Exotic Heavy Quarkonium States

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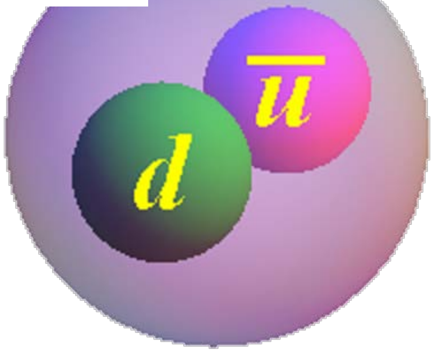
Constituent Quark Model

<u>mesons</u> **are bound states of a of quark and anti-quark:**

$$\pi^+ = u\bar{d} \quad \pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \quad \pi^- = d\bar{u}$$

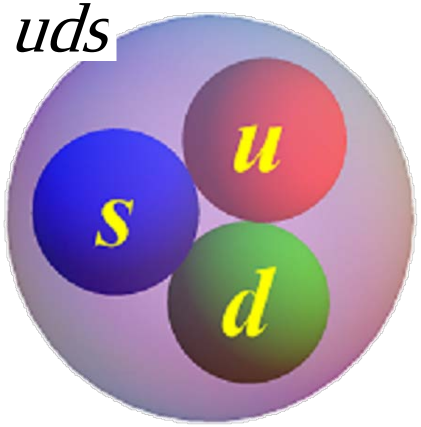
$$K^+ = u\bar{s} \quad K^0 = d\bar{s} \quad \bar{K}^0 = s\bar{d} \quad K^- = s\bar{u}$$

$$\pi^- = d\bar{u}$$



<u>baryons</u> **are bound state of 3 quarks:**

$$\Lambda = uds$$



$$p = uud \quad n = udd \quad \Lambda = uds$$

$$\bar{p} = \bar{u}\bar{u}\bar{d} \quad \bar{n} = \bar{u}\bar{d}\bar{d} \quad \bar{\Lambda} = \bar{u}\bar{d}\bar{s}$$

Quarkonium Basics

c, b -quarks are heavy:

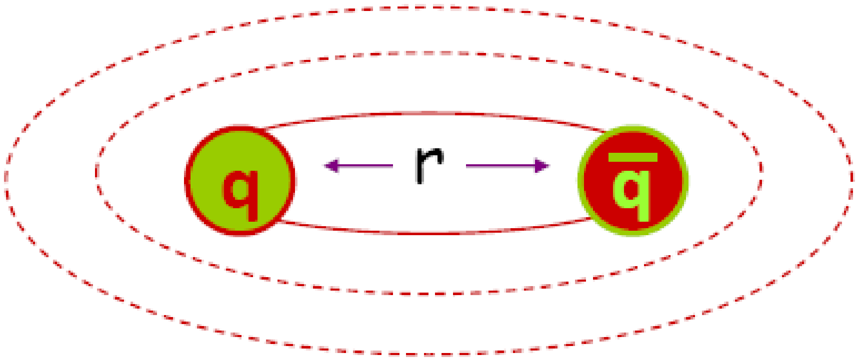
m_c ~ 1.5 GeV ~1.6 m_p ;

m_b ~ 4.5 GeV ~4.8 m_p ;

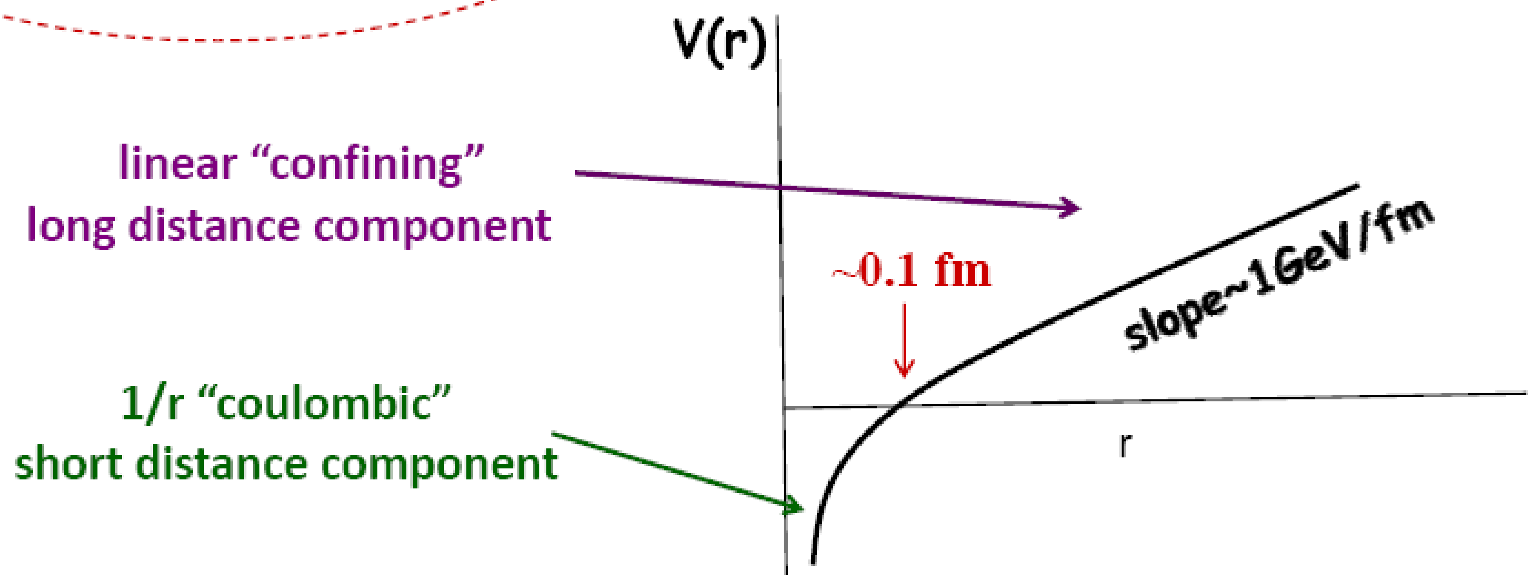
velocities are small:

v/c~1/4 (for $b\bar{b}$, v/c~0.1)

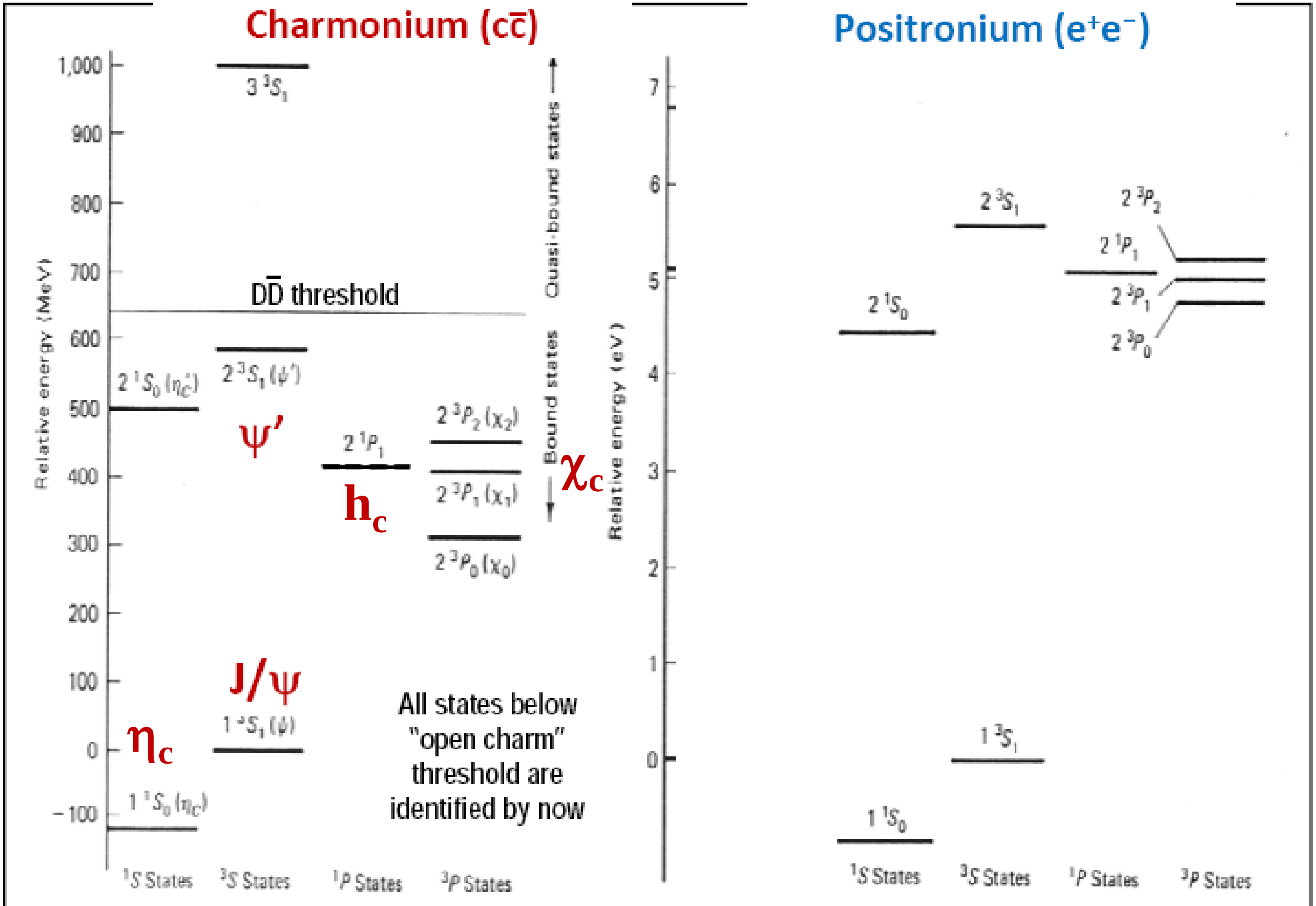
non-relativistic QM applies



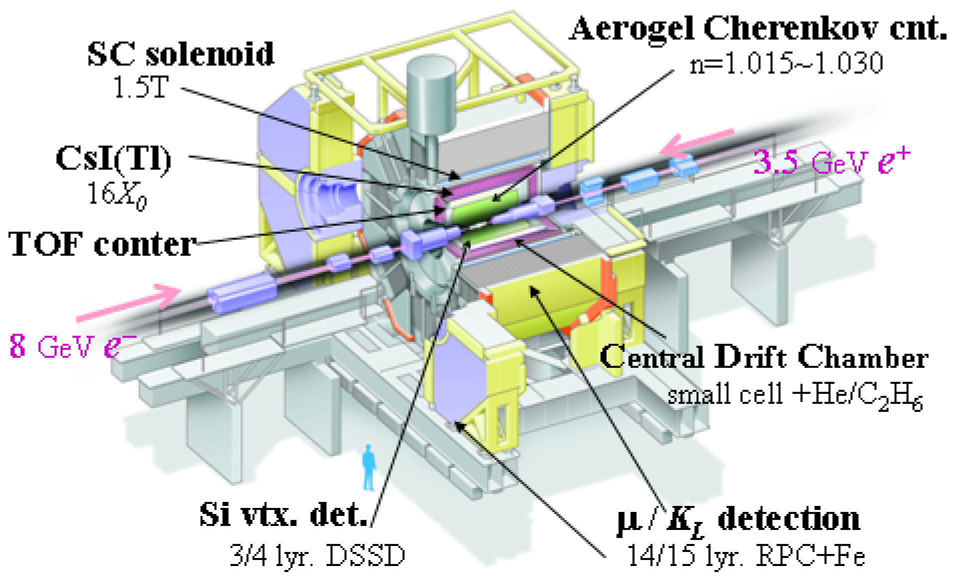
$$-\frac{\hbar^2}{2m_r}\nabla^2\Psi + V(r)\Psi = E\Psi$$

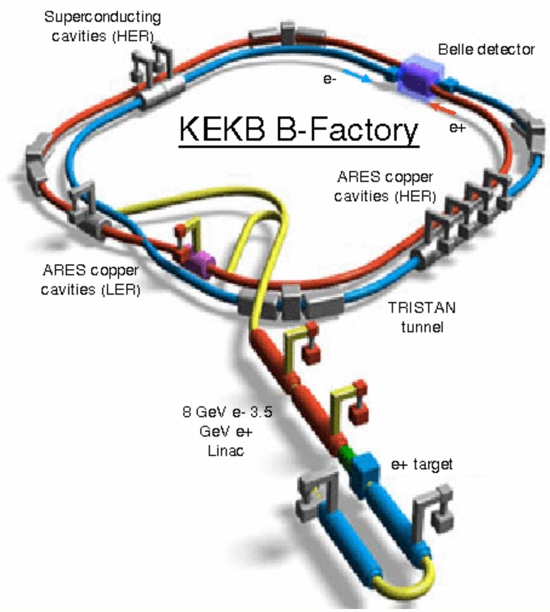


Quarkonium vs Positronium

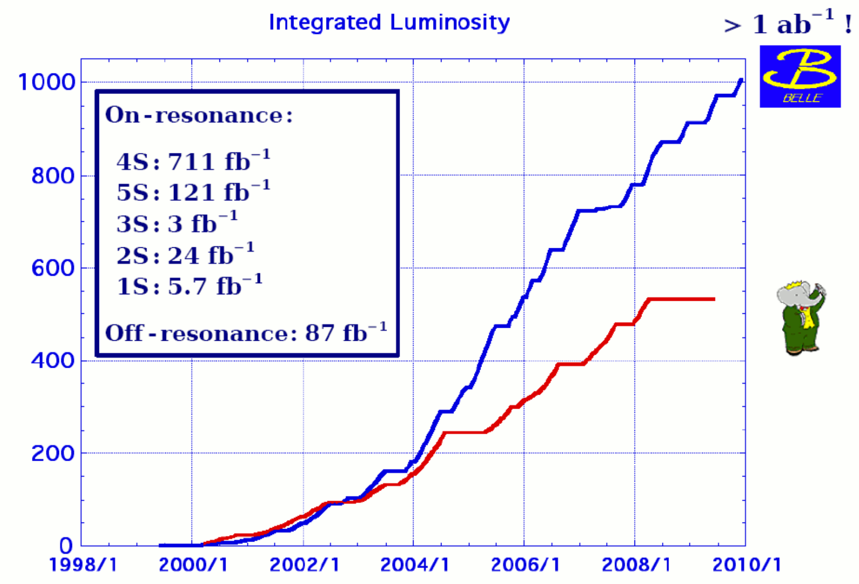


Belle Detector

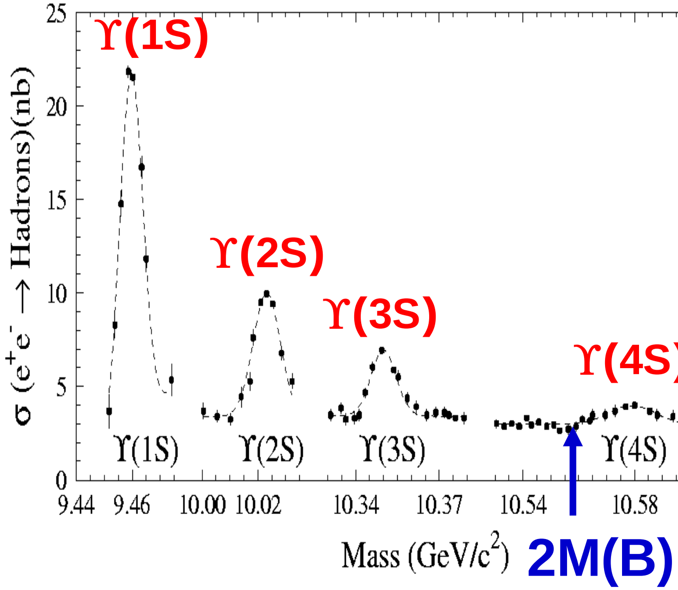


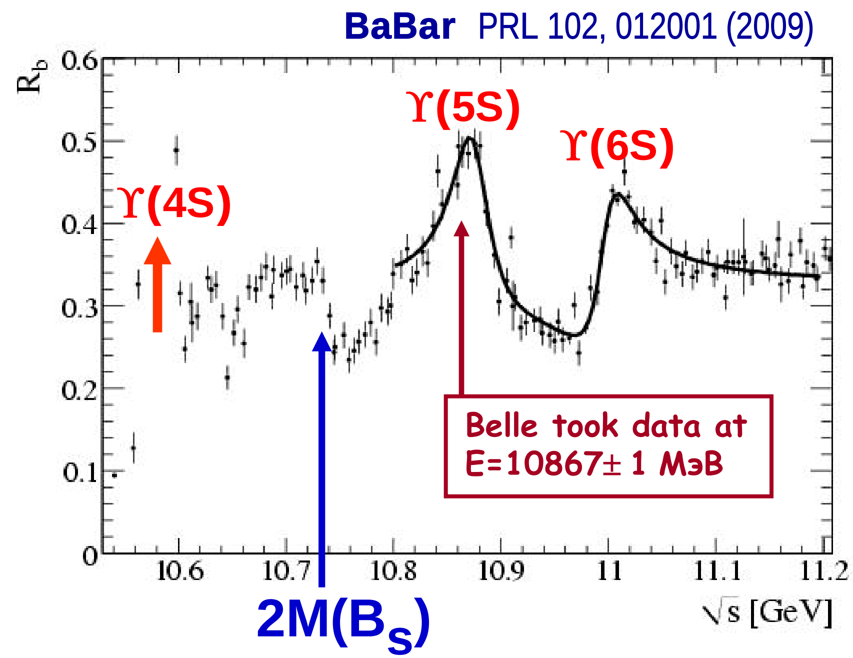


- 3.5 GeV $e^+ \times 8.0$ GeV e^-.
- $\mathcal{L}_{\max} = 2.1 \times 10^{34} cm^{-2} s^{-1}$
- Continuous injection $\rightarrow 1.1\,\mathrm{fb}^{-1}/\mathrm{day}$.
- $\int \mathcal{L} dt \approx 1\, ab^{-1}$



e^+e^- hadronic cross-section





$e^+ e^- \to \Upsilon(4S) \to B\bar{B}$, where B is B^+ or B^0

$e^+ e^- \to b\bar{b}\ (\Upsilon(5S)) \to B^{(*)}\bar{B}^{(*)}$, $B^{(*)}\bar{B}^{(*)}\pi$, $B\bar{B}\pi\pi$, $B_s^{(*)}\bar{B}_s^{(*)}$

main motivation
for taking data at ϒ(5S)

Puzzles of Υ(5S) decays

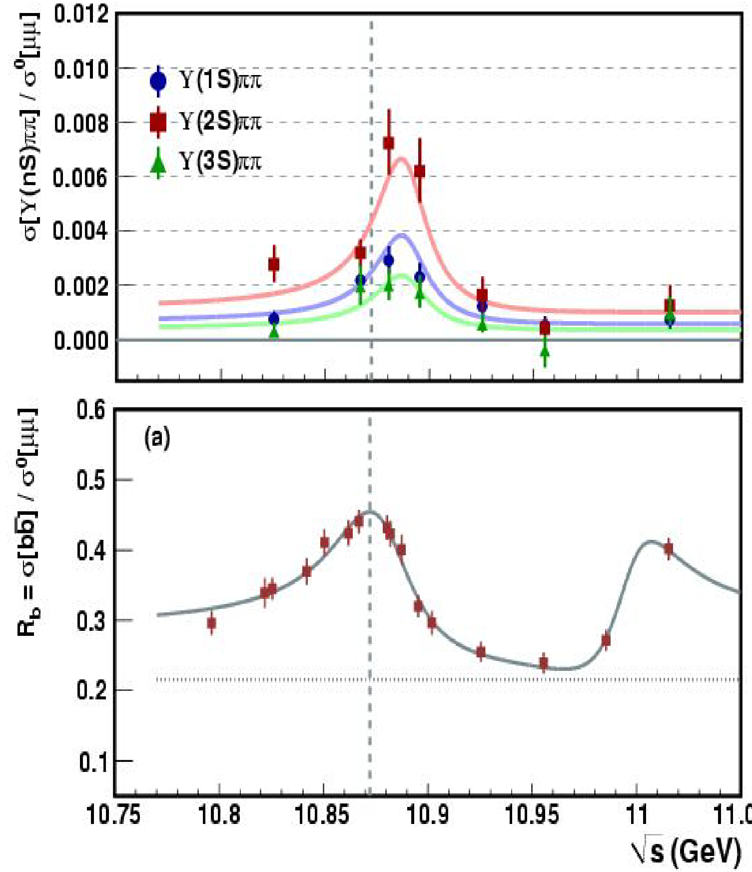
Anomalous production of $\Upsilon(nS)\,\pi^+\pi^-$ with 21.7 fb^{-1}

PRL100,112001(2008)

	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

10^2

PRD82,091106R(2010)



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

Simonov JETP Lett 87,147(2008)

(2) Exotic resonance Y_b near Υ(5S)
analogue of Y(4260) resonance
with anomalous $\Gamma(J/\psi\,\pi^+\pi^-)$

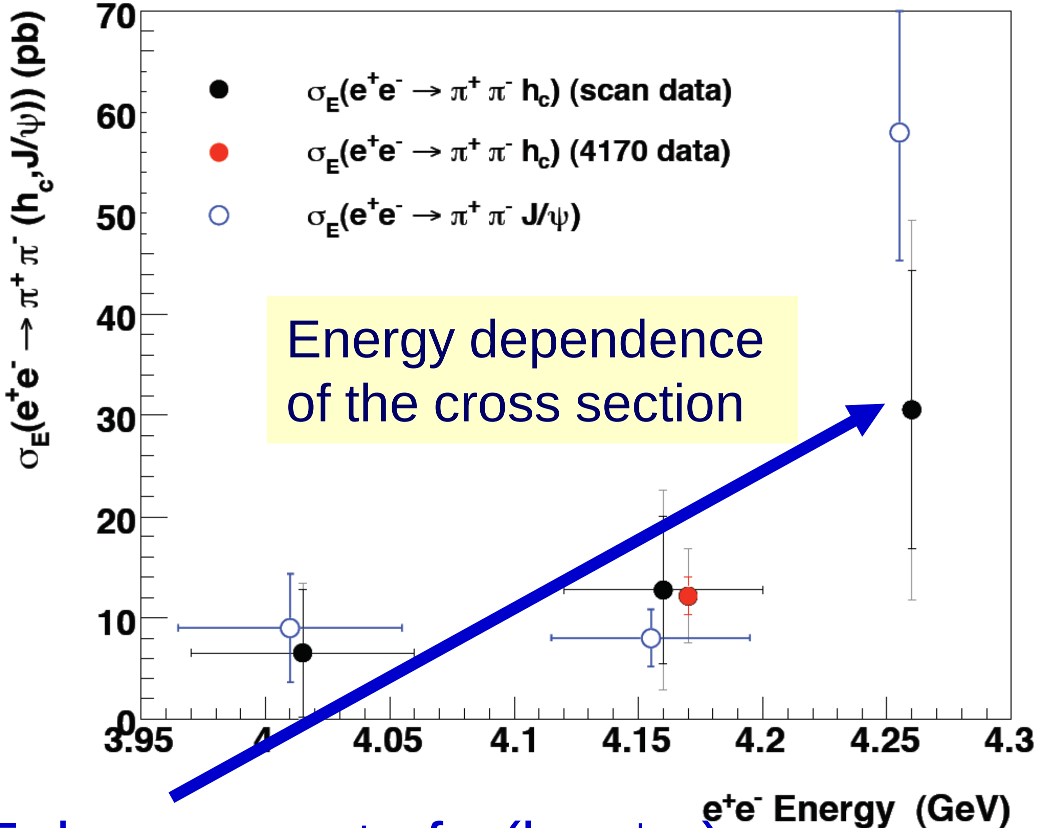
Dedicated energy scan $\Rightarrow$
shapes of R_b and $\sigma(\Upsilon\pi\pi)$ different (2σ)

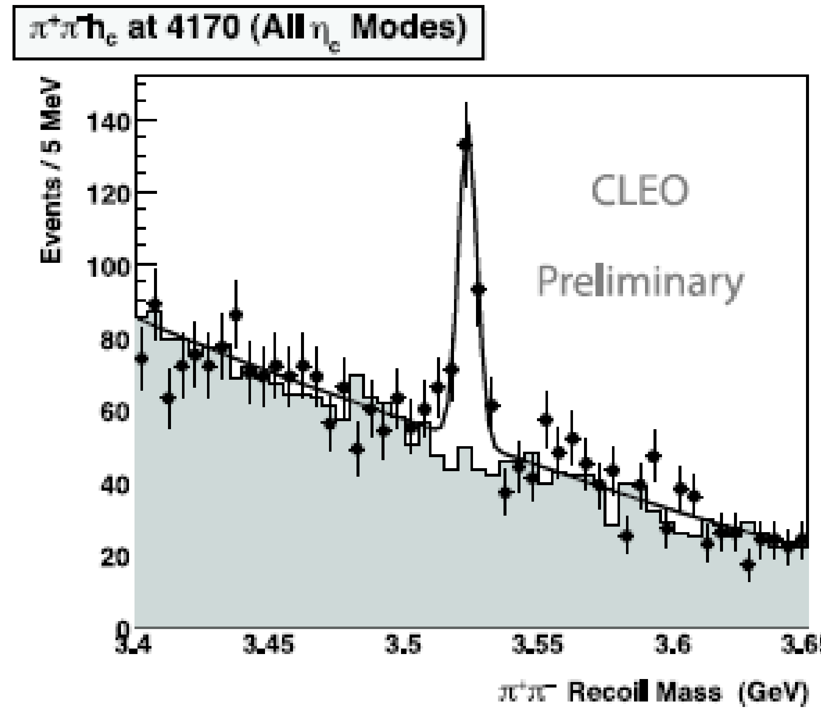
Υ(5S) is very interesting and not yet understood
Finally Belle recorded 121.4fb^{-1} data set at Υ(5S)

Motivation

Observation of $e^+e^- \to \pi^+\pi^- h_c$ by CLEO arXiv:1104.2025

Ryan Mitchell @ CHARM2010





Enhancement of $\sigma(h_c\,\pi^+\pi^-)$ @ Y(4260) $\Rightarrow$ $\sigma(h_b\,\pi^+\pi^-)$ is enhanced @ Y_b?

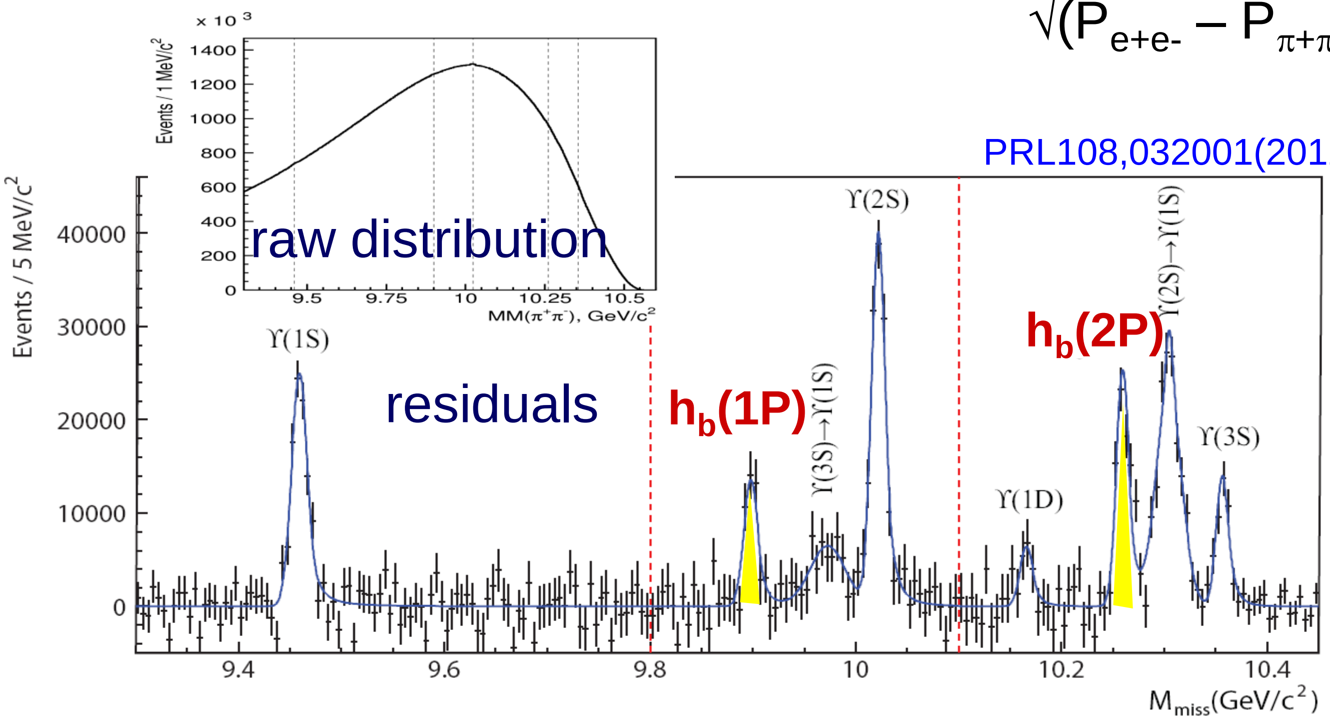
$\Rightarrow$ Belle search for h_b in $\Upsilon(5S)$ data

Observation of $h_b(1P,2P)$

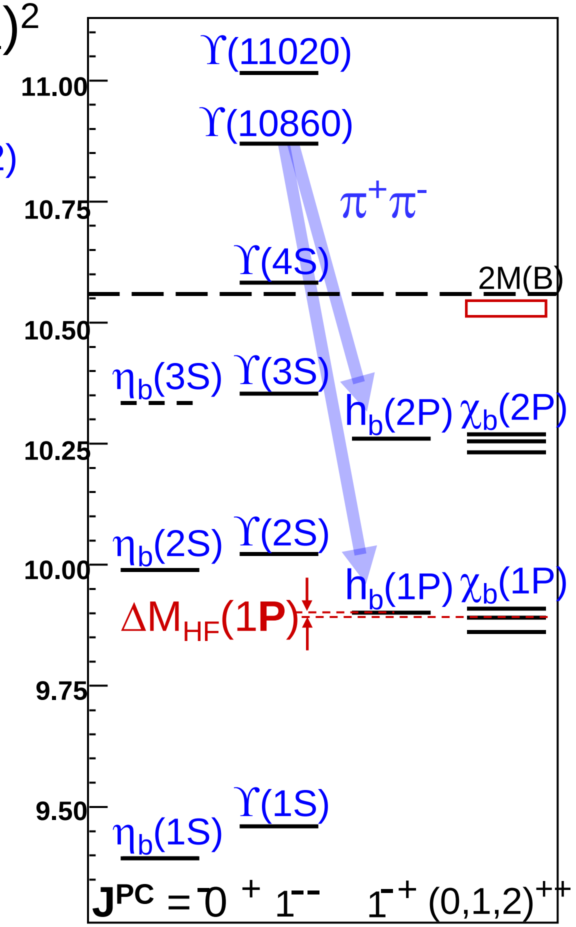
$e^+e^- \to \Upsilon(5S) \to h_b(nP)\ \pi^+\pi^-$ ← reconstructed, use $M_{miss}(\pi^+\pi^-)$

$\sqrt{(P_{e+e-} - P_{\pi+\pi-})^2}$

PRL108,032001(2012)



Belle arxiv:1205.6351



$\Delta M_{HF}(\mathbf{1P}) = +0.8 \pm 1.1$ MeV
$\Delta M_{HF}(\mathbf{2P}) = +0.5 \pm 1.2$ MeV

consistent with zero, as expected

Large $h_b(1,2P)$ production rates

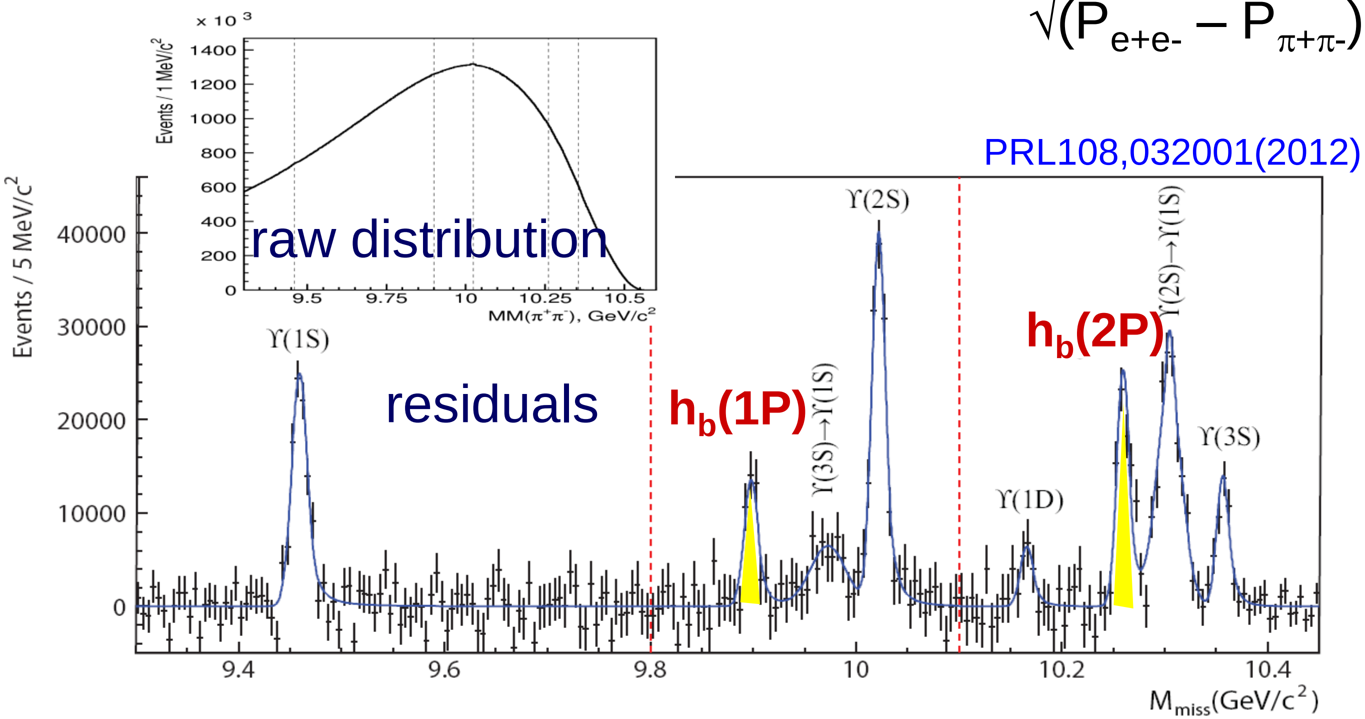
c.f. CLEO $e^+e^- \to \psi(4170) \to h_c\ \pi^+\pi^-$

Observation of h_b(1P,2P)

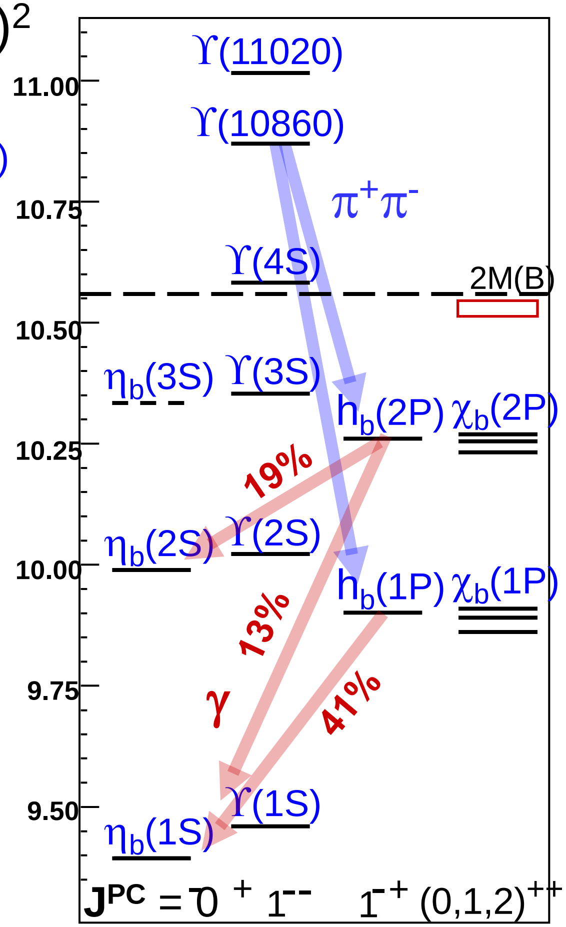
$e^+e^- \to \Upsilon(5S) \to h_b(nP)\ \pi^+\pi^-$ ← reconstructed, use **$M_{miss}(\pi^+\pi^-)$**

$\sqrt{(P_{e+e-} - P_{\pi+\pi-})^2}$

PRL108,032001(2012)



Belle arxiv:1205.6351



ΔM_{HF}(**1P**) = +0.8 ± 1.1 MeV

ΔM_{HF}(**2P**) = +0.5 ± 1.2 MeV

consistent with zero, as expected

Large h_b(1,2P) production rates

c.f. CLEO $e^+e^- \to \psi(4170) \to h_c\ \pi^+\pi^-$

h_b(nP) decays are a source of η_b(mS)

Observation of $h_b(1P,2P) \to \eta_b(1S)\,\gamma$

$e^+e^- \to \Upsilon(5S) \to h_b(nP)\ \pi^+\pi^-$ reconstruct

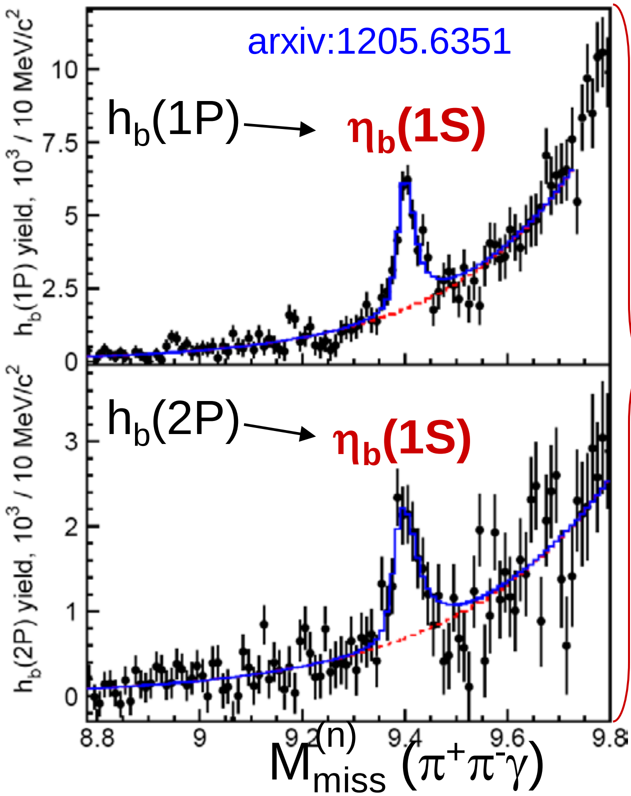
$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \lfloor\!\to \eta_b(1S)\ \gamma$

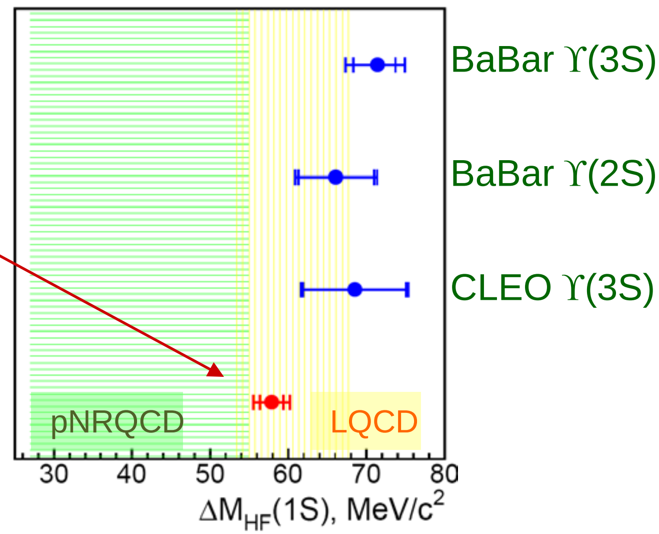
$\Delta M_{HF}(1S)$

Belle : 57.9 ± 2.3 MeV

PDG'12 : 69.3 ± 2.8 MeV

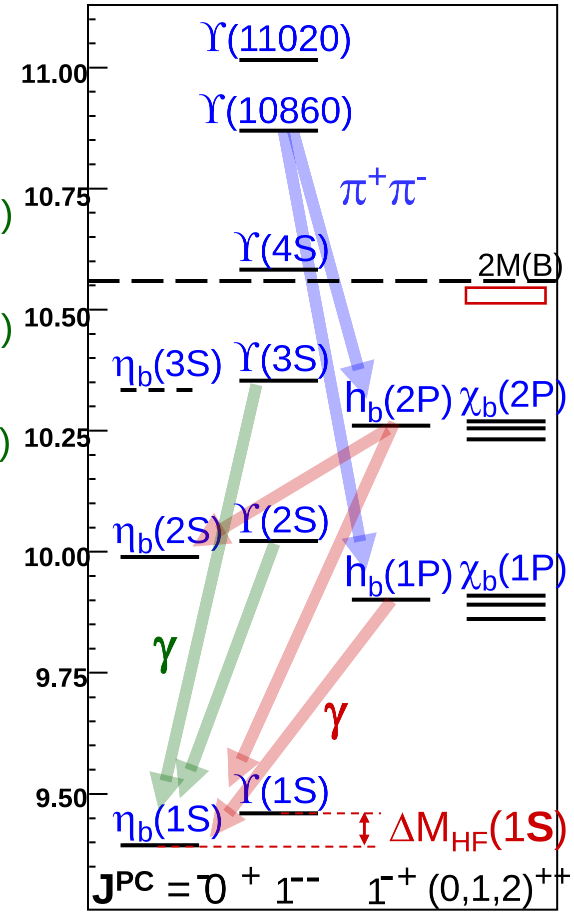
3σ





Kniehl et al, PRL92,242001(2004)

Meinel, PRD82,114502(2010)



Mizuk et al. Belle PRL 109 (2012) 232002

Belle result decreases tension with theory

First measurement $\Gamma = 10.8\,^{+4.0}_{-3.7}\,^{+4.5}_{-2.0}$ MeV

as expected

Observation of $h_b(1P,2P) \to \eta_b(1S)\,\gamma$

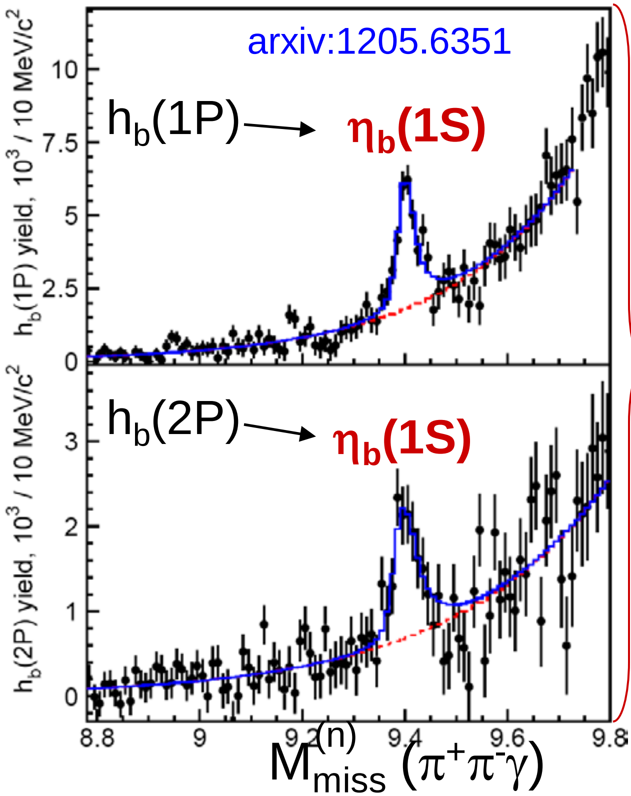
$e^+e^- \to \Upsilon(5S) \to h_b(\mathbf{nP})\ \pi^+\pi^-$

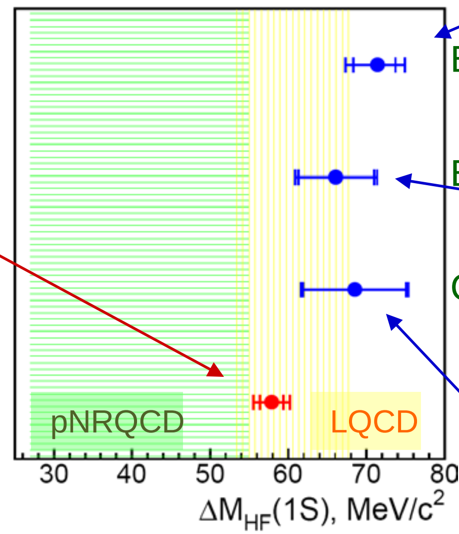
$\quad\quad\quad\quad\quad\quad\quad\ \ ^{|}\!\!\to \eta_b(\mathbf{1S})\ \gamma$

reconstruct $\Delta M_{HF}(\mathbf{1S})$

Belle : 57.9 ± 2.3 MeV

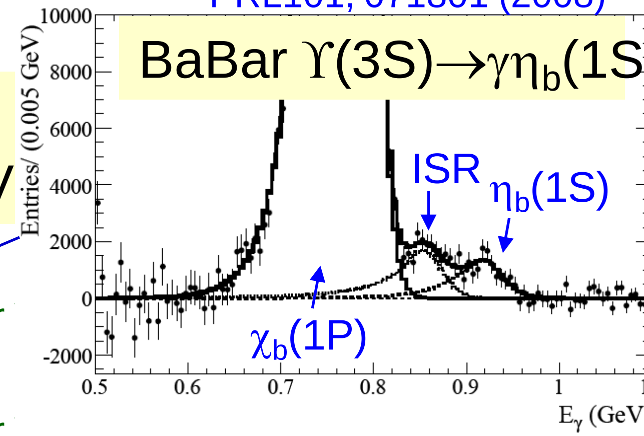
PDG'12 : 69.3 ± 2.8 MeV



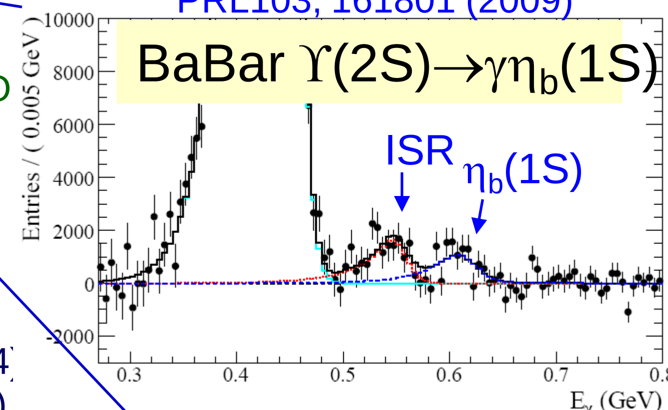


Kniehl et al, PRL92,242001(2004)
Meinel, PRD82,114502(2010)

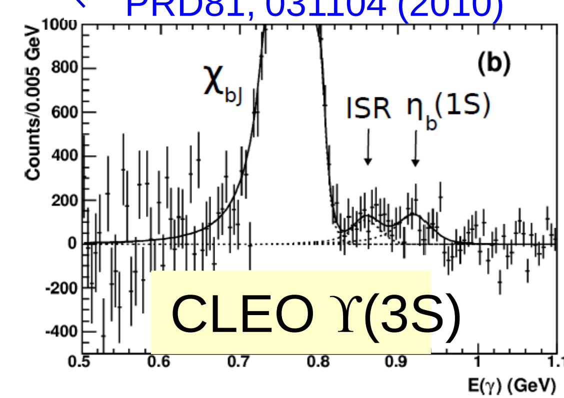
PRL101, 071801 (2008)



PRL103, 161801 (2009)



PRD81, 031104 (2010)



Mizuk et al. Belle PRL 109 (2012) 232002

Belle result decreases tension with theory

First measurement $\Gamma = 10.8\,^{+4.0}_{-3.7}\,^{+4.5}_{-2.0}$ MeV

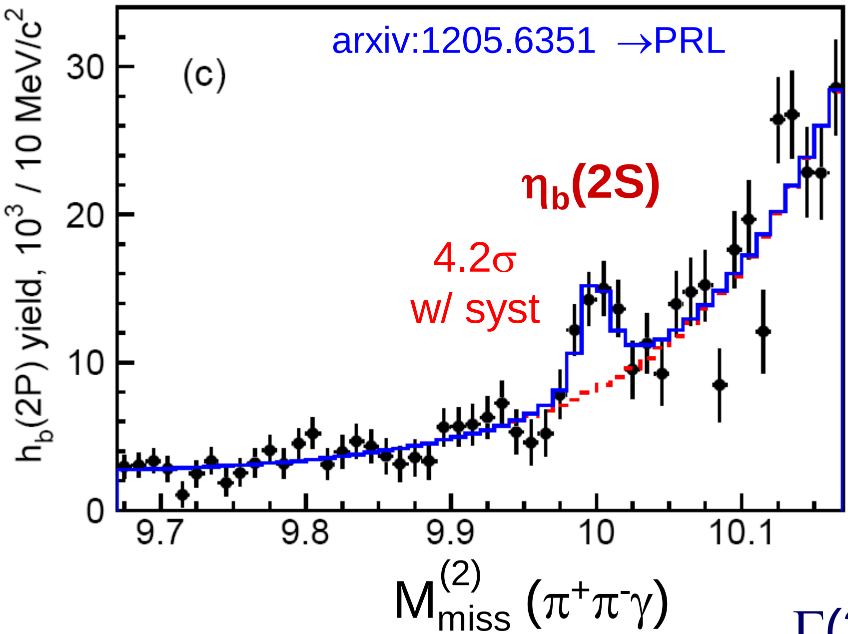
as expected

First evidence for $\eta_b(2S)$

$e^+e^- \to \Upsilon(5S) \to h_b(\mathbf{2P})\ \pi^+\pi^-$

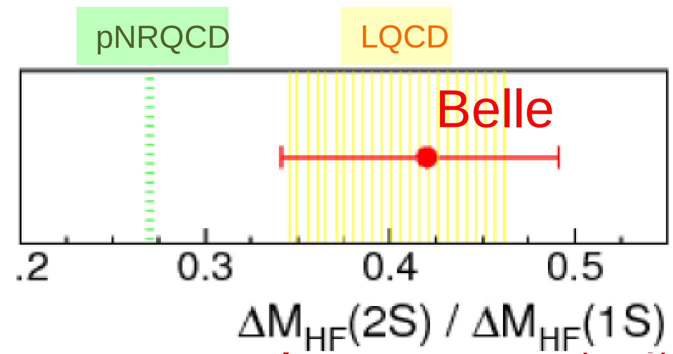
$\to \eta_b(\mathbf{2S})\ \gamma$

Mizuk et al. Belle PRL 109 (2012) 232002



$\Delta M_{HF}(\mathbf{2S}) = 24.3\ ^{+4.0}_{-4.5}$ MeV

First measurement



In agreement with theory

$\Gamma(2S) = 4 \pm 8$ MeV, < 24MeV @ 90% C.L.
expect ~4MeV

Branching fractions

$BF[h_b(1P) \to \eta_b(1S)\ \gamma] = 49.2 \pm 5.7^{+5.6}_{-3.3}$ %

$BF[h_b(2P) \to \eta_b(1S)\ \gamma] = 22.3 \pm 3.8^{+3.1}_{-3.3}$ %

$BF[h_b(2P) \to \eta_b(2S)\ \gamma] = 47.5 \pm 10.5^{+6.8}_{-7.7}$ %

Expectations

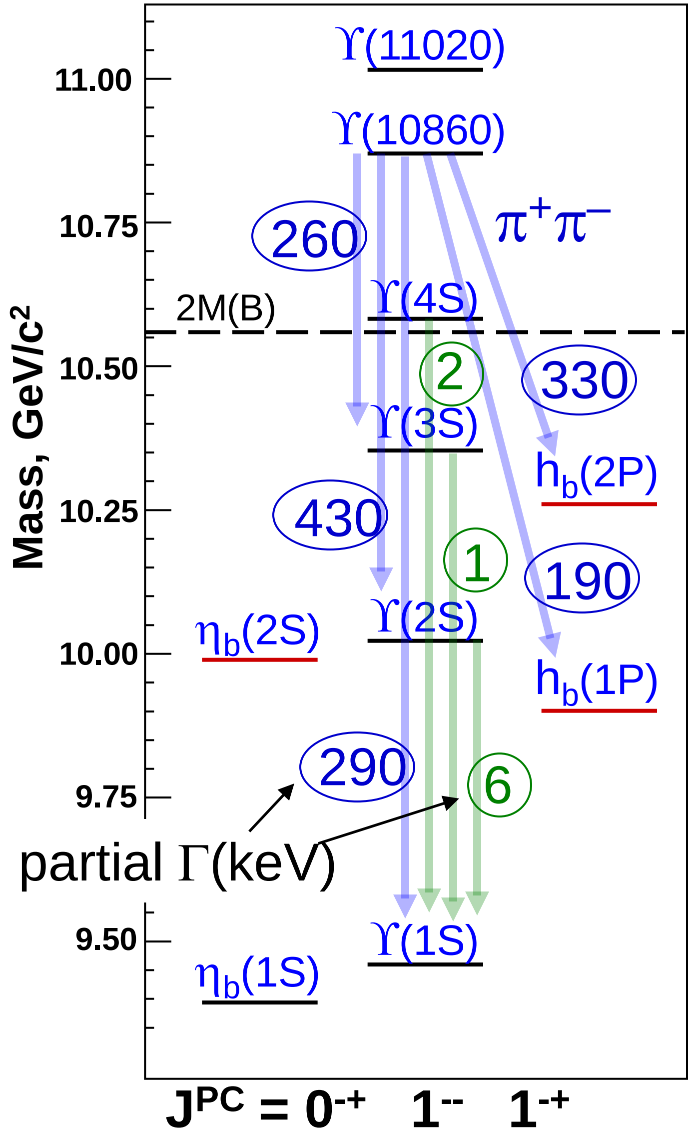
41% Godfrey Rosner PRD66,014012(2002)

13%

19%

c.f. BESIII $BF[h_c(1P) \to \eta_c(1S)\ \gamma] = 54.3 \pm 8.5$ % 39%

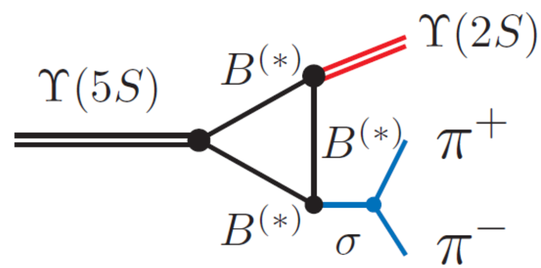
Anomalies in $\Upsilon(5S)\to(b\bar{b})\pi^+\pi^-$ transitions



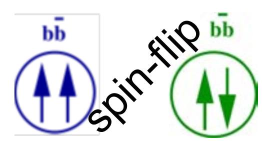
Belle: PRL100, 112001 (2008)

$\Gamma[\Upsilon(\mathbf{5S})\to\Upsilon(1,2,3S)\,\pi^+\pi^-] \overset{\sim 100}{>>} \Gamma[\Upsilon(\mathbf{4,3,2S})\to\Upsilon(1S)\,\pi^+\pi^-]$

$\Leftarrow$ Rescattering of on-shell $B^{(*)}\bar{B}^{(*)}$?



Belle: PRL108, 032001 (2012)



expect suppression $\sim\Lambda_{QCD}/m_b$

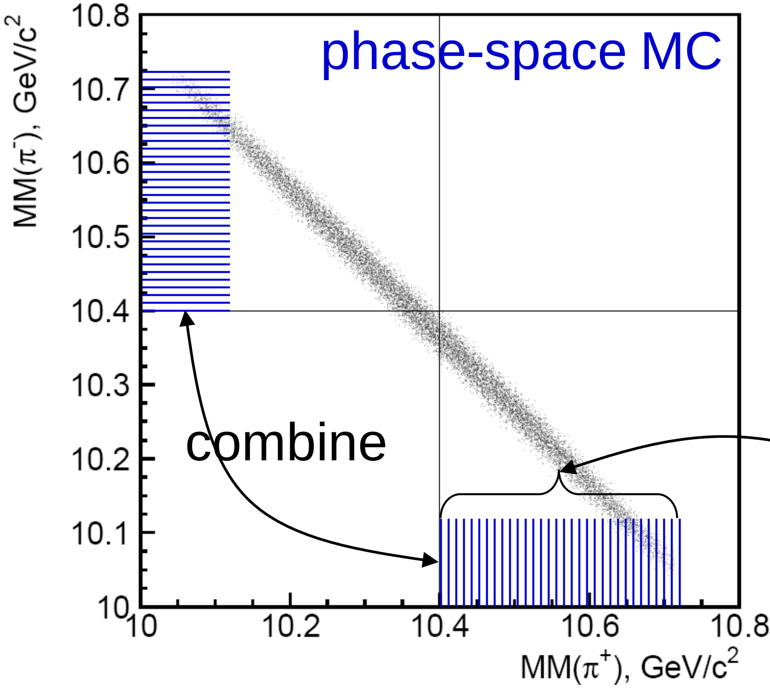
~~Heavy Quark Symmetry~~

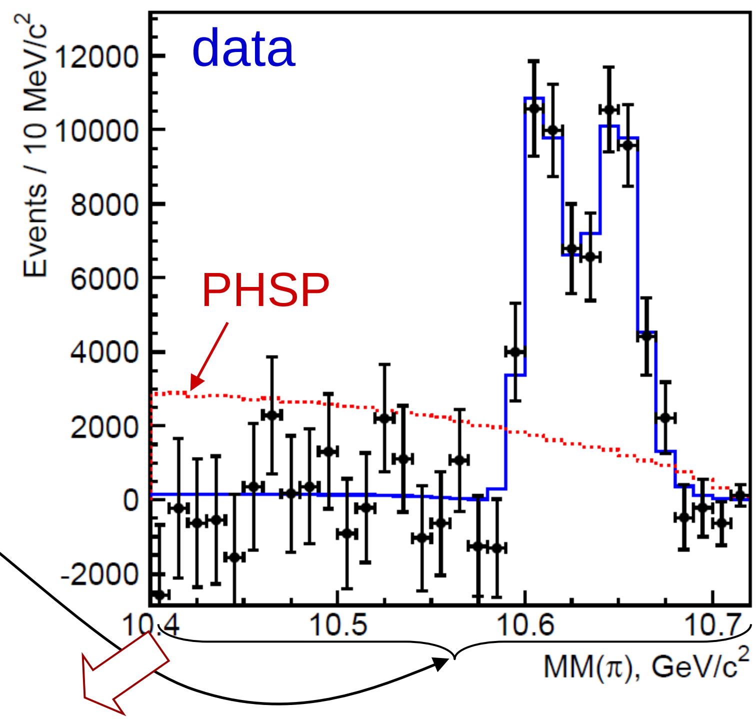
Υ(5S) $\to$ h_b(1,2P) $\pi^+\pi^-$ are not suppressed

h_b production mechanism? $\Rightarrow$ Study resonant structure in $h_b(mP)\pi^+\pi^-$

Resonant substructure of $\Upsilon(5S) \to h_b(1P)\,\pi^+\pi^-$

$P(h_b) = P_{\Upsilon(5S)} - P(\pi^+\pi^-) \;\Rightarrow\;$ **$M(h_b\pi^+) = MM(\pi^-) \Rightarrow$** ***measure $\Upsilon(5S)\to h_b\pi\pi$ yield in bins of $MM(\pi)$***





Fit function $|BW(s,M_1,\Gamma_1) + ae^{i\phi}BW(s,M_2,\Gamma_2) + be^{i\psi}|^2\ \dfrac{qp}{\sqrt{s}}$

[preliminary]

Results

$M_1 = 10605.1 \pm 2.2\,^{+3.0}_{-1.0}$ MeV/c² ~$B\bar{B}^*$ threshold

$\Gamma_1 = 11.4\,^{+4.5}_{-3.9}\,^{+2.1}_{-1.2}$ MeV $\qquad a = 1.8\,^{+1.0}_{-0.7}\,^{+0.1}_{-0.5}$

$M_2 = 10654.5 \pm 2.5\,^{+1.0}_{-1.9}$ MeV/c² ~$B^*\bar{B}^*$ threshold

$\Gamma_2 = 20.9\,^{+5.4}_{-4.7}\,^{+2.1}_{-5.7}$ MeV $\qquad \varphi = 188\,^{+44}_{-58}\,^{+4}_{-9}$ degree

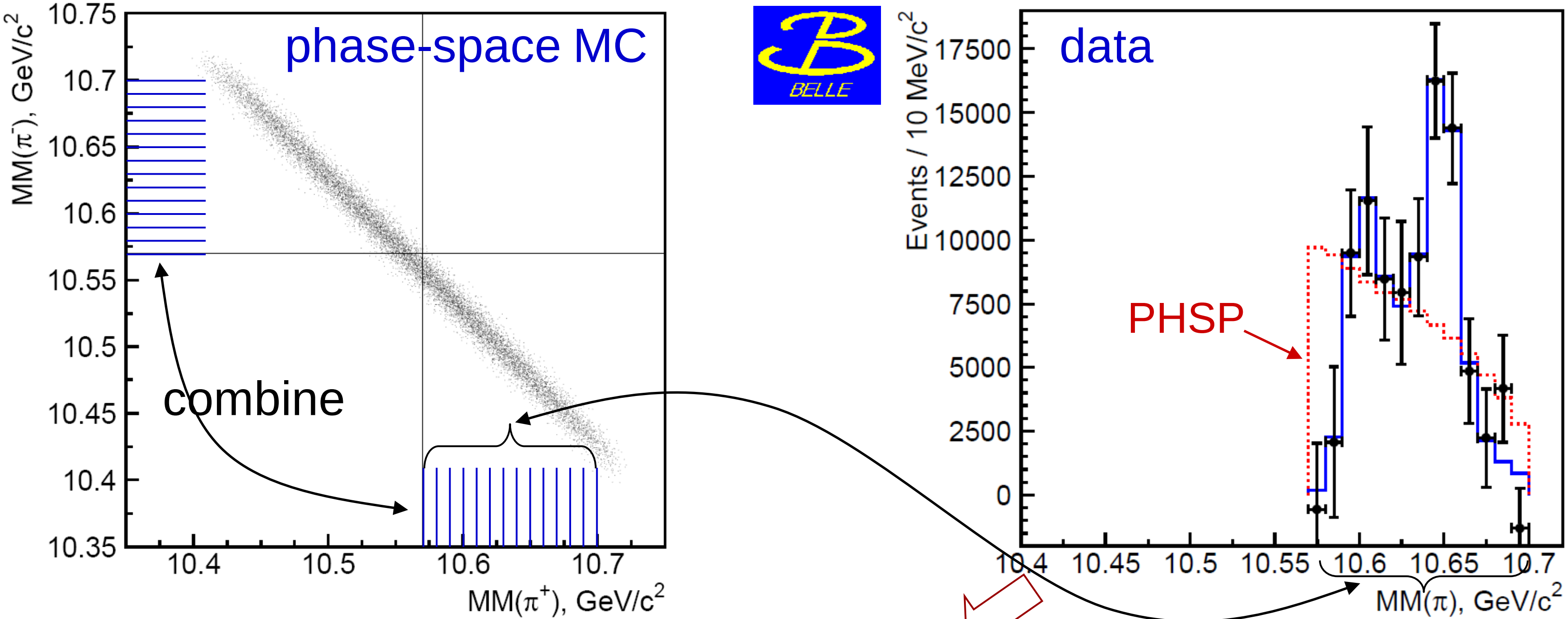
Significances

2 vs.1 : 7.4σ (6.6σ w/ syst)

2 vs.0 : 18σ (16σ w/ syst)

non-res. amplitude ~0

Resonant substructure of $\Upsilon(5S) \to h_b(2P)\,\pi^+\pi^-$



[preliminary]

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

$M_1 = 10605.1 \pm 2.2\,^{+3.0}_{-1.0}$ MeV/c²

$\Gamma_1 = 11.4\,^{+4.5}_{-3.9}\,^{+2.1}_{-1.2}$ MeV

$M_2 = 10654.5 \pm 2.5\,^{+1.0}_{-1.9}$ MeV/c²

$\Gamma_2 = 20.9\,^{+5.4}_{-4.7}\,^{+2.1}_{-5.7}$ MeV

$a = 1.8\,^{+1.0}_{-0.7}\,^{+0.1}_{-0.5}$

$\varphi = 188\,^{+44}_{-58}\,^{+4}_{-9}$ degree

consistent

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

$10596 \pm 7\,^{+5}_{-2}$ MeV/c²

$16\,^{+16}_{-10}\,^{+13}_{-4}$ MeV

$10651 \pm 4 \pm 2$ MeV/c²

$12\,^{+11}_{-9}\,^{+8}_{-2}$ MeV

$1.3\,^{+3.1}_{-1.1}\,^{+0.4}_{-0.7}$

$255\,^{+56}_{-72}\,^{+12}_{-183}$ degree

Significances

2 vs.1 : 2.7σ (1.9σ w/ syst)

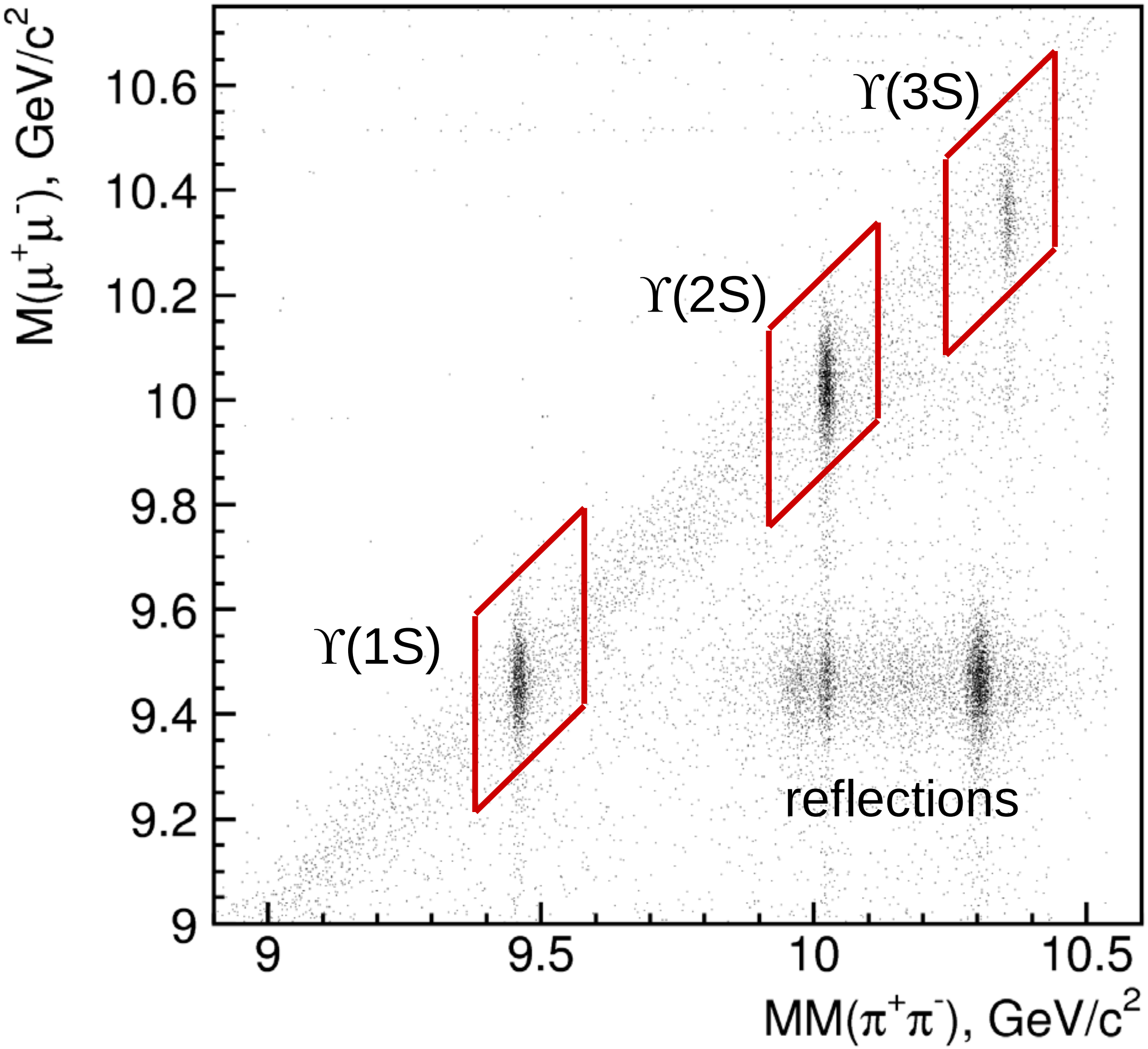
2 vs.0 : 6.3σ (4.7σ w/ syst)

Exclusive $\Upsilon(5S) \to \Upsilon(nS)\ \pi^+\pi^-$

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

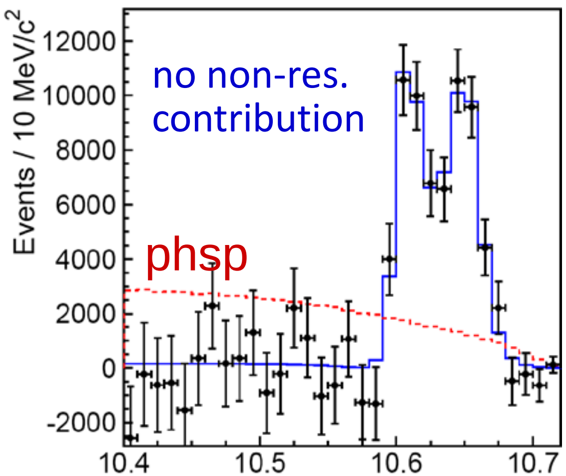
$\Upsilon(nS) \to \mu^+\mu^-$

(n = 1,2,3)



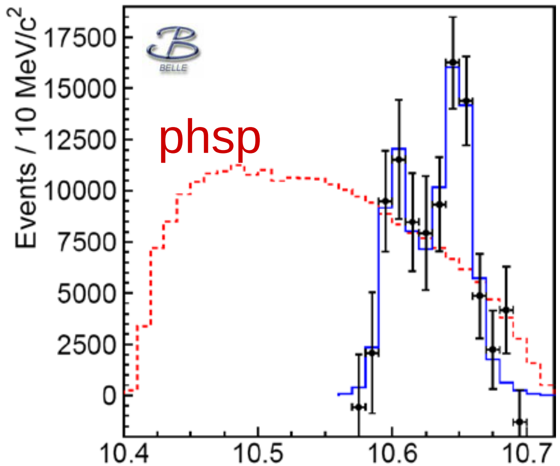
Resonant structure of $\Upsilon(5S)\to(b\bar{b})\pi^+\pi^-$

$\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$



M[$h_b(1P)\ \pi^\pm$]

$\Upsilon(5S) \to h_b(2P)\pi^+\pi^-$



M[$h_b(2P)\ \pi^\pm$]

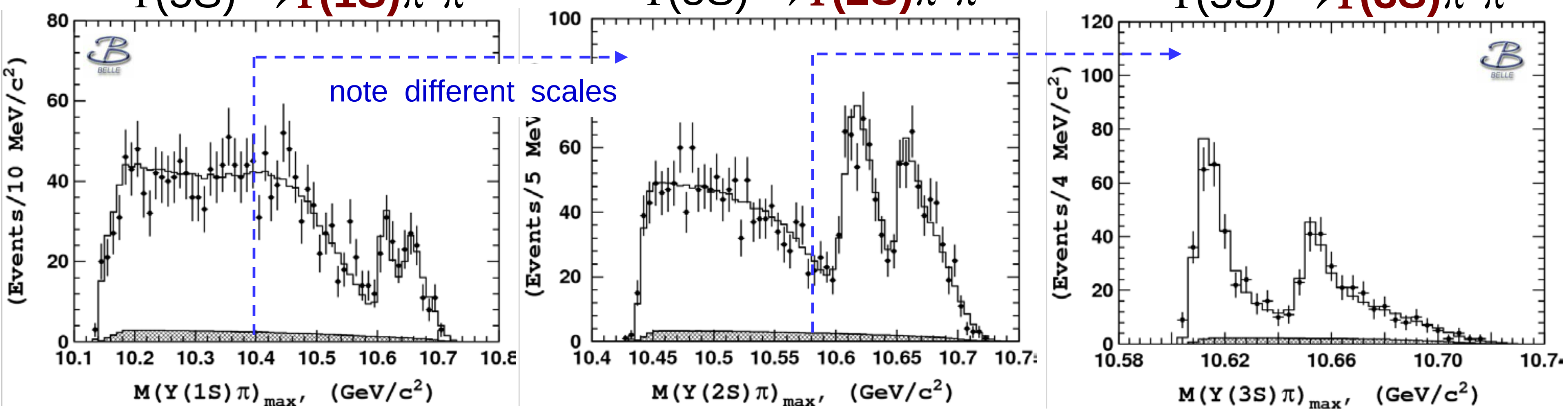
Two peaks are observed in all modes!

Belle: PRL108, 232001 (2012)

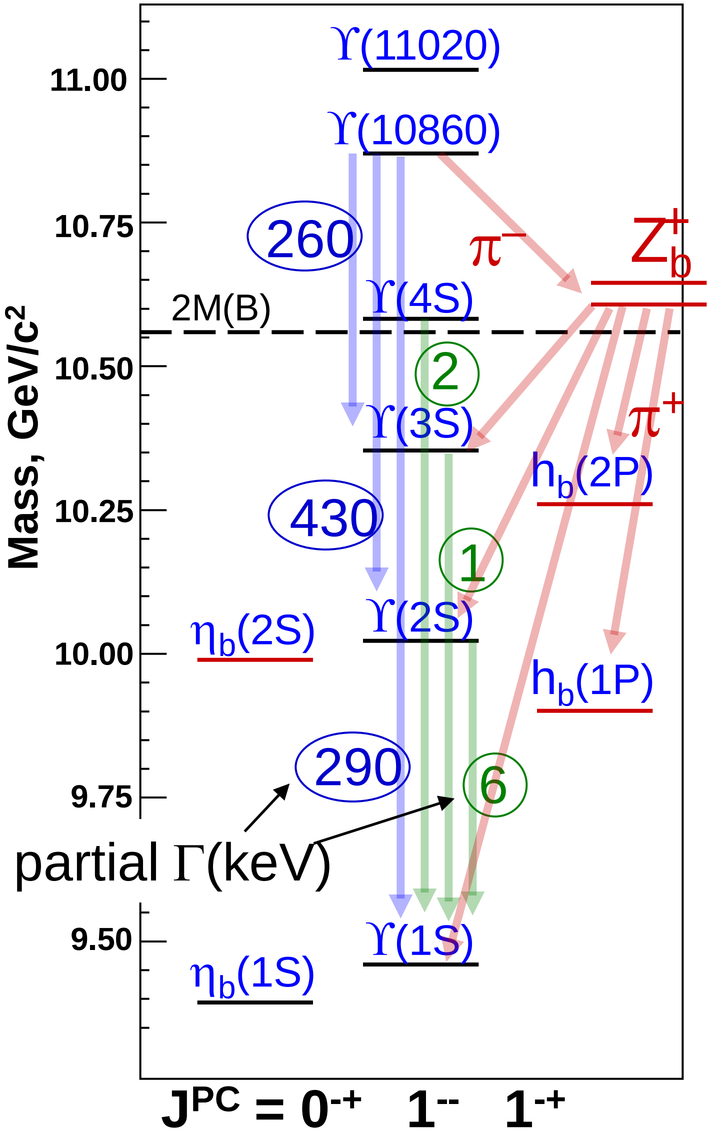
$Z_b(10610)$ and $Z_b(10650)$ should be multiquark states

Dalitz plot analysis

$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$ $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ $\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$



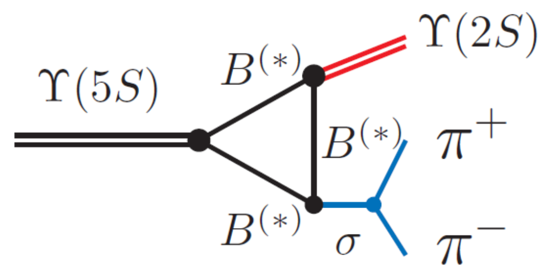
Anomalies in $\Upsilon(5S)\to(b\bar{b})\pi^+\pi^-$ transitions



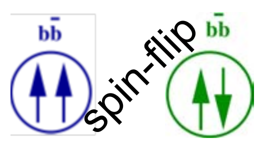
Belle: PRL100, 112001 (2008)

$$\Gamma[\Upsilon(\mathbf{5S})\to\Upsilon(1,2,3S)\,\pi^+\pi^-] \overset{\sim 100}{>>} \Gamma[\Upsilon(\mathbf{4,3,2S})\to\Upsilon(1S)\,\pi^+\pi^-]$$

$\Leftarrow$ Rescattering of on-shell $B^{(*)}\bar{B}^{(*)}$?



Belle: PRL108, 032001 (2012)

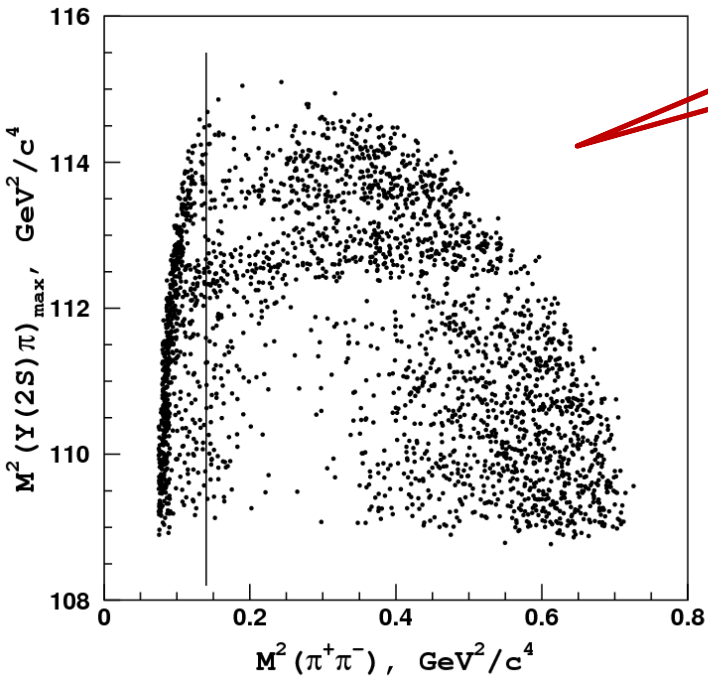


expect suppression $\sim\Lambda_{QCD}/m_b$

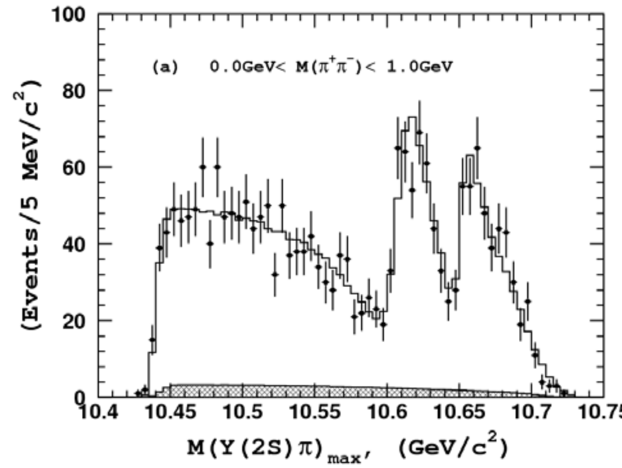
~~Heavy Quark Symmetry~~

Υ(5S) $\to$ h_b(1,2P) $\pi^+\pi^-$ are not suppressed

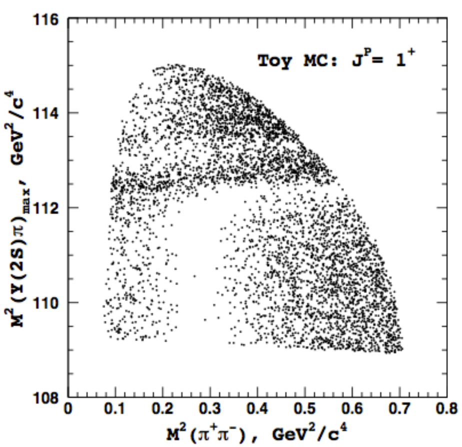
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$: J^P Results



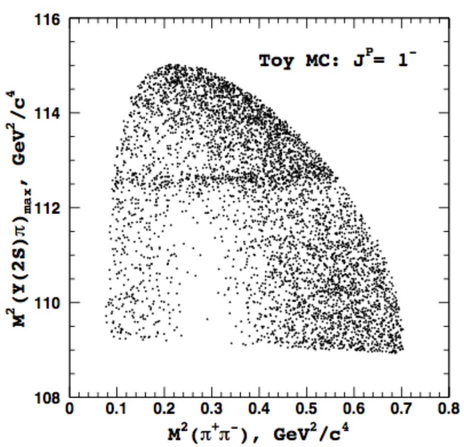
$\Upsilon(2S)\pi^+\pi$ Data



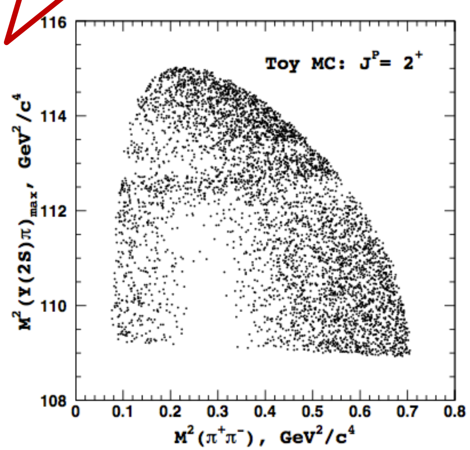
Toy MC with various J^P



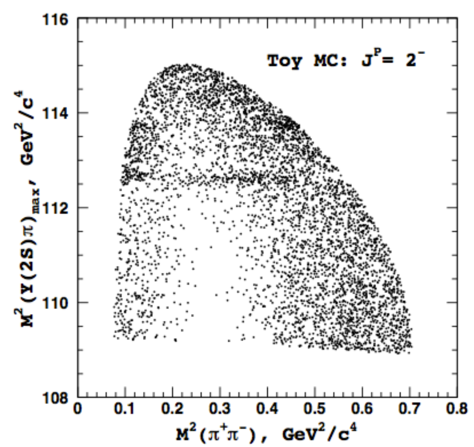
$J^P = 1^+$



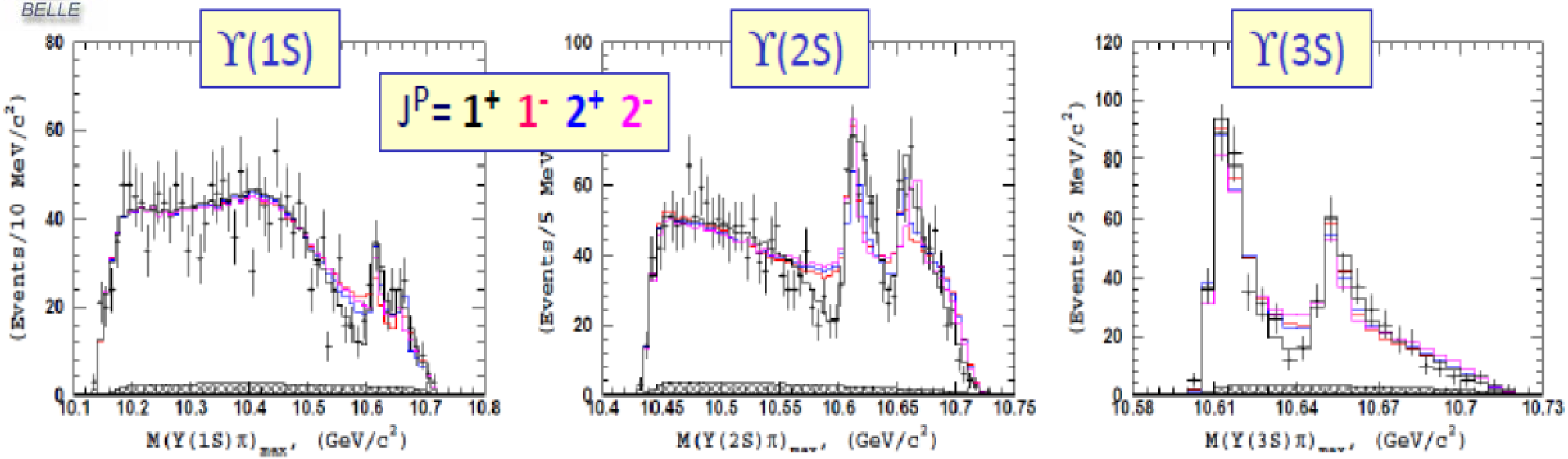
$J^P = 1^-$

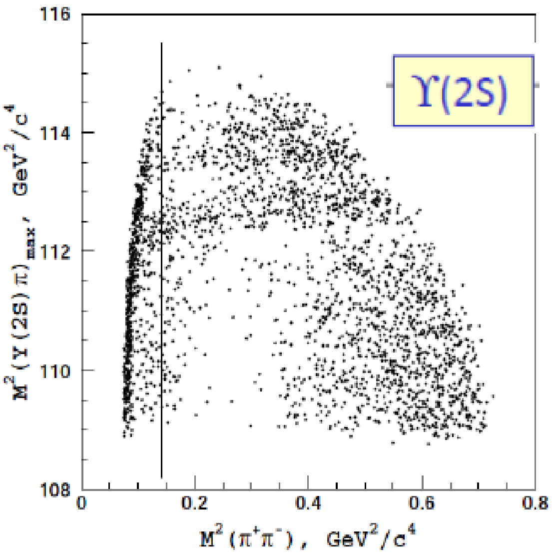


$J^P = 2^+$



$J^P = 2^-$





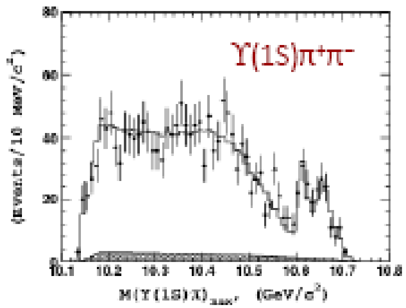
$Z_b(10610)$ \ $Z_b(10650)$	1^+	1^-	2^+	2^-
1^+	0 (0)	60 (33)	42 (33)	77 (63)
1^-	226 (47)	264 (73)	224 (68)	277 (106)
2^+	205 (33)	235 (104)	207 (87)	223 (128)
2^-	289 (99)	319 (111)	321 (110)	304 (125)

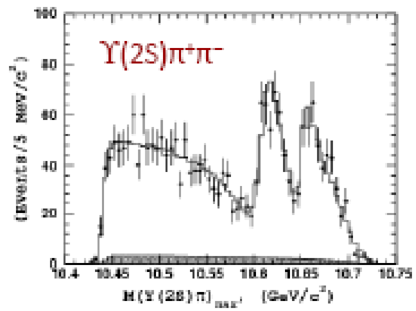
Spin parity of Zb(10610) and Zb(10650) is 1^+.

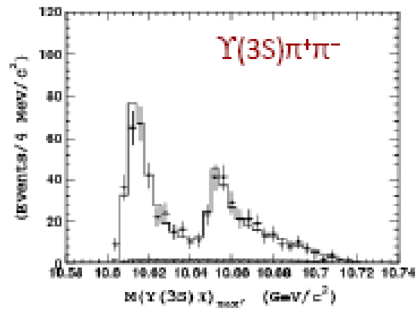
All other J^P<3 are excluded.

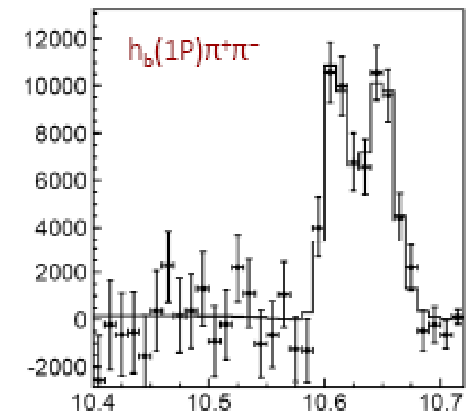
Propertie of $Z_b(10610)$ & $Z_b(10650)$

$Z_b^{\pm}$ Observed in five different modes: PRL 108, 122001(2012)

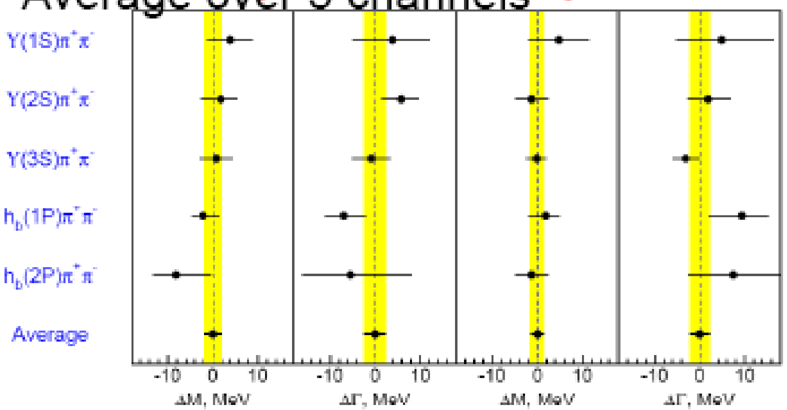








Average over 5 channels



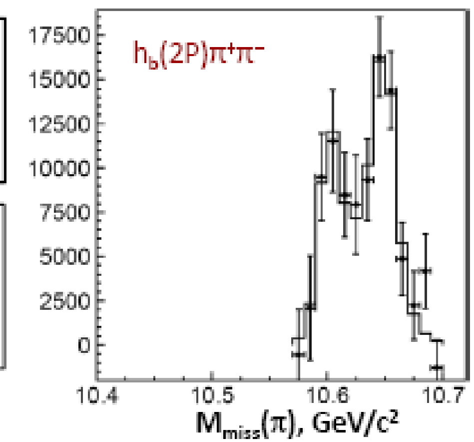
Average for $Z_b^{\pm}$:

$\langle M_1 \rangle = 10607.2 \pm 2.0$ MeV

$\langle \Gamma_1 \rangle = 18.4 \pm 2.4$ MeV

$\langle M_2 \rangle = 10652.2 \pm 1.5$ MeV

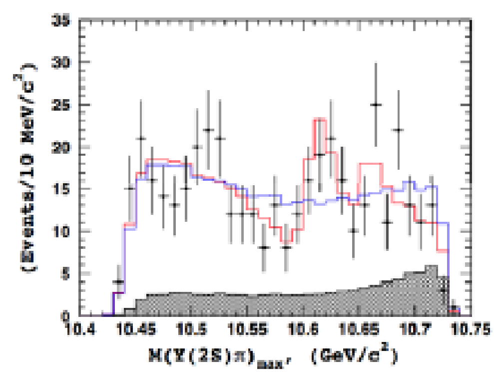
$\langle \Gamma_2 \rangle = 11.5 \pm 2.2$ MeV



Z_b^0 Results:

$\langle M_1 \rangle = 10609 \pm 7 \pm 6$ MeV

Consistent with $Z_b^{\pm}$



Angular analysis strongly favors $J^P=1^+$ assignement

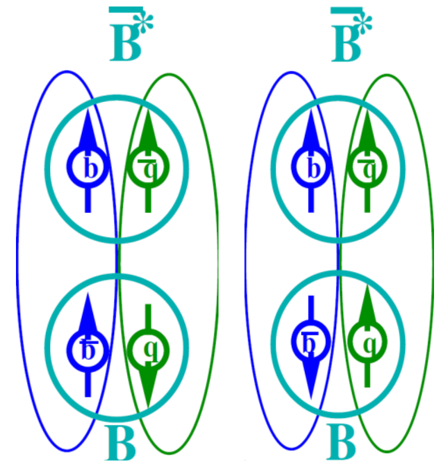
Heavy quark structure in Z_b

A.B.,A.Garmash,A.Milstein,R.Mizuk,M.Voloshin PRD84 054010 (arXiv:1105.4473)

Wave func. at large distance – B(*)B*

$$\left|Z_b'\right\rangle = \frac{1}{\sqrt{2}} 0^{-}_{b\bar{b}} \otimes 1^{-}_{Q\bar{q}} - \frac{1}{\sqrt{2}} 1^{-}_{b\bar{b}} \otimes 0^{-}_{Q\bar{q}}$$

$$\left|Z_b\right\rangle = \frac{1}{\sqrt{2}} 0^{-}_{b\bar{b}} \otimes 1^{-}_{Q\bar{q}} + \frac{1}{\sqrt{2}} 1^{-}_{b\bar{b}} \otimes 0^{-}_{Q\bar{q}}$$



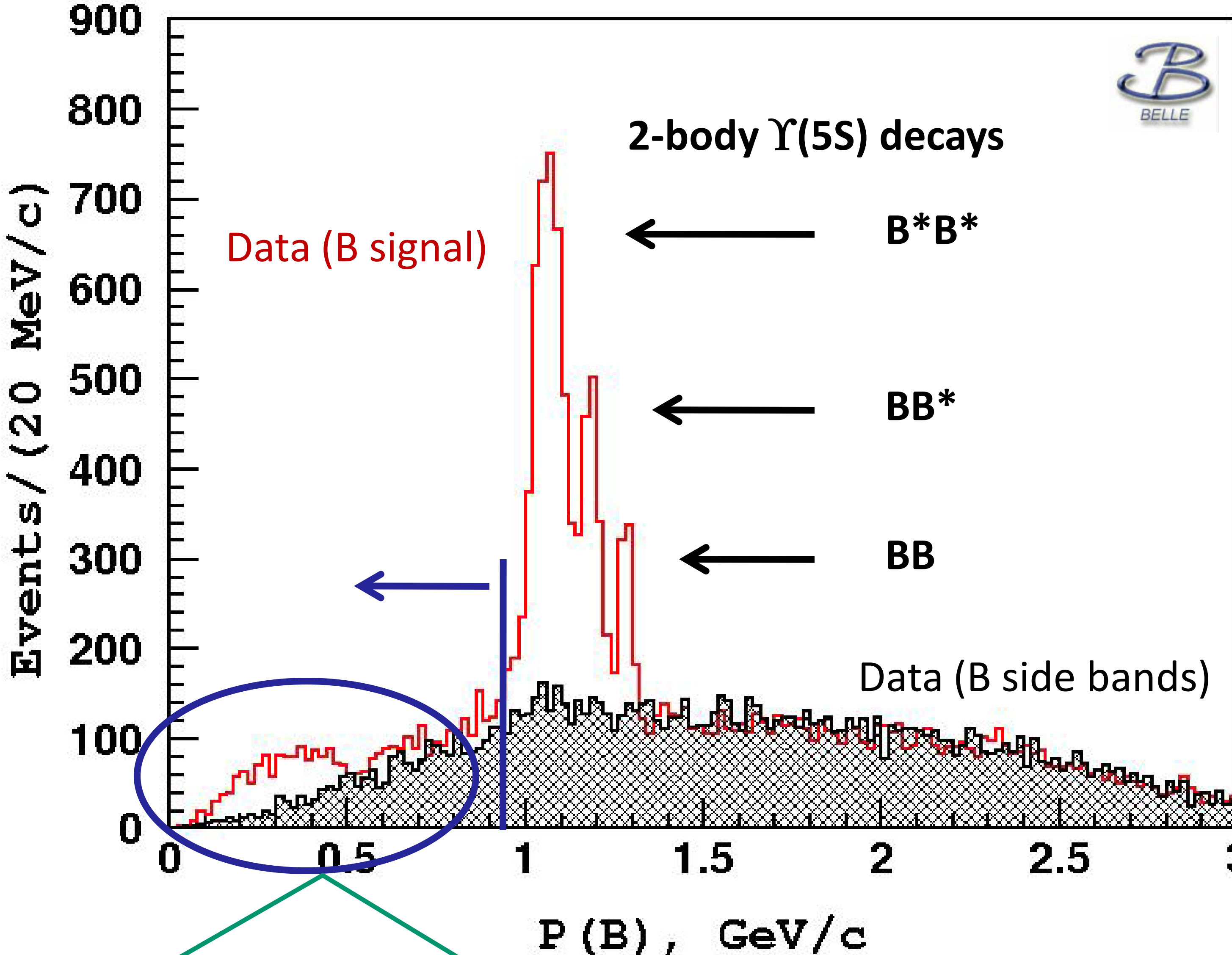
Explains

- Why $h_b\pi\pi$ is unsuppressed relative to $\Upsilon\pi\pi$
- Relative phase ~0 for Υ and ~180^0 for h_b
- Production rates of Z_b(10610) and Z_b(10650) are similar
- Widths –”–
- Dominant decays to B(*)B*

Other Possible Explanations

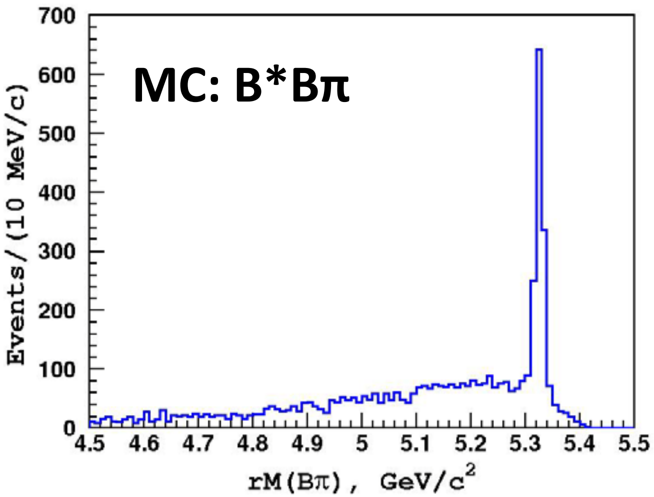
- Coupled channel resonances (I.V.Danilkin et al, arXiv:1106.1552)
- Cusp (D.Bugg Europhys.Lett.96 (2011),arXiv:1105.5492)
- Tetraquark (M.Karliner, H.Lipkin, arXiv:0802.0649)

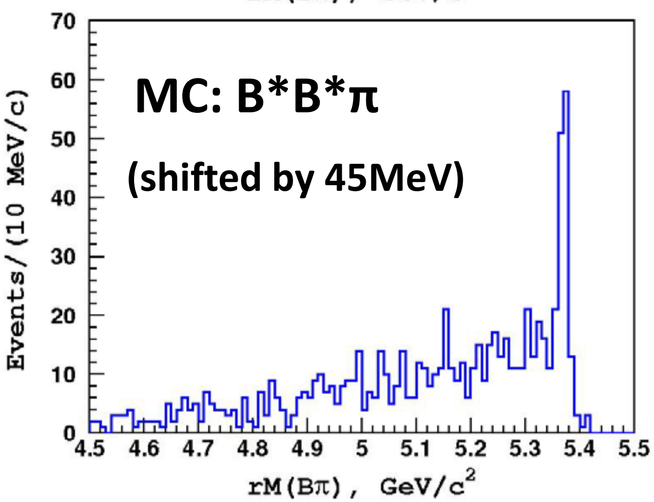
$\Upsilon(5S) \to B^* B^{(*)} \pi$: B Selection

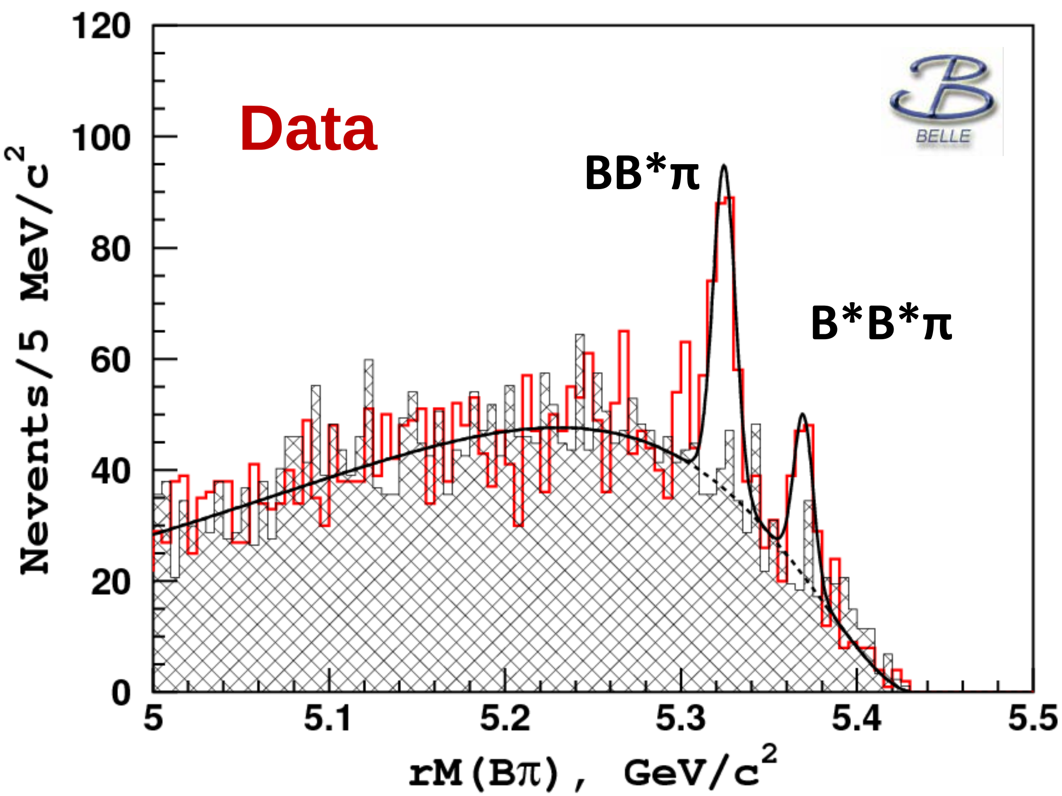


3-body ϒ(5S) -> B(*)B(*)π decays & rad. return to ϒ(4S): P(B)<0.9 GeV/c

$\Upsilon(5S)\to B^*B^{(*)}\pi$: Data





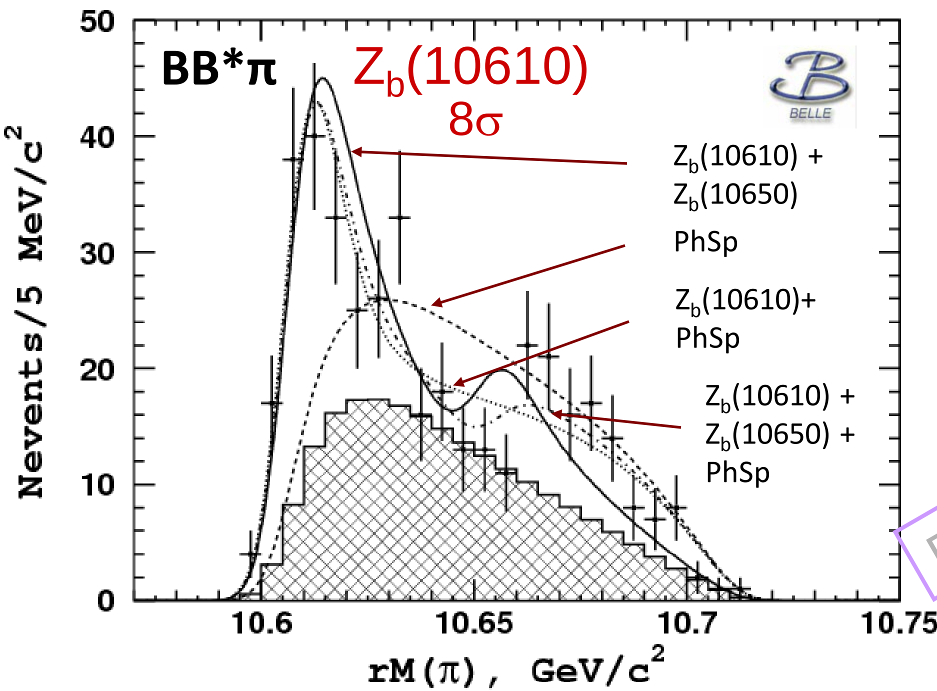


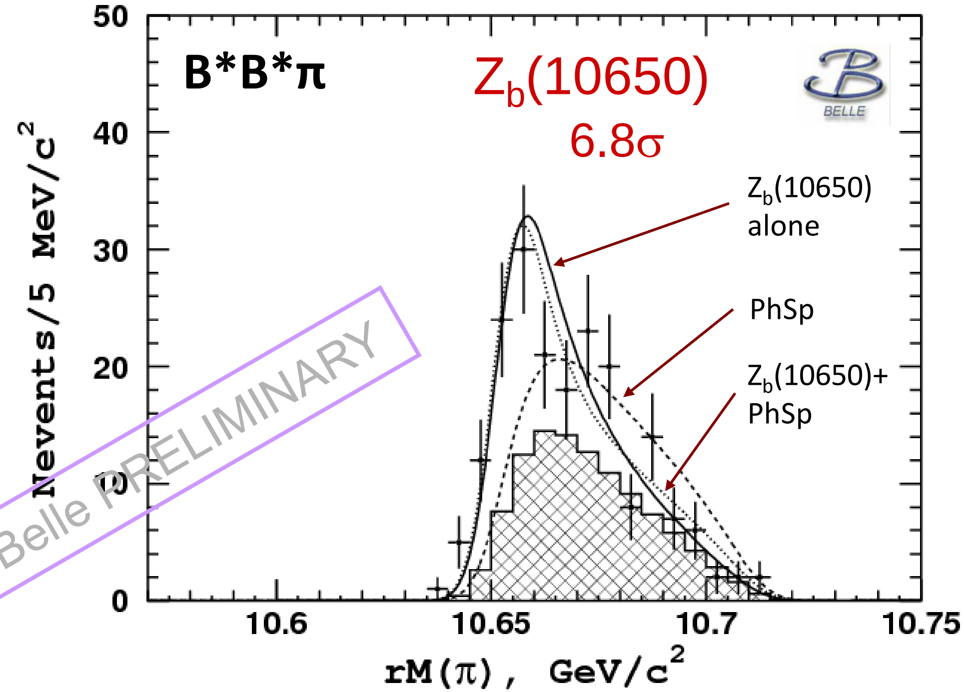
Red histogram – right sign Bπ combinations;
Hatched histogram – wrong sign Bπ combinations;
Solid line – fit to right sign data.

Fit yields: $N(BB\pi) = 0.3 \pm 14$

$N(BB^*\pi) = 184 \pm 19$ (9.3σ) $N(B^*B^*\pi) = 82 \pm 11$ (5.7σ)

$\Upsilon(5S) \to B^*B^{(*)}\pi$: Signal Region





points – right sign Bπ combinations (data);

lines – fit to data with various models (times PHSP, convolved with resolution function = Gaussian with σ=6MeV).

hatched histogram – background component

$B^*B^*\pi$ signal is well fit to just $Z_b(10650)$ signal alone

$BB^*\pi$ data fits (almost) equally well to a sum of $Z_b(10610)$ and $Z_b(10650)$ or to a sum of $Z_b(10610)$ and non-resonant.

$\Upsilon(5S) \to B^*B^{(*)}\pi$: Results

Branching fractions of $\Upsilon(10680)$ decays (including neutral modes):

$B B\pi$ < 0.60% (90%CL)

$B B^*\pi$ = 4.25 ± 0.44 ± 0.69%

$B^*B^*\pi$ = 2.12 ± 0.29 ± 0.36%

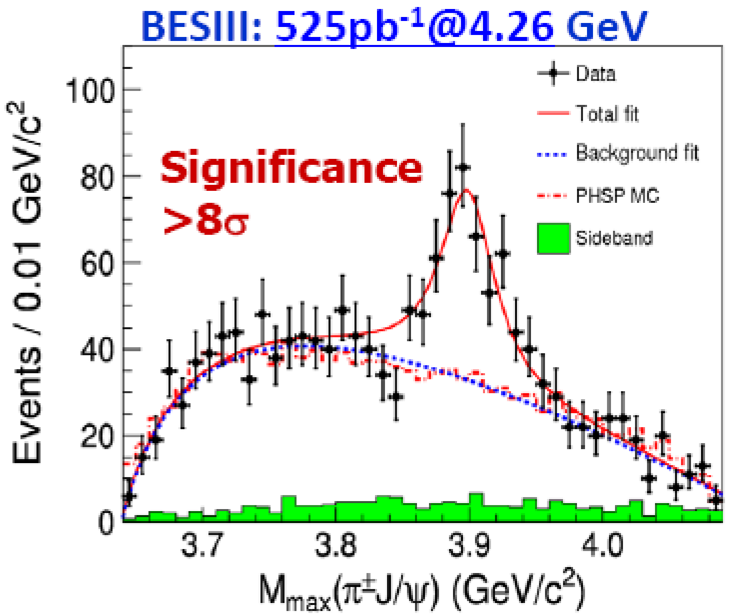
To be compared with PRD 81 (2010)
f($BB^*\pi$) = (7.3±2.2±0.8)%
f($B^*B^*\pi$) = (1.0±1.4±0.4)%

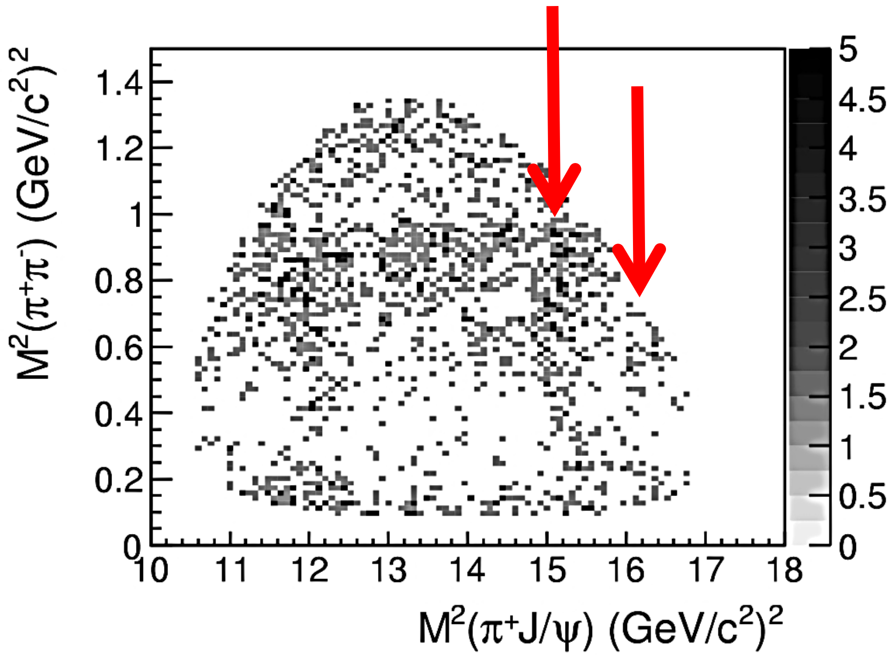
Assuming Z_b decays are saturated by the already observed $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and $B^{(*)}B^*$ channels, one can calculate complete table of relative branching fractions:

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

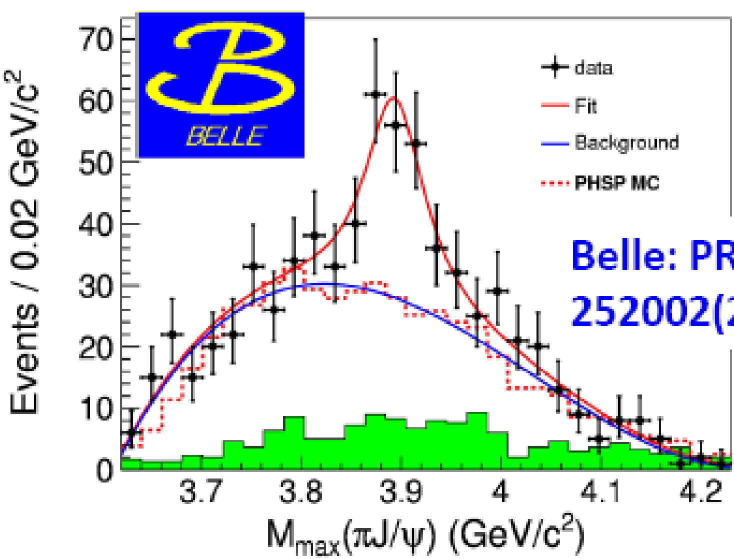
$B^{(*)}B^*$ channels dominate Z_b decays !

Observation of $Z_c(3900)$ at BESIII





BESIII: PRL110, 252001 (2013)

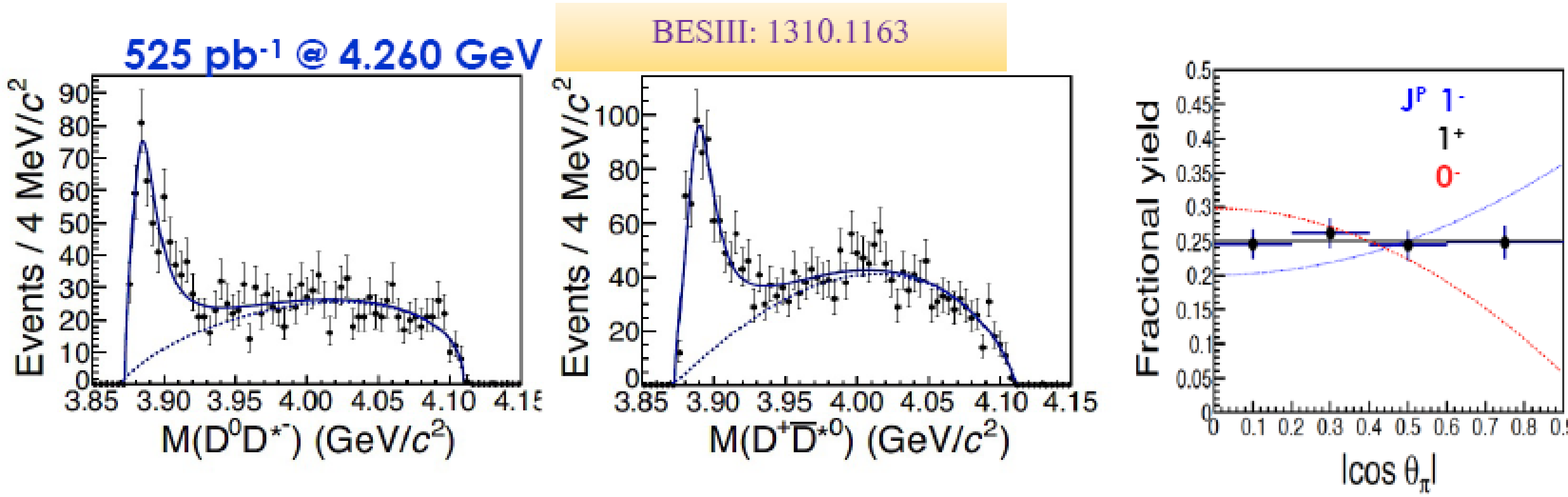


Belle: PRL 110, 252002(2013)

- **M = 3899.0±3.6±4.9 MeV**
- **Γ = 46±10±20 MeV**
- **307 ± 48 events**

The mass position is 24 MeV away from DD* threshold!
A Partial wave analysis is on going!

Observation of $Z_c(3885)$ in $e^+e^- \to \pi^-(D^*D)^+$



- M = 3883.9±1.5±4.2 MeV; Γ = 24.8±3.3±11.0 MeV
- σ×B = 85.3±6.6±22.0 pb [pole position]
- **fits favor 1^+ distribution assumption**

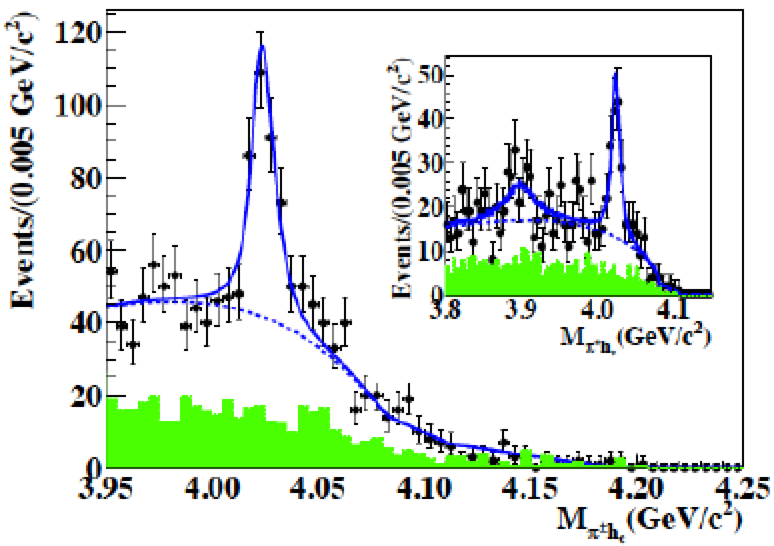
fit with mass-dependent-width BW with phase space and efficiency correction

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

Assuming $Z_c(3885)$ due to $Z_c(3900)$

Observation of $Z_c(4020)$ in $e^+e^- \to h_c\pi^+\pi^-$

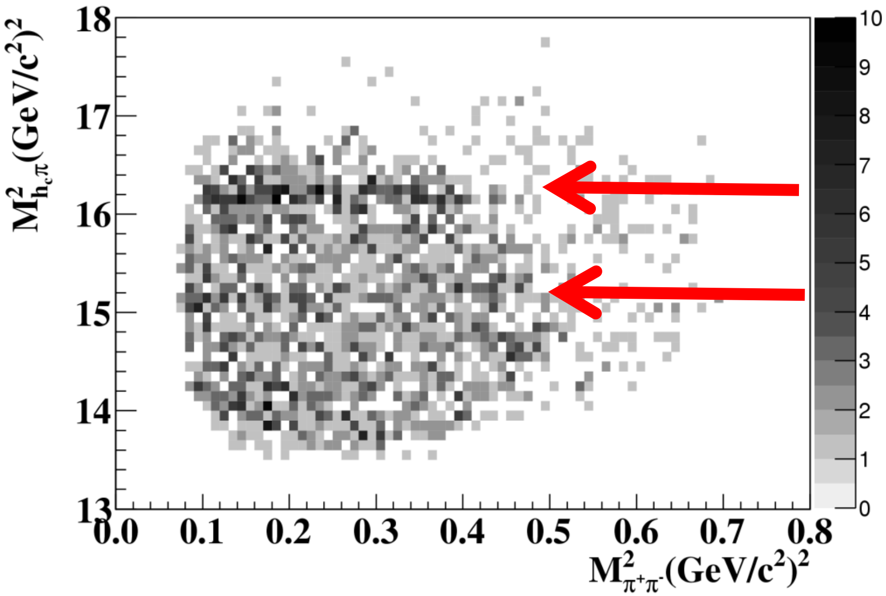
BESIII: 1309.1896



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

$M = 4022.9 \pm 0.8 \pm 2.7$ MeV/c^2

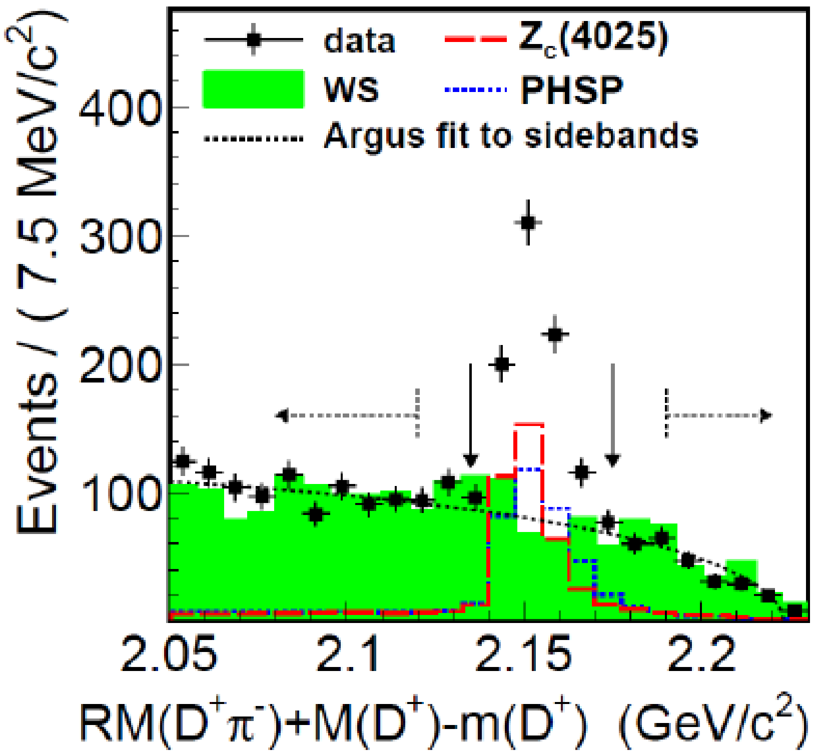
$\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV

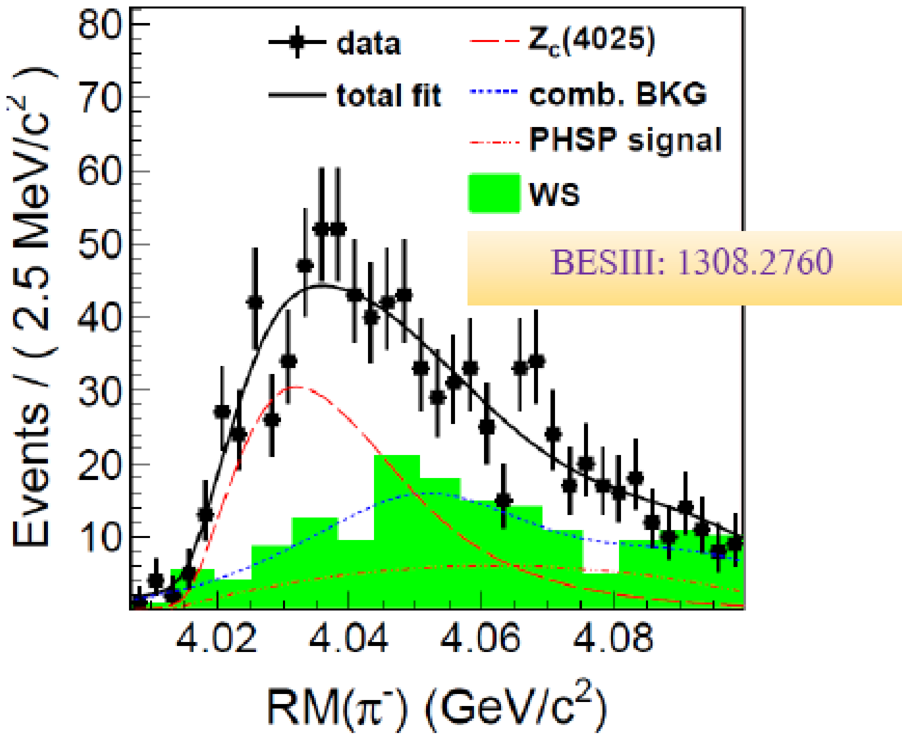


Significance: 8.9σ ($Z_c(4020)$)

No significant $Z_c(3900)$ (2.1σ)

Observation of $Z_c(4025)$ in $e^+e^- \to \pi^-(D^*D^*)^+$





Fit to $\pi^\pm$ recoil mass yields 401±47 $Z_c(4025)$ events. **>10σ**

$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV; $\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7$ MeV

$$\sigma(e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp) = (137 \pm 9 \pm 15)\ \text{pb}$$

$$R = \frac{\sigma(e^+e^- \to \pi^\pm Z_c^\mp(4025) \to \pi^\pm(D^*\bar{D}^*)^\mp)}{\sigma(e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp)} = (65 \pm 9 \pm 6)\%$$

Summary of the Z_c states

Channel	Mass (MeV/c^2)	Width (MeV)
$\pi^{\pm}J/\psi$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$
$(D\bar{D}^*)^{\pm}$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
	2σ difference	1σ difference
$\pi^{\pm}h_c$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$
$(D^*\bar{D}^*)^{\pm}$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$
	1σ difference	2σ difference

Close to $D\bar{D}^*$ threshold (3875 MeV)

Close to $D^*\bar{D}^*$ threshold (4017 MeV)

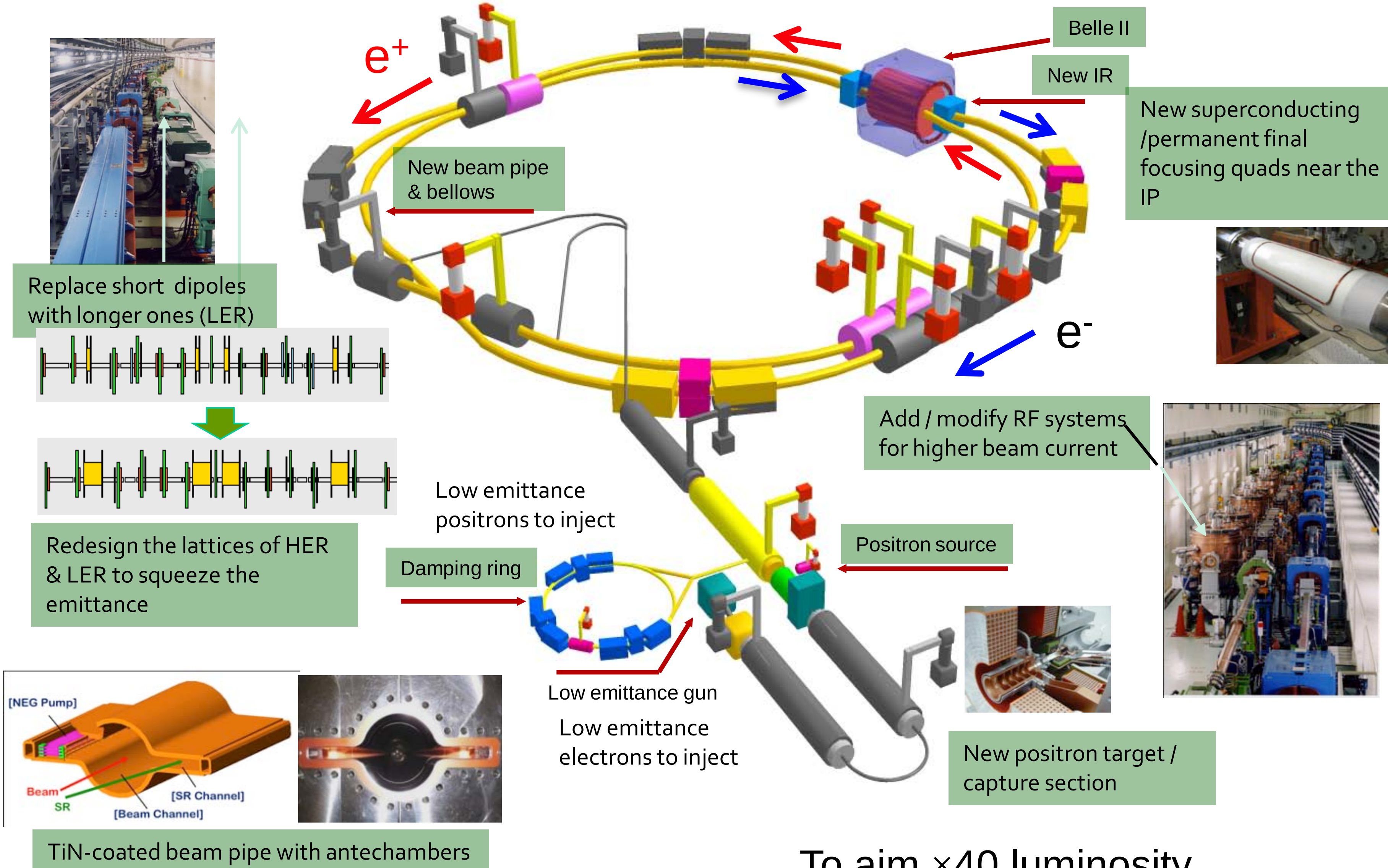
- At least 4-quarks; Charged; Near threshold;
- Couples to DD final states larger than charmonium final states;

Bottomonium-like vs Charmonium-like states

- Charged Upsilon-like structure
- Z_b are very close to $\bar{B}B^*$, $B^*\bar{B}^*$ threshold
- $I^G J^{P(C)} = 1^+ \, 1^{+\,(-)}$
- Observed both in the hidden-bottom modes: $\pi\Upsilon(1S,2S,3S)$, $\pi\, h_b(1P,2P)$ and open-bottom modes: $\bar{B}B^*$, $B^*\bar{B}^*$
- $B(^*)\bar{B}^*$ domonate Z_b decays with the branching ratio 86% and 73%

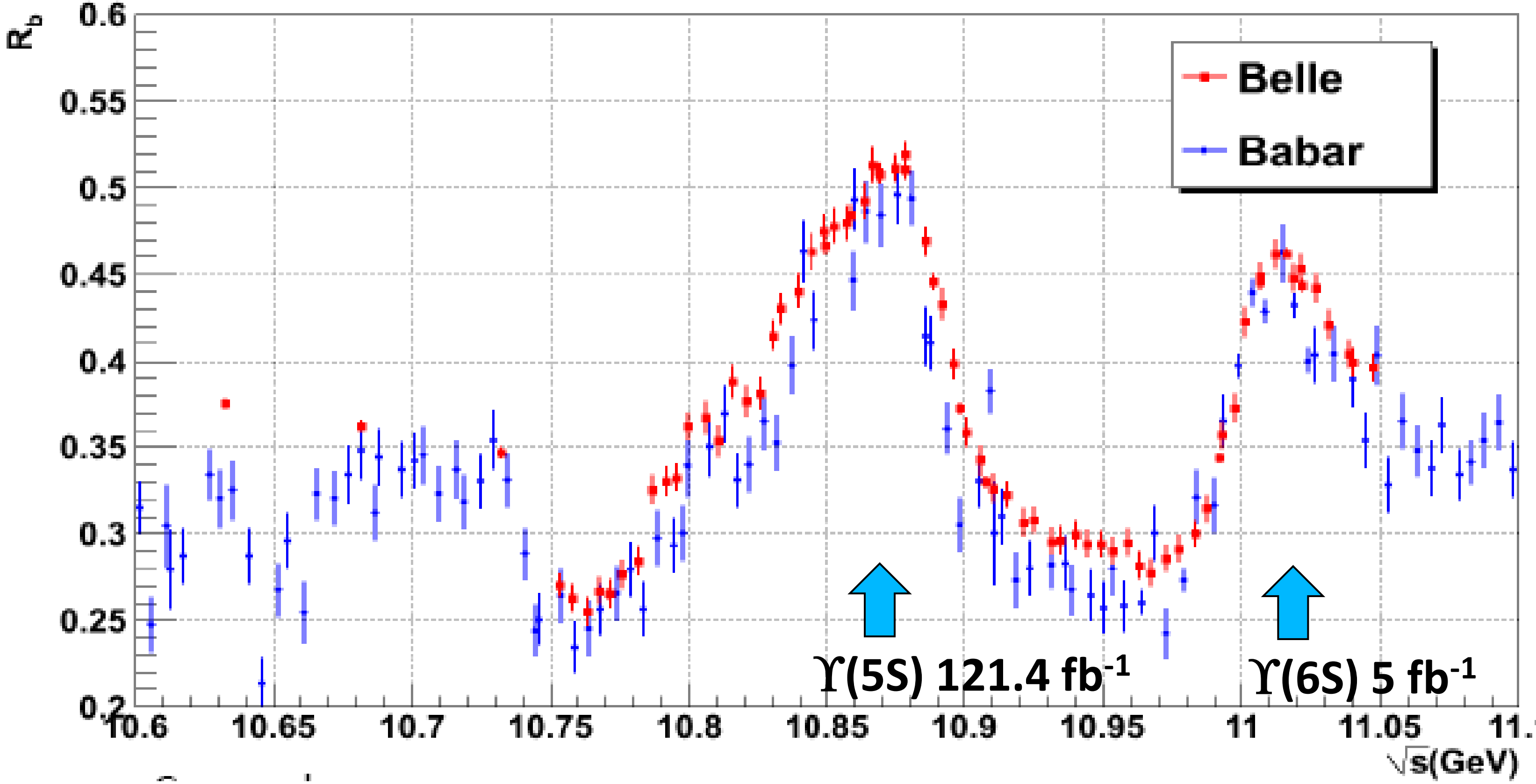
- Charged charmonium-like structure
- Z_c are very close to $\bar{D}D^*$, $D^*\bar{D}^*$ threshold
- $I^G J^{P(C)} = 1^+ \, 1^{+\,(-)}$
- Observed both in the hidden-charm modes: $\pi\, J/\psi$, $\pi\, h_c$ and open-charm modes: $\bar{D}D^*$, $D^*\bar{D}^*$
- $\bar{D}D^*$ dominates $Z_c(3900)$ decay

SuperKEKB



To aim ×40 luminosity

First measurements



- Measurements of the $\Upsilon(nS)\pi^+\pi^-$, $h_b\pi^+\pi^-$ cross-section vs energy
- Z_b's cross-section
- Radiative and hadronic transitions

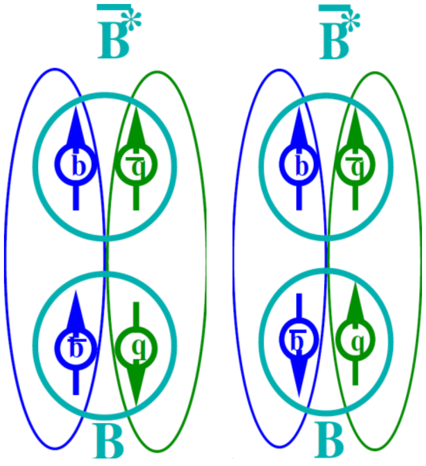
Heavy quark structure in Z_b

A.B.,A.Garmash,A.Milstein,R.Mizuk,M.Voloshin PRD84 054010 (arXiv:1105.4473)

Wave func. at large distance – B(*)B*

$$\left|Z_b'\right\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} - \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$

$$\left|Z_b\right\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} + \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$



Explains

- Why $h_b\pi\pi$ is unsuppressed relative to $\Upsilon\pi\pi$
- Relative phase ~0 for Υ and ~180^0 for h_b
- Production rates of Z_b(10610) and Z_b(10650) are similar
- Widths –"–

Predicts

- Existence of other similar states

arXiv:1105.5829

$$|Z_b'\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} - \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$

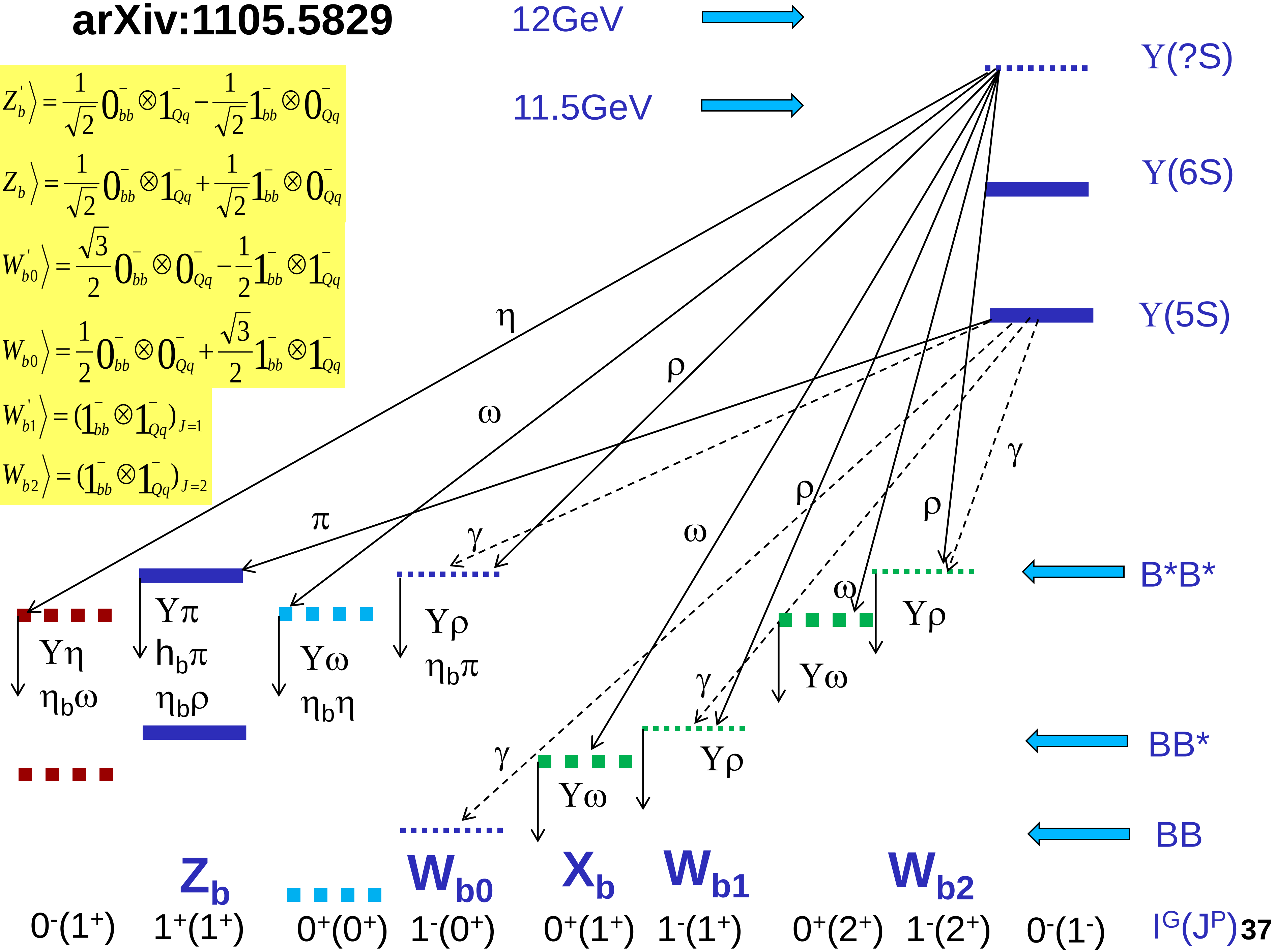
$$|Z_b\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} + \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$

$$|W_{b0}'\rangle = \frac{\sqrt{3}}{2} 0^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}} - \frac{1}{2} 1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}}$$

$$|W_{b0}\rangle = \frac{1}{2} 0^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}} + \frac{\sqrt{3}}{2} 1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}}$$

$$|W_{b1}'\rangle = (1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}})_{J=1}$$

$$|W_{b2}\rangle = (1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}})_{J=2}$$



Summary

- **The first exotic bottomonium-like Z_b^+ states were discovered in decays to $\Upsilon(1S)\pi^+$, $\Upsilon(2S)\pi^+$, $\Upsilon(3S)\pi^+$, $h_b(1P)\pi^+$, $h_b(2P)\pi^+$**
- **Spin parity of Zbs is 1^+**
- **Zbs mainly decay to BB* and B*B*final states**

  $Z_b(10610)$ dominantly decays to BB*, but $Z_b(10650)$ to B*B*
  Decay fraction of $Z_b(10650)$ to BB* is currently not statistically significant, but at least less than to B*B*
- **Phase space of Y(5S)->B(*)B*π is tiny, relative motion B(*)B*is small, which is favorable to the formation of the molecular type states**
- **Y(5S) [and possible Y(6S)] is ideal factory of molecular states**
- **In heavy quark limit we can expect more molecular states in vicinity of the BB, BB* and B*B*. To study the new states we need the energy up to 12GeV**

Studies of Z_b's properties may help us to understand exotic states in charm sector

We enter the new region –
Physics of Highly Excited Quarkonium
or/and
Chemistry of Heavy Flavor

We can expect much more from Super B factory

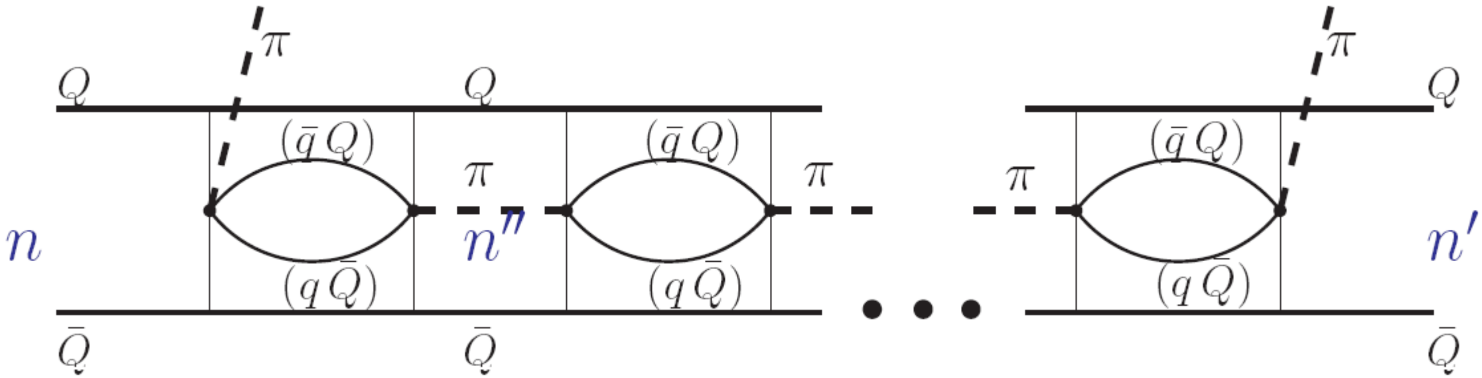
Back up slides

Tetraquark?

M ~ 10.2 – 10.3 GeV	Ying Cui, Xiao-lin Chen, Wei-Zhen Deng, Shi-Lin Zhu, High Energy Phys.Nucl.Phys.31:7-13, 2007 (hep-ph/0607226)
M ~ 10.5 – 10.8 GeV	Tao Guo, Lu Cao, Ming-Zhen Zhou, Hong Chen, (1106.2284)
M ~ 9.4, 11 GeV	M.Karliner, H.Lipkin, (0802.0649)

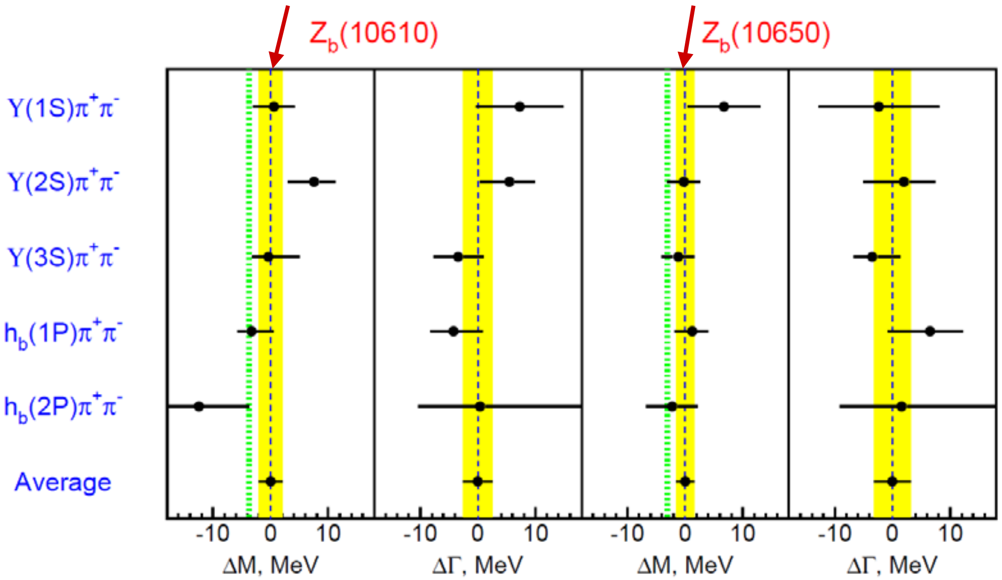
Coupled channel resonance?

I.V.Danilkin, V.D.Orlovsky, Yu.Simonov arXiv:1106.1552



No interaction between B(*)B* or ϒπ is needed to form resonance

No other resonances predicted

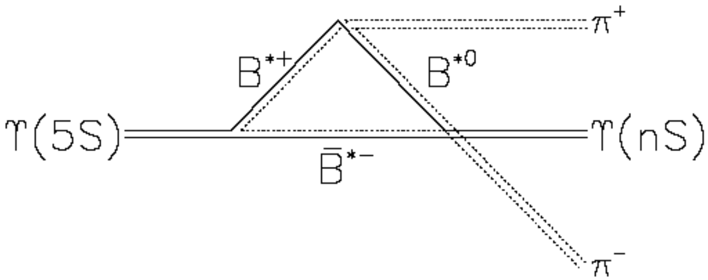


B(*)B* interaction switched on ⇒ individual mass in every channel?

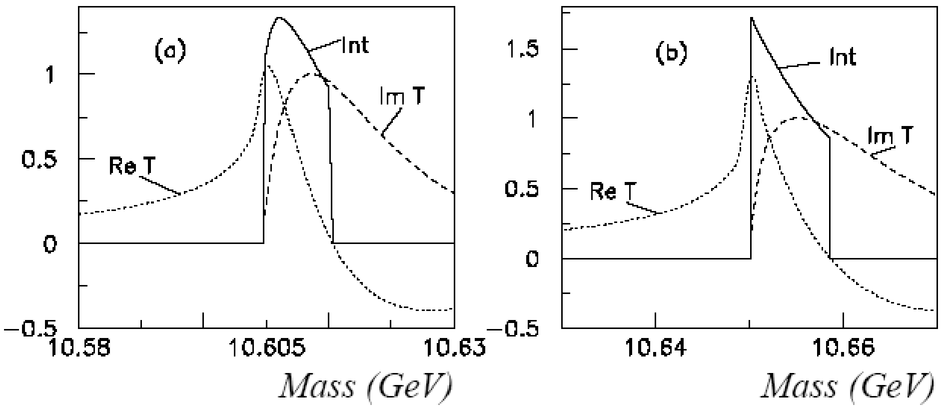
Cusp?

D.Bugg Europhys.Lett.96 (2011) (arXiv:1105.5492)

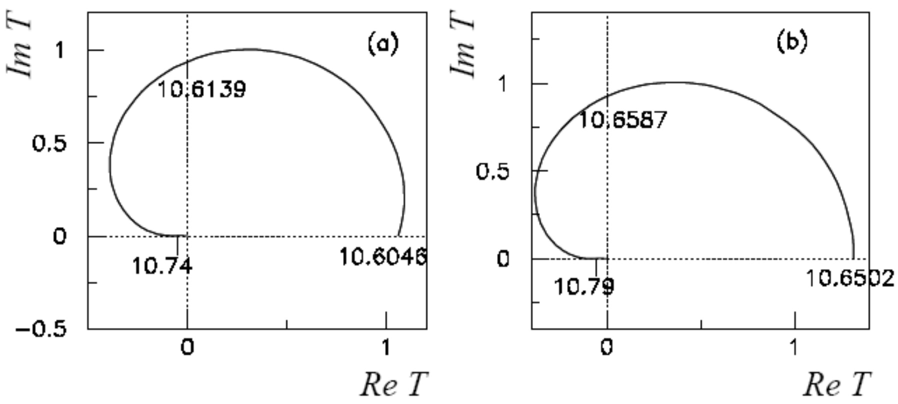
Amplitude



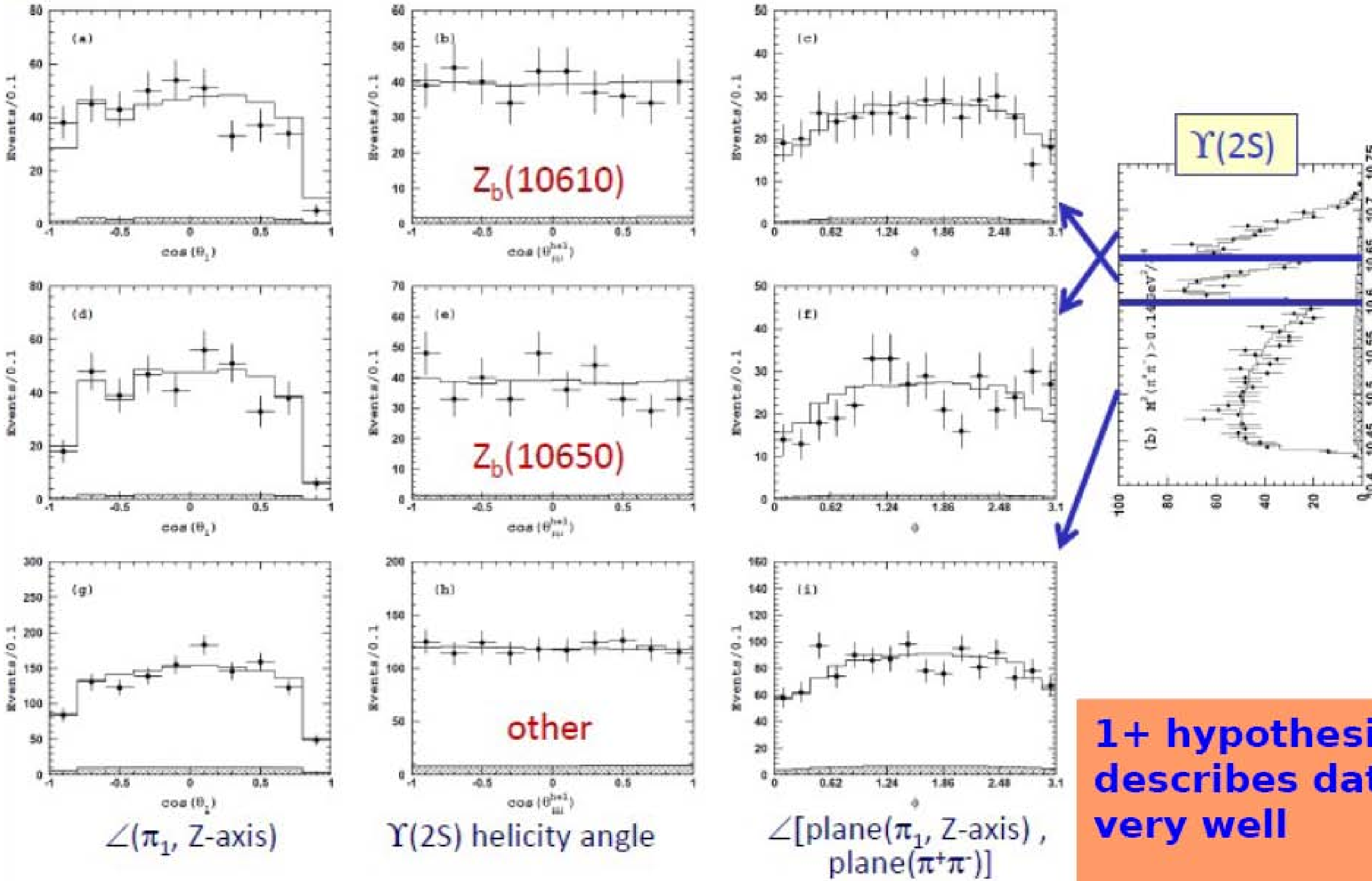
Line-shape



Not a resonance



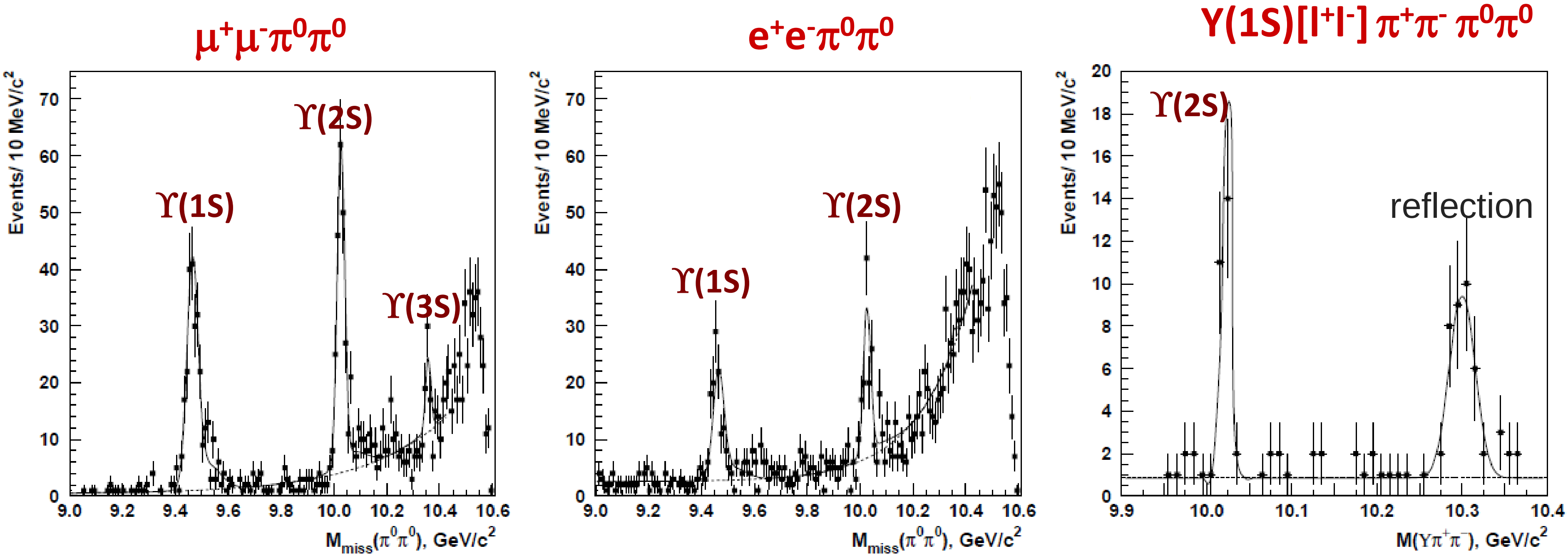
BELLE



1+ hypothesis describes data very well

$\Upsilon(5S)\rightarrow\Upsilon(nS)\pi^0\pi^0$

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



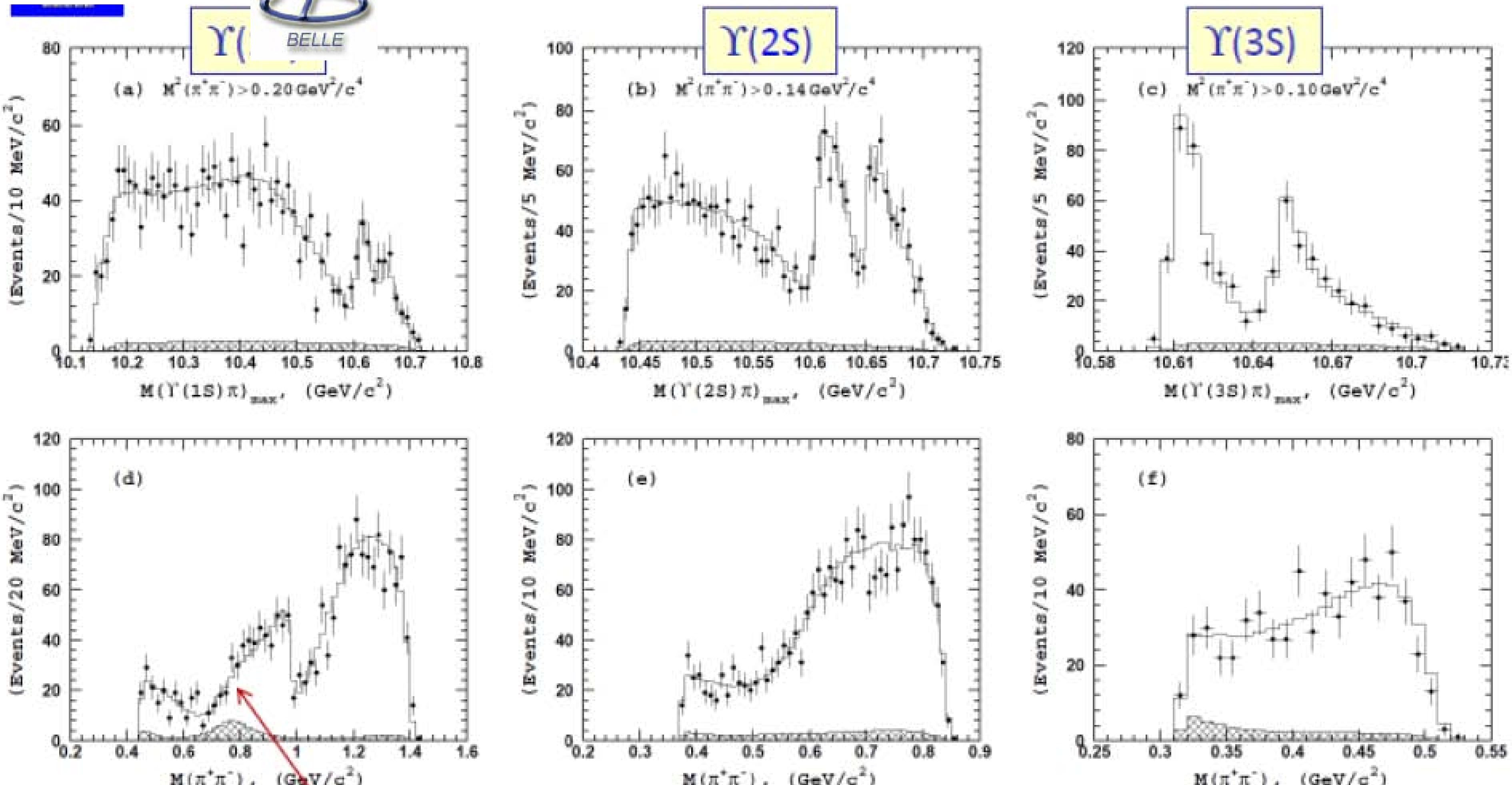
$\sigma[e^+e^-\rightarrow\Upsilon(5S)\rightarrow\Upsilon(1S)\pi^0\pi^0] = (1.16\pm0.06\pm0.10)$ pb

$\sigma[e^+e^-\rightarrow\Upsilon(5S)\rightarrow\Upsilon(2S)\pi^0\pi^0] = (1.87\pm0.11\pm0.23)$ pb

$\sigma[e^+e^-\rightarrow\Upsilon(5S)\rightarrow\Upsilon(3S)\pi^0\pi^0] = (0.98\pm0.24\pm0.19)$ pb

Consistent with ½ of $Y(nS)\pi^+\pi^-$

arXiv:1308.2646, accepted for publication in Phys. Rev. D



Improvement due to inclusion of σ state

BW amplitudes describe Z_b states very well.

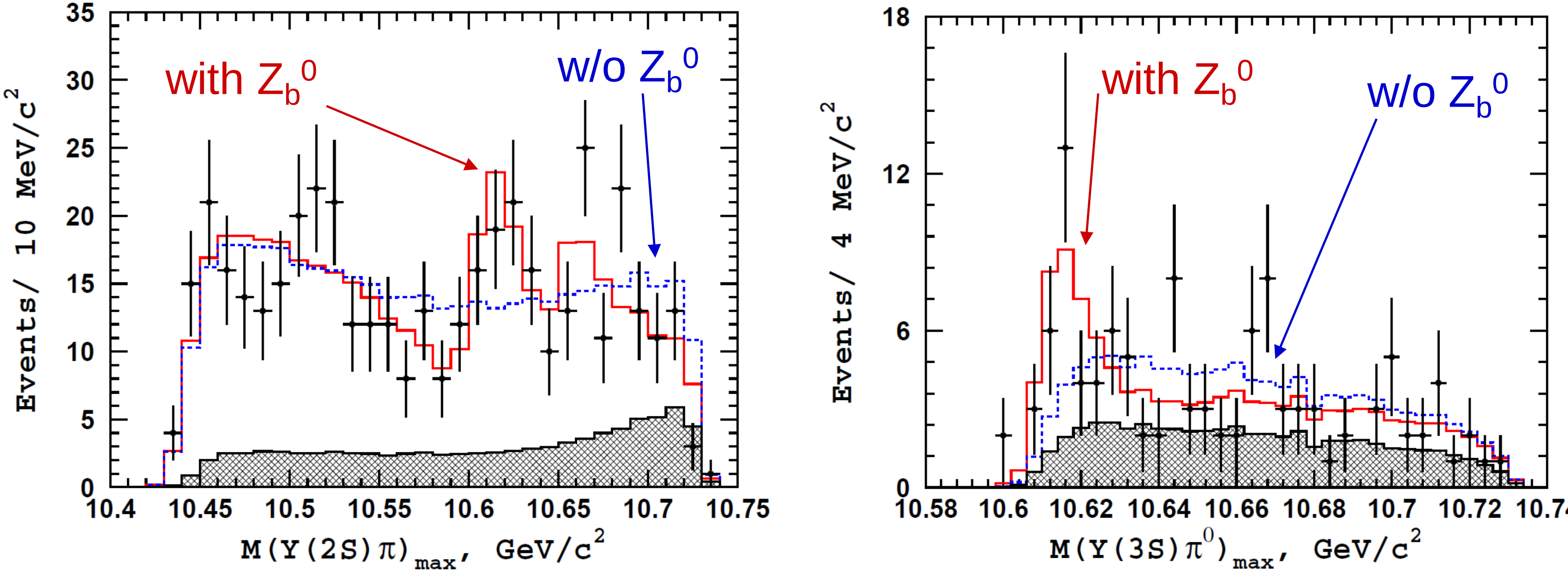
Resonant behavior of Z_b amplitudes (intensity & phase).

21

$\Upsilon(2S)\pi^0\pi^0$ Dalitz analysis

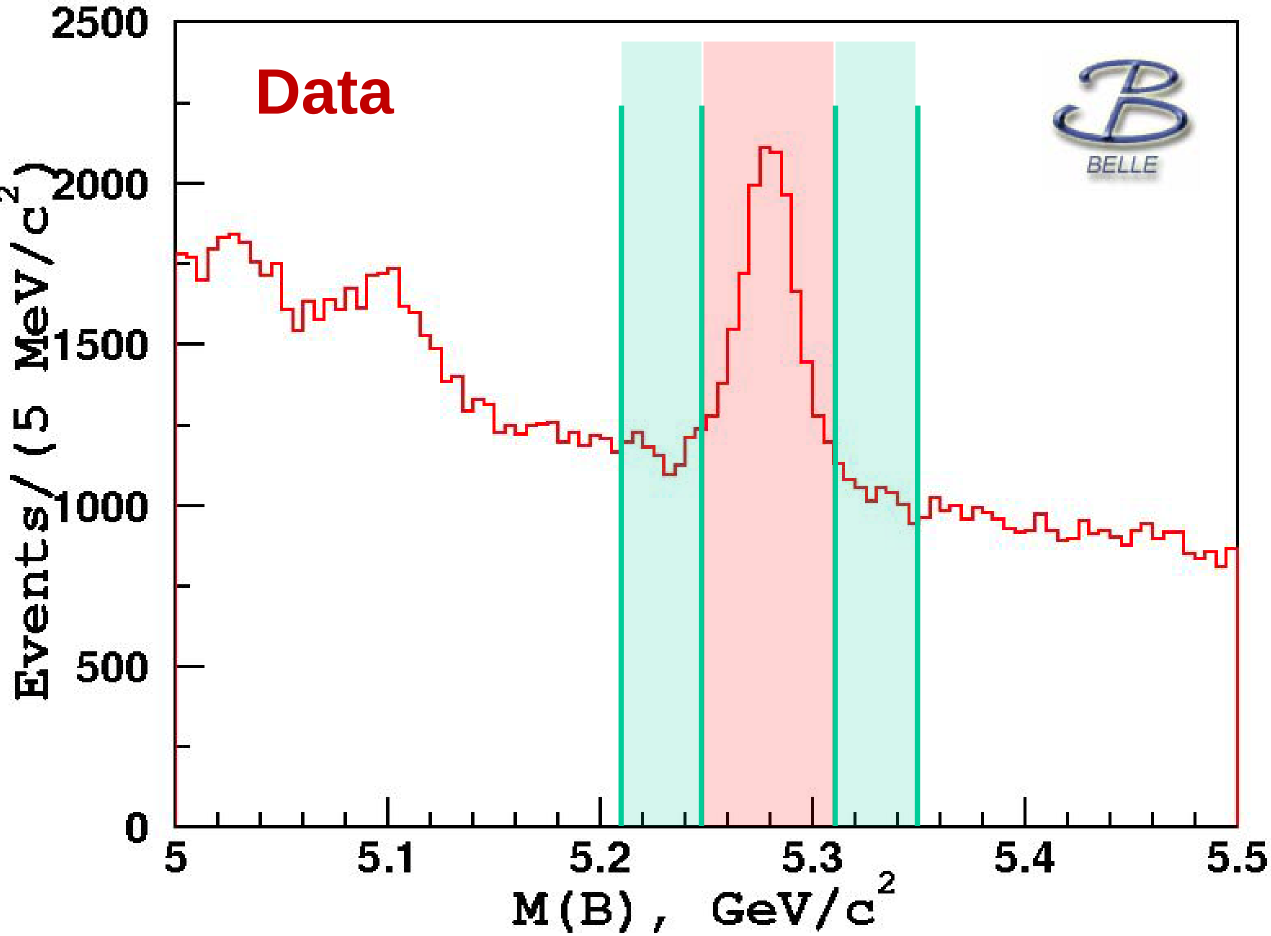
arXiv:1308.2646

$$M(s_1, s_2) = A_{Z1} + A_{Z2} + A_{f_0} + A_{f_2} + A_{NR}$$



- Z_b^0 resonant structure has been observed in $\Upsilon(2S)\pi^0\pi^0$ and $\Upsilon(3S)\pi^0\pi^0$
- Statistical significance of Z_b^0(10610) signal is 6.5σ including systematics
- Z_b^0(10650) signal is not significant (~2σ), not contradicting with its existence
- Z_b^0(10610) mass from the fit M=10609 ± 4 ± 4 MeV/c^2 $M(Z_b^+)$=10607±2 MeV/c^2

$\Upsilon(5S) \to B^* B^{(*)} \pi$: B Reconstruction



Charged B:

- $D^0[K\pi, K\pi\pi\pi]\pi^-$
- $J/\psi[\mu\mu]\ K^-$

Neutral B:

- $D^+[K\pi\pi]\pi^-$
- $J/\psi[\mu\mu]\ \bar{K}^{*0}$
- $D^{*+}[K\pi, K\pi\pi, K\pi\pi\pi]\pi^-$

Effective B fraction:
$Br[B \to f] = (143 \pm 15) \times 10^{-5}$

B candidate invariant mass distribution. All modes combined. Select B signal within 30-40 MeV (depending on B decay mode) around B nominal mass.

Selection

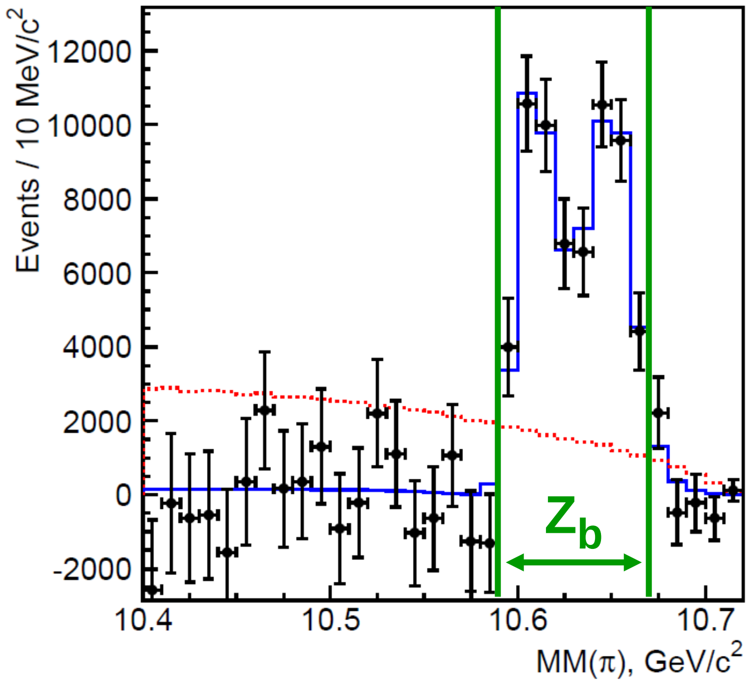
Decay chain

$\Upsilon(5S) \to Z_b^+ \pi^-$
$\hookrightarrow h_b(nP)\, \pi^+$
$\hookrightarrow \eta_b(mS)\, \gamma$

reconstruct

R_2<0.3
Hadronic event selection; continuum suppression using event shape; π^0 veto.

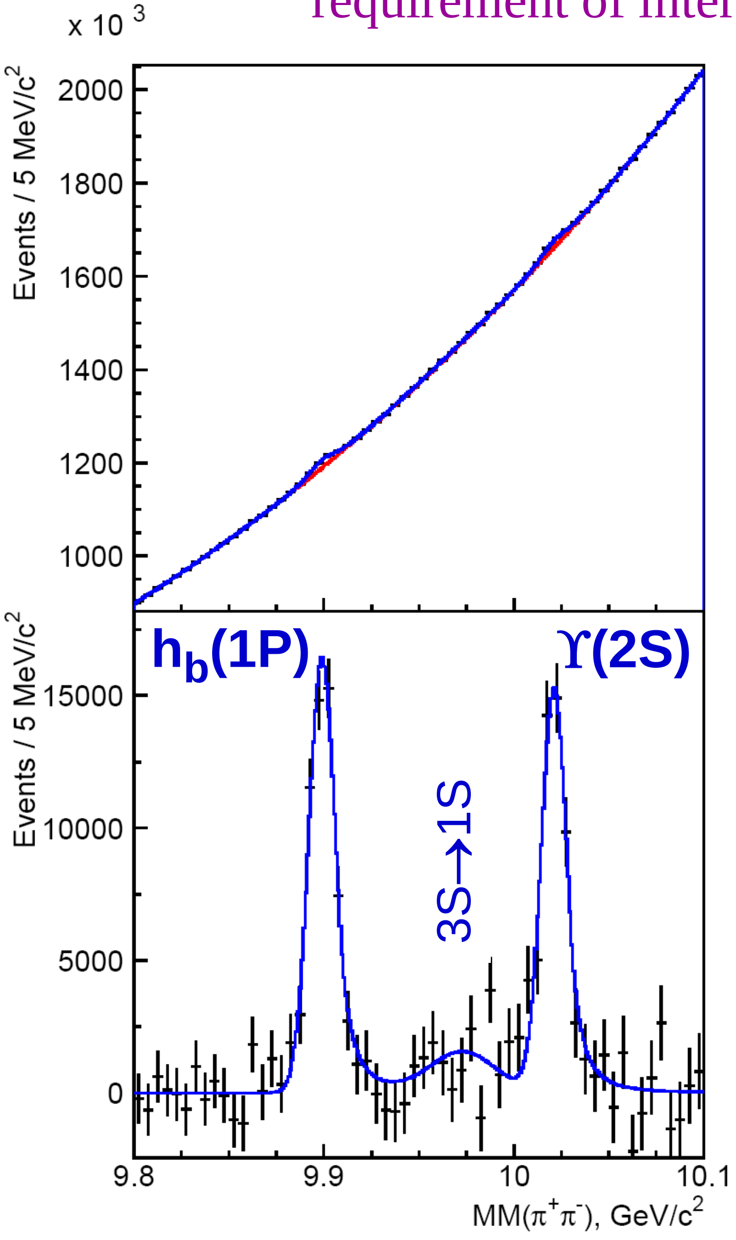
Require intermediate Z_b : **10.59 < MM(π) < 10.67 GeV**



bg. suppression ×5.2

$M_{miss}(\pi^+\pi^-)$ spectrum

requirement of intermediate Z_b



Update of M [$h_b(1P)$] :

$$(9899.0 \pm 0.4 \pm 1.0)\ \mathrm{MeV}/c^2$$

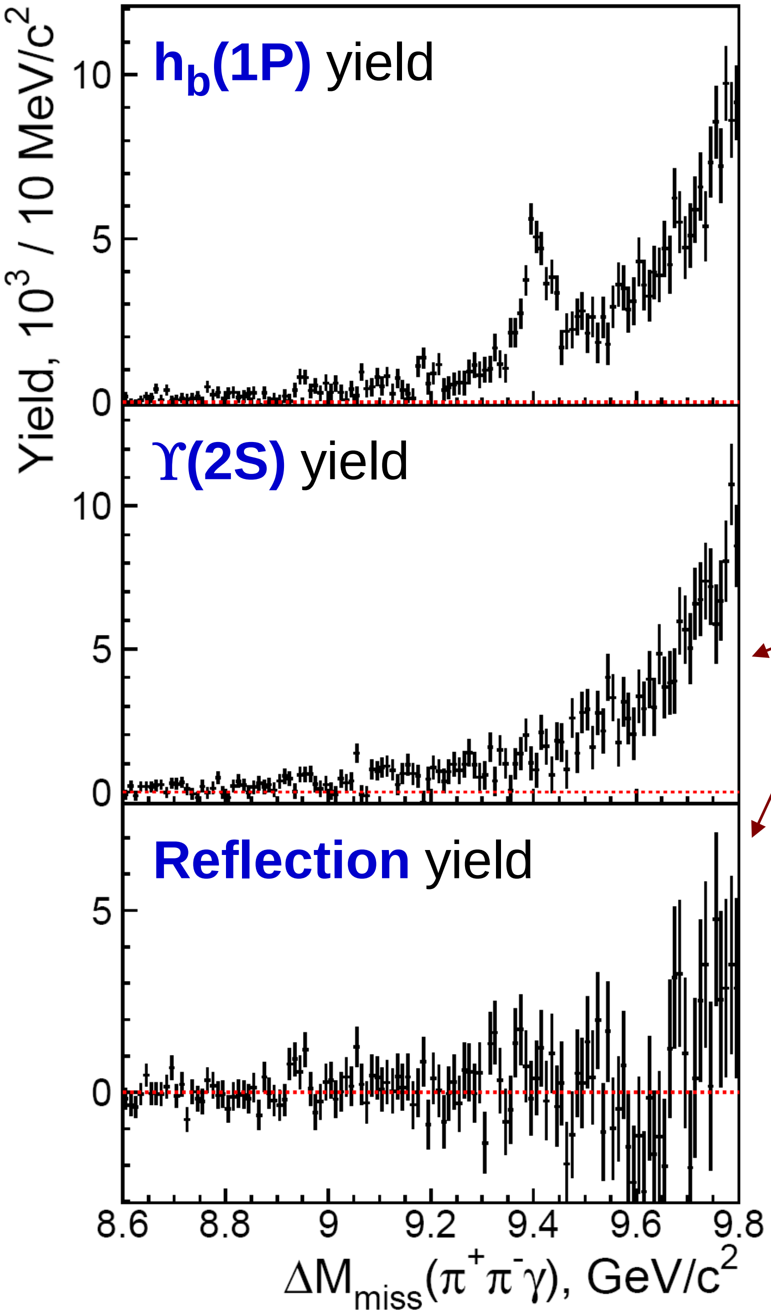
ΔM_{HF} [$h_b(1P)$] = $(+0.8 \pm 1.1)\mathrm{MeV}/c^2$

Previous Belle meas.: arXiv:1103.3411

$$(9898.3 \pm 1.1^{+1.0}_{-1.1})\ \mathrm{MeV}/c^2$$

ΔM_{HF} [$h_b(1P)$] = $(+1.6 \pm 1.5)\mathrm{MeV}/c^2$

Results of fits to $M_{miss}(\pi^+\pi^-)$ spectra



$\eta_b(1S)$

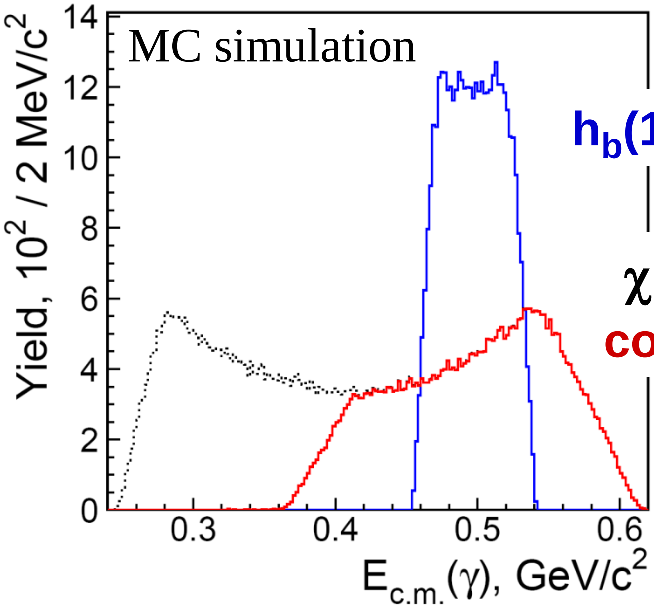
Peaking background?
MC simulation ⇒ none.

no significant structures

Calibration

Use decays $B^+ \to \chi_{c1} K^+ \to (J/\psi\ \gamma)\ K^+$

Photon energy spectrum



$h_b(1P) \to \eta_b(1S)\,\gamma$

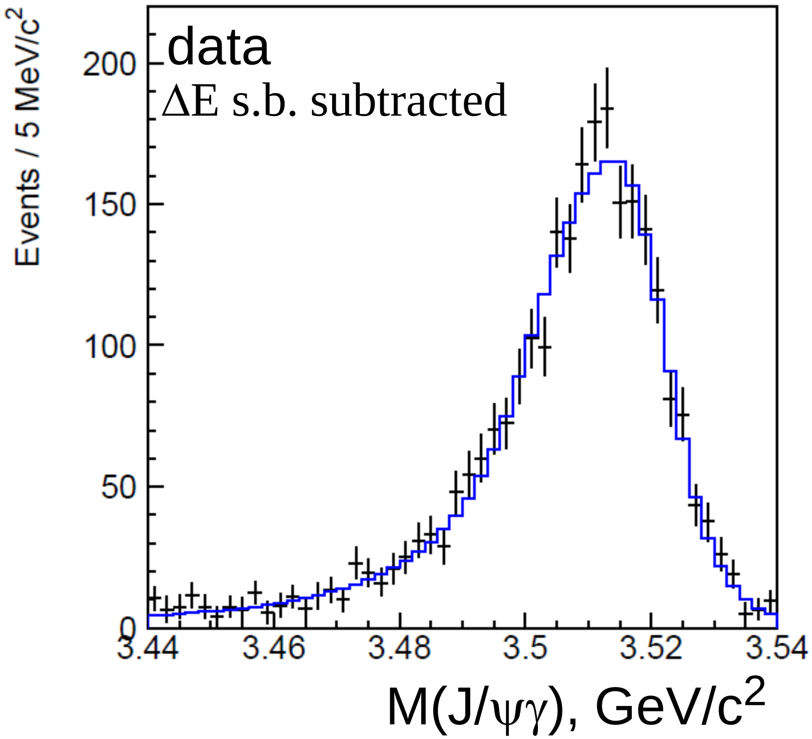
$\chi_{c1} \to J/\psi\,\gamma$

$\cos\theta_{Hel} > -0.2$

$\cos\theta_{Hel}\,(\chi_{c1}) > -0.2 \Rightarrow$ match γ energy of **signal** & **callibration** channels

Calibration (2)

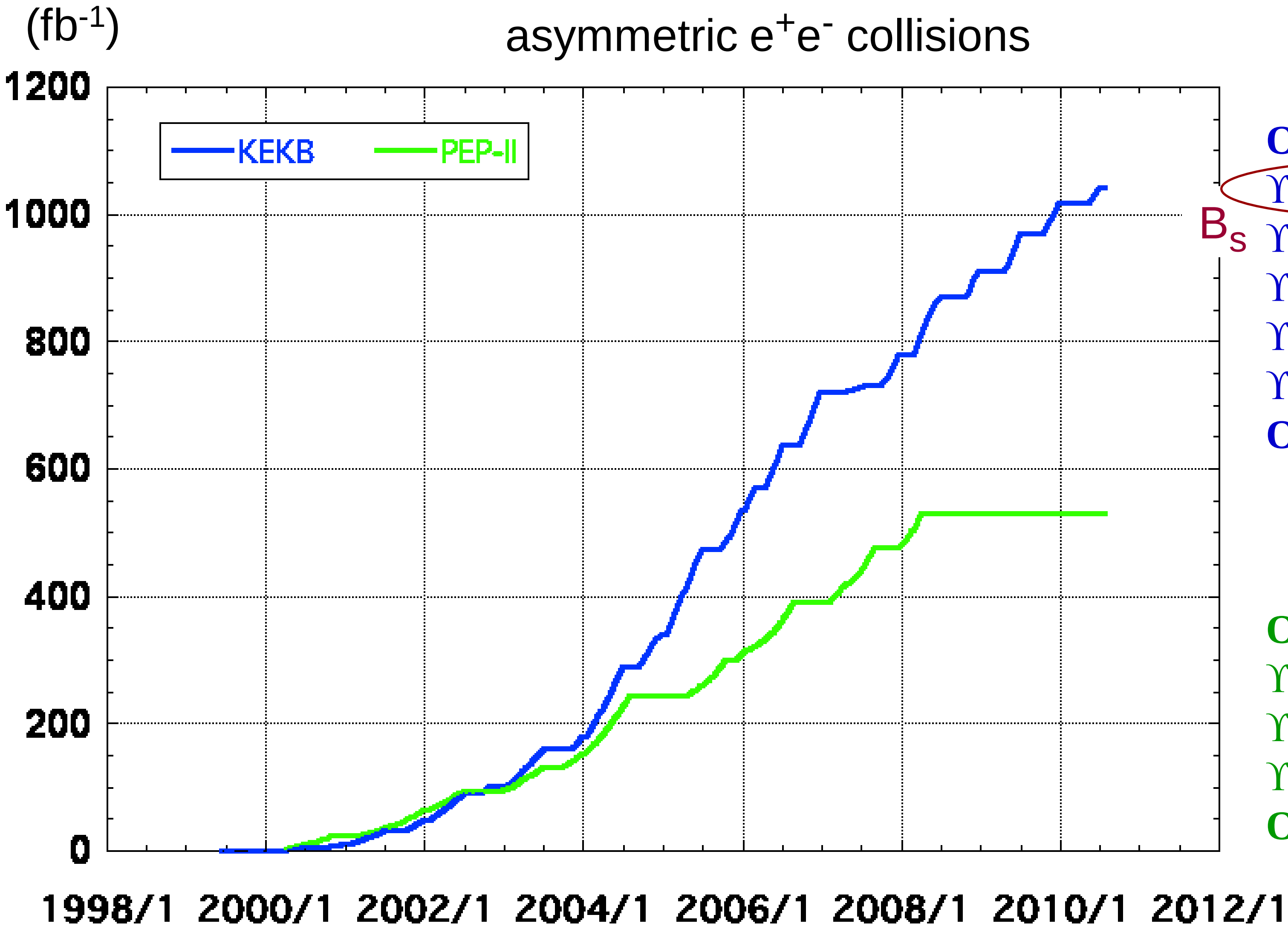
Resolution: double-sided CrystalBall function with asymmetric core



⇒ Correction of MC

mass shift	$-0.7 \pm 0.3\ ^{+0.2}_{-0.4}$ MeV
fudge-factor for resolution	$1.15 \pm 0.06 \pm 0.06$

Integrated Luminosity at B-factories



> 1 ab^{-1}

On resonance:

B_s ϒ(5S): 121 fb^{-1}

ϒ(4S): 711 fb^{-1}

ϒ(3S): 3 fb^{-1}

ϒ(2S): 24 fb^{-1}

ϒ(1S): 6 fb^{-1}

Off reson./scan :

~100 fb-1

530 fb^{-1}

On resonance:

ϒ(4S): 433 fb^{-1}

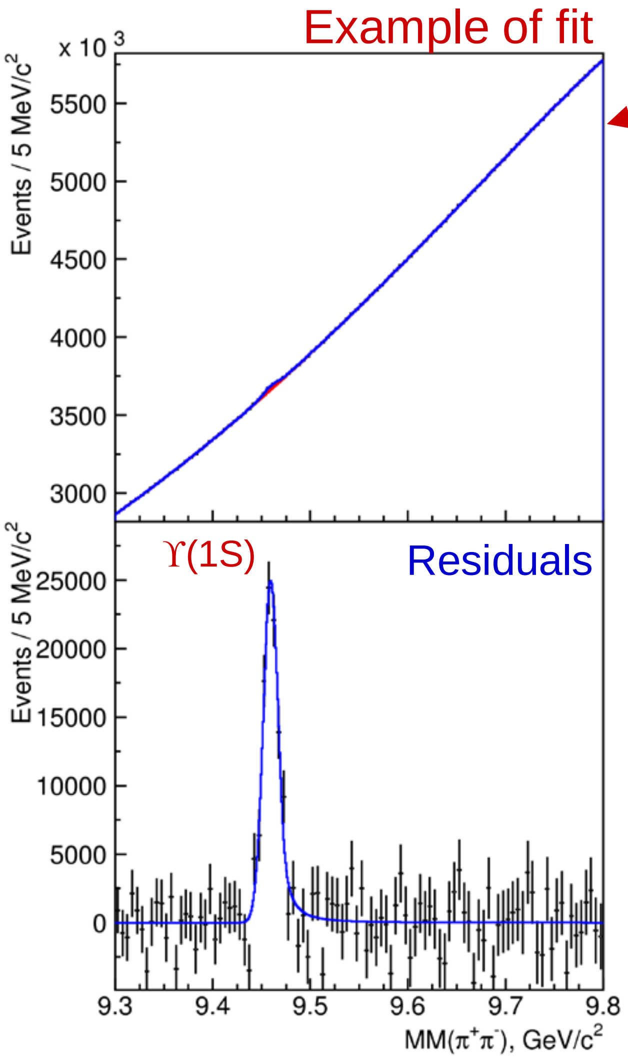
ϒ(3S): 30 fb^{-1}

ϒ(2S): 14 fb^{-1}

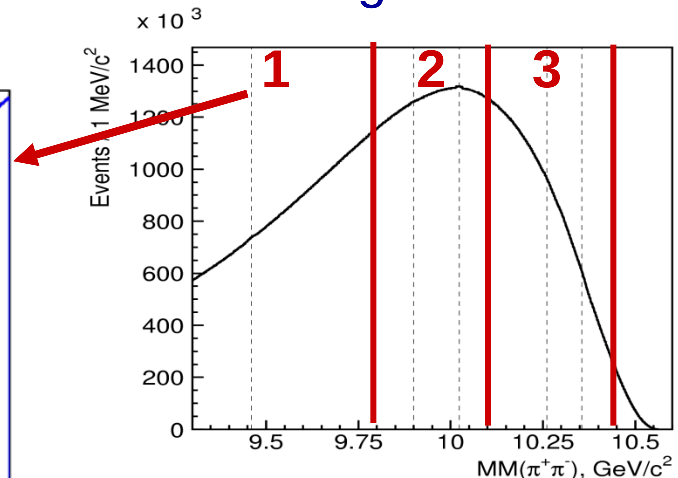
Off reson./scan :

~54 fb-1

Description of fit to MM($\pi^+\pi^-$)



Three fit regions

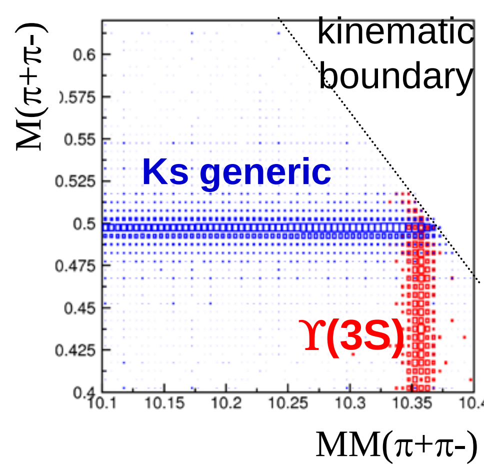


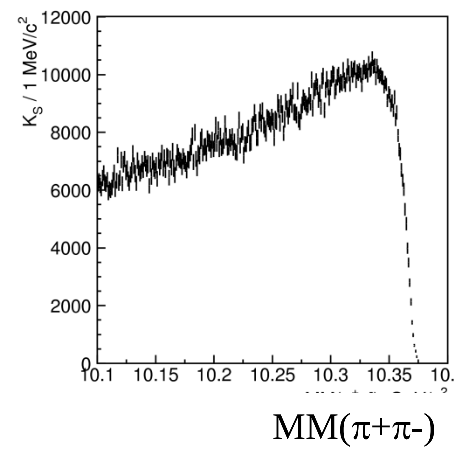
BG: Chebyshev polynomial, 6th or 7th order

Signal: shape is fixed from $\mu^+\mu^-\pi^+\pi^-$ data

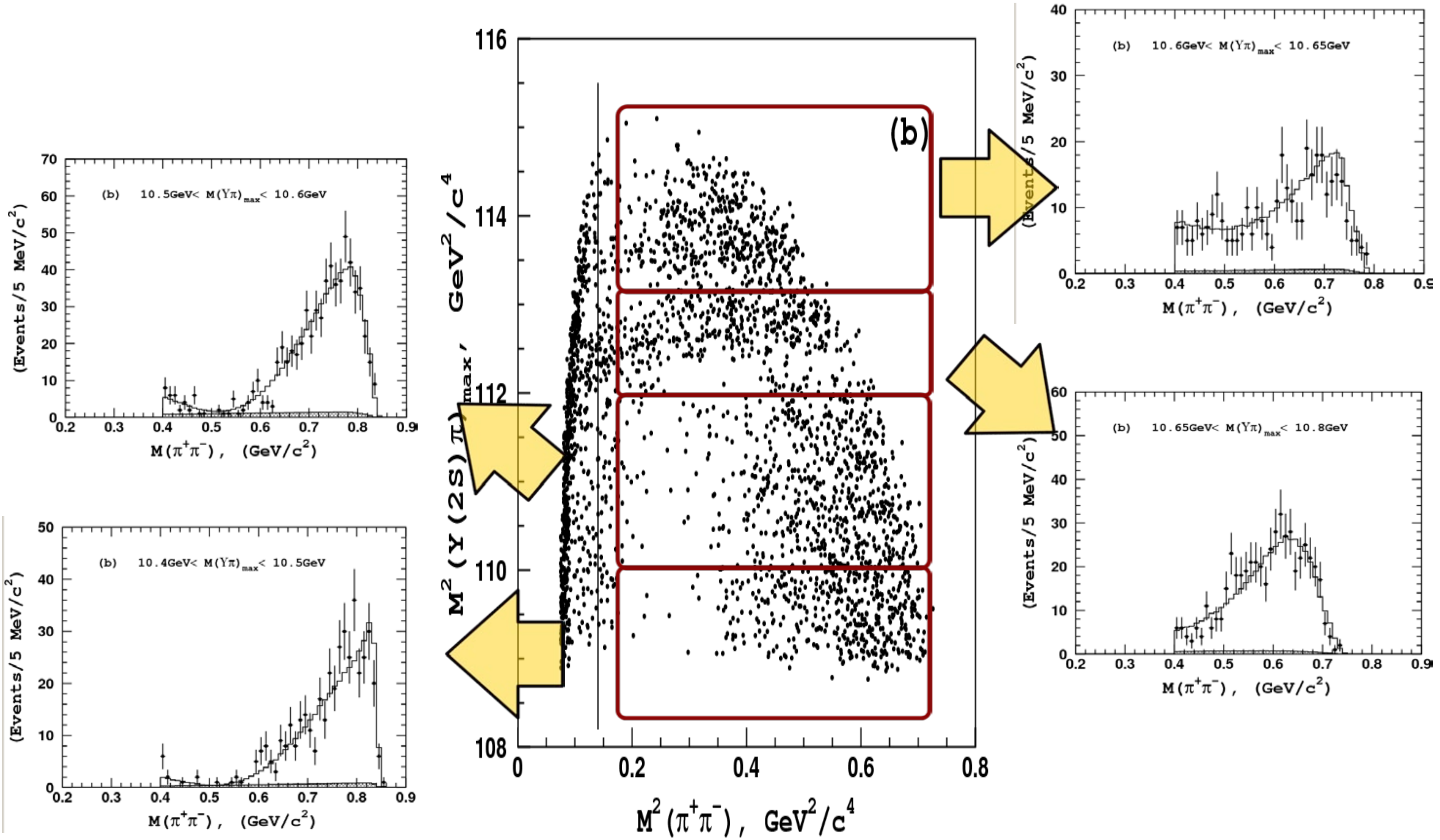
"Residuals" – subtract polynomial from data points

K_S contribution: subtract bin-by-bin

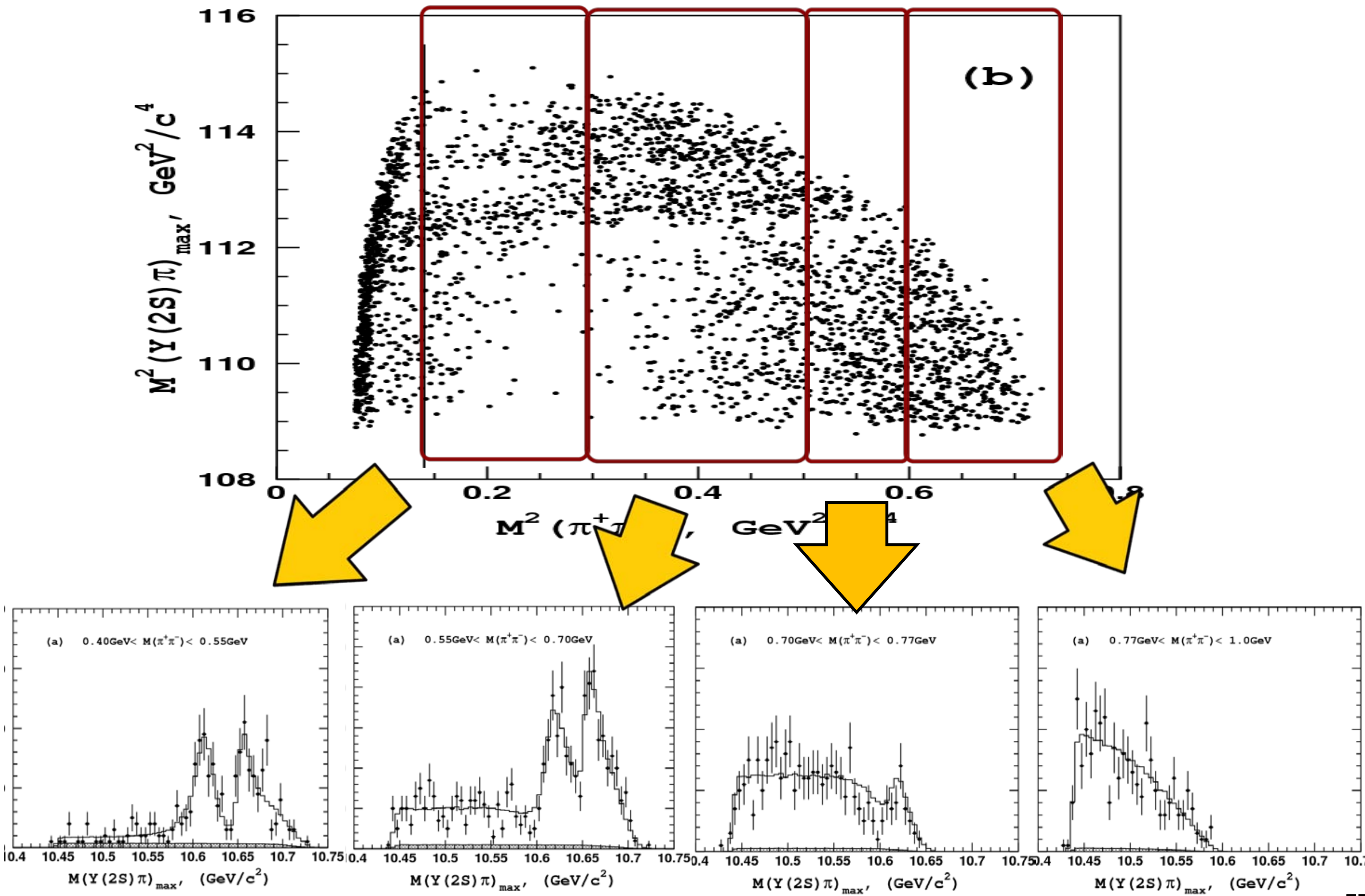




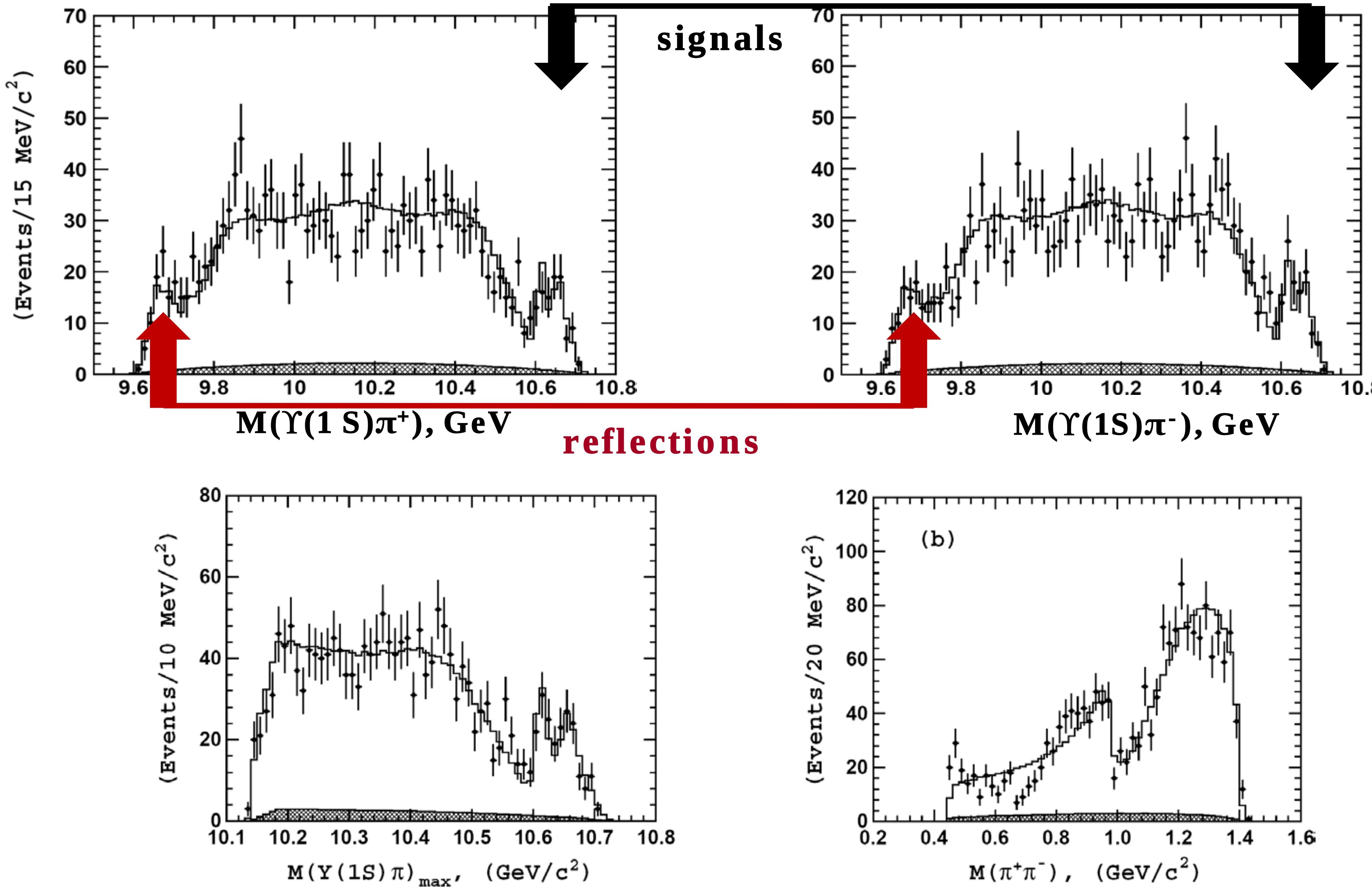
Results: $\Upsilon(5S)\to\Upsilon(2S)\pi^+\pi^-$



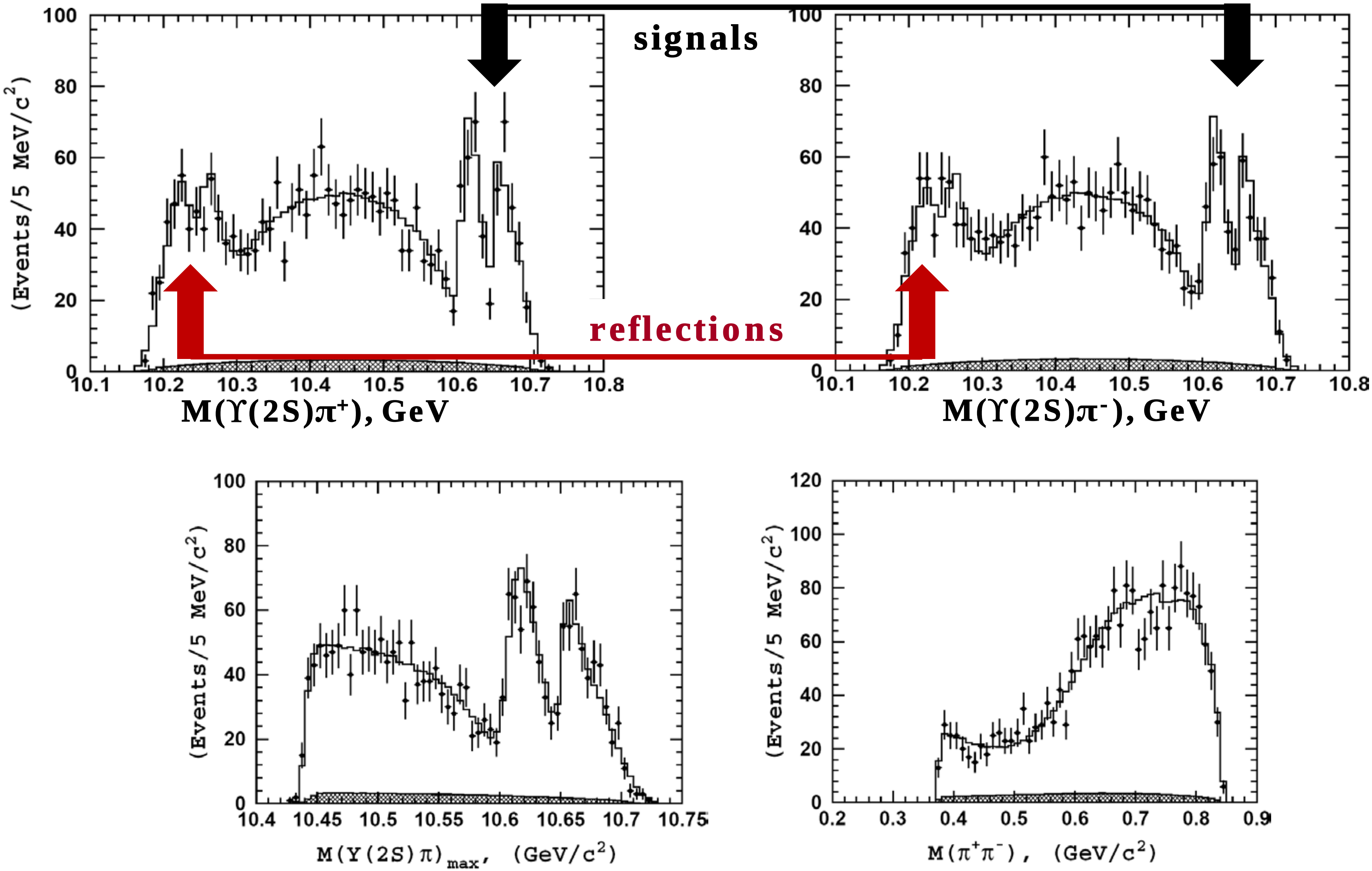
Results: $\Upsilon(5S)\rightarrow\Upsilon(2S)\pi^+\pi^-$



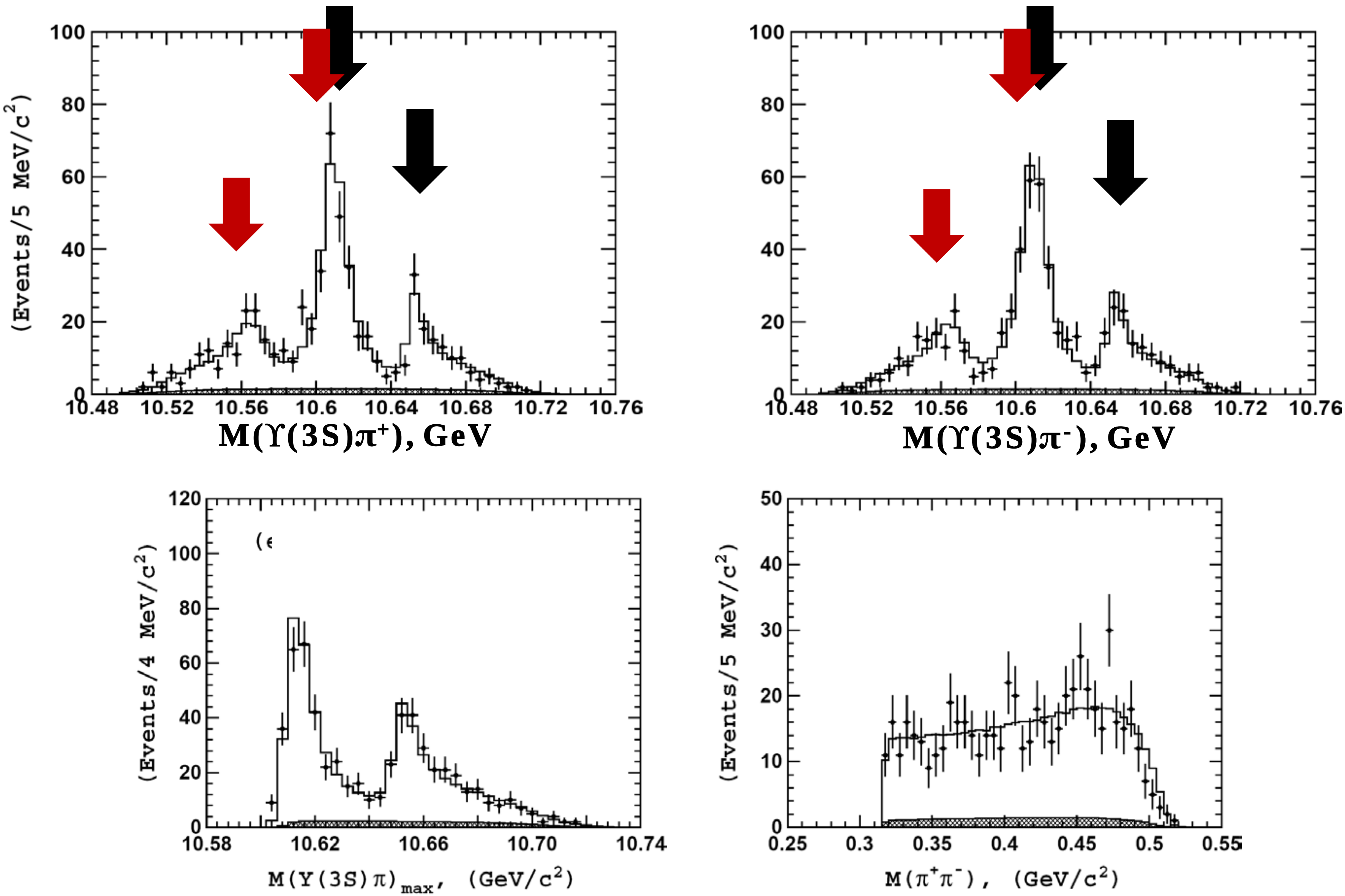
Results: $\Upsilon(1S)\pi^+\pi^-$



Results: $\Upsilon(2S)\pi^+\pi^-$



Results: $\Upsilon(3S)\pi^+\pi^-$



Summary of Z_b parameters

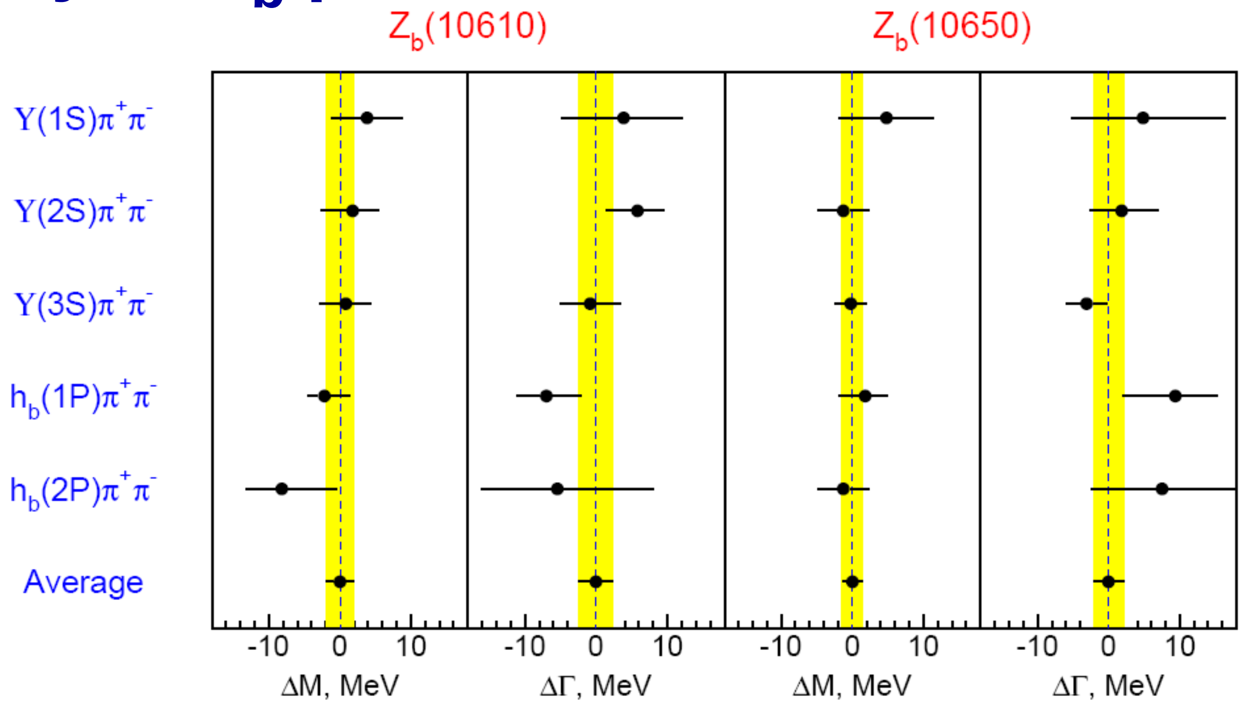
Average over 5 channels

$\langle M_1 \rangle = 10607.2 \pm 2.0$ MeV

$\langle \Gamma_1 \rangle = 18.4 \pm 2.4$ MeV

$\langle M_2 \rangle = 10652.2 \pm 1.5$ MeV

$\langle \Gamma_2 \rangle = 11.5 \pm 2.2$ MeV



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	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\,^{+4.5+2.1}_{-3.9-1.2}$	$13\,^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, MeV/c^2	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3\,^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9\,^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7\,^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

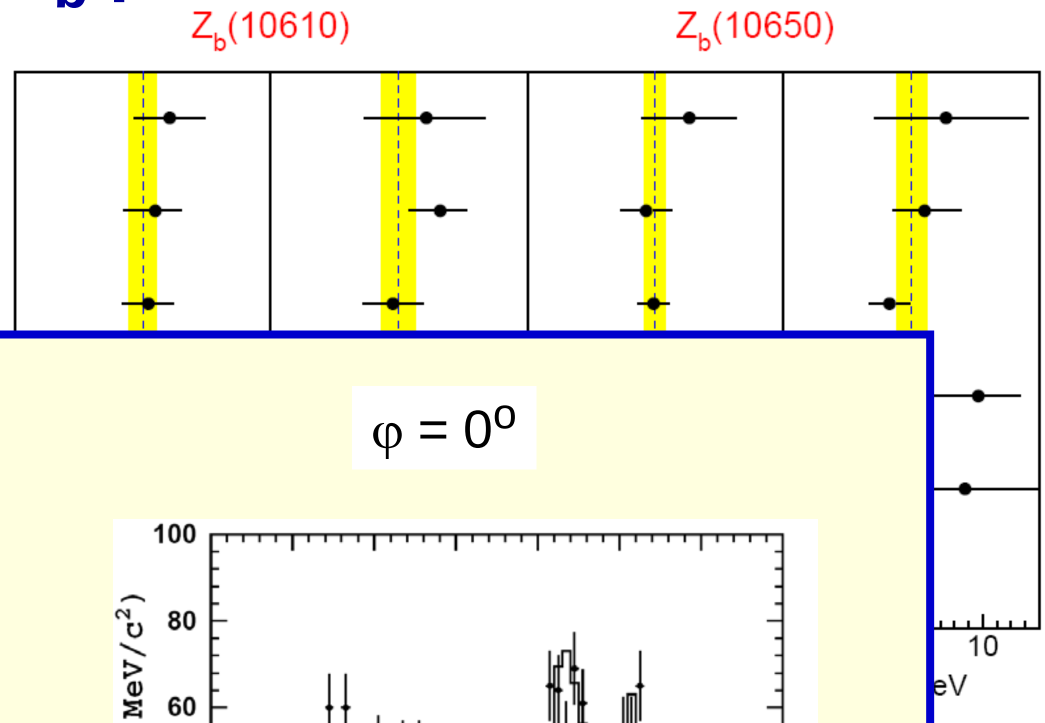
$Z_b(10610)$ yield ~ $Z_b(10650)$ yield in every channel
Relative phases: 0^o for $\Upsilon\pi\pi$ and 180^o for $h_b\pi\pi$

Summary of Z_b parameters

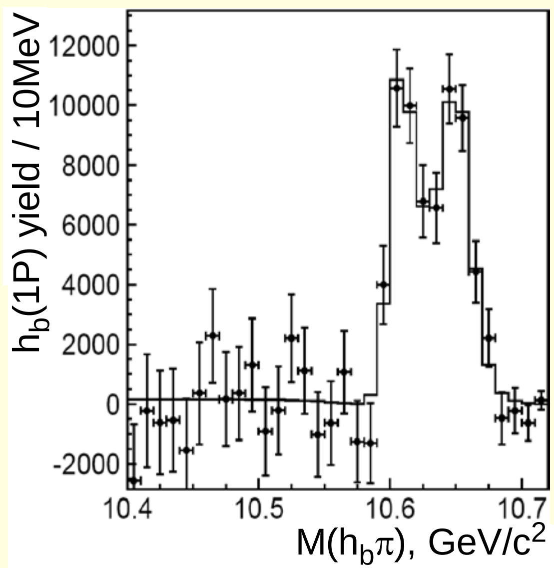
Average over 5 channels

$\langle M_1 \rangle = 10607.2 \pm 2.0$ MeV

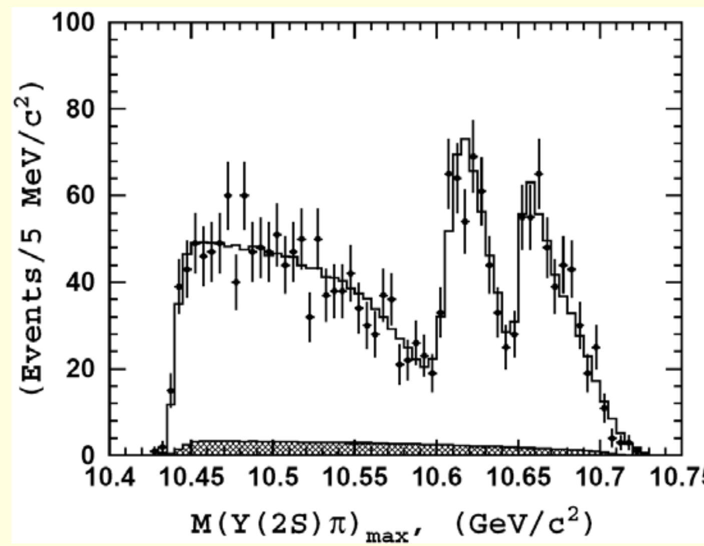
$\langle \Gamma_1 \rangle = 18.4 \pm 2.4$ MeV



φ = 180°



φ = 0°

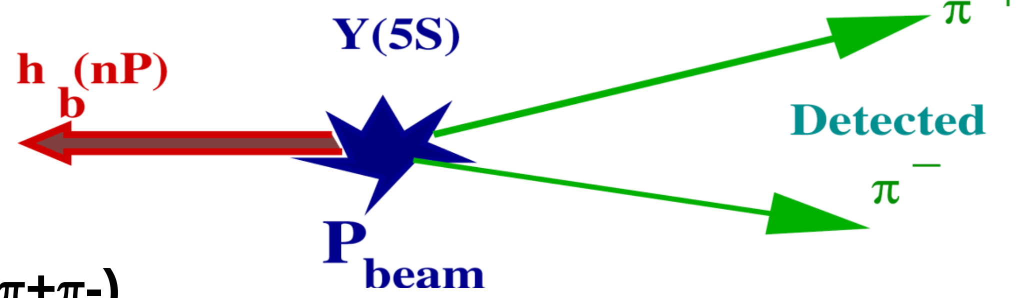


$Z_b(10610)$ yield ~ $Z_b(10650)$ yield in every channel

Relative phases: 0^o for $\Upsilon\pi\pi$ and 180^o for $h_b\pi\pi$

h_b reconstruction

Missing mass to $\pi\pi$ system



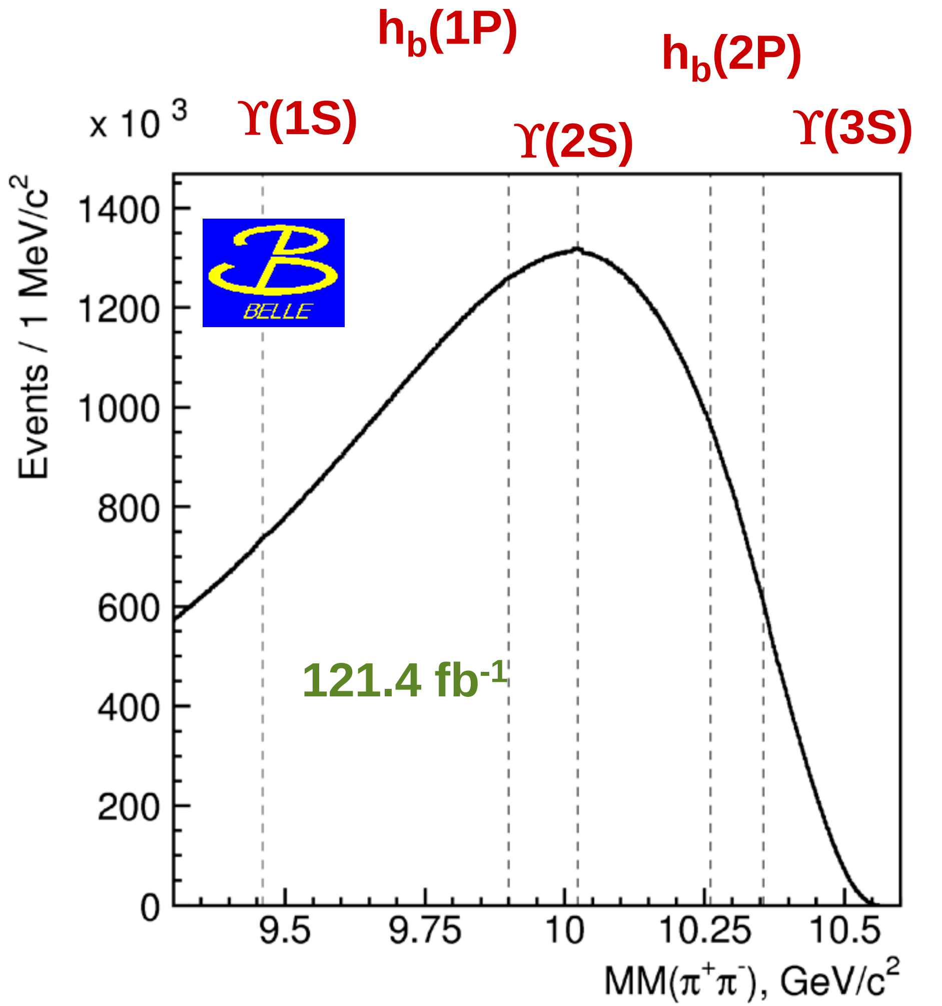
$$M_{hb(nP)} = \sqrt{(P_{\Upsilon(5S)} - P_{\pi+\pi-})^2} \equiv MM(\pi+\pi-)$$

Simple selection :

$\pi^+\pi^-$: good quality, positively identified

Suppression of continuum events
FW R2<0.3

⇒ Search for $h_b(nP)$ peaks in $MM(\pi^+\pi^-)$ spectrum



Branching Fractions

$\Upsilon(nS)\pi^+\pi^-$ production cross section (corrected for the ISR) at sqrt(s) = 10.865 GeV:

$\sigma(e^+e^- \to \Upsilon(1S)\,\pi^+\pi^-) = [2.27 \pm 0.12(\textit{stat.}) \pm 0.09(\textit{syst.})]$ pb
$\sigma(e^+e^- \to \Upsilon(2S)\,\pi^+\pi^-) = [4.07 \pm 0.16(\textit{stat.}) \pm 0.45(\textit{syst.})]$ pb
$\sigma(e^+e^- \to \Upsilon(3S)\,\pi^+\pi^-) = [1.46 \pm 0.09(\textit{stat.}) \pm 0.16(\textit{syst.})]$ pb

Fractions of individual sub-modes:

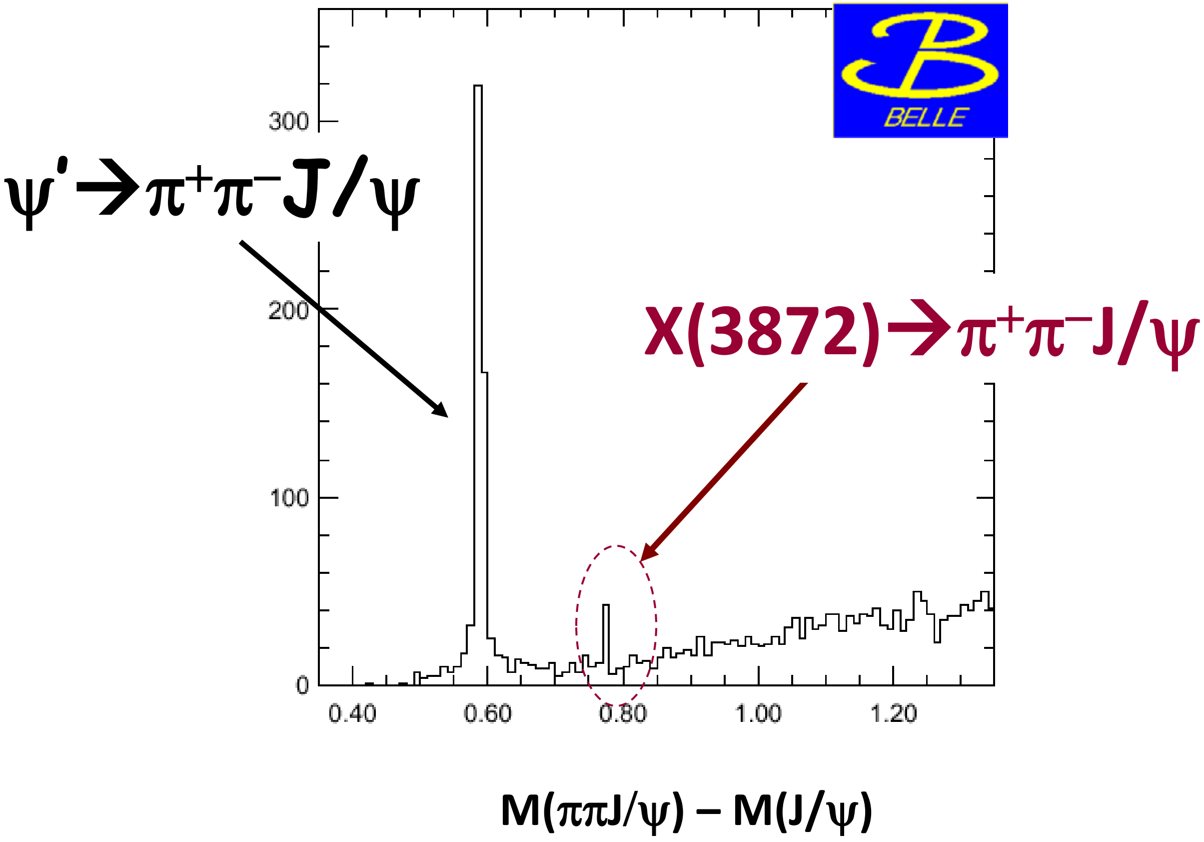
Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
$Z(10610)\pi^\pm$, %	$4.8 \pm 1.2^{+1.5}_{-0.3}$	$18.1 \pm 3.1^{+4.2}_{-0.3}$	$30.0 \pm 6.3^{+5.4}_{-7.1}$
$Z(10650)\pi^\pm$, %	$0.87 \pm 0.32^{+0.16}_{-0.12}$	$4.05 \pm 1.2^{+0.95}_{-0.15}$	$13.3 \pm 3.6^{+2.6}_{-1.4}$
$f_2(1270)$, %	$14.6 \pm 1.5^{+6.3}_{-0.7}$	$4.09 \pm 1.0^{+0.33}_{-1.0}$	–
Total $S-$wave, %	$86.5 \pm 3.2^{+3.3}_{-4.9}$	$101.0 \pm 4.2^{+6.5}_{-3.5}$	$44.0 \pm 6.2^{+1.8}_{-4.3}$
	$h_b(1P)\pi$		$h_b(2P)\pi$
non-resonant, %	3.2 (< 22 at 90% C.L.)		–
$Z_b(10610)$, %	$42.3^{+9.5}_{-12.7}{}^{+6.7}_{-0.8}$		$35.2^{+15.6}_{-9.4}{}^{+0.1}_{-13.4}$
$Z_b(10650)$, %	$60.2^{+10.3}_{-21.1}{}^{+4.1}_{-3.8}$		$64.8^{+15.2}_{-11.4}{}^{+6.7}_{-15.5}$

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$	CDF [88–90] (np), DØ [91] (5.2)	
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)	
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)	
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)	
				$B \to K(\gamma\psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)	
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)	
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007
				$e^+e^- \to J/\psi\ (\ldots)$	Belle [54] (5.0)	
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005
					CLEO [110] (5.4)	
					Belle [104] (15)	
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)	
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)	
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	Belle [114] (5.8)	2007

The X(3872) in B→K $\pi^+\pi^-$J/ψ

discovered by Belle (140/fb)

PRL 91, 262001 (2003)

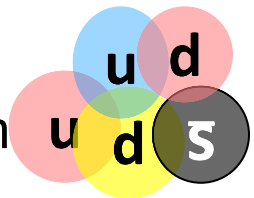


What about other color-singlet combinations?

Other possible "white" combinations of quarks & gluons:

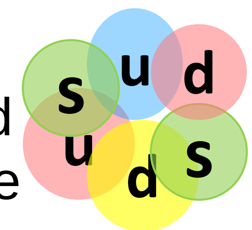
Pentaquark:

S=+1 Baryon



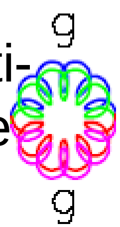
H-diBaryon

tightly bound
6-quark state



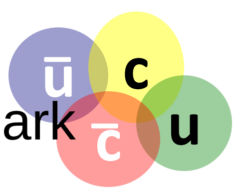
Glueball

Color-singlet multi-
gluon bound state

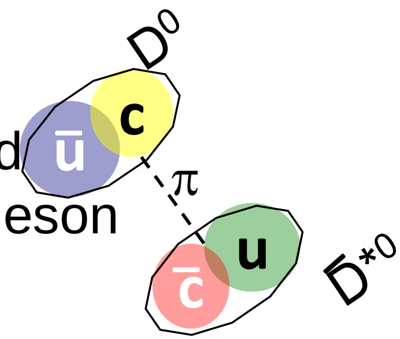


Tetraquark mesons

tightly bound
diquark-diantiquark



loosely bound
meson-antimeson
"molecule"



$q\bar{q}$-gluon hybrid mesons