QWG meeting, 22-26 April 2013, IHEP, Beijing

Charged bottomonium-like states at Belle

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ITEP, Moscow

Content

Introduction to Z_b states

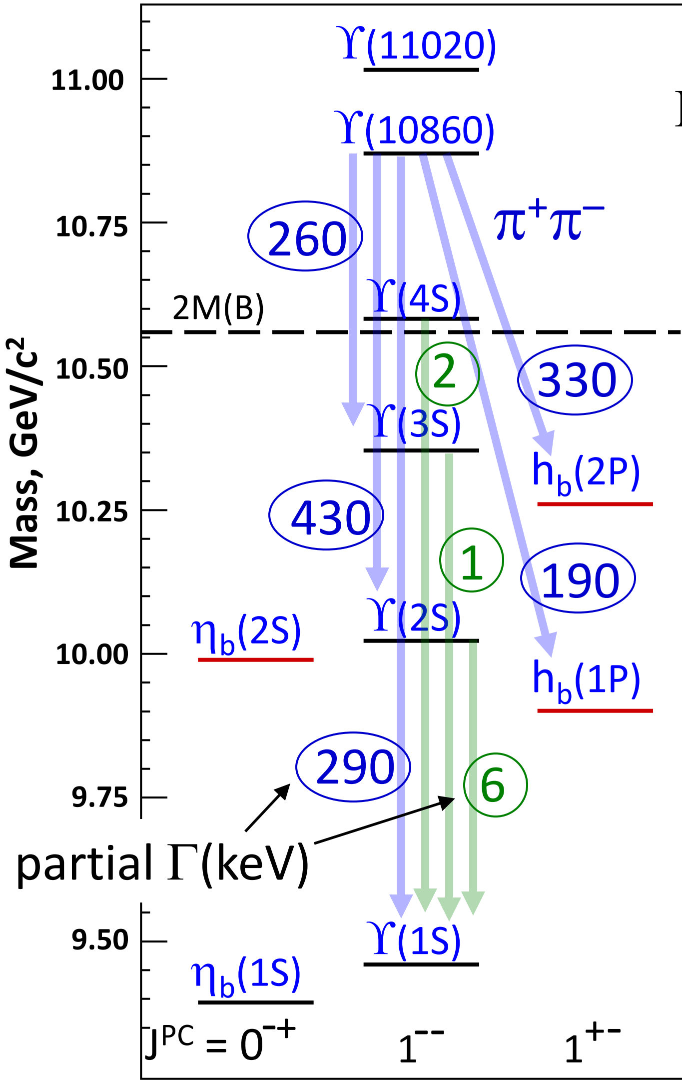
PRELIMINARY

Observation of $Z_b \rightarrow B\bar{B}^*$, $B^*\bar{B}^*$

Dalitz plot analysis of $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^0\pi^0$

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

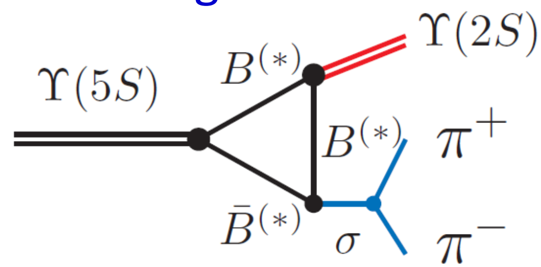
Anomalies in $\Upsilon(5S) \to (b\bar{b})\,\pi^+\pi^-$ transitions



Belle PRL100,112001(2008)

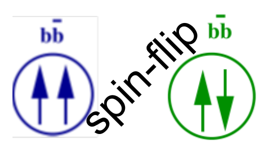
$$\Gamma[\Upsilon(\mathbf{5S}) \to \Upsilon(1,2,3S)\,\pi^+\pi^-] \overset{\sim 100}{>>} \Gamma[\Upsilon(\mathbf{2,3,4S}) \to \Upsilon(1S)\,\pi^+\pi^-]$$

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



Belle PRL108,032001(2012)

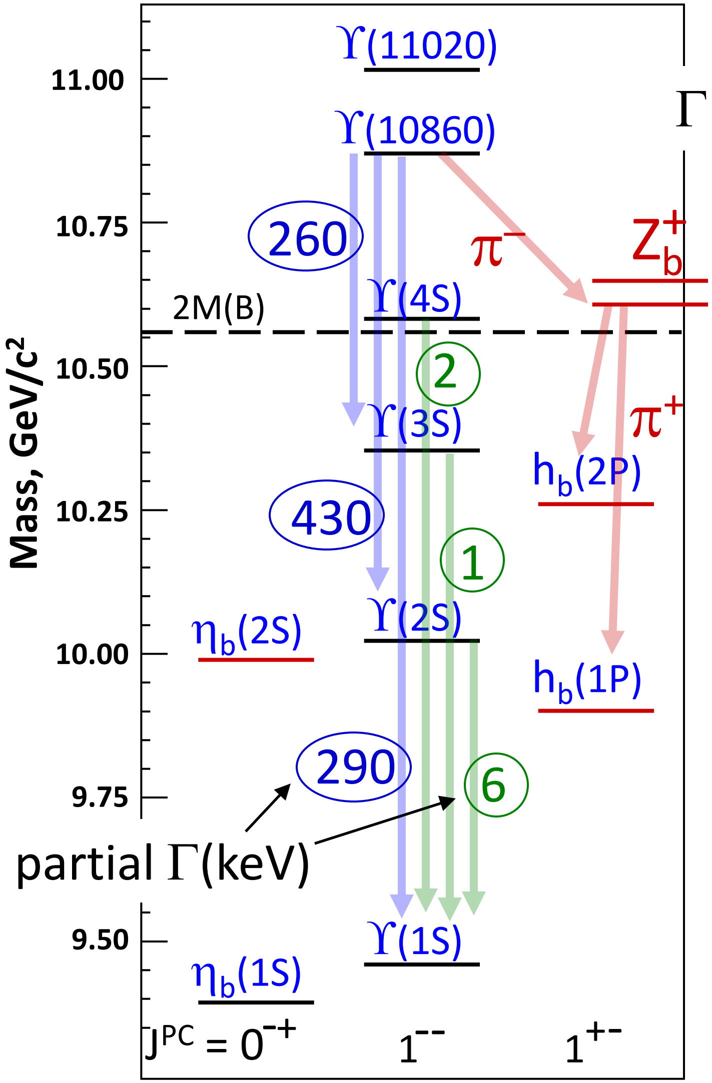
$\Upsilon(5S) \to h_b(1,2P)\,\pi^+\pi^-$ are **not suppressed**



~~Heavy Quark Symmetry~~

expect suppression $(\Lambda_{QCD}/m_b)^2 \sim 10^{-2}$

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



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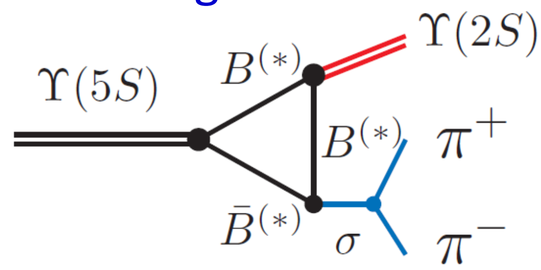

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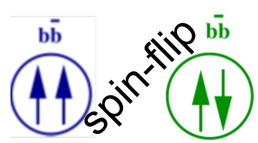


~~Heavy Quark Symmetry~~

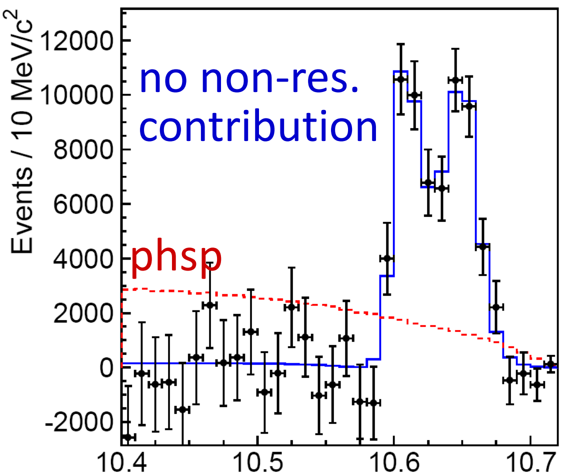
expect suppression $(\Lambda_{QCD}/m_b)^2 \sim 10^{-2}$

$h_b(nP)$ production mechanism could be exotic.

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

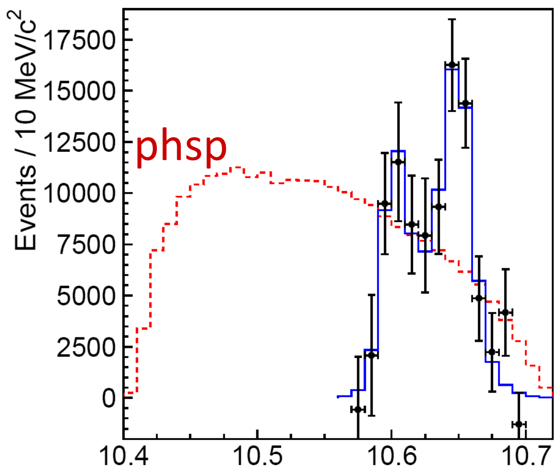
Belle PRL108,122001(2012)

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



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

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



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

Two peaks in all 5 modes

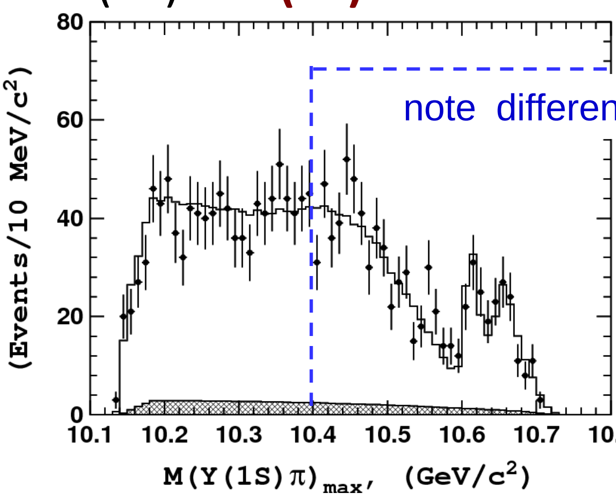
minimal quark content

$|\, b\bar{b}u\bar{d}\, \rangle$

flavor-exotic states

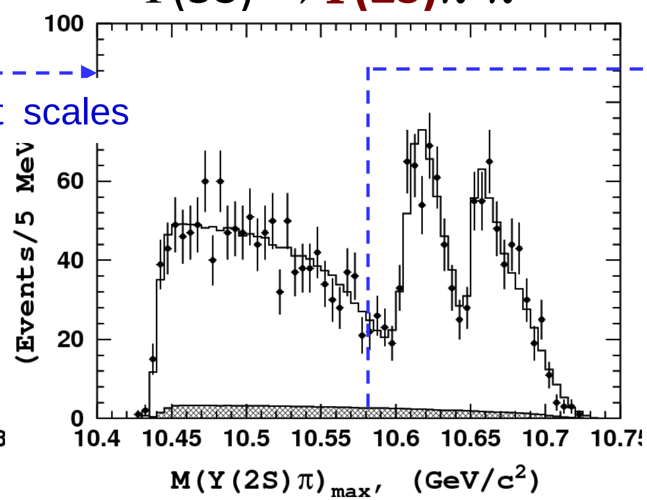
Dalitz plot analysis

$\Upsilon(5S) \to \mathbf{\Upsilon(1S)}\pi^+\pi^-$

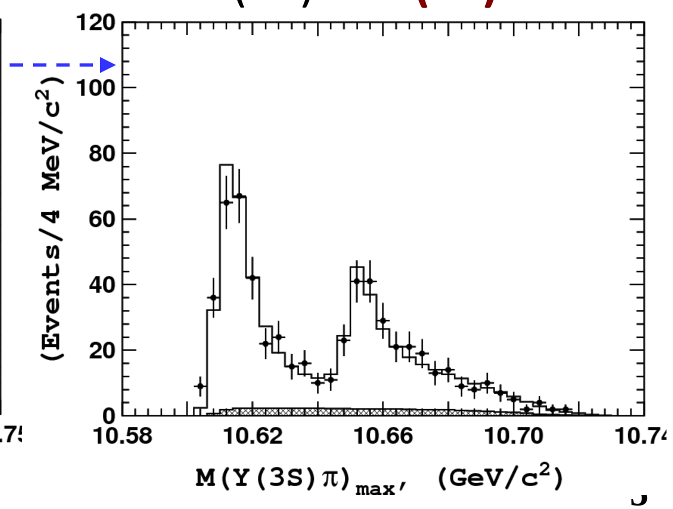


note different scales

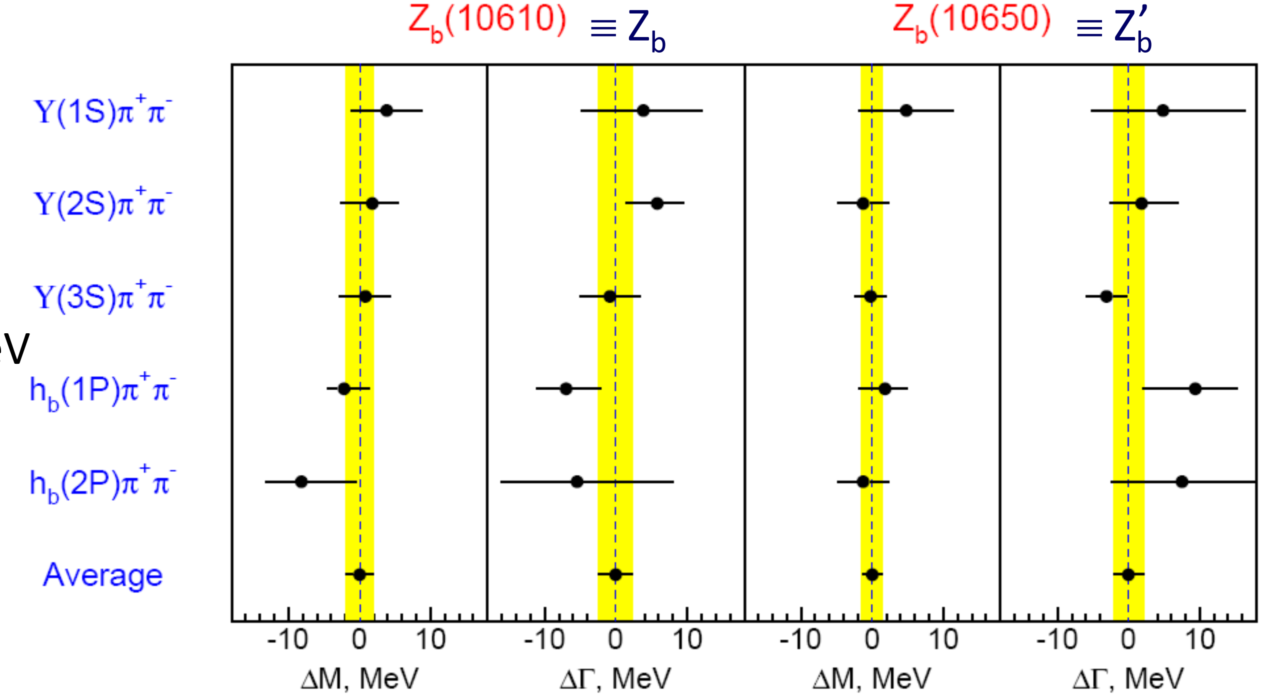
$\Upsilon(5S) \to \mathbf{\Upsilon(2S)}\pi^+\pi^-$



$\Upsilon(5S) \to \mathbf{\Upsilon(3S)}\pi^+\pi^-$



Fit results



Average over 5 channels

$M_1 = 10607.2 \pm 2.0$ MeV

$\Gamma_1 = 18.4 \pm 2.4$ MeV

$M_{Zb} - (M_B + M_{B*}) = +\,2.6 \pm 2.1$ MeV

$M_2 = 10652.2 \pm 1.5$ MeV

$\Gamma_2 = 11.5 \pm 2.2$ MeV

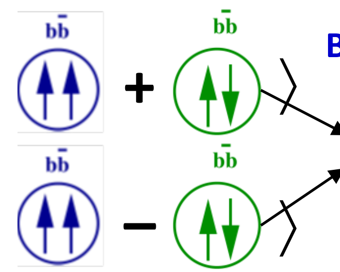
$M_{Zb'} - 2M_{B*} = +\,1.8 \pm 1.7$ MeV

Angular analysis ⇒ both states are $J^P = 1^+$ Decays ⇒ $I^G = 1^+$ (C= – for Z_b^0)

Proximity to thresholds favors molecule over tetraquark

$Z_b \sim |\,B\ B^*\,\rangle = |$ S-wave

$Z_b' \sim |\,B^*B^*\,\rangle = |$



Bondar et al, PRD84,054010(2011)

$h_b(mP)\pi$ not suppressed

Phase btw Z_b and Z_b' amplitudes is **~0°** for $\Upsilon(nS)\pi\pi$ and **~180°** for $h_b(mP)\pi\pi$

Fit results

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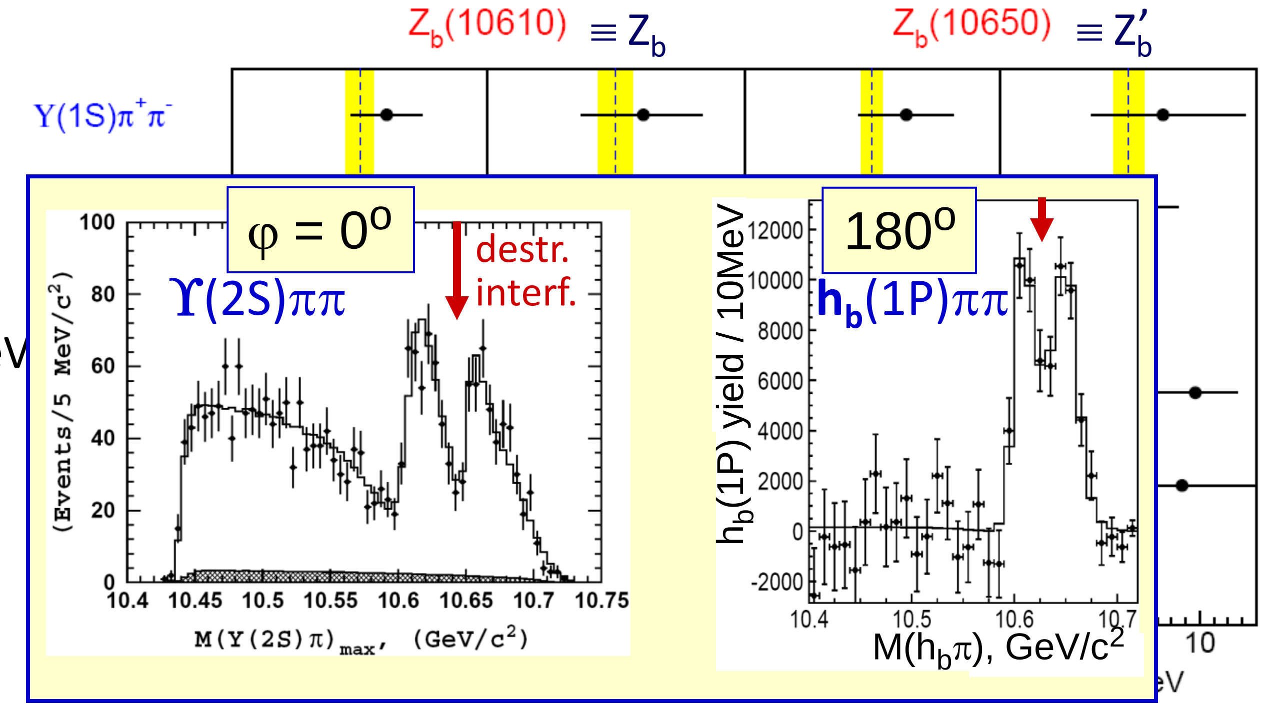

Angular analysis $\Rightarrow$ both states are $J^P = 1^+$ Decays $\Rightarrow$ $I^G = 1^+$ (C= – for Z_b^0)

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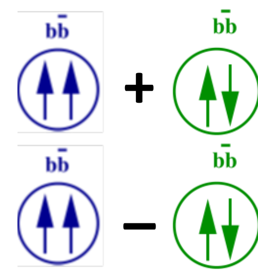
$Z_b \sim |\,B\;B^*\,\rangle = |$  $\rangle$
S-wave
$Z_b' \sim |\,B^*B^*\,\rangle = |$ $\rangle$

Bondar et al, PRD84,054010(2011)

$h_b(mP)\pi$
not suppressed

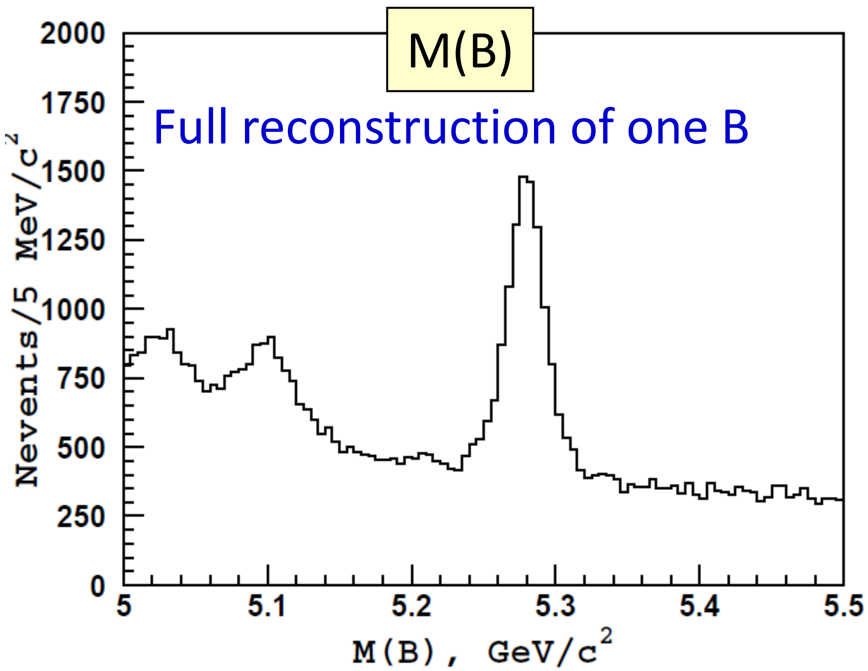
Phase btw Z_b and Z_b' amplitudes is **~0°** for $\Upsilon(nS)\pi\pi$ and **~180°** for $h_b(mP)\pi\pi$

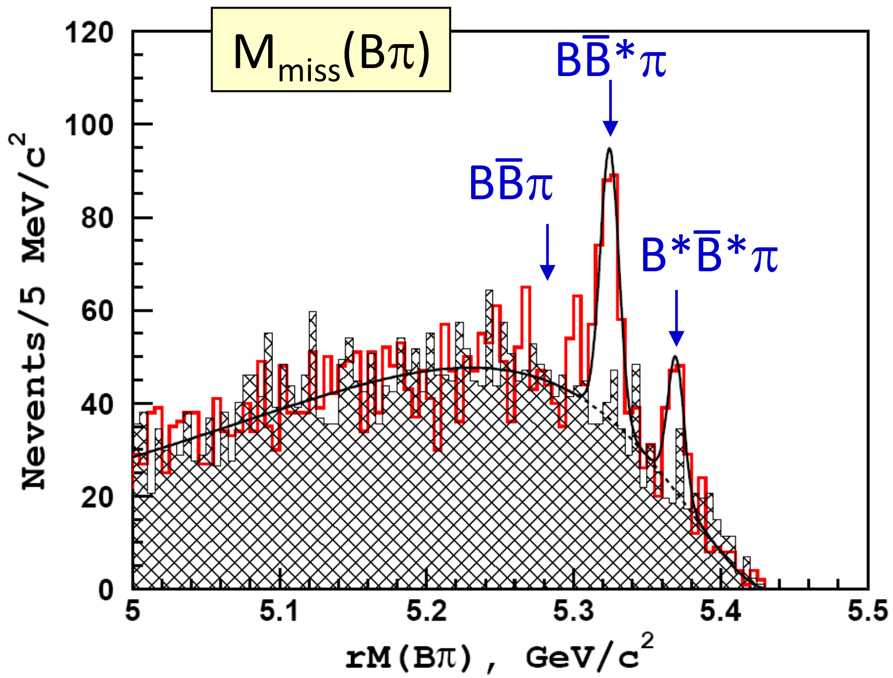
Properties of Z_b states are consistent with molecular structure.

Observation of $Z_b \to B\bar{B}^*$, $B^*\bar{B}^*$

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

arXiv:1209.6450



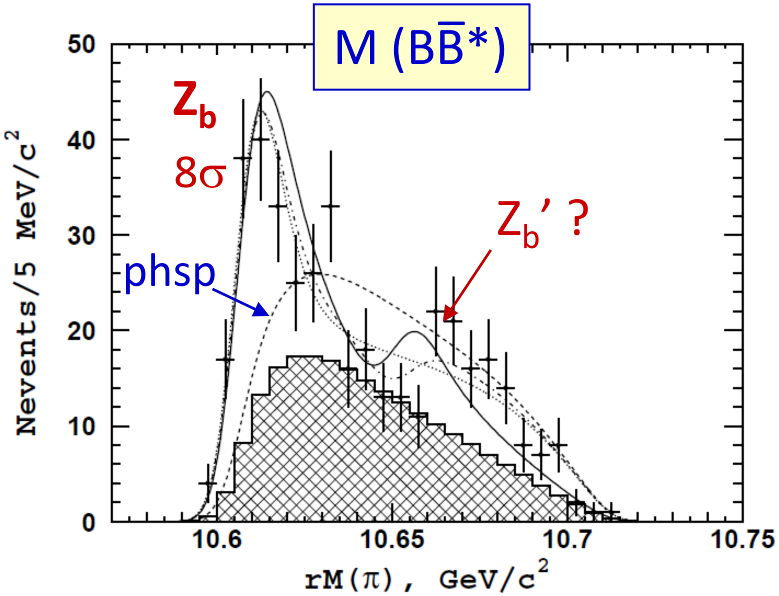


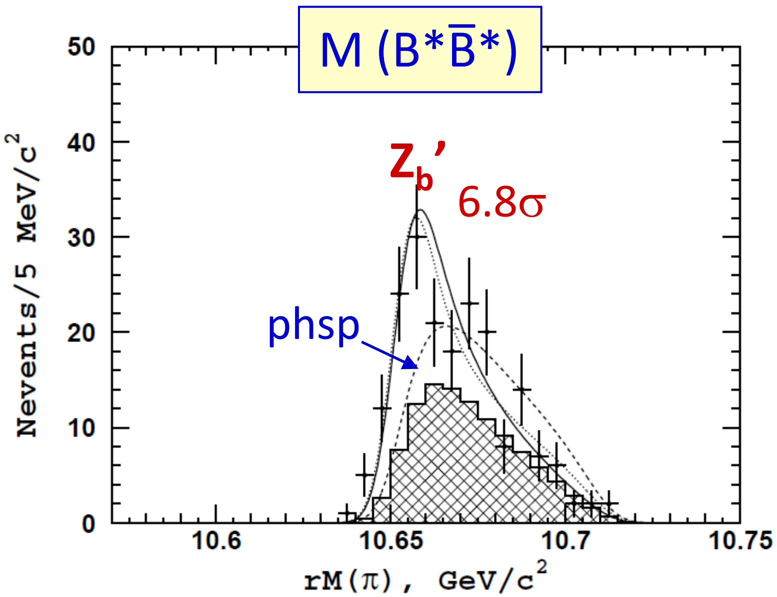
BF[$\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi$]	Belle 121.4 fb^{-1}	significance	PRD81,112003(2010) Belle 23.6 fb^{-1}
$B\bar{B}$	<0.60 % at 90% C.L.		(0 ± 1.2) %
$B\bar{B}^* + B\bar{B}^*$	$(4.25 \pm 0.44 \pm 0.69)$ %	9.3σ	(7.3 ± 2.3) %
$B^*\bar{B}^*$	$(2.12 \pm 0.29 \pm 0.36)$ %	5.7σ	(1.0 ± 1.4) %

First observation, consistent with previous measurement.

Observation of $Z_b \to B\bar{B}^*$ and $Z_b' \to B^*\bar{B}^*$

arXiv:1209.6450





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

$BF[Z_b' \to B\bar{B}^*] = (25 \pm 10)\%$ insignificant

If included, other fractions of Z_b' are reduced by 1.33.

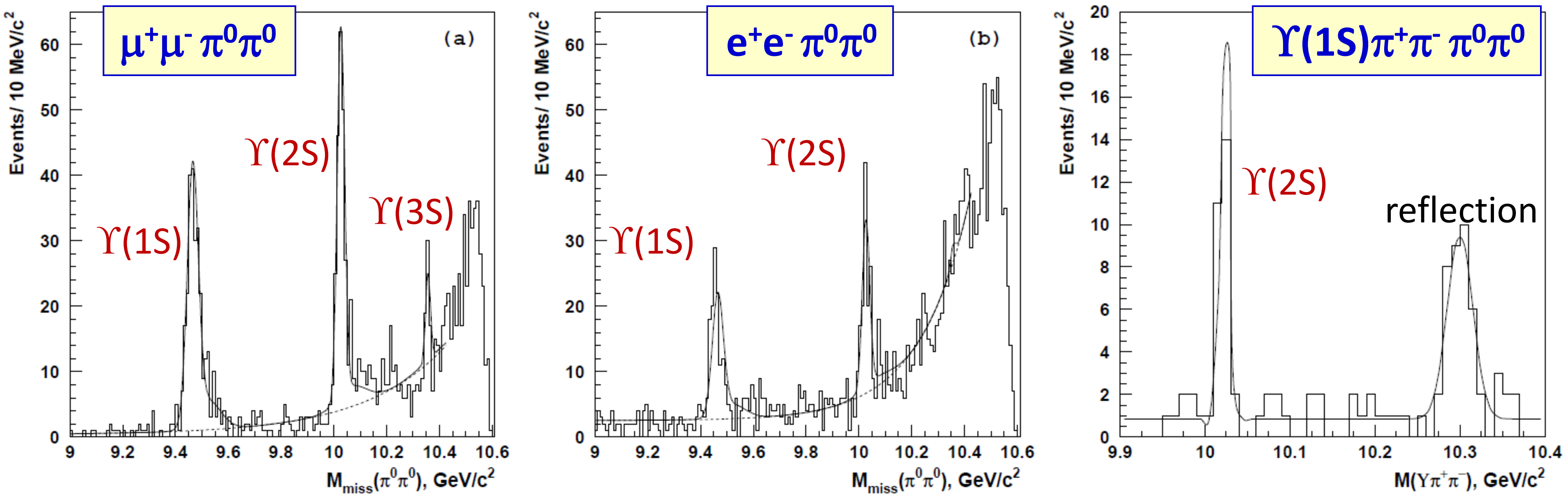
$Z_b' \to B\bar{B}^*$ is suppressed w.r.t. $B^*\bar{B}^*$ despite much larger PHSP.

Explanations:

Molecule $\Rightarrow$ admixture of $B\bar{B}^*$ in Z_b' is small.
Challenging for tetraquark?

Dalitz plot analysis of $\Upsilon(5S) \to \Upsilon(nS)\, \pi^0\pi^0$

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



First observations

$BF[\Upsilon(5S)\to\Upsilon(1S)\pi^0\pi^0] = (2.25 \pm 0.11 \pm 0.20)\times10^{-3}$ — 380 events

$BF[\Upsilon(5S)\to\Upsilon(2S)\pi^0\pi^0] = (3.79 \pm 0.24 \pm 0.49)\times10^{-3}$ — 370 events

arxiv:1207.4345

$BF[\Upsilon(5S)\to\Upsilon(3S)\pi^0\pi^0] = (2.09 \pm 0.51 \pm 0.34)\times10^{-3}$ NEW — 50 events

C.f. $BF[\Upsilon(5S)\to\Upsilon(1S)\pi^+\pi^-] = (4.45 \pm 0.16 \pm 0.35)\times10^{-3}$

$BF[\Upsilon(5S)\to\Upsilon(2S)\pi^+\pi^-] = (7.97 \pm 0.31 \pm 0.96)\times10^{-3}$

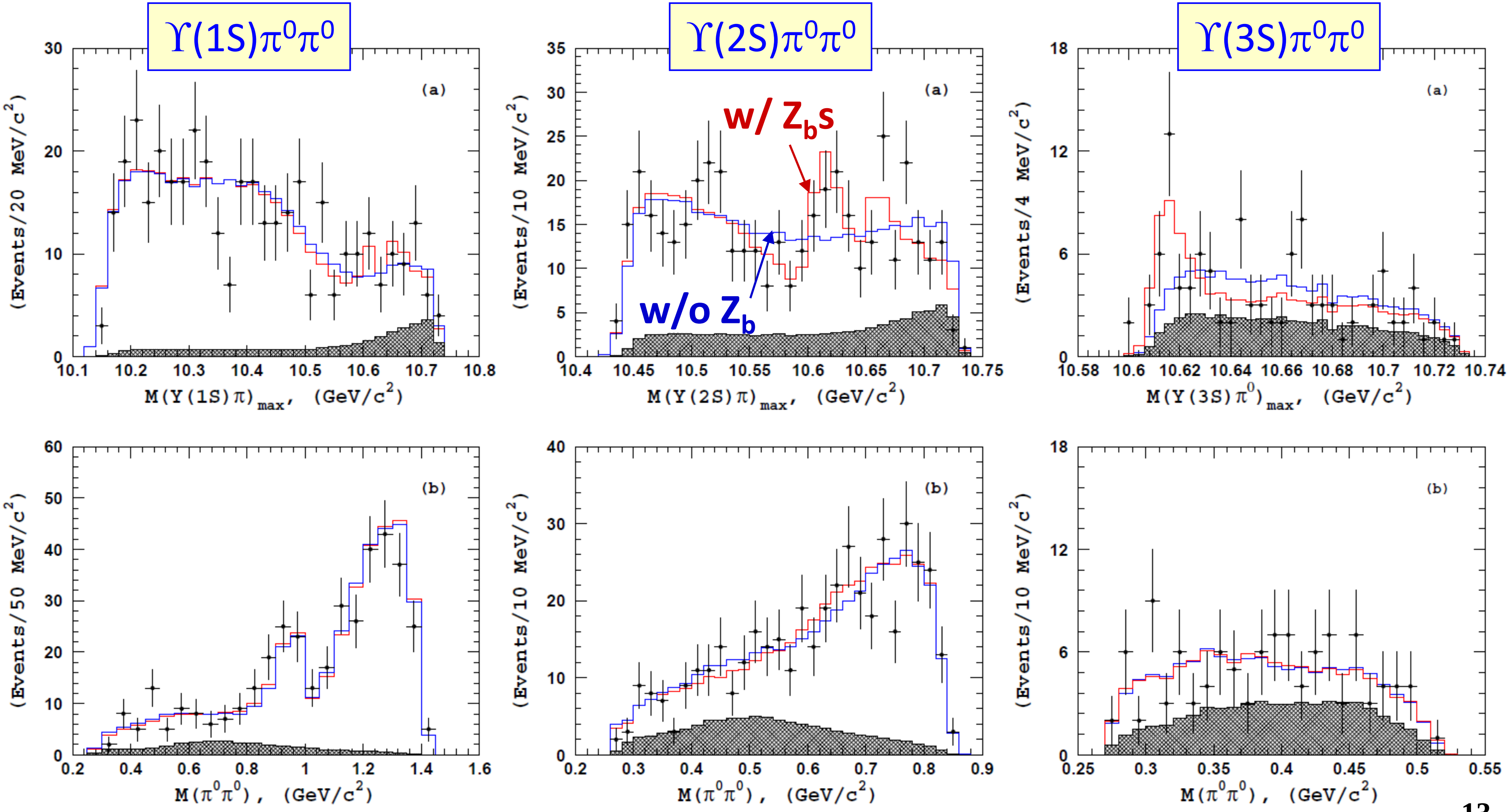
$BF[\Upsilon(5S)\to\Upsilon(3S)\pi^+\pi^-] = (2.88 \pm 0.19 \pm 0.36)\times10^{-3}$

In agreement with isospin relations.

Dalitz plot analysis of $\Upsilon(5S)\to\Upsilon(nS)\pi^0\pi^0$

Analysis procedure is the same as for charged pions

$$S(s1,s2) = A(Z_{b1}) + A(Z_{b2}) + A(f_0(980)) + A(f_2(1275)) + A_{NR}$$



Results of Dalitz plot analysis

NEW

Fit fractions

	$\Upsilon(1S)$	$\Upsilon(2S)$		$\Upsilon(3S)$
		solution A	solution B	
$Z_b(10610)^0$	< 3.5	$13.5 \pm 4.0 \pm 1.8$	$30.0 \pm 6.1 \pm 3.6$	$44 \pm 11 \pm 3$
$Z_b(10650)^0$	< 3.5	< 7	< 13	< 4.2 (90% C.L.)

C.f. arxiv:1207.4345

$Z_b(10610)^+$	$2.54^{+0.87}_{-0.75}$	$19.6^{+4.0}_{-3.2}$	$26.8^{+6.8}_{-4.2}$
$Z_b(10650)^+$	$1.04^{+0.65}_{-0.33}$	$5.8^{+1.5}_{-1.8}$	$11.0^{+4.3}_{-2.4}$

Fit fractions of neutral and charged Z_bs are consistent

	$\Upsilon(2S)\pi^0$	$\Upsilon(3S)\pi^0$	Combined
Significance of $Z_b(10610)$ *(including systematics)*	4.9σ	4.3σ	6.5σ

observation of $Z_b(10610)^0$

$\Upsilon(nS)\pi^0\pi^0$ channels are consistent with Z_b states being isotriplets

NEW

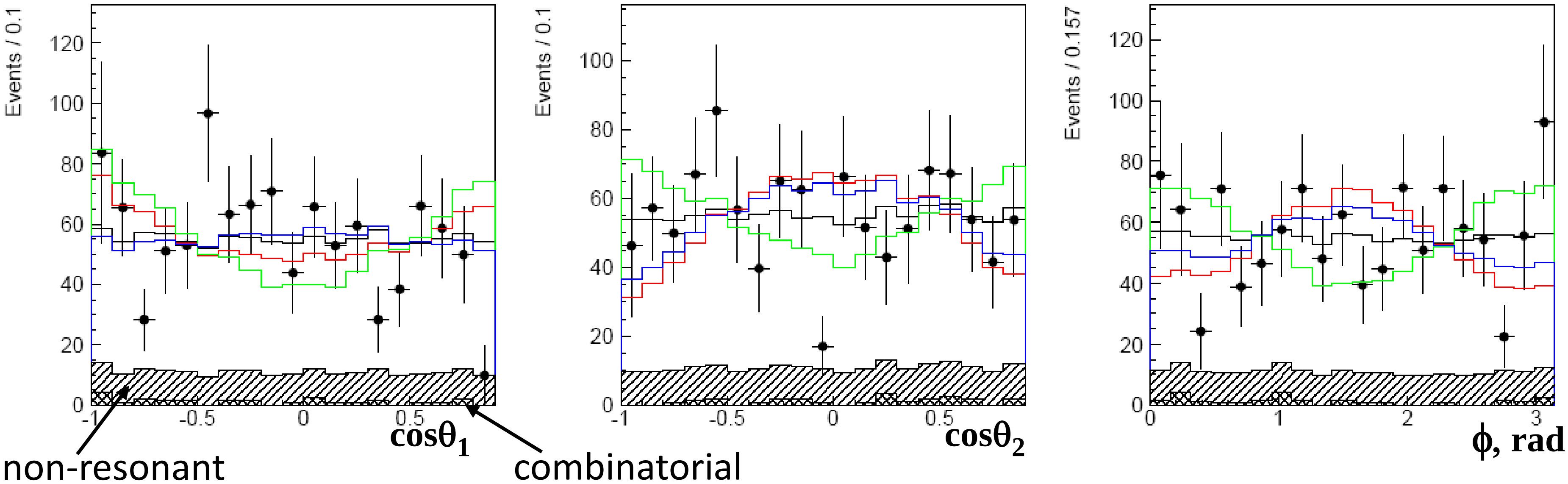
6D amplitude analysis of $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$

Spin-parity of Z_b states

One-dimensional angular analyses

arxiv:1105.4583

Example : $\Upsilon(5S) \to Z_b^+(10610)\,\pi^- \to [\Upsilon(2S)\pi^+]\,\pi^-$



$\theta_i = \angle(\pi_i, e^+)$, $\phi = \angle[\text{plane}(\pi_1, e^+), \text{plane}(\pi_1, \pi_2)]$

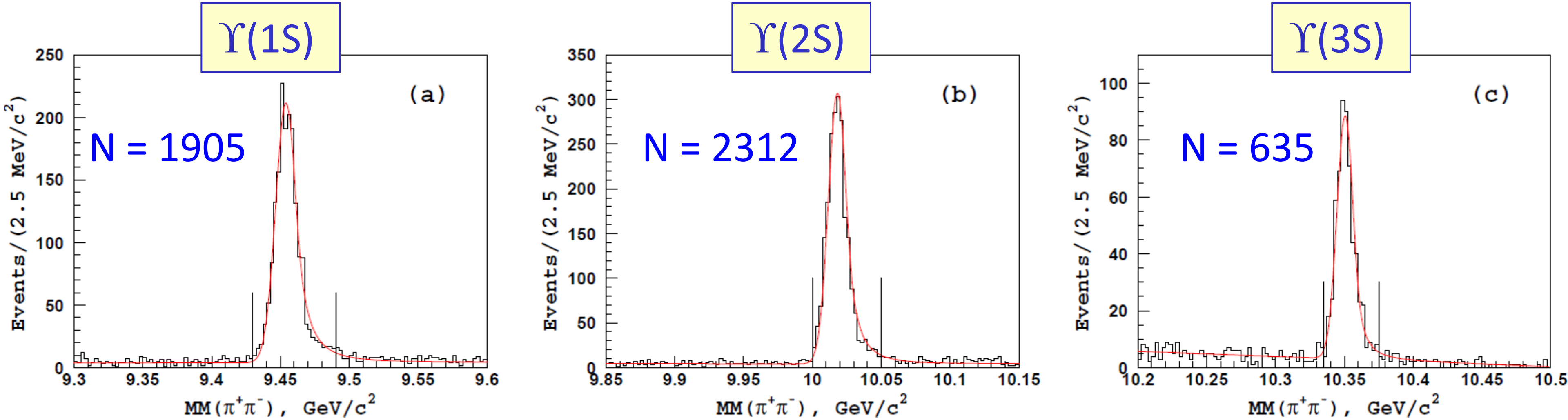
Color coding: J^P= **1^+** **1^-** **2^+** **2^-** ($0^\pm$ is forbidden by parity conservation)

All angular distributions are consistent with $J^P=1^+$ for $Z_b(10610)$ & $Z_b(10650)$.

All other J^P with $J\leq 2$ are disfavored at typically 3σ level.

Results are not conclusive.

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



12 – 4 (energy-momentum) – 1 (Υ(nS) mass) – 1 (rotation around beam axis) = 6 d.o.f.

e.g. $M^2(\Upsilon(nS)\pi)$, $M^2(\pi^+\pi^-)$ and 4 angles

difference w.r.t. previous analysis

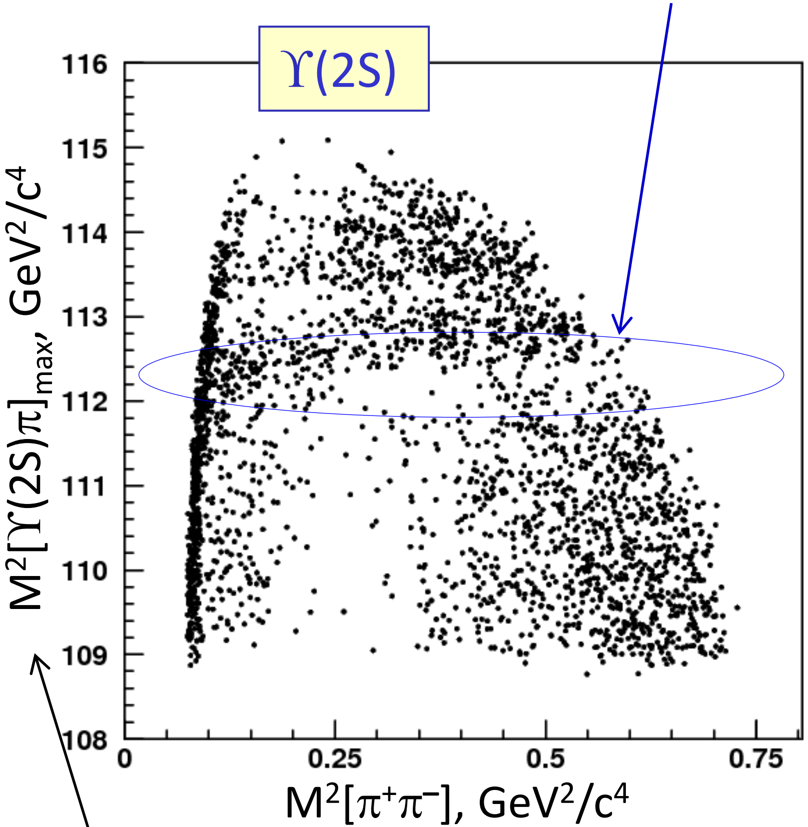
$$S(s1,s2) = \underbrace{A(Z_{b1})}_{\text{BW}} + \underbrace{A(Z_{b2})}_{\text{BW}} + \underbrace{A(f_0(980))}_{\text{Flatte}} + \underbrace{A(f_2(1275))}_{\text{BW}} + \underbrace{A_{NR}}_{C_1 + C_2 \cdot m^2(\pi\pi)} + \boxed{\underbrace{A(\sigma)}_{\text{BW}}}$$

Amplitudes in Lorentz invariant form. Background: Υ(nS) sidebands.

Efficiency: integrate PDFs using reconstructed phase-space MC (non-parametric).

Comparison of spin-parity hypotheses

Clear picture of interference between Z_b and non-resonant S-wave amplitude



Useful projection to explore "deficit" due to interference.

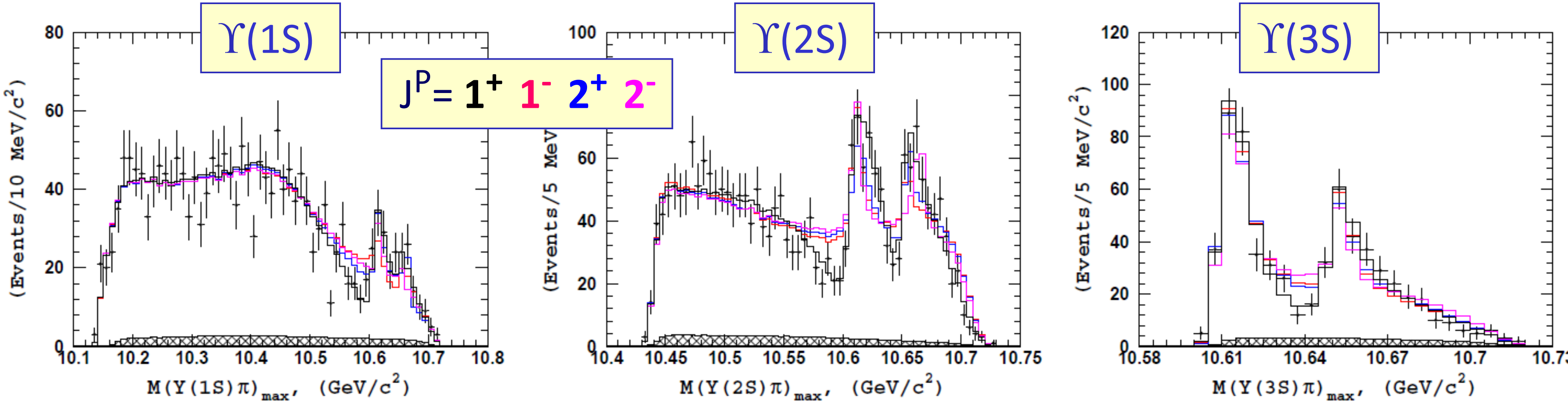
Z_b helicity angle ~ $M^2(\pi^+\pi^-)$

$$Z_b \to \Upsilon(nS)\pi \begin{cases} 1^+ & \text{S-wave} \\ 1^- & \text{P-wave} \\ 2^+ & \text{D-wave} \\ 2^- & \text{P-wave} \end{cases}$$

$\Rightarrow$ A_{Zb} is ~independent on $M^2(\pi^+\pi^-)$ for 1^+, other hypotheses change sign over $M^2(\pi^+\pi^-)$

Interference region has high sensitivity.

Comparison of spin-parity hypotheses



Δ2logL

J^P hypothesis \ Decay Mode	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	rejection power
1^+	0	0	0	
1^-	64	264	73	20σ
2^+	41	207	87	18σ
2^-	59	304	125	22σ

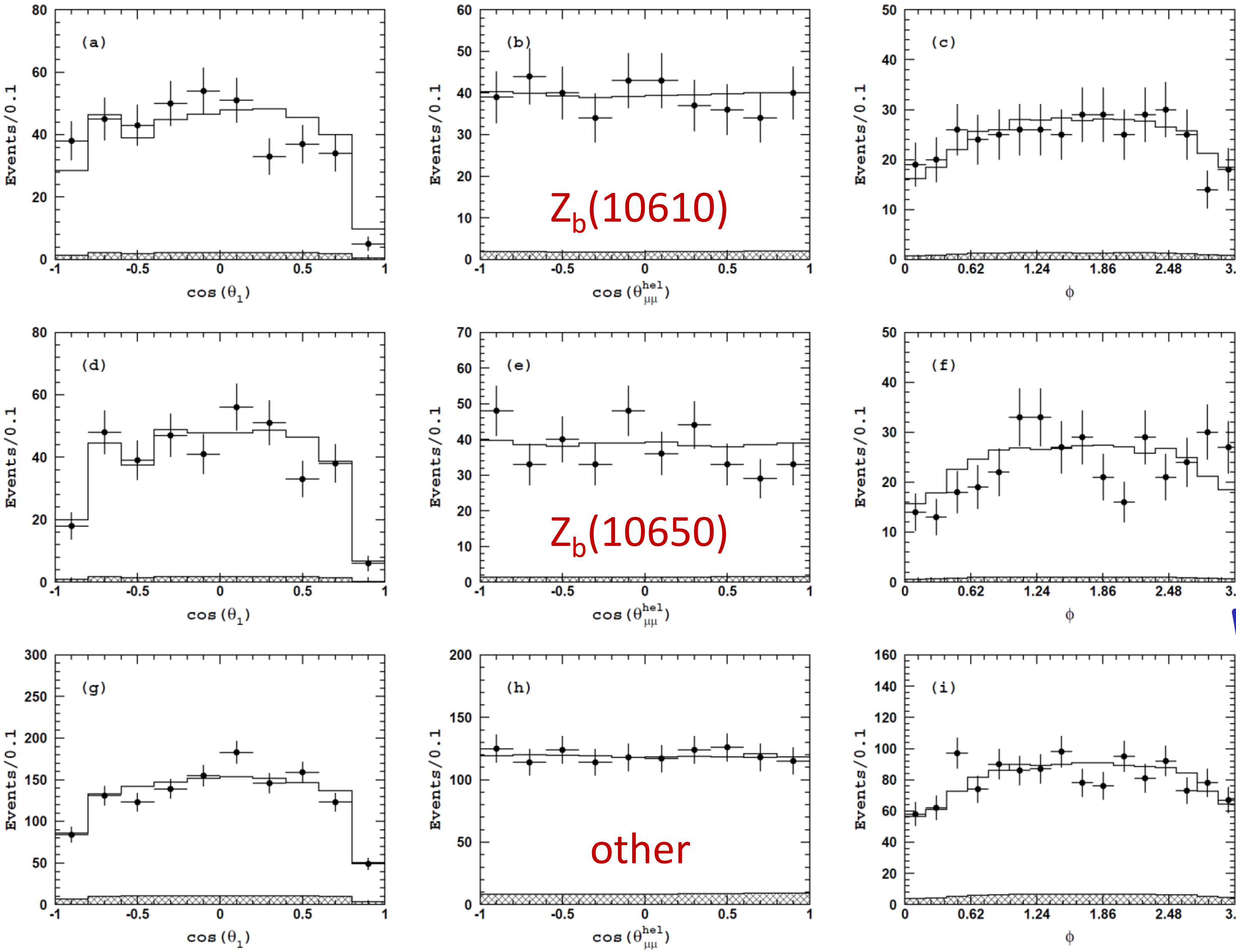
Best discriminating power is in Υ(2S) channel where A_{Zb} and $A_{non\text{-}res}$ are of similar size.

Spin-parity of $Z_b(10610)$ and $Z_b(10650)$ is **1^+**. All other J≤2 are excluded.

As expected for S-wave molecule.

Angular projections of 6D fit

$J^P=1^+$

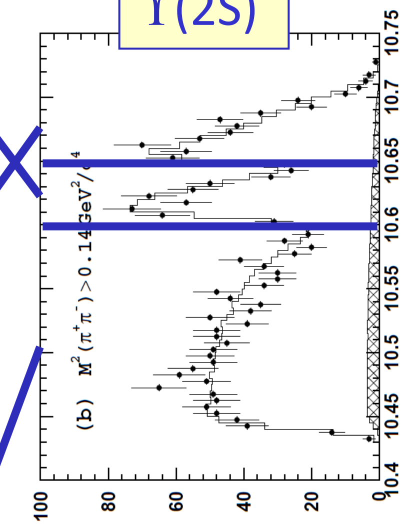


$\angle(\pi_1$, Z-axis)

$\Upsilon(2S)$ helicity angle

$\angle$[plane(π_1, Z-axis), plane($\pi^+\pi^-$)]

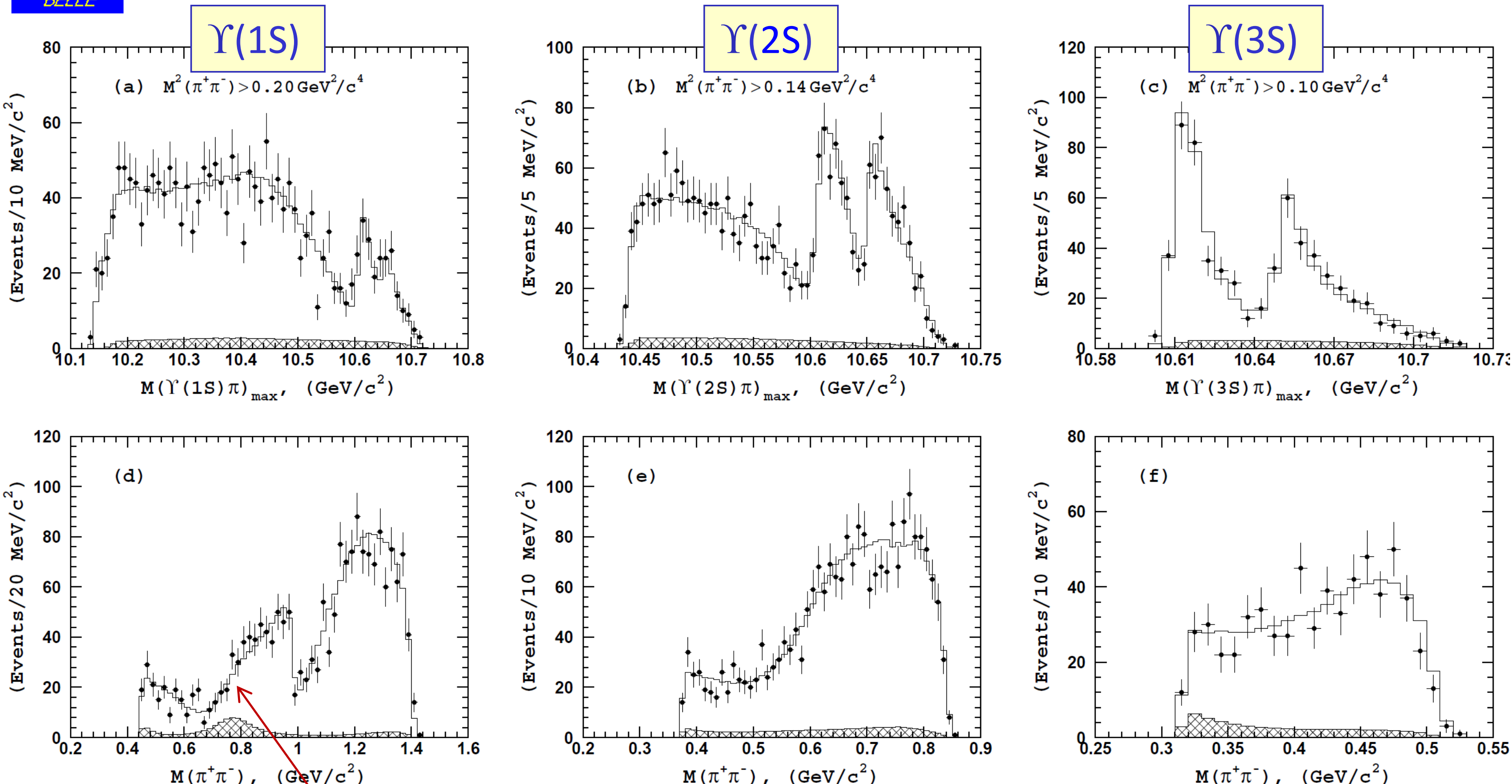
$\Upsilon(2S)$



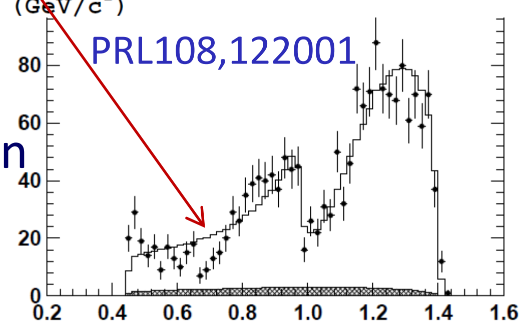
1^+ hypotheses describe data very well

Mass projections of 6D fit

$J^P=1^+$



Improvement due to inclusion of σ state



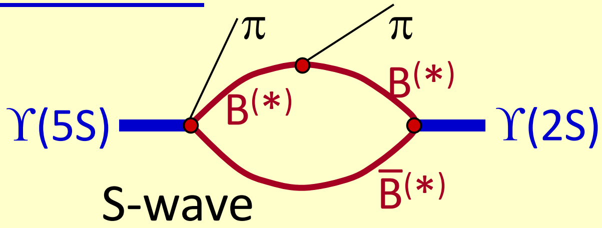
BW amplitudes describe Z_b states very well.

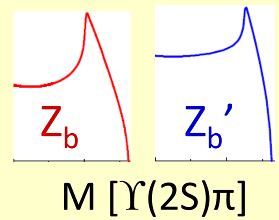
Resonant behavior of Z_b amplitudes (intensity & phase).

Origin of structure at threshold?

1. Threshold effect

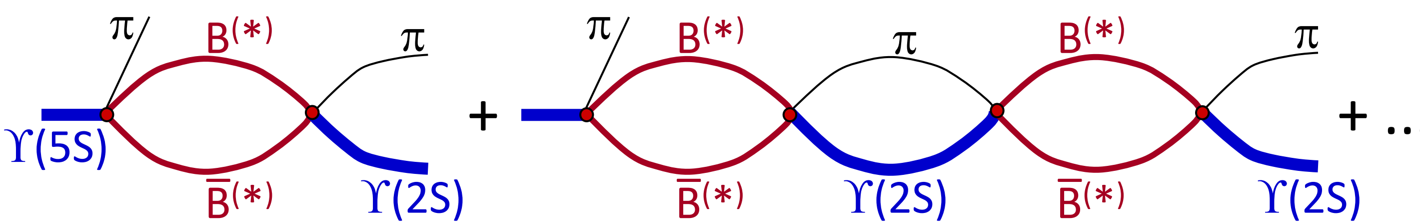
Chen Liu PRD84,094003(2011)

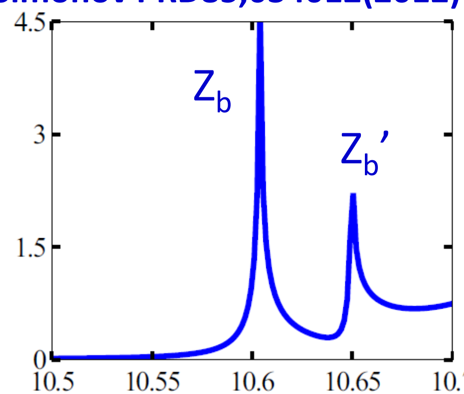




2. Coupled-channel resonance multiple re-scatterings $\Rightarrow$ pole

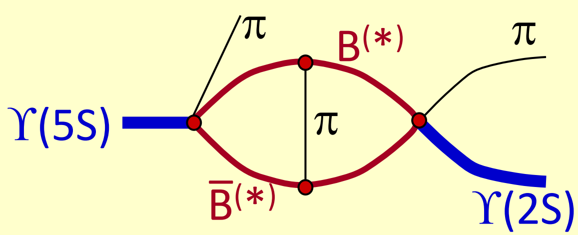
Danilkin Orlovsky Simonov PRD85,034012(2012)





3. Deuteron-like molecule

π,ρ,ω,σ exchange



Ohkoda et al arxiv:1111.2921

Request to theory: predictions (formulas) to fit data !

Summary

$Z_b(10610)$ and $Z_b(10650)$ states observed in 5 decay modes:

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

Masses close to BB* and B*B* thresholds.

Observation of $Z_b(10610)^\pm \to B\bar{B}^*$, $Z_b(10650)^\pm \to B^*\bar{B}^*$ Dominant modes: BF~80%

$Z_b(10650)^\pm \to B\bar{B}^*$ is suppressed "smoking gun" of molecular structure?

Dalitz plot analysis of $\Upsilon(nS)\pi^0\pi^0$ consistent with $\Upsilon(nS)\pi^+\pi^-$, observation of $Z_b(10610)^0$

6D amplitude analysis Z_b spin-parity is unambiguously **1+**

All experimental data point to molecular structure of Z_b.

Fit to data with various predictions is crucial to discriminate dynamical model.

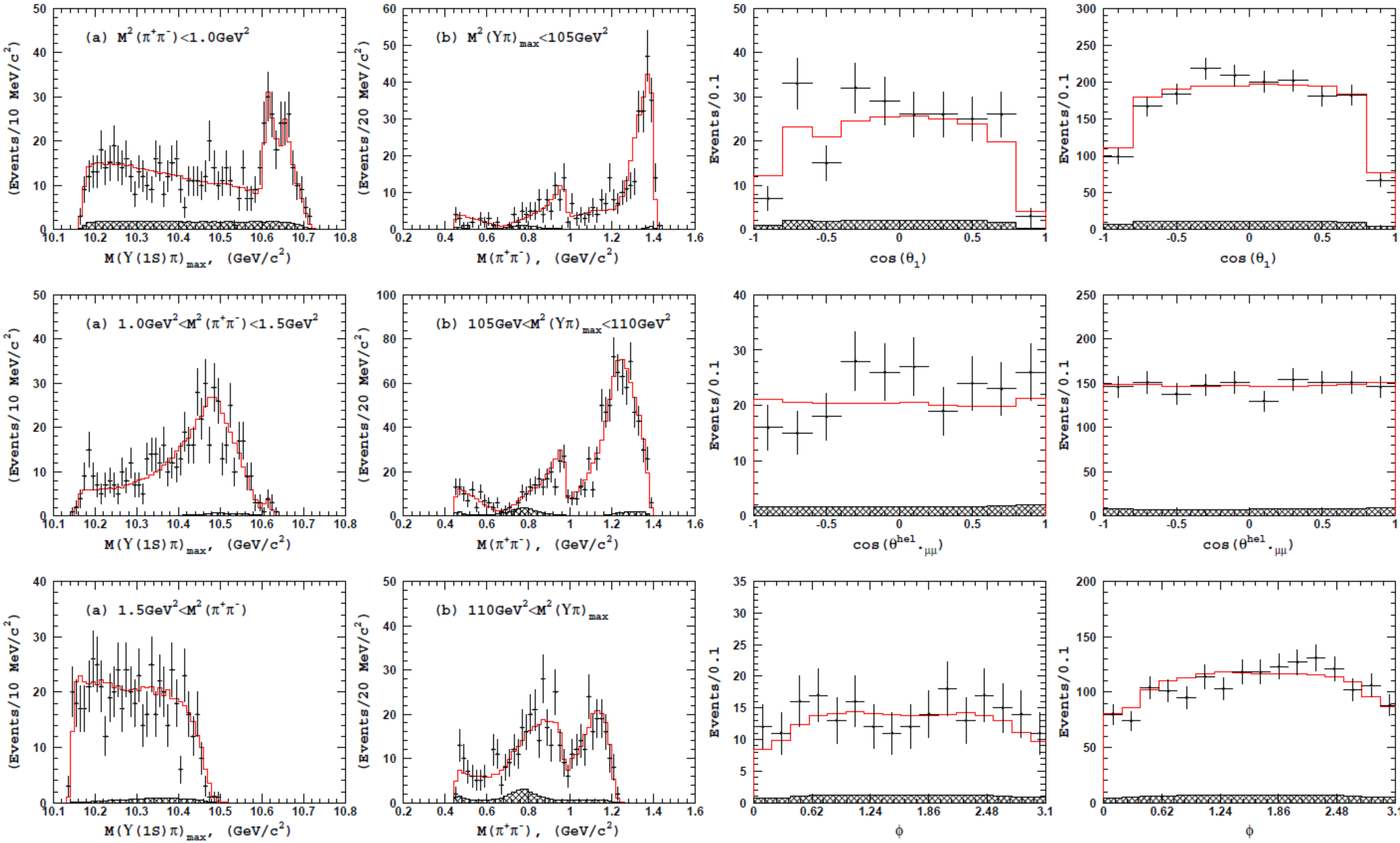
Collaboration btw. theory and experiment.

Z_b – very rich phenomenological objects, can help to understand highly excited states?

Back-up

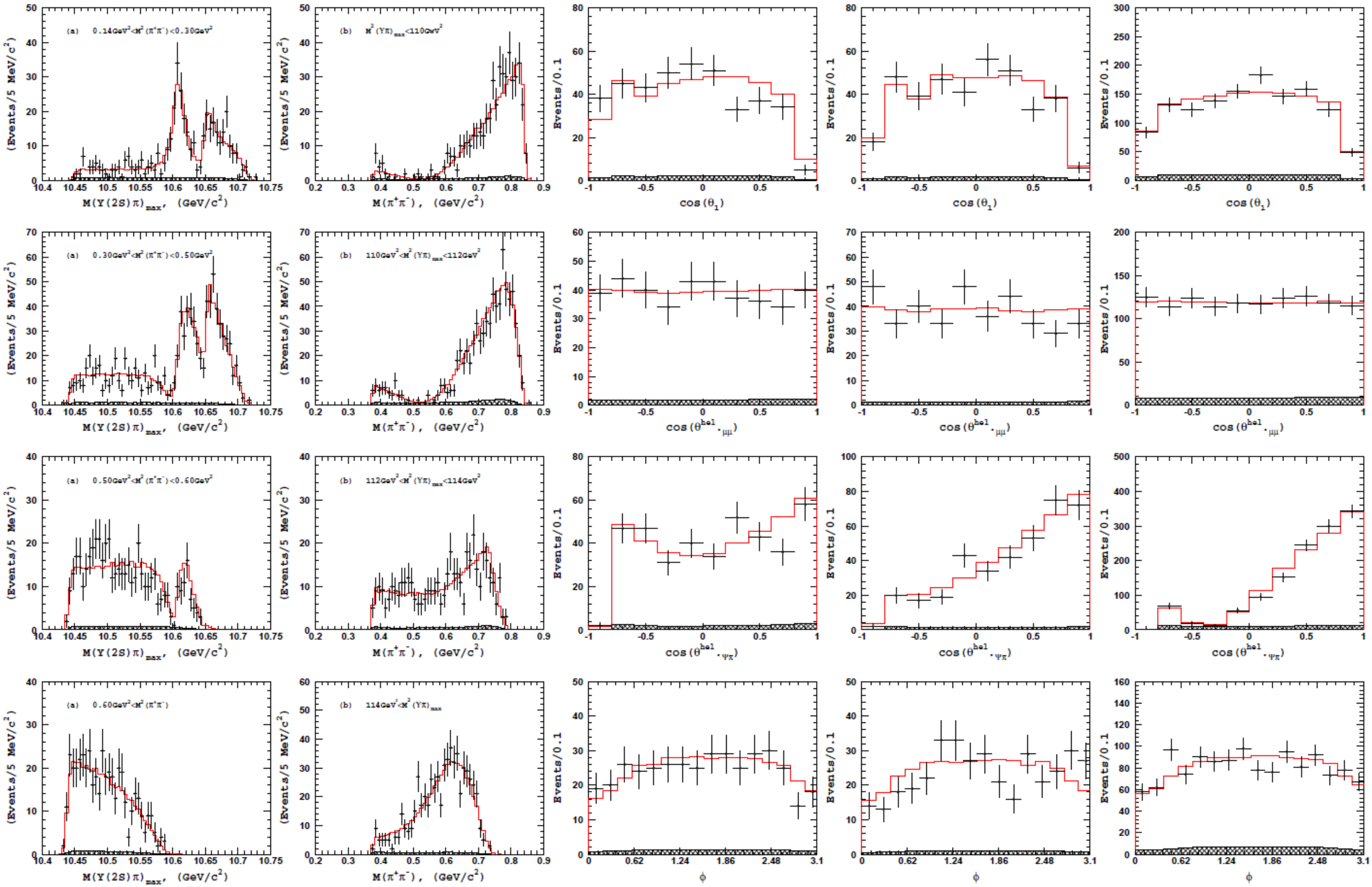
Fit projections for $\Upsilon(1S)\,\pi^+\pi^-$

$J^P=1^+$



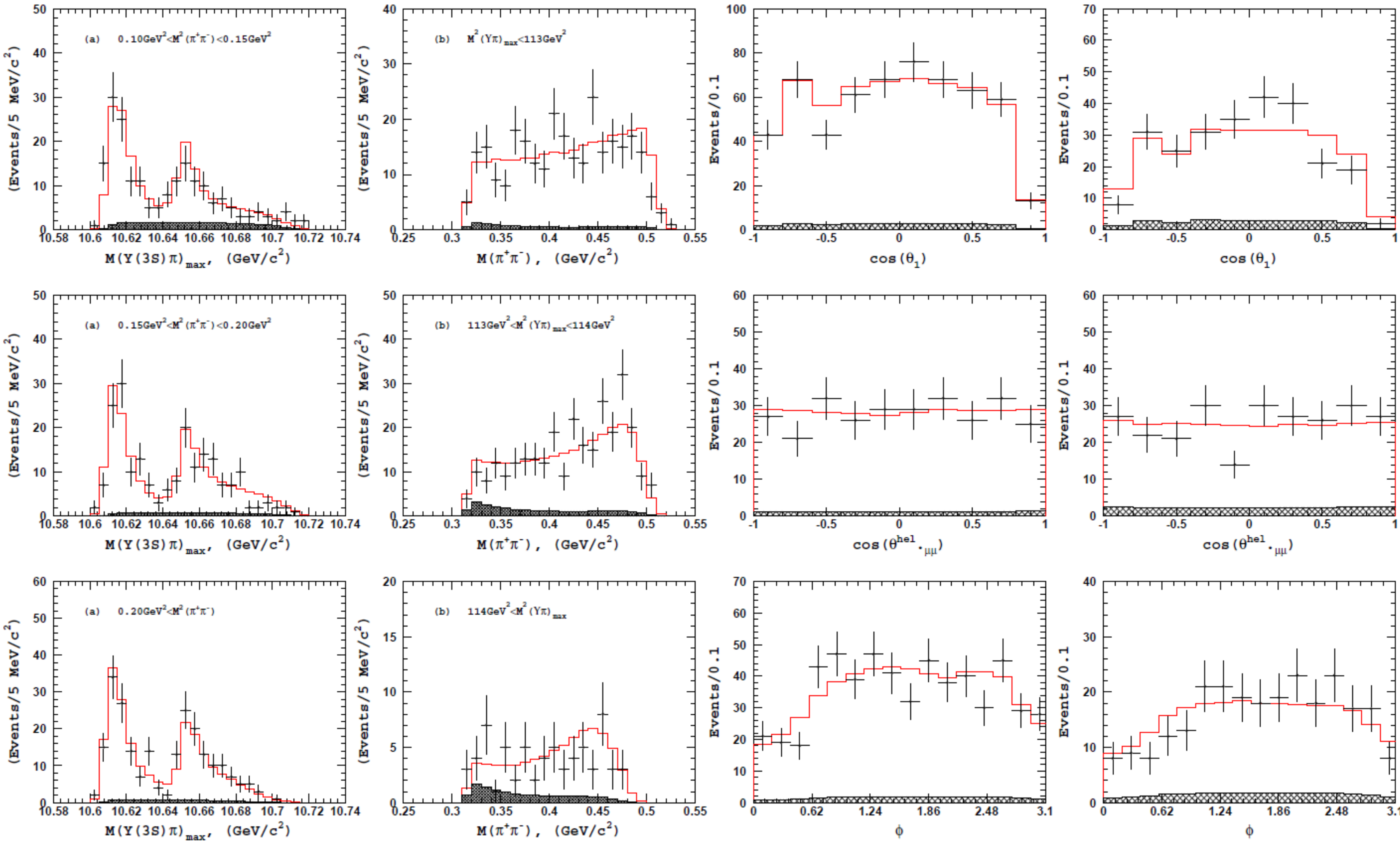
Fit projections for $\Upsilon(2S)\,\pi^+\pi^-$

$J^P=1^+$



Fit projections for $\Upsilon(3S)\,\pi^+\pi^-$

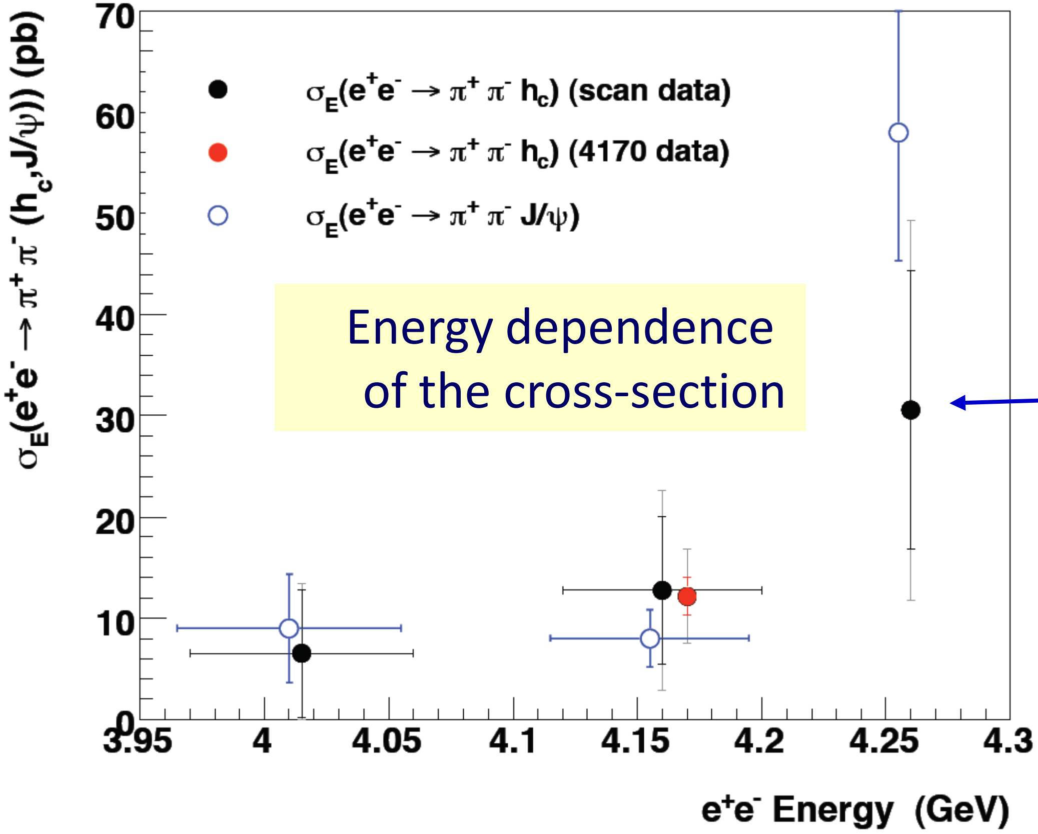
$J^P=1^+$



Trigger

Observation of $e^+e^- \to \pi^+\pi^- h_c$ above $D\bar{D}$ threshold by CLEOc

Ryan Mitchell @ CHARM2010



Production of h_c is unsuppressed relative to J/ψ.

Enhancement @ Y(4260)?

Belle sees $\Upsilon(5S)\to\Upsilon\pi^+\pi^- \Rightarrow$ should search for $\Upsilon(5S)\to h_b\pi^+\pi^-$