Zb and Zc states at Belle

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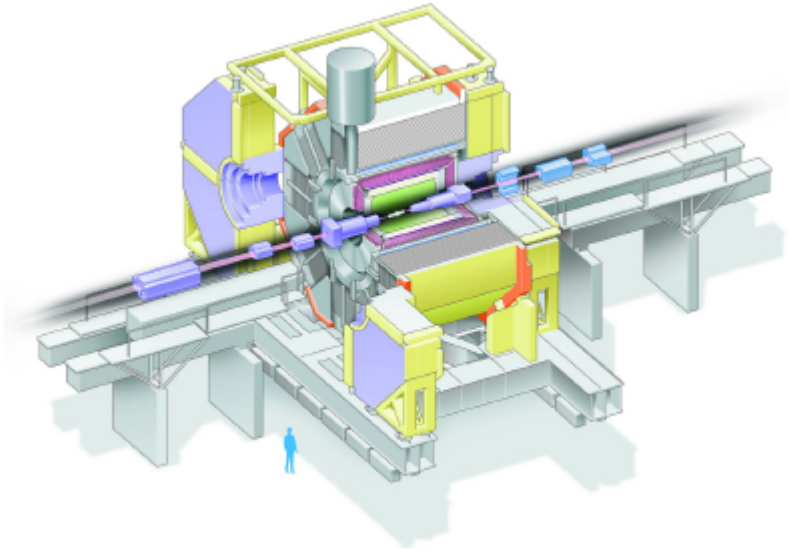
Outline:

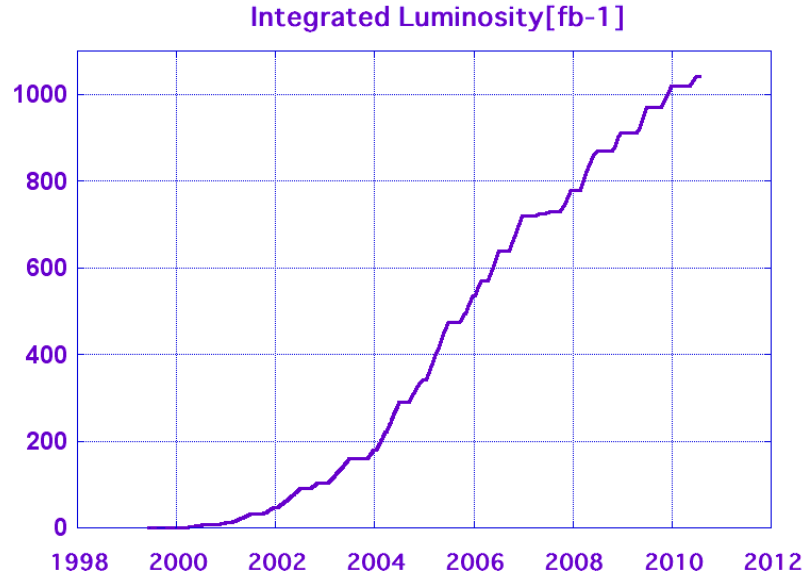
- Z_b^+ in $\Upsilon(5S) \rightarrow \Upsilon(nS)\ \pi^+\pi^-$
- Z_b^0 in $\Upsilon(5S) \rightarrow \Upsilon(nS)\ \pi^0\pi^0$
- Determinition of Z_b^+ quantum numbers
- Z_b^+ in $\Upsilon(5S) \rightarrow B^{(*)}B^{(*)}\pi$

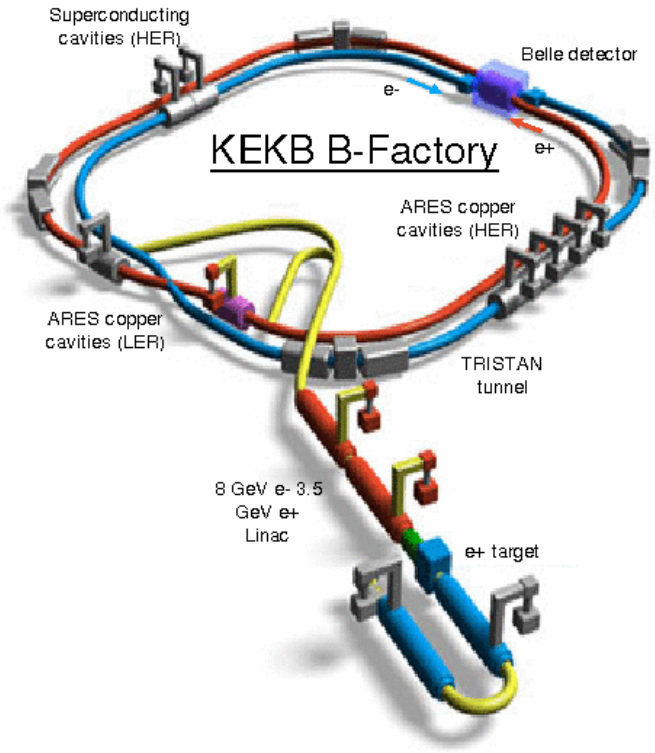
- Observation of $Z^+(4200)$ in $B \rightarrow J/\psi\ K\ \pi$
- Evidence of $Z^+(4050)$ in $e^+e^- \rightarrow \psi(2S)\ \pi\ \pi$

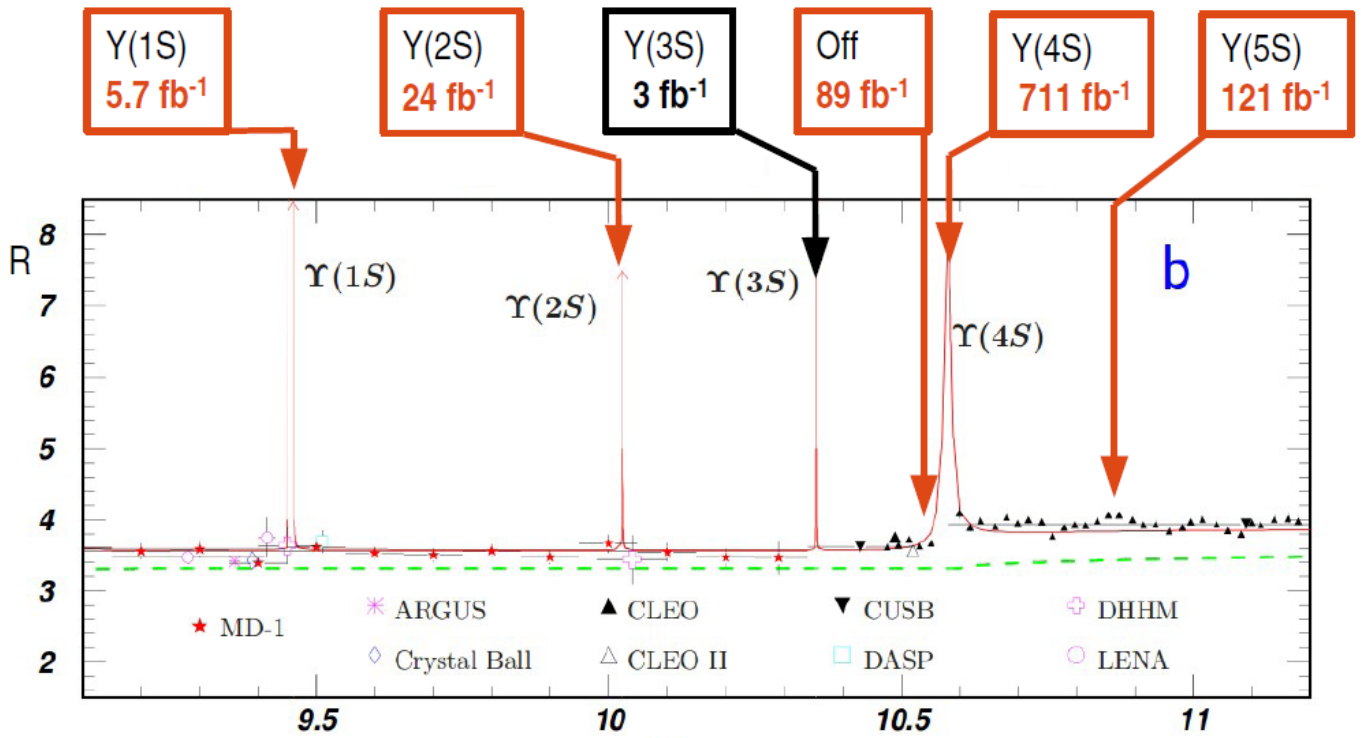
- Summary

The Belle experiment

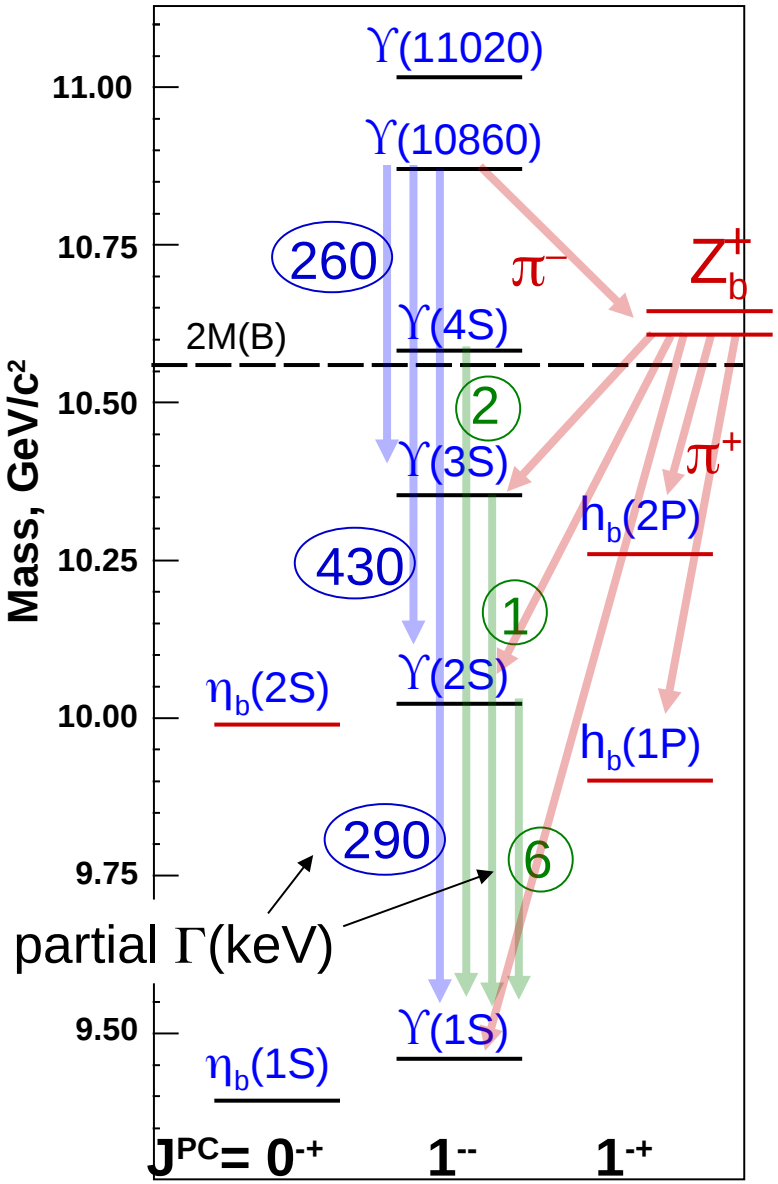








Introduction



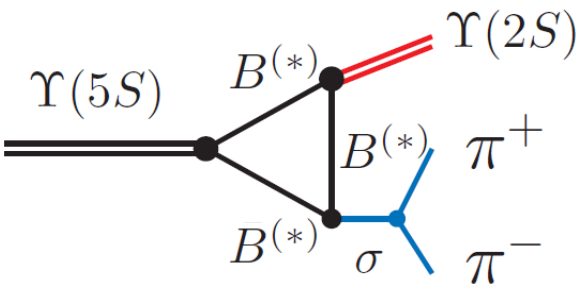
Belle collected 121 fb^{-1} at Υ(5S)

Belle: PRL100, 112001 (2008)

~ 100

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

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



Belle: PRL108, 032001 (2012)

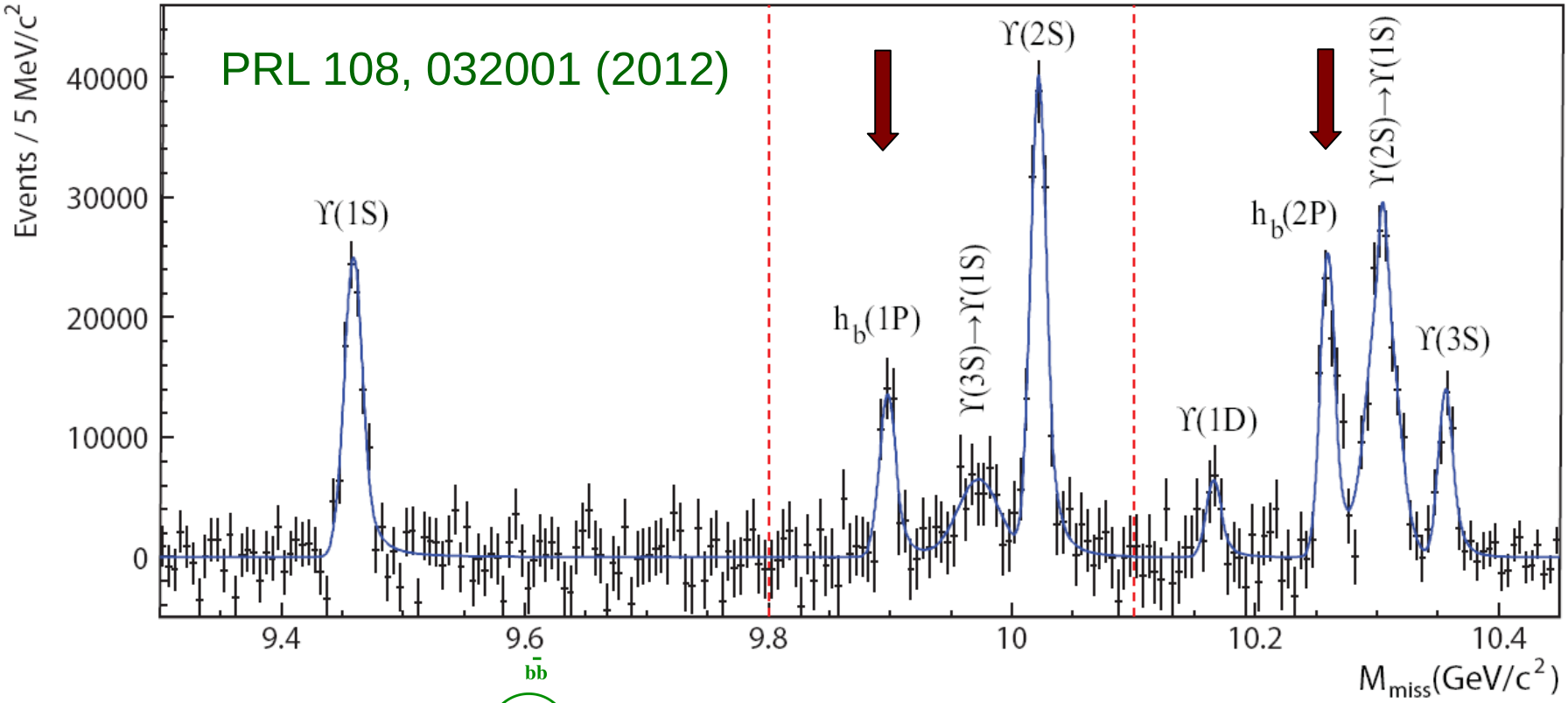
expect suppression $\sim \Lambda_{QCD}/m_b$

~~Heavy Quark Symmetry~~

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

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

Observation of $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$



spin-flip

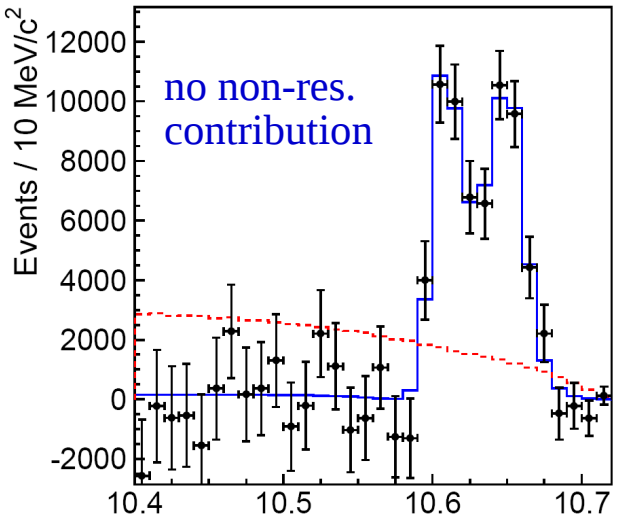
$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-]} = \begin{cases} 0.45 \pm 0.08^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

no spin-flip

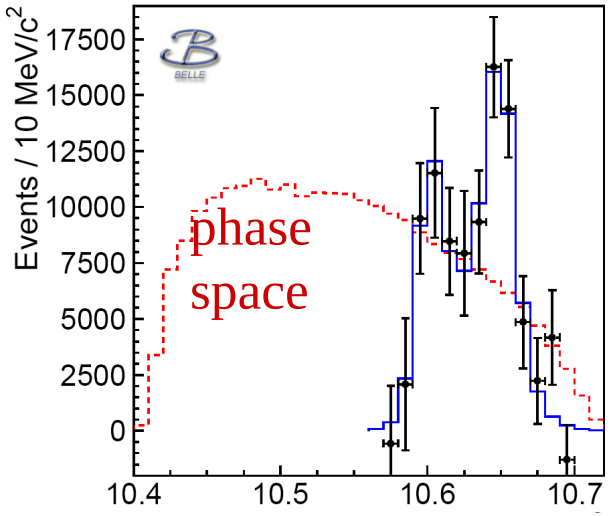
Process with spin flip of heavy quark is not suppressed: mechanism of $\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-$ decay violates Heavy Quark Spin Symmetry

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

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



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



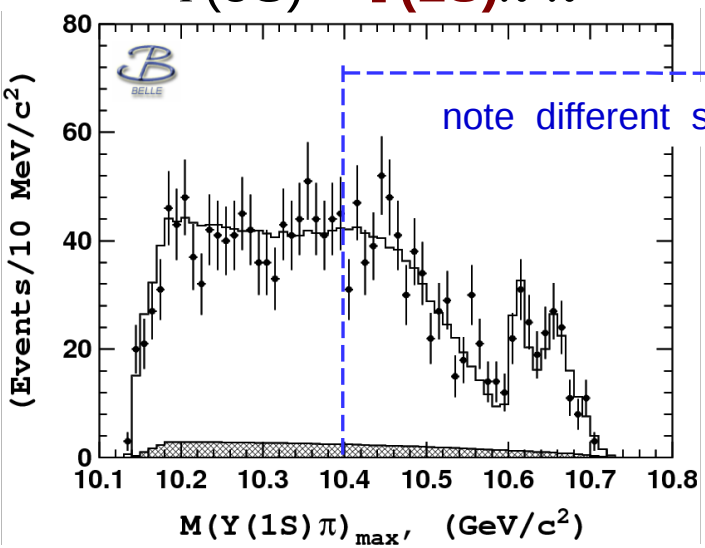
Two peaks are observed in all modes!

Belle: PRL108, 232001 (2012)

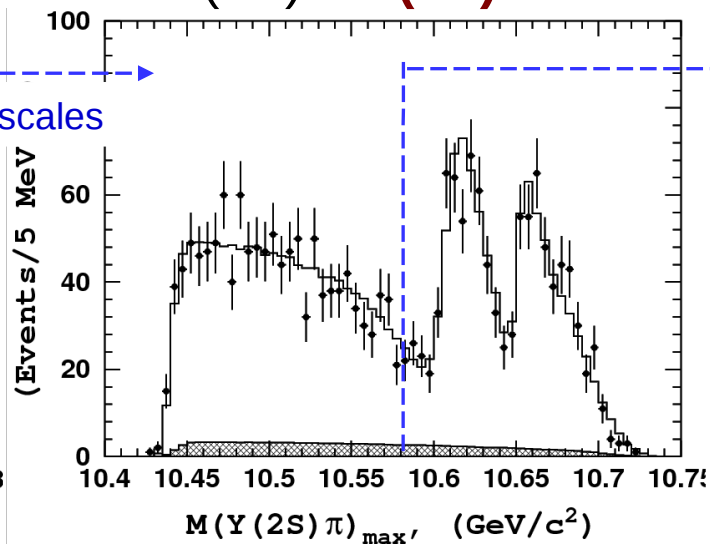
$Z_b(10610)$ and $Z_b(10650)$ should be multiquark states

Dalitz plot analysis

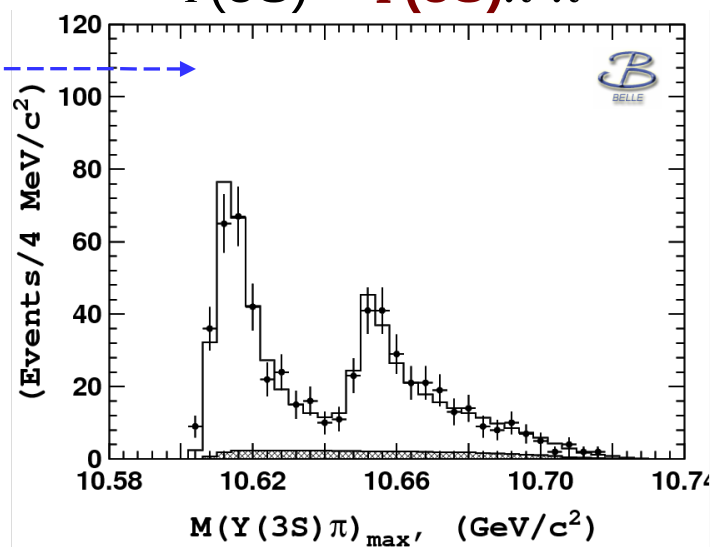
$\Upsilon(5S) \to$ **$\Upsilon(1S)\pi^+\pi^-$**



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



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



note different scales

Summary of Z_b parameters

Average over 5 channels

‹ M_1 = 10607.2±2.0 MeV

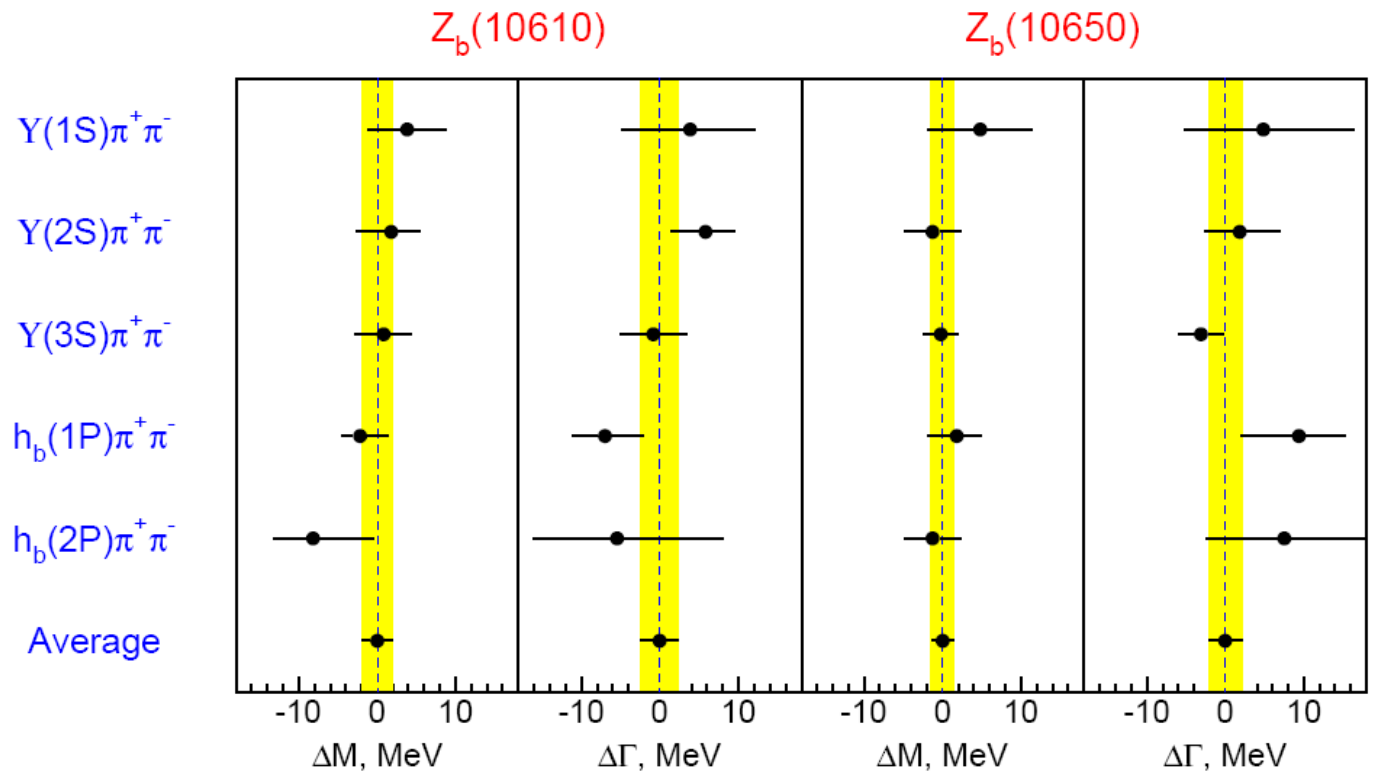
‹ Γ_1 = 18.4±2.4 MeV

M(BB*)=10604.8 ± 0.4 MeV

‹ M_2 = 10652.2±1.5 MeV

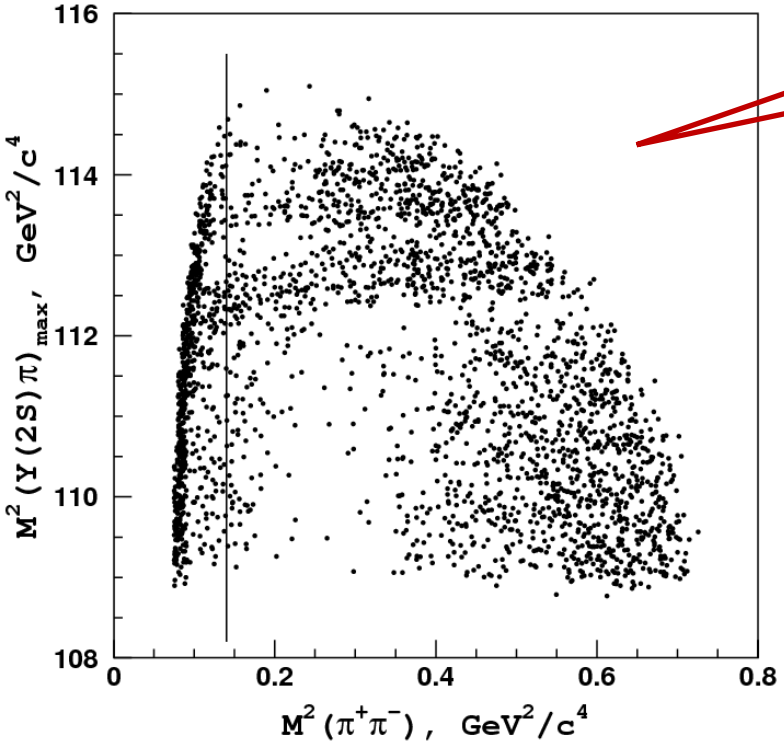
‹ Γ_2 = 11.5 ± 2.2 MeV

M(B*B*)=10650.4 ± 0.8 MeV

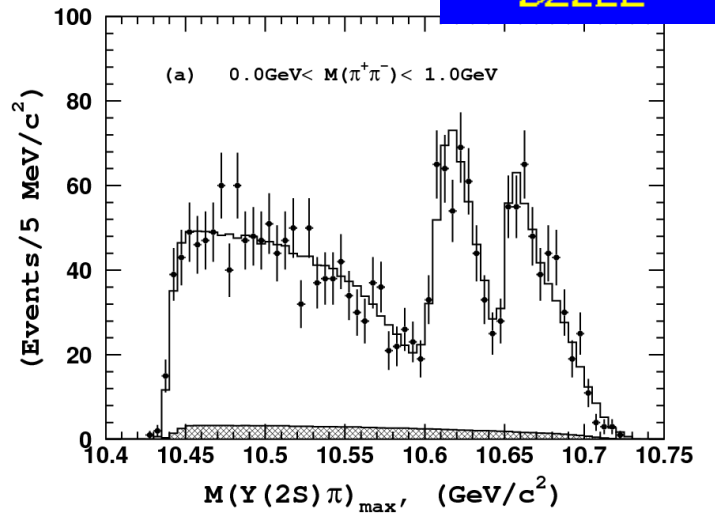


Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV/c^2	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\,^{+4.5+2.1}_{-3.9-1.2}$	$13\,^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, 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}	$181^{+65+74}_{-105-109}$

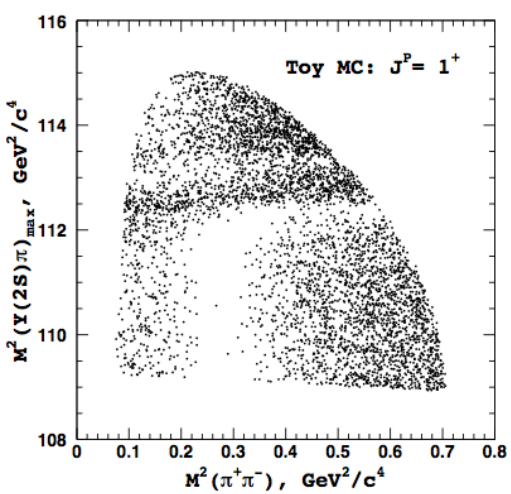
$\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$: J^P Analysis



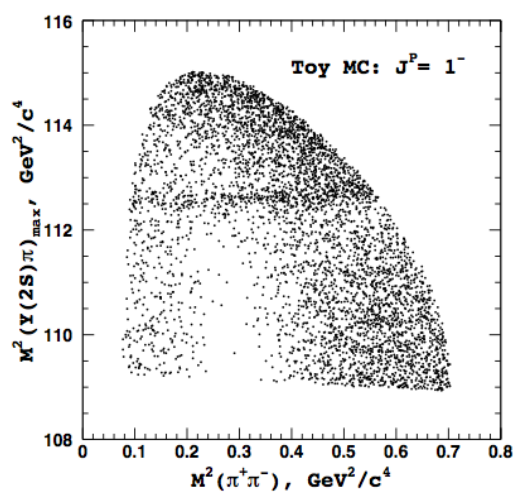
$\Upsilon(2S)\pi^+\pi$ Data



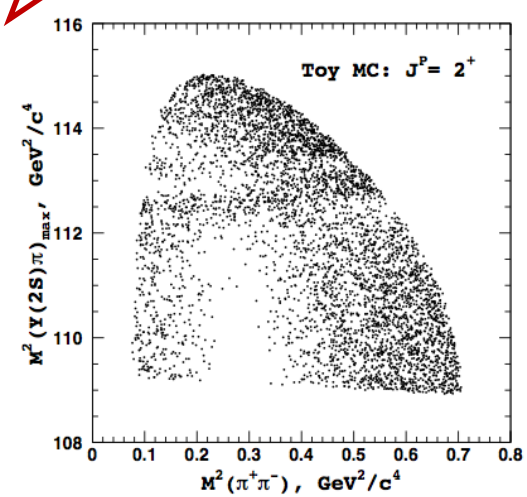
Toy MC with various J^P



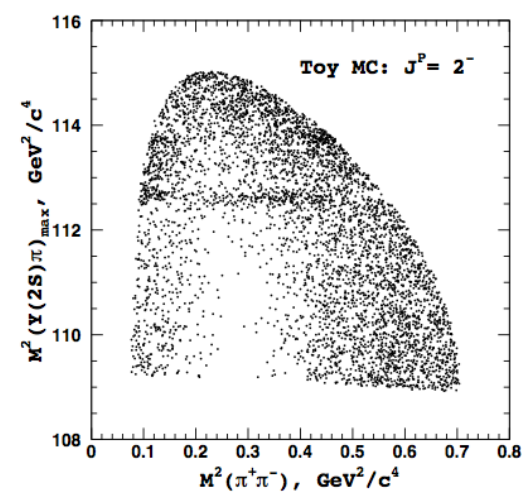
$J^P = 1^+$



$J^P = 1^-$

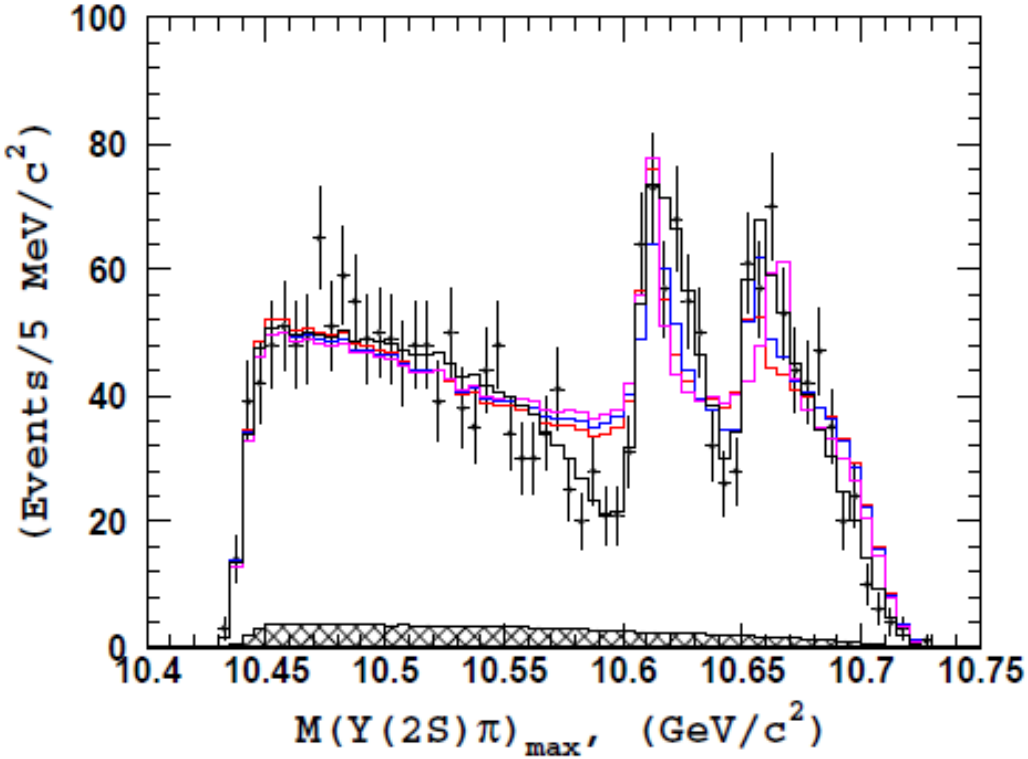


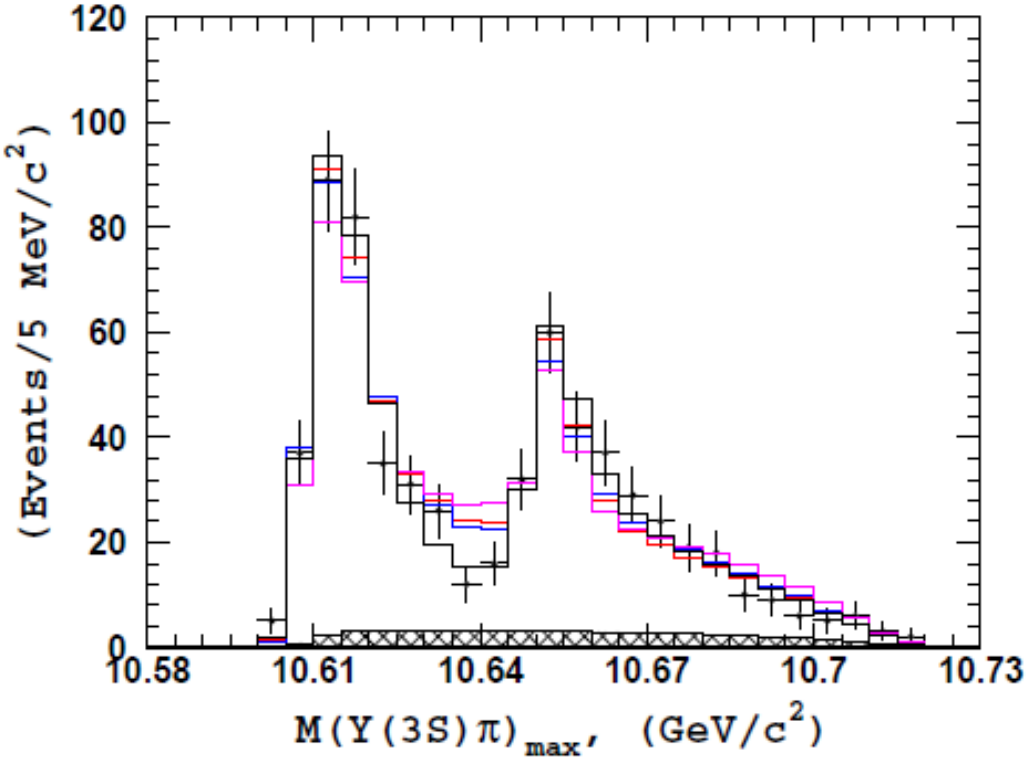
$J^P = 2^+$



$J^P = 2^-$

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



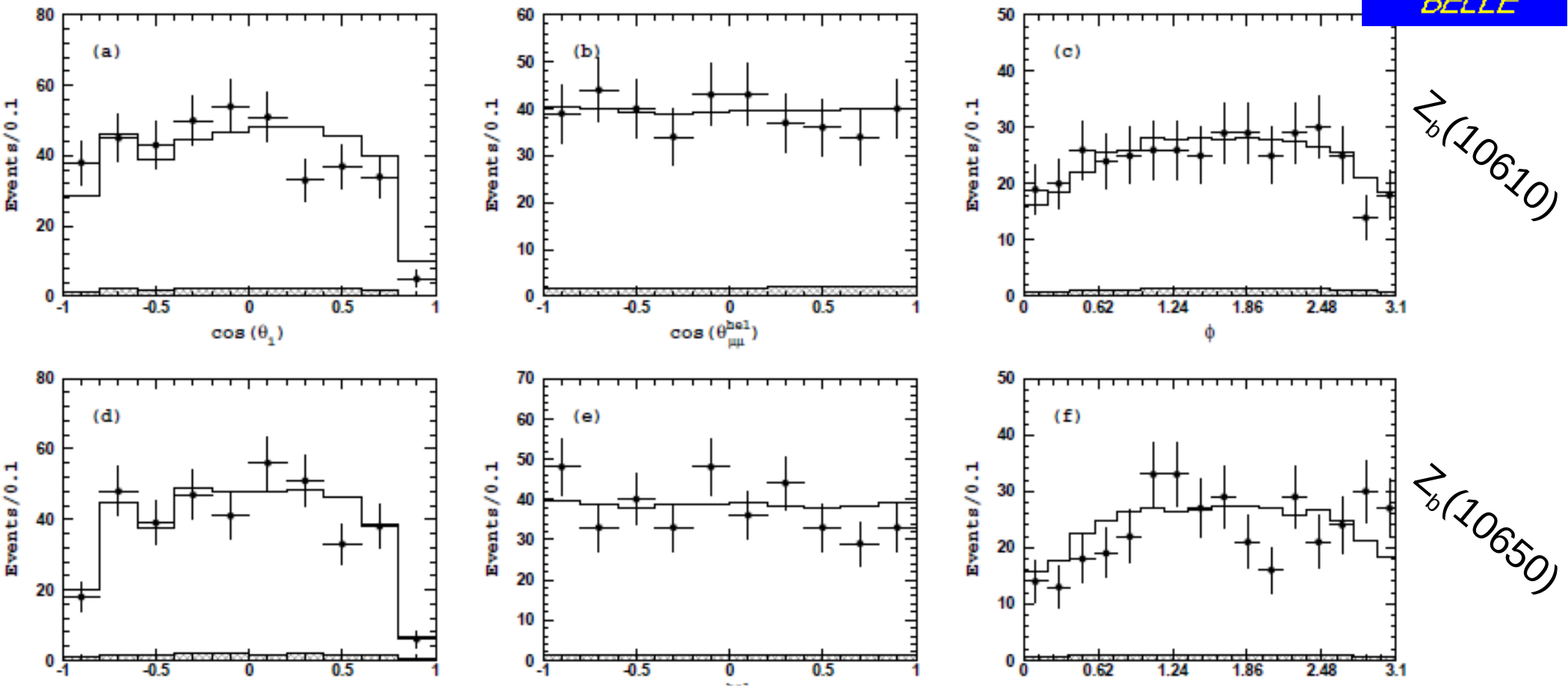


6D amplitude analysis of decays $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$

$Z_b(10650)$ / $Z_b(10610)$	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

Z_b angular analysis



Angle between prompt pion and beam axis

$\Upsilon\to\mu^+\mu^-$ helicity angle

Angle between planes formed by $(\pi^+\pi^-)$ and (Υ, beam axes)

J^P \ Mode	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
1^+	0	0	0
1^-	64	264	73
2^+	41	207	87
2^-	59	304	125

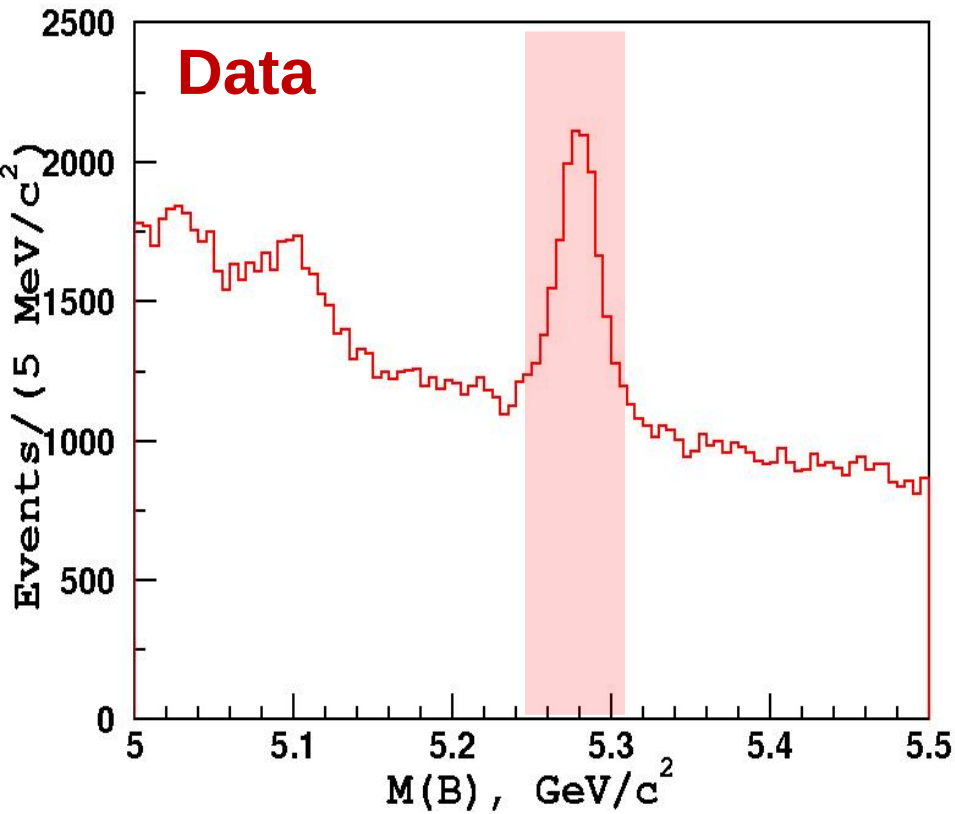
Confirms $J^P=1^+$ hypothesis

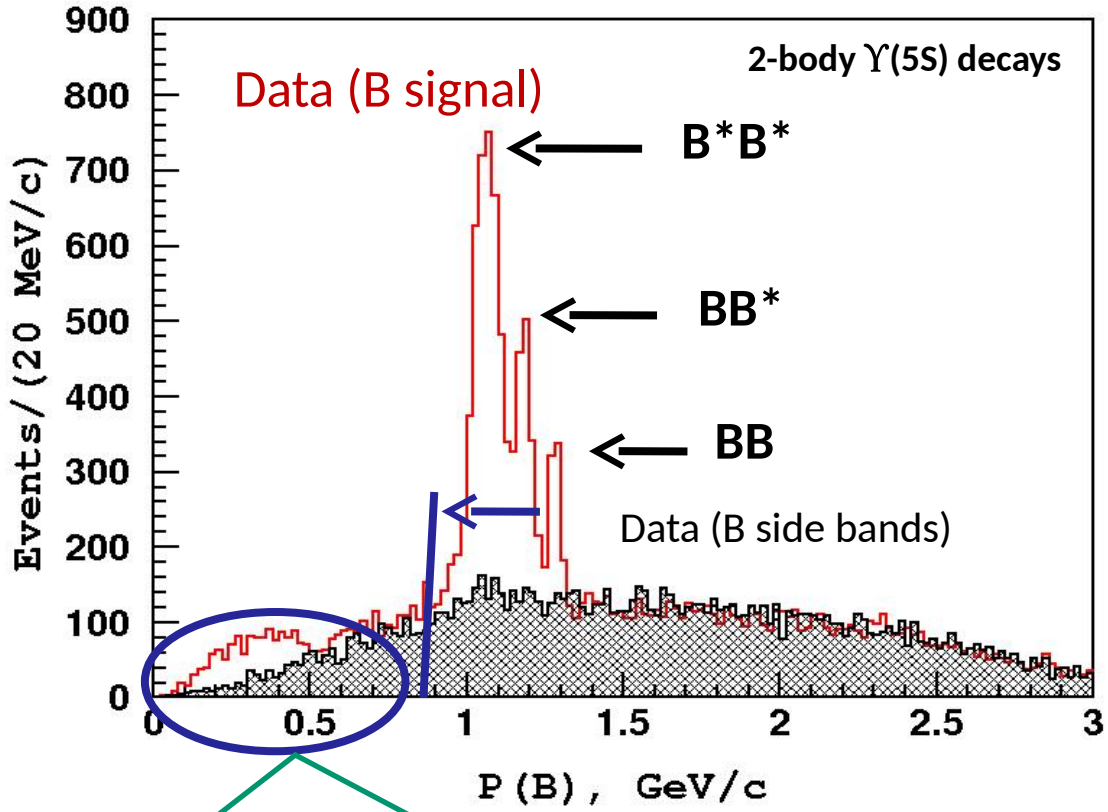
6D amplitude analysis of decays $\Upsilon(5S)\to\Upsilon(nS)\pi^+\pi^-$

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

Masses of $Z_b(10610)$ and $Z_b(10650)$ are close to BB* and B*B* threshold.

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



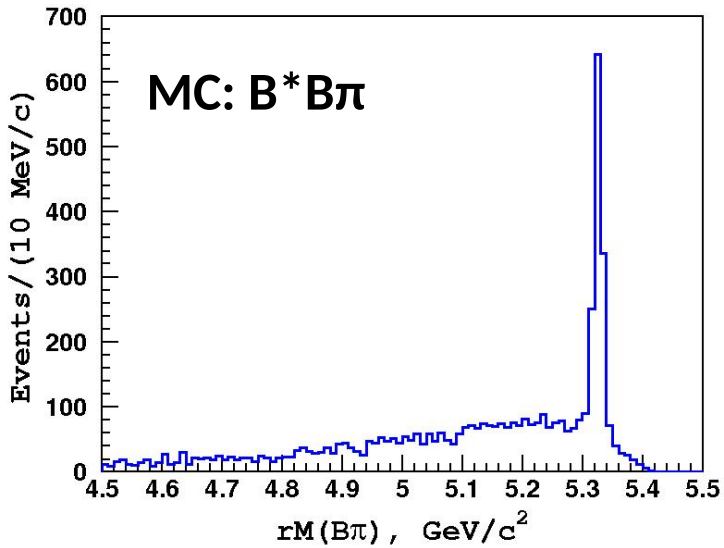


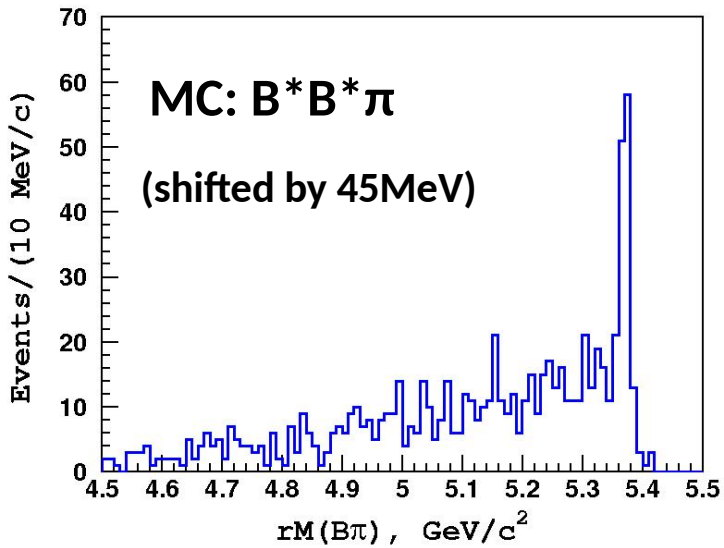
3-body $\Upsilon(5S) \to B^{(*)}B^{(*)}\pi$ decays & ISR to $\Upsilon(4S)$: $P(B)<0.9$ GeV/c

Effective B fraction:
$Br[B \to f] = 1.4 \times 10^{-3}$

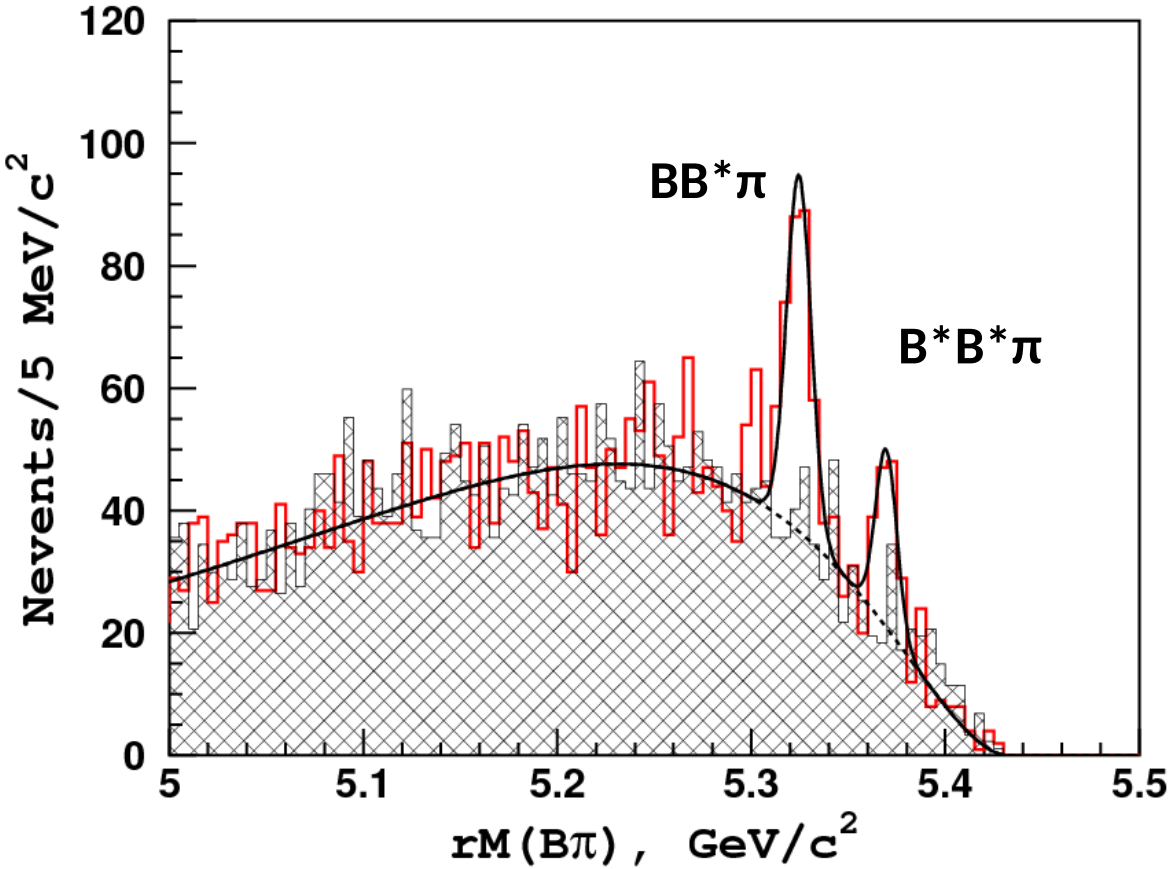
Charged B: $D^0[K\pi, K\pi\pi\pi]\pi^-$, $J/\psi[\mu\mu]\,K^-$
Neutral B: $D^+[K\pi\pi]\pi^-$, $J/\psi[\mu\mu]\,K^{*0}$, $D^{*+}[K\pi, K\pi\pi^0, K\pi\pi\pi]\pi^-$

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





Recoil mass to Bπ combinations

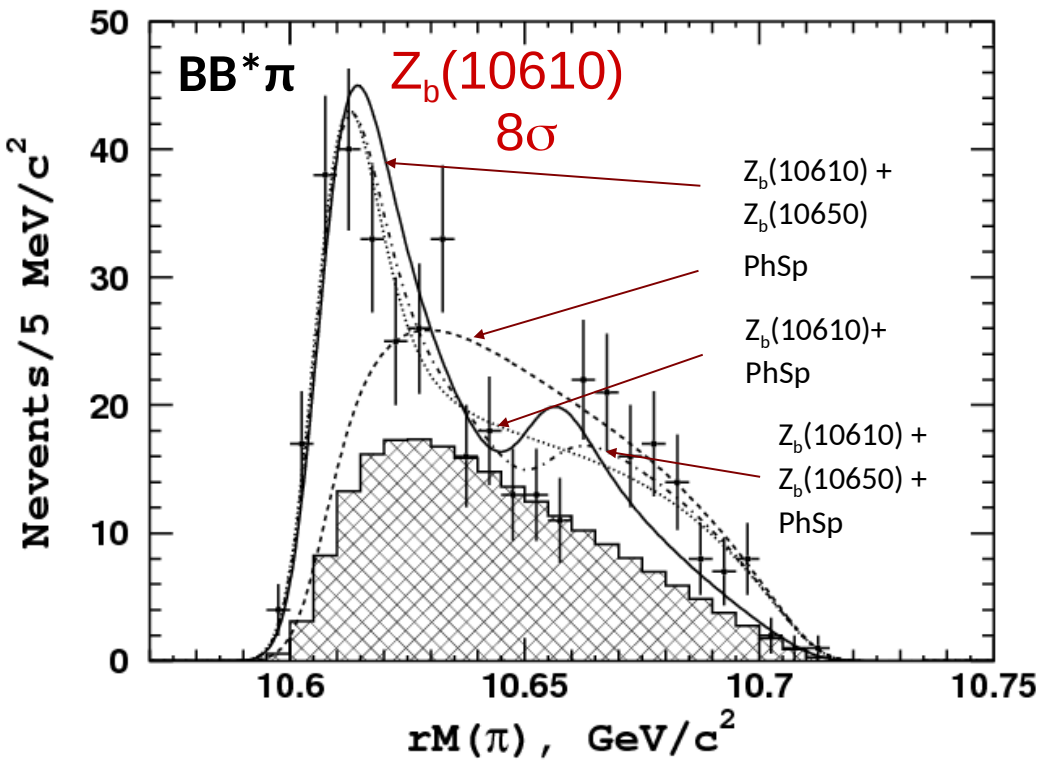


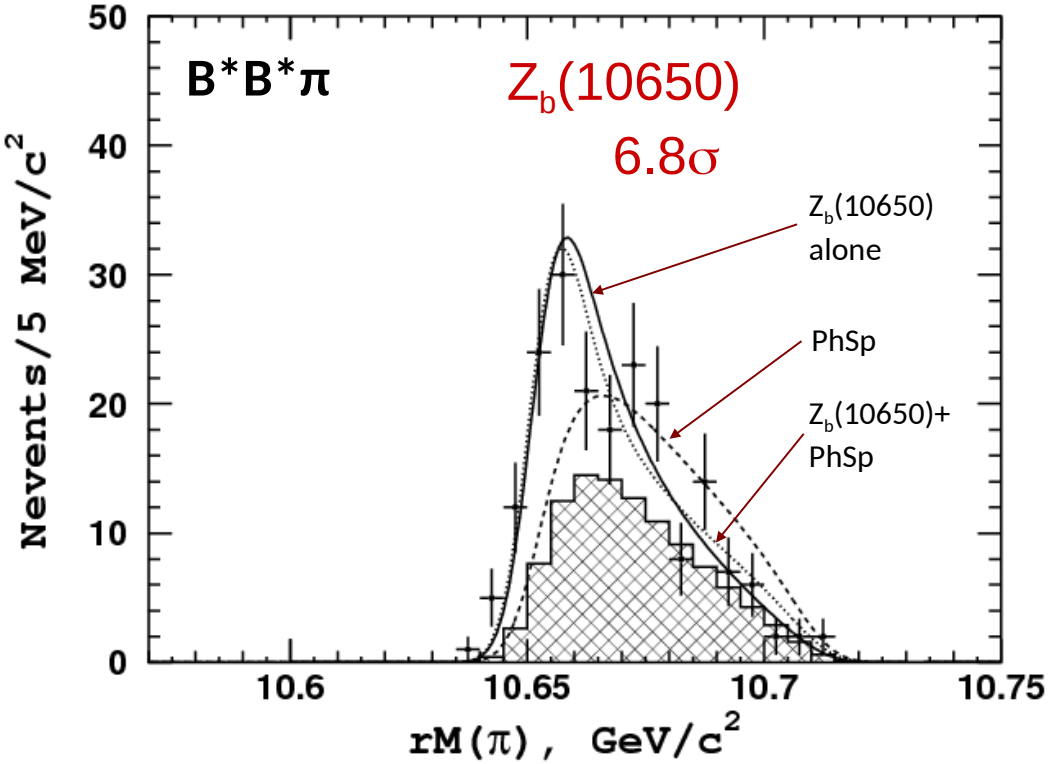
Red histogram: right charge combination Bπ;
Hatched histogram: wrong charge combination;
The curve show the fit to the data.

arXiv:1209.6450

Fit yields: N(BBπ) = 0.3 ± 14
N(BB*π) = 184 ± 19 (9.3σ) N(B*B*π) = 82 ± 11 (5.7σ)

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





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

arXiv:1209.6450

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

$BB^*\pi$ can be described by two models:

- $Z_b(10610) + Z_b(10650)$;
- $Z_b(10610)$ + non-resonant amplitude.

Z_b branching fractions

arXiv:1209.6450

$\Upsilon(5S)$ branching fractions:

$BB\pi$ < 0.60 % (at 90% CL)

$BB^*\pi$ = 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 decaying to $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and B(*)B*only:

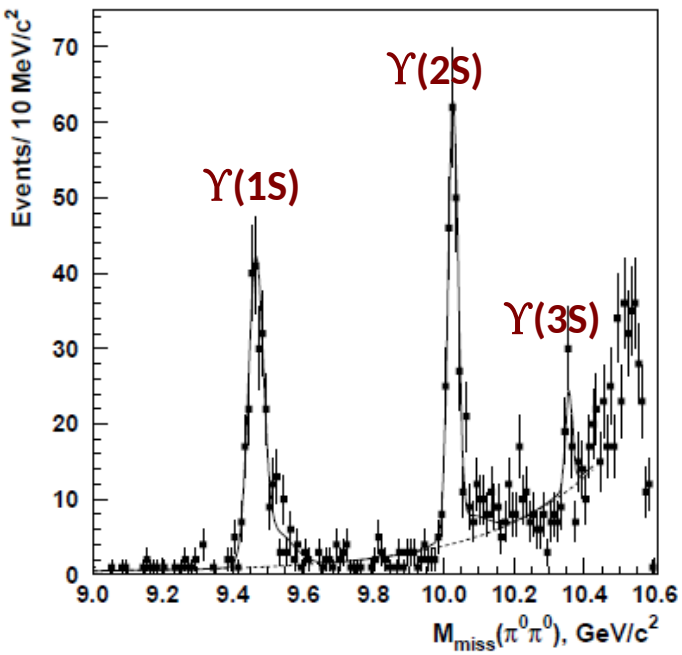
Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ±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

B(*)B* - is the dominant mode of Z_b decays

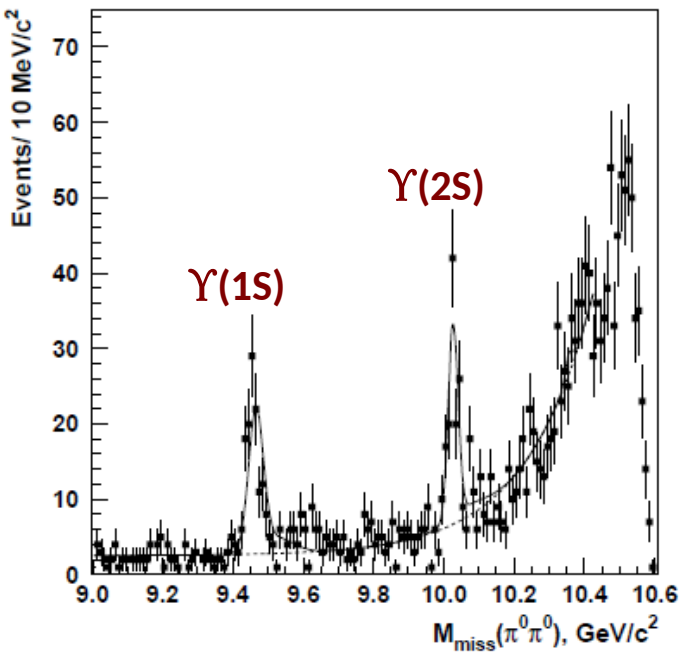
$\Upsilon(5S)\to\Upsilon(nS)\pi^0\pi^0$

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

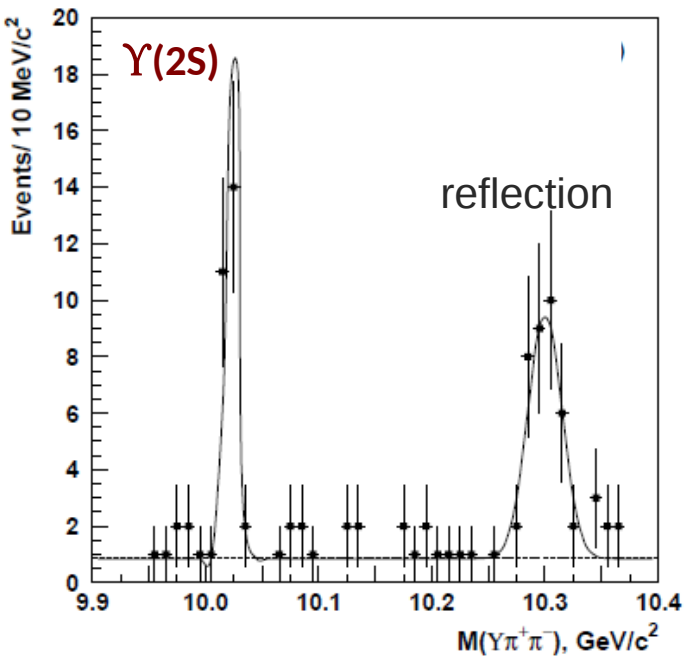
$\mu^+\mu^-\pi^0\pi^0$



$e^+e^-\pi^0\pi^0$



$\Upsilon(1S)[l^+l^-]\pi^+\pi^-\pi^0\pi^0$



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

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

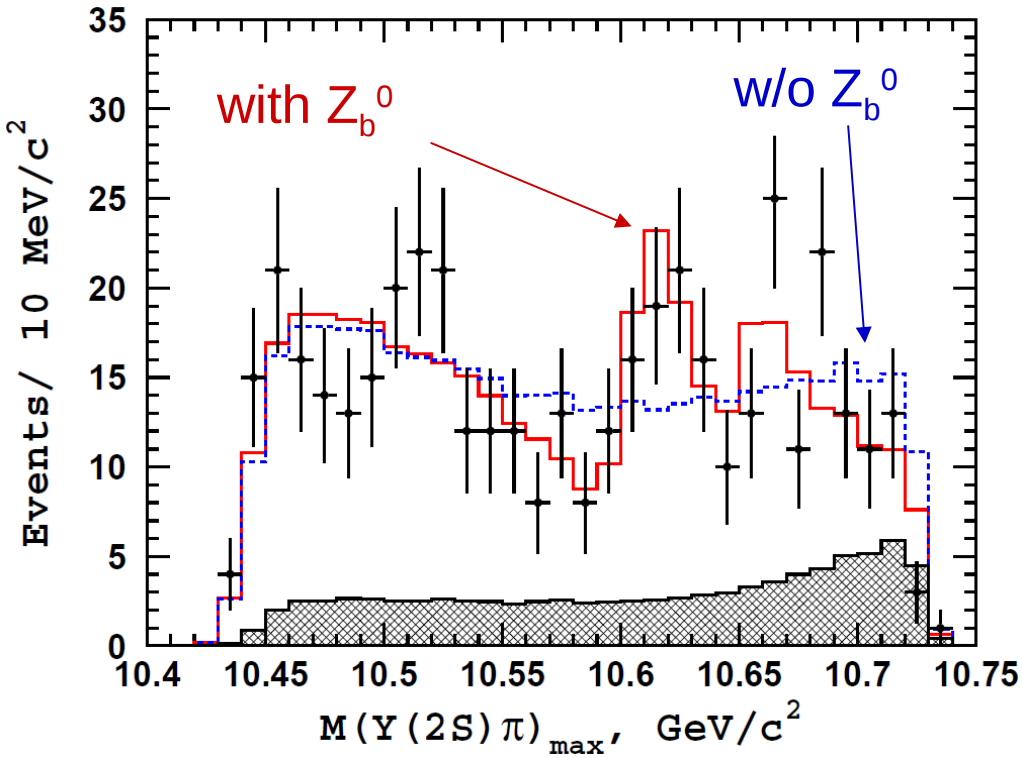
$\sigma[e^+e^-\to\Upsilon(5S)\to\Upsilon(3S)\pi^0\pi^0] = (0.98\pm0.24\pm0.19)$ pb

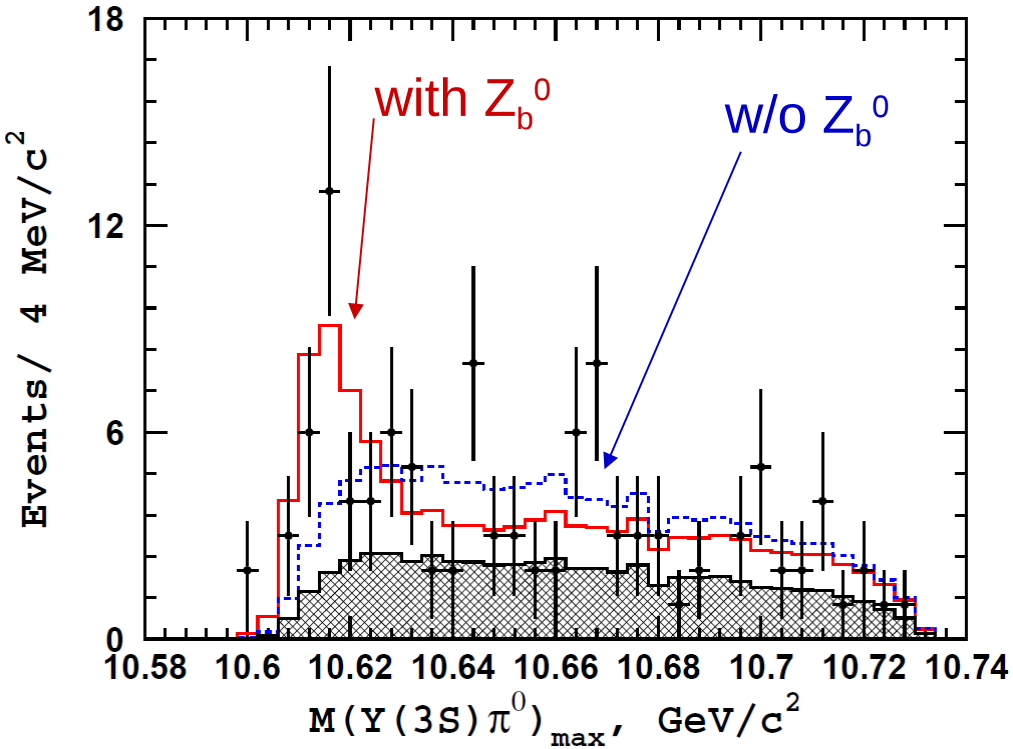
Consistent with ½ of $\Upsilon(nS)\pi^+\pi^-$

Phys. Rev. D 88, 052016 (2013)

$\Upsilon(2,3S)\pi^0\pi^0$ Dalitz analysis

Phys. Rev. D 88, 052016 (2013)

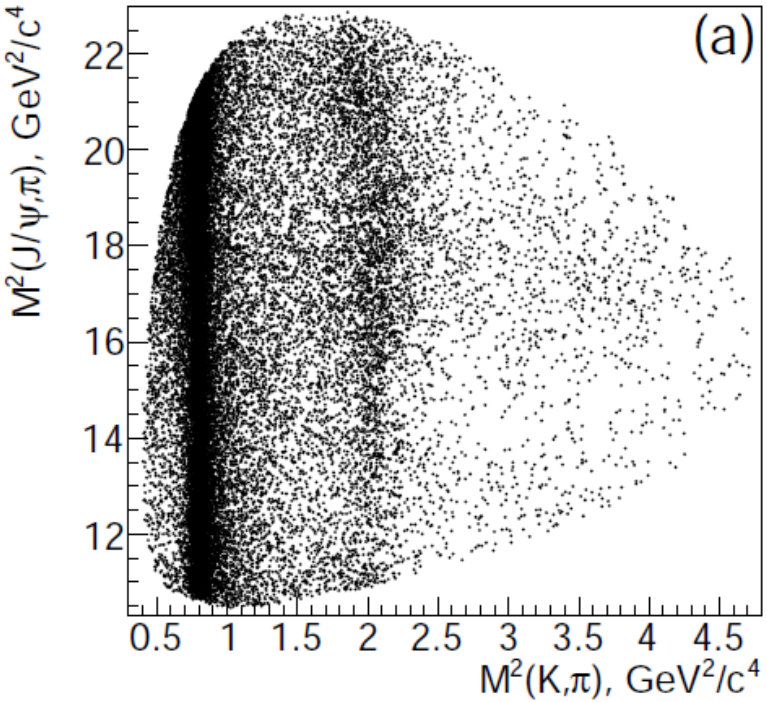


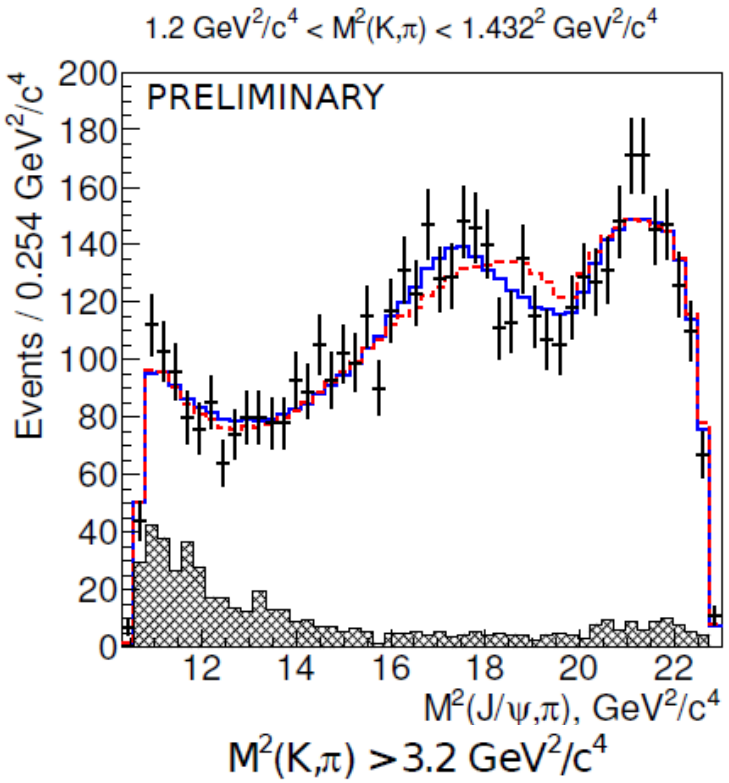


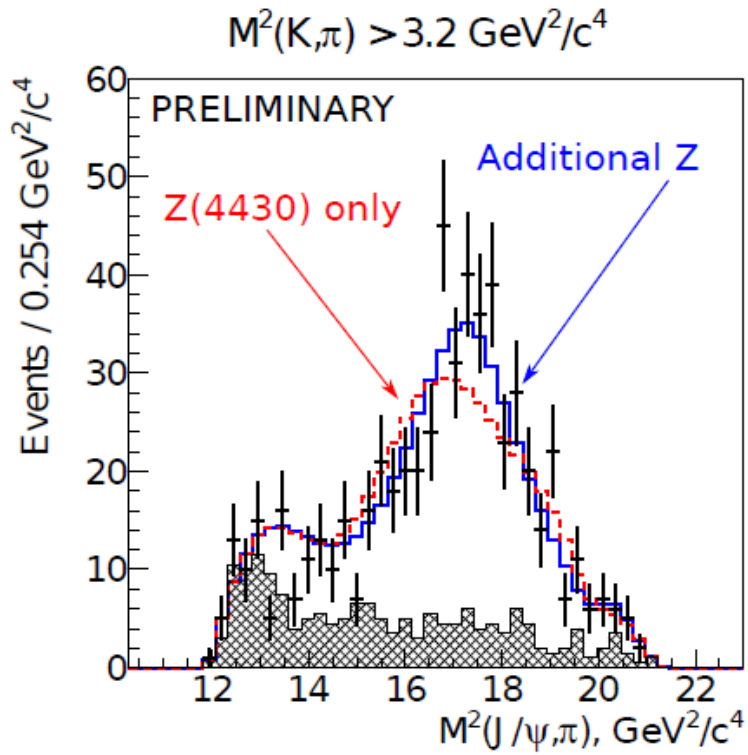
- Z_b^0 resonant structure has been observed in $\Upsilon(2S)\pi^0\pi^0$ and $\Upsilon(3S)\pi^0\pi^0$
- Statistical significance of $Z_b^0(10610)$ signal is 6.5σ including systematics
- $Z_b^0(10650)$ signal is not significant (~2σ), not contradicting with its existence
- $Z_b^0(10610)$ mass from the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

Phys. Rev. D 90, 112009 (2014)

$B^0 \to J/\psi\, K^- \pi^+$

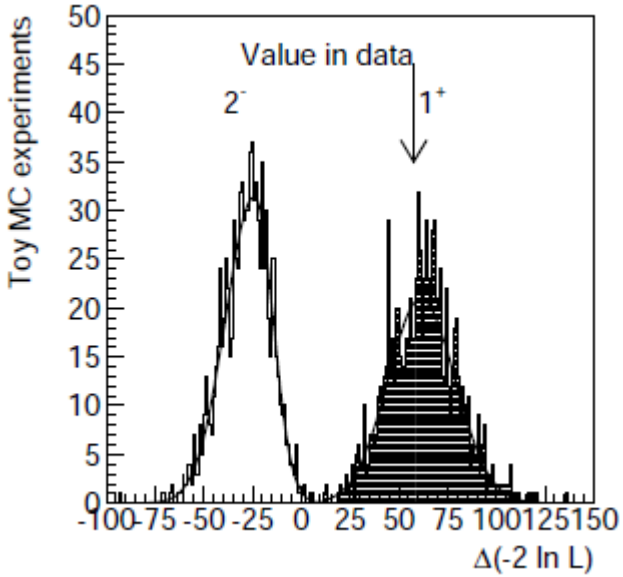






- 4D amplitude analysis
- 10 K* resonances, $Z^+(4430)$, $Z^+(\text{new})$
- 6.6σ significance
- $M = 4196\ ^{+31}_{-29}\ ^{+17}_{-13}\ \text{MeV}/c^2$
- $G = 370 \pm 70\ ^{+70}_{-132}\ \text{MeV}$
- $J^P = 1^+$

Observation of $Z^+(4200)$



Exclusion levels of other spin-parity hypothesis

Model	0^-	1^-	2^-	2^+
Without $K^*(1680)$	8.5σ	8.5σ	8.0σ	9.0σ
Without $K_0^*(1950)$	8.4σ	8.8σ	7.3σ	8.9σ
LASS	6.1σ	7.4σ	4.4σ	7.0σ
Free masses and widths	7.6σ	7.9σ	5.9σ	7.8σ
Free r	7.4σ	8.7σ	7.5σ	9.2σ
Nonresonant ampl. (S)	7.6σ	8.1σ	7.2σ	8.5σ
Nonresonant ampl. (S,P)	7.4σ	8.1σ	7.2σ	8.4σ
Nonresonant ampl. (S,P,D)	7.2σ	8.1σ	7.1σ	8.4σ

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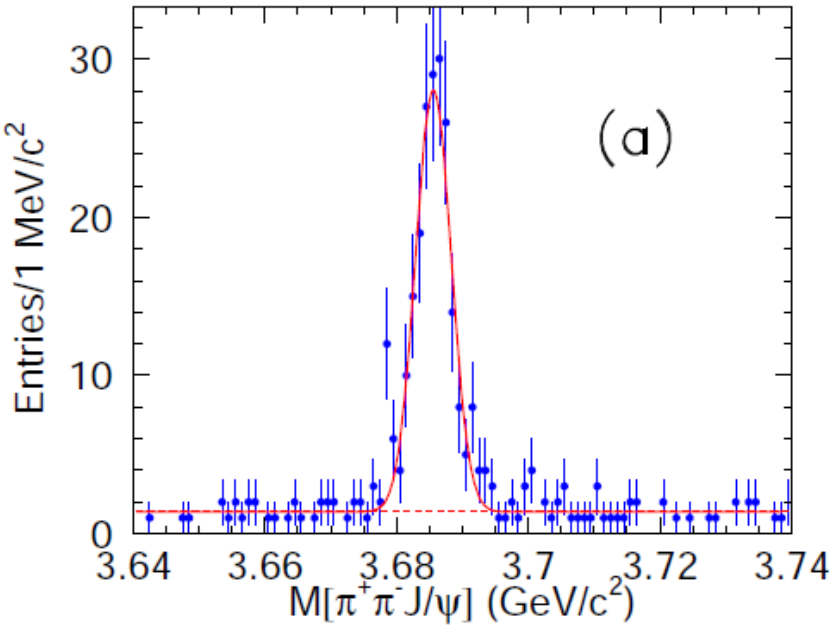
$J^P=1^+$, other J^P are excluded

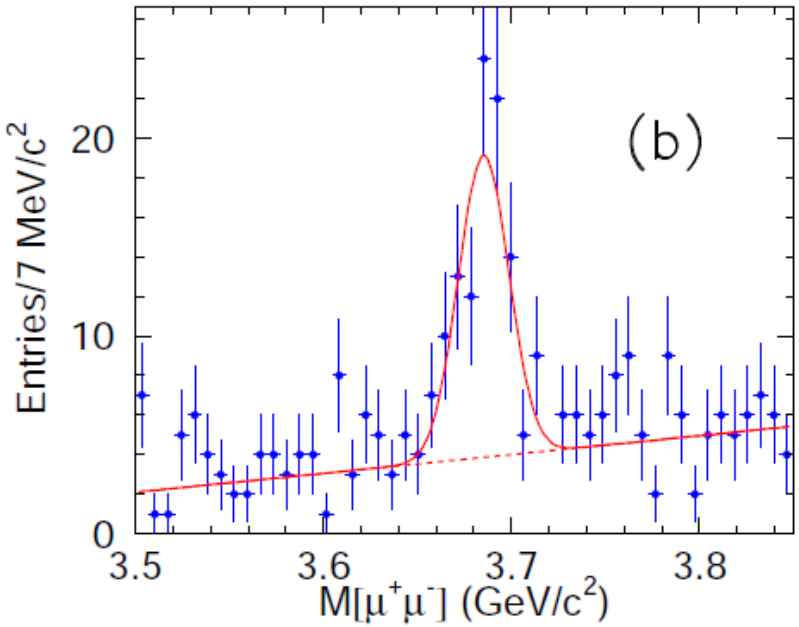
TABLE III. The fit fractions and significances of all resonances in the default model ($J^P = 1^+$).

Resonance	Fit fraction	Significance (local)
$K_0^*(800)$	$(7.1^{+0.7}_{-0.5})\%$	22.5σ
$K^*(892)$	$(69.0^{+0.6}_{-0.5})\%$	166.4σ
$K^*(1410)$	$(0.3^{+0.2}_{-0.1})\%$	4.1σ
$K_0^*(1430)$	$(5.9^{+0.6}_{-0.4})\%$	22.0σ
$K_2^*(1430)$	$(6.3^{+0.3}_{-0.4})\%$	23.5σ
$K^*(1680)$	$(0.3^{+0.2}_{-0.1})\%$	2.7σ
$K_3^*(1780)$	$(0.2^{+0.1}_{-0.1})\%$	3.8σ
$K_0^*(1950)$	$(0.1^{+0.1}_{-0.1})\%$	1.2σ
$K_2^*(1980)$	$(0.4^{+0.1}_{-0.1})\%$	5.3σ
$K_4^*(2045)$	$(0.2^{+0.1}_{-0.1})\%$	3.8σ
$Z_c(4430)^+$	$(0.5^{+0.4}_{-0.1})\%$	5.1σ
$Z_c(4200)^+$	$(1.9^{+0.7}_{-0.5})\%$	8.2σ

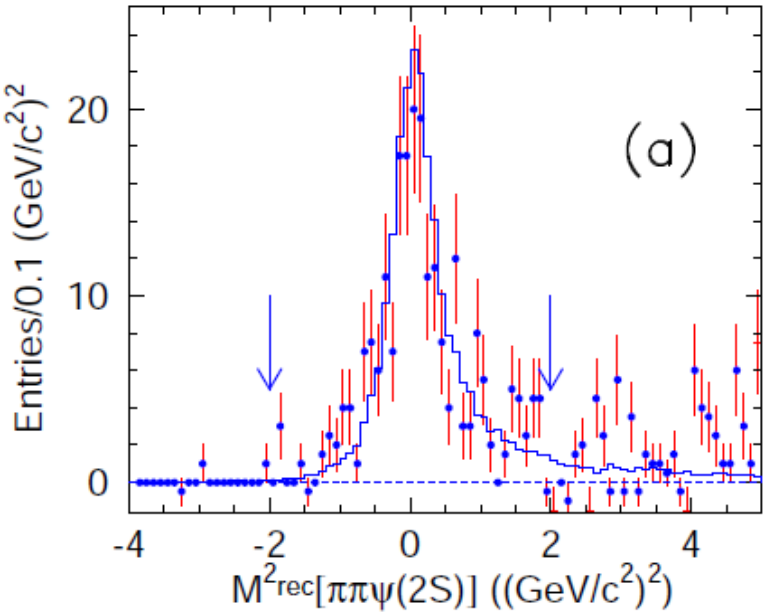
$e^+e^- \to \psi(2S)\,\pi^+\pi^-$ via ISR

New





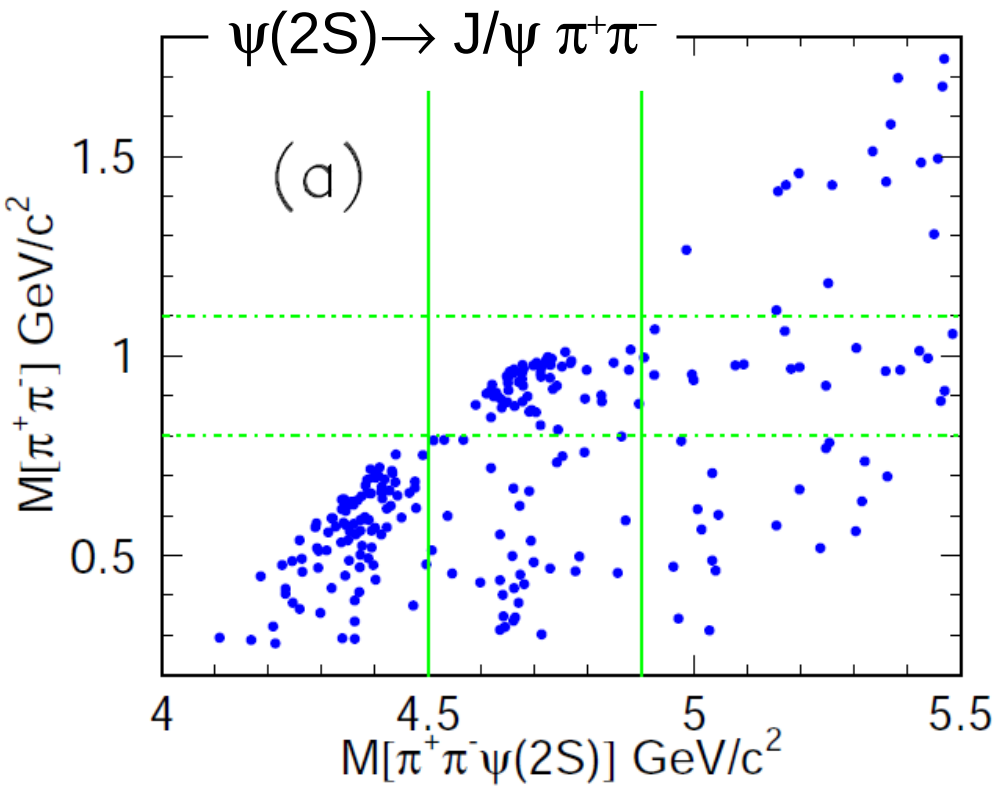
- $\psi(2S) \to J/\psi\pi^+\pi^-$ and $\mu^+\mu^-$
- $M^2_{rec}[\psi(2S)\pi^+\pi^-] < 2\ (GeV/c^2)^2$

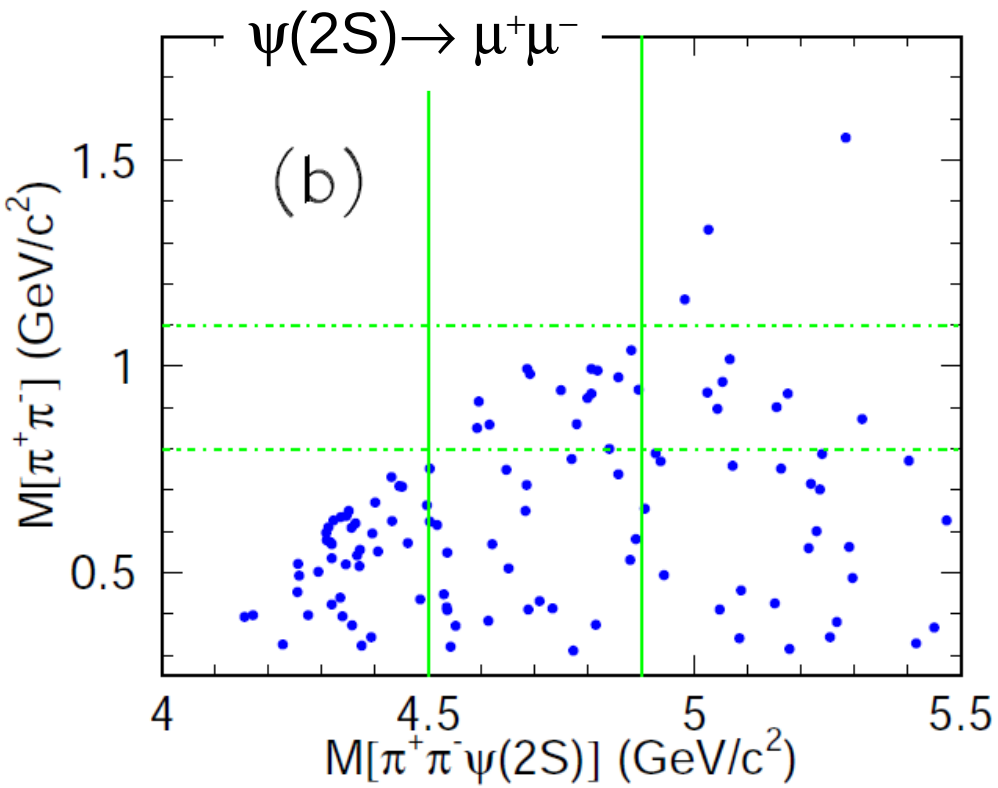


arXiv:1410.7641

$e^+e^- \to \psi(2S)\,\pi^+\pi^-$ via ISR intermediate states

New

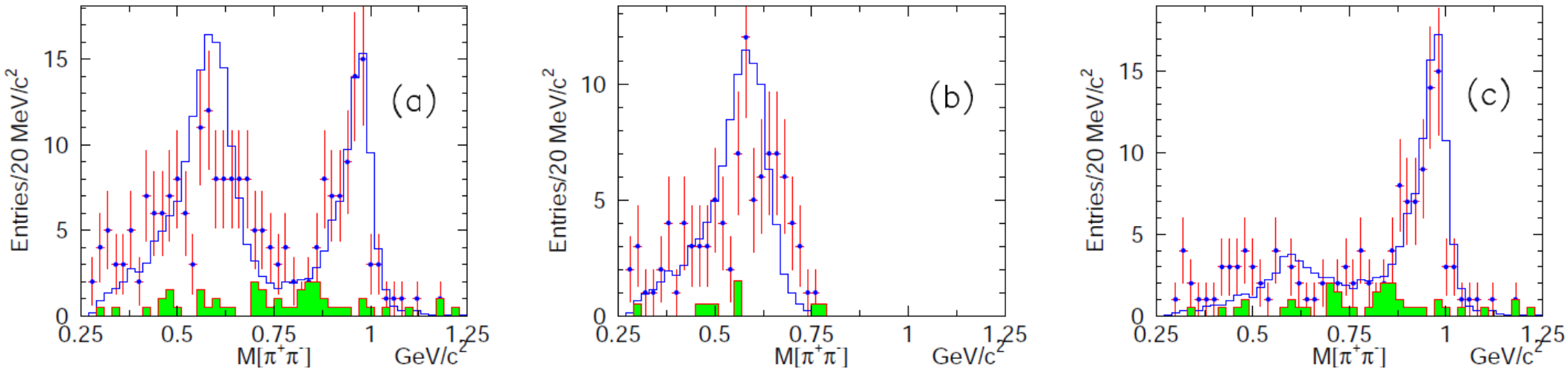




arXiv:1410.7641

$e^+e^- \to \psi(2S)\,\pi^+\pi^-$ via ISR
$M[\pi^+\pi^-]$

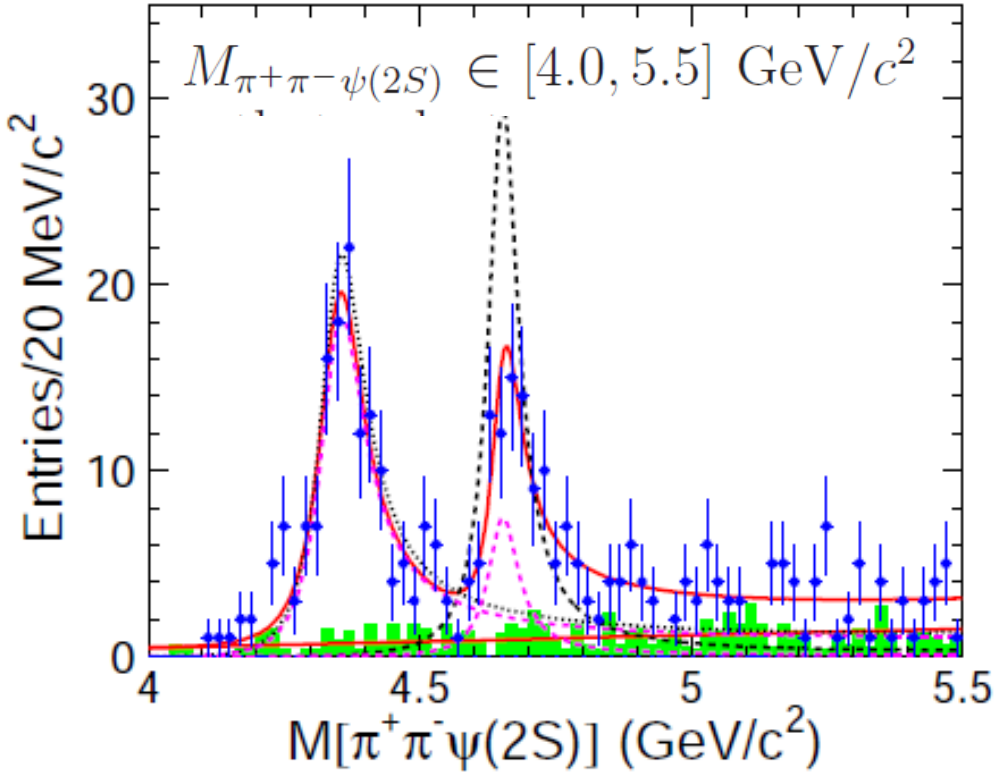
New



arXiv:1410.7641

$e^+e^- \to \psi(2S)\,\pi^+\pi^-$ via ISR

New



fit to $M[\psi(2S)\pi^+\pi^-]$

Two solutions when fitting by

Y(4360) and Y(4660)

χ^2 / n.d.f. = 18.7 / 21

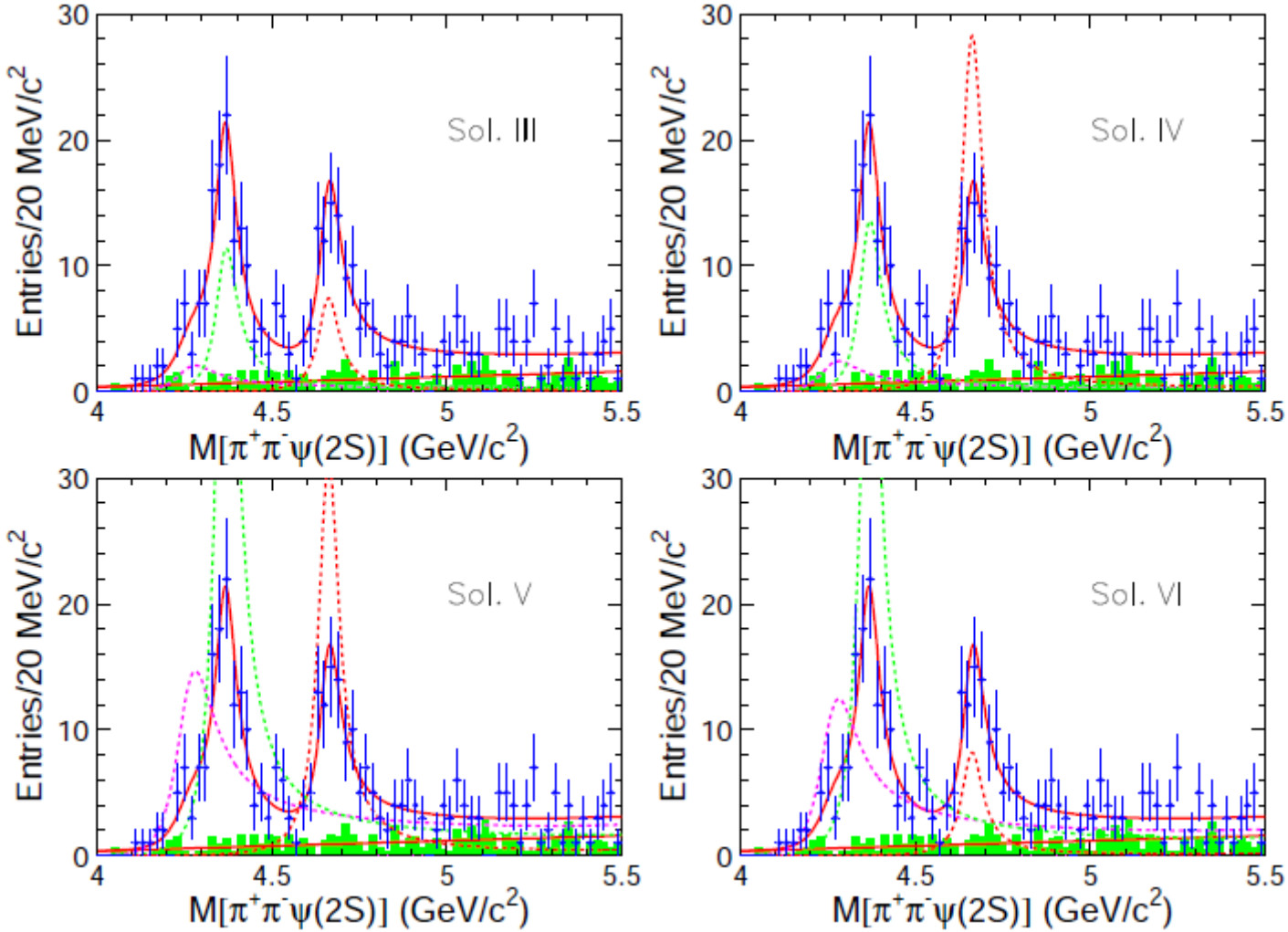
Parameters	Solution I	Solution II
$M_{Y(4360)}$	$4347 \pm 6 \pm 3$	
$\Gamma_{Y(4360)}$	$103 \pm 9 \pm 5$	
$\mathcal{B}[Y(4360) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4360)}$	$9.2 \pm 0.6 \pm 0.6$	$10.9 \pm 0.6 \pm 0.7$
$M_{Y(4660)}$	$4652 \pm 10 \pm 11$	
$\Gamma_{Y(4660)}$	$68 \pm 11 \pm 5$	
$\mathcal{B}[Y(4660) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4660)}$	$2.0 \pm 0.3 \pm 0.2$	$8.1 \pm 1.1 \pm 1.0$
ϕ	$32 \pm 18 \pm 20$	$272 \pm 8 \pm 7$

arXiv:1410.7641

$e^+e^- \to \psi(2S)\,\pi^+\pi^-$ via ISR

New

arXiv:1410.7641



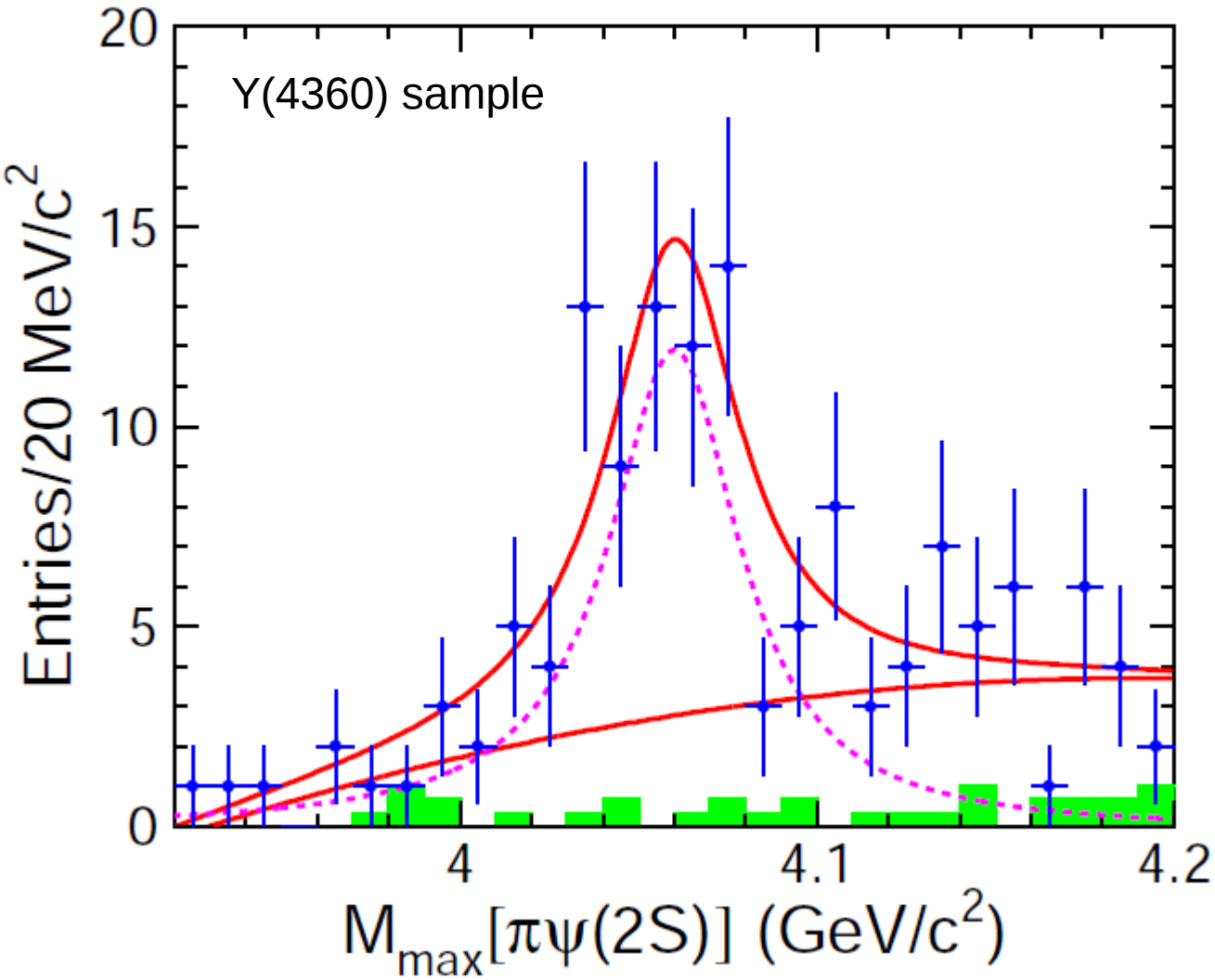
Four solutions when Y(4260) is included

χ^2 / n.d.f. = 18.7 / 21 Y(4260) significance is 2.4 σ

$e^+e^- \to \psi(2S)\,\pi^+\pi^-$ via ISR

New

search for Zc



Evidence for a new charged Zc state

3.5 σ significance

$M = 4054 \pm 3 \pm 1$ MeV/c^2

$\Gamma = 45 \pm 11 \pm 6$ MeV

arXiv:1410.7641

Summary

- Neutral $Z_b^0(10610)$ has been observed in amplitude analysis of $\Upsilon(5S) \to \Upsilon(5S)\ \pi^0\pi^0$
- 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 BB^* and B^*B^*. These modes are found to be dominant for Z_b^+ decays.

- A new charged charmonium-like state, $Z^+(4200)$ has been observed in amplitude analysis of $B \to J/\psi\ K^-\ \pi^+$ decay.
- New An evidence for a new charged charmonium-like state, $Z^+(4050)$ has been obtained in amplitude analysis of $e^+e^- \to \psi(2S)\ \pi^+\pi^-$ decay.

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