Observation of $h_b(nP)$ and Z_b's states at $\Upsilon(5S)$

arXiv:1103.3419, arXiv:1105.4583

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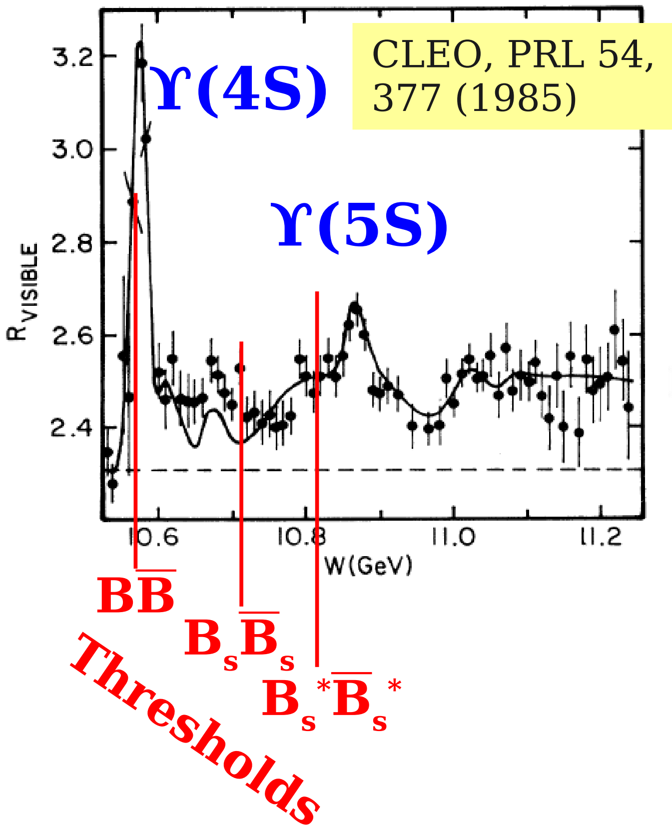
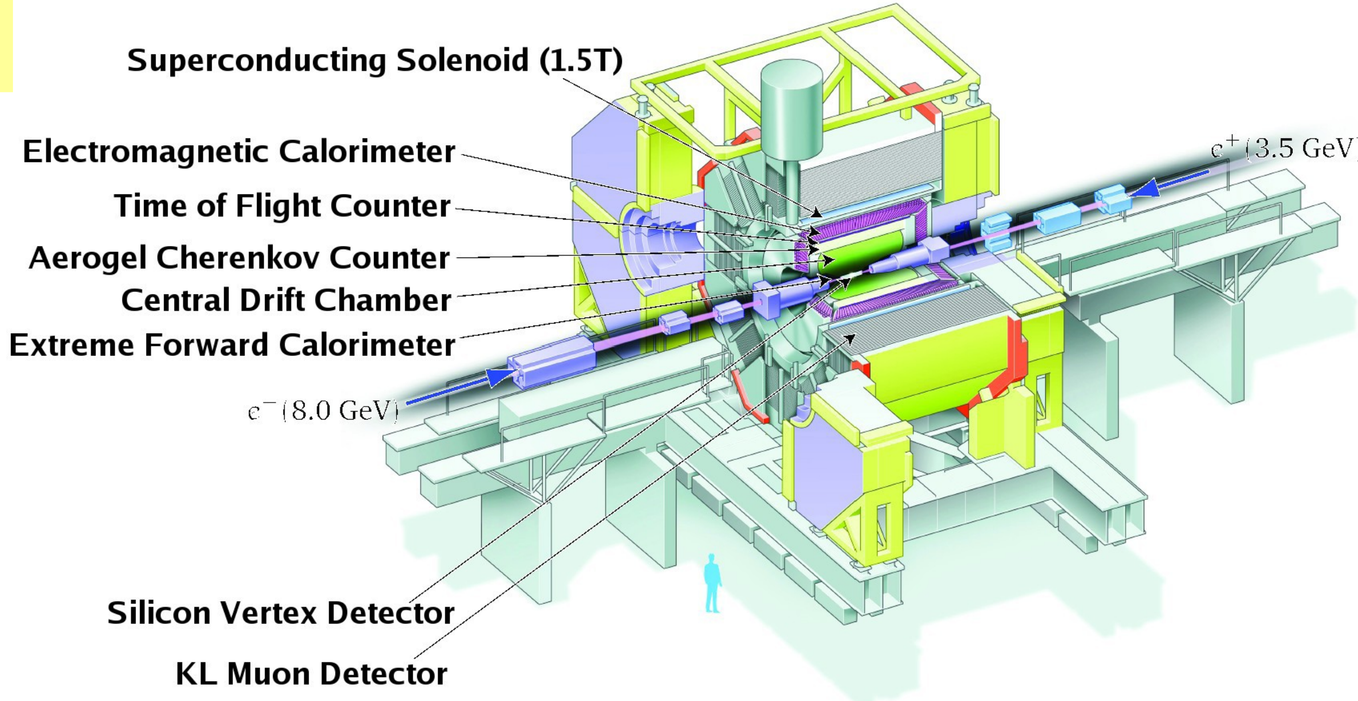
Data samples at $\Upsilon(5S)$





Belle took about ~140 fb^{-1} around the $\Upsilon(5S)$

- **121.4 fb^{-1} at the resonance**
- ~20 fb^{-1} in scans
- Much larger than CLEO, BaBar: <1 fb^{-1}

Compared to 711 fb^{-1} at the $\Upsilon(4S)$

$\Upsilon(5S)$ above $B_s^{(*)}B_s^{(*)}$ threshold

- B_s can be produced and studied at a B-factory
  - This was established by CLEO
- $\Upsilon(5S)$ does also of course decay to B^+ and B^0
  - Can be excited and produced with pions
    - $\Rightarrow B^{(*)}B^{(*)}(n\pi)$
- **And to bottomonia ($\Upsilon(nS)\pi\pi$, etc...)**

$\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ decays

K.F. Chen et al. (Belle), PRL 100, 112001 (2008); PRD 82, 091106(R) (2010)

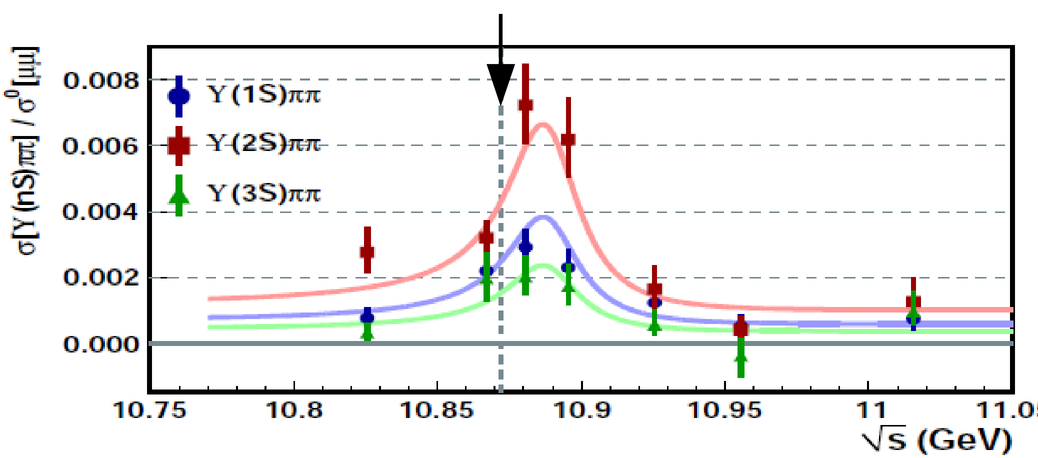
- Anomalously large $\Upsilon(nS)\pi\pi$ transitions at the $\Upsilon(5S)$ (on-resonance)

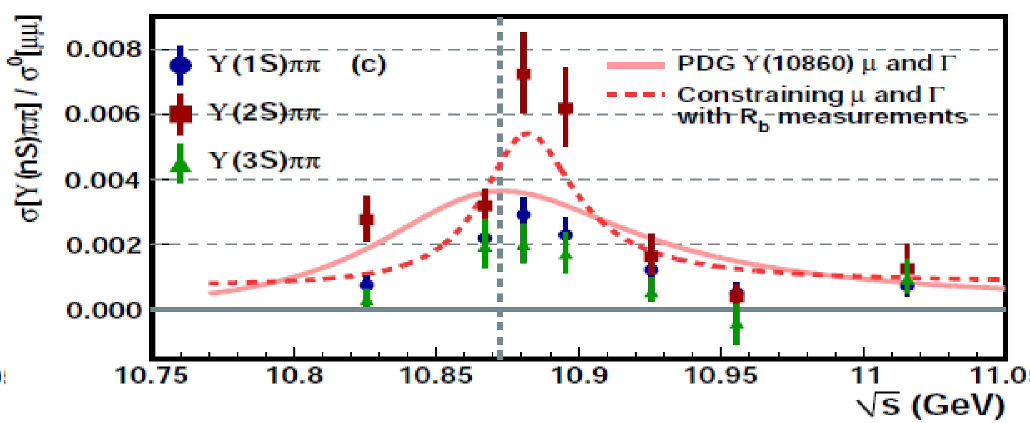
Process	Γ_{total} [MeV]	$\Gamma_{e^+e^-}$ [keV]	$\Gamma_{\Upsilon(1S)\pi^+\pi^-}$ [MeV]
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.032	0.612	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.020	0.443	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	20.5	0.272	0.0019
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	110	0.31	0.59

- 2007: 6-points scan (~1fb^{-1} per point)

>100x larger

Maximum of hadrons' production



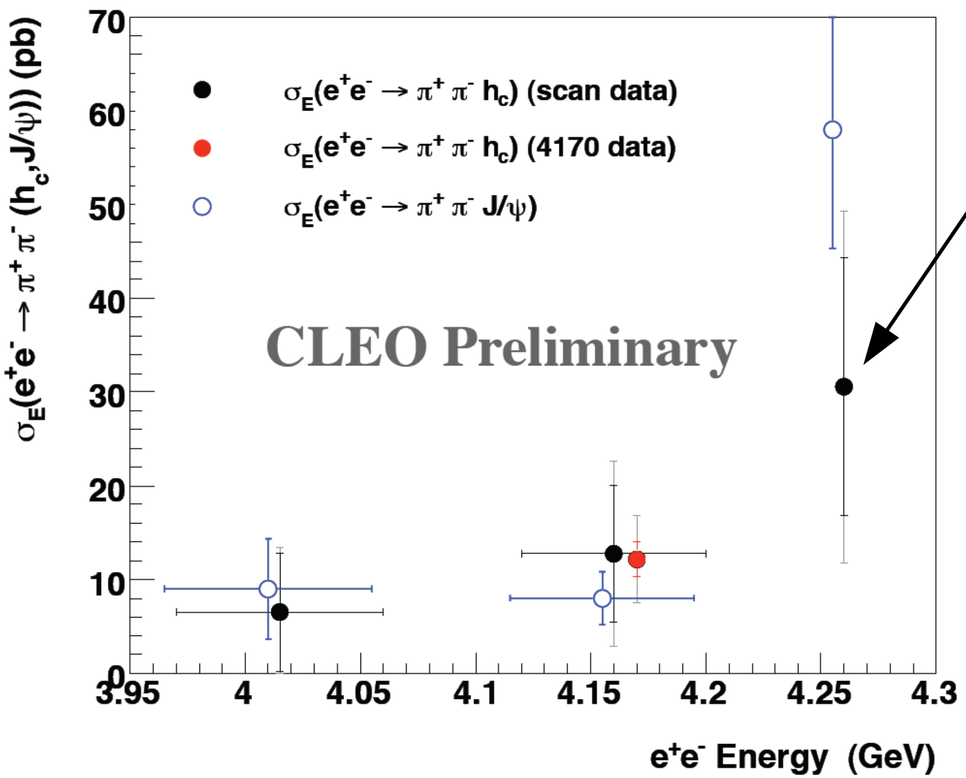


Does not agree well with the conventional $\Upsilon(10860)$ line shape

1) Y_b particle: analog to Y(4260) that has anomalously large $\Gamma(J/\psi\pi\pi)$
2) Rescattering of $\Upsilon(5S) \to BB\pi\pi \to \Upsilon(nS)\pi\pi$
3) something else?

Discovery of h_c by CLEO

- CLEO observed $e^+e^- \to h_c \pi^+\pi^-$
  - h_c production cross-section seems to be **enhanced near Y(4260)**

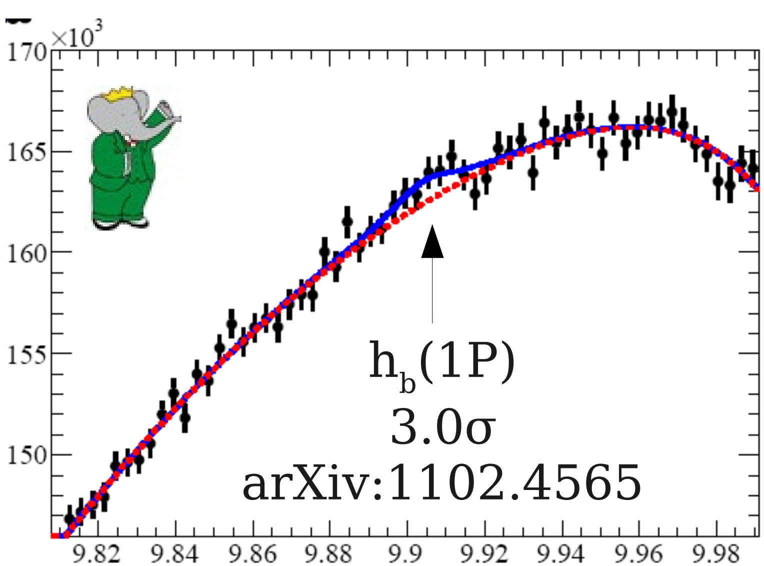


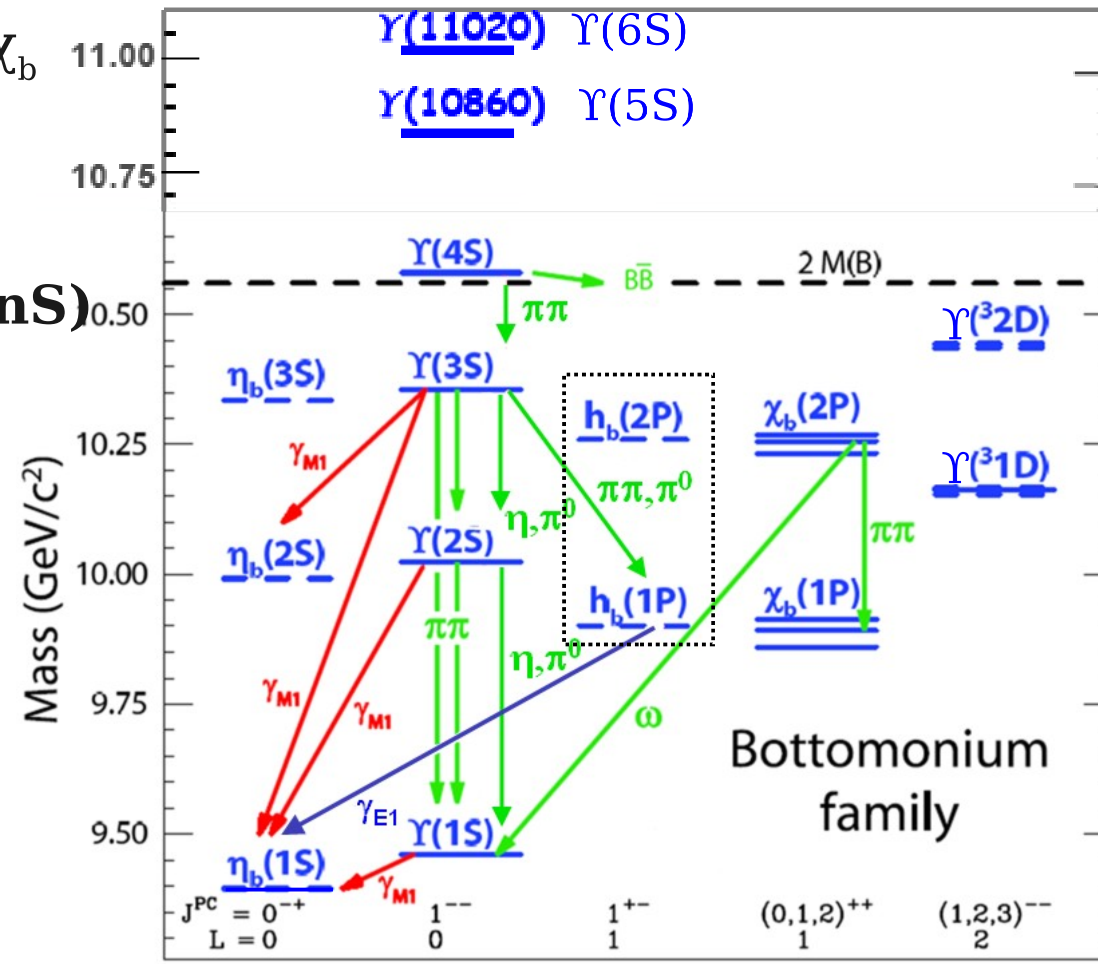
- Do we have more chance of seeing h_b at $\Upsilon(5S)$ if it is in fact Y_b?

h_b(nP) properties

$b\bar{b}$ states, spin 0, L=1, $J^{PC}=1^{+-}$

- Expected mass of h_b(nP) at the **Center of Gravity** (CoG) of χ_b states
  - Test of **hyperfine** splitting
- **Radiative transition to η_b(nS)**
  - BaBar has obtained evidence of h_b(1P) in $\Upsilon(3S)\rightarrow\pi^0 h_b(1P)\rightarrow\pi^0\gamma\eta_b(1S)$

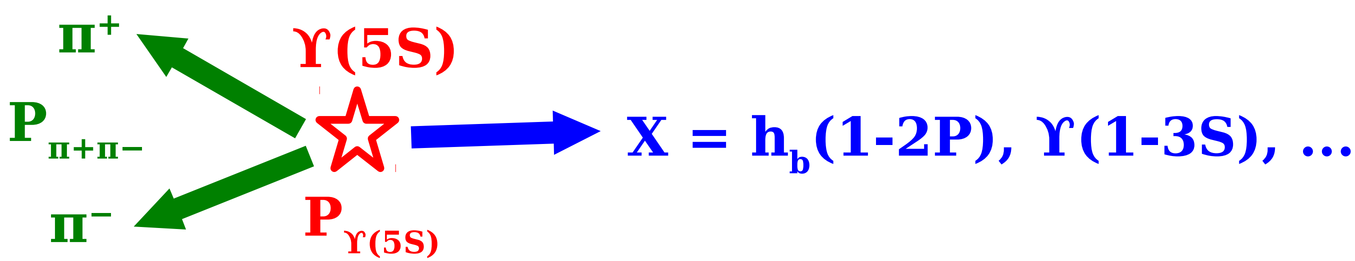




Analysis procedure

- Similar to CLEO's h_c analysis: missing mass (MM) to $\pi^+\pi^-$ system
  - Implicit reconstruction of h_b et al. (X) thanks to e^+e^- annihilation
    - $e^+e^- \rightarrow \Upsilon(5S) \rightarrow X\ \pi^+\pi^-$

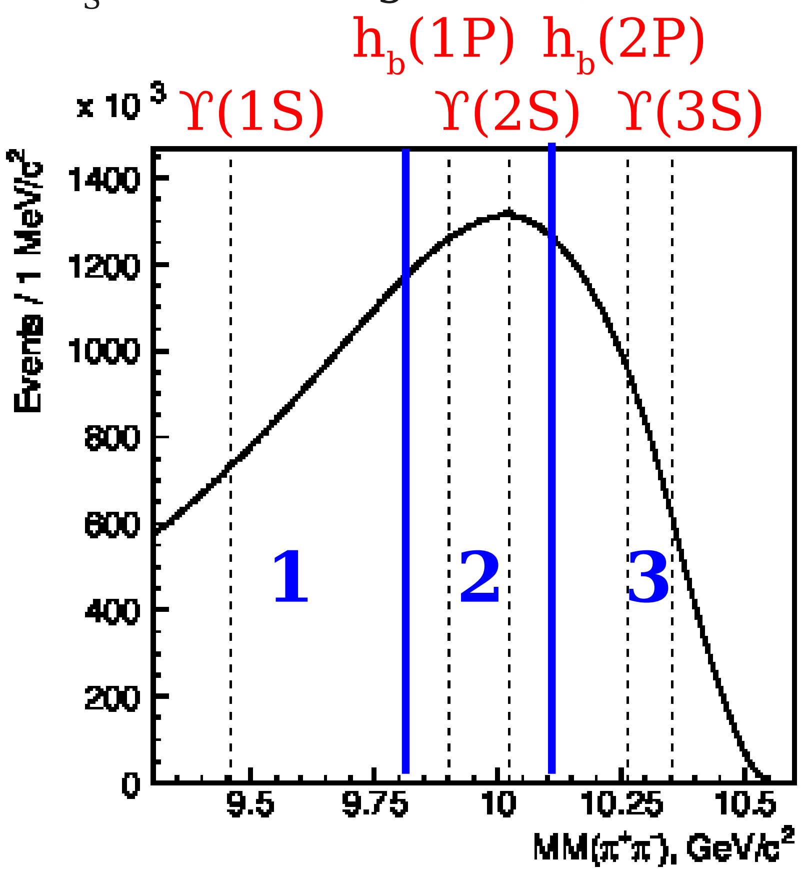
$$MM(\pi^+\pi^-) \equiv M_X = \sqrt{(P_{\Upsilon(5S)} - P_{\pi^+\pi^-})^2}$$

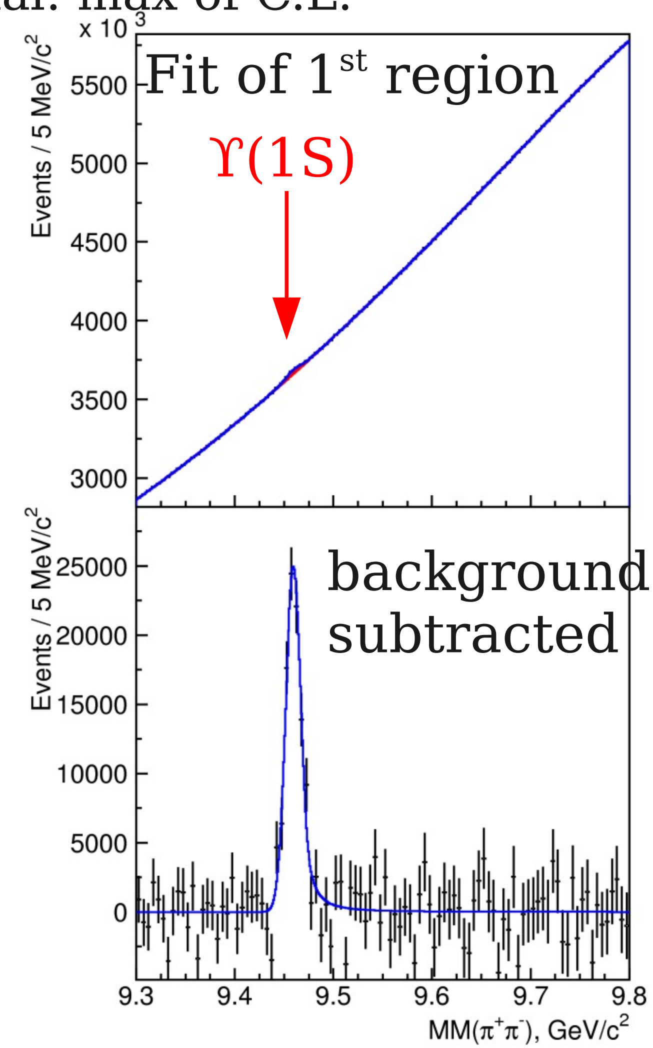


  - $P_{\Upsilon(5S)}$: CM-energy and boost (accelerator information)
  - $P_{\pi+\pi-}$: we detect and measure
- Selection is simple
  - Pions with opposite charges
    - tracks originating from IP region and particle identification
  - Continuum ($e^+e^- \rightarrow q\bar{q}$) suppression with event shape

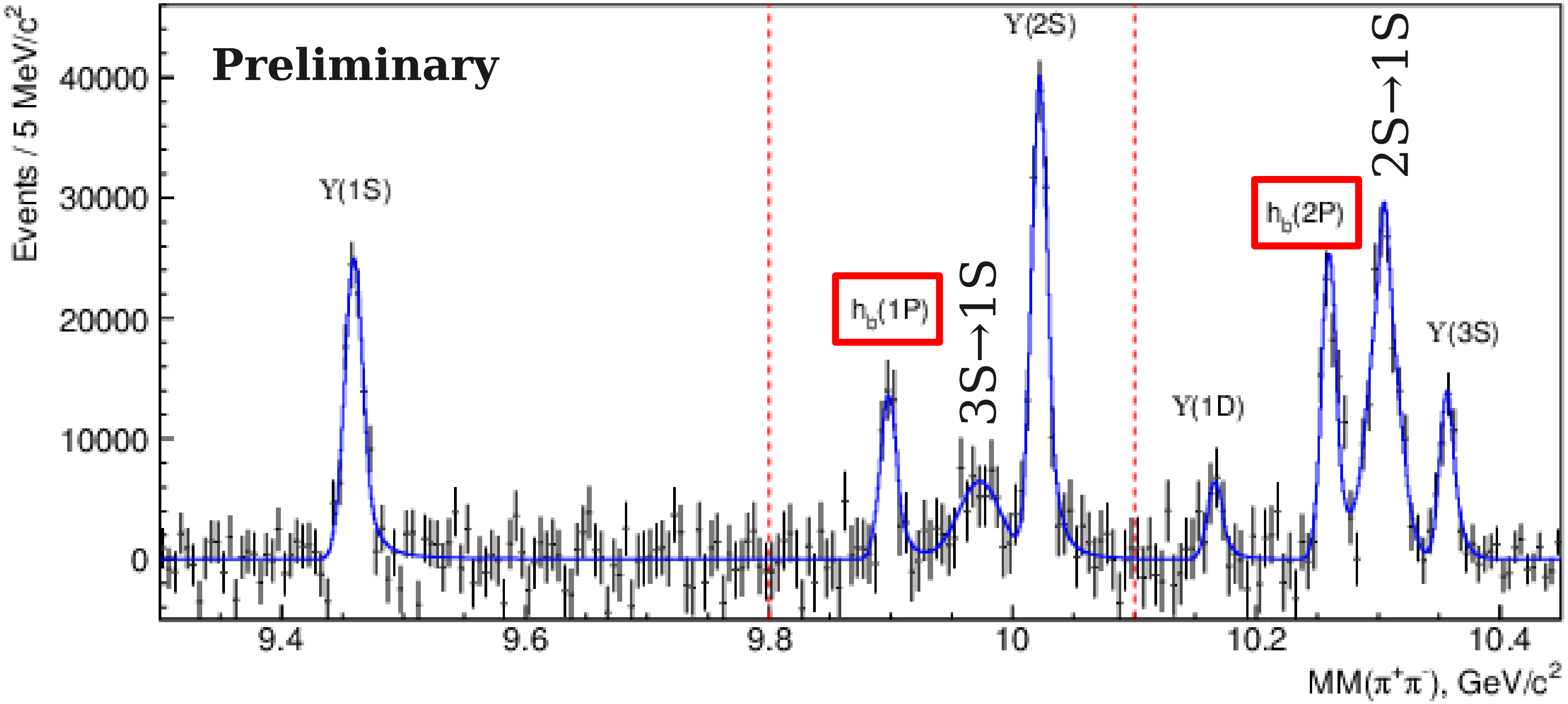
Fit procedure

- Three independent fit are performed to MM distribution
  - signals and reflections
    - calibrated with exclusive $\Upsilon(5S) \to \Upsilon(nS)\ [\to \mu^+\mu^-]\ \pi^+\pi^-$ decays
  - combinatorial background: order of polynomial: max of C.L.
  - $K_S \to \pi^+\pi^-$ background (threshold in 3[rd] region)





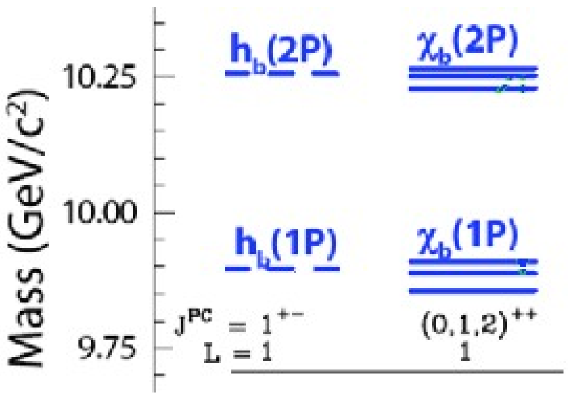
h_b(nP) results



	Yield [10^3]	Mass [MeV/c^2]	Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.42 \pm 0.53 \pm 1.02$	18.2
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.25 \pm 1.06^{+1.03}_{-1.07}$	5.5
$\Upsilon(3S) \to \Upsilon(1S)$	55 ± 19	9973.01	2.9
$\Upsilon(2S)$	$143.4 \pm 8.7 \pm 6.8$	$10022.25 \pm 0.41 \pm 1.01$	16.6
$\Upsilon(1D)$	22.1 ± 7.8	10166.2 ± 2.4	2.4
$h_b(2P)$	$84 \pm 7^{+23}_{-10}$	$10259.76 \pm 0.64^{+1.43}_{-1.03}$	11.2
$\Upsilon(2S) \to \Upsilon(1S)$	$151.6 \pm 9.7^{+9.0}_{-20.0}$	$10304.57 \pm 0.61 \pm 1.03$	15.7
$\Upsilon(3S)$	$44.9 \pm 5.1 \pm 5.1$	$10356.56 \pm 0.87 \pm 1.06$	8.5

$h_b(nP)$ results

- Could the observed states be $\chi_{b1}(nP)$? No
  - Measured masses are ~3σ off compared to $\chi_{b1}(nP)$
  - $\Upsilon(5S) \to \chi_{b1}(nP)\pi^+\pi^-$ violates isospin (strong interaction)



- Mass are in very good agreement with CoG of χ_b states
  - $h_b(1P)$: $\Delta M = 1.62 \pm 1.52$ MeV/c^2
  - $h_b(2P)$: $\Delta M = 0.48 \pm 1.57$ MeV/c^2

Consistent with hyperfine interaction

- Ratio of production rates

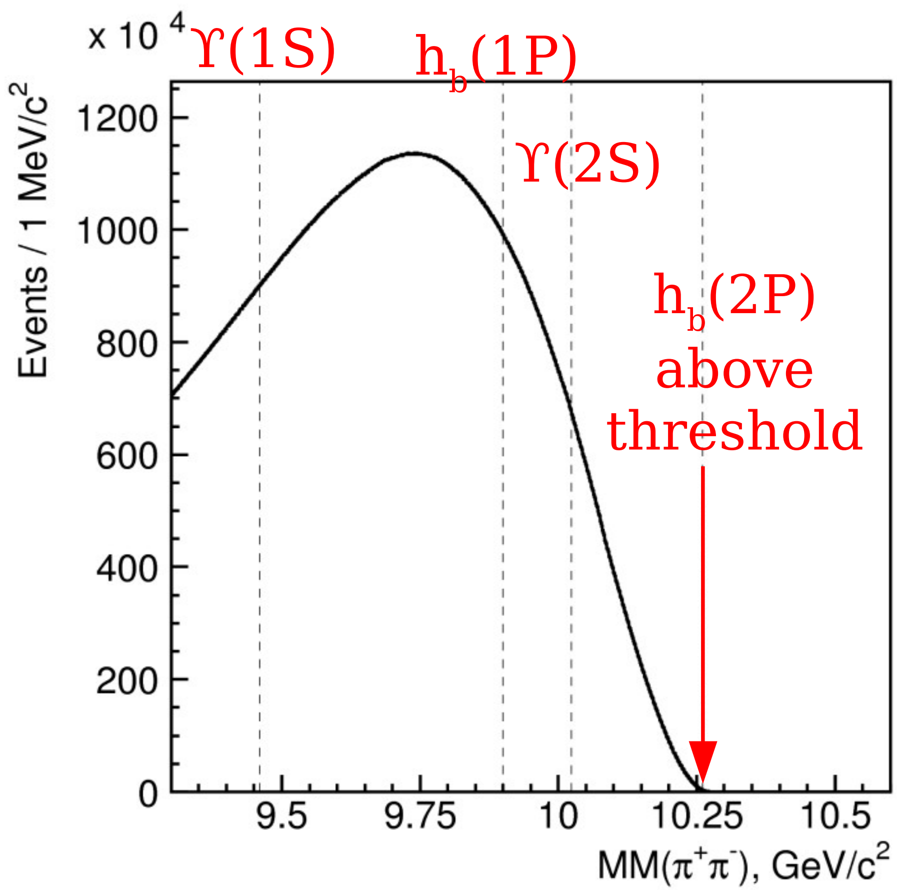
$$\frac{\Gamma(\Upsilon(5S) \to h_b(nP)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = \begin{cases} 0.407 \pm 0.079^{+0.043}_{-0.076} & \text{for } h_b(1P) \\ 0.78 \pm 0.09^{+0.22}_{-0.10} & \text{for } h_b(2P) \end{cases}$$

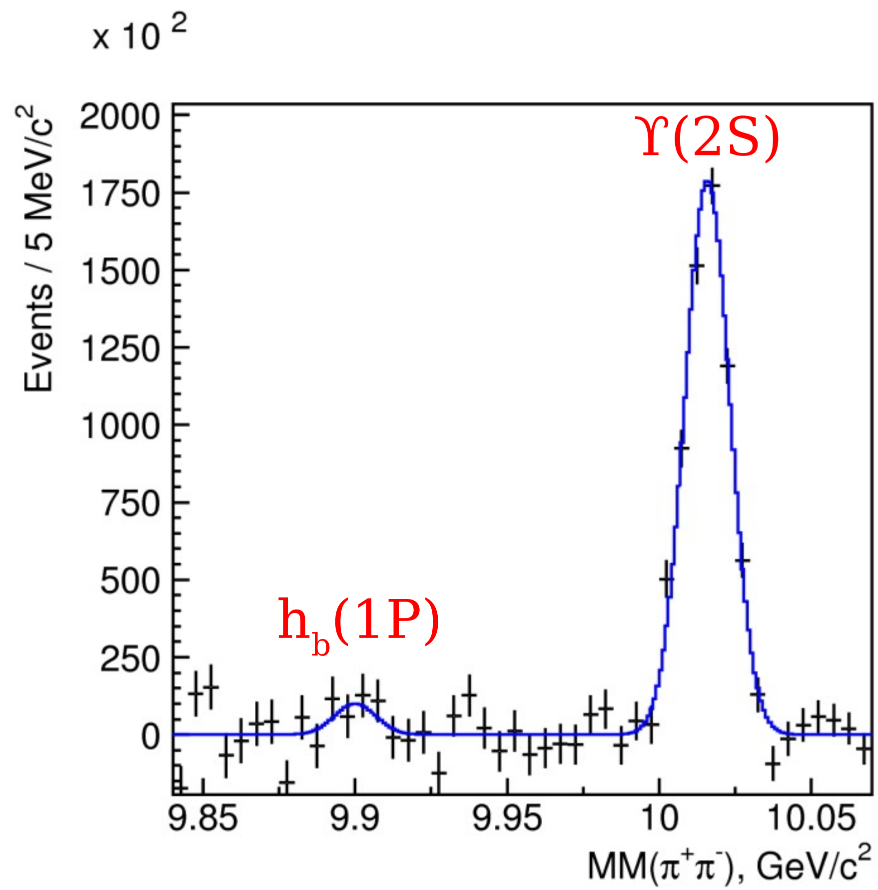
  - Decays to h_b should be suppressed due to spin-flip
    - $\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-$ decays seem exotic!

$S(h_b(nP))=0$
$S(\Upsilon(nS))=1$

Search for $h_b(1P)$ at $\Upsilon(4S)$

Using all our data: 711 fb^{-1} (ie six times more data than at $\Upsilon(5S)$)





No significant h_b signal
$(34 \pm 20)\ 10^3$ (1.7σ)

$$\frac{\sigma(e^+e^- \to h_b(1P)\pi^+\pi^-)@\Upsilon(4S)}{\sigma(e^+e^- \to h_b(1P)\pi^+\pi^-)@\Upsilon(5S)} < \mathbf{0.28\ (90\%\ CL)}$$

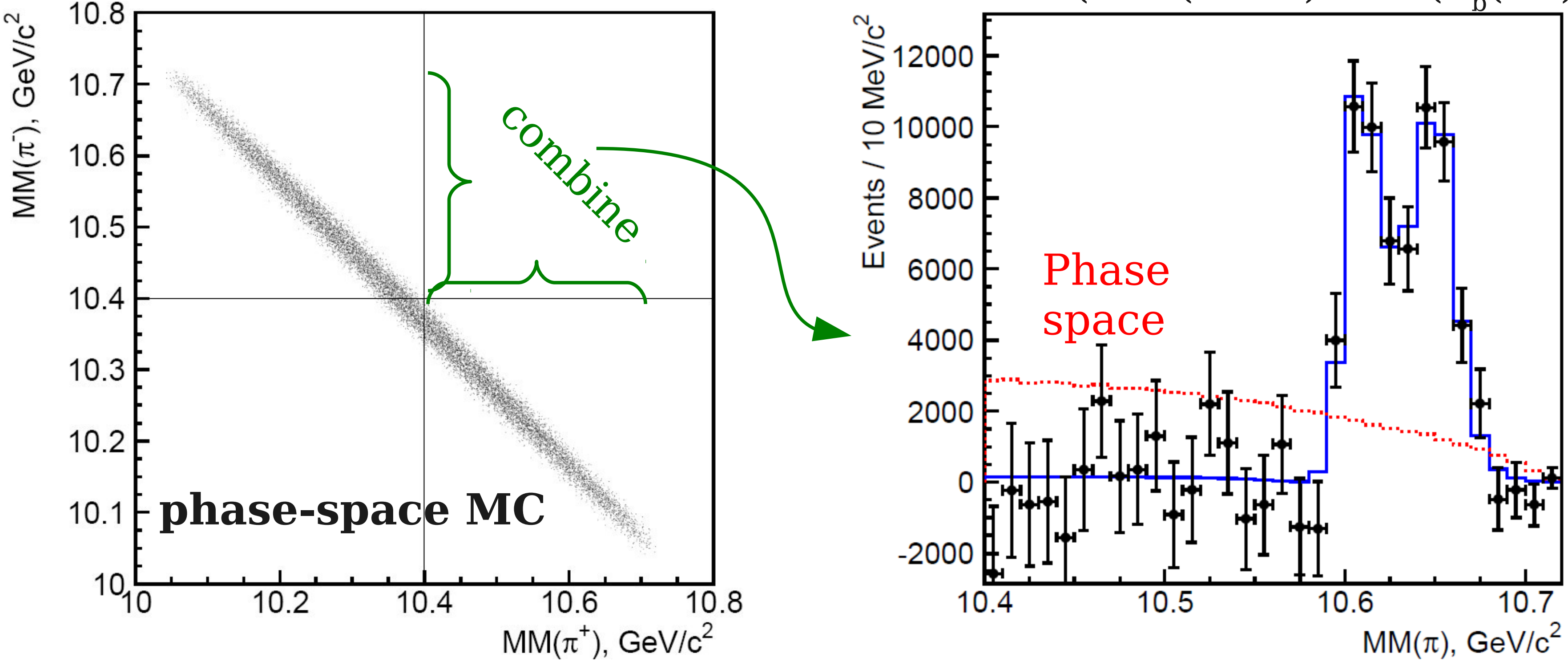
$\Upsilon(4S)$ decay to h_b is not enhanced

Source of $h_b(1P)$

Inspect the mass of $h_b\pi^{\pm}$: look at the missing mass of a single pion

$M(h_b\pi^+) \equiv MM(\pi^-)$

data $(MM(\pi^+\pi^-) \sim M(h_b(1P)))$



$$\left|BW(s, M_1, \Gamma_1) + ae^{i\phi_2}BW(s, M_2, \Gamma_2) + be^{i\phi_3}\right|^2 \frac{qp}{\sqrt{s}}$$

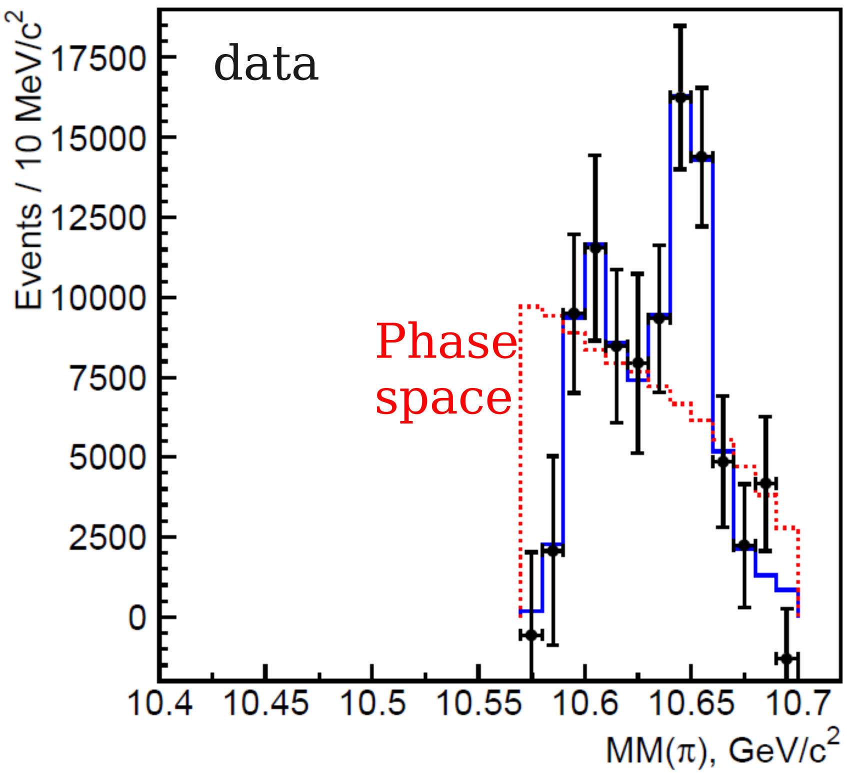
Significances: 1 resonances vs 0: **6.6σ**
2 resonance vs 0: **16σ**

incl. syst. effects

Source of $h_b(2P)$

For $MM(\pi^+\pi^-) \sim M(h_b(2P))$, the allowed phase space is smaller but two structures can also be seen

Significances: 1 reso. vs 0: **1.9σ**
2 reso. vs 0: **4.7σ**



	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M_{Z_{b1}}$	$10605.1 \pm 2.2^{+3.0}_{-1.0}$	$10596 \pm 7^{+5}_{-2}$
$\Gamma_{Z_{b1}}$	$11.4^{+4.5+2.1}_{-3.9-1.2}$	16^{+16+13}_{-10-4}
$M_{Z_{b2}}$	$10654.5 \pm 2.5^{+1.0}_{-1.9}$	$10651 \pm 4 \pm 2$
$\Gamma_{Z_{b2}}$	$11.4^{+5.4+2.1}_{-4.7-5.7}$	$12^{+11+8}_{-9\ -2}$
a	$1.8^{+1.0+0.1}_{-0.7-0.5}$	$1.3^{+3.1+0.4}_{-1.1-0.7}$
ϕ	188^{+44+4}_{-58-9}	$255^{+56+12}_{-72-183}$
NR	~ 0	~ 0

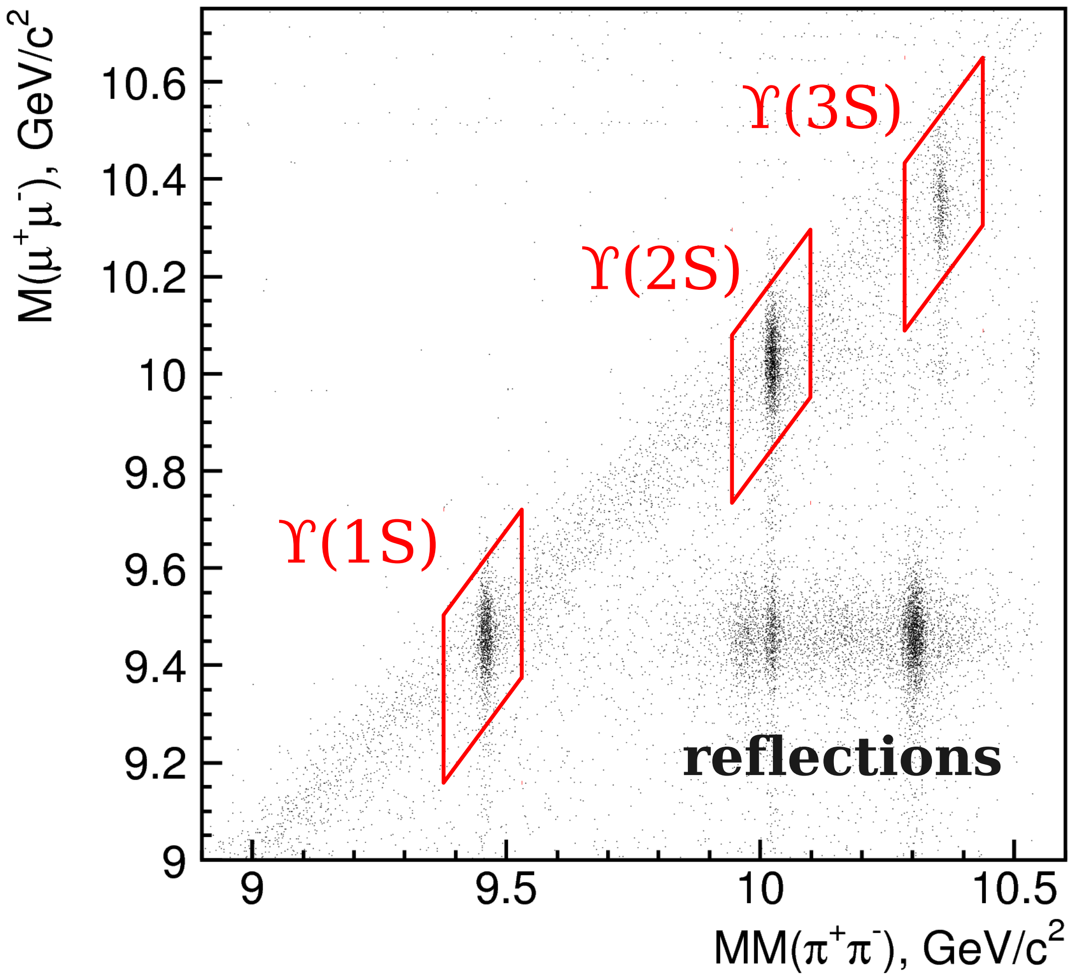
Mass/width in MeV(/c²), phase in degrees

Resonances parameters **agree well** between $h_b(1P)$ and $h_b(2P)$

NR~0: almost all $h_b(nP)$ are produced through $\Upsilon(5S) \to Z_b^{\pm}\pi^{\mp} \to h_b\pi^+\pi^-$

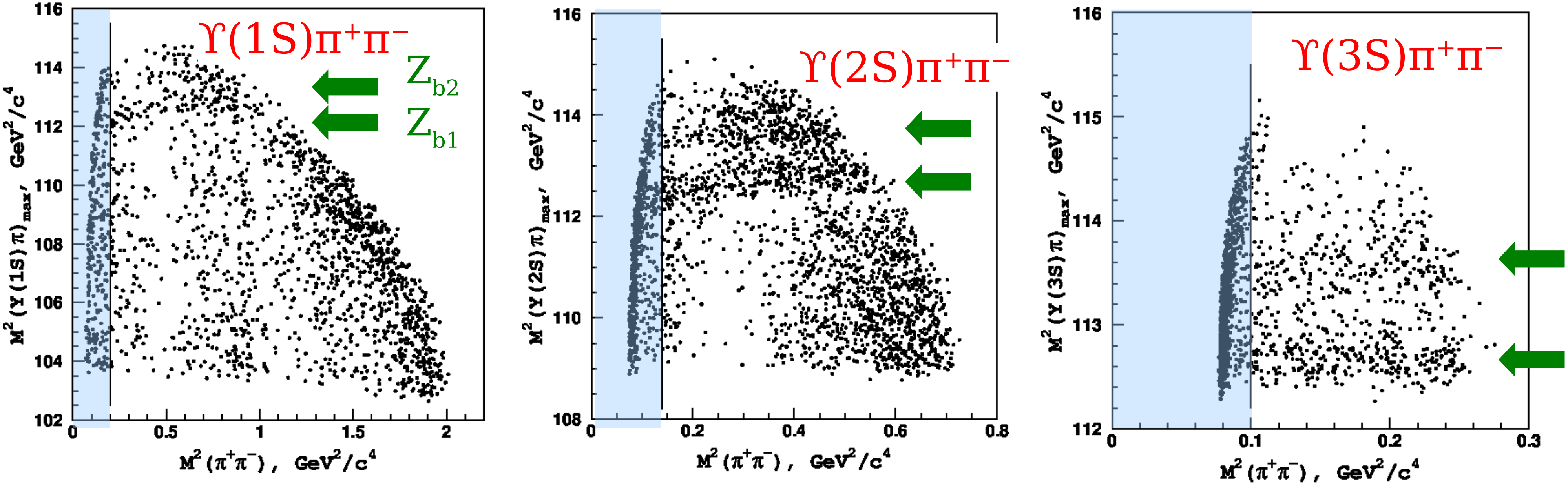
Back to $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$

Select $\Upsilon(5S) \to \Upsilon(nS)[\to \mu^+\mu^-]\ \pi^+\pi^-$ exclusive decays



Perform Dalitz plot analysis!

Dalitz plots and fit model



Exclude region with large bkg from photon conversions

$$S(s_1, s_2) = |A_{Z_{b1}} + A_{Z_{b2}} + A_{\mathrm{NR}} + A_{f_0(980)} + A_{f_2(1270)}|^2$$

$$s_i = M^2_{\pi_i \Upsilon}$$

Flatté (from our $B^+ \to K^+\pi^+\pi^-$ analysis)

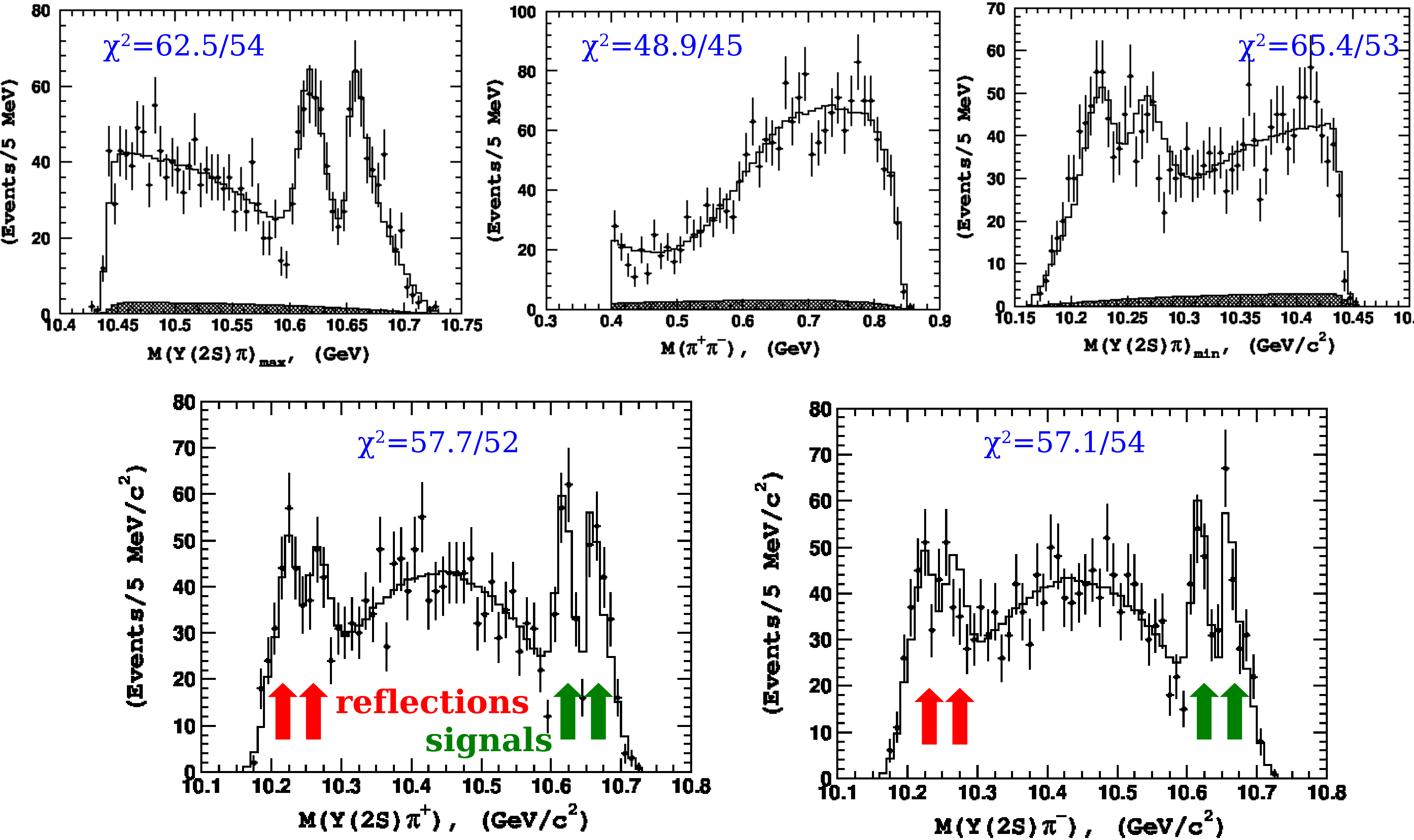
D-wave BW (PDG)

$$A_{Z_{bk}} = a_k e^{i\phi_k} \left(\frac{\Gamma_k}{M_k^2 - s_1 - iM_k\Gamma_k} + \frac{\Gamma_k}{M_k^2 - s_2 - iM_k\Gamma_k} \right)$$

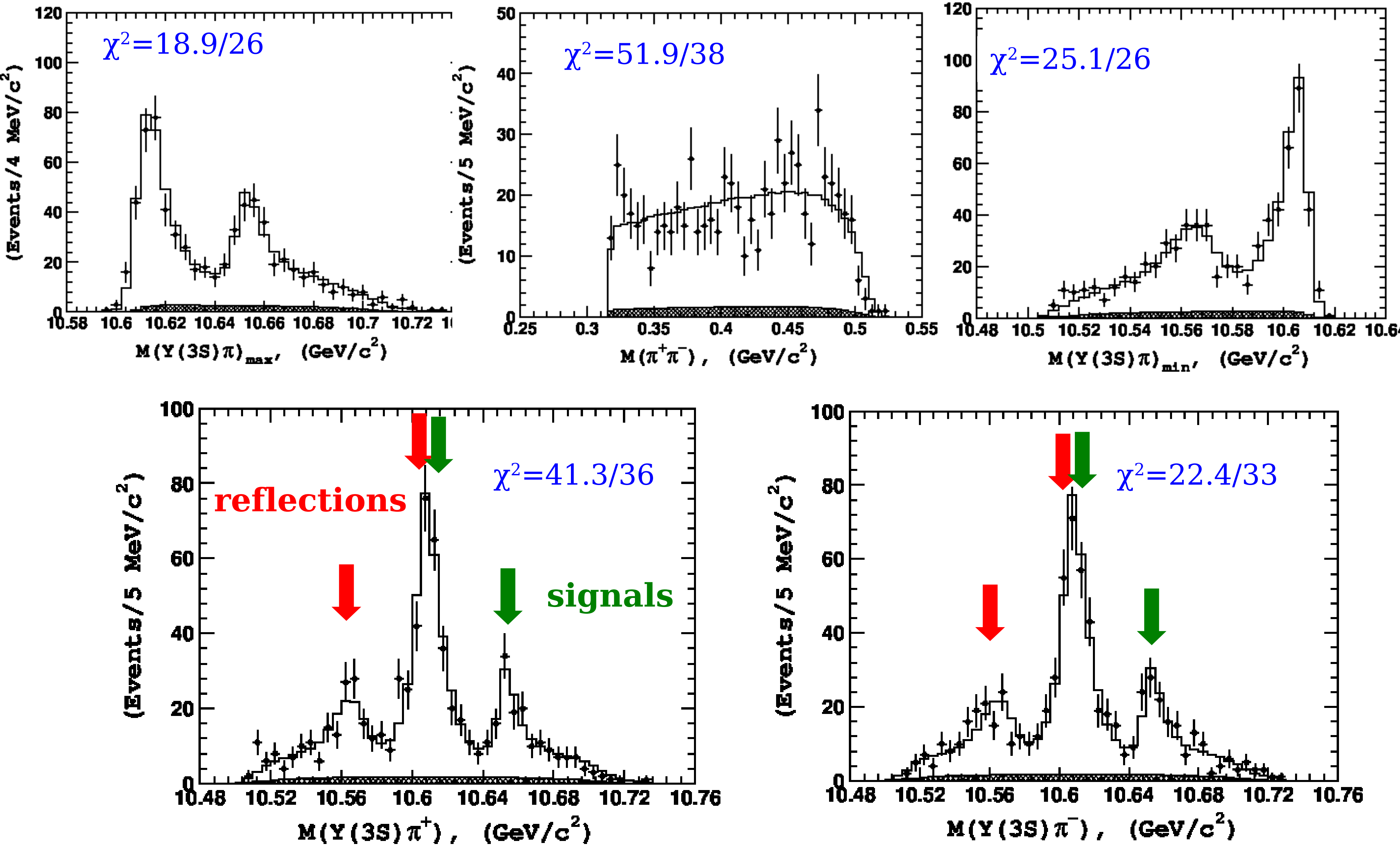
$$A_{\mathrm{NR}} = c_1 + c_2 M^2_{\pi\pi}$$

A. Voloshin, PRD74:054022, 2006
Prog. Part. Nucl. Phys. 61:455, 2008

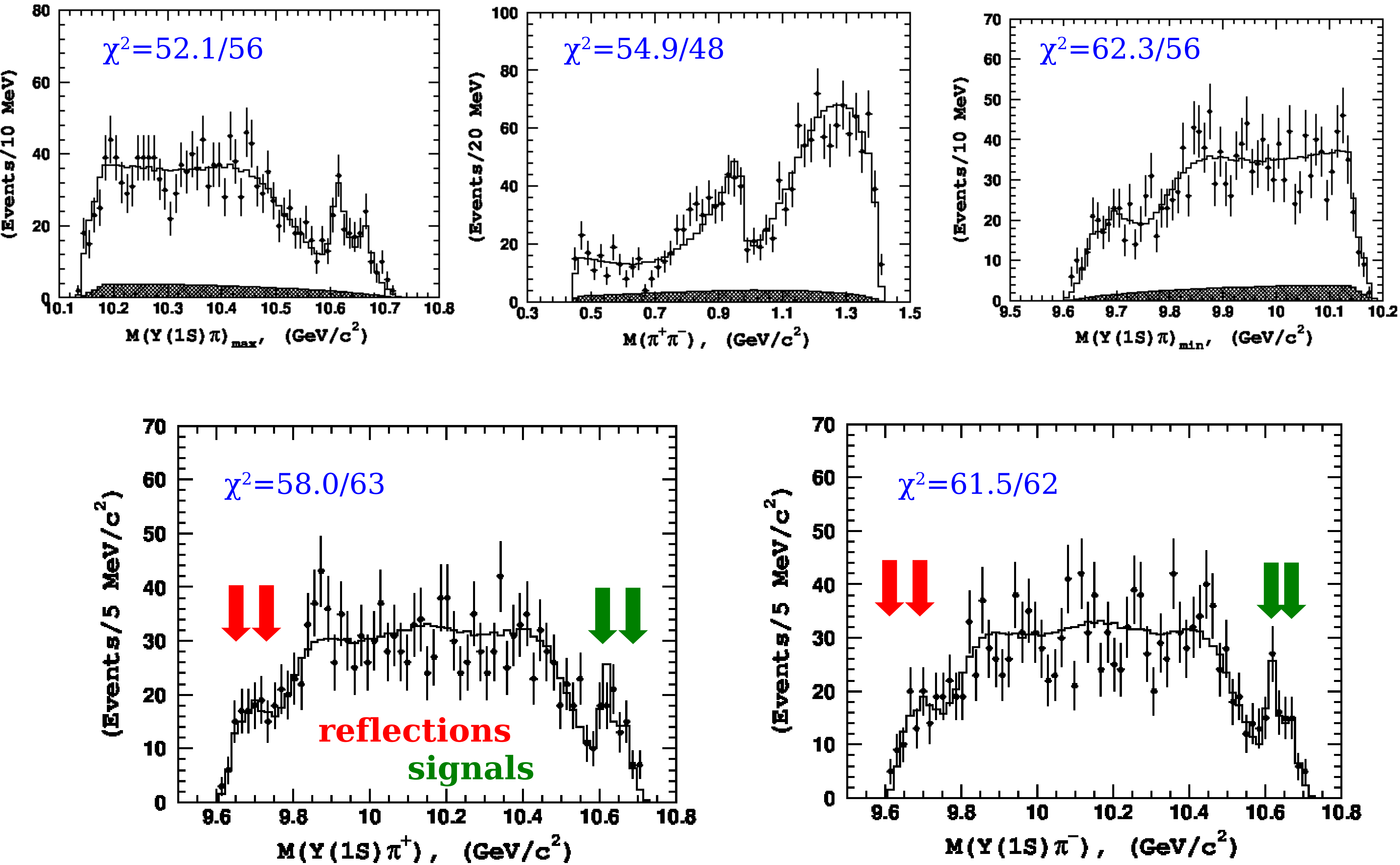
Results: $\Upsilon(2S)\pi^+\pi^-$



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



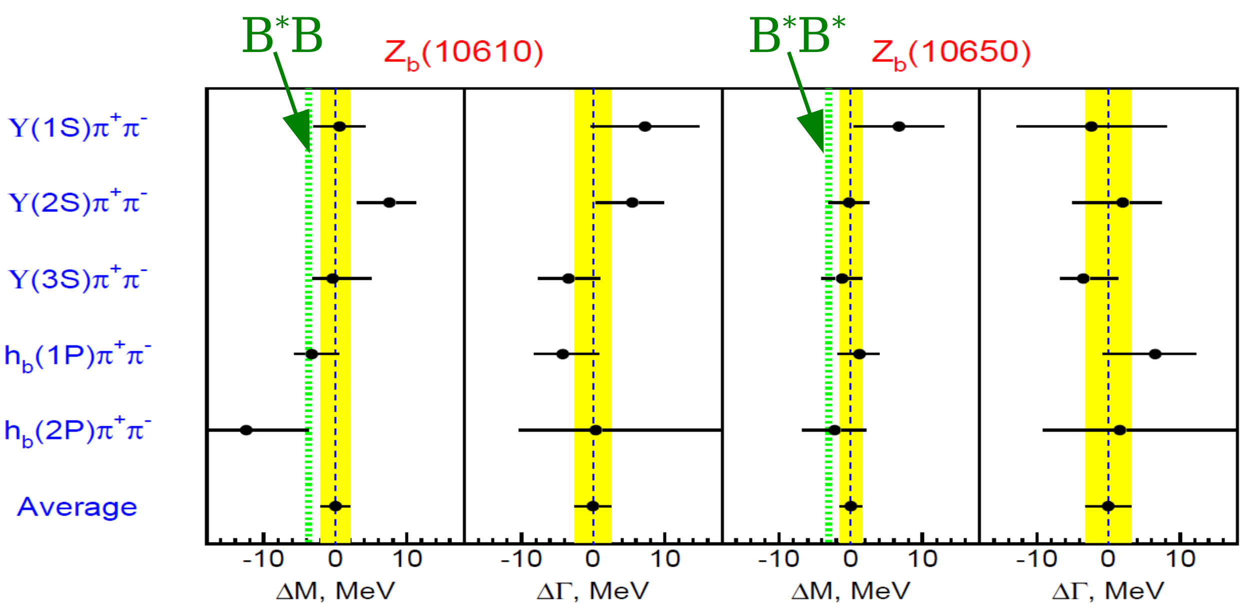
Results: $\Upsilon(1S)\pi^+\pi^-$



Z_b's parameters summary

	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M_{Z_{b1}}$ [MeV/c^2]	$10609 \pm 3 \pm 2$	$10616 \pm 2^{+3}_{-4}$	$10608 \pm 2^{+5}_{-2}$	$10605.1 \pm 2.2^{+3.0}_{-1.0}$	$10596 \pm 7^{+5}_{-2}$
$\Gamma_{Z_{b1}}$ [MeV]	$22.9 \pm 7.3 \pm 2$	$21.4 \pm 4^{+2}_{-3}$	$12.2 \pm 1.7 \pm 4$	$11.4^{+4.5+2.1}_{-3.9-1.2}$	16^{+16+13}_{-10-4}
$M_{Z_{b2}}$ [MeV/c^2]	$10660 \pm 6 \pm 2$	$10653 \pm 2 \pm 2$	$10652 \pm 2 \pm 2$	$10654.5 \pm 2.5 \pm {}^{+1.0}_{-1.9}$	$10651 \pm 4 \pm 2$
$\Gamma_{Z_{b2}}$ [MeV]	$12 \pm 10 \pm 3$	$16.4 \pm 3.6^{+4}_{-6}$	$10.9 \pm 2.6^{+4}_{-2}$	$20.9^{+5.4+2.1}_{-4.7-5.7}$	$12^{+11+8}_{-9\ -2}$
Rel. ampl.	$0.59 \pm 0.19^{+0.09}_{-0.03}$	$0.91 \pm 0.11^{+0.04}_{-0.03}$	$0.73 \pm 0.10^{+0.15}_{-0.05}$	$1.8^{+1.0+0.1}_{-0.7-0.5}$	$1.3^{+3.1+0.4}_{-1.1-0.7}$
Rel. phase [°]	$53 \pm 61^{+5}_{-50}$	$-20 \pm 18^{+14}_{-9}$	$6 \pm 24^{+23}_{-59}$	188^{+44+4}_{-58-9}	$255^{+56+12}_{-72-183}$

Preliminary



	$Z_b(10610)$	$Z_b(10650)$
M	10608.4±2.0	10653.2±1.5
Γ	15.6±2.5	14.4±3.2

Parameters **consistent** between **all five studied final states**
Masses just above **B^*B and B^*B^* thresholds**
Relative phases swapped between Υ (~0°) and h_b (~180°)

Indicates Z_b's could be **molecules**

Angular analysis

We perform angular analysis of $\Upsilon(5S) \to Z_b \pi_2 \to \{\Upsilon(2\text{-}3S), h_b(1P)\} \pi_1 \pi_2$ decays.

Angles:

$\theta_1 = \angle(\pi_1, e^+)$ [π_1 comes from Z_b]

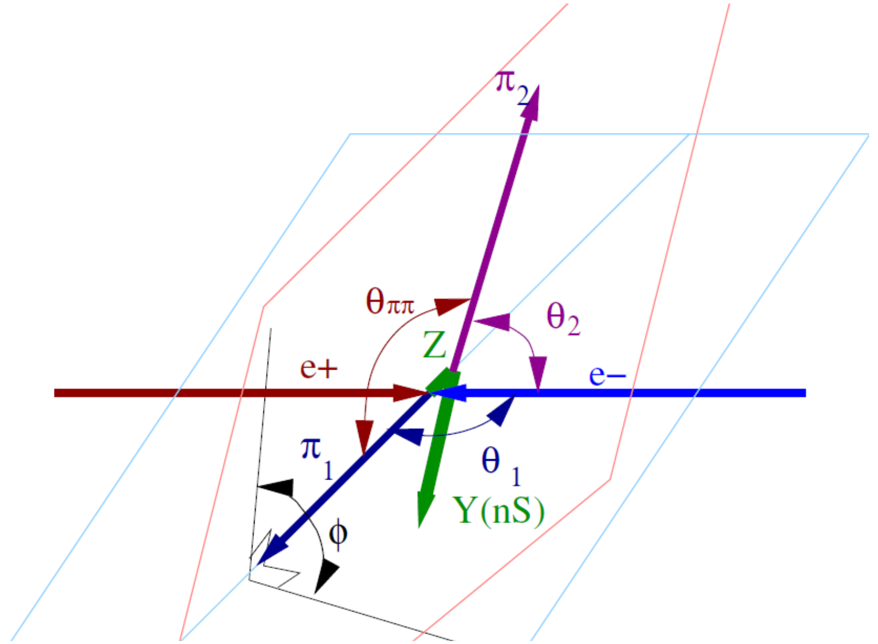
Sensitive to **2^+**

$\theta_2 = \angle(\pi_2, e^+)$ [π_2 comes from $\Upsilon(5S)$]

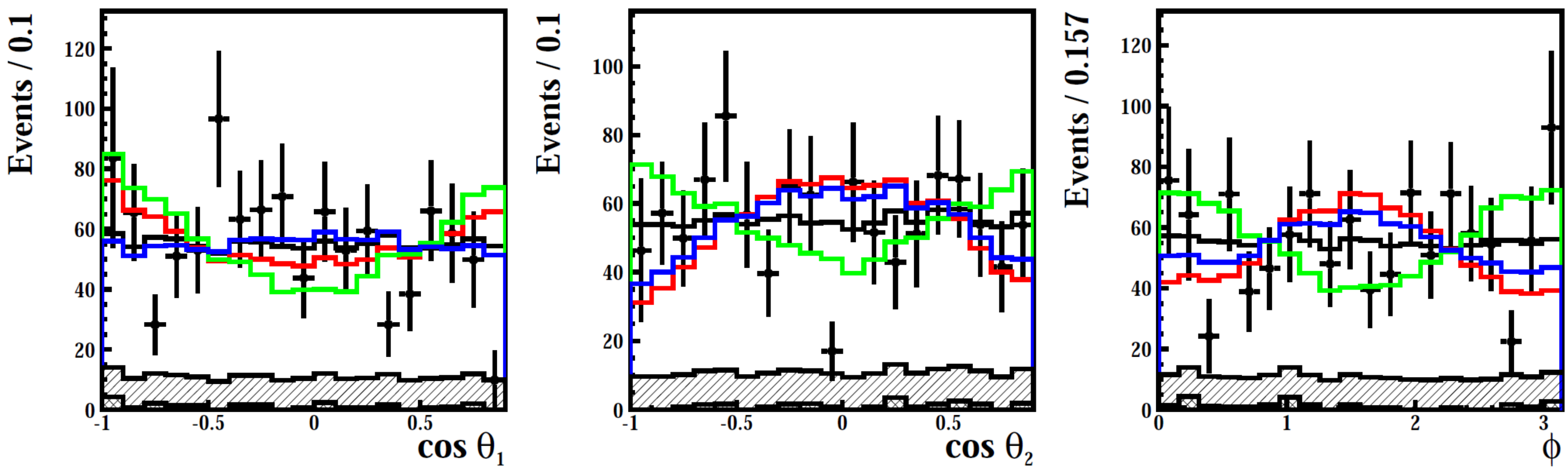
Sensitive to **1^-** and **2^-**

$\theta_{\pi\pi} = \angle(\pi_1, \pi_2)$

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



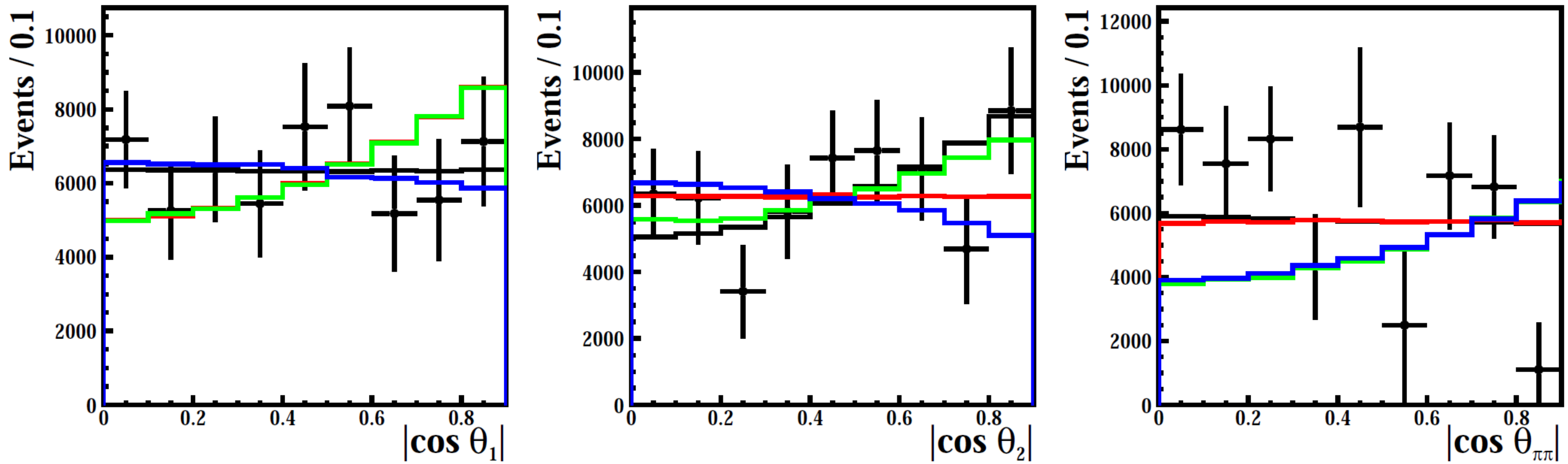
Colors: J^P=**1^+**, **1^-**, **2^+**, **2^-**



Angular analysis: results

Example: $\Upsilon(5S)\to Z_b(10610)\pi_2\to h_b(1P)\pi_1\pi_2$

Colors: J^P=**1^+**, **1^-**, **2^+**, **2^-**



Confidence levels of angular fits above to 1^+ hypothesis

	$\cos\theta_1$	$\cos\theta_2$	$\cos\theta_{\pi\pi}$
$Z_b(10610)$	84%	37%	1.1%
$Z_b(10650)$	15%	63%	7.2%

Probabilities at which other J^P hypotheses are disfavored with respect to 1^+

	$Z_b(10610)$			$Z_b(10650)$		
J^P	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$
1^-	3.6σ	0.3σ	0.3σ	3.7σ	2.6σ	2.7σ
2^+	4.3σ	3.5σ	4.3σ	4.4σ	2.7σ	2.1σ
2^-	2.7σ	2.8σ	4.3σ	2.9σ	2.6σ	2.1σ

$J^P=1^+$ is favored!

Summary

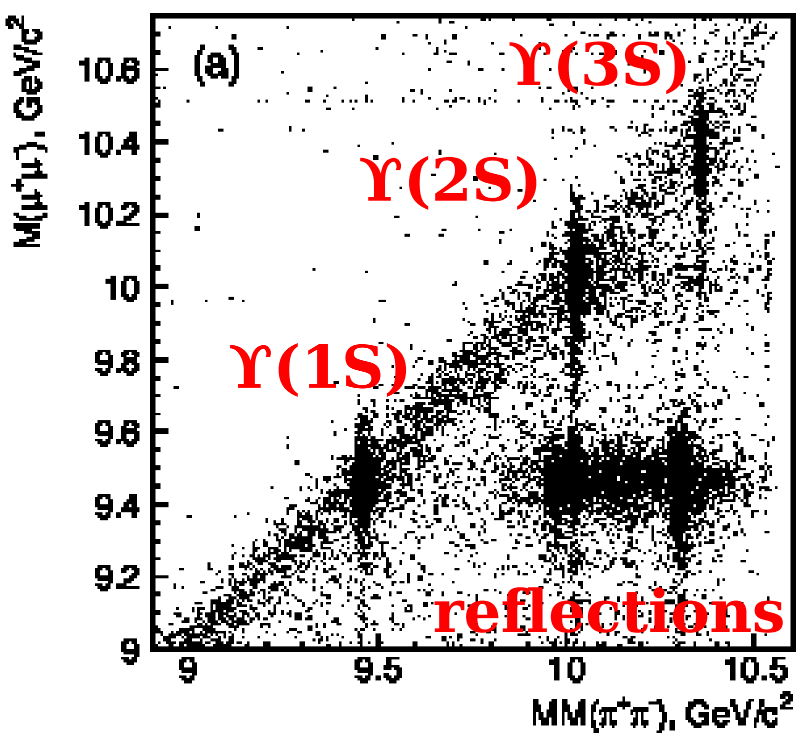
- Belle collected 121.4 fb^{-1} at the $\Upsilon(5S)$ resonance
- **First observation of two $b\bar{b}$ states: $h_b(1P)$ and $h_b(2P)$**
  - Masses in agreement with expectations (CoG of χ_b)
  - Production ratio of h_b with respect to $\Upsilon(2S)$ is not suppressed as expected due to the spin-flip: production of h_b at $\Upsilon(5S)$ is exotic
  - No evidence of h_b in 711 fb^{-1} at $\Upsilon(4S)$
- **Two charged bottomonia resonances** are seen in five different final states: $\Upsilon(5S) \to Z_b^{\pm}\pi^{\mp} \to \{\Upsilon(1\text{-}3S), h_b(1\text{-}2P)\}\pi^+\pi^-$

	$Z_b(10610)$	**$Z_b(10650)$**
M (MeV/c^2)	10608.4±2.0	10653.2±1.5
Γ (MeV)	15.6±2.5	14.4±3.2

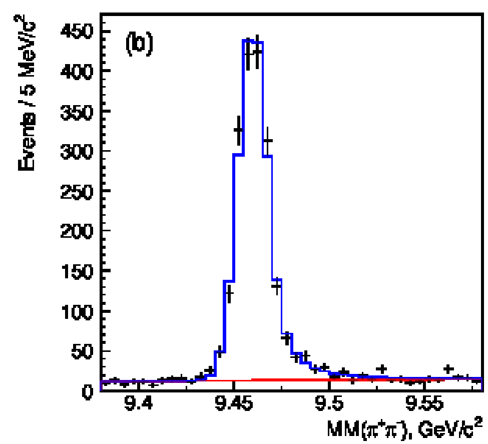
  - Masses just above B^*B and B^*B^* thresholds
  - Angular analysis favors $J^P=1^+$ at ~3σ levels over other assignments
  - Compatible with $B^*B^{(*)}$ molecule interpretation

Signal calibration

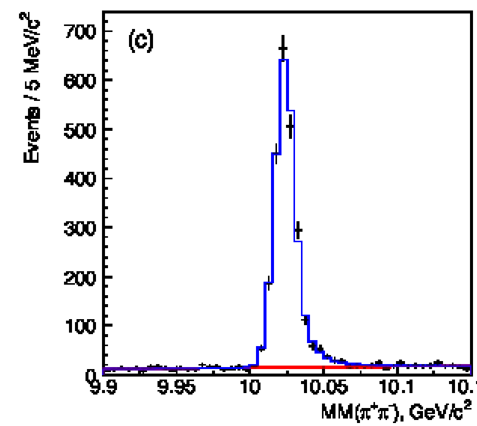
- Use the large exclusive "$\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-$ with $\Upsilon(nS) \to \mu^+\mu^-$" as reference
  - Signal: CrystalBall tail due to ISR
  - Reflections are also calibrated



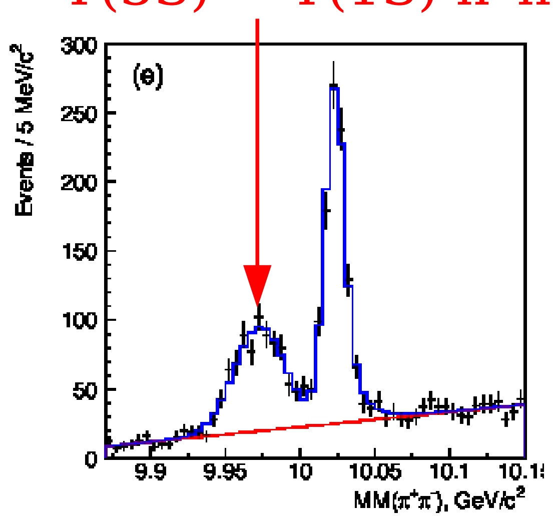
$\Upsilon(5S) \to \Upsilon(1S)\,\pi^+\pi^-$



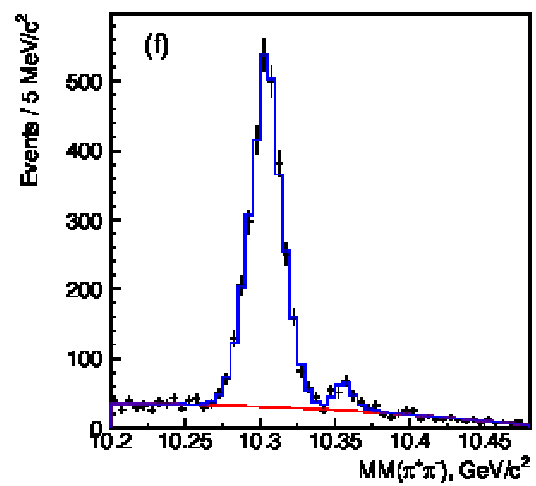
$\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-$



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



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



Systematics

	Polynomial order	Fit range	Signal shape	Selection requirements
$N[h_b]$, 10^3	± 2.4	± 3.6	$^{+1.2}_{-8.0}$	–
$M[h_b]$, MeV/c^2	$\pm .04$	$\pm .10$	$^{+0.04}_{-0.20}$	$^{+.20}_{-.30}$
$N[h_b(2P)]$, 10^3	± 2.2	± 2.6	$^{+23.}_{-9.0}$	–
$M[h_b(2P)]$, MeV/c^2	$\pm .10$	$\pm .20$	$^{+1.0}_{-0.0}$	$\pm .08$

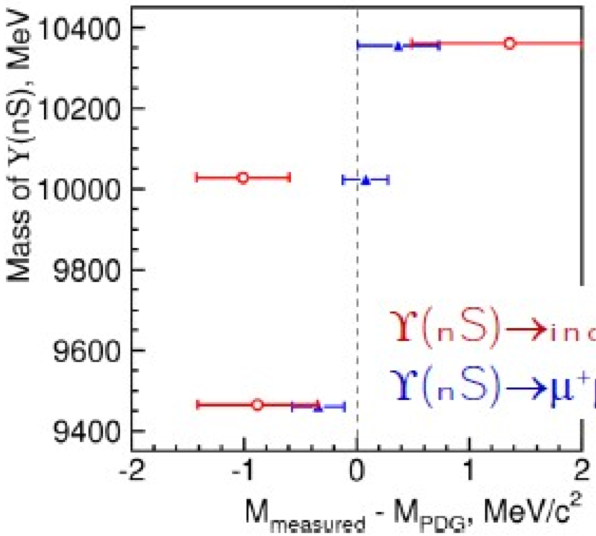
Results are stable

Significance w/ systematics

$h_b(1P)$ 5.5σ

$h_b(2P)$ 11.2σ

$M_{measured} - M_{PDG}$ for reference channels



Deviations of reference channels from PDG

⇒ additional uncertainty ±1MeV

local variations of background shape?

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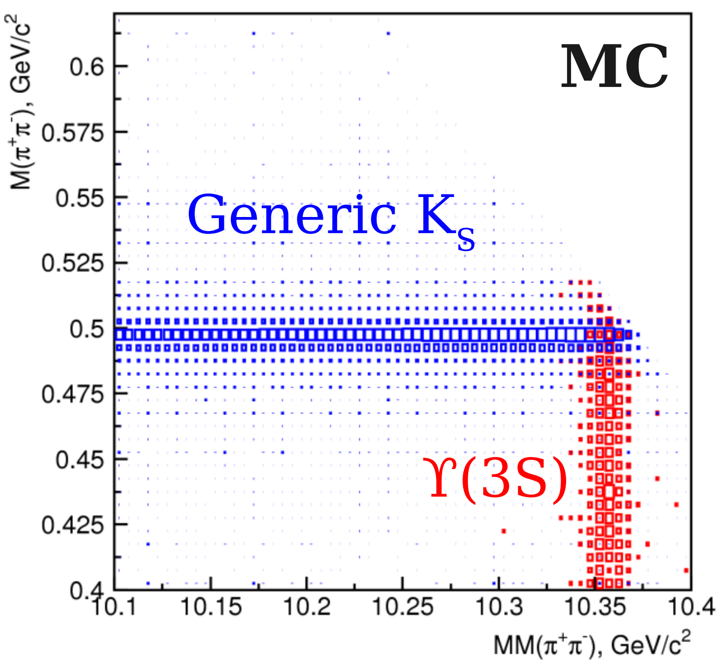
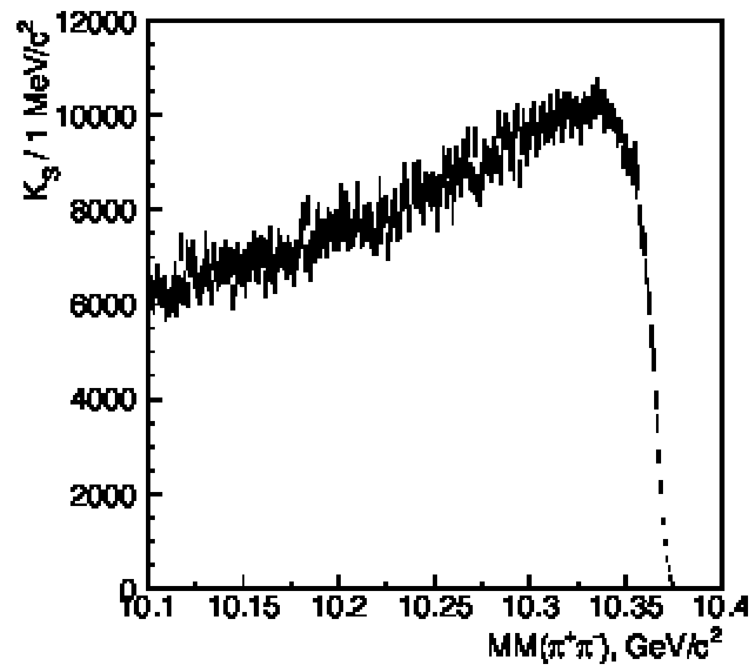
K_S background

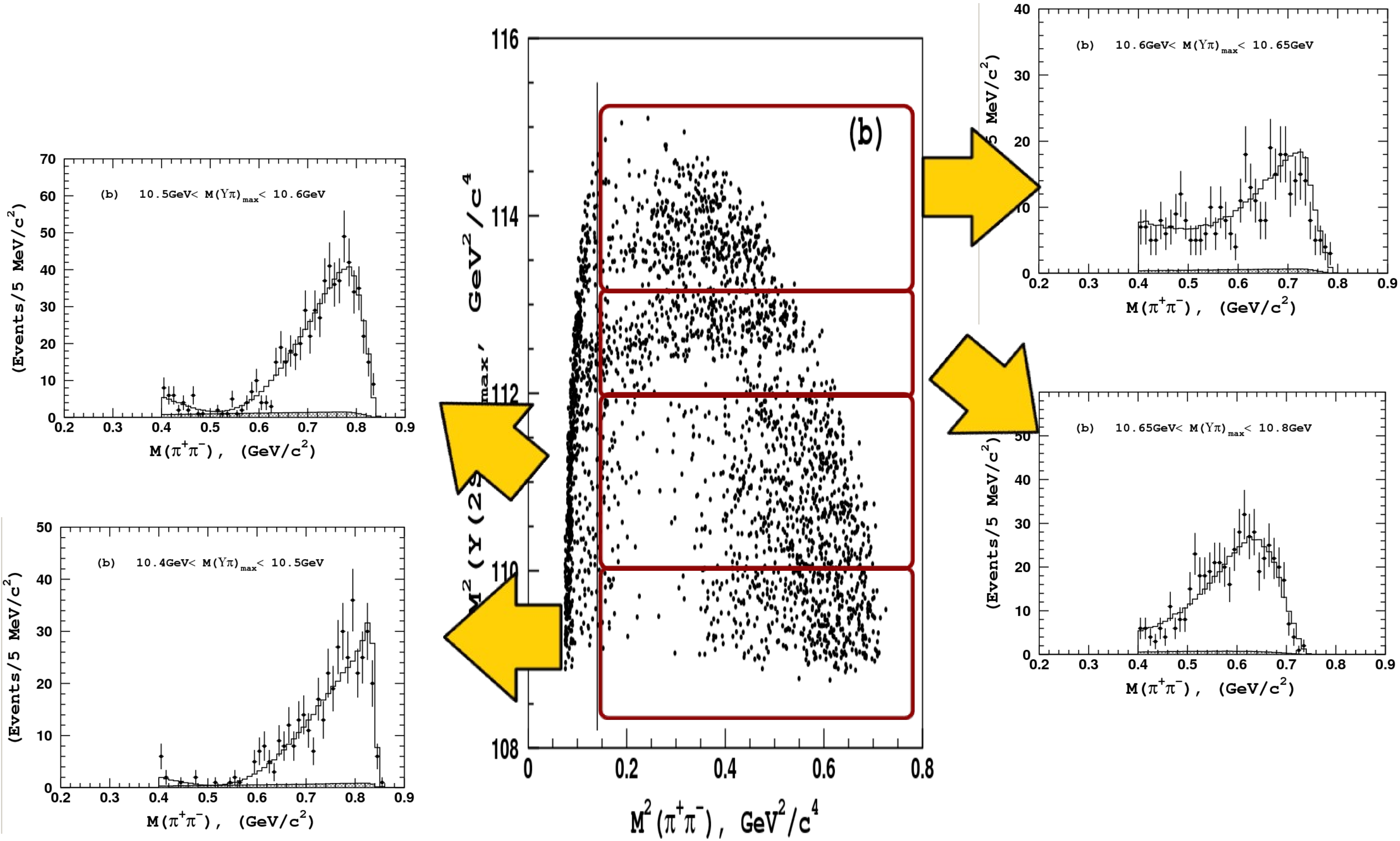
- Most background is random combination of pions that can be described by polynomial function
- At MM~$M_{\Upsilon(3S)}$ region: contribution from real $K_S \to \pi^+\pi^-$ peaks
  - Near threshold: $M_{\Upsilon(3S)} \sim E_{CM} - M_{KS}$



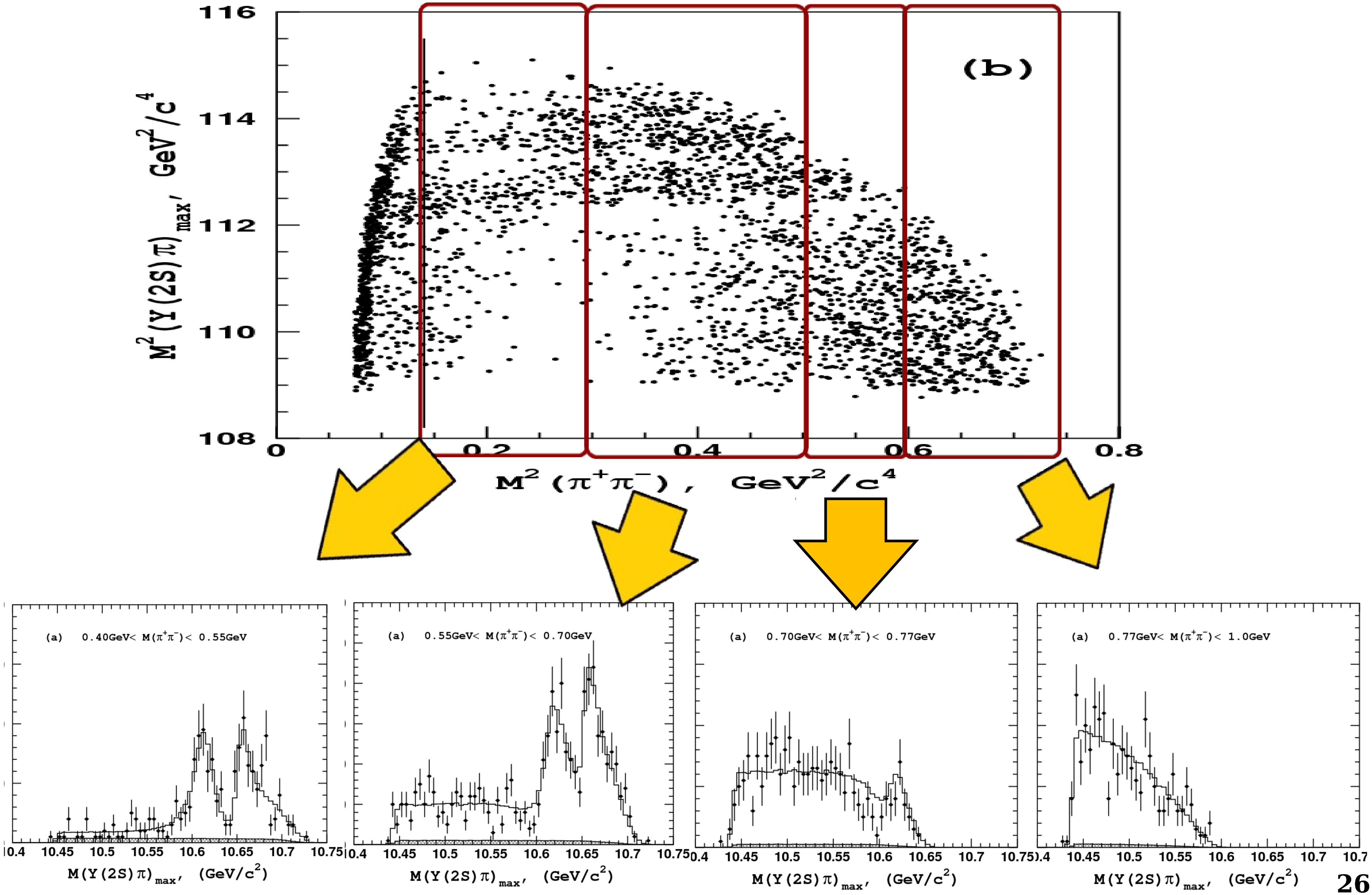


K_S yield fitted in data as a function of MM
Will be used as PDF in the fit

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



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



Angular analysis

Expectations $\Upsilon(5S) \to Z_b\, \pi_1 \to [\Upsilon(2S)\, \pi_2]\, \pi_1$

many thanks to A. Milstein (BINP)

λ – *beam direction*

1^+ isotropic

1^- $\overline{|M_{tot}|^2} \propto p_1^2[p_2^2 - (\boldsymbol{\lambda p}_2)^2] + 2(\boldsymbol{p}_1\boldsymbol{p}_2)(\boldsymbol{\lambda p}_1)(\boldsymbol{\lambda p}_2)$

2^+ $\overline{|M_{tot}|^2} \propto (\boldsymbol{\lambda}[\boldsymbol{p}_1 \times \boldsymbol{p}_2])^2[2(\boldsymbol{p}_1\boldsymbol{p}_2)^2 - \frac{1}{2}p_1^2p_2^2] + \frac{1}{2}(p_1^2)^2(p_2^2)^2$

$+(\boldsymbol{p}_1\boldsymbol{p}_2)^2[2(\boldsymbol{p}_1\boldsymbol{p}_2)^2 - 2p_1^2p_2^2 + \frac{1}{2}(\boldsymbol{\lambda p}_1)^2p_2^2]\,.$

2^- $\overline{|M_{tot}|^2} \propto 6(\boldsymbol{p}_1\boldsymbol{p}_2)^2 + 17p_1^2p_2^2 - 9p_1^2(\boldsymbol{\lambda p}_2)^2 - 8p_2^2(\boldsymbol{\lambda p}_1)^2 + 12(\boldsymbol{p}_1\boldsymbol{p}_2)(\boldsymbol{\lambda p}_1)(\boldsymbol{\lambda p}_2)$

neglect Z_b recoil motion ($\beta<0.02 \Rightarrow$ very good approximation)

also formulae for h_b are available

Consider 1D projections

θ_1, θ_2 – polar angles of 1st and 2nd pions

φ_p – angle btw planes defined by (1) π_1 & Z axis, (2) π_1 & π_2 .

- Interference terms vanish after integration over other angular variables
  $\Rightarrow$ subtraction of non-resonant contribution is possible.

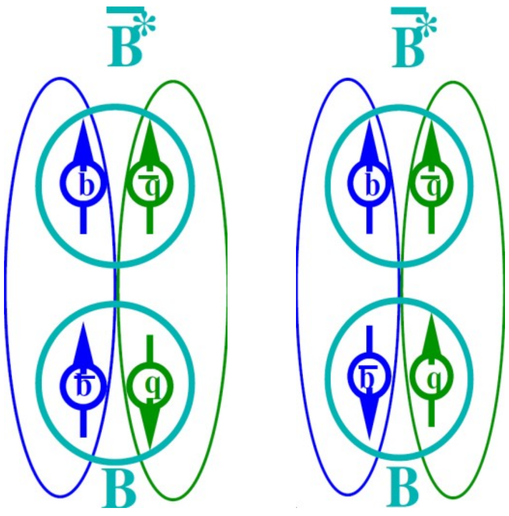
Possible nature of Z_b's

arXiv:1105.4473

B*B and B*B* S-wave molecules

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

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



Masses of Z_b are close to B*B(*) thresholds

- **Quantum numbers $J^P=1^+$**
- **Amplitude ratio A[Z_b(10610)] / A[Z_b(10650)] ~1**
- **Relative phase ~0 for ϒ and ~180^0 for h_b**
- **Explains why $h_b\pi\pi$ is unsuppressed relative to ϒππ**
- **Neutral partners of Z_b**
- **Additional measurements in B*B and B*B* mode should be done**
- **Existence of other molecular states is predicted**