Bottomonium states at Belle

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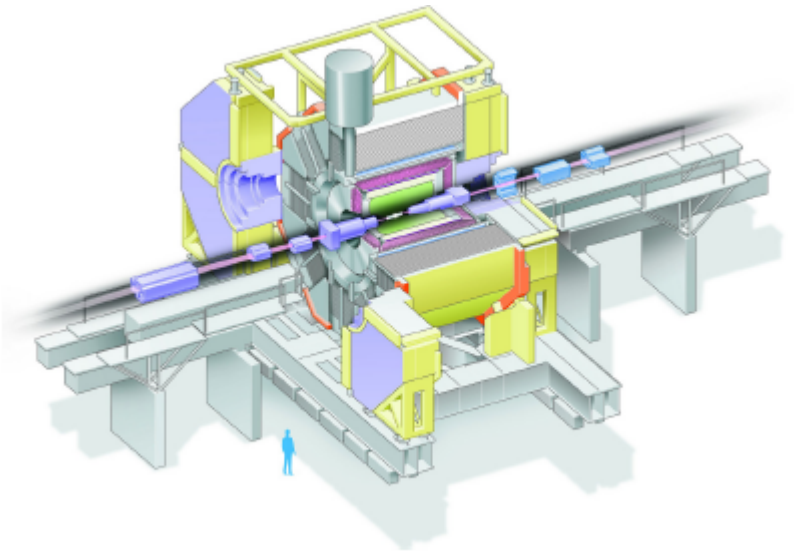
Outline:

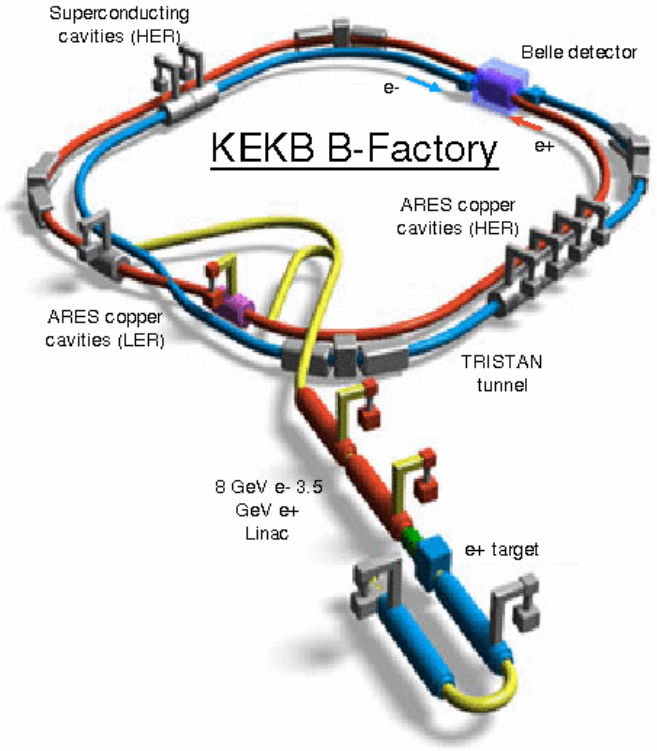
- Introduction
- Determination of Z_b^+ quantum numbers
- Observation of Z_b^+ in $\Upsilon(5S) \rightarrow B^{(*)}\overline{B}^{(*)}\pi$
- Energy scan of $e^+e^- \rightarrow hb(nP)\,\pi^+\pi^-$ and evidence for $\Upsilon(11020)$ decays into charged bottomonium-like states

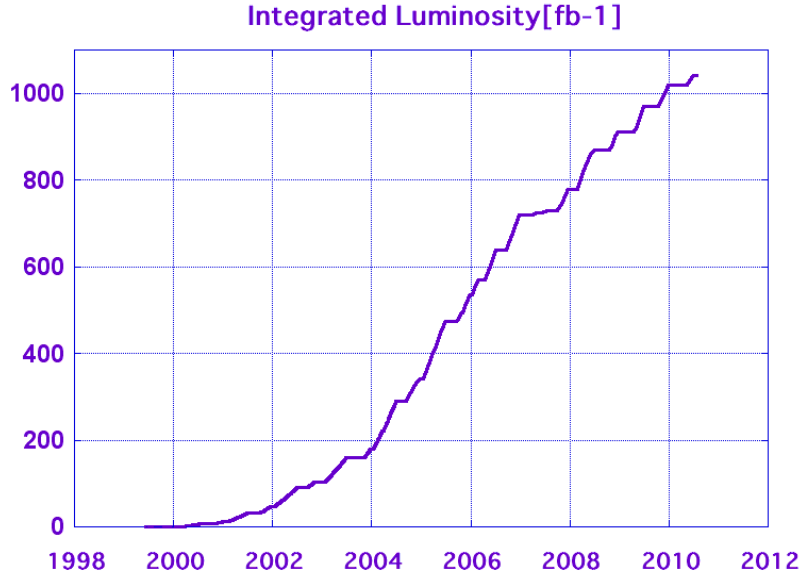
- Search for X, Y, Z states in $\Upsilon(1S)$ inclusive decays
- Search for the 0^{--} Glueball in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays

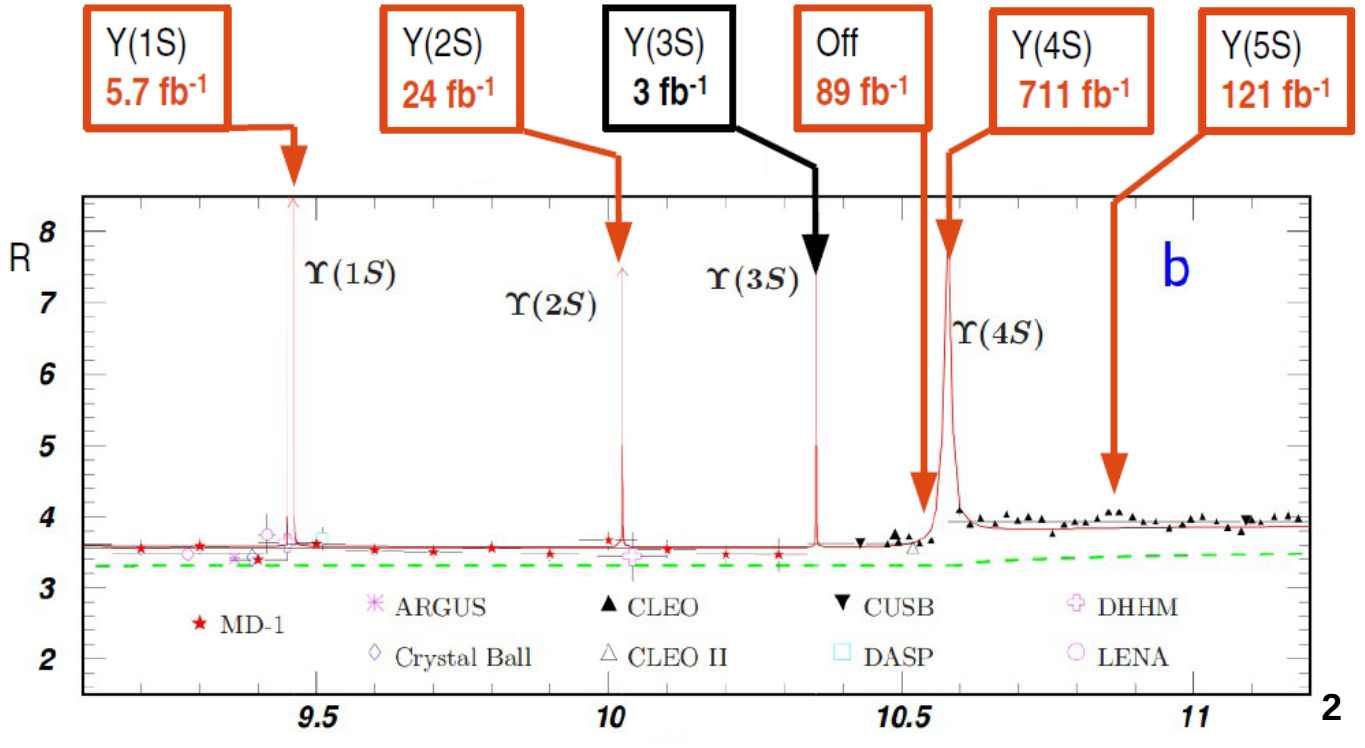
- Summary

The Belle experiment

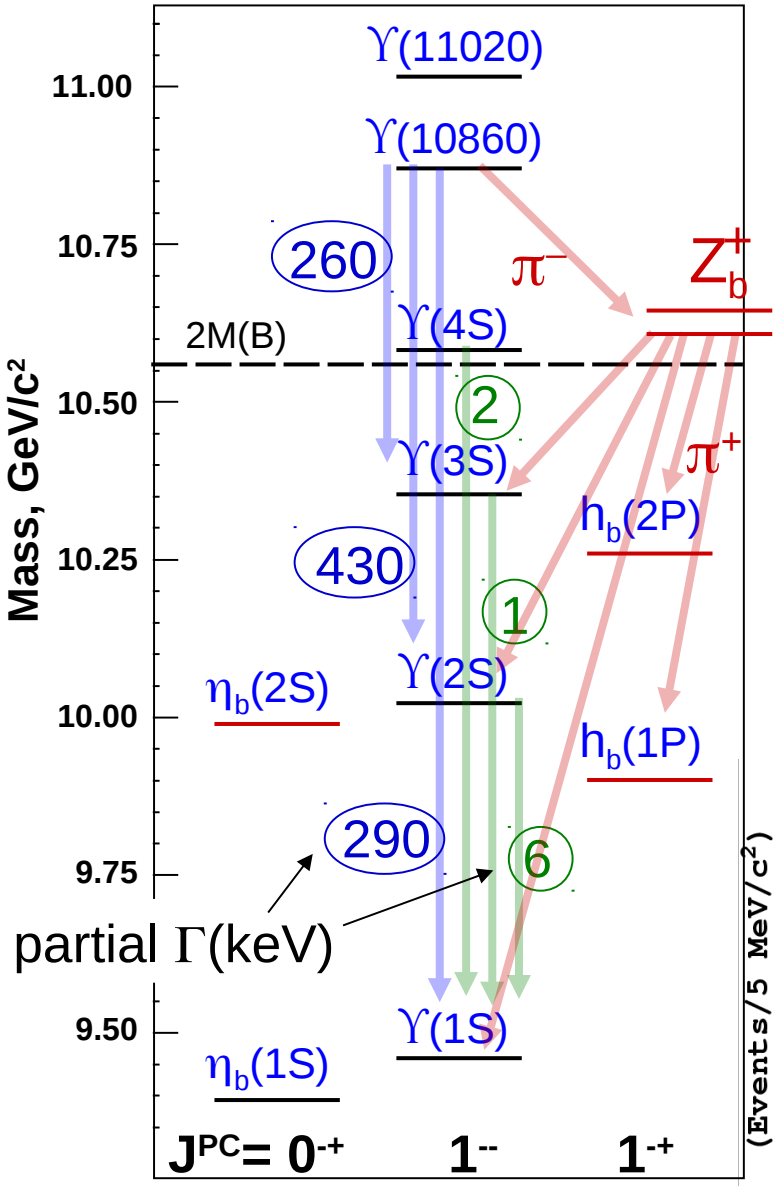




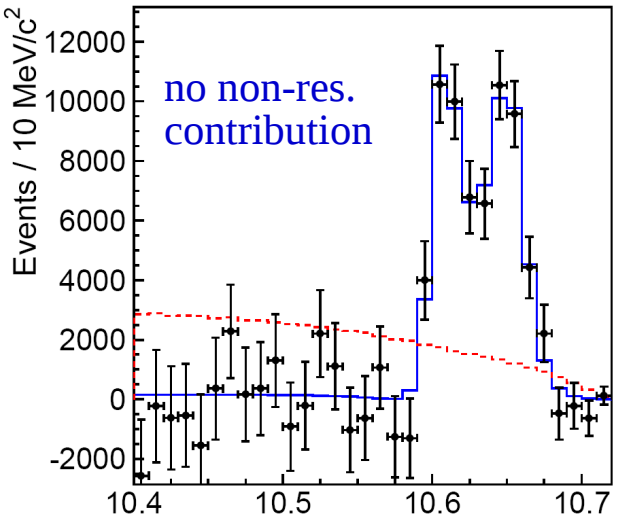




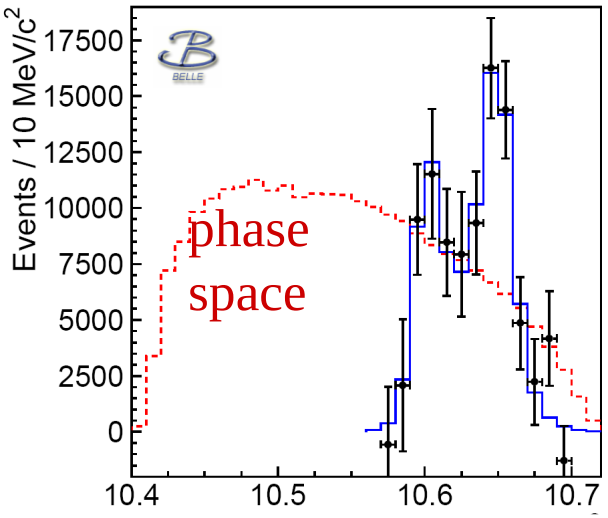
Introduction



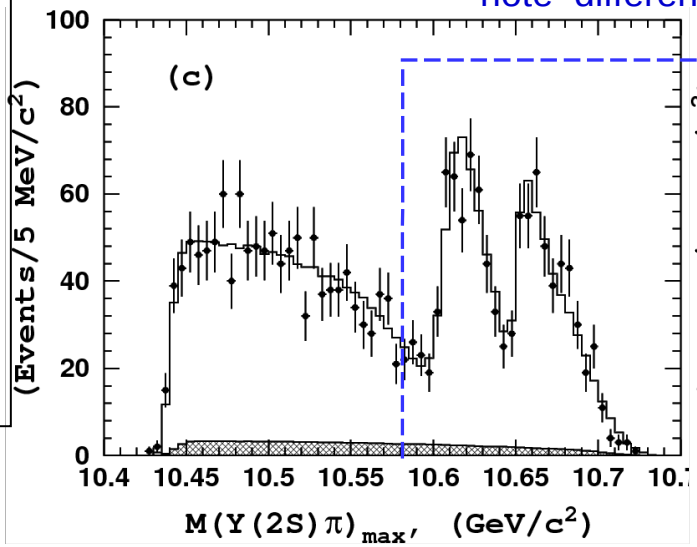
$\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$

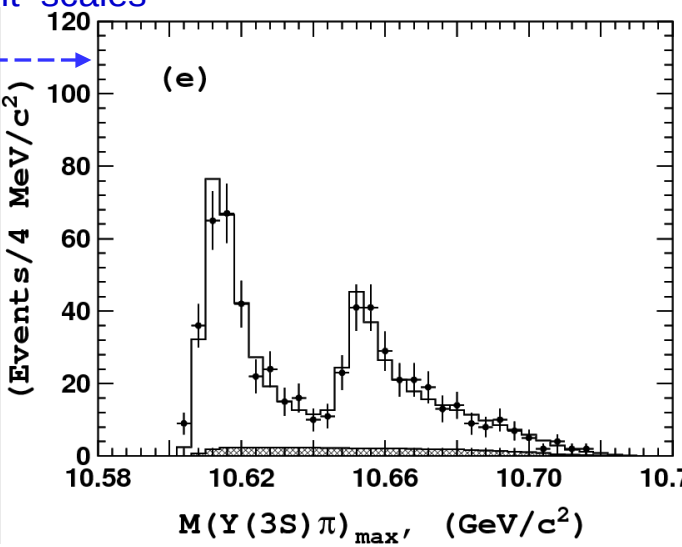


$\Upsilon(5S) \to h_b(2P)\pi^+\pi^-$



note different scales

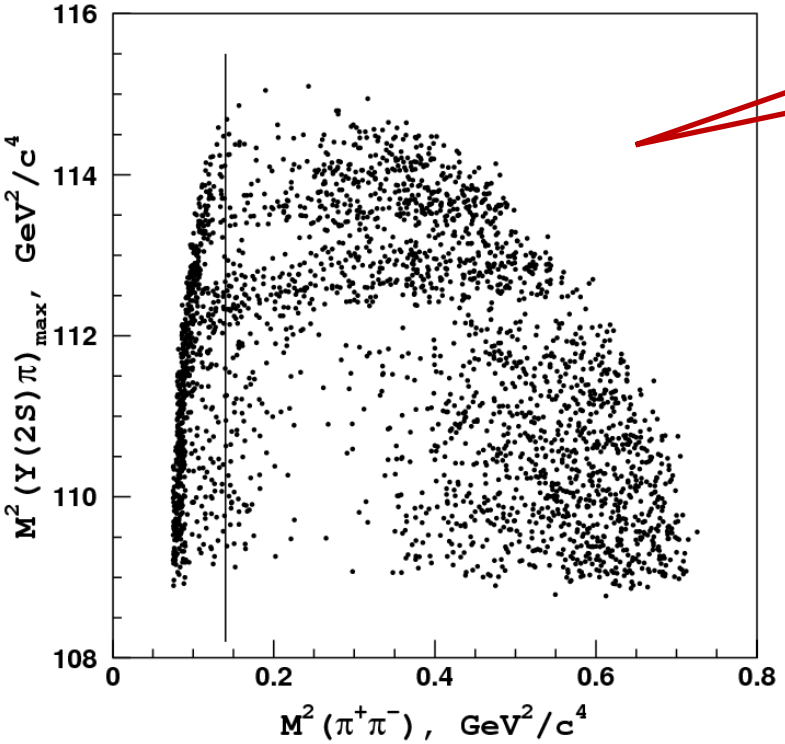




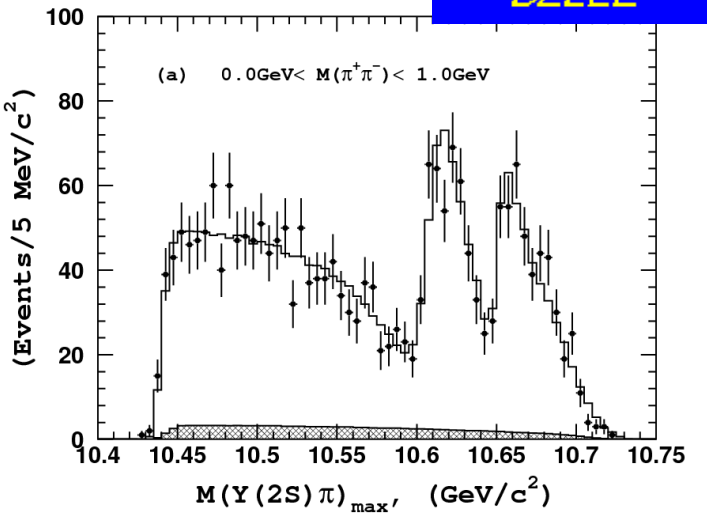
Two peaks are observed in all modes!

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

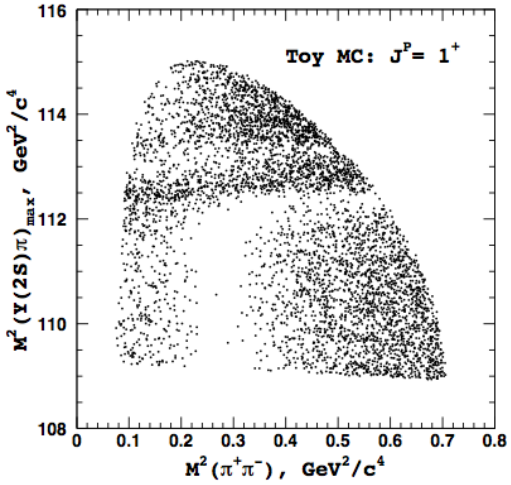
$\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$: J^P Analysis



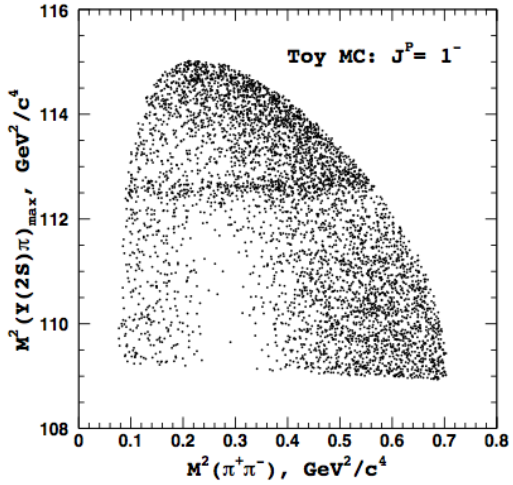
$\Upsilon(2S)\pi^+\pi^-$ Data



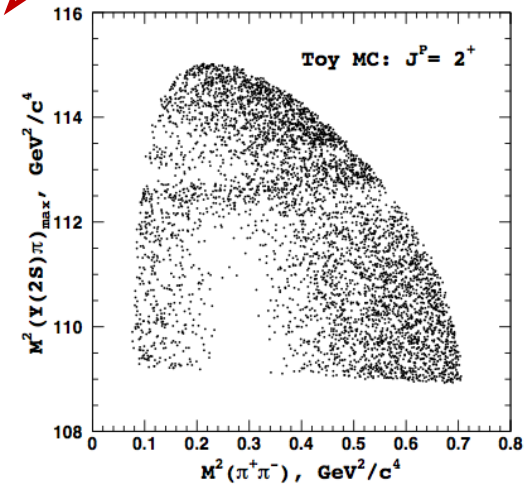
Toy MC with various J^P



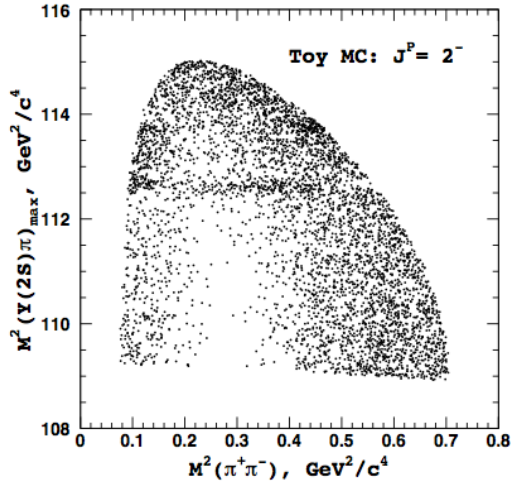
$J^P = 1^+$



$J^P = 1^-$

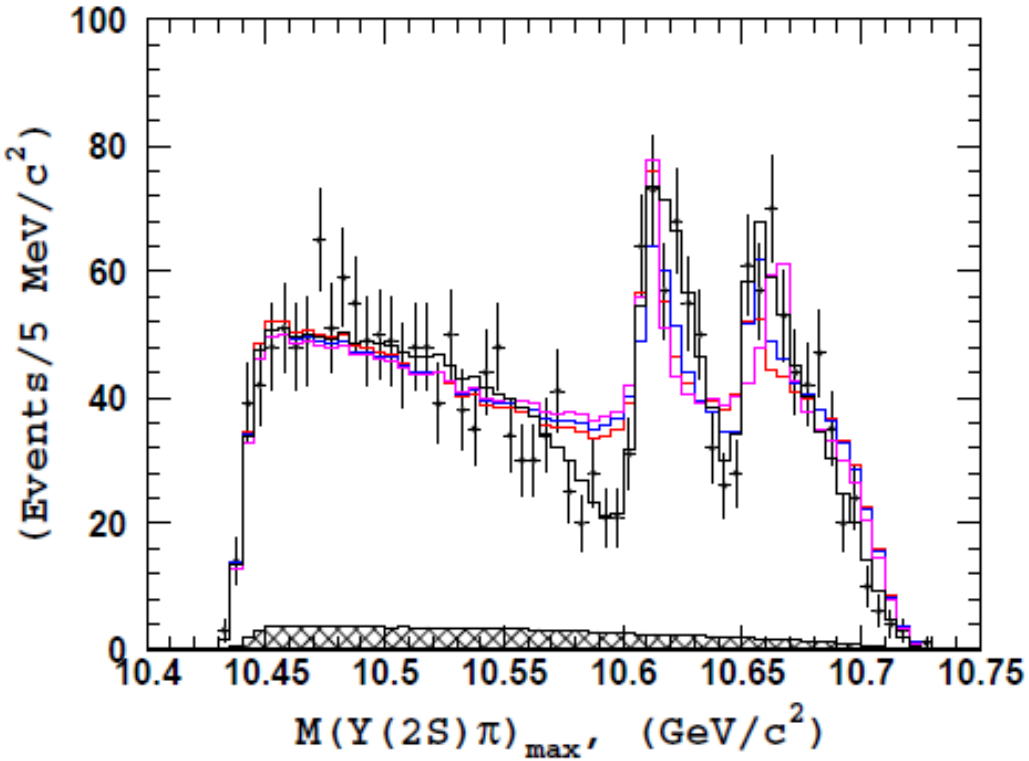


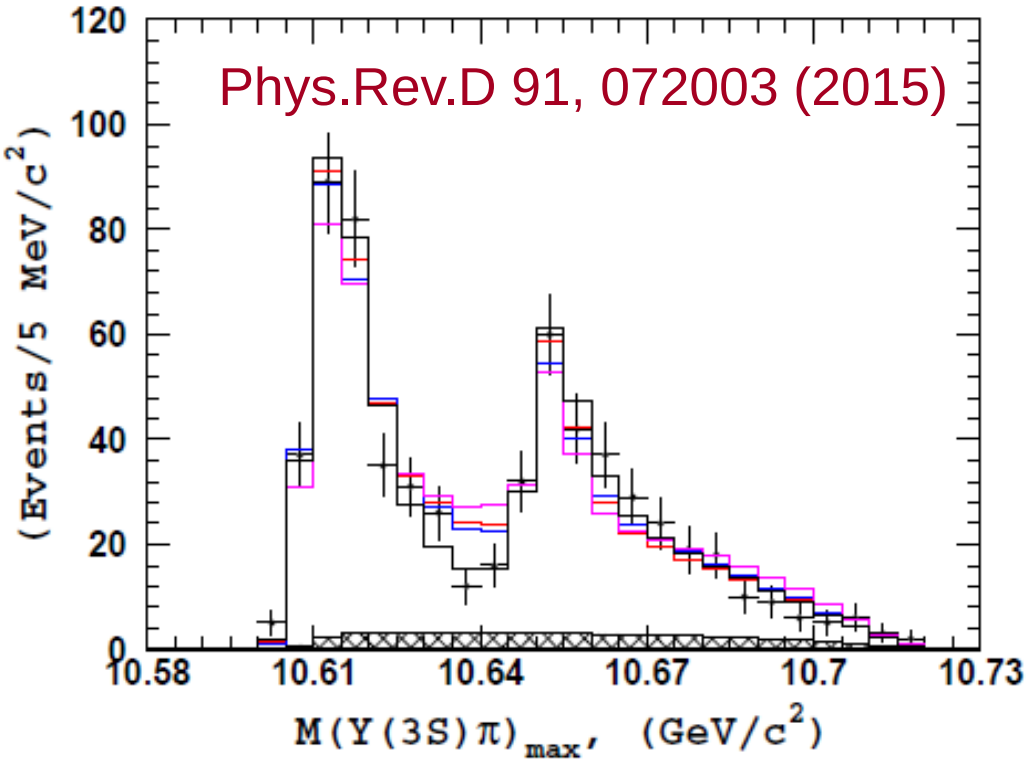
$J^P = 2^+$



$J^P = 2^-$

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





6D amplitude analysis of decays $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$

Results of the fit to Υ(2S)ππ (Υ(3S)ππ) events with different J^P values assigned to the Zb's. The difference in L values are shown for fits to an alternative model and the nominal one.

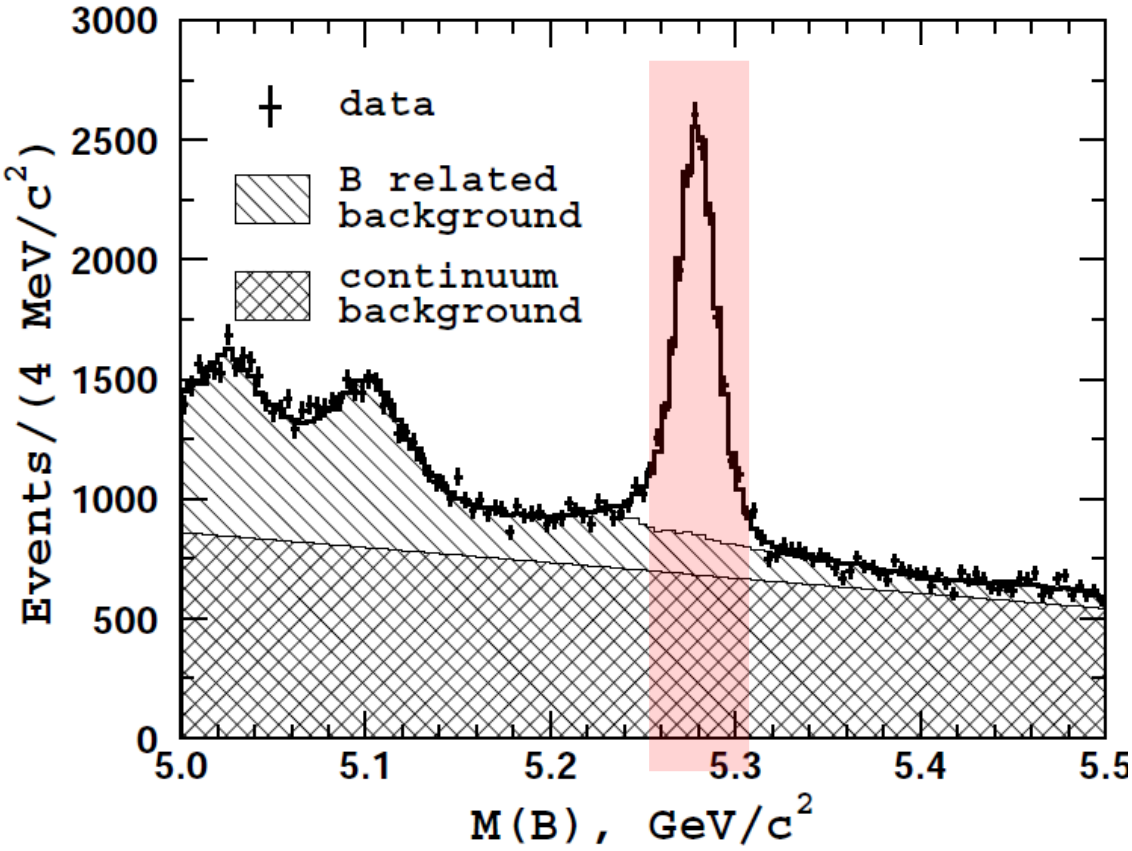
$Z_b(10650)$ / $Z_b(10610)$	1^+	1^-	2^+	2^-
1^+	0 (0)	60 (33)	42 (33)	77 (63)
1^-	226 (47)	264 (73)	224 (68)	277 (106)
2^+	205 (33)	235 (104)	207 (87)	223 (128)
2^-	289 (99)	319 (111)	321 (110)	304 (125)

Spin parity of both Zb is $J^P=1^+$
All other J^P are excluded

$\Upsilon(5S) \to B^{*}\bar{B}^{(*)}\pi$: reconstruction of B

Masses of $Z_b(10610)$ and $Z_b(10650)$ are close to $B\bar{B}^*$ and $B^*\bar{B}^*$ threshold.

Search for $\Upsilon(5S) \to Z_b\pi$ decay with $Z_b \to B^{(*)}\bar{B}^*$; reconstruct only one B and prompt pion

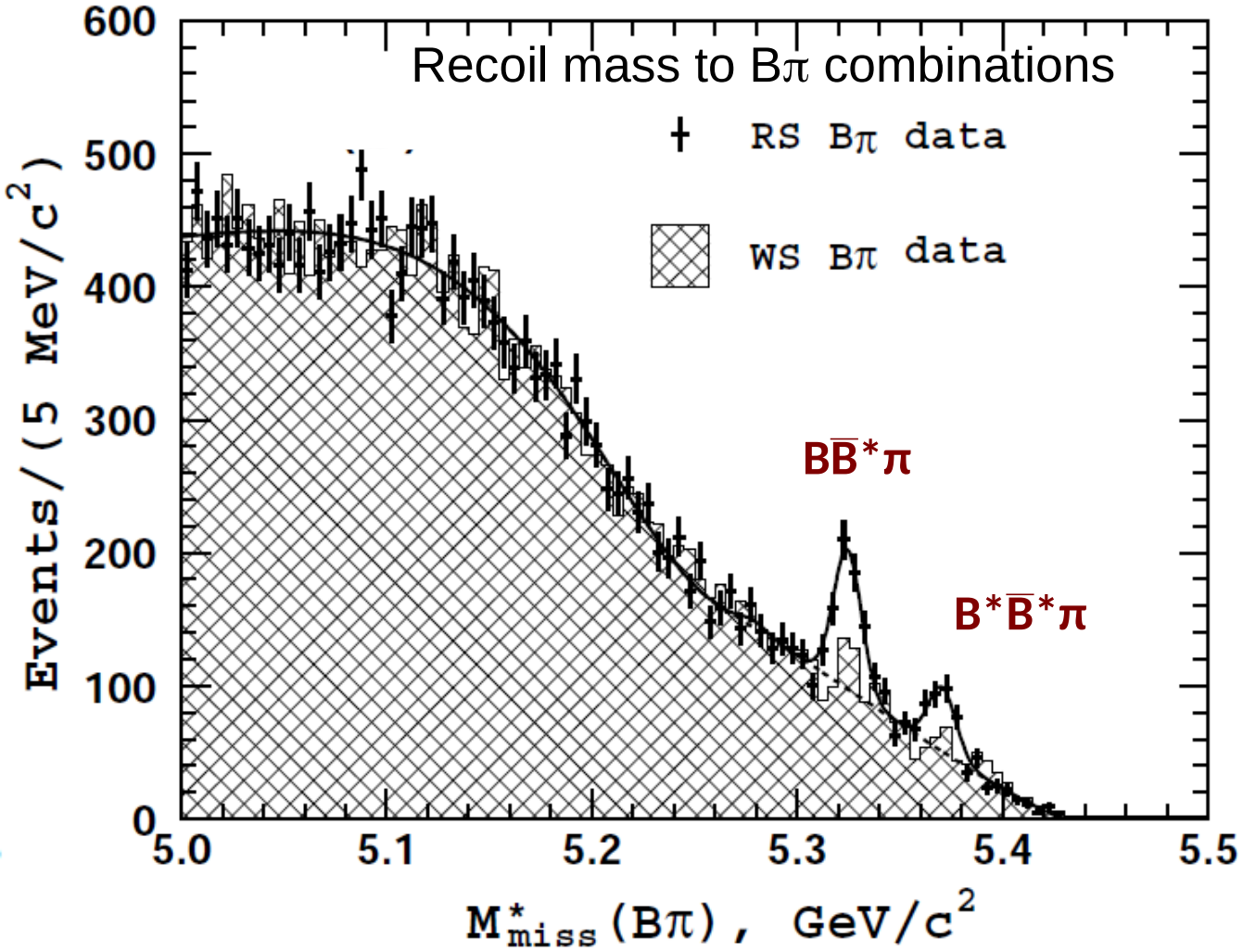


Charged B: $D^0[K\pi,K\pi\pi\pi]\pi^-$, $J/\psi[\mu\mu]\,K^-$
Neutral B: $D^+[K\pi\pi]\pi^-$, $J/\psi[\mu\mu]\,K^{*0}$,
$D^{*+}[K\pi,K\pi\pi^0,K\pi\pi\pi]\pi^-$

12263 ± 168 B candidates

Phys.Rev.Lett. 116, 212001 (2016)

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



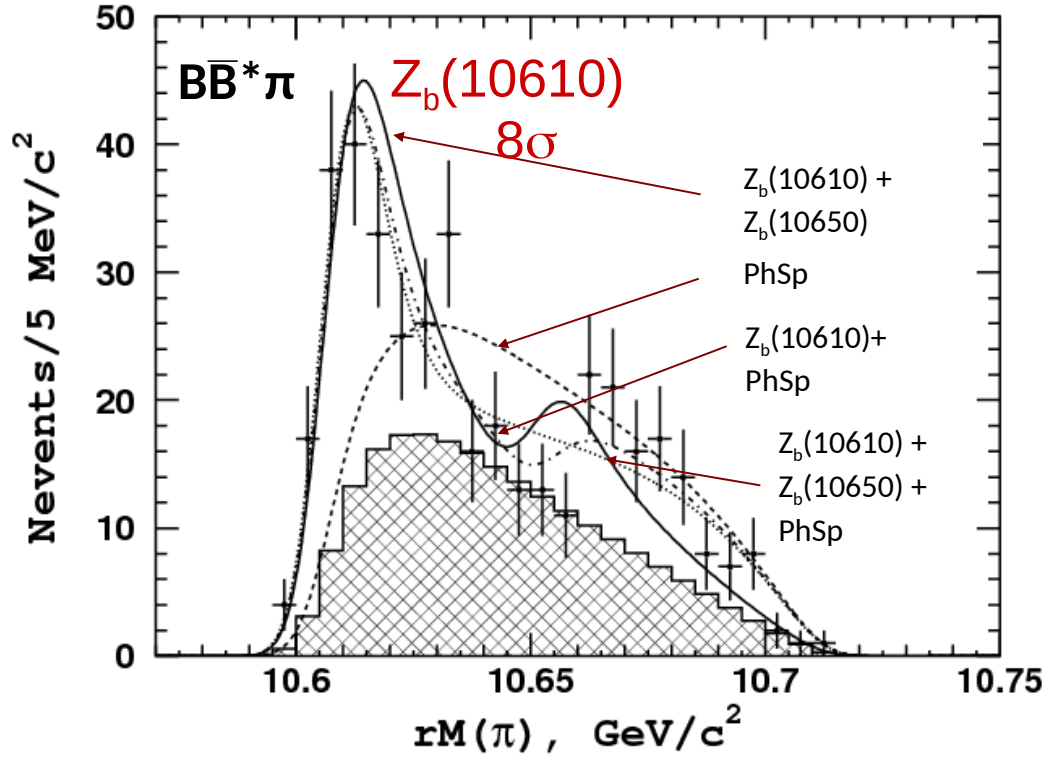
Fit yields:

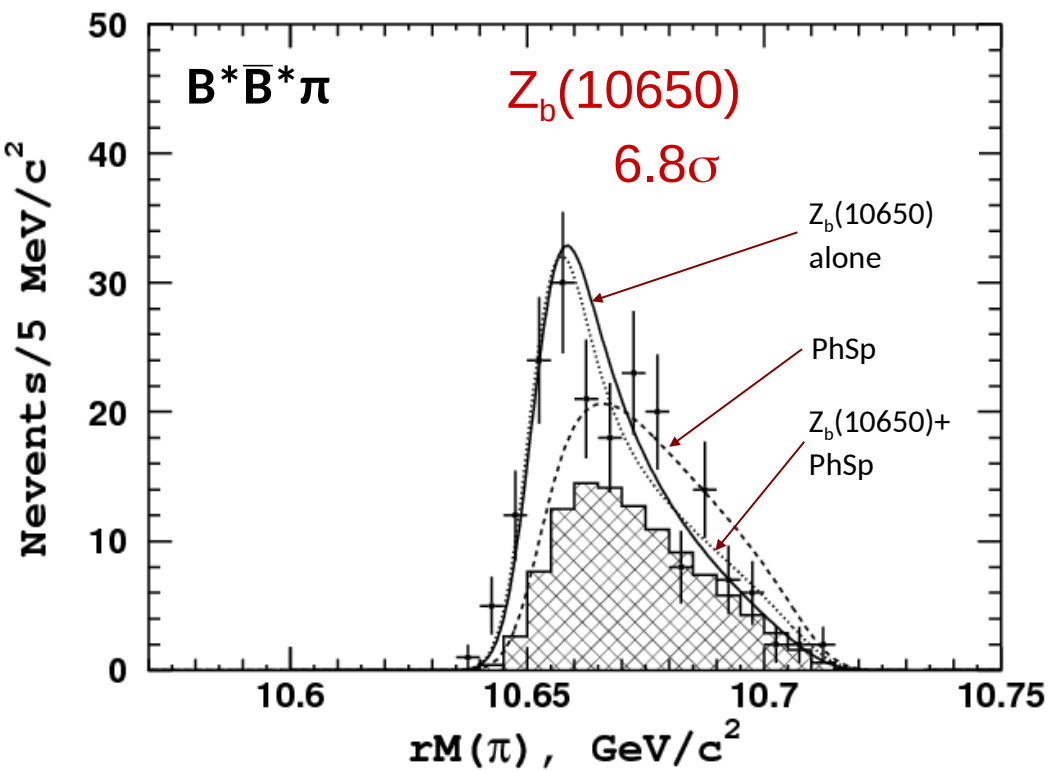
- $N(B\bar{B}\pi) = 13 \pm 25$
- $N(B\bar{B}^{*}\pi) = 357 \pm 30$
- $N(B^{*}\bar{B}^{*}\pi) = 161 \pm 21$

Points: right charge combination Bπ;
Hatched histogram: wrong charge combination;
The curve show the fit to the data.

Phys.Rev.Lett. 116, 212001 (2016)

$\Upsilon(5S) \to B^{*}\bar{B}^{(*)}\pi$: Search for Z_b





Points represent the data.
Curves show the fit with various models.
Hatched histogram is the background contribution.

Phys.Rev.Lett. 116, 212001 (2016)

$B^{*}\bar{B}^{*}\pi$ candidates are well described by $Z_b(10650)$ only contribution.

$B\bar{B}^{*}\pi$ can be described by two models:

$Z_b(10610) + Z_b(10650)$;

$Z_b(10610)$ + non-resonant amplitude.

Z_b branching fractions

Phys.Rev.Lett. 116, 212001 (2016)

Assuming Z_b decaying to $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and $B^{(*)}\bar{B}^*$ only:

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.60 \pm 0.17 \pm 0.07$	$0.17 \pm 0.06 \pm 0.02$
$\Upsilon(2S)\pi^+$	$4.05 \pm 0.81 \pm 0.58$	$1.38 \pm 0.45 \pm 0.21$
$\Upsilon(3S)\pi^+$	$2.40 \pm 0.58 \pm 0.36$	$1.62 \pm 0.50 \pm 0.24$
$h_b(1P)\pi^+$	$4.26 \pm 1.28 \pm 1.10$	$9.23 \pm 2.88 \pm 2.28$
$h_b(2P)\pi^+$	$6.08 \pm 2.15 \pm 1.63$	$17.0 \pm 3.74 \pm 4.1$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$82.6 \pm 2.9 \pm 2.3$	–
$B^{*+}\bar{B}^{*0}$	–	$70.6 \pm 4.9 \pm 4.4$

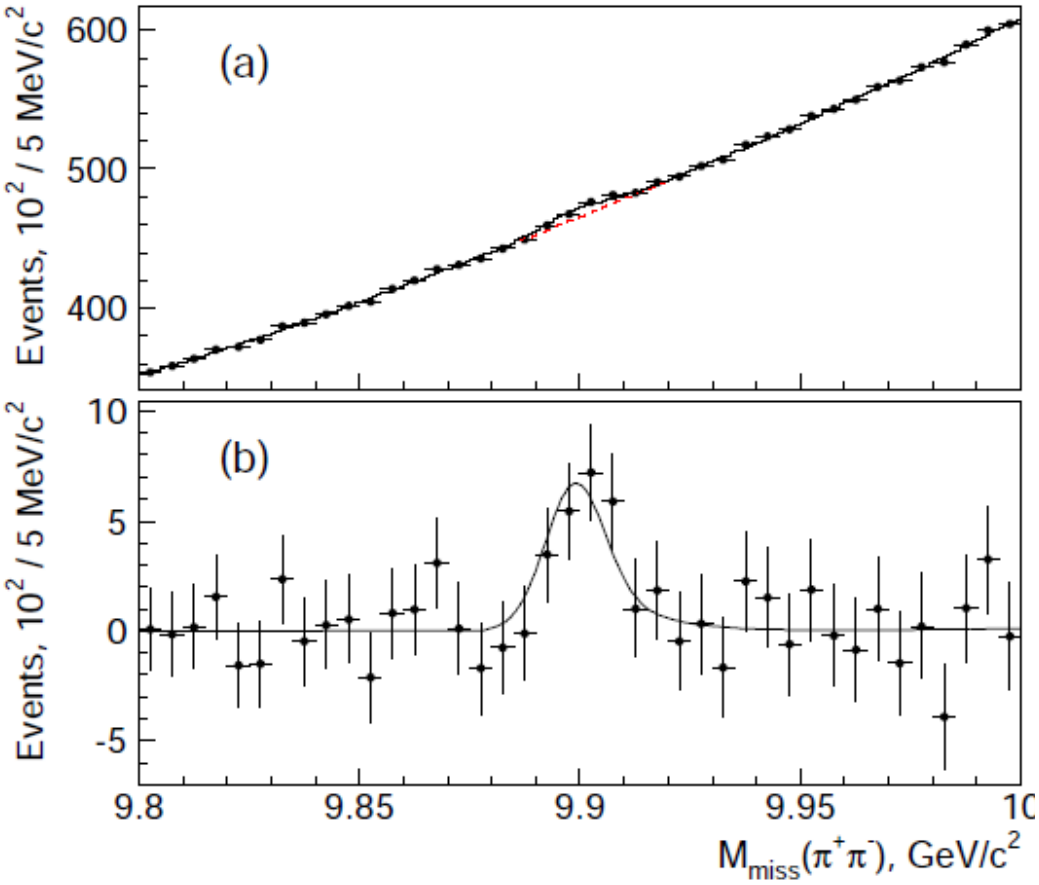
$B^{(*)}\bar{B}^*$ - is the dominant mode of Z_b decays

New

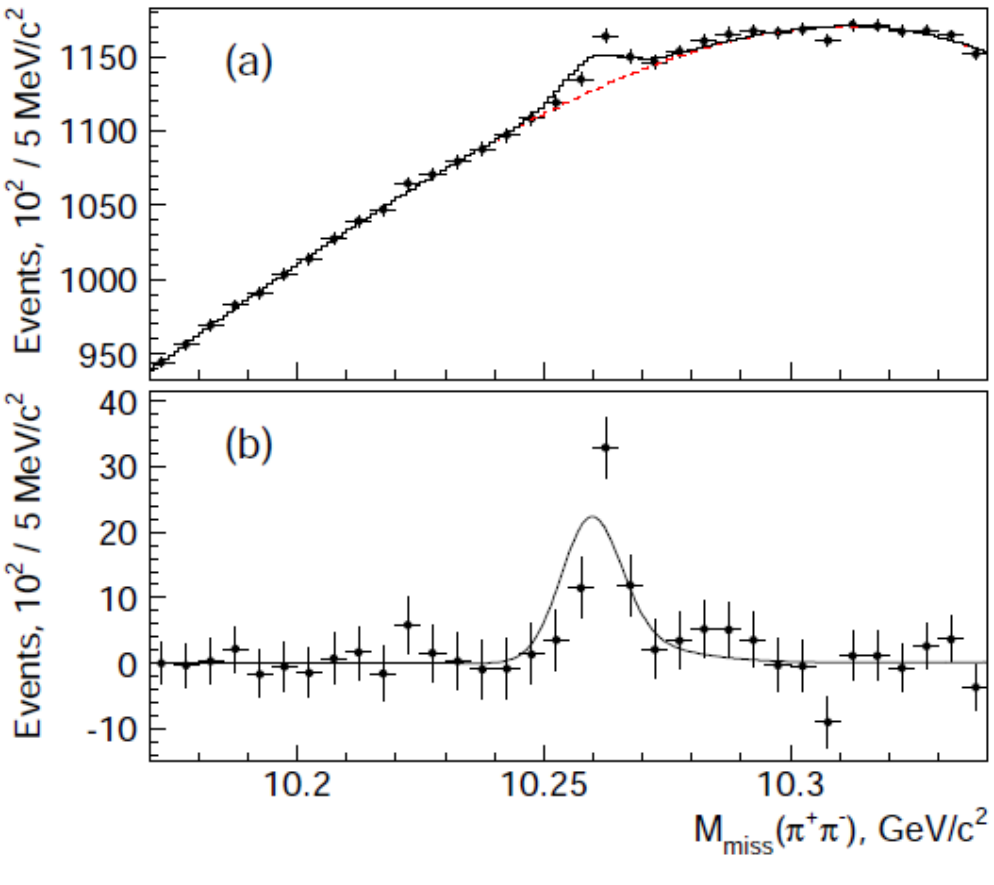
Measurement of cros section $e^+e^- \to h_b(nP)\pi^+\pi^-$

Phys.Rev.Lett. 117, 142001 (2016)

h_b signal is extracted by the fit to $\pi^+\pi^-$ recoil mass

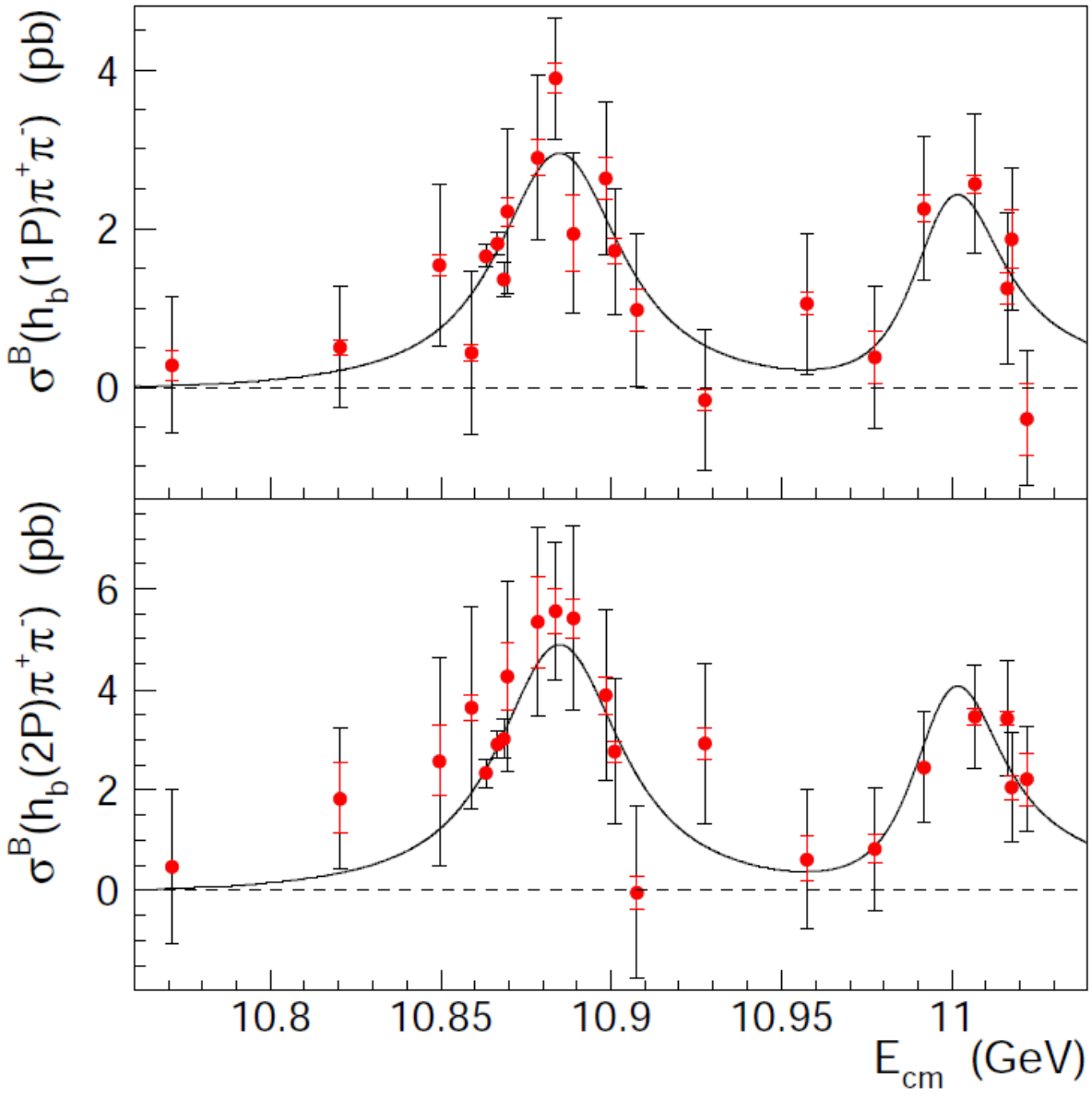


$h_b(1P)$ near Y(6S)



$h_b(2P)$ near Y(6S)

New Measurement of $\sigma[e^+e^- \to h_b(nP)\pi^+\pi^-]$



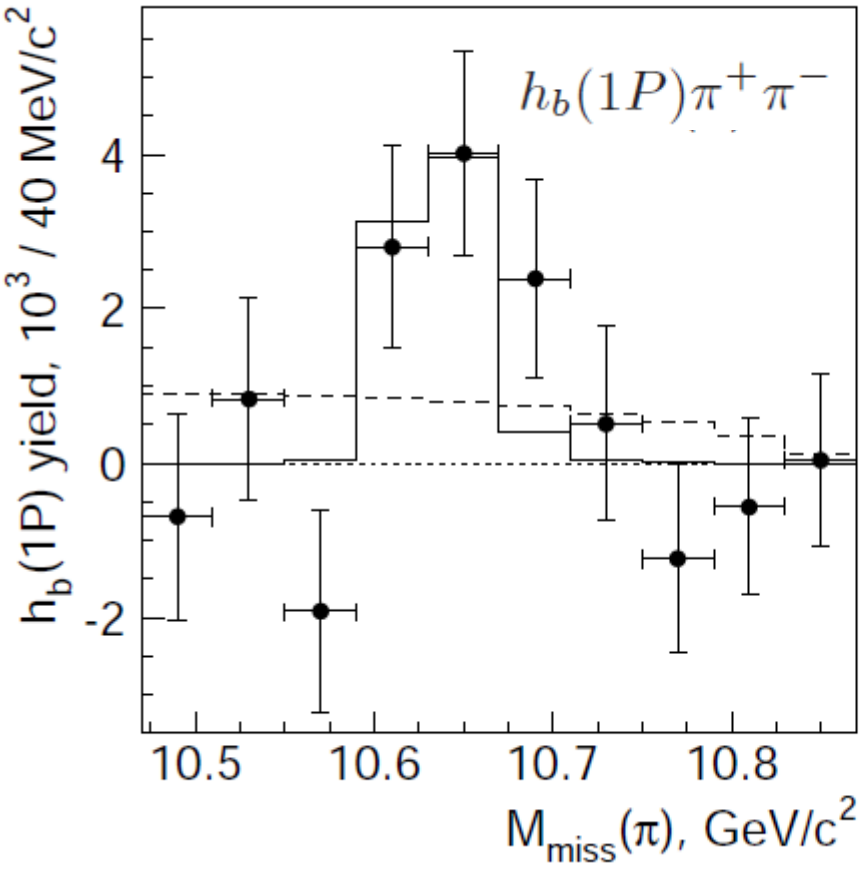
Phys.Rev.Lett. 117, 142001 (2016)

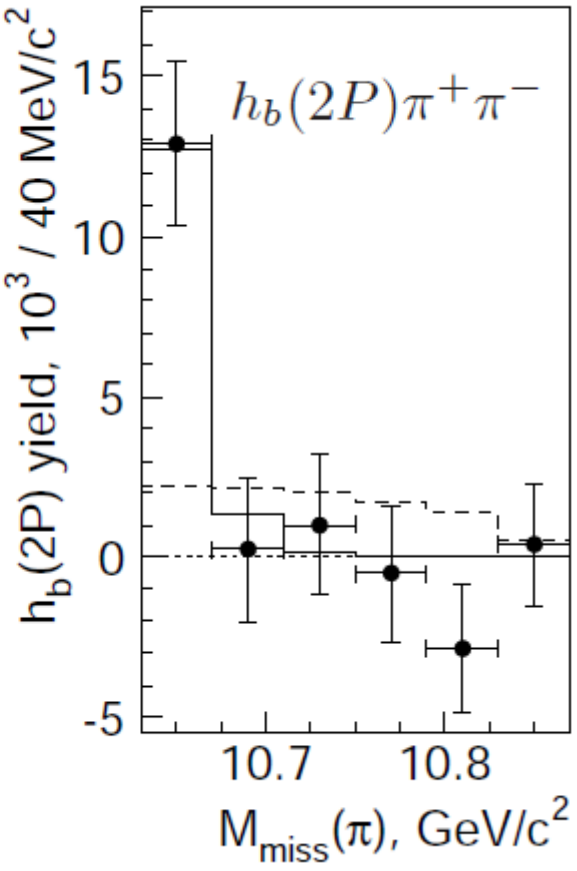
$$A_n\ \Phi_n(s)\ |F_{\rm BW}(s, M_5, \Gamma_5) + a\, e^{i\,\phi}\, F_{\rm BW}(s, M_6, \Gamma_6)|^2$$

$$M_5 = (10884.7^{+3.6+8.9}_{-3.4-1.0})\ {\rm MeV}/c^2,$$
$$\Gamma_5 = (40.6^{+12.7+\ 1.1}_{-\ 8.0-19.1})\ {\rm MeV},$$
$$M_6 = (10999.0^{+7.3+16.9}_{-7.8-\ 1.0})\ {\rm MeV}/c^2,$$
$$\Gamma_6 = (27^{+27+\ 5}_{-11-12})\ {\rm MeV},$$
$$a = 0.65^{+0.36+0.17}_{-0.12-0.10}$$
$$\phi = (0.1^{+0.4}_{-0.8} \pm 0.3)\,\pi$$

$Zb \rightarrow h_b(nP)\pi$

Phys.Rev.Lett. 117, 01 (2016)





Consistent with dominant Zb's contribution

Search for X, Y, Z in $\Upsilon(1S)$ decays

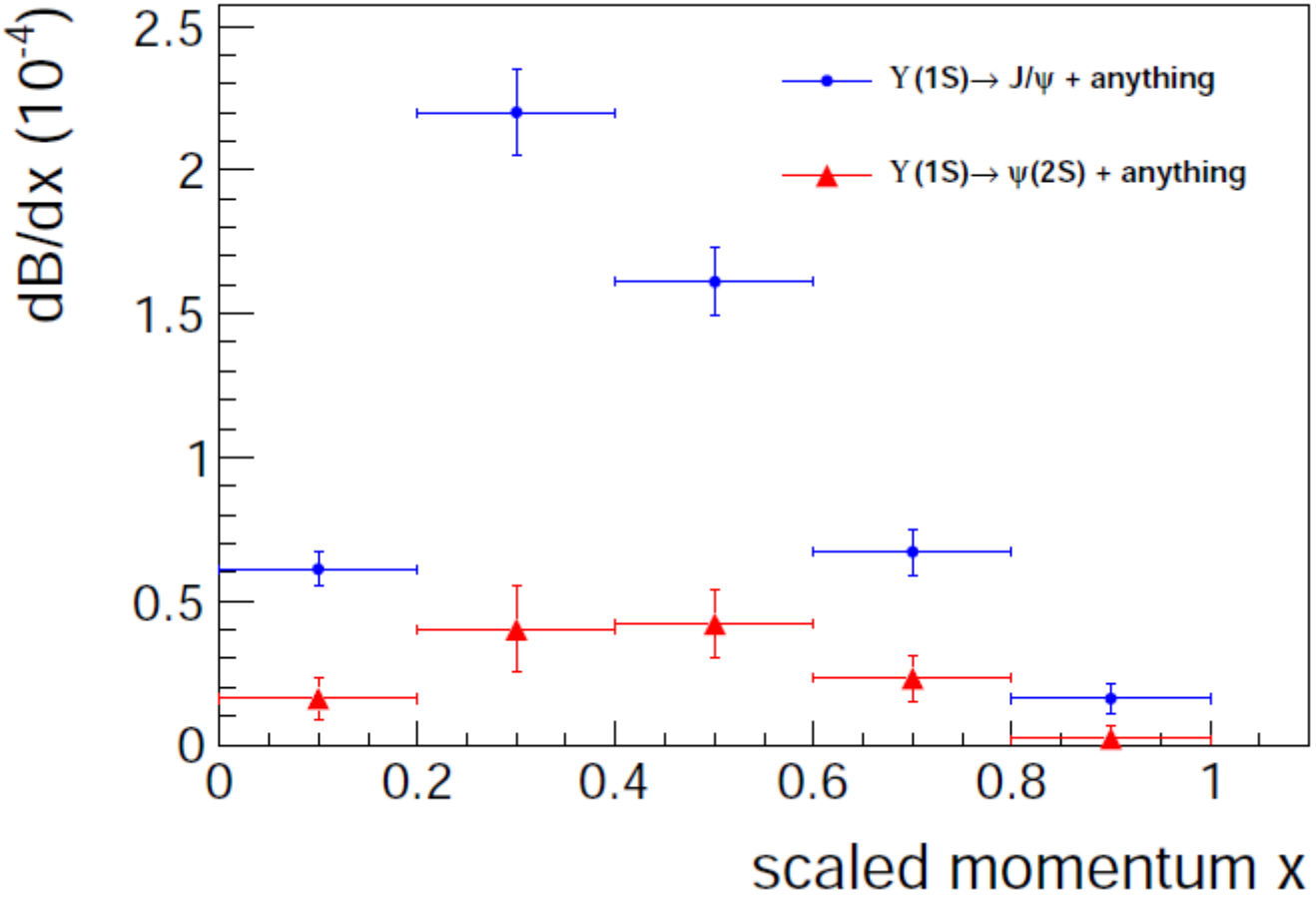
- Measure Bf(Y1S → ψ(1S, 2S) + anything)

- Search for the following states
  - X(3872) & Y(4260) → $\pi^+\pi^-$J/ψ;
  - Y(4260), Y(4360) & Y(4660) → $\pi^+\pi^-$ψ(2S);
  - Y (4260) → K^+K^-J/ψ;
  - Y (4140) & X(4350) → φJ/ψ
  - $Zc(3900)^{\pm}$ $Zc(4200)^{\pm}$ & $Zc(4430)^{\pm}$ → $\pi^{\pm}$J/ψ;
  - $Zc(4050)^{\pm}$ & $Zc(4430)^{\pm}$ → $\pi^{\pm}$ψ(2S);

Phys.Rev.D 93, 112013 (2016)

New

$\Upsilon(1S) \rightarrow J/\psi$ and $\psi(2S)$ + anything



Differential branching fractions for $\Upsilon(1S)$ inclusive decays into the J/ψ and ψ(2S) versus the scaled momentum $x = p^*_\psi / (\frac{1}{2\sqrt{s}} \times (s - m^2_\psi))$

Phys.Rev.D 93, 112013 (2016)

New

Search for X, Y, Z in $\Upsilon(1S)$

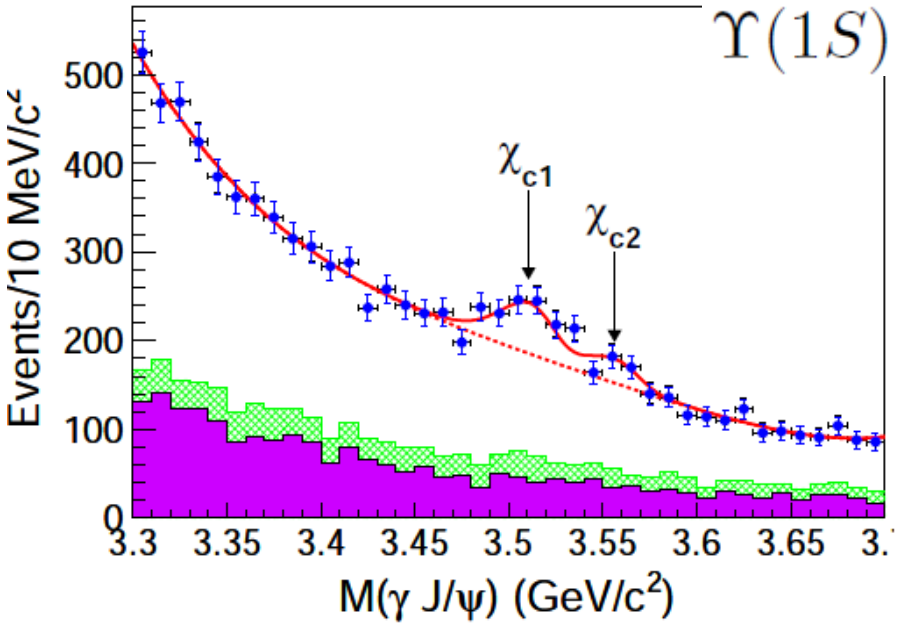
State	$N_{\rm fit}$	$N_{\rm up}$	$\varepsilon(\%)$	$\sigma_{\rm syst}(\%)$	$\Sigma(\sigma)$	$\mathcal{B}_R^{\rm prod}$
$X(3872) \to \pi^+\pi^- J/\psi$	4.8 ± 15.4	31.4	3.26	18.7	0.3	$< 9.5 \times 10^{-6}$
$Y(4260) \to \pi^+\pi^- J/\psi$	-31.1 ± 88.9	134.6	3.50	35.6	–	$< 3.8 \times 10^{-5}$
$Y(4260) \to \pi^+\pi^- \psi(2S)$	6.7 ± 29.4	56.9	0.71	35.0	0.2	$< 7.9 \times 10^{-5}$
$Y(4360) \to \pi^+\pi^- \psi(2S)$	-25.4 ± 30.1	45.6	0.86	50.0	–	$< 5.2 \times 10^{-5}$
$Y(4660) \to \pi^+\pi^- \psi(2S)$	-55.0 ± 26.2	23.1	1.06	40.7	–	$< 2.2 \times 10^{-5}$
$Y(4260) \to K^+K^- J/\psi$	-13.7 ± 10.9	14.5	1.91	45.8	–	$< 7.5 \times 10^{-6}$
$Y(4140) \to \phi J/\psi$	-0.1 ± 1.2	3.6	0.69	11.0	–	$< 5.2 \times 10^{-6}$
$X(4350) \to \phi J/\psi$	2.3 ± 2.5	7.6	0.92	10.4	1.2	$< 8.1 \times 10^{-6}$
$Z_c(3900)^\pm \to \pi^\pm J/\psi$	-26.5 ± 39.1	57.5	4.39	47.3	–	$< 1.3 \times 10^{-5}$
$Z_c(4200)^\pm \to \pi^\pm J/\psi$	-238.6 ± 154.2	235.1	3.87	48.4	–	$< 6.0 \times 10^{-5}$
$Z_c(4430)^\pm \to \pi^\pm J/\psi$	94.2 ± 71.4	195.8	3.97	34.4	1.2	$< 4.9 \times 10^{-5}$
$Z_c(4050)^\pm \to \pi^\pm \psi(2S)$	37.0 ± 47.7	112.7	1.27	46.2	0.4	$< 8.8 \times 10^{-5}$
$Z_c(4430)^\pm \to \pi^\pm \psi(2S)$	23.2 ± 42.4	92.0	1.35	47.1	0.1	$< 6.7 \times 10^{-5}$
$Z_{cs}^\pm \to K^\pm J/\psi$	-22.2 ± 17.4	22.4	3.88	48.7	–	$< 5.7 \times 10^{-6}$

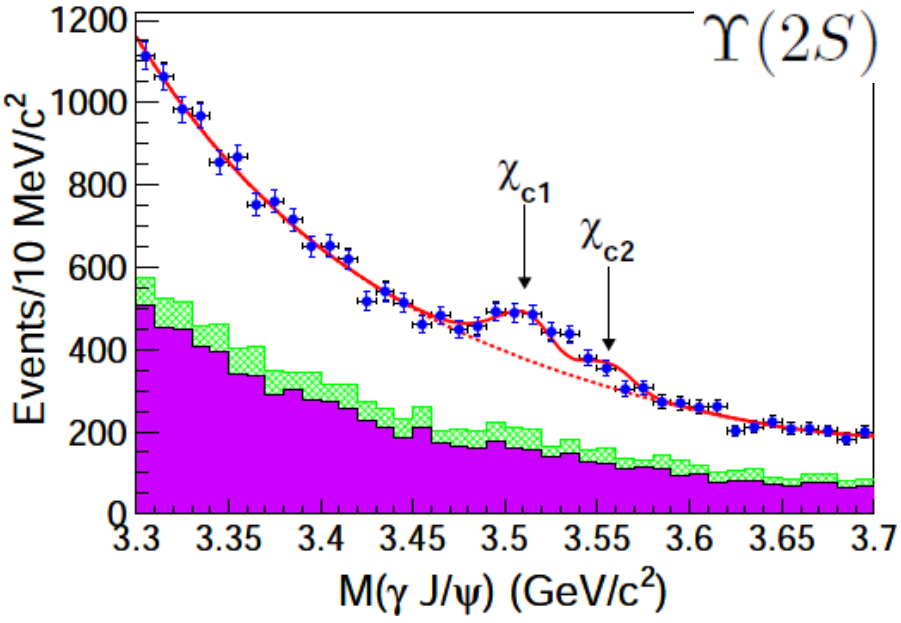
Upper limits for $\Upsilon(1S)$ branching fractions to X, Y, Z

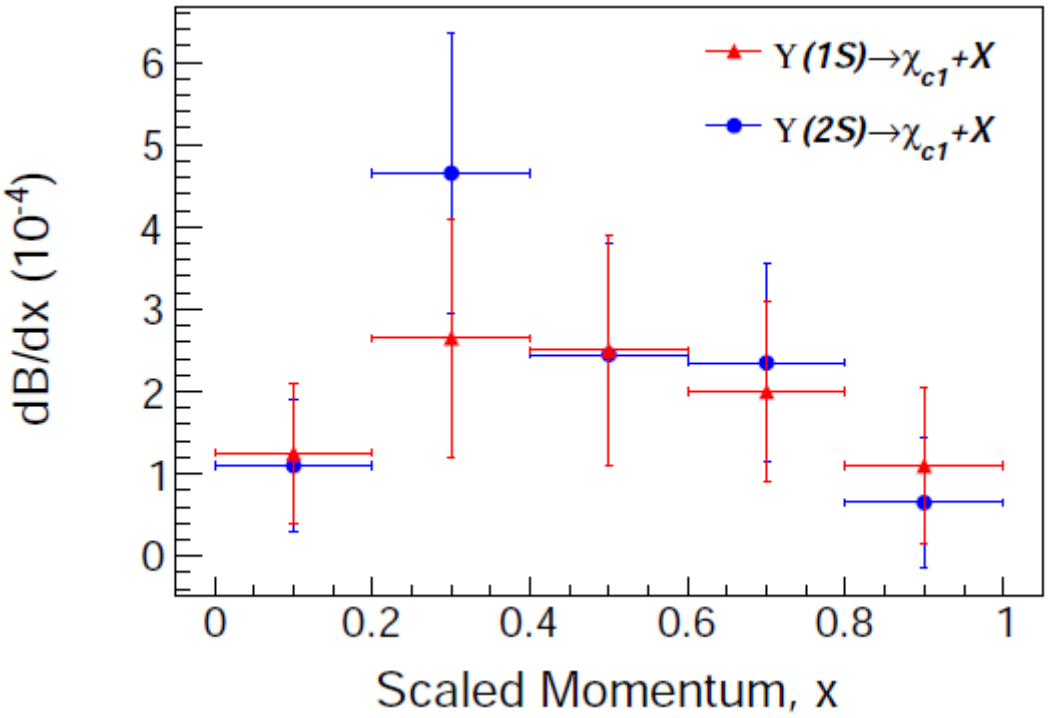
Phys.Rev.D 93, 112013 (2016)

New

$\Upsilon(1S, 2S) \rightarrow \chi_{c1,2}$ + anything







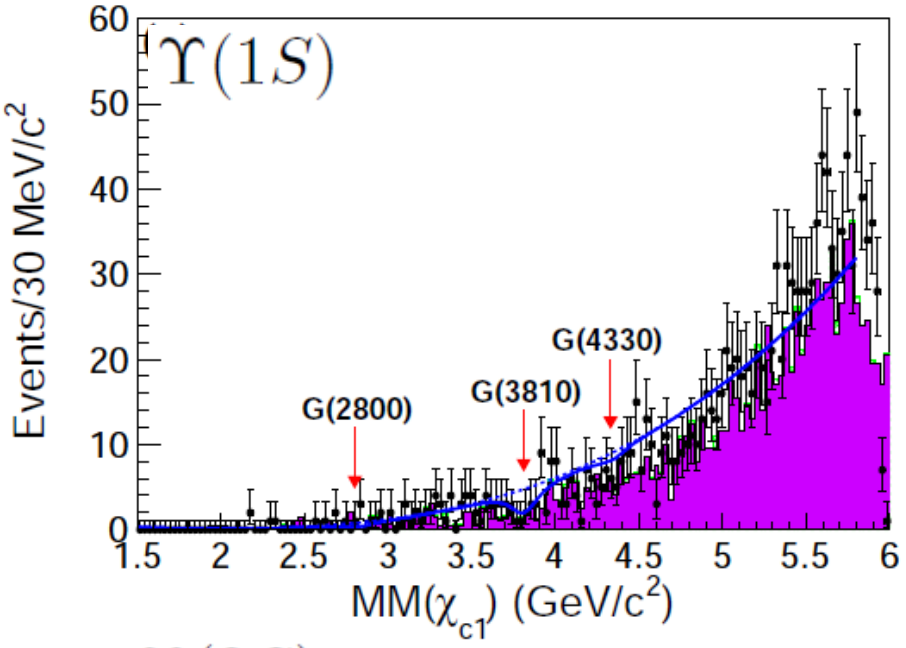
Differential branching fractions for (1S) inclusive decays into the J/ψ and ψ(2S) versus the scaled momentum

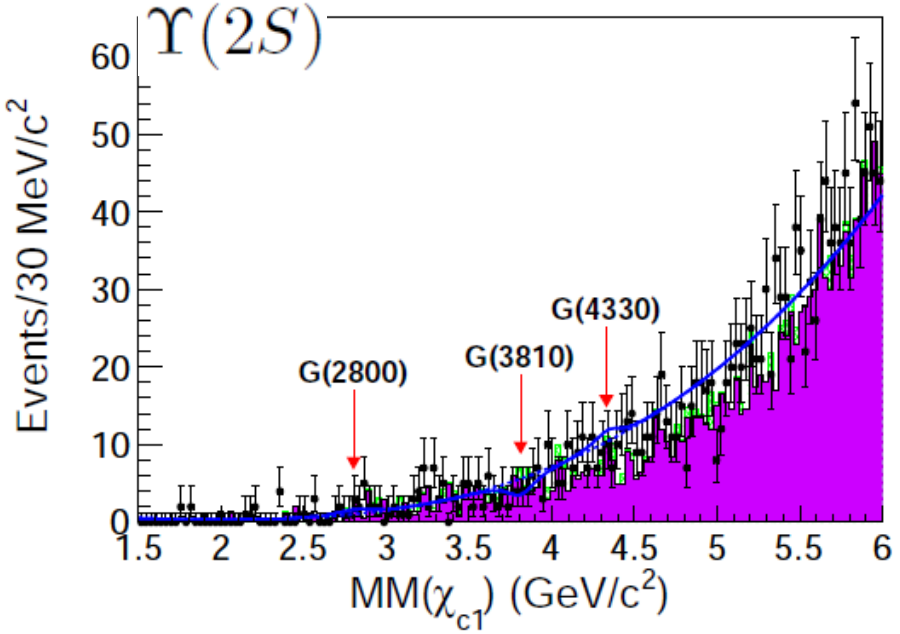
X = $p^*_{\chi c1} / (\frac{1}{2\sqrt{s}} \times (s - m^2_{\chi c1}))$

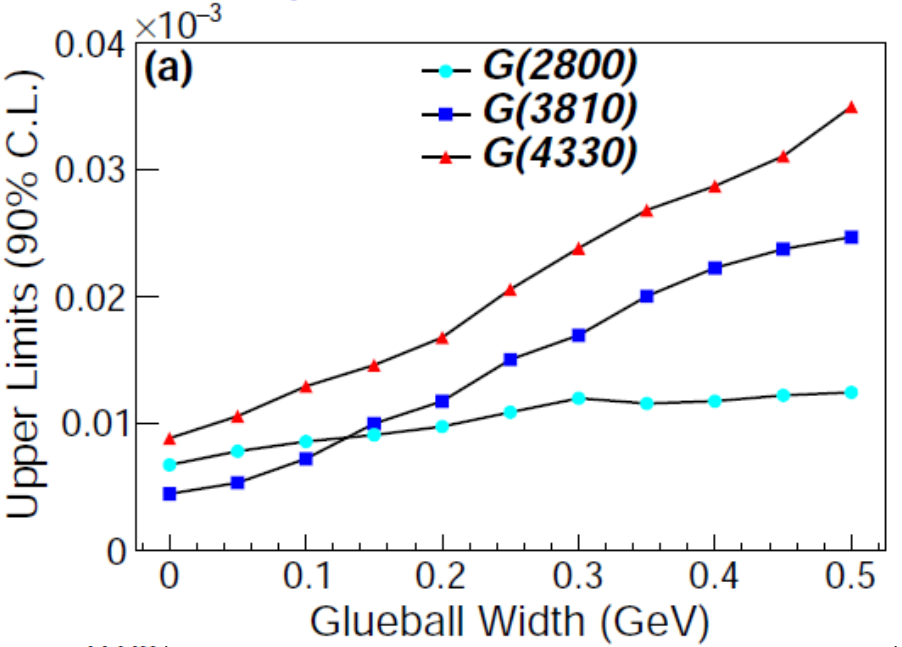
Phys.Rev. D95, 012001 (2017)

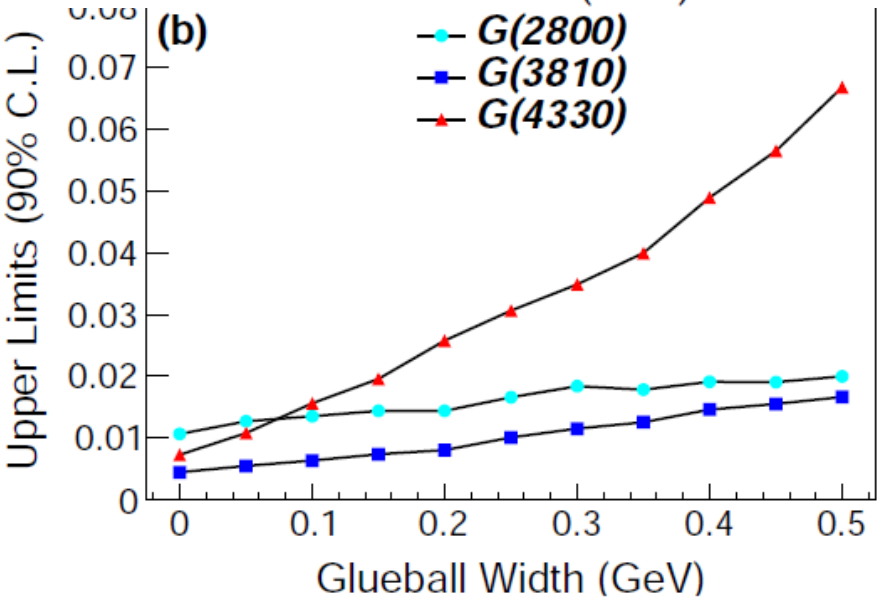
New

Search for the 0^{--} Glueball in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays









Phys.Rev. D95, 012001 (2017)

Summary

- Advanced amplitude analysis confirms $J^P=1^+$ hypothesis for $Z_b^+(10610)$ and $Z_b^+(10650)$ states.
- Both $Z_b^+(10610)$ and $Z_b^+(10650)$ have been observed in decays to $B\bar{B}^*$ and $B^*\bar{B}^*$. These modes are found to be dominant for Z_b^+ decays.

New $h_b(1P,2P)\,\pi^+\pi^-$ cross section have been measured from threshold up to 11.02 GeV. Clear $\Upsilon(10860)$ and $\Upsilon(11020)$ peaks are observed with no continuum contribution. The evidence found that they proceed entirely via the intermediate isovector states $Z_b^+(10610)$ and $Z_b^+(10650)$.

New No X, Y or Z states are found in $\Upsilon(1S)$ decays.

New Search for 0^{--} glueballs in $\Upsilon(1S, 2S)$ decays give negative results.

- More exciting results are going to come from Belle II.

Summary of Z_b parameters

Average over 5 channels

‹ M_1 = 10607.2±2.0 MeV

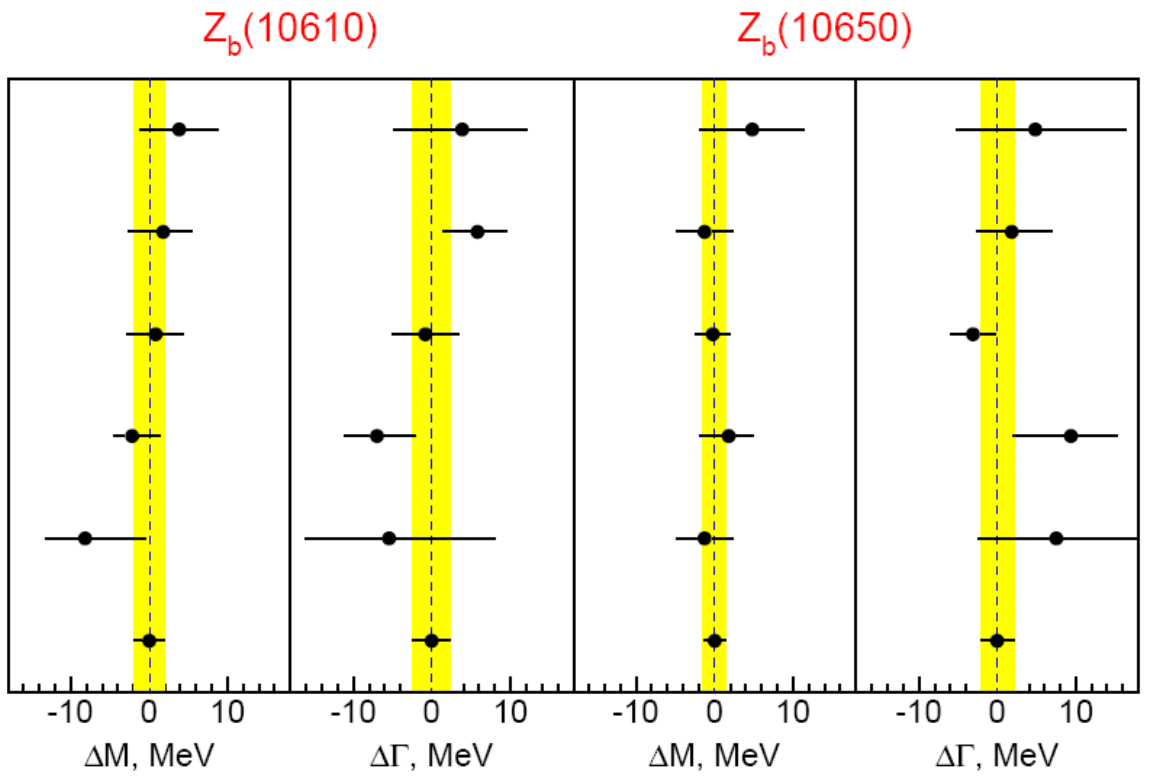
‹ Γ_1 = 18.4±2.4 MeV

M(BB*)=10604.8 ± 0.4 MeV

‹ M_2 = 10652.2±1.5 MeV

‹ Γ_2 = 11.5 ± 2.2 MeV

M(B*B*)=10650.4 ± 0.8 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}	$181^{+65+74}_{-105-109}$

New

Search for the 0^{--} Glueball in Y(1S) and Y(2S) decays