News on heavy quarkonia

Simon Eidelman

Budker Institute of Nuclear Physics RAS
and Novosibirsk State University,
Novosibirsk, Russia

Outline

1. X, Y, Z in charmonium
2. About bottomonia: $(h_b(1P, 2P)$, Z_b, $\eta_b)$
3. Conclusions

Introduction

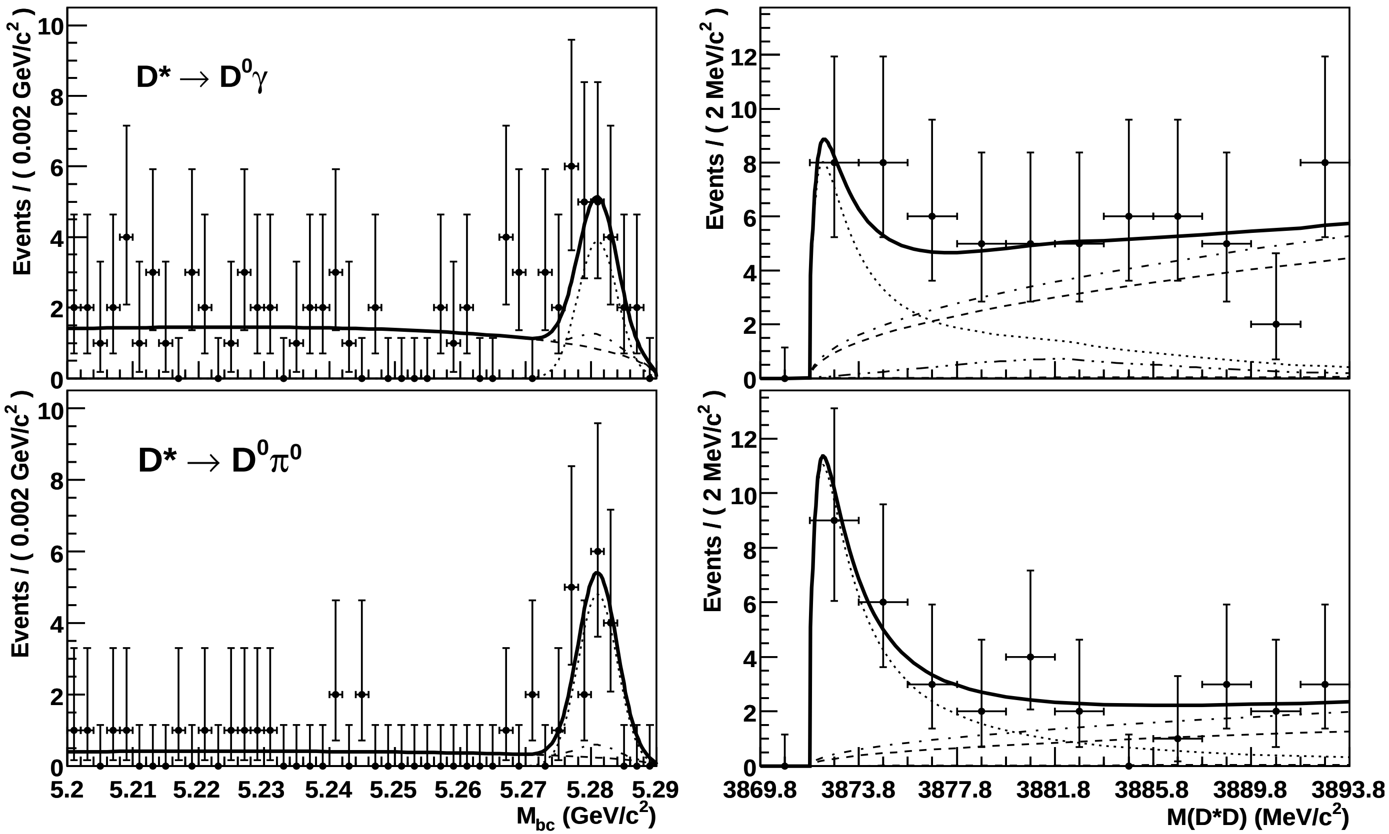
- The era of X, Y, Z (charmonium-like) states started in 2003 when Belle discovered $X(3872)$
- These states have mass above the open charm threshold, but mysteriously open charm decay modes are suppressed
- About 20 states belong to this family and usually do not find a place in the charmonium model
- Many models: tetraquark, hybrid, molecules, hadrocharmonium or, alternatively, effects of close thresholds, coupled channels and rescattering
- New exotic states found in bottomonia
- 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. (Belle), 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
- No evidence for two close $X(3872)$

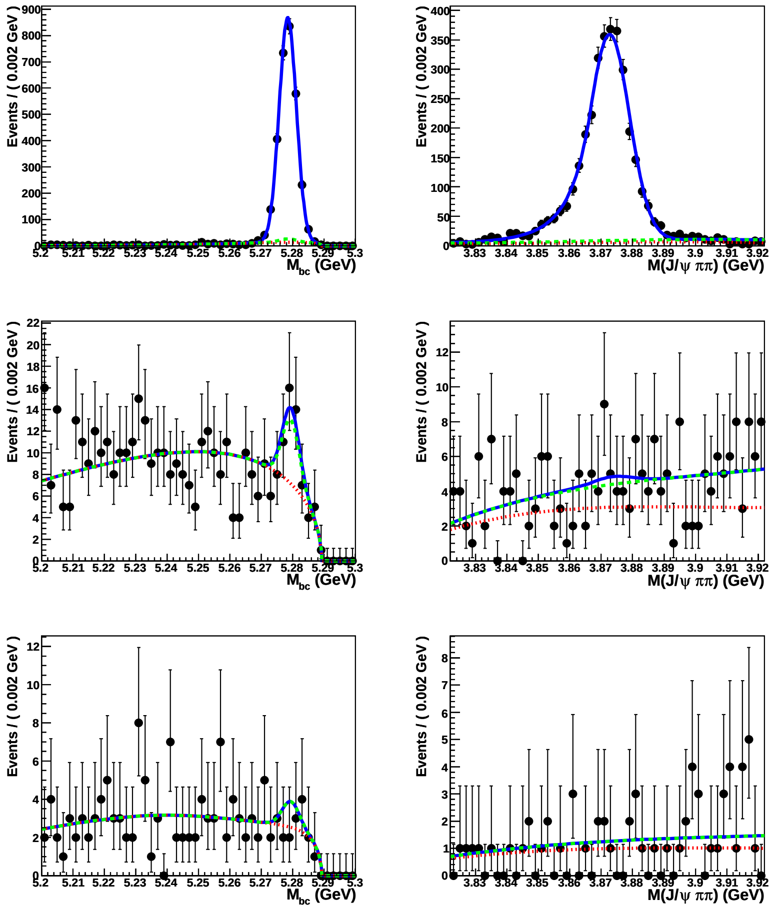
Study of $X(3872) \to \pi\pi J/\psi$ – I

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 $B^0 \to K^0 X$
- 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
- No evidence for different $X(3872)$ in B^+ and B^0
- $M = (3871.84 \pm 0.27 \pm 0.19)$ MeV – Belle
  $M = (3871.61 \pm 0.16 \pm 0.19)$ MeV – CDF

S.-K. Choi et al. (Belle), Phys. Rev. D 84, 052004 (2011)

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

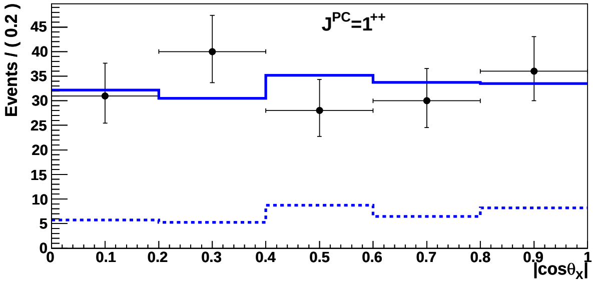


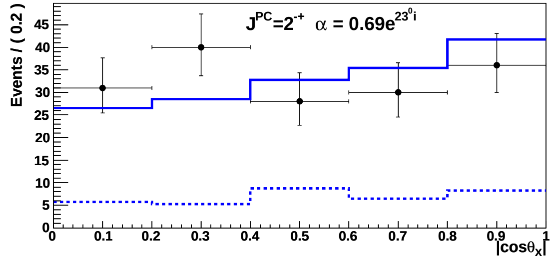
$\mathcal{B}(\bar{B}^0 \to K^- X^+) \cdot \mathcal{B}(X^+ \to \rho^+ J/\psi) <$ $3.9(5.4) \cdot 10^{-6}$

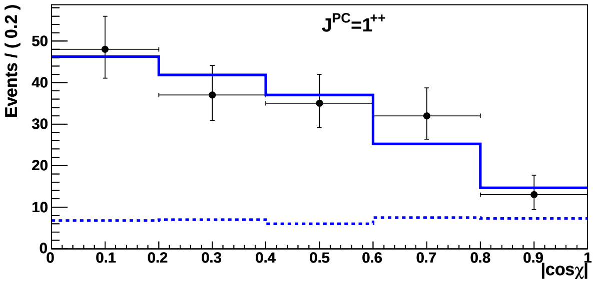
$\mathcal{B}(B^+ \to K^0 X^+) \cdot \mathcal{B}(X^+ \to \rho^+ J/\psi) <$ $4.5(22) \cdot 10^{-6}$

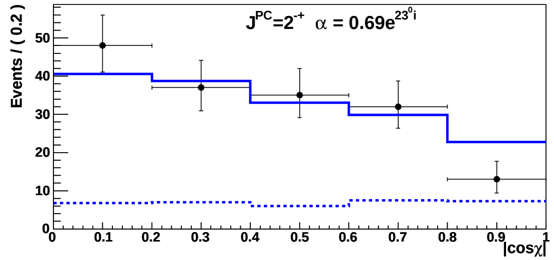
disfavoring $X^+(3872) \Rightarrow \ I = 0$

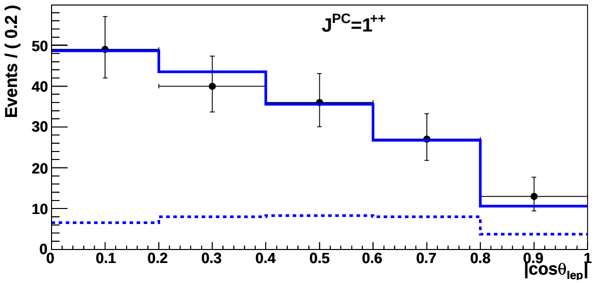
Study of $X(3872) \to \pi\pi J/\psi$ – III

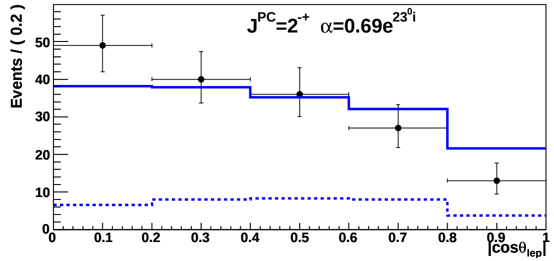








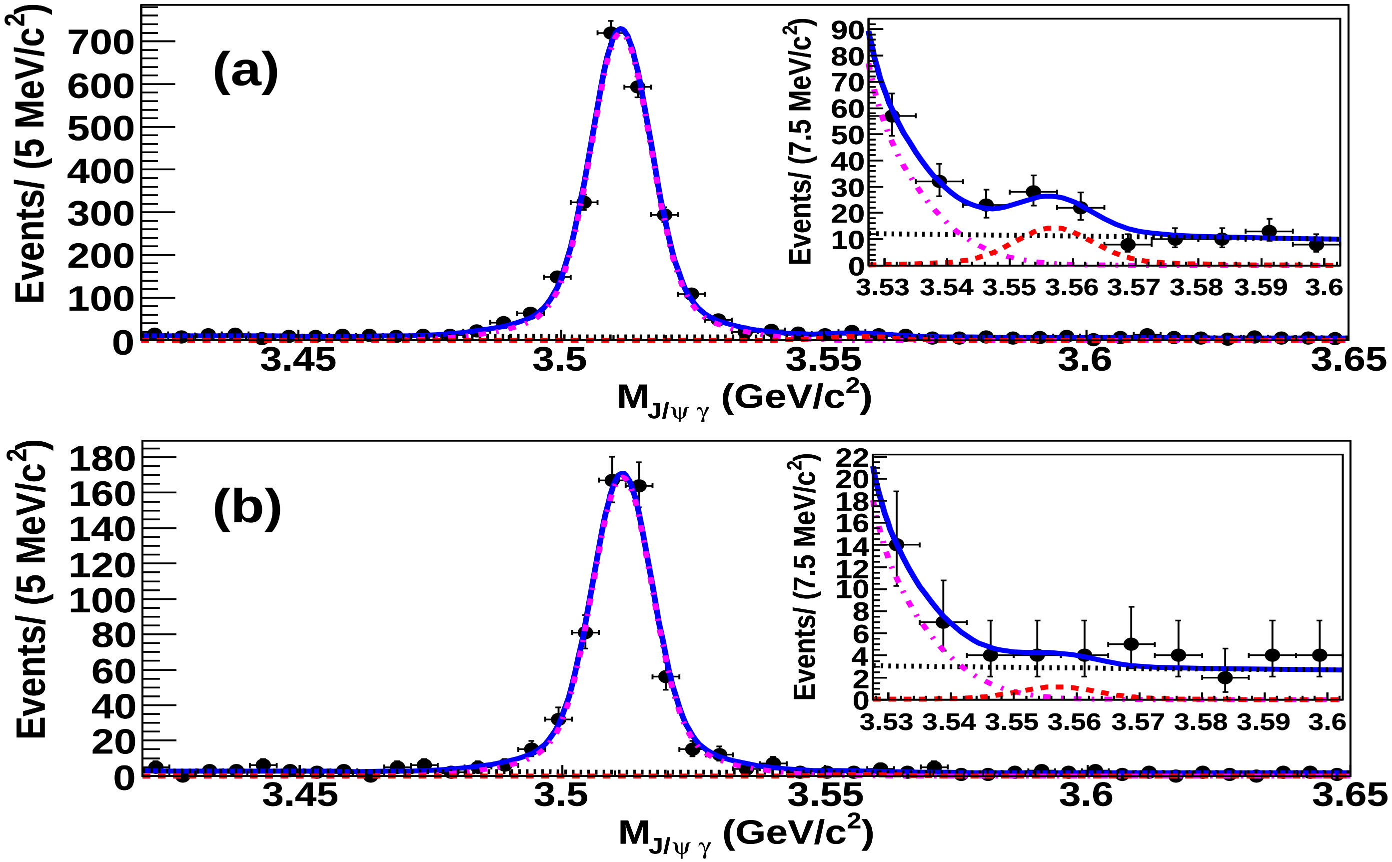




Both $J^{PC} = 1^{++}$ and 2^{-+} are possible

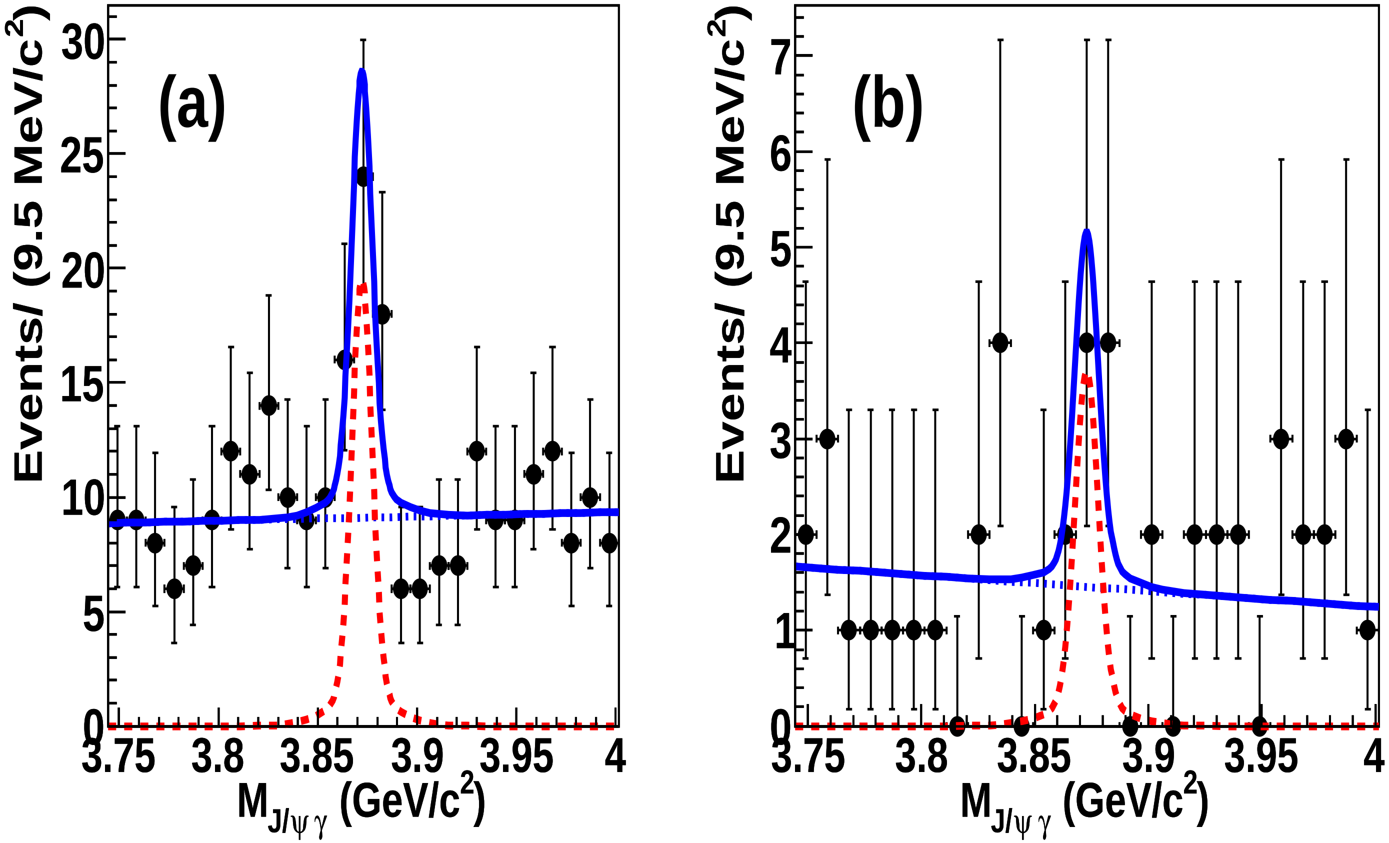
Study of $X(3872) \to J/\psi\gamma$ and Search for $X(3872) \to \psi'\gamma$ – I

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

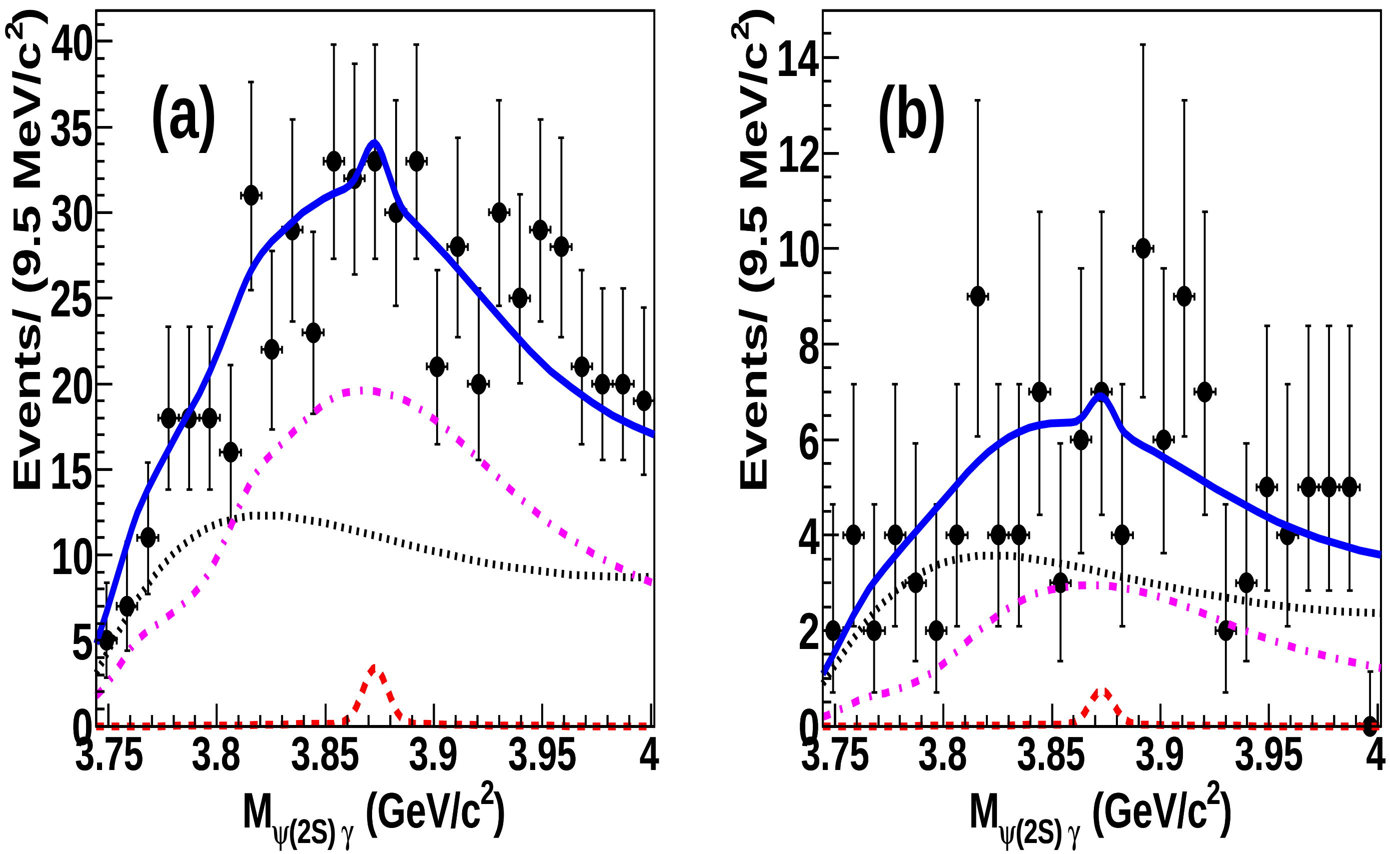


V. Bhardwaj et al. (Belle), Phys. Rev. Lett. 107, 091803 (2011)

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



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



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
$\int \mathcal{L}dt$, 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	$9.5 \pm 2.7 \pm 0.6$

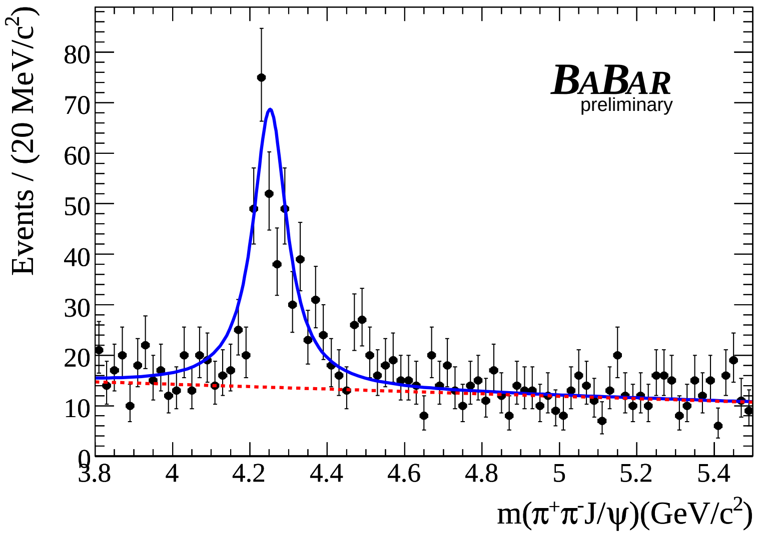
From the absence of $X(3872) \to \psi'\gamma$ it may not have a large $c\bar{c}$ admixture with a $D^{*0}\bar{D}^0$ molecular component

$Y(4260)$ 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 $(D^{(*)}\bar{D}^{(*)}$, $D_s^{(*)}\bar{D}_s^{(*)}$, $\psi'\pi^+\pi^-$, $\ldots)$ 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

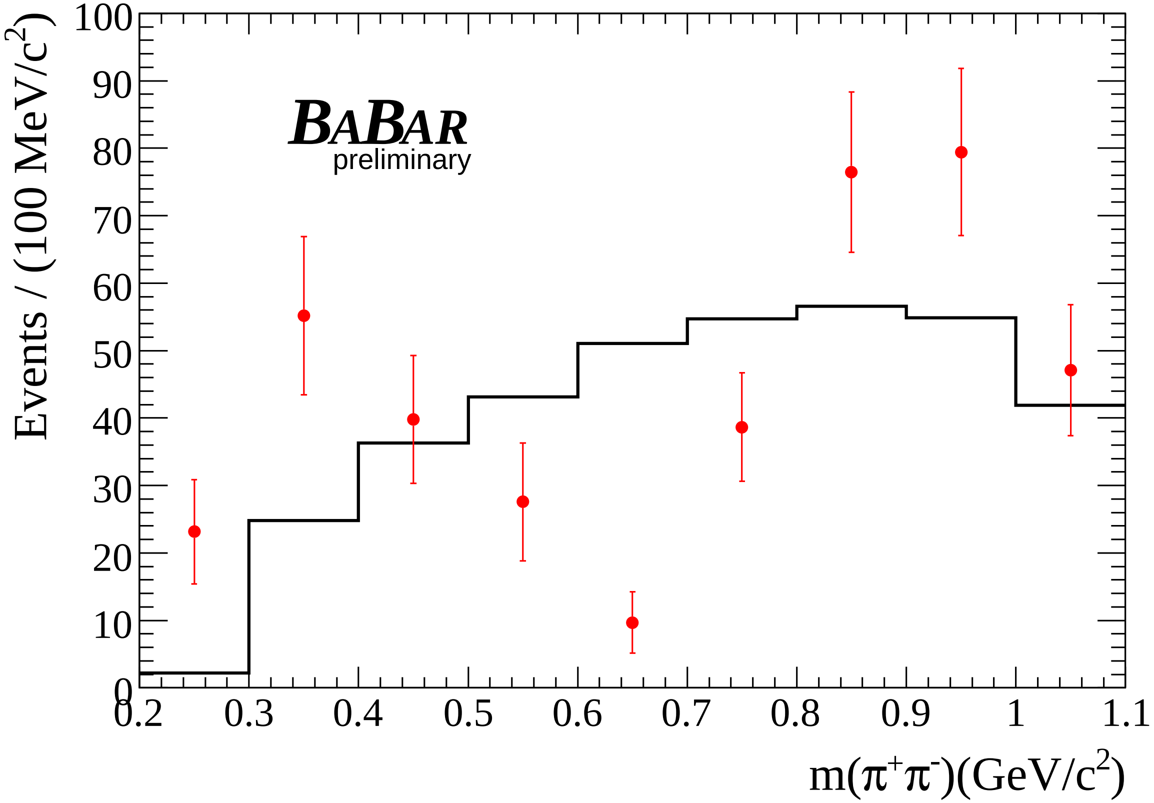


$M = 4252 \pm 6^{+2}_{-3}$ MeV, $\Gamma = 105 \pm 18^{+4}_{-6}$ MeV, $\Gamma_{e^+e^-}\mathcal{B}(J/\psi\pi^+\pi^-) = 7.5^{+0.9}_{-0.8}$ eV

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

$Y(4260) \to J/\psi\pi^0\pi^0$ at Belle

- CLEO in 2006 saw hints of two other decay modes at 4.26 GeV:

Mode	σ, pb
$J/\psi\pi^+\pi^-$	$58^{+12}_{-10} \pm 4$
$J/\psi\pi^0\pi^0$	$23^{+12}_{-8} \pm 1$
$J/\psi K^+K^-$	$9^{+9}_{-5} \pm 1$

- Belle observes a signal of $Y(4260) \to J/\psi\pi^0\pi^0$ using ISR from $\Upsilon(4S)$
- $\Gamma_{ee}\mathcal{B}(J/\psi\pi^0\pi^0) = (3.2^{+1.8+0.6}_{-1.5-0.4})$ eV or $\approx 0.5 \cdot (5.9^{+1.2}_{-0.9})$ eV for $J/\psi\pi^+\pi^-$

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

PRL100,112001(2008)

Puzzles of $\Upsilon(5S)$ decays

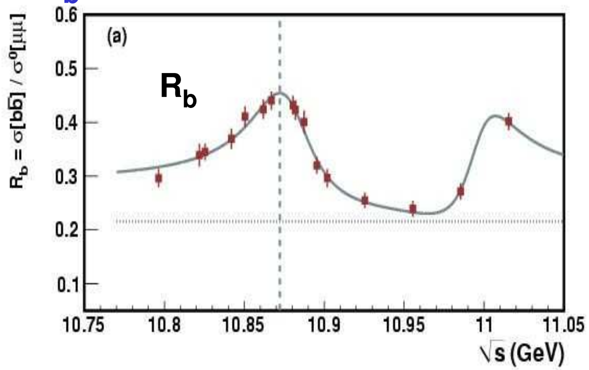
At 21.7 fb^{-1} Υ (5S) ->Υ(nS) $\pi^+\pi^-$ two orders of magnitude larger than in Υ (4S) decay

	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 $\sigma(\Upsilon\pi\pi)$ different (2σ)



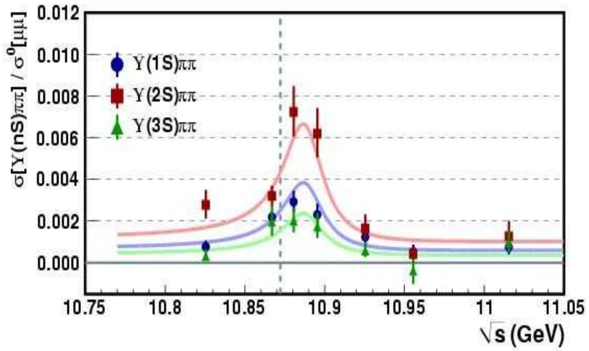
-Rescattering $\Upsilon(5S) \to BB\pi\pi \to \Upsilon(nS)\pi\pi$

Simonov JETP Lett 87,147(2008)

-Exotic resonance Y_b near $\Upsilon(5S)$

$\Upsilon(5S)$ is very interesting and not yet understood

Finally Belle recorded 121.4fb^{-1} at $\Upsilon(5S)$



arXiv:1104.2025

Observation of $e^+e^- \to \pi^+\pi^- h_c$ by CLEO

⇒ Belle search for h_b in $\Upsilon(5S)$ data

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

Dalitz plot analysis of $\Upsilon(5S)$ decays to

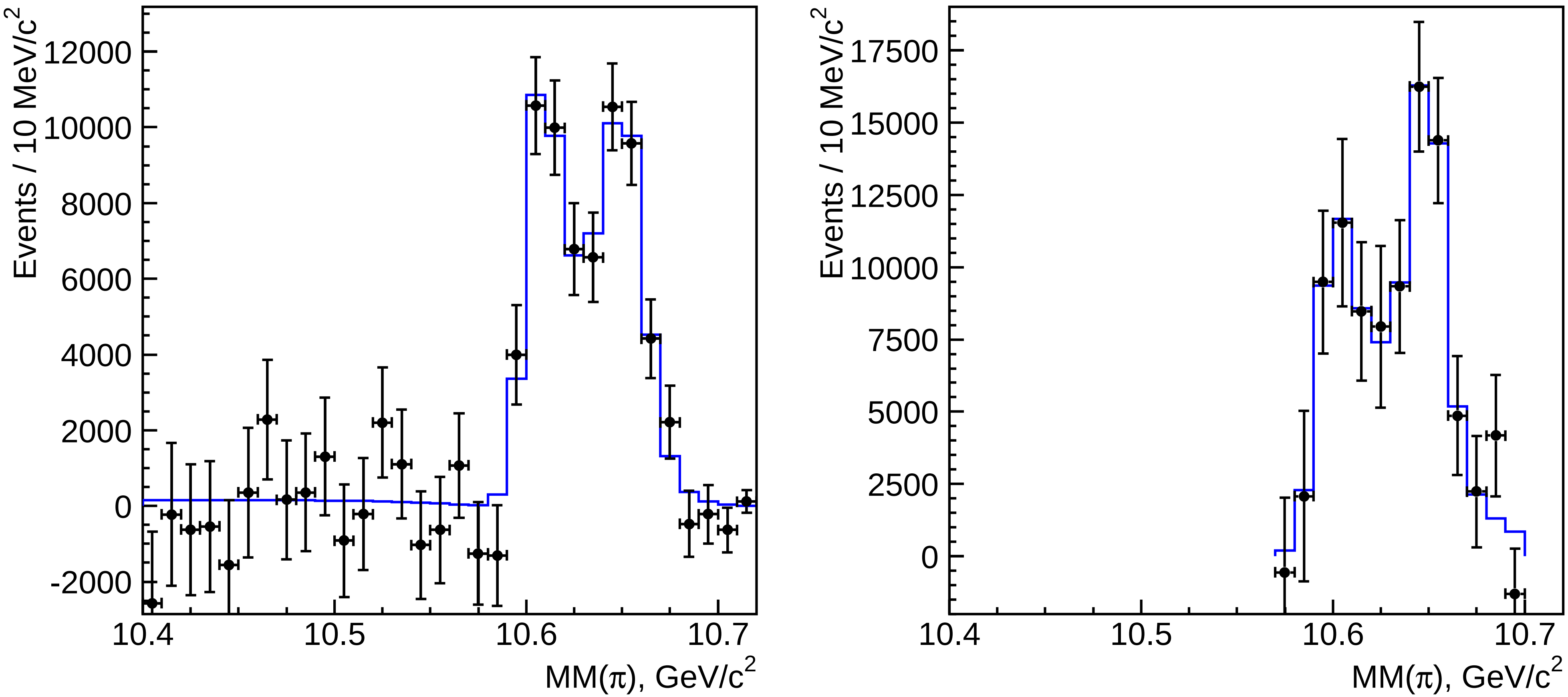
$h_b(1P)\pi^+\pi^-,\ h_b(2P)\pi^+\pi^-,$

$\Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(3S)\pi^+\pi^-$

shows the resonant structure in

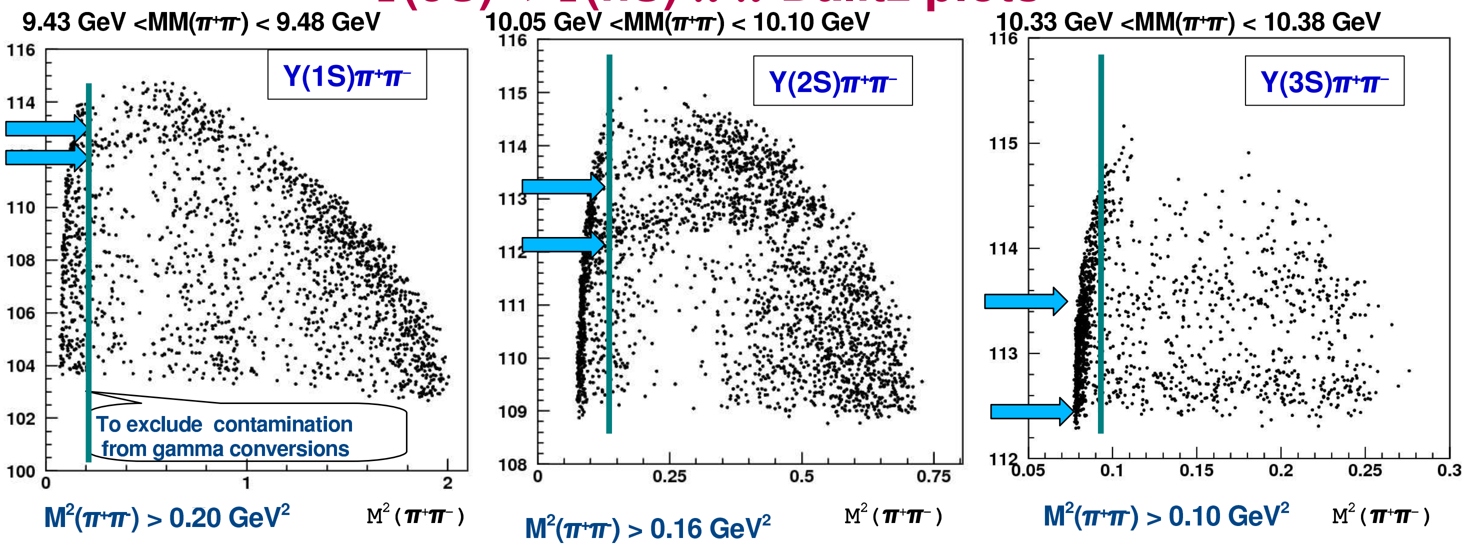
$\Upsilon(h_b)$ – Z_b.

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

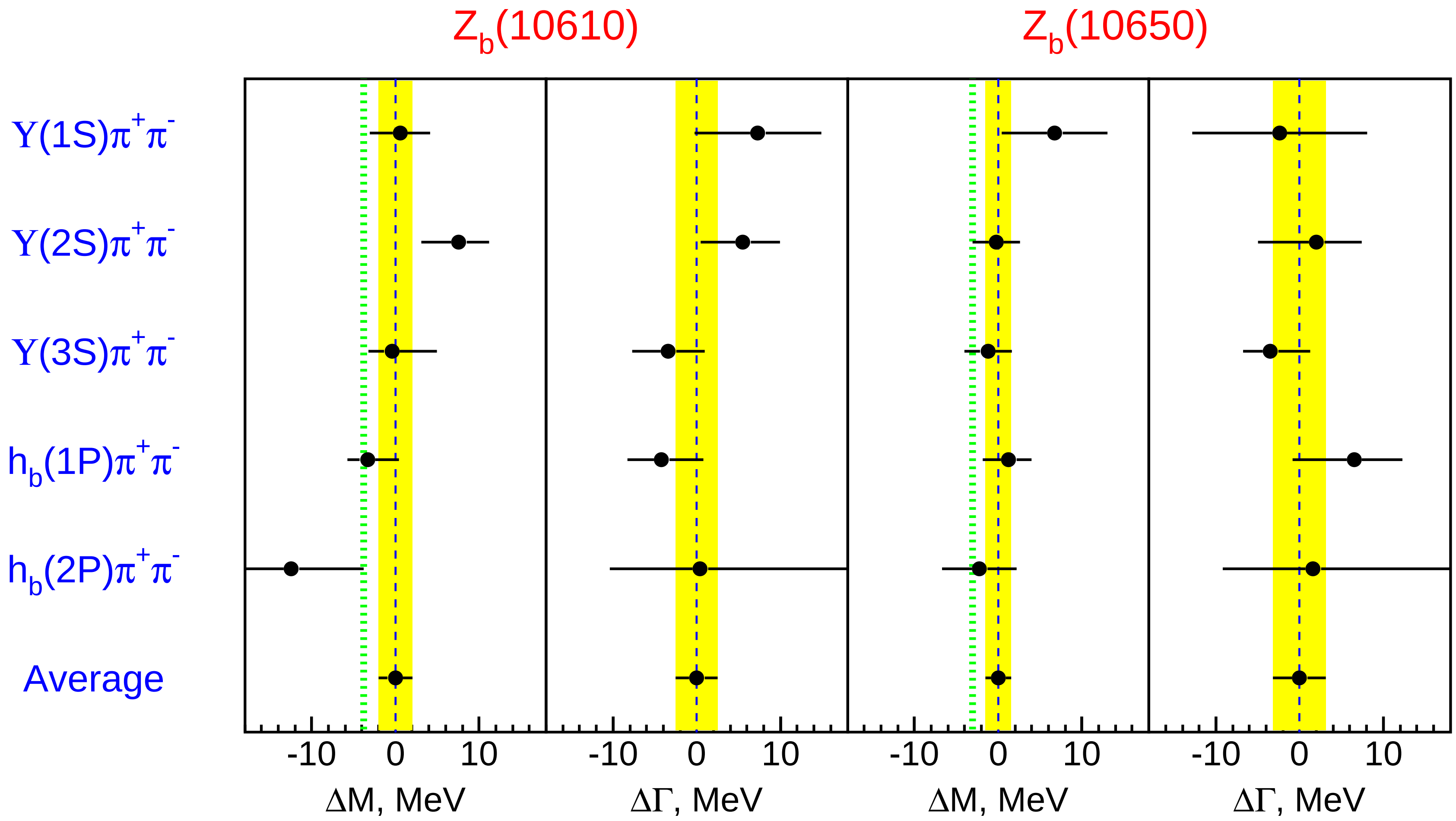
Relative phases are swapped for Υ and h_b final states ⇐ expectation from a 'molecular' model

$Z_b(10610)$
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

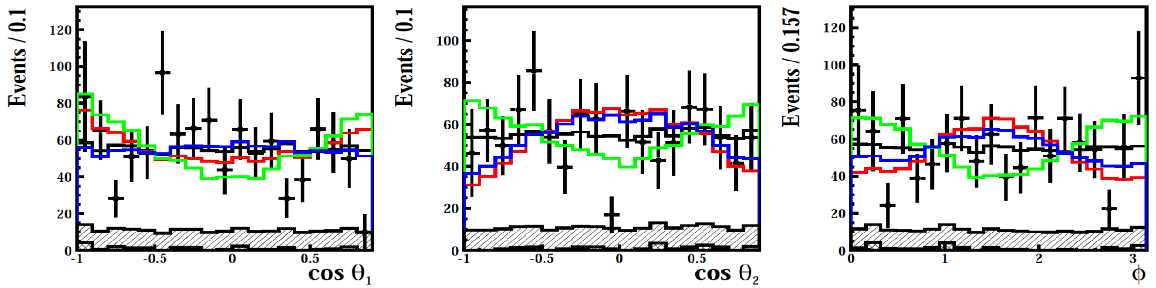
Observation of Charged $Z_b(10610)$ and $Z_b(10650)$ – I



Angular analysis

[preliminary]

$J^P = 1^+ \; 1^- \; 2^+ \; 2^-$



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

<table>
<tr><th rowspan="2">J^P</th><th colspan="3">$Z_b(10610)$</th><th colspan="3">$Z_b(10650)$</th></tr>
<tr><th>$\Upsilon(2S)\pi^+\pi^-$</th><th>$\Upsilon(3S)\pi^+\pi^-$</th><th>$h_b(1P)\pi^+\pi^-$</th><th>$\Upsilon(2S)\pi^+\pi^-$</th><th>$\Upsilon(3S)\pi^+\pi^-$</th><th>$h_b(1P)\pi^+\pi^-$</th></tr>
<tr><td>1^-</td><td>3.6σ</td><td>0.3σ</td><td>0.3σ</td><td>3.7σ</td><td>2.6σ</td><td>2.7σ</td></tr>
<tr><td>2^+</td><td>4.3σ</td><td>3.5σ</td><td rowspan="2">4.3σ</td><td>4.4σ</td><td>2.7σ</td><td rowspan="2">2.1σ</td></tr>
<tr><td>2^-</td><td>2.7σ</td><td>2.8σ</td><td>2.9σ</td><td>2.6σ</td></tr>
</table>

1+ assignment is favorable.

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

1

Observation of $h_b(1P) \to \eta_b(1S)\gamma$

- Belle recently observed $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$:
  $N(h_b(1P) \approx 50 \cdot 10^3$ 6σ 1103.3411
  $N(h_b(2P) \approx 84 \cdot 10^3$ 12σ 1105.4583
- It is tempting to search for η_b
- Expected decays (S. Godfrey and J. Rosner, Phys. Rev. D66, 014012 (2002)):

Branching fractions (%)

State	ggg	$\eta_b(1S)\gamma$	$gg\gamma$	$\eta_b(2S)\gamma$
$h_b(1P)$	57	41	2	–
$h_b(2P)$	63	13	2	19

What do we know about $\eta_b(1S)$?

- First claim from ALEPH in 2002 in 200 GeV e^+e^- at $9300 \pm 20 \pm 20$ MeV
- First observations by BaBar (2008, 2009) and CLEO (2010) in $\Upsilon(2S, 3S) \to \eta_b(1S)\gamma$
- World-average mass $M(\eta_b(1S)) = 9390.9 \pm 2.8$ MeV
- Hyperfine mass splitting $\Delta M_{\rm hf} = M(\Upsilon(1S)) - M(\eta_b(1S))$

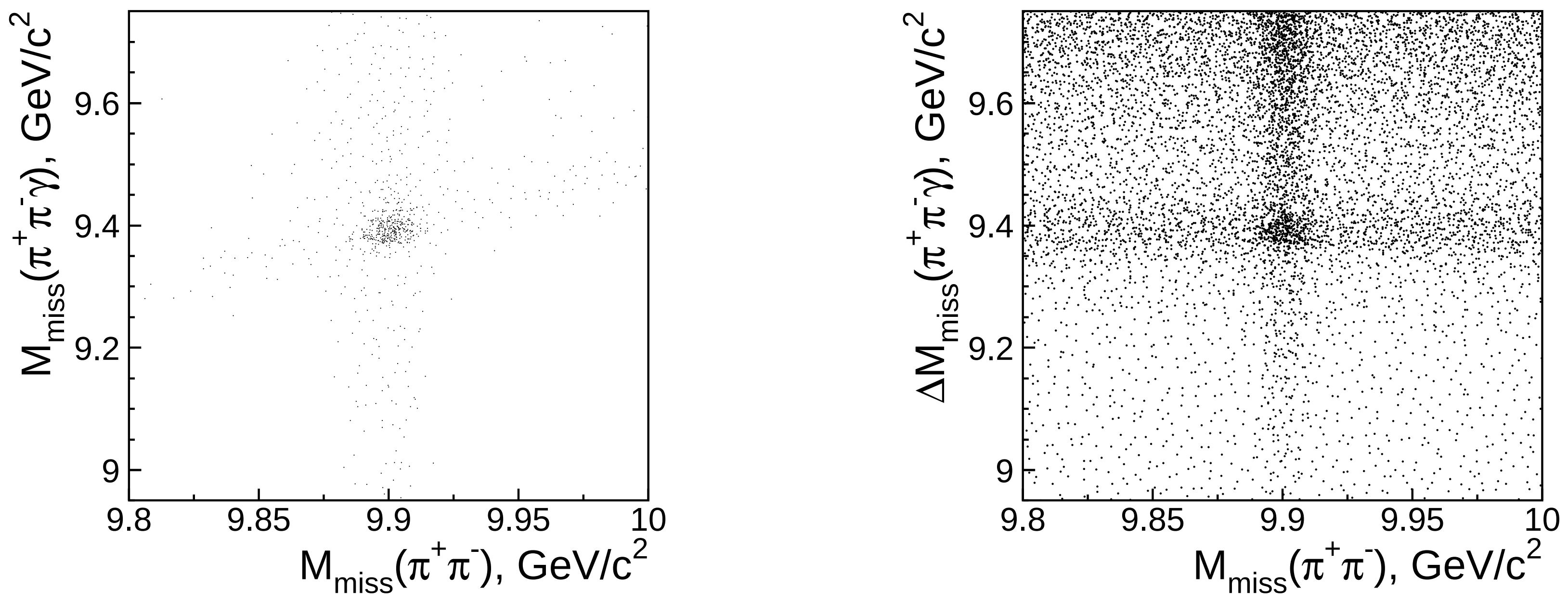
Source	ΔM, MeV	Reference
PDG, 2011	69.3 ± 2.8	PDG, 2011
pNRQCD	41 ± 14	B. Kniehl et al., PRL 92, 242001 (2004)
Lattice	60 ± 8	S. Meinel, PRD 82, 114502 (2010)

- Nothing is known about its width

Method – I

- Decay chain $\Upsilon(5S) \to Z_b^+ \pi^-$
  $\hookrightarrow \quad h_b(nP)\pi^+$
  $\hookrightarrow \quad \eta_b(mS)\gamma$
- We reconstruct π^-, π^+, γ and use missing masses to identify signal
- Missing mass to π^- is $M(Z_b^+)$,
  missing mass to $\pi^+\pi^-$ is $M(h_b)$,
  and missing mass to $\pi^+\pi^-\gamma$ is $M(\eta_b)$
- $\Delta M_{\rm miss}(\pi^+\pi^-\gamma) \equiv M_{\rm miss}(\pi^+\pi^-\gamma) - M_{\rm miss}(\pi^+\pi^-) + M(h_b)$
- We fit $M_{\rm miss}(\pi^+\pi^-)$ spectra in $\Delta M_{\rm miss}(\pi^+\pi^-\gamma)$ bins

Method – II



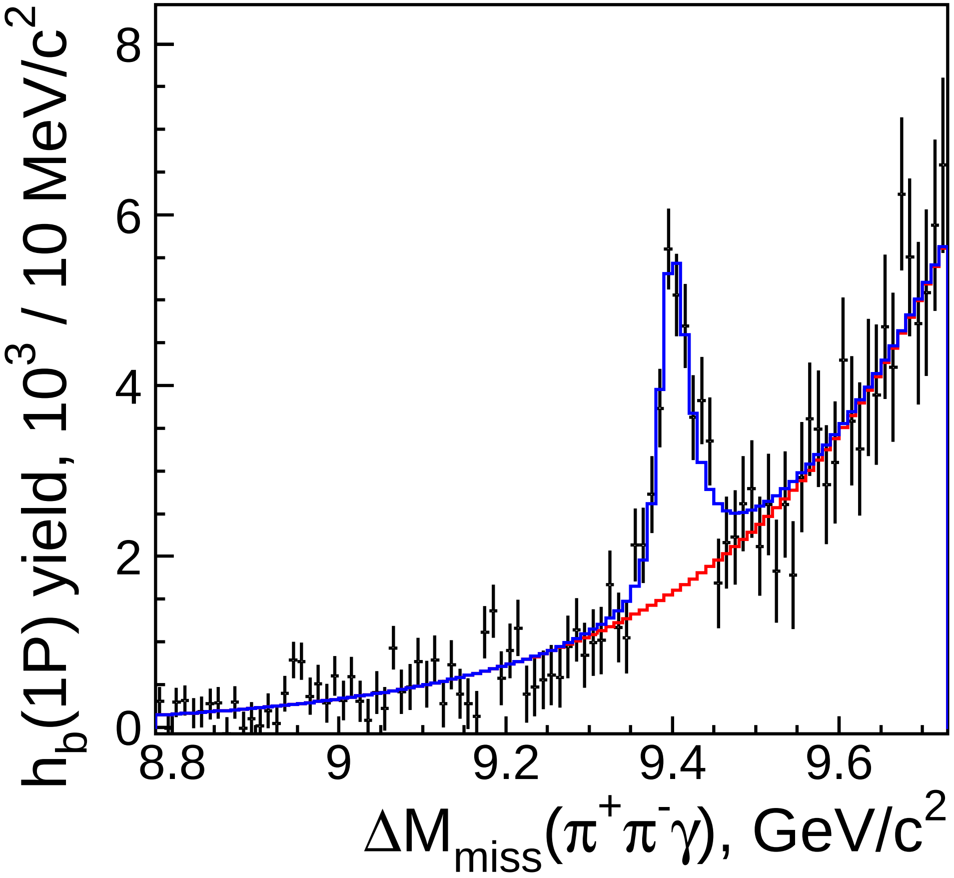
In the ideal world all events group in the center,

in reality there is resolution as well as background π and γ

The horizontal band for $\Delta M_{\text{miss}}(\pi^+\pi^-\gamma)$ corresponds to η_b, true γ and bg $\pi^+\pi^-$

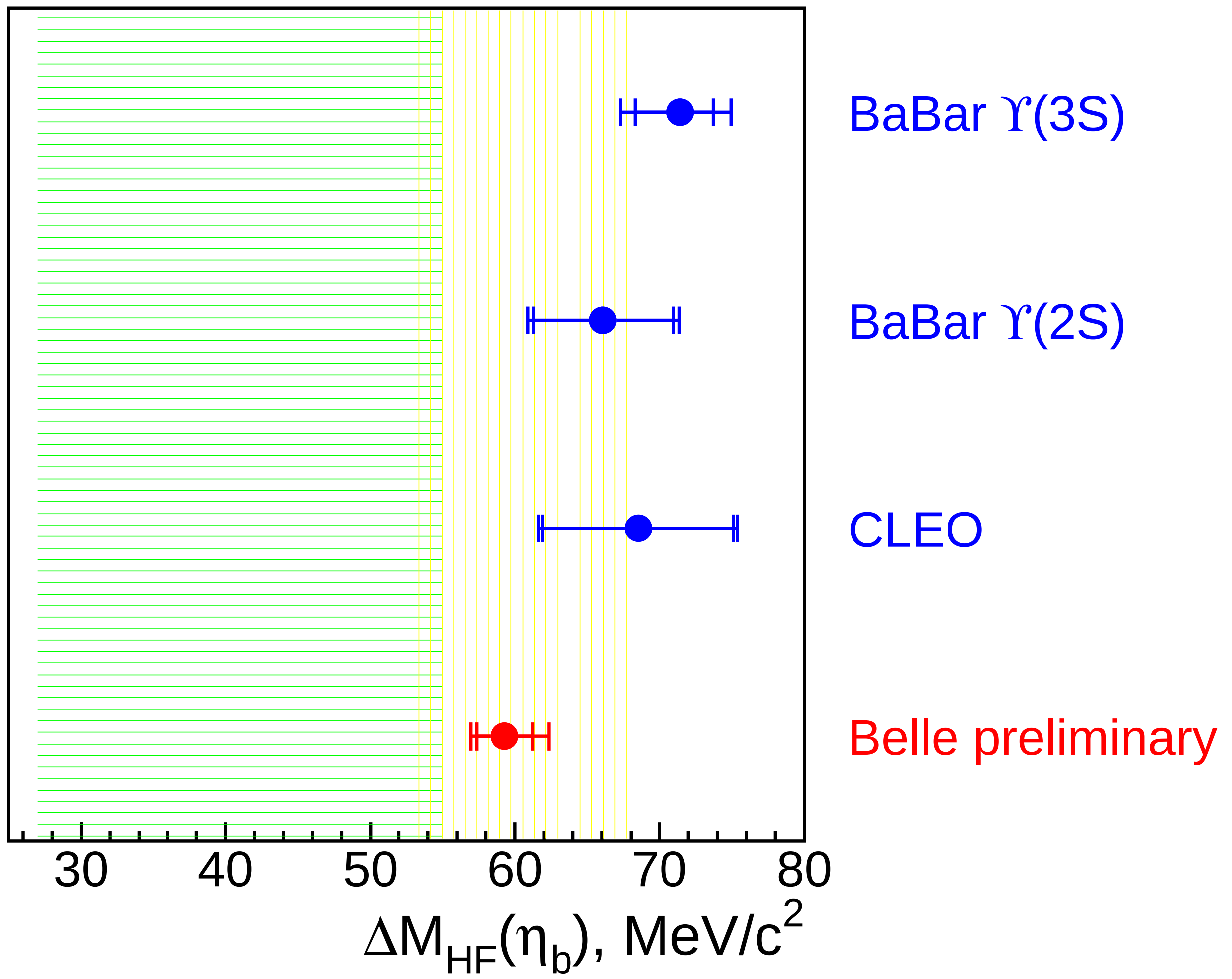
The vertical band for $M_{\text{miss}}(\pi^+\pi^-)$ corresponds to h_b, true $\pi^+\pi^-$ and bg γ

A final fit



$(21.9 \pm 2.0^{+5.7}_{-1.7}) \cdot 10^3$ events, or $13(14)\sigma$ significance(w/o syst.)

Comparison of mass measurements with theory



Summary on $\eta_b(1S)$

Quantity	Belle, 2011	PDG, 2011	Theory
Mass, MeV	$9401.0 \pm 1.9^{+1.9}_{-2.4}$	9390.9 ± 2.8	–
$\Delta M_{\rm hf}$, MeV	$59.3 \pm 1.9^{+2.4}_{-1.9}$	69.3 ± 2.8	40-60
Width, MeV	$12.4^{+5.5+11.5}_{-4.6-3.4}$	–	4-20, Potential
$\mathcal{B}(h_b(1P) \to \eta_b(1S)\gamma)$, %	$49.8 \pm 6.8^{+10.9}_{-\ 5.2}$	–	41 (GR, 2002)

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
- Properties of $\eta_b(1S)$ are well understood
- 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

Future

Measurement of Charming Form Factors
of Light Cones in QCD Penguin B-mesons

HAPPY BIRTHDAY,
ALEXANDER!