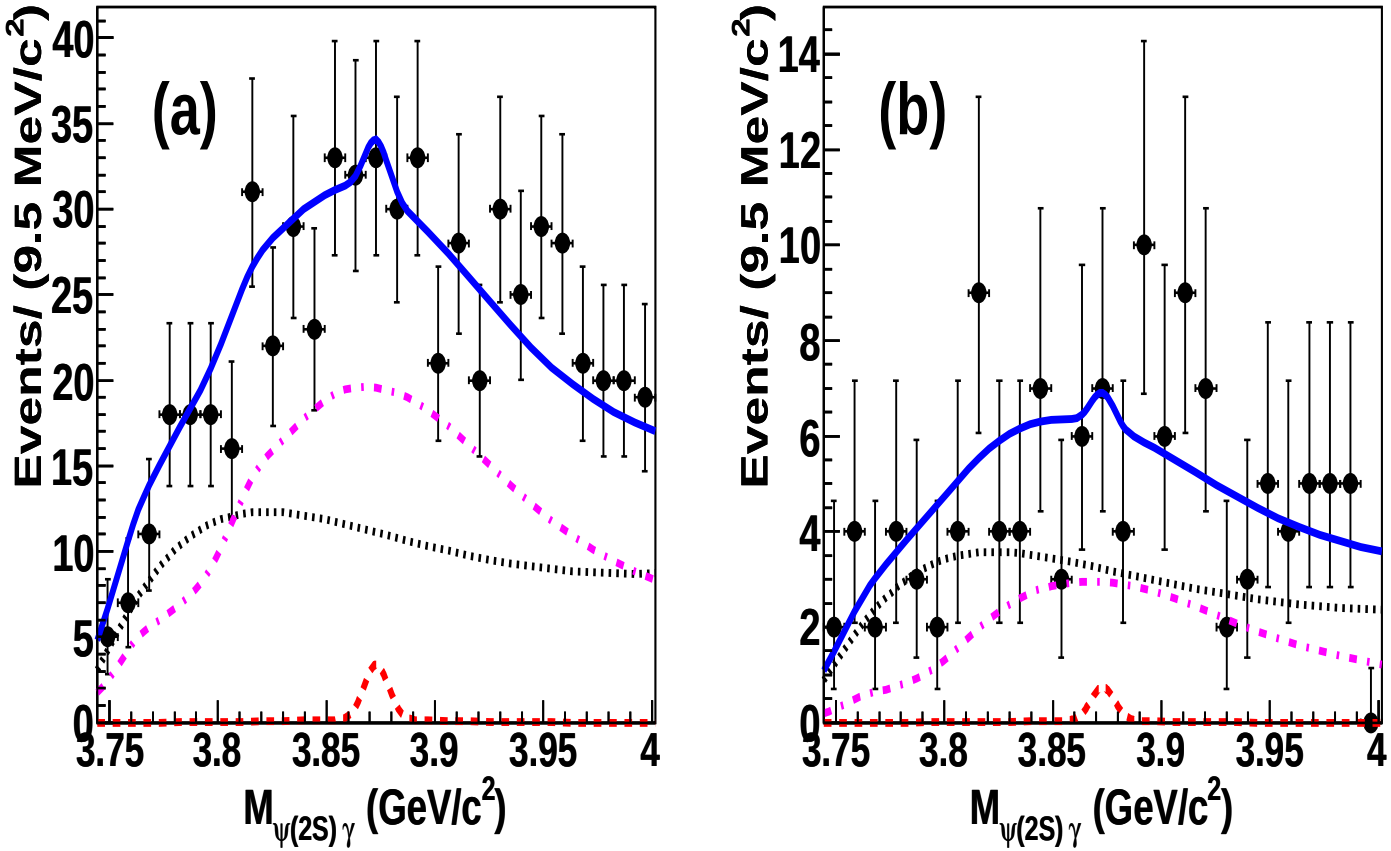
V. Bhardwaj et al., arXiv:1105.0177

Study of $X(3872) \to J/\psi\gamma$ and Search for $X(3872) \to \psi'\gamma$ – II



V. Bhardwaj et al., arXiv:1105.0177

Study of $X(3872) \to J/\psi\gamma$ and Search for $X(3872) \to \psi'\gamma$ – III



Study of $X(3872) \to J/\psi\gamma$ and Search for $X(3872) \to \psi'\gamma$ – IV

Decay	Yield (Y)	Branching fraction	$\mathcal{S}$ (σ)
$B \to \chi_{c1}(\to J/\psi\gamma)K$		$\mathcal{B}$ ($\times 10^{-4}$)	
K^+	2308^{+53}_{-52}	$4.94 \pm 0.11 \pm 0.33$	79
K^0	542 ± 24	$3.78^{+0.17}_{-0.16} \pm 0.33$	37
$B \to \chi_{c2}(\to J/\psi\gamma)K$		$\mathcal{B}$ ($\times 10^{-5}$)	
K^+	$32.8^{+10.9}_{-10.2}$	$1.11^{+0.36}_{-0.34} \pm 0.09$	3.6
K^0	$2.8^{+4.7}_{-3.9}$	$0.32^{+0.53}_{-0.44} \pm 0.03$ (< 1.5)	0.7
$B \to X(3872)(\to J/\psi\gamma)K$		$\mathcal{B}$ ($\times 10^{-6}$)	
K^+	$30.0^{+8.2}_{-7.4}$	$1.78^{+0.48}_{-0.44} \pm 0.12$	4.9
K^0	$5.7^{+3.5}_{-2.8}$	$1.24^{+0.76}_{-0.61} \pm 0.11$ (< 2.4)	2.4
$B \to X(3872)(\to \psi'\gamma)K$		$\mathcal{B}$ ($\times 10^{-6}$)	
K^+	$5.0^{+11.9}_{-11.0}$	$0.83^{+1.98}_{-1.83} \pm 0.44$ (< 3.45)	0.4
K^0	$1.5^{+4.8}_{-3.9}$	$1.12^{+3.57}_{-2.90} \pm 0.57$ (< 6.62)	0.3

Summary of $X(3872) \to J/\psi(\psi')\gamma$ Studies

Results on $\mathcal{B}(B^+ \to K^+ X(3872)) \cdot \mathcal{B}(X(3872) \to R\gamma), 10^{-6}$

Group	Belle	BaBar
$\int \mathcal{L}dt,\ \mathrm{fb}^{-1}$	711	424
$R = J/\psi$	$1.78^{+0.48}_{-0.44} \pm 0.12$	$2.8 \pm 0.8 \pm 0.1$
$R = \psi$	< 3.45	$9.5 \pm 2.7 \pm 0.6$

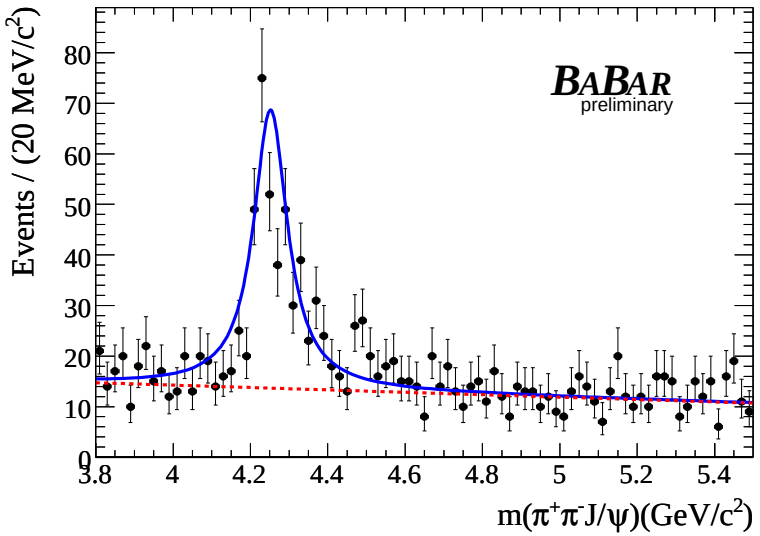
From the absence of $X(3872) \to \psi'\gamma$ it may not have a large $c\bar{c}$ admixture with a $D^{*0}\bar{D}^0$ molecular component

$Y(4260)$ General

- Discovered by BaBar in $e^+e^- \to J/\psi\pi^+\pi^-\gamma$ in B.Aubert et al., PRL 95, 142001 (2005)
- Confirmed by CLEO both with ISR and a direct scan in Q.He et al., PRD 74, 091104 (2006), T.Coan et al., PRL 96, 162003 (2006)
- Observed by Belle with ISR, C.Z.Yuan et al., PRL 99, 182004 (2007)
- Possibly seen in $B^- \to J/\psi\pi^+\pi^-K^-$ by BaBar, B.Aubert et al., PRD 73, 011101 (2006)
- $J^{PC} = 1^{--}$, $M = 4263^{+8}_{-9}$ MeV, $\Gamma = 95 \pm 14$ MeV, $\Gamma_{e^+e^-}\mathcal{B}(J/\psi\pi^+\pi^-) = 5.9^{+1.2}_{-0.9}$ eV
- No serious signal in any other decay mode ($D^{(*)}\bar{D}^{(*)}$, $D_s^{(*)}\bar{D}_s^{(*)}$, $\psi'\pi^+\pi^-$, ...) the position of $Y(4260)$ coincides with a dip in R

$Y(4260)$ at BaBar – II

BaBar used a data sample of 454 fb^{-1}, B.Aubert et al., 0808.1543

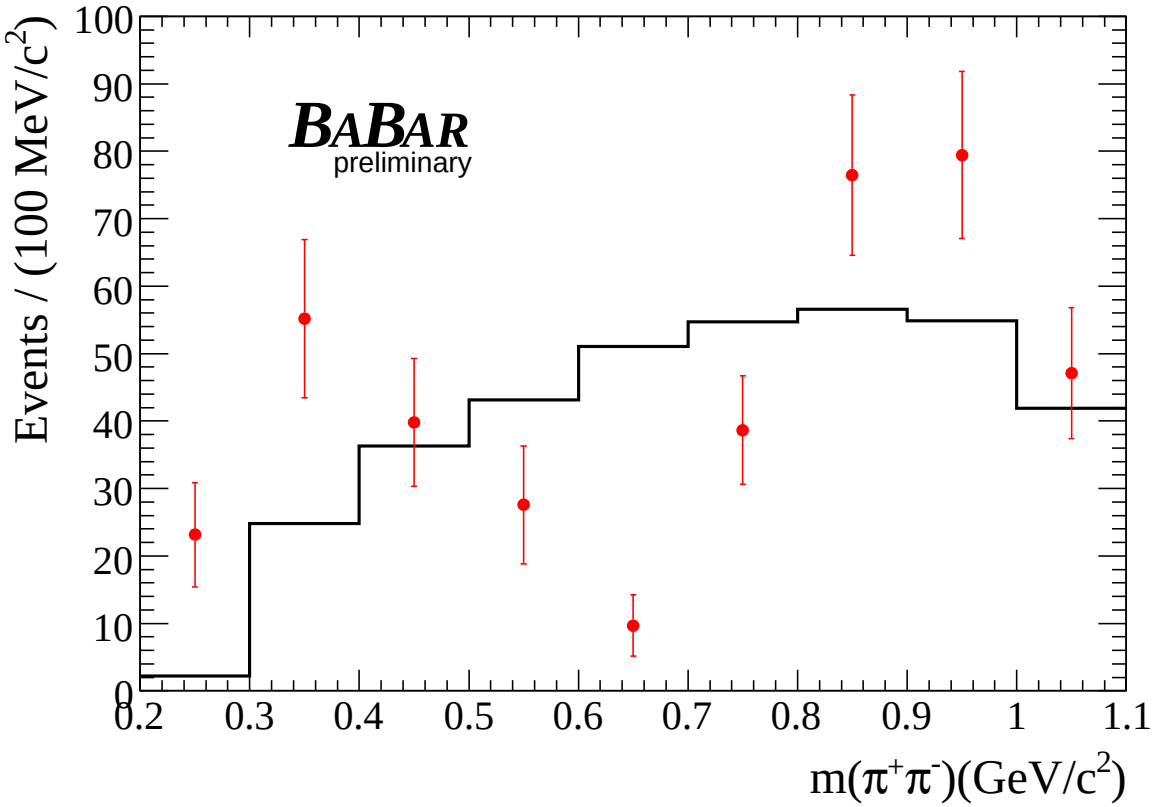


$M = 4252 \pm 6^{+2}_{-3}$ MeV, $\Gamma = 105 \pm 18^{+4}_{-6}$ MeV, $\Gamma_{e^+e^-}\mathcal{B}(J/\psi\pi^+\pi^-) = 7.5^{+0.9}_{-0.8}$ eV

Does not confirm $Y(4050)$ observed by Belle with 548 fb^{-1}:

$\Gamma_{e^+e^-}\mathcal{B}(J/\psi\pi^+\pi^-) < 0.7$ eV at 90%CL

$Y(4260)$ at BaBar – II

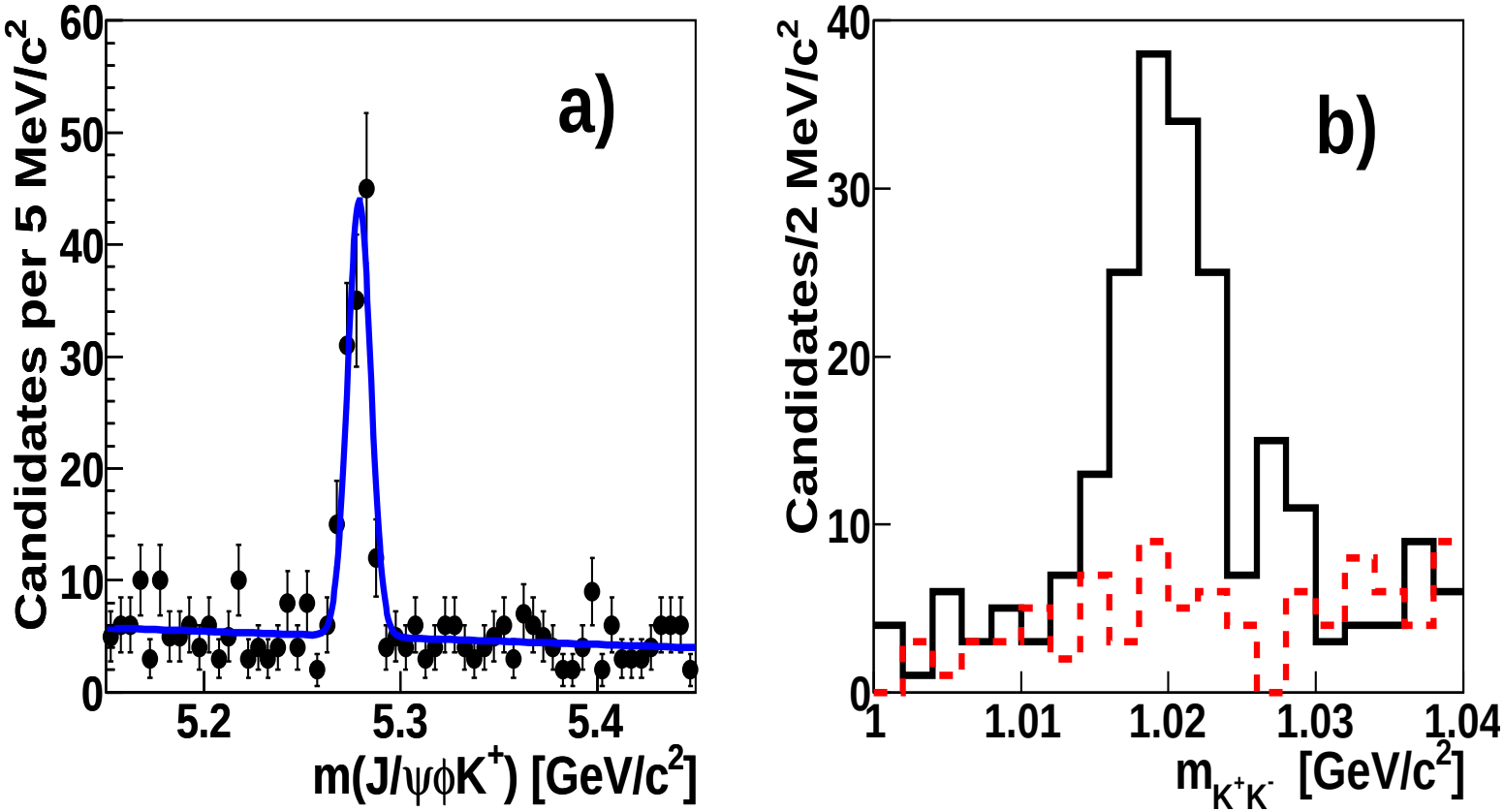


As previously observed, $m_{\pi^+\pi^-}$ is not described by phase space

$Y(4140)$ at CDF – I

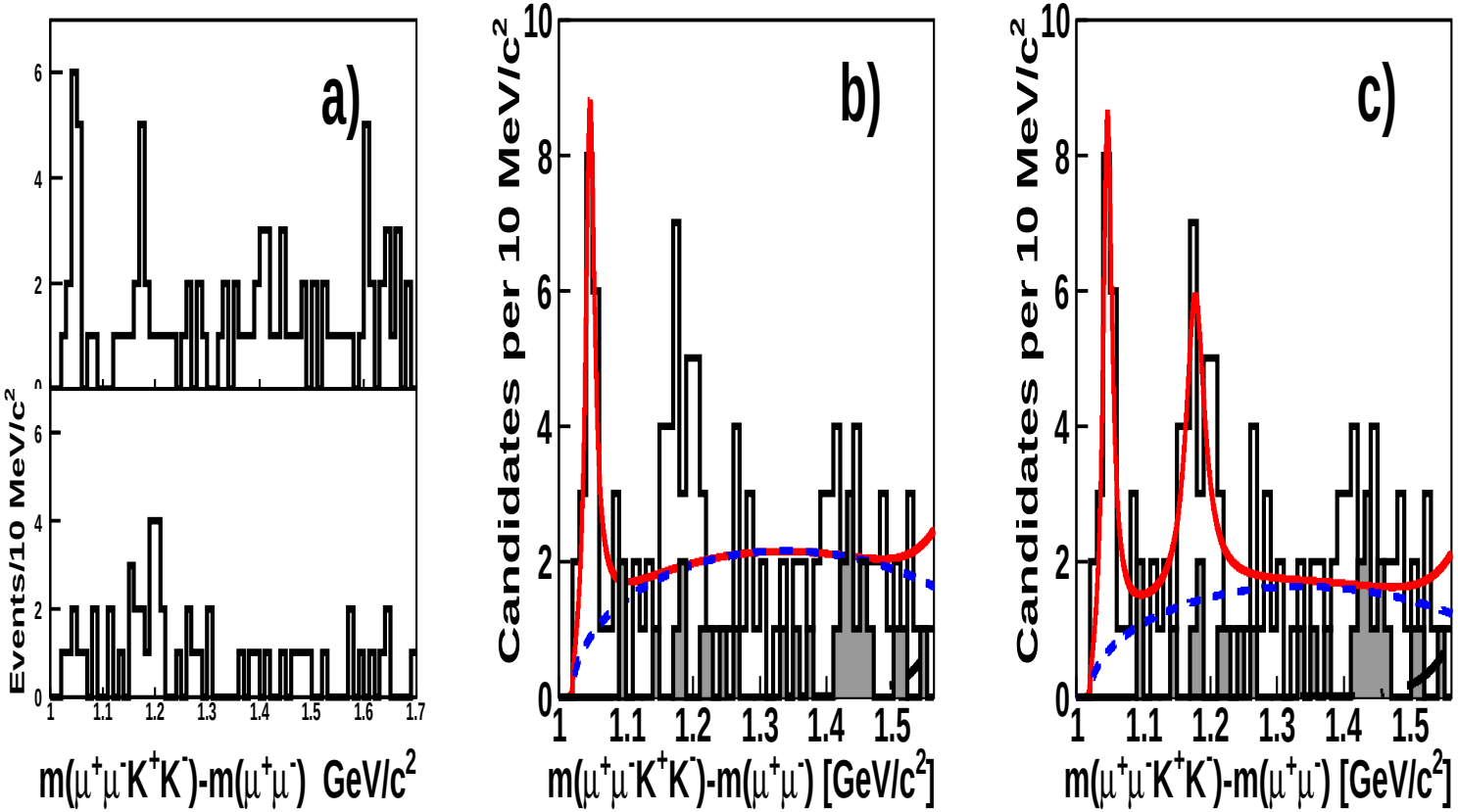
- First evidence (3.8σ) from CDF as $B^+ \to Y(4140)K^+$, $Y(4140) \to J/\psi\phi$, $N = 14 \pm 5$, $M = (4143.0 \pm 2.9 \pm 1.2)$ MeV, $\Gamma = (11.7^{+8.3}_{-5.0} \pm 3.7)$ MeV, T.Aaltonen et al., PRL 102, 242002 (2009)
- Belle searched for $Y(4140)$ in B decays with a negative, but not inconsistent with CDF result, J.Brodzicka, LP-09
- Belle also didn't see $Y(4140)$ in $\gamma\gamma$, but found $Y(4350)$ with 3.2σ significance
- In 1101.0658 CDFII reports x2.2 (6 fb^{-1}) and confirms $Y(4140)$
- As before, they use $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$

$Y(4140)$ at CDF – II



115 ± 12 events of $B^+ \to J/\psi\phi K^+$

$Y(4140)$ at CDF – III



Two significant structures seen!

$Y(4140)$ at CDF – IV

Parameters of two J/ϕ states

State	Events	Mass, MeV	Width, MeV	Sign. (σ)
1	$19 \pm 6 \pm 3$	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-\ 6.1} \pm 2.5$	5.0
2	22 ± 8	$4274.4^{+8.4}_{-6.7} \pm 1.9$	$32.3^{+21.9}_{-15.3} \pm 7.6$	3.1

$$\mathcal{B}(B^+ \to Y(4140)K^+)/\mathcal{B}(B^+ \to J/\psi\phi K^+) = 0.149 \pm 0.039 \pm 0.024$$

The first state of two heavy quarkonia - $c\bar{c}s\bar{s}$

Charged Z States

- No news on $Z(4430)$ seen by Belle in $B \to K\pi^+\psi'$ with 605 fb^{-1}, S.-K.Choi et al., PRL 100, 142001 (2008)
- Not seen by BaBar with 413 fb^{-1}, also in $J/\psi\pi^+$ decay, B.Aubert et al., PRD 80, 031104 (2009)
- Confirmed by Belle in Dalitz plot reanalysis of the same data sample, R.Mizuk et al., PRD 80, 031104 (2010), $M = 4443^{+15+19}_{-12-13}$ MeV, $\Gamma = 107^{+86+74}_{-43-56}$ MeV
- No statistical inconsistency between Belle and BaBar
- With the same 605 fb^{-1} Belle observes in B^0 decays two $\chi_{c1}\pi^-$ states – $Z(4050)$ and $Z(4350)$, R.Mizuk et al., PRD 80, 031104 (2010)
- Non-zero charge $\Rightarrow$ exotic, non-$q\bar{q}$ nature

Puzzles of ϒ(5S) decays

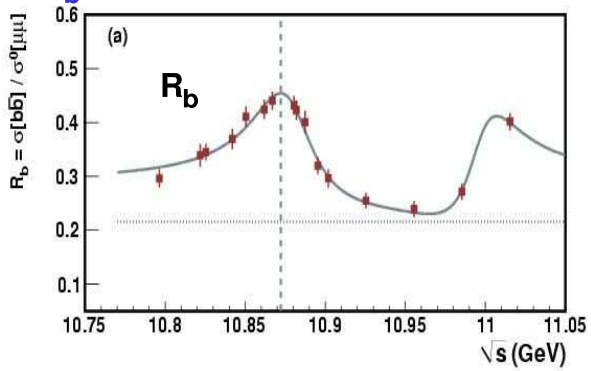
PRL100,112001(2008)

At 21.7 fb^{-1} ϒ (5S) ->ϒ(nS) $\pi^+\pi^-$ two orders of magnitude larger than in ϒ (4S) decay

	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

PRD82,091106R(2010)

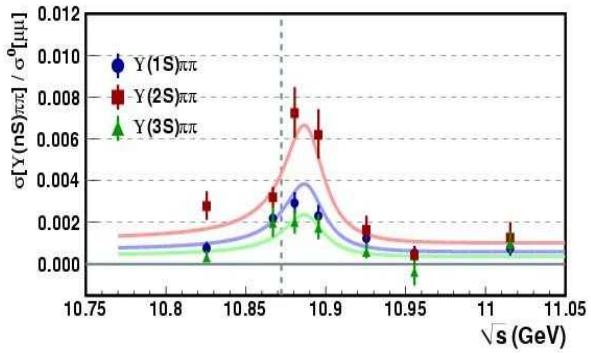
Dedicated energy scan ⇒
shapes of R_b and σ(ϒππ) different (2σ)



-Rescattering ϒ(5S)→BBππ→ϒ(nS)ππ

Simonov JETP Lett 87,147(2008)

-Exotic resonance Y_b near ϒ(5S)



ϒ(5S) is very interesting and not yet understood

Finally Belle recorded 121.4fb^{-1} at ϒ(5S)

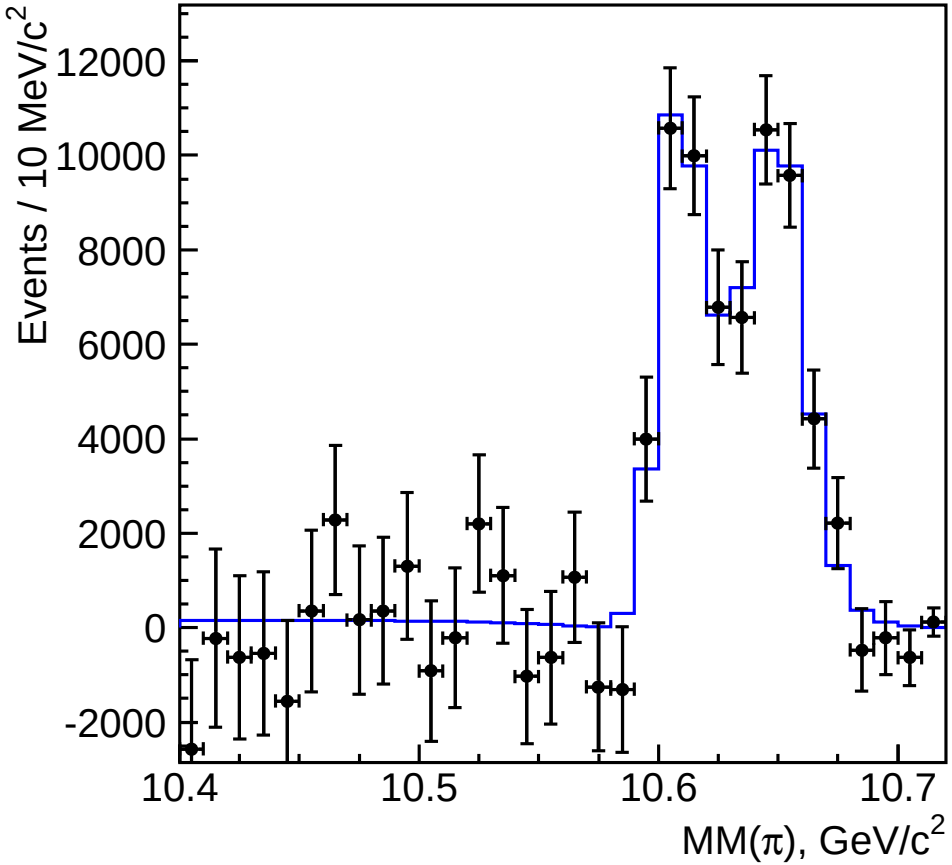
arXiv:1104.2025

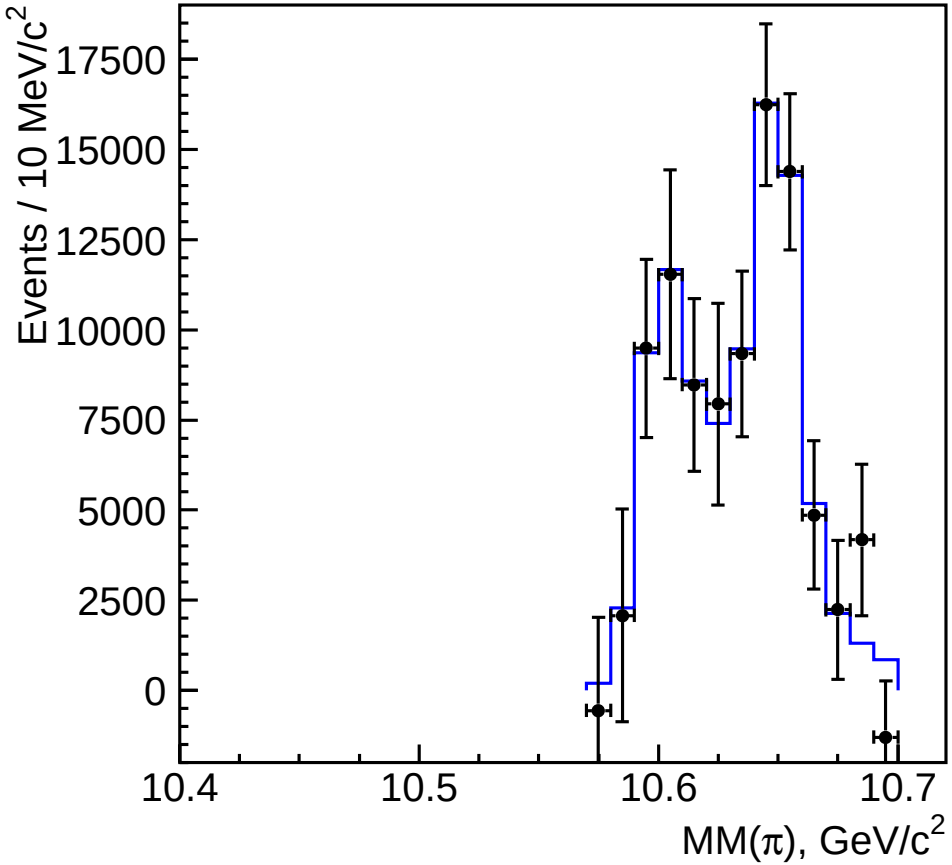
Observation of $e^+e^- \to \pi^+\pi^- h_c$ by CLEO
⇒ Belle search for h_b in ϒ(5S) data

Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – I

Dalitz plot analysis of $\Upsilon(5S)$ decays to
$h_b(1P)\pi^+\pi^-$, $h_b(2P)\pi^+\pi^-$,
$\Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(3S)\pi^+\pi^-$
shows the resonant structure in
$\Upsilon(h_b) - Z_b$.

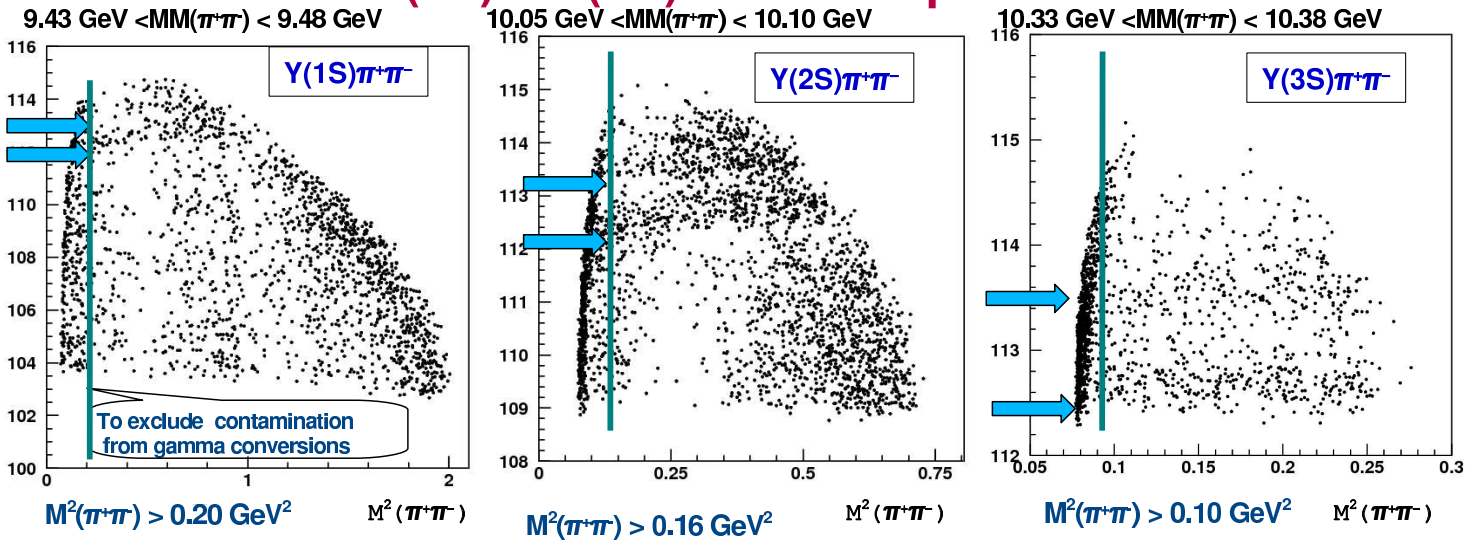
Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – I





$h_b(1P)$ and $h_b(2P)$ decay into $Z_b(10610)$ and $Z_b(10650)$

$\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-$ Dalitz plots



$s_i \equiv M^2_{\pi_i \Upsilon}$ **Unbinned fit of DP with signal function:**

Flatte m=950 MeV/c²

D-wave Breit-Wigner

$$S(s_1, s_2) = |A_{Z_{b1}} + A_{Z_{b2}} + A_{NR} + A_{f_0(980)} + A_{f_2(1275)}|^2$$

$$A_{Z_{bi}} = \frac{\sqrt{M_i\Gamma_i}}{M_i^2 - s_1 + iM_i\Gamma_i} + \frac{a_i e^{i\phi_i}\sqrt{M_i\Gamma_i}}{M_i^2 - s_2 + iM_i\Gamma_i}$$

$$A_{NR} = c_1 + c_2 m^2_{\pi\pi}$$

[1] M.B. Voloshin, Prog. Part. Nucl. Phys. 61:455, 2008.

[2] M.B. Voloshin, Phys. Rev. D74:054022, 2006.

1

Fit results

[preliminary]

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M(Z_b(10610))$, MeV/c^2	$10609 \pm 3 \pm 2$	$10616 \pm 2^{+3}_{-4}$	$10608 \pm 2^{+5}_{-2}$	$10605.1 \pm 2.2^{+3.0}_{-1.0}$	$10596 \pm 7^{+5}_{-2}$
$\Gamma(Z_b(10610))$, MeV	$22.9 \pm 7.3 \pm 2$	$21.1 \pm 4^{+2}_{-3}$	$12.2 \pm 1.7 \pm 4$	$11.4^{+4.5}_{-3.9}{}^{+2.1}_{-1.2}$	$16^{+16}_{-10}{}^{+13}_{-4}$
$M(Z_b(10650))$, MeV/c^2	$10660 \pm 6 \pm 2$	$10653 \pm 2 \pm 2$	$10652 \pm 2 \pm 2$	$10654.5 \pm 2.5^{+1.0}_{-1.9}$	$10651 \pm 4 \pm 2$
$\Gamma(Z_b(10650))$, MeV	$12 \pm 10 \pm 3$	$16.4 \pm 3.6^{+4}_{-6}$	$10.9 \pm 2.6^{+4}_{-2}$	$20.9^{+5.4}_{-4.7}{}^{+2.1}_{-5.7}$	$12^{+11}_{-9}{}^{+8}_{-2}$
Rel. amplitude	$0.59 \pm 0.19^{+0.09}_{-0.03}$	$0.91 \pm 0.11^{+0.04}_{-0.03}$	$0.73 \pm 0.10^{+0.15}_{-0.05}$	$1.8^{+1.0}_{-0.7}{}^{+0.1}_{-0.5}$	$1.3^{+3.1}_{-1.1}{}^{+0.4}_{-0.7}$
Rel. phase, degrees	$53 \pm 61^{+5}_{-50}$	$-20 \pm 18^{+14}_{-9}$	$6 \pm 24^{+23}_{-59}$	$188^{+44}_{-58}{}^{+4}_{-9}$	$255^{+56}_{-72}{}^{+12}_{-183}$

Masses, widths, relative amplitudes are consistent

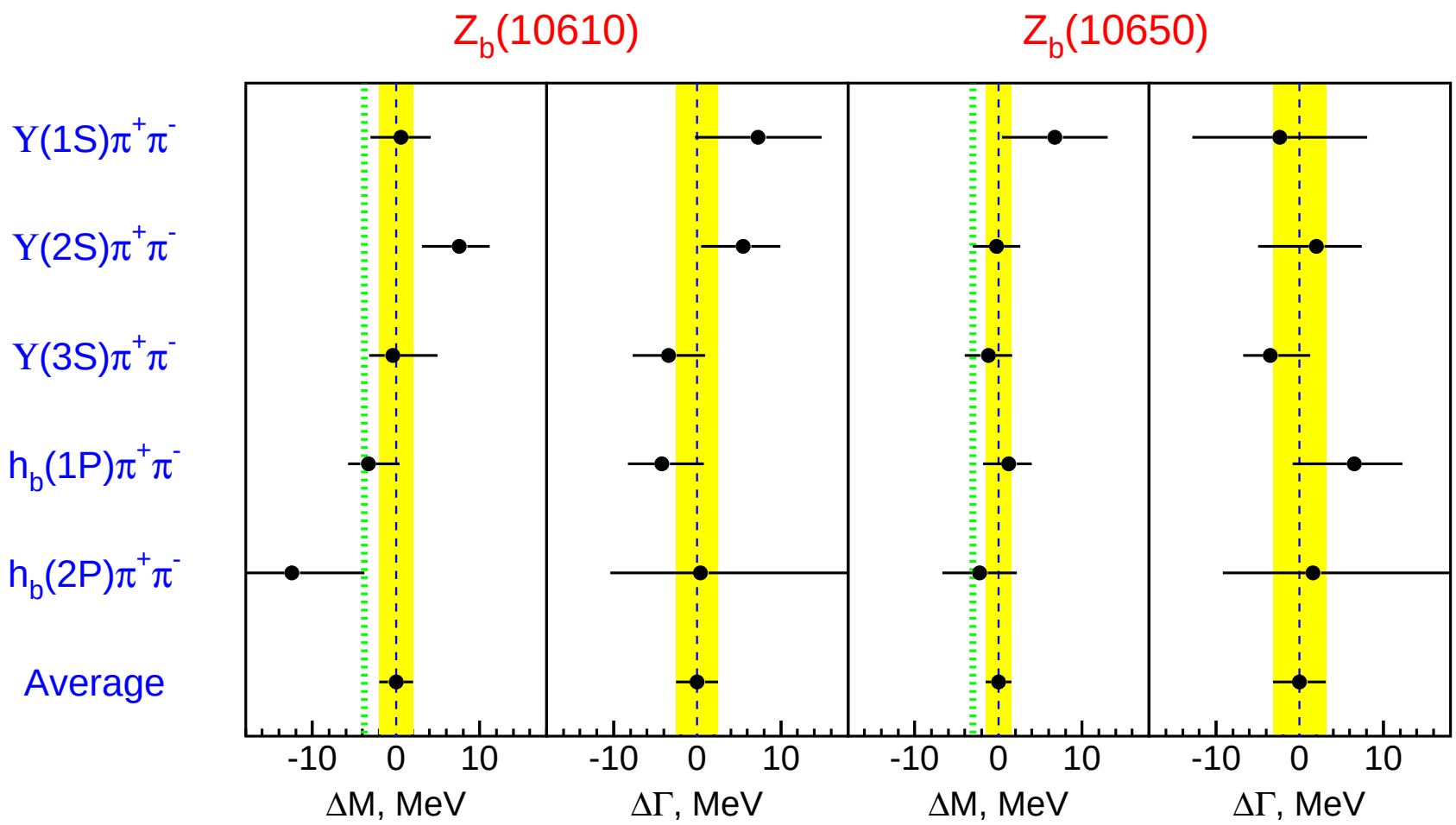
Relative phases are swapped for Υ and h_b final states ⇐ expectation from a 'molecular' model

$Z_b(10610)$
M=10608.4±2.0 MeV
Γ=15.6±2.5 MeV

$Z_b(10650)$
M=10653.2±1.5 MeV
Γ=14.4 ± 3.2 MeV

1

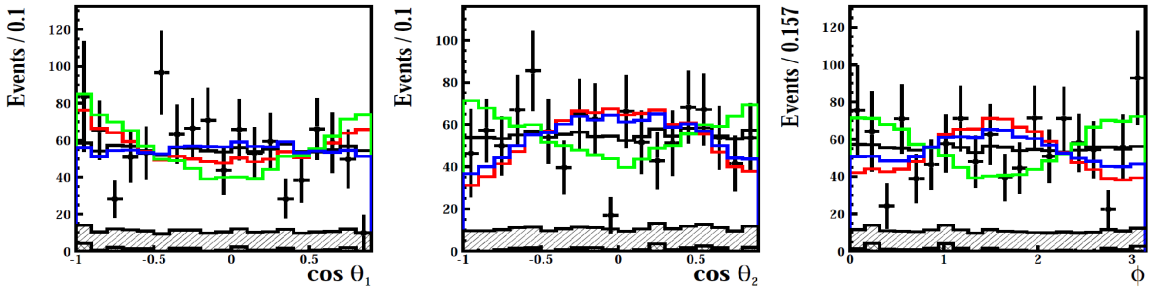
Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – I



Angular analysis

[preliminary]

J^P= 1^+ 1^- 2^+ 2^-



Probabilities at which different J^P hypotheses are disfavored compared to 1^+

J^P	$Z_b(10610)$			$Z_b(10650)$		
	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$
1^-	$3.6\,\sigma$	$0.3\,\sigma$	$0.3\,\sigma$	$3.7\,\sigma$	$2.6\,\sigma$	$2.7\,\sigma$
2^+	$4.3\,\sigma$	$3.5\,\sigma$	$4.3\,\sigma$	$4.4\,\sigma$	$2.7\,\sigma$	$2.1\,\sigma$
2^-	$2.7\,\sigma$	$2.8\,\sigma$		$2.9\,\sigma$	$2.6\,\sigma$	

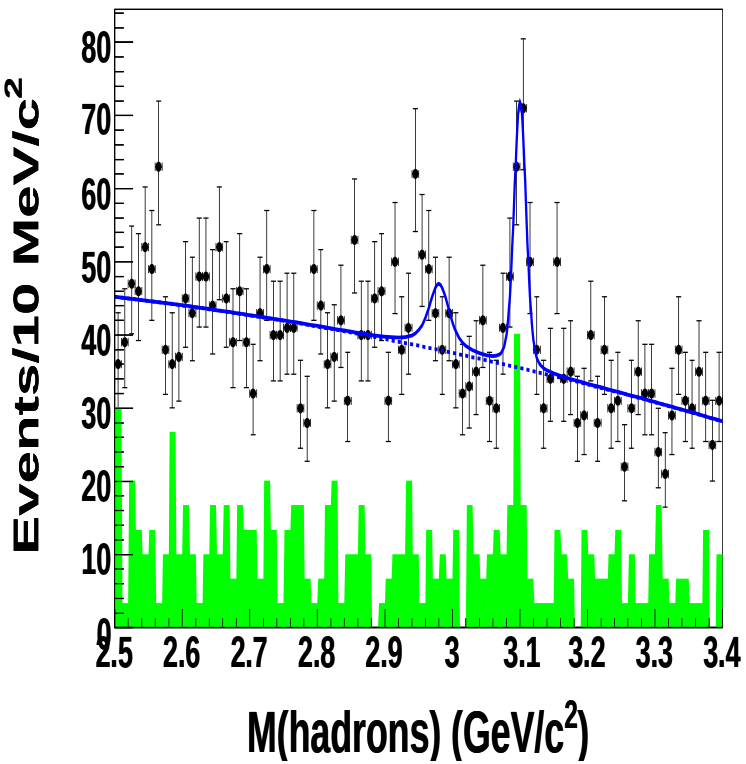
1+ assignment is favorable.

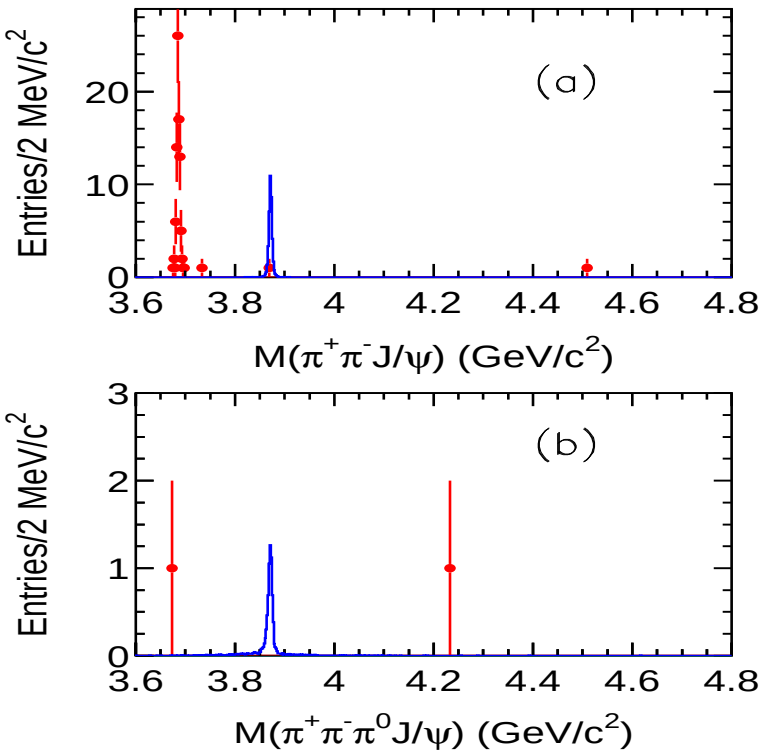
1-, 2+ ,2- are disfavored at typically 3σ level.

1

Search for Charmonium(like) States in $\Upsilon(1S)$ Decays – I

Belle searched for $\Upsilon(1S) \to R\gamma$ using 102×10^6 $\Upsilon(1S)$ events





C.P. Shen et al., Phys. Rev. D82, 051504 (2010)

Search for Charmonium(like) States in $\Upsilon(1S)$ Decays – II

Upper Limits on $\mathcal{B}(\Upsilon(1S) \to R\gamma)$ at 90%CL

State (R)	$\mathcal{B}_R, 10^{-5}$
χ_{c0} $(J/\psi\gamma)$	65
χ_{c1} $(J/\psi\gamma)$	2.3
χ_{c2} $(J/\psi\gamma)$	0.76
η_c (5 modes)	5.7
$X(3872) \to \pi^+\pi^- J/\psi$	0.16
$X(3872) \to \pi^+\pi^-\pi^0 J/\psi$	0.28
$X(3915) \to \omega J/\psi$	0.30
$Y(4140) \to \phi J/\psi$	0.22

No contradiction with Y.-J. Gao et al., hep-ph/0701009

No excited charmonium states below 4.8 GeV

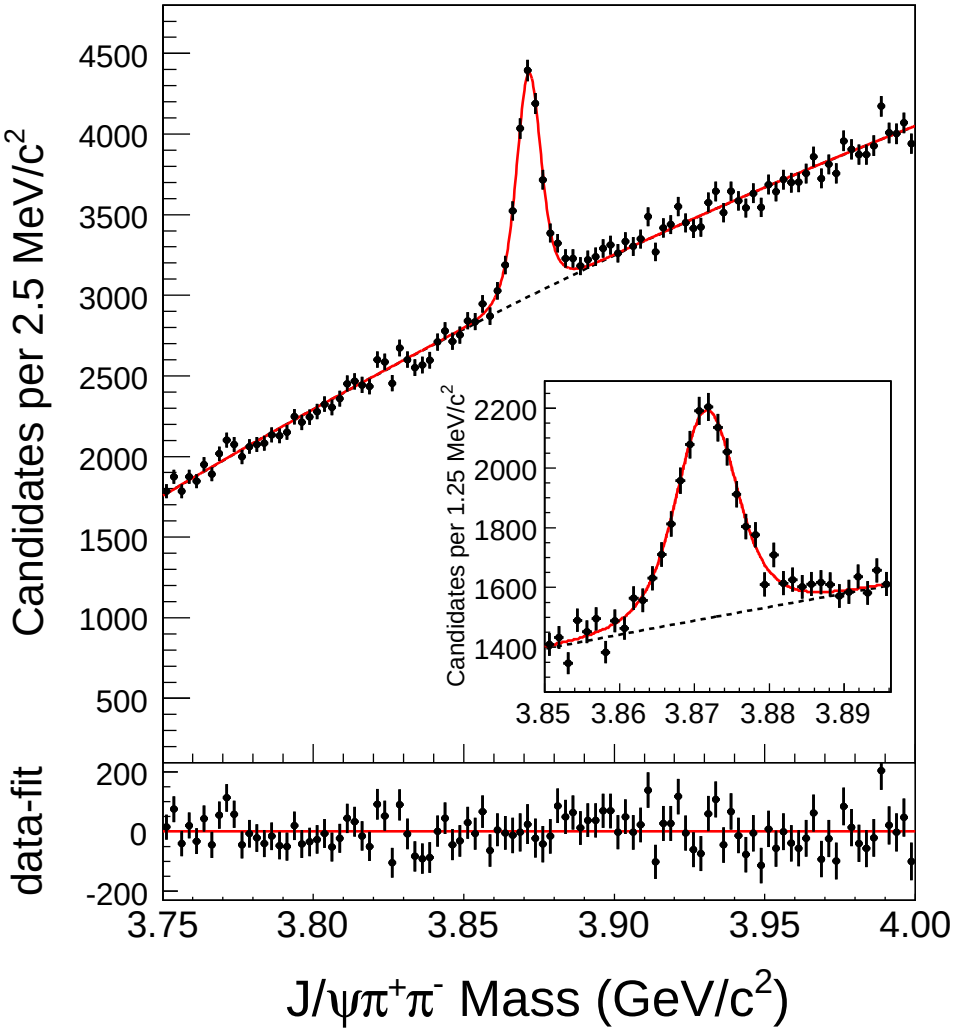
Similar analysis is in progress for 158×10^6 $\Upsilon(2S)$ events

Conclusions

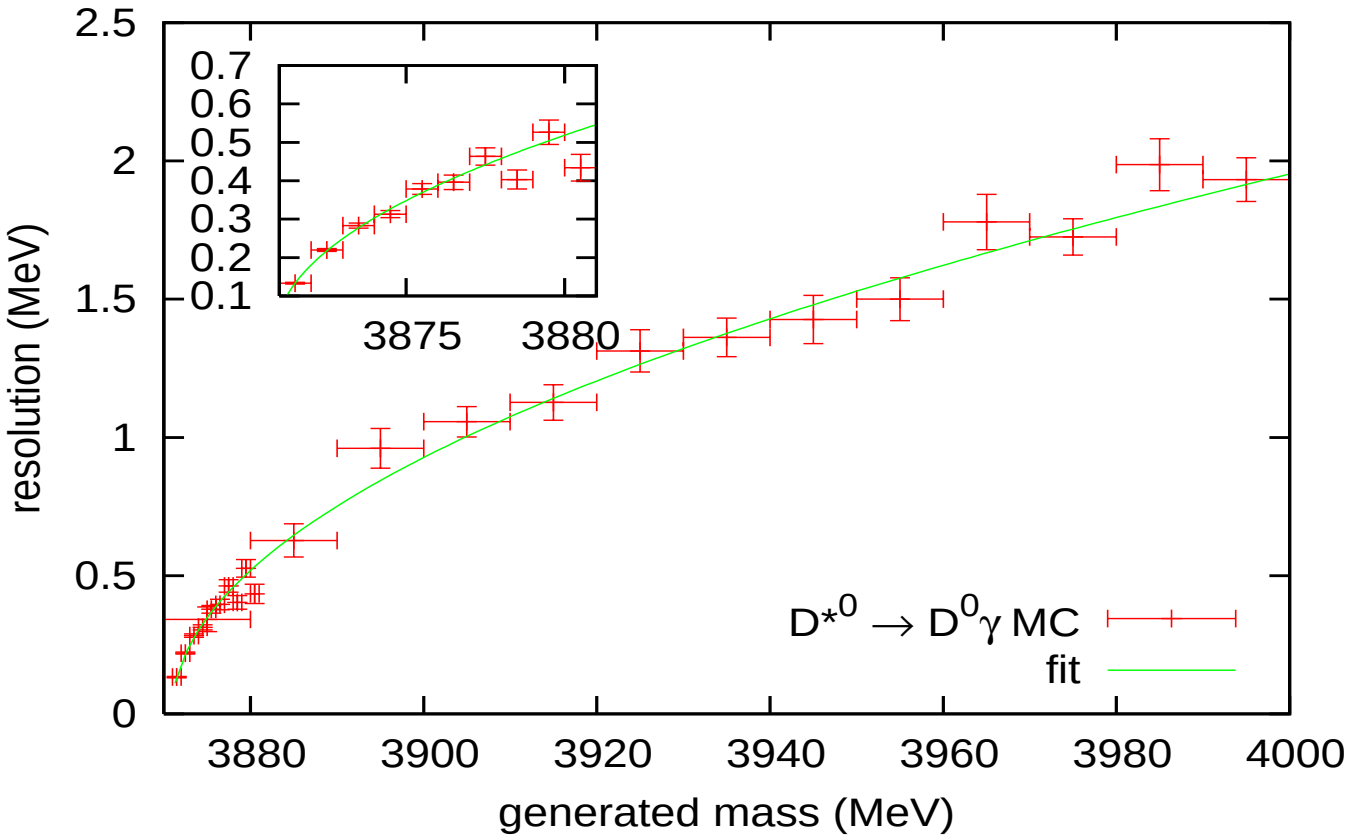
- Theoretical interpretation very far from final
- The exotic family is proliferating,
  "babies" are heavy: Y_b, $Z_b(10610)$, $Z_b(10650)$
- In many cases detailed analysis is limited by statistics,
  a breakthrough expected at SuperB-factories, PANDA and LHC
- LHCb: $M_{X(3872)} = 3871.96 \pm 0.46 \pm 0.10$ MeV
- About 20 new states are not yet assigned
- Enrico Fermi: If I could remember the names of all these particles, I'd be a botanist

Back-up

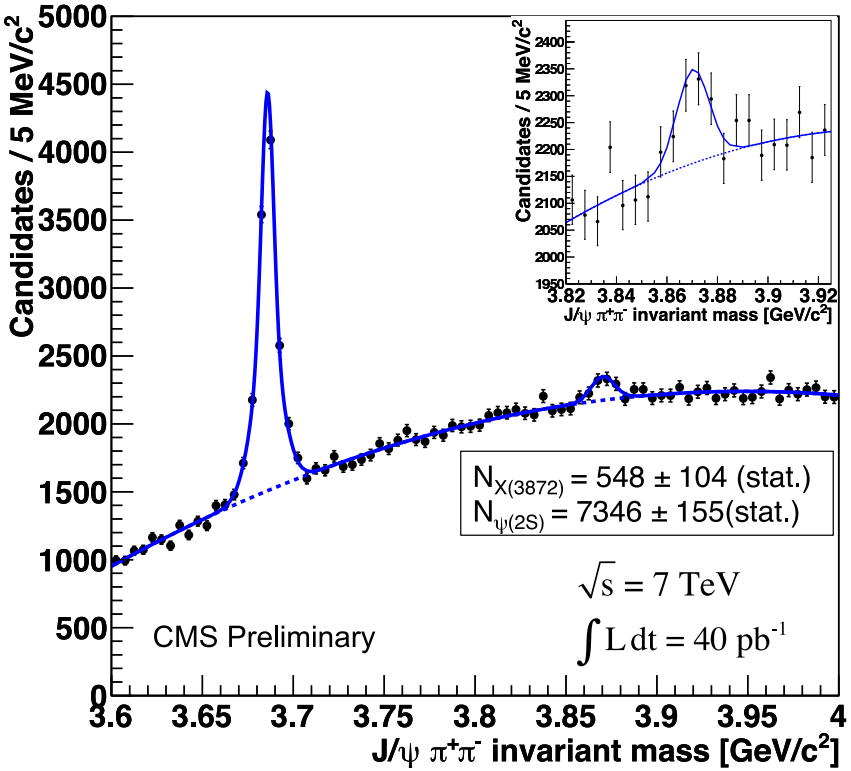
Confirmation of $X(3872)$ at CDF



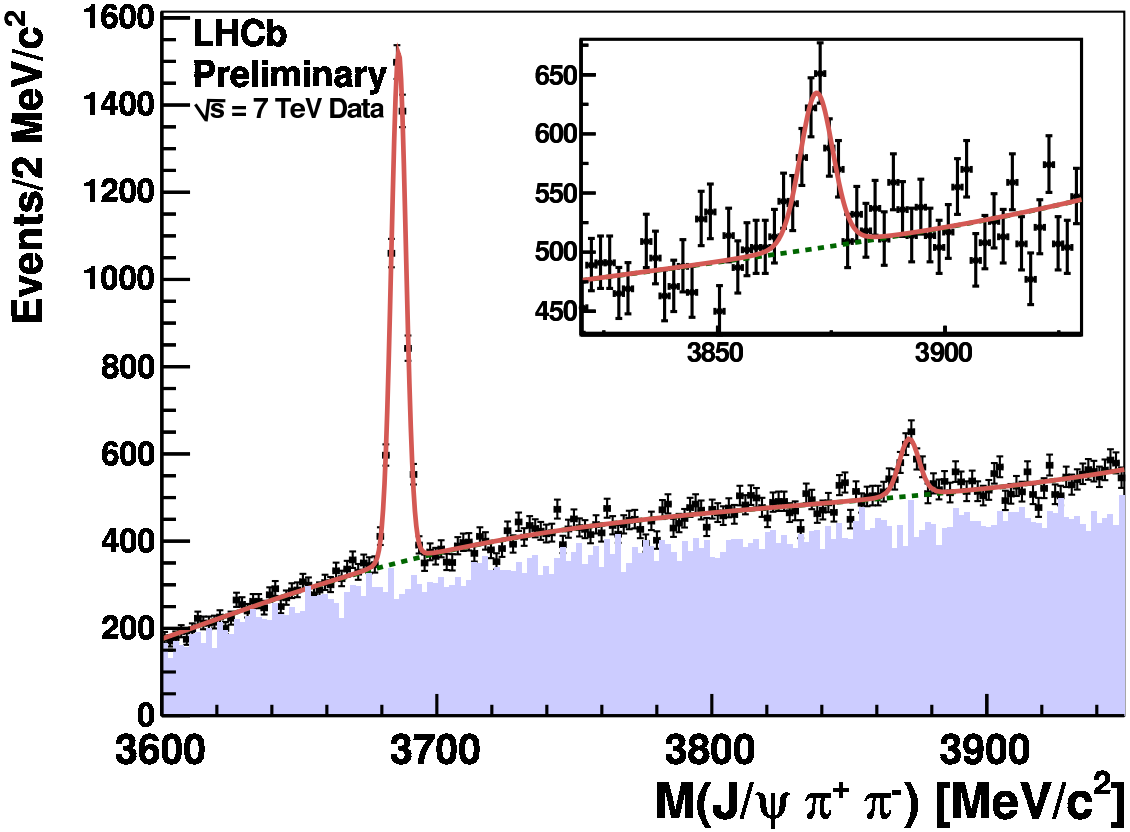
Study of $X(3872) \to D^{*0}\bar{D}^0$



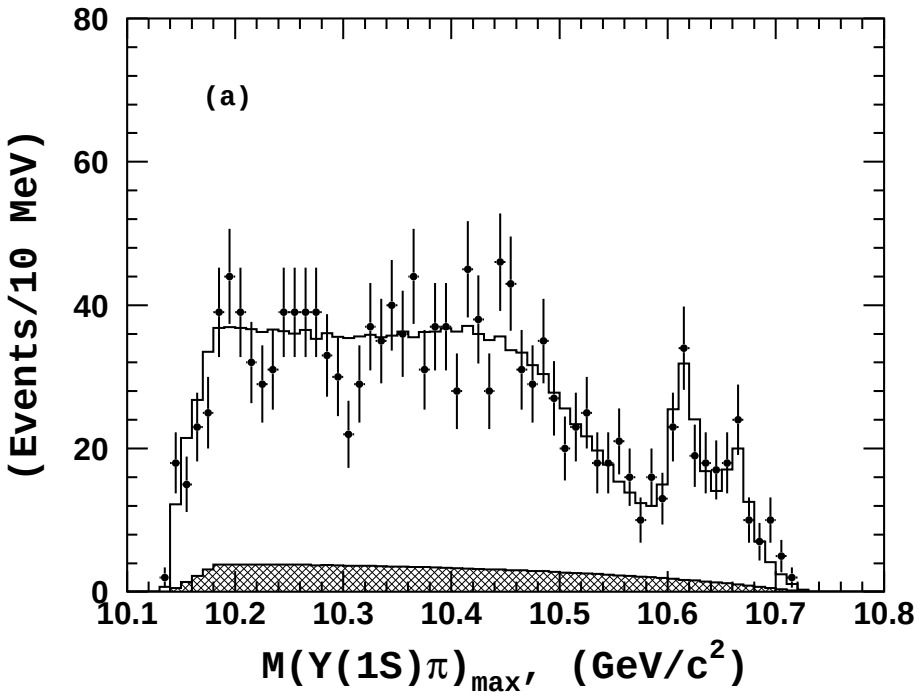
$X(3872)$ at CMS

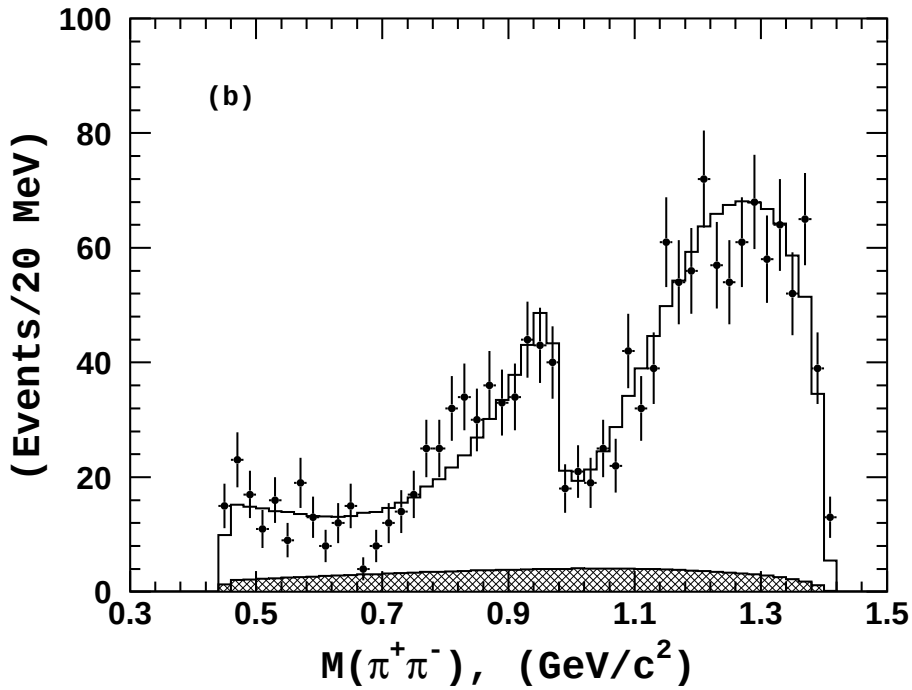

Candidates / 5 MeV/c²
J/ψ π⁺π⁻ invariant mass [GeV/c²]
N_X(3872) = 548 ± 104 (stat.)
N_ψ(2S) = 7346 ± 155(stat.)
√s = 7 TeV
∫L dt = 40 pb⁻¹
CMS Preliminary

$X(3872)$ at LHCb

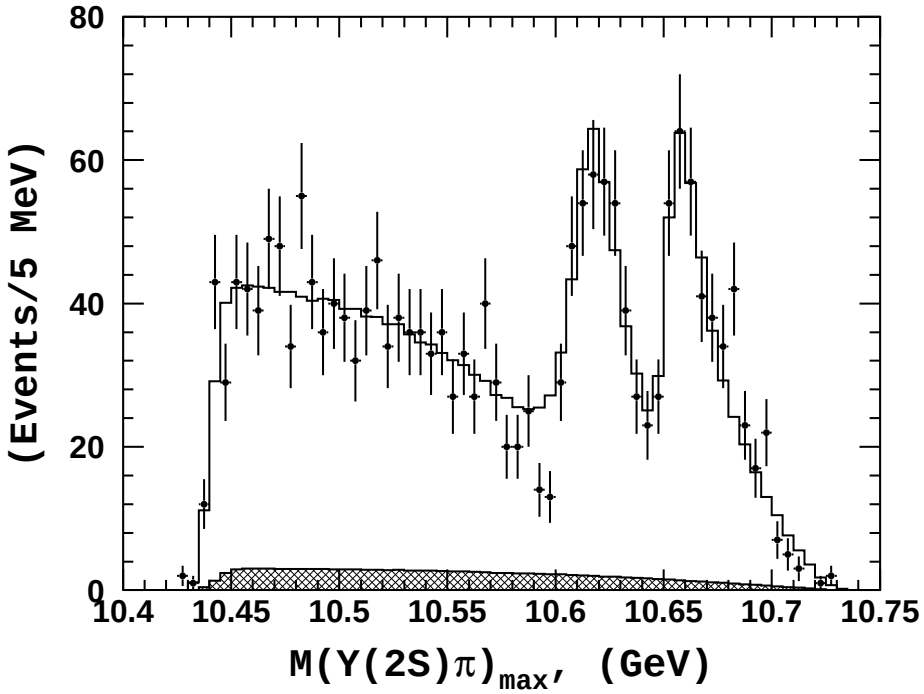


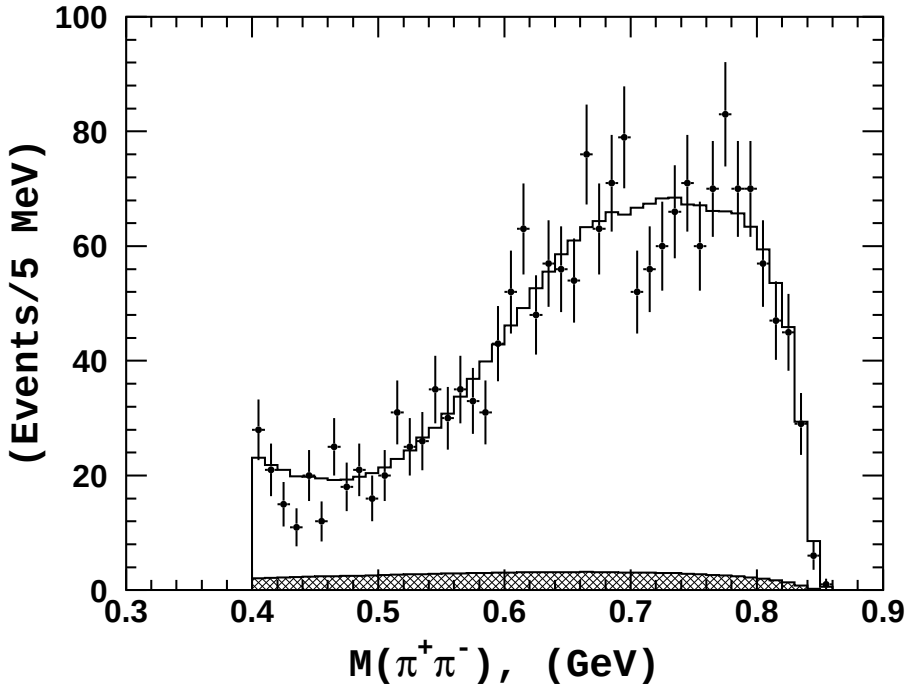
Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – II





Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – III





Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – IV