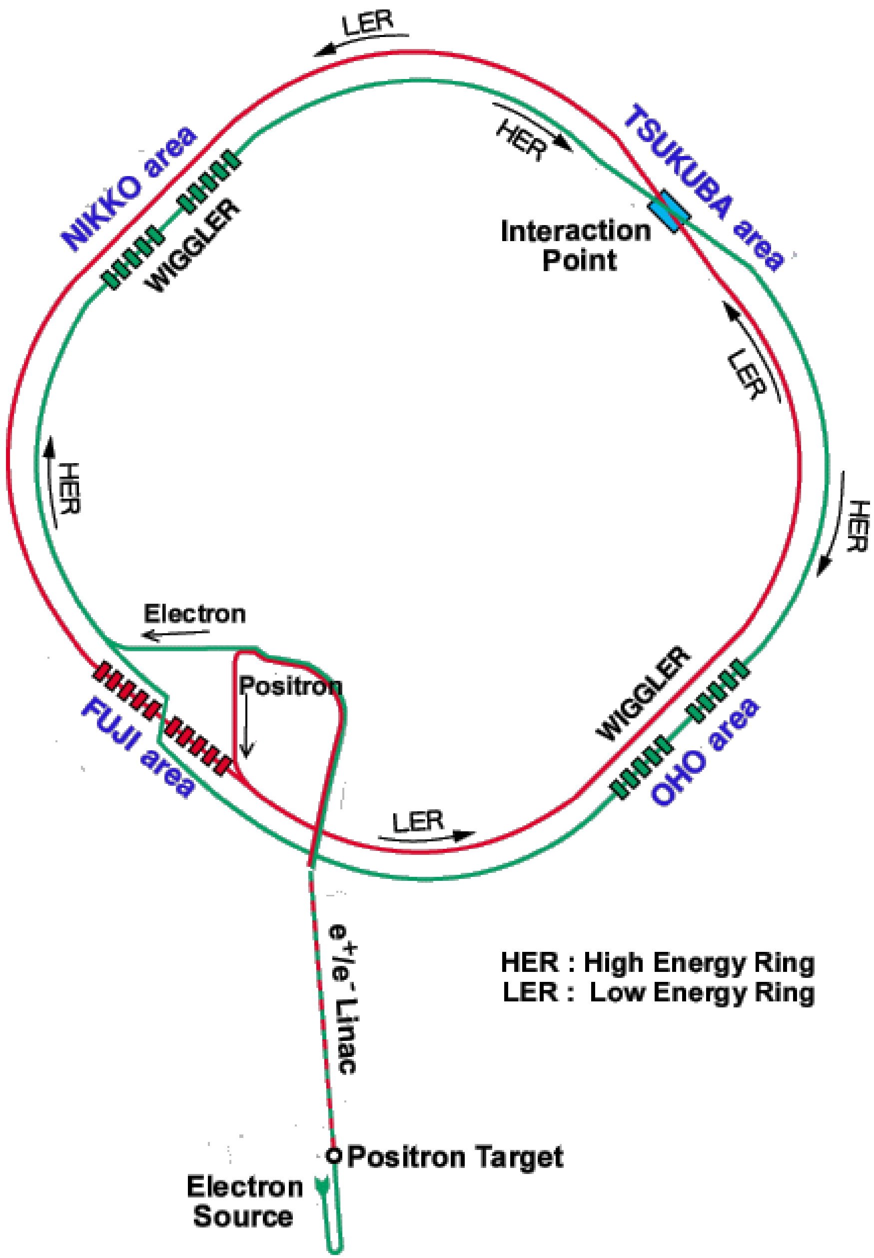
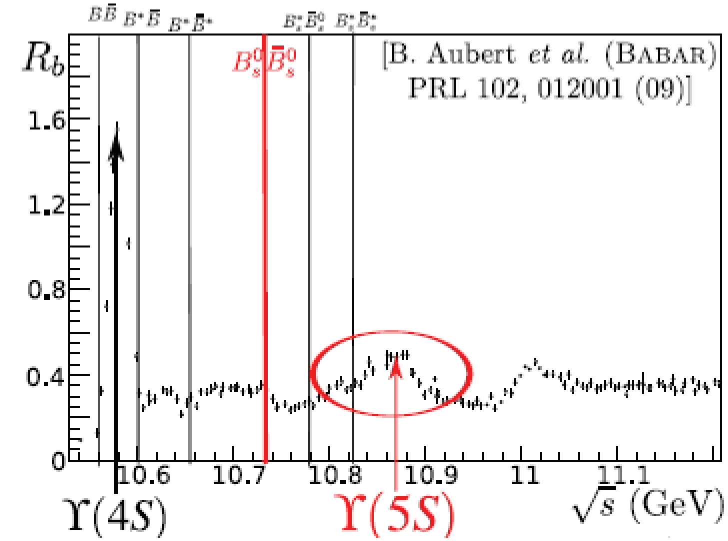
Bottomonium results

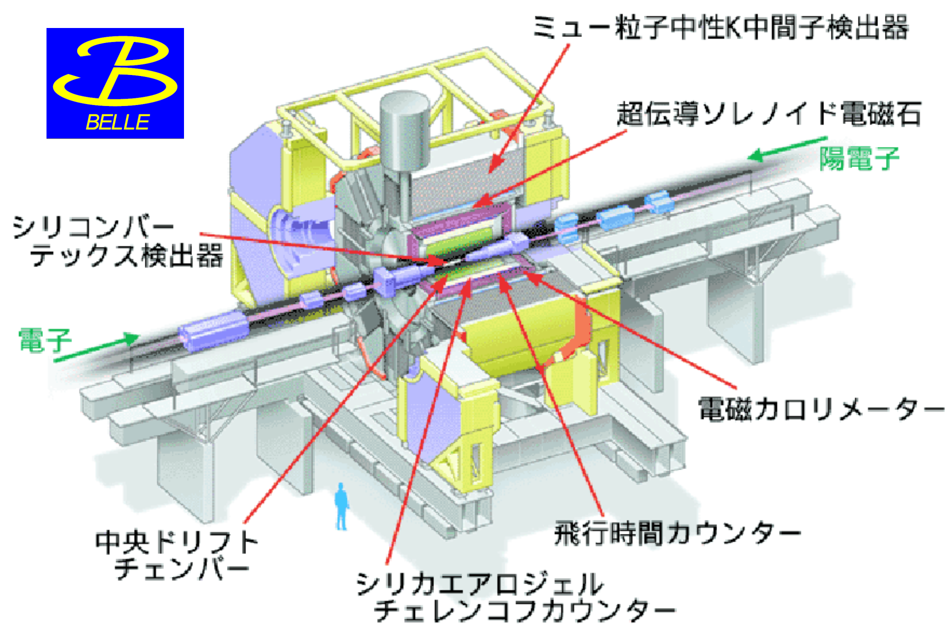
K.Trabelsi
(karim.trabelsi@kek.jp)

KEKB collider and Belle in a nutshell





Belle is an international collaboration
15 countries, 64 institutes
365 members



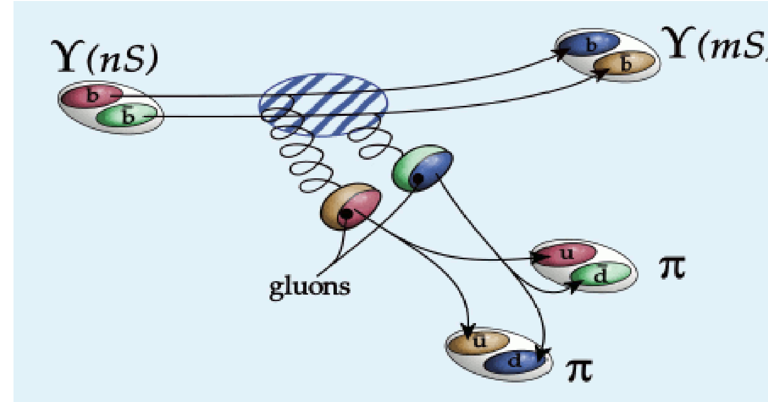
Nature of $\Upsilon(5S)$

Anomalous production of $\Upsilon(nS)\pi^+\pi^-$

PRL 100, 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

$\times\ \mathbf{10^2}$



Zweig-suppressed diagram
for the transition $\Upsilon(nS) \to \Upsilon(mS)\pi^+\pi^-$

1. Rescattering $\Upsilon(5S) \to BB\pi\pi \to \Upsilon(nS)\pi\pi$?
   Simonov, JETP Lett 87, 147 (2008)

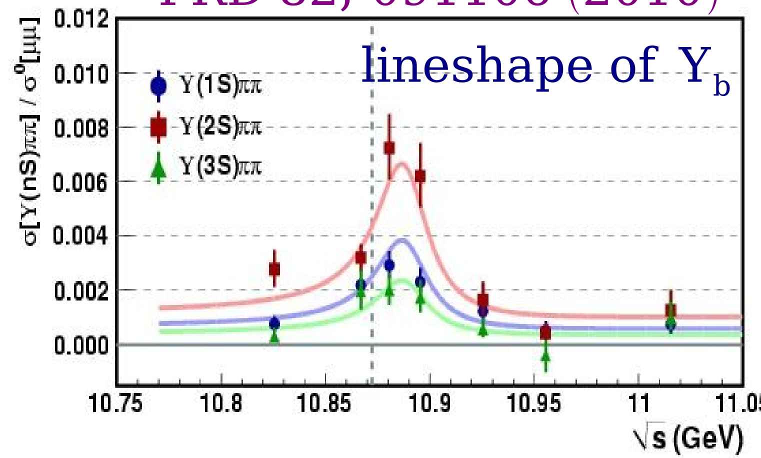
2. Similar effect as in charmonium ?

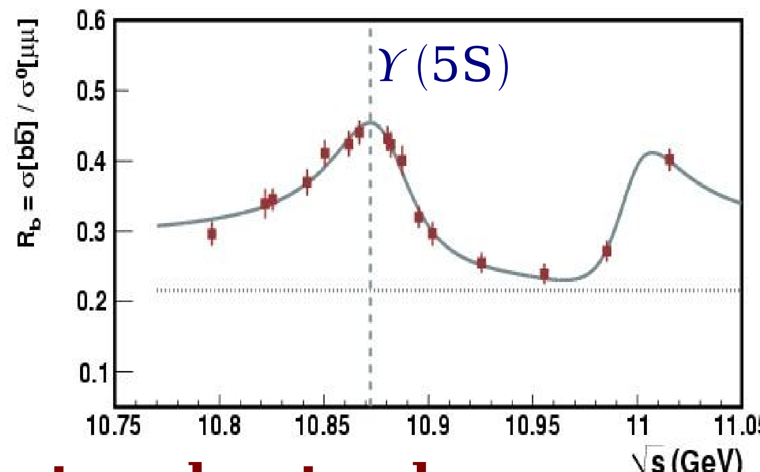
   $\Rightarrow$ assume a Y_b exists close to $\Upsilon(5S)$

   to distinguish them: energy scan

   $\Rightarrow$ shapes of R_b and $\sigma(\Upsilon\pi\pi)$ different (only 2σ)

PRD 82, 091106 (2010)





Nature of $\Upsilon(5S)$ is puzzling and not yet understood

Looking for $h_b(nP)$

(triggered by the observation of $e^+e^- \to \pi^+\pi^- h_c$ above $D\bar{D}$ threshold by CLEO)

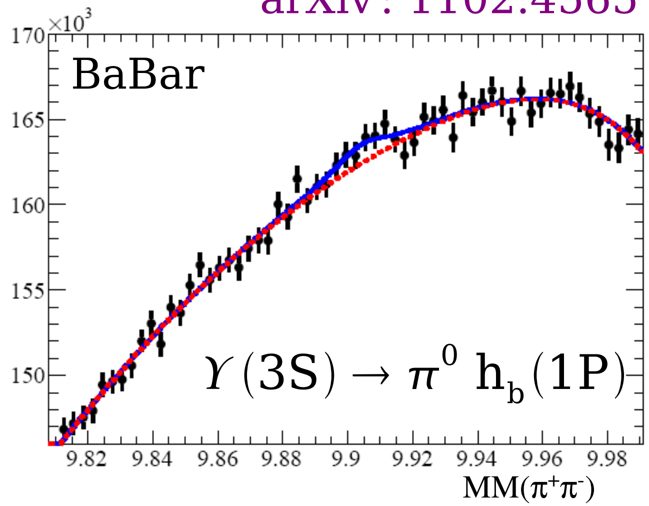
$(b\bar{b})$: $S=0$, $L=1$, $J^{PC}=1^{+-}$

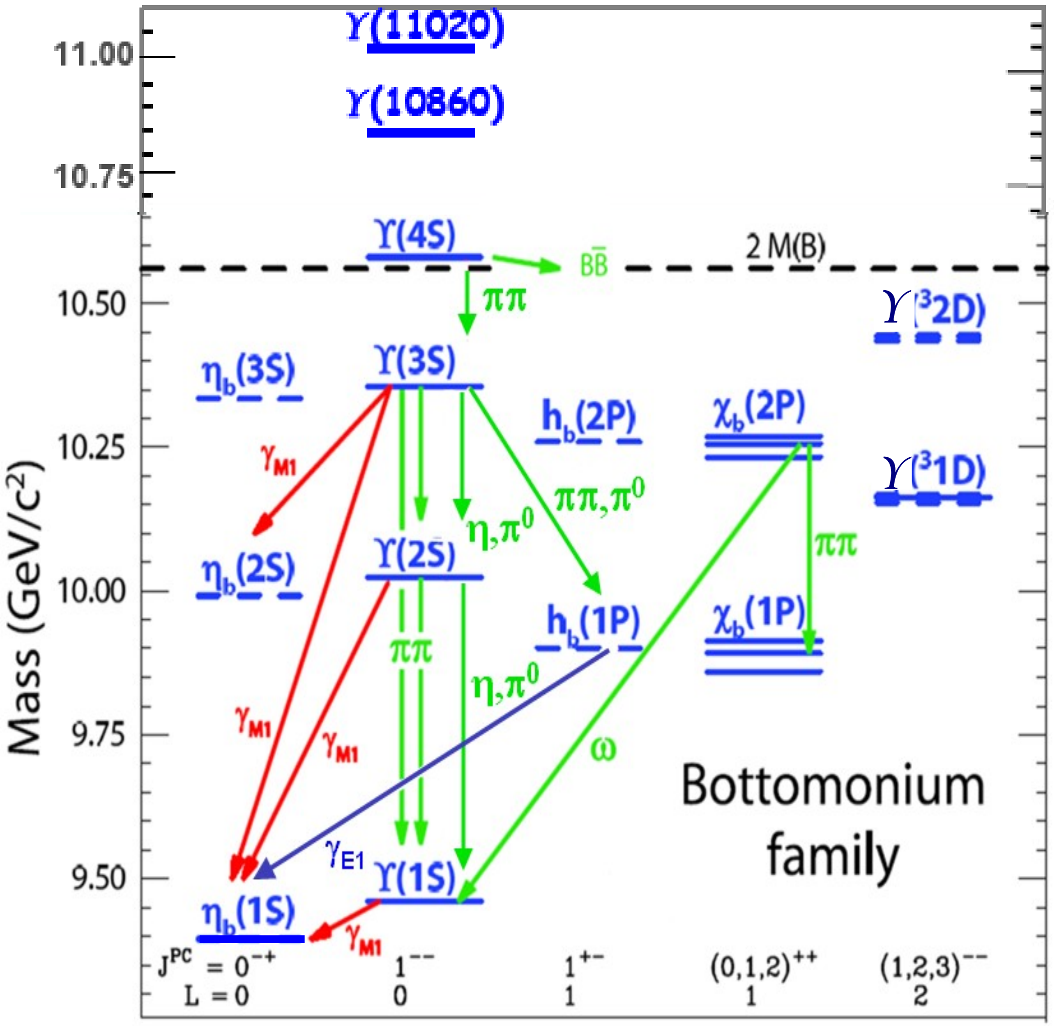
Expected mass
$\approx (M(\chi_{b0}) + 3\,M(\chi_{b1}) + 5\,M(\chi_{b2}))/9$

$\Delta M_{HF} \Rightarrow$ test of hyperfine interaction

for h_c: $\Delta M_{HF} = -0.12 \pm 0.30$ MeV,
expect smaller deviation for $h_b(nP)$

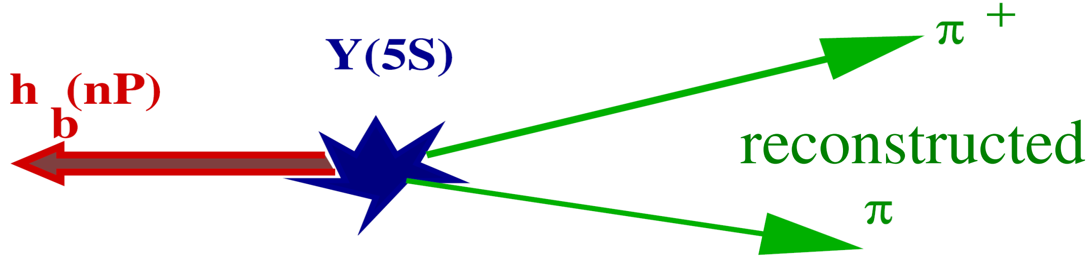
arXiv: 1102.4565



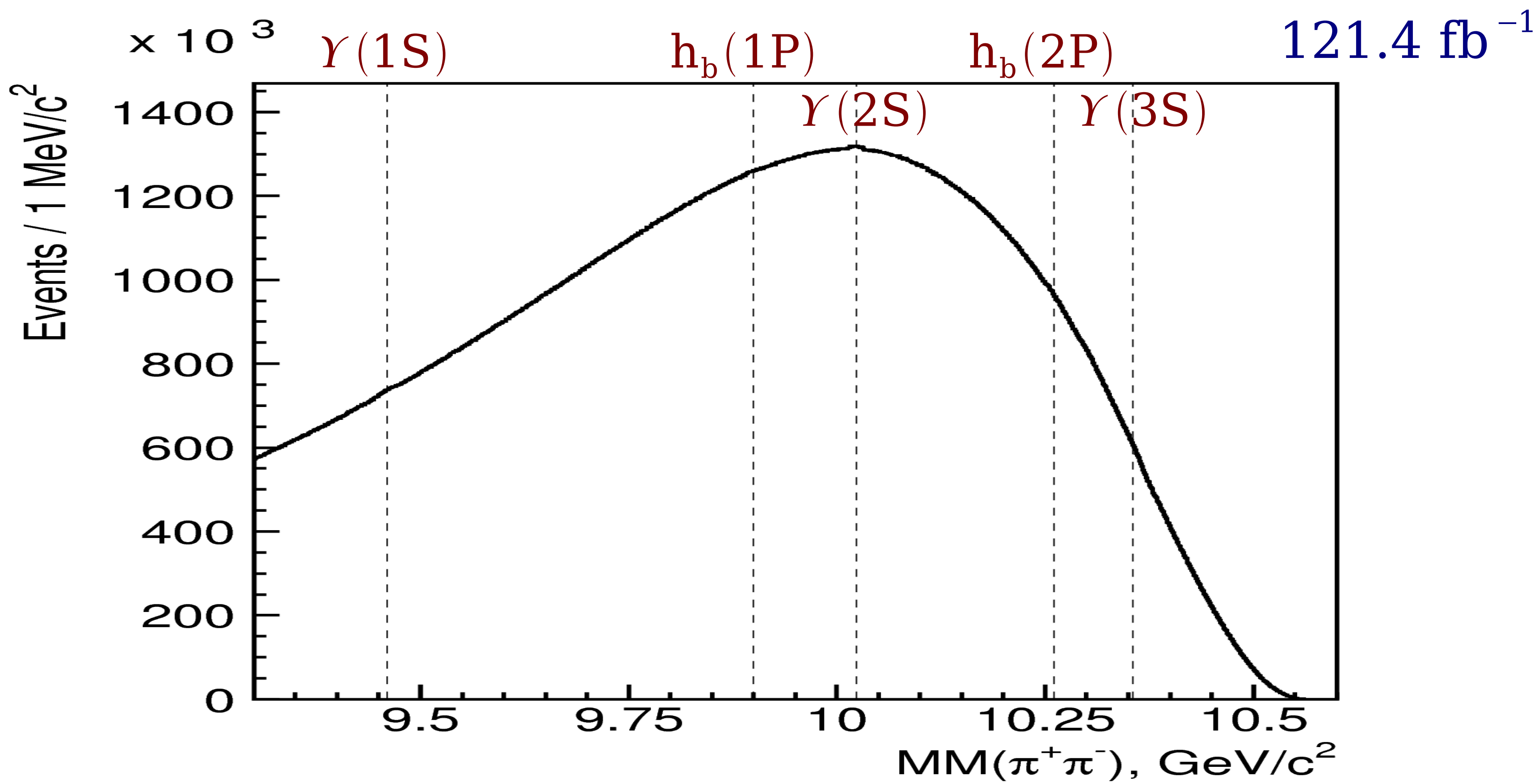


$\Upsilon(5S) \to h_b \pi^+ \pi^-$ reconstruction

$h_b \to ggg\,,\ \eta_b\,\gamma \ \Rightarrow$ no good exclusive final states



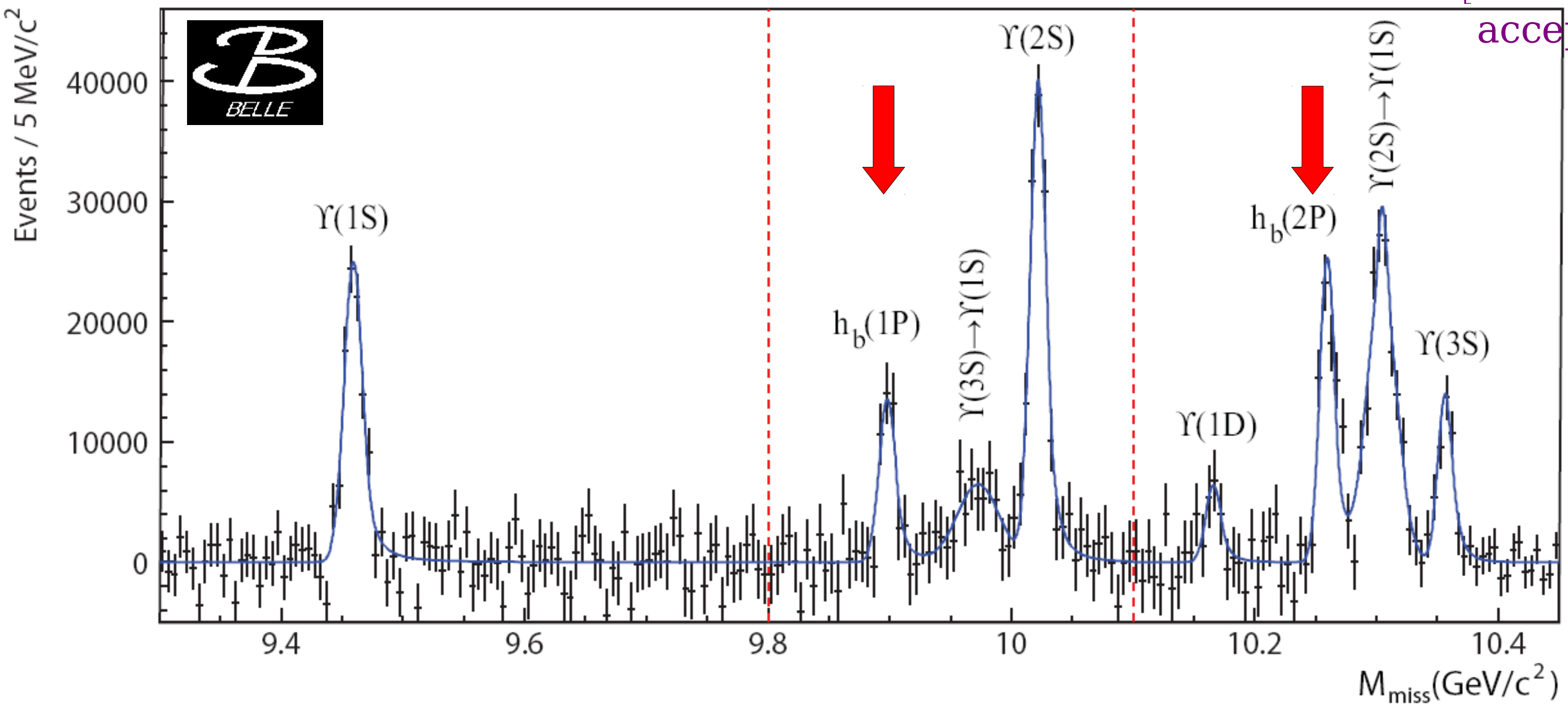
''Missing mass'' $\quad M(h_b) = \sqrt{(E_{CM} - E^*_{\pi^+\pi^-})^2 - p^{*2}_{\pi^+\pi^-}} \equiv M_{miss}(\pi^+\pi^-)$



Results

121.4 fb^{-1}

[arXiv:1103.3419] accepted by PRL



	Yield, 10^3	Mass, MeV/c^2	Significance
$\Upsilon(1S)$	$105.0 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.1\,\sigma$
$h_b(1P)$	$50.0 \pm 7.8^{+4.5}_{-9.1}$	$9898.2^{+1.1+1.0}_{-1.0-1.1}$	$6.1\,\sigma$
$3S \to 1S$	55 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.8 \pm 8.7 \pm 6.8$	$10022.2 \pm 0.4 \pm 1.0$	$17.1\,\sigma$
$\Upsilon(1D)$	22.4 ± 7.8	10166.1 ± 2.6	$2.4\,\sigma$
$h_b(2P)$	$84.0 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.3\,\sigma$
$2S \to 1S$	$151.3 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\,\sigma$
$\Upsilon(3S)$	$45.5 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\,\sigma$

Significance w/ systematics

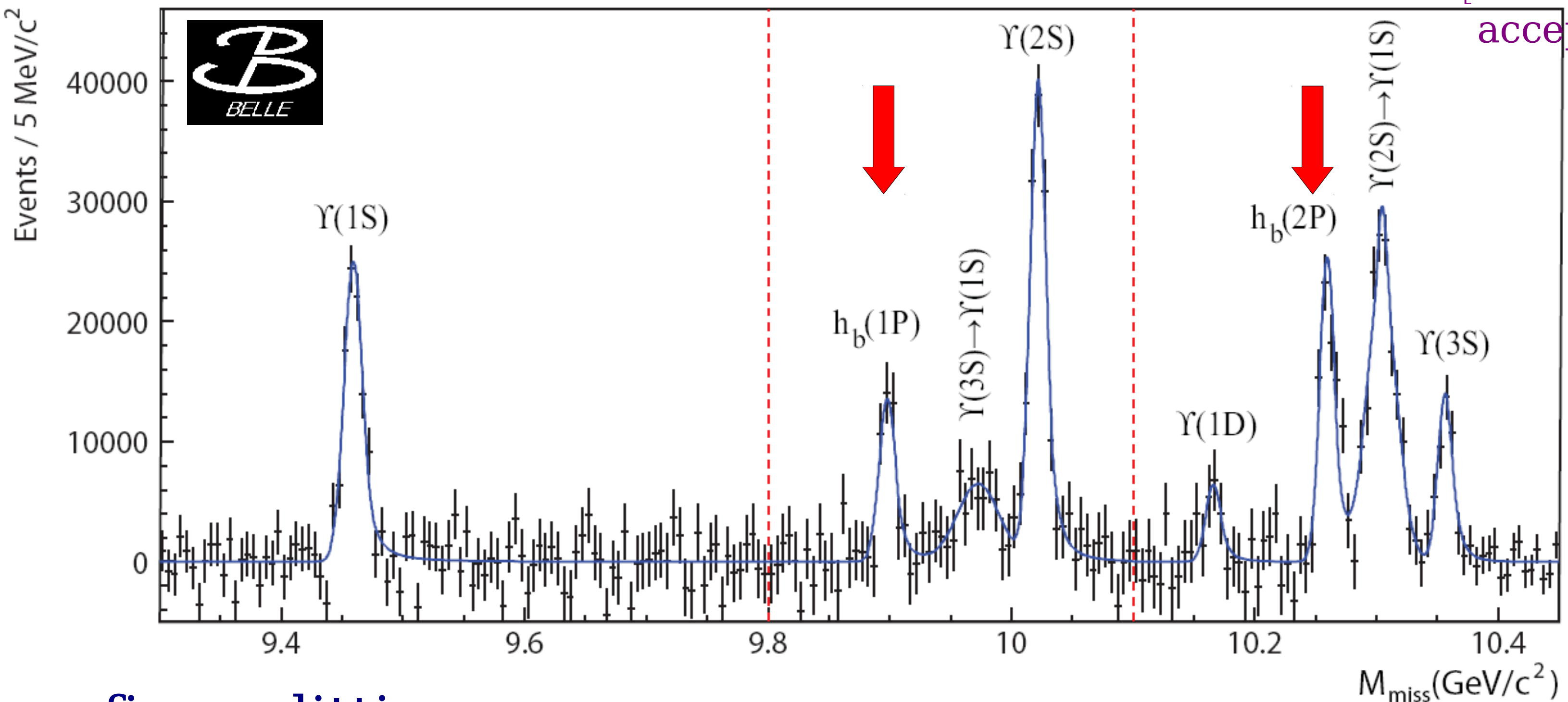
$h_b(1P)$ $5.5\,\sigma$

$h_b(2P)$ $11.2\,\sigma$

Results

$121.4\ \text{fb}^{-1}$

[arXiv:1103.3419]
accepted by PRL



Hyperfine splitting

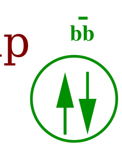
deviations from CoG of χ_{bJ} masses consistent with zero, as expected

$(1.7 \pm 1.5)\ \text{MeV}/c^2$ for $h_b(1P)$

$(0.5\ ^{+1.6}_{-1.2})\ \text{MeV}/c^2$ for $h_b(2P)$

Ratio of production rates

splin-flip



$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-]} = \begin{cases} 0.45 \pm 0.08\ ^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08\ ^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

no splin-flip

supposed to be suppressed by $1/m_b$ in the amplitude

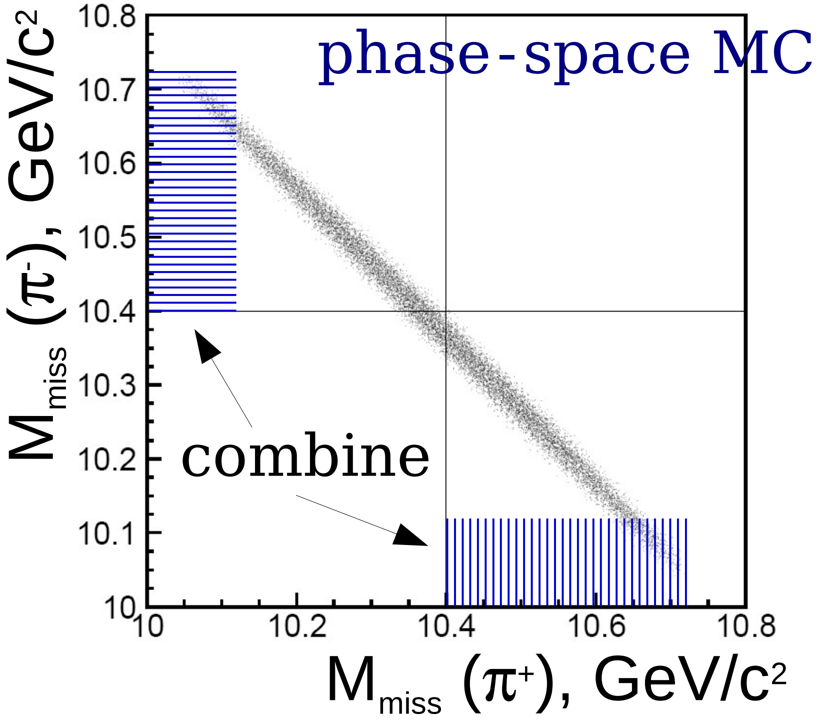
Mechanism of $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ decay seems exotic ! [arXiv:1108.2197]

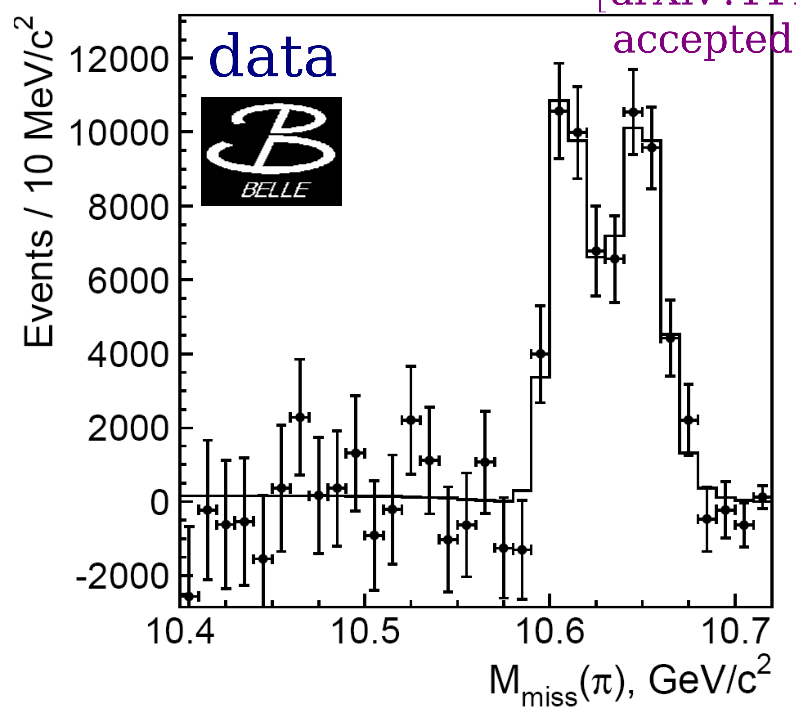
Resonant structure of $\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$

$M(h_b\pi^+) \equiv M_{miss}(\pi^-)$

121.4 fb^{-1}

[arXiv:1110.2251]
accepted by PRL





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

Results

$M_1 = 10605 \pm 2 \,^{+3}_{-1}$ MeV/c^2 $\quad \sim B\bar{B}^*$ threshold

$\Gamma_1 = 11.4 \,^{+4.5}_{-3.9}\,^{+2.1}_{-1.2}$ MeV $\quad a = 1.39 \pm 0.37 \,^{+0.05}_{-0.15}$

$M_2 = 10654 \pm 3 \,^{+1}_{-2}$ MeV/c^2 $\quad \sim B\bar{B}^*$ threshold

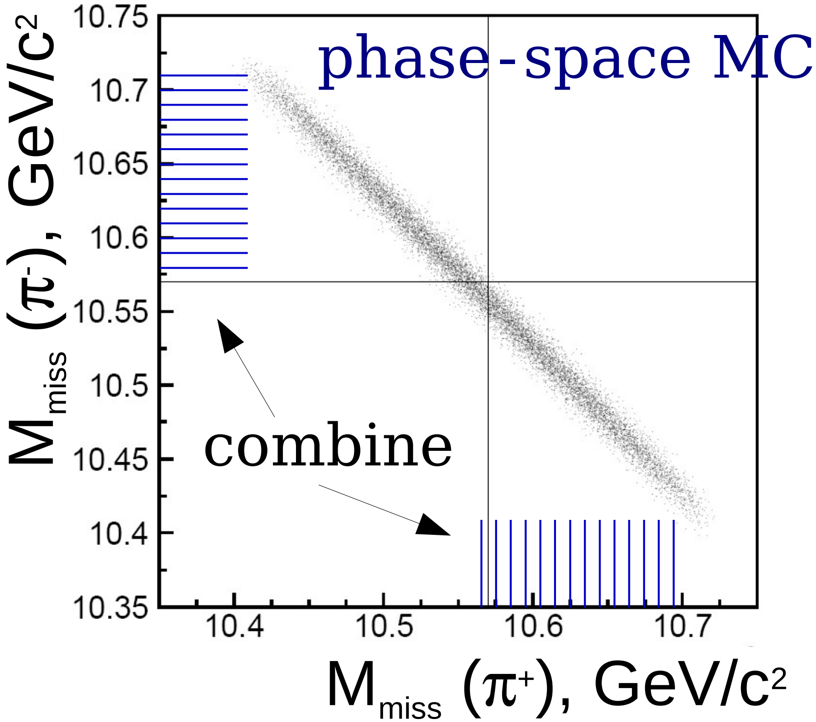
$\Gamma_2 = 20.9 \,^{+5.4}_{-4.7}\,^{+2.1}_{-5.7}$ MeV $\quad \phi = (187 \,^{+44}_{-57}\,^{+3}_{-12})^\circ$

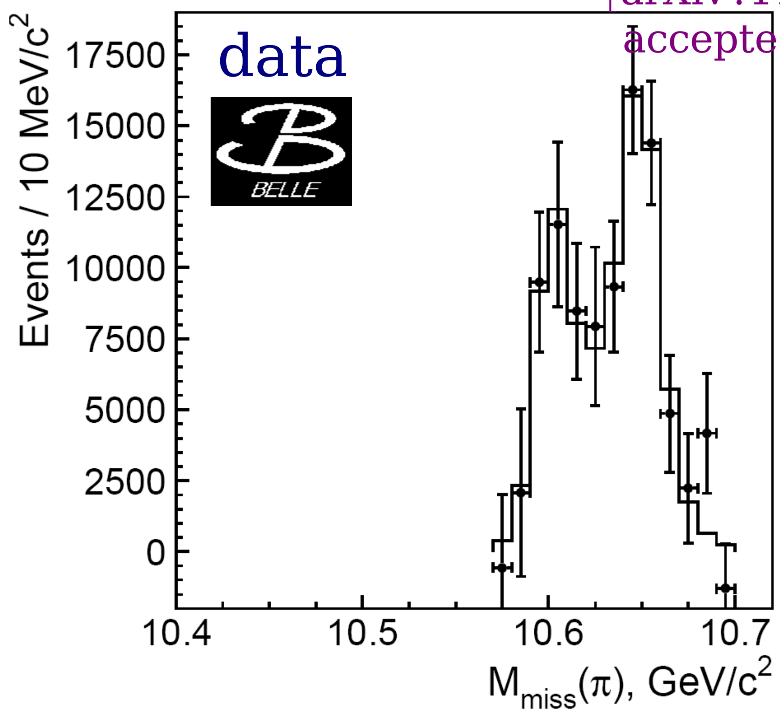
Significances
18σ (16σ w/syst)

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

$M(h_b\pi^+) \equiv M_{miss}(\pi^-)$

121.4 fb^{-1}
[arXiv:1110.2251]
accepted by PRL





$h_b(1P)\pi^+\pi^-$ | **$h_b(2P)\pi^+\pi^-$** (consistent)

$M_1 = 10605 \pm 2\ ^{+3}_{-1}$ MeV/c^2 | $10599\ ^{+6}_{-3}\ ^{+5}_{-4}$ MeV/c^2

$\Gamma_1 = 11.4\ ^{+4.5}_{-3.9}\ ^{+2.1}_{-1.2}$ MeV | $13\ ^{+10}_{-8}\ ^{+9}_{-7}$ MeV

$M_2 = 10654 \pm 3\ ^{+1}_{-2}$ MeV/c^2 | $10651\ ^{+2}_{-3}\ ^{+3}_{-2}$ MeV/c^2

$\Gamma_2 = 20.9\ ^{+5.4}_{-4.7}\ ^{+2.1}_{-5.7}$ MeV | $19 \pm 7\ ^{+11}_{-7}$ MeV

$a = 1.39 \pm 0.37\ ^{+0.05}_{-0.15}$ | $1.6\ ^{+0.6}_{-0.4}\ ^{+0.4}_{-0.6}$

$\phi = (187\ ^{+44}_{-57}\ ^{+3}_{-12})^\circ$ | $(181\ ^{+65}_{-105}\ ^{+74}_{-109})^\circ$

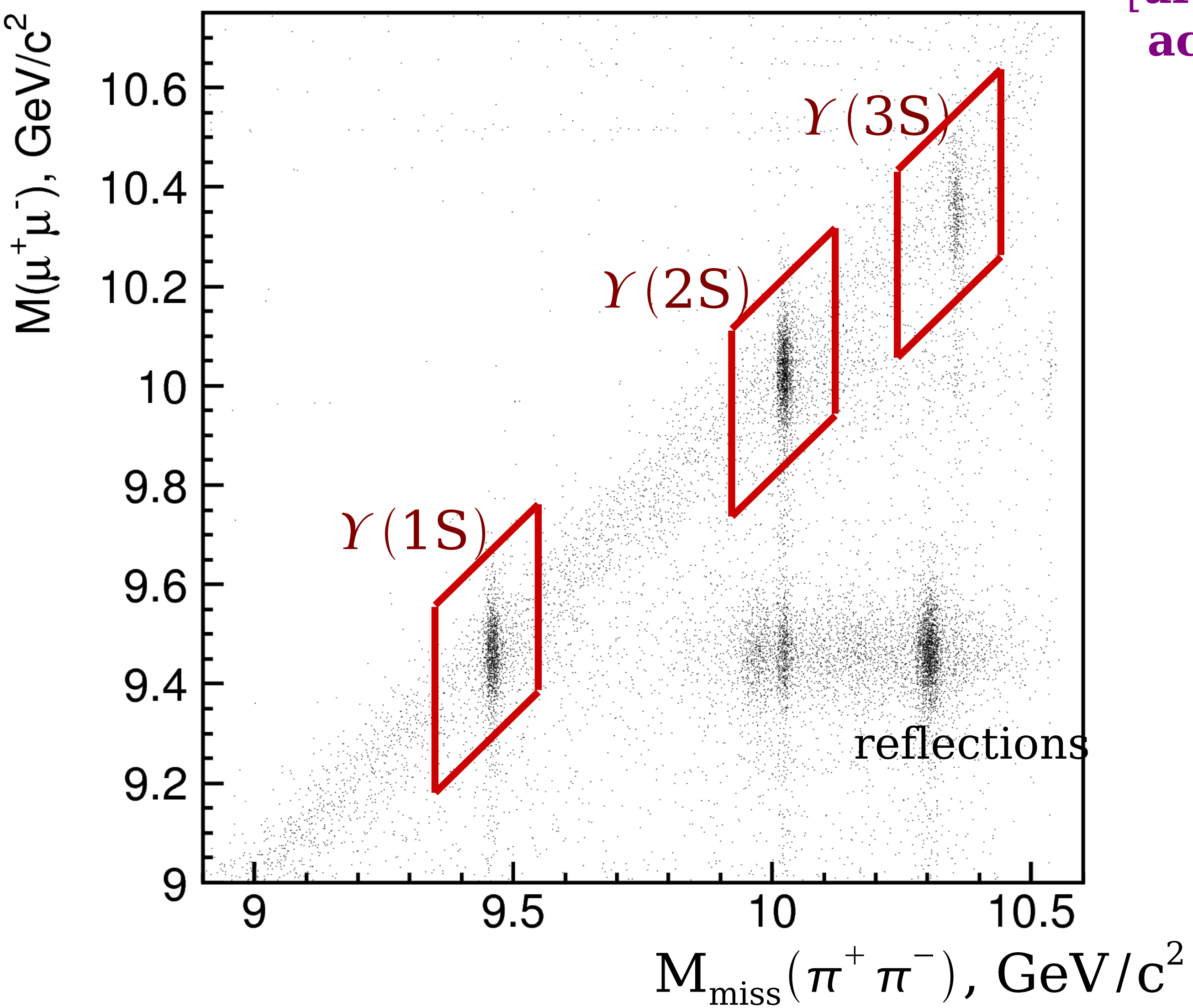
Significances
6.7σ (5.6σ w/syst)

...and what about $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ final state ?

(n = 1, 2, 3)

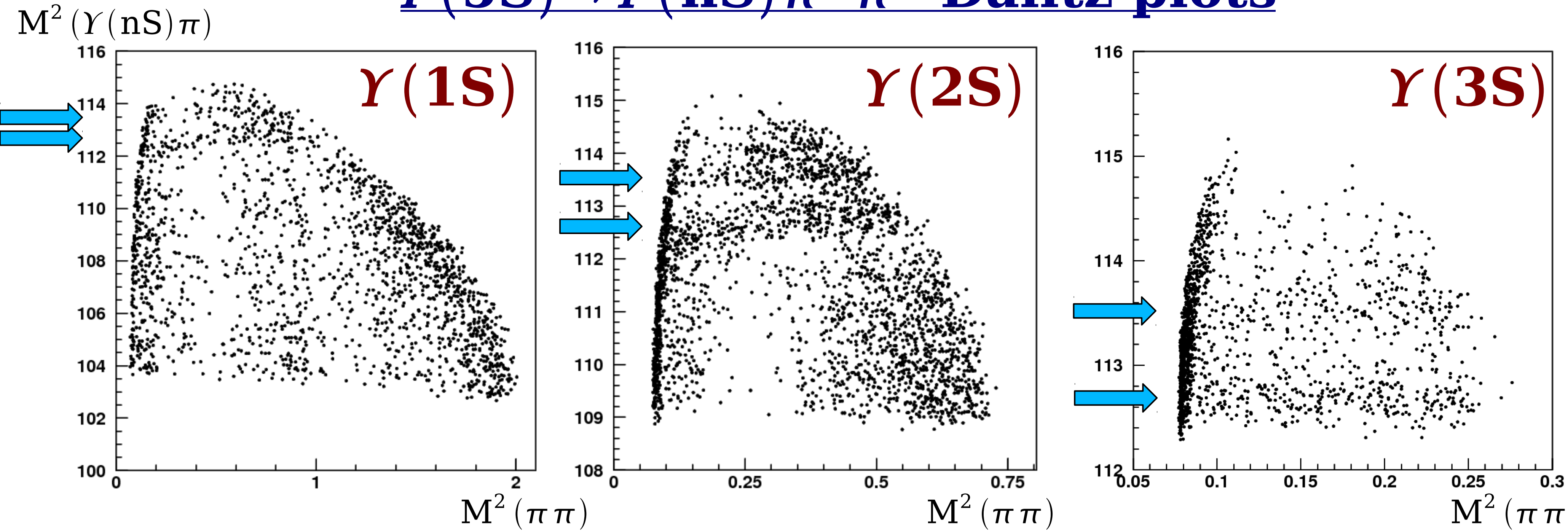
$121.4\ fb^{-1}$

[arXiv:1110.2251] accepted by PRL



Note: here $\Upsilon(nS)$ is reconstructed in the $\mu^+\mu^-$ channel !!

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



⇒ **two resonances**

⇒ **clear signs of interference ⇒ amplitude analysis is required**

Signal amplitude parameterization: Flatte

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

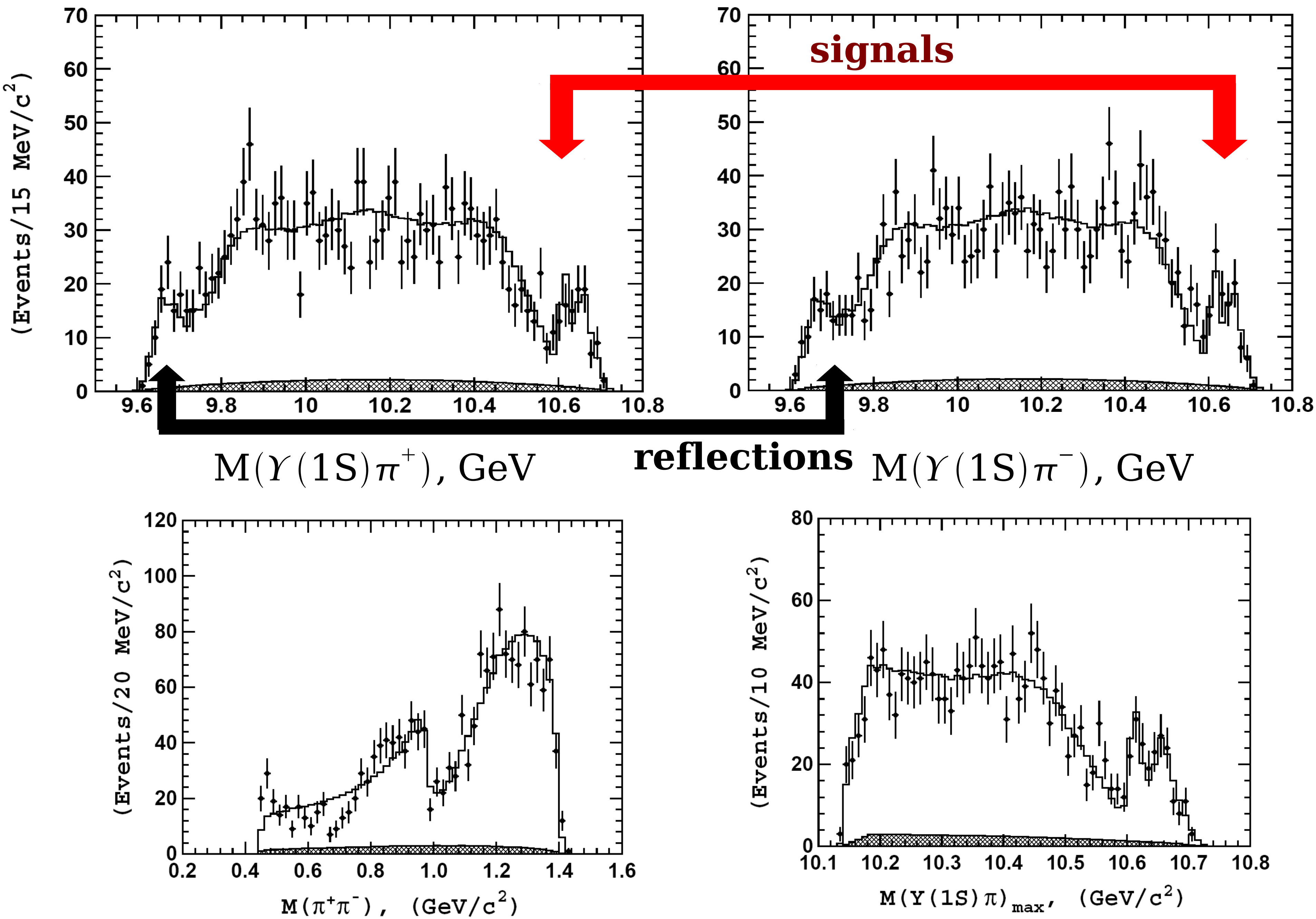
Breit-Wigner

$$A_{NR} = C_1 + C_2 \,.\, m^2(\pi\pi)$$

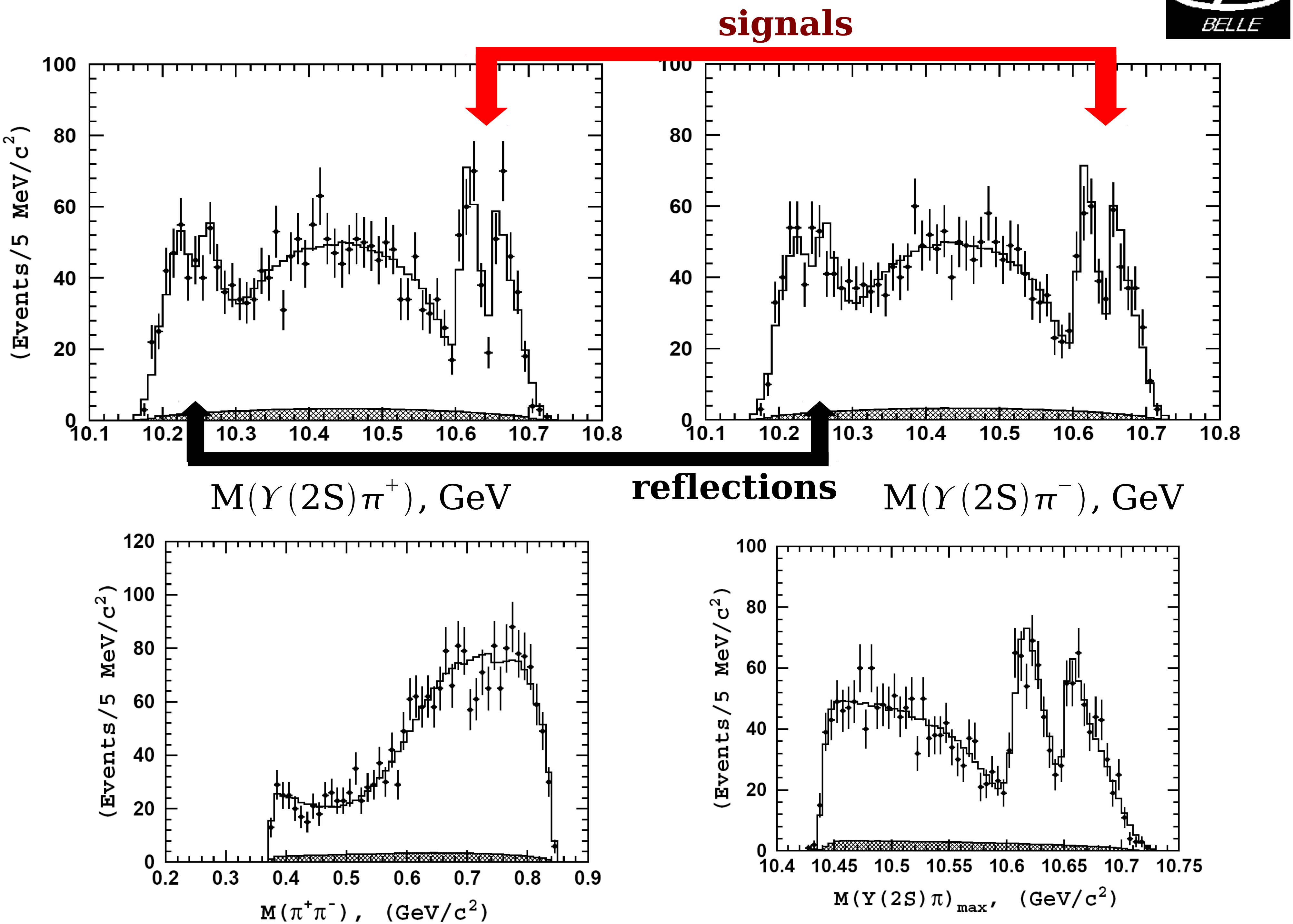
Parameterization of the non-resonant amplitude as discussed in:

[1] M.B.Voloshin, Prog. Part. Nucl. Phys. 61:455, 2008
[2] M.B.Voloshin, Phys. Rev. D74:054022, 2006

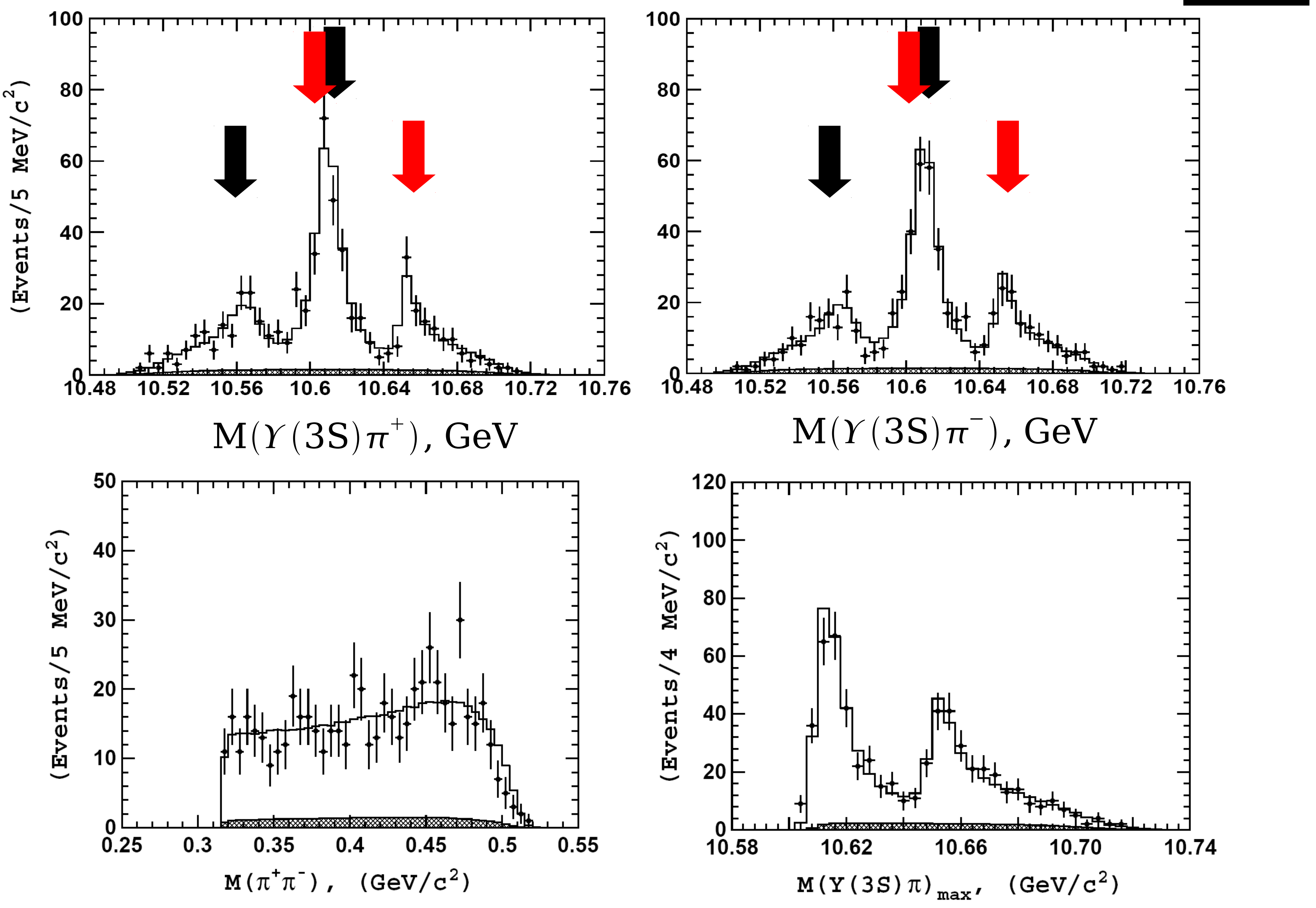
Results: $\Upsilon(1S)\pi^+\pi^-$



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

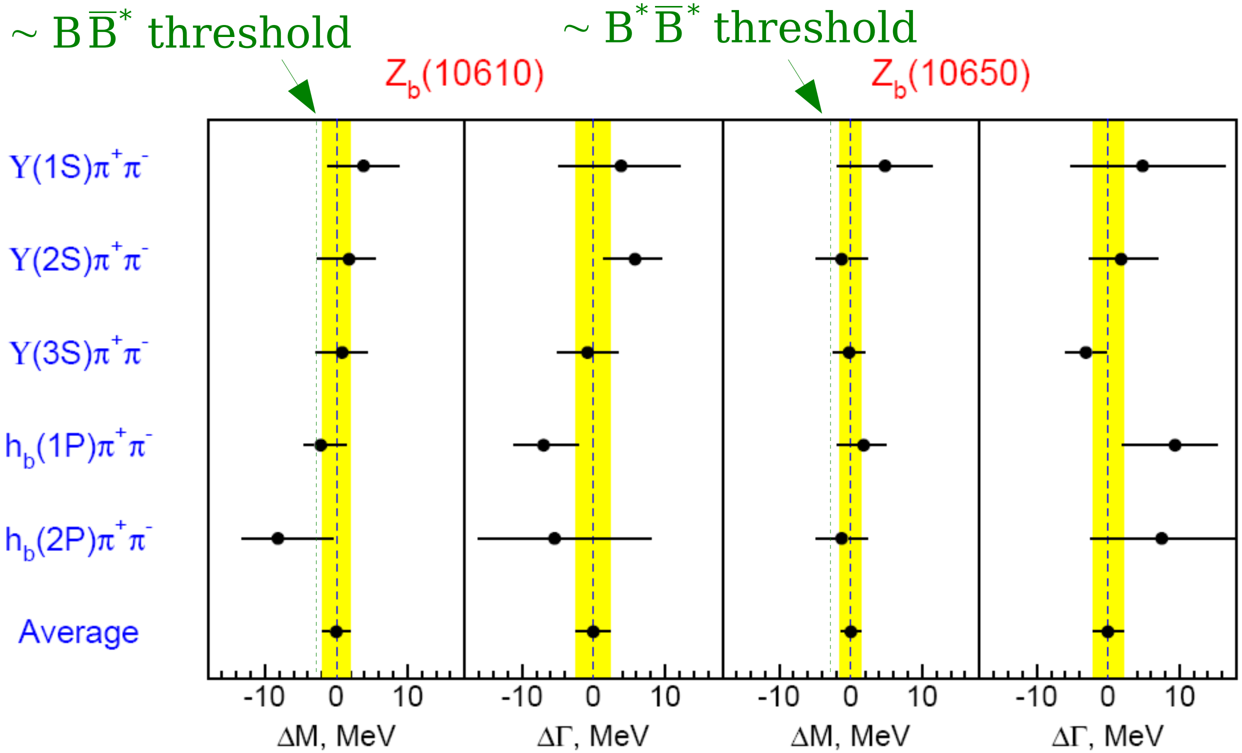


Results: $\Upsilon(3S)\pi^+\pi^-$



Summary of parameters of charged Z_b states

[arXiv:1110.2251]



$Z_b(10610)$

$M = 10607.2 \pm 2.0$ MeV

$\Gamma = 18.4 \pm 2.4$ MeV

$Z_b(10650)$

$M = 10652.2 \pm 1.5$ MeV

$\Gamma = 11.5 \pm 2.2$ 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}	$181^{+65+74}_{-105-109}$

- Masses and width are consistent
- Relative yield of $Z_b(10610)$ and $Z_b(10650)$ ~ 1
- Relative phases are swapped for Υ and h_b final states

and more…

Expected decays of h_b [Godfrey & Rosner, PRD 66, 014012 (2002)]

$$h_b(1P) \to ggg\ (57\%),\ \eta_b(1S)\gamma\ (41\%),\ \gamma gg\ (2\%)$$
$$h_b(2P) \to ggg\ (63\%),\ \eta_b(1S)\gamma\ (13\%),\ \eta_b(2S)\gamma\ (19\%),\ \gamma gg\ (2\%)$$

and Belle recently observed large yields of $h_b(1P)$ and $h_b(2P)$!

opportunity to study $\eta_b(nS)$ states…

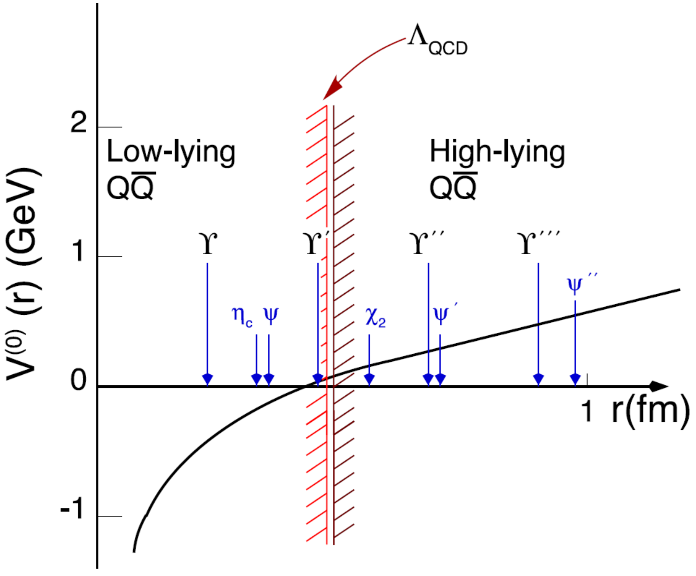
Experimental status of η_b

$$M[\eta_b(1S)] = 9390.9 \pm 2.8 \text{ MeV (BaBar + CLEO)}$$
$$M[\Upsilon(1S)] - M[\eta_b(1S)] = 69.3 \pm 2.8 \text{ MeV}$$

pNRQCD: 41 ± 14 MeV
[Kniehl et al., PRL 92, 242001 (2004)]

Lattice: 60 ± 8 MeV
[Meinel, PRD 82, 114502 (2010)]

η_b – small radius system, precise calculation of mass



Method

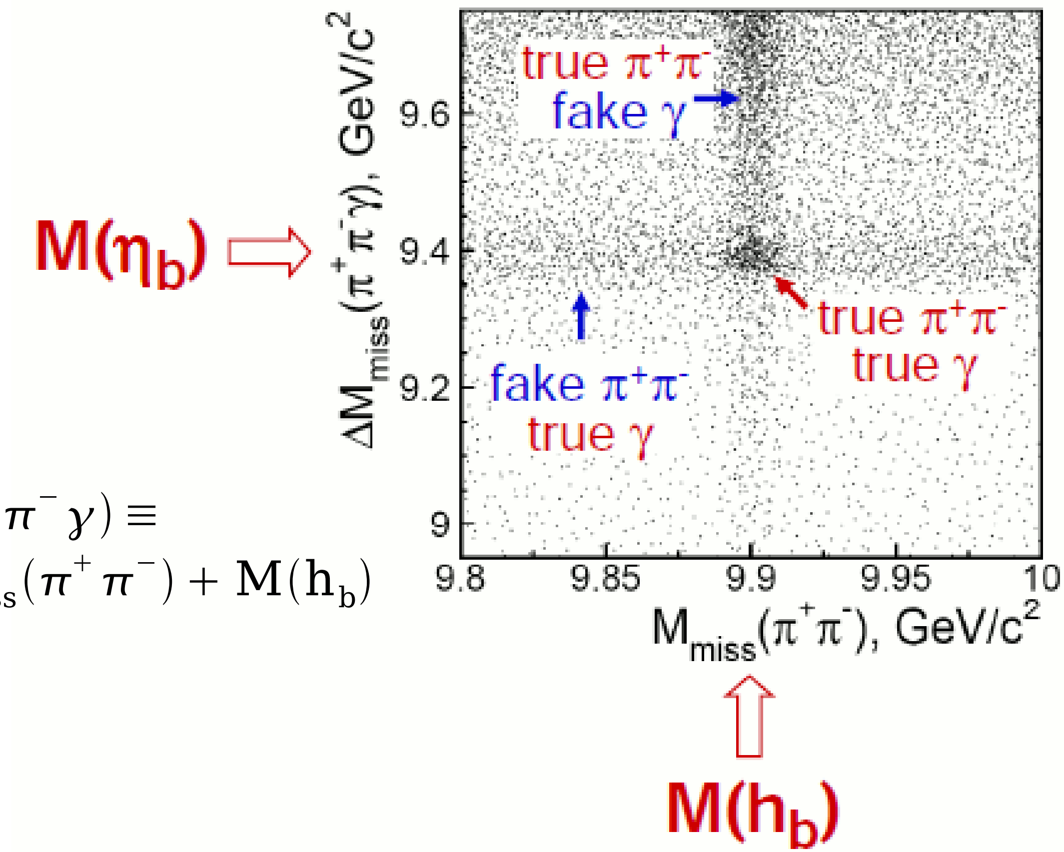
Decay chain:

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

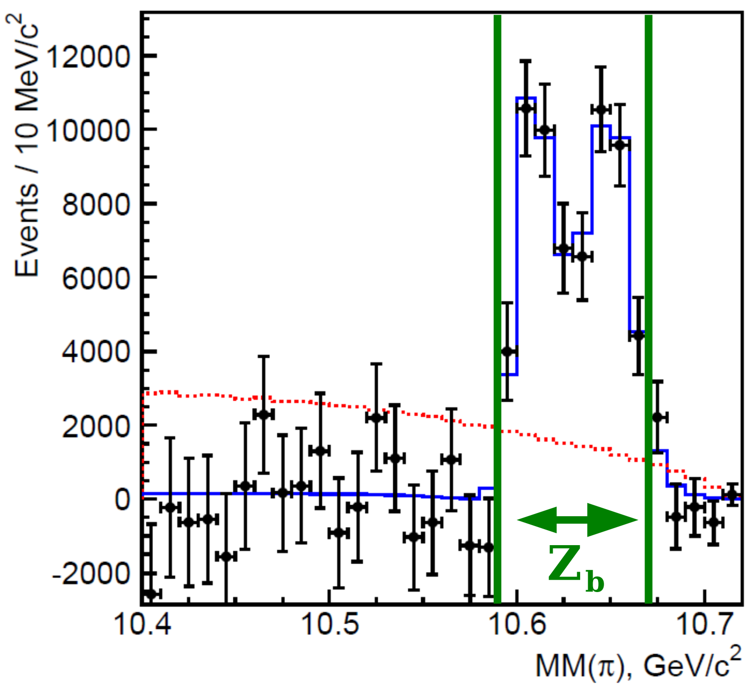
$\hookrightarrow h_b(nP)\, \pi^+$

$\hookrightarrow \eta_b(mS)\, \gamma$

MC simulation



$$\Delta M_{miss}(\pi^+\pi^-\gamma) \equiv$$
$$M_{miss}(\pi^+\pi^-\gamma) - M_{miss}(\pi^+\pi^-) + M(h_b)$$



Require intermediate Z_b:

$$10.59 < MM(\pi) < 10.67 \text{ GeV}$$

bg. suppression $\times$ 5.2

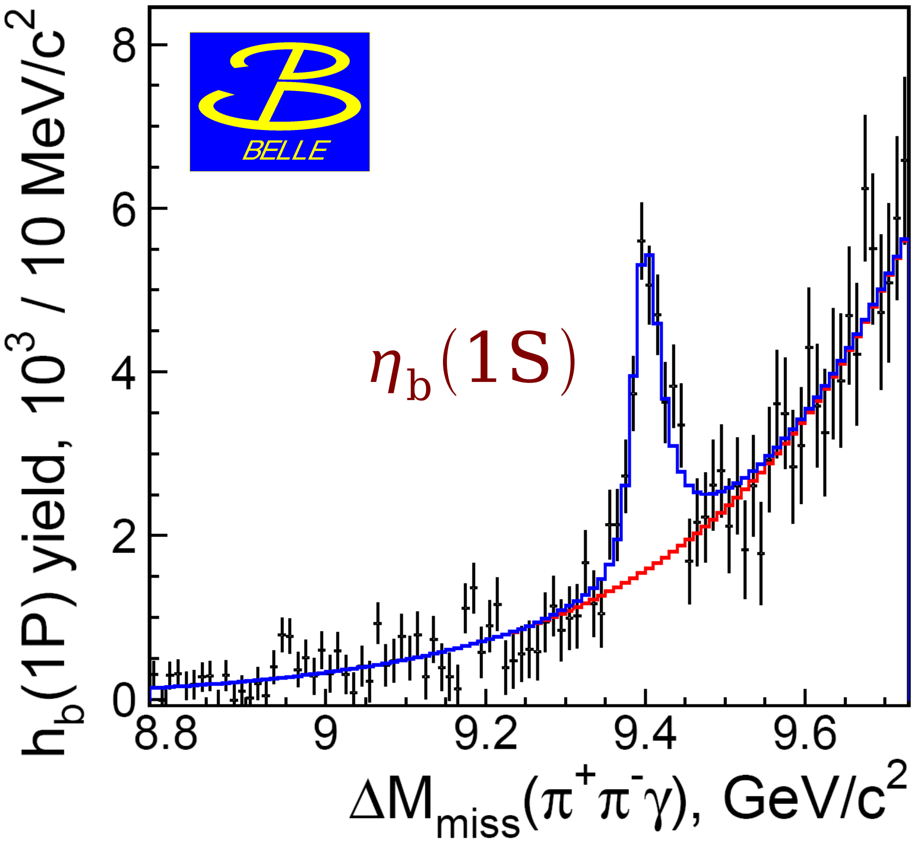
approach:

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

in $\Delta M_{miss}(\pi^+\pi^-\gamma)$ bins arXiv: 1110.3934

Results

non-relativistic BW ⊗ resolution + exponential func.

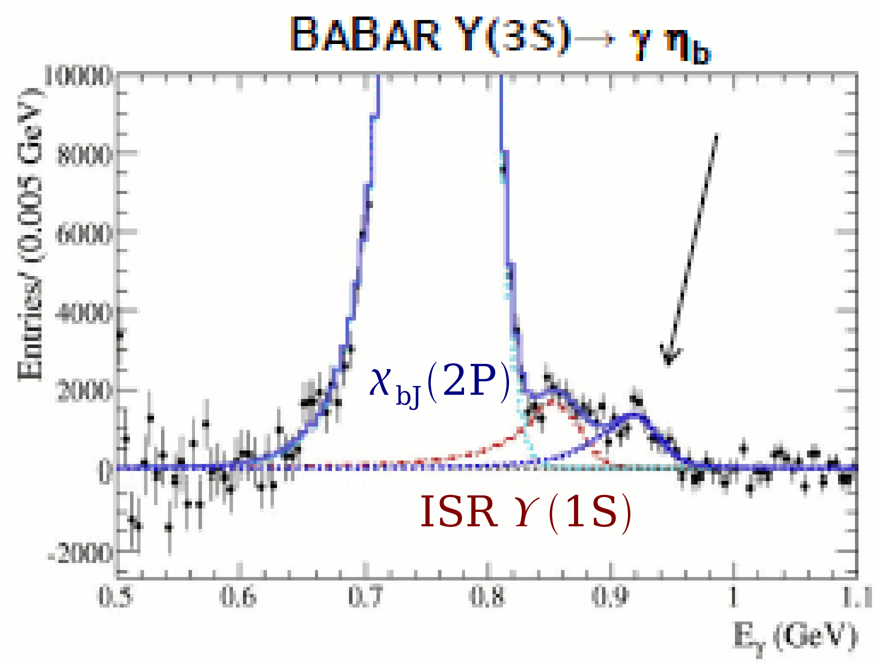


$N[\eta_b(1S)] = (21.9 \pm 2.0\, ^{+5.6}_{-1.7}) \times 10^3$

$M[\eta_b(1S)] = (9401.0 \pm 1.9\, ^{+1.4}_{-2.4})$ MeV/c^2

$\Gamma[\eta_b(1S)] = (12.4\, ^{+5.5}_{-4.6}\, ^{+11.5}_{-3.4})$ MeV

$B[h_b(1P) \to \eta_b(1S)\gamma] = (49.8 \pm 6.8\, ^{+10.9}_{-5.2})\%$



Hyperfine splitting
$\Delta M_{HF}[\eta_b(1S)] = 59.3 \pm 1.9\, ^{+2.4}_{-1.4}$ MeV/c^2

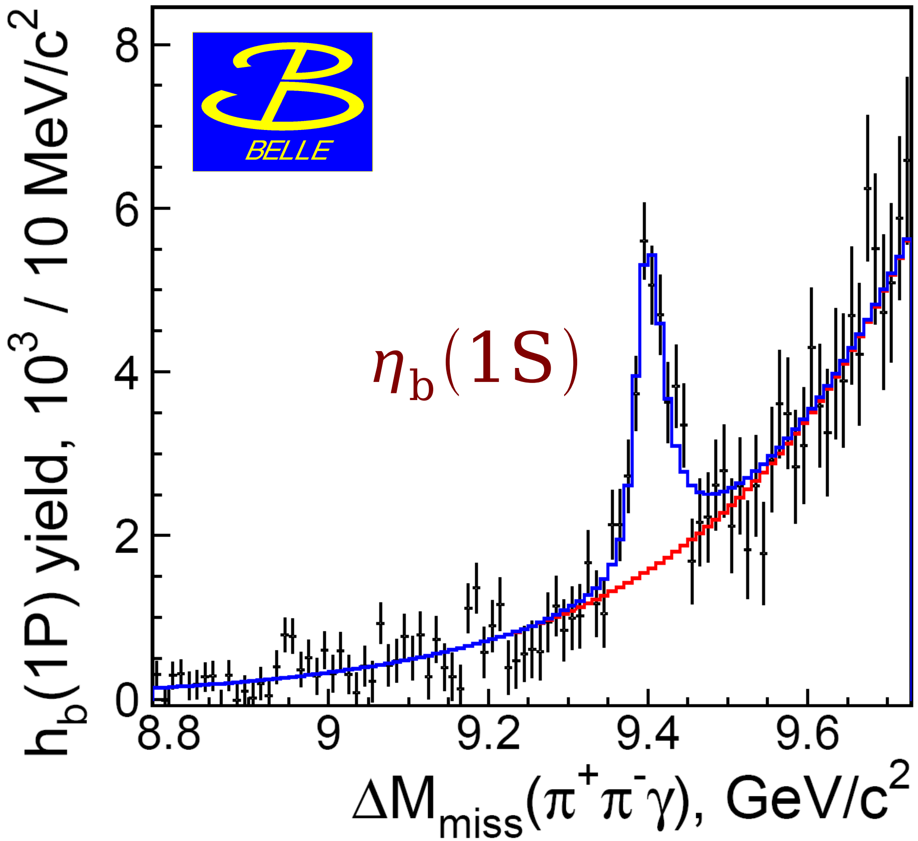
single most precise
measurement of $\eta_b(1S)$ mass

⇒ radiative decays of $h_b(2P)$, search for $\eta_b(2S)$ coming...

Results

arXiv : 1110.3934

non-relativistic BW ⊗ resolution + exponential func.



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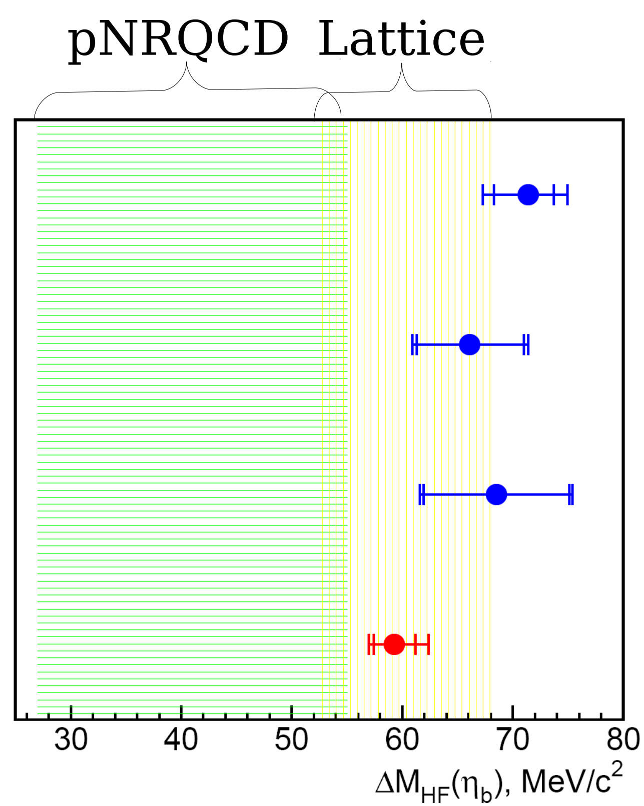


BaBar
$\Upsilon(3S) \to \eta_b(1S)\gamma$

BaBar
$\Upsilon(2S) \to \eta_b(1S)\gamma$

CLEO
$\Upsilon(3S) \to \eta_b(1S)\gamma$

Belle
preliminary

Hyperfine splitting
$\Delta M_{HF}[\eta_b(1S)] = 59.3 \pm 1.9\ ^{+2.4}_{-1.4}$ MeV/c^2

single most precise
measurement of $\eta_b(1S)$ mass

⇒ radiative decays of $h_b(2P)$, search for $\eta_b(2S)$ coming...

Non-observation of the bottomonium ground state was an annoying thorn in the side of quarkonium spectroscopy. Finally, after 30 years of work

First measurement of η_b by BABAR in radiative $\Upsilon(3S)$ and $\Upsilon(2S)$ decays, followed by CLEO.

Measured parameters

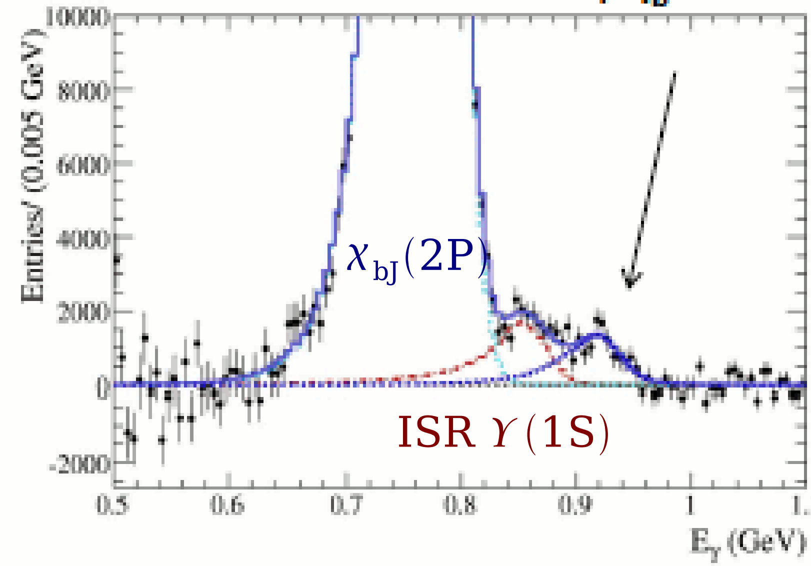
BF ($\Upsilon(3,2S) \to \gamma\, \eta_b$) ($10^{-4}$)	5.1 ± 0.7 / 3.9 ± 1.5
$\Upsilon(1S) - \eta_b(1S)$ mass splitting:	69.3 ± 2.8 MeV

Hyperfine mass splitting predictions (MeV):

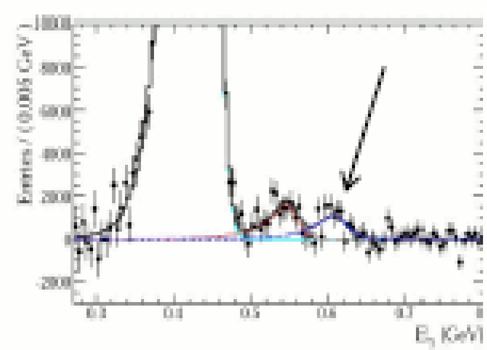
Potential models:	36-100 (36-87 recent models)
pNRQCD:	$60.3 \pm 5.5 \pm 3.8 \pm 2.1$
Lattice QCD:	40-71

Confirmation from independent experiment or other decay channel desirable, as well as observation of $\eta_b(2S)$

BABAR $\Upsilon(3S) \to \gamma\, \eta_b$



BABAR $\Upsilon(2S) \to \gamma\, \eta_b$



CLEO $\Upsilon(3S) \to \gamma\, \eta_b$