Bottomonium(-like) spectroscopy at Belle

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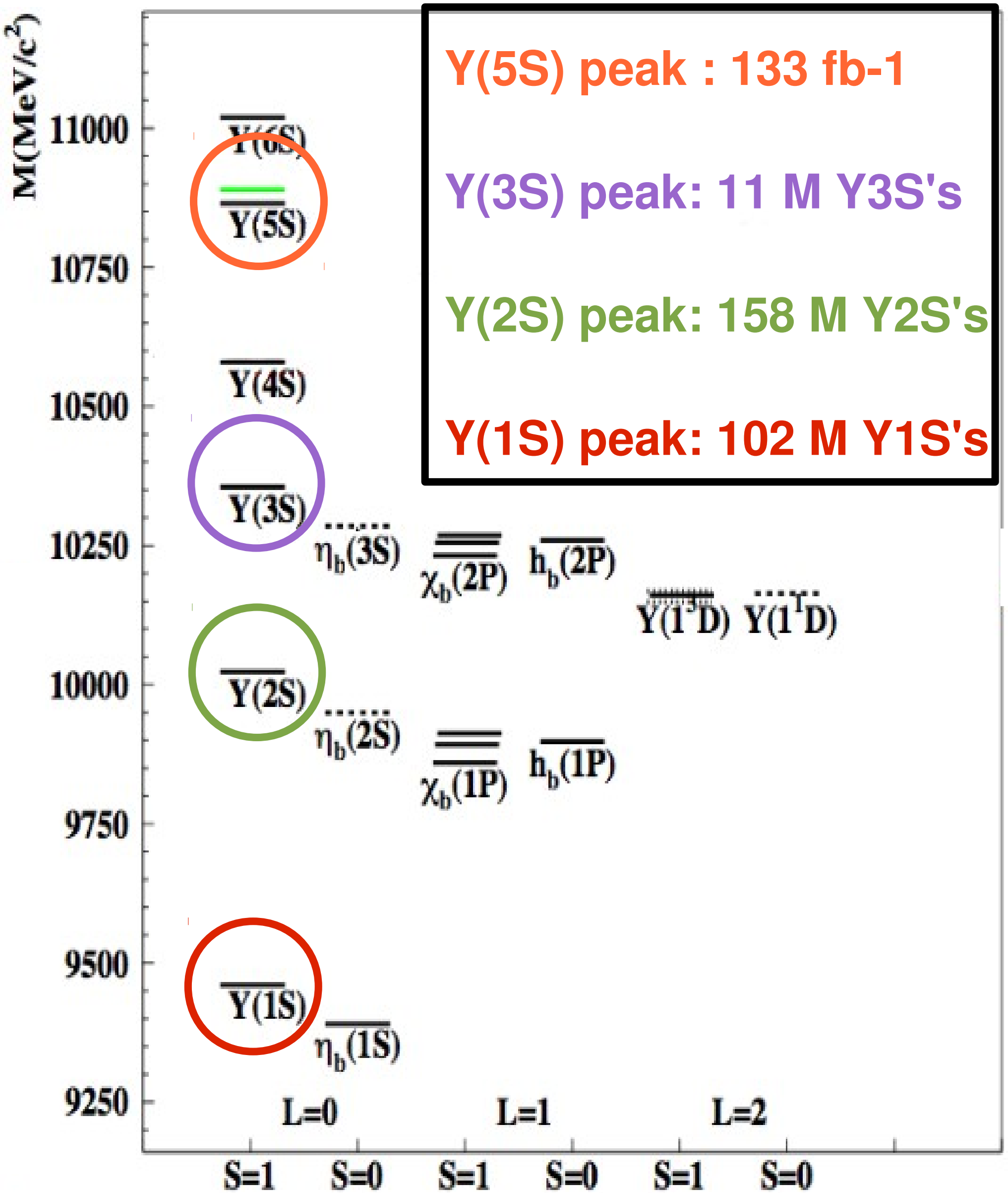
The Belle experiment

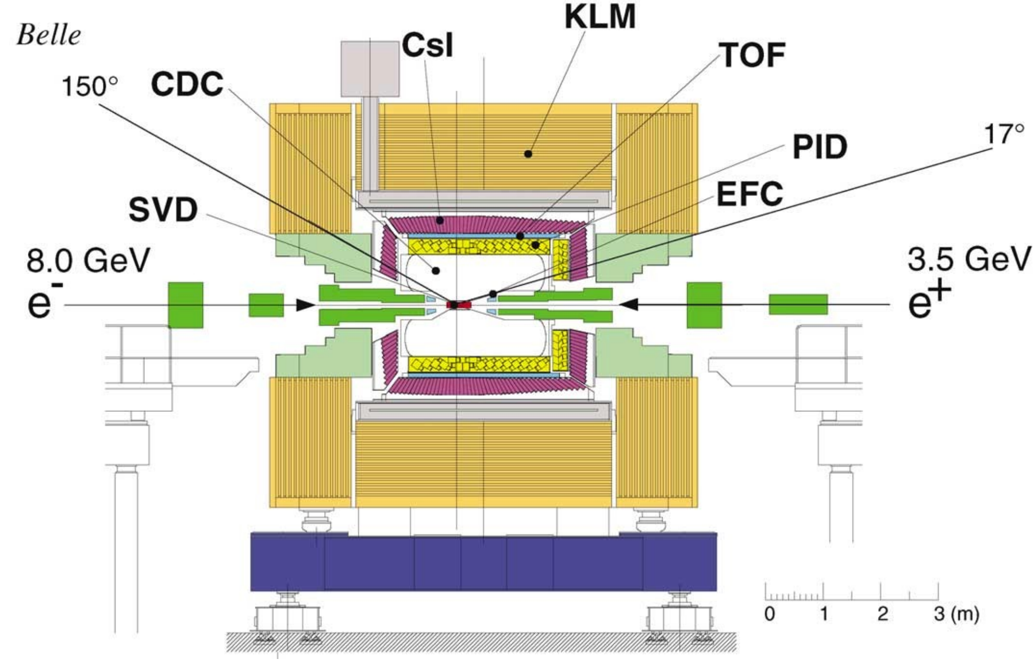


Y(5S) peak : 133 fb-1

Y(3S) peak: 11 M Y3S's

Y(2S) peak: 158 M Y2S's

Y(1S) peak: 102 M Y1S's



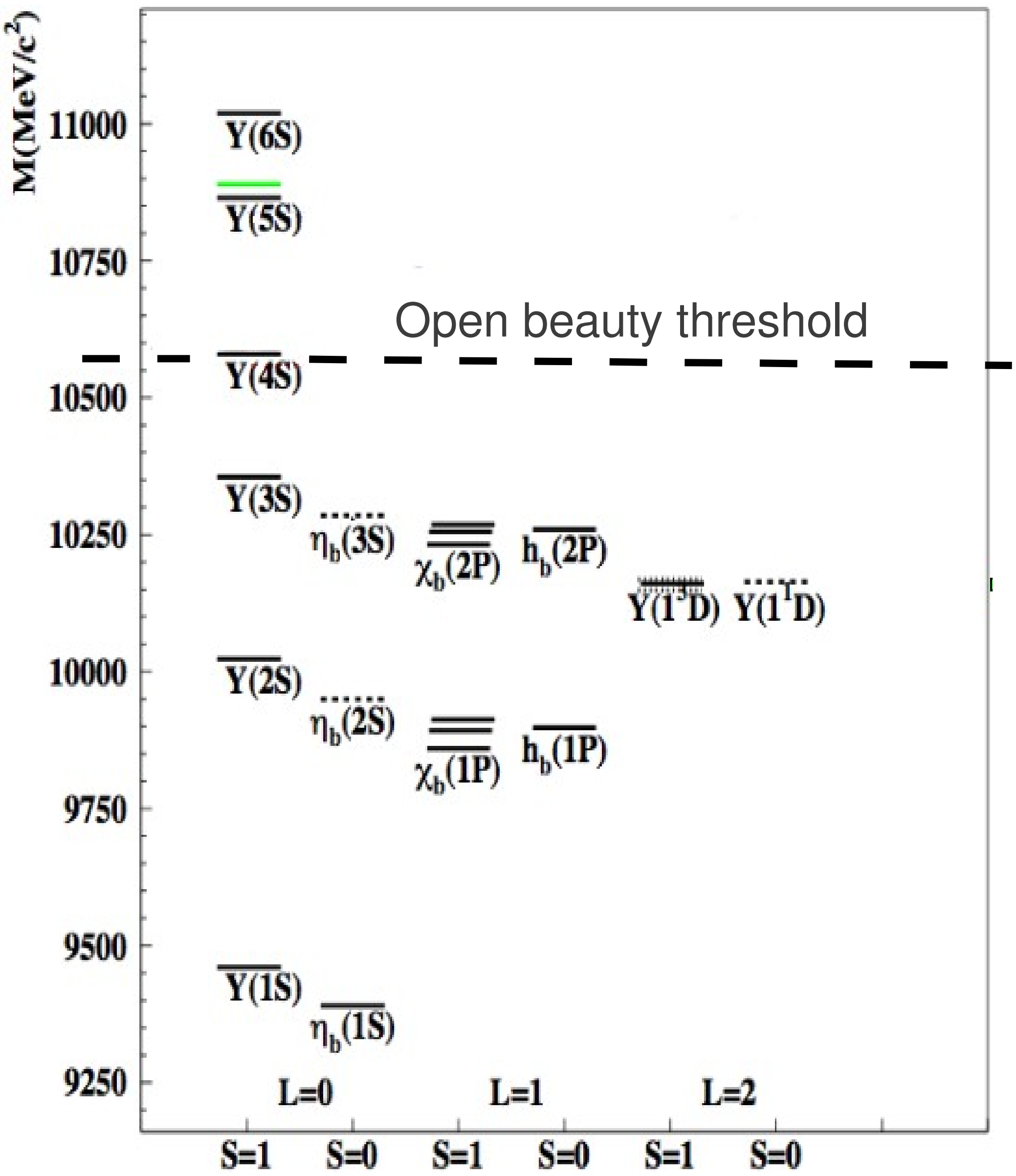
KEKB asymmetric e^+e^- collider @Y(nS) energies

- Study of B mesons (~770 M of BB pairs!)
- World largest samples of Y(1,2,5 S)
- e^+e^- → only 1^{--} states

Complete knowledge of initial state

- Can compute Center-of-mass quantity
- Missing mass

Outline



$b\bar{b}$ bound state

→ spectroscopy
→ radial excitations, singlets, triplets...

Strong interacting system

→ hadronic transitions

b quark is heavy

→ (almost) non relativistic system
→ Large range of scales in the same system

Lots of models

→ Non relativistic QCD
→ Potential model
→ QCD multipole expansion ...

I - New states

II - Transitions

III - Bottomonium decays

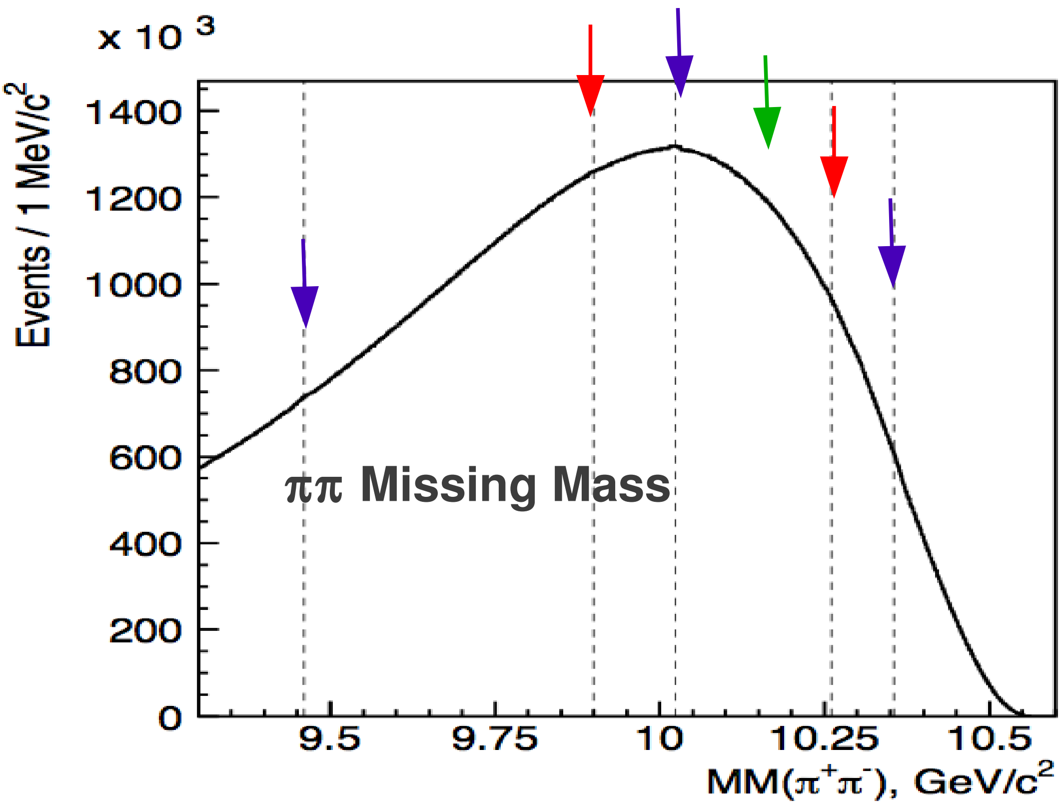
Part I

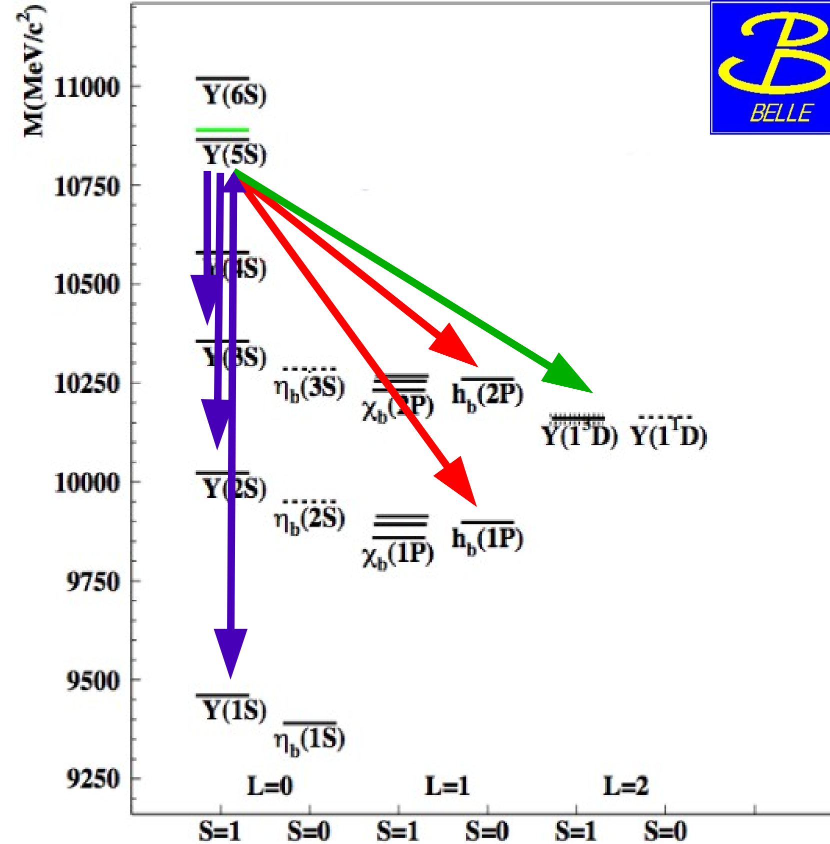
New states from Υ(5S)

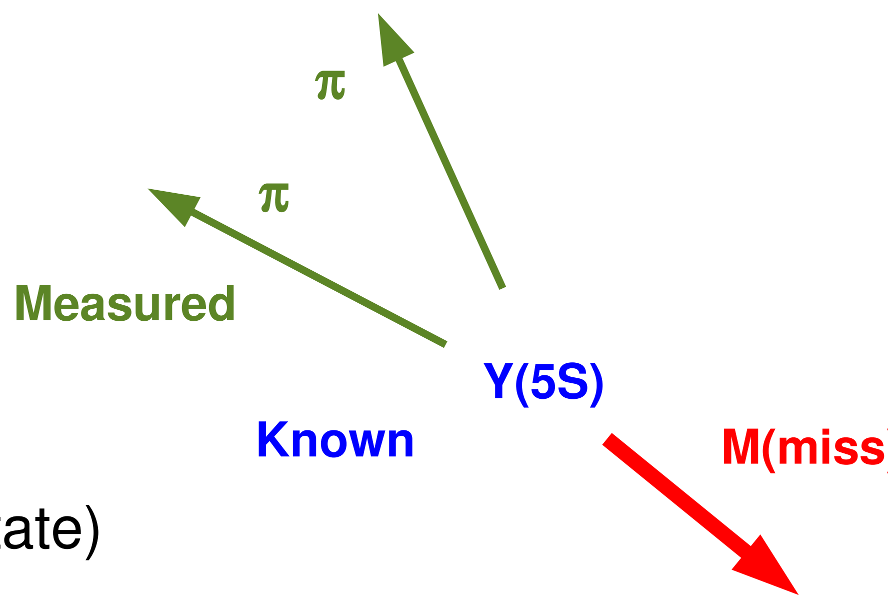
h_b(1,2P) from Υ(5S)

PRL108,032001

Inclusive search : $e^+e^- \rightarrow \Upsilon(5S) \rightarrow \pi^+\pi^- + X$
(inspired by $e^+e^- \rightarrow \psi(4170) \rightarrow \pi^+\pi^- h_c$ @ Cleo)







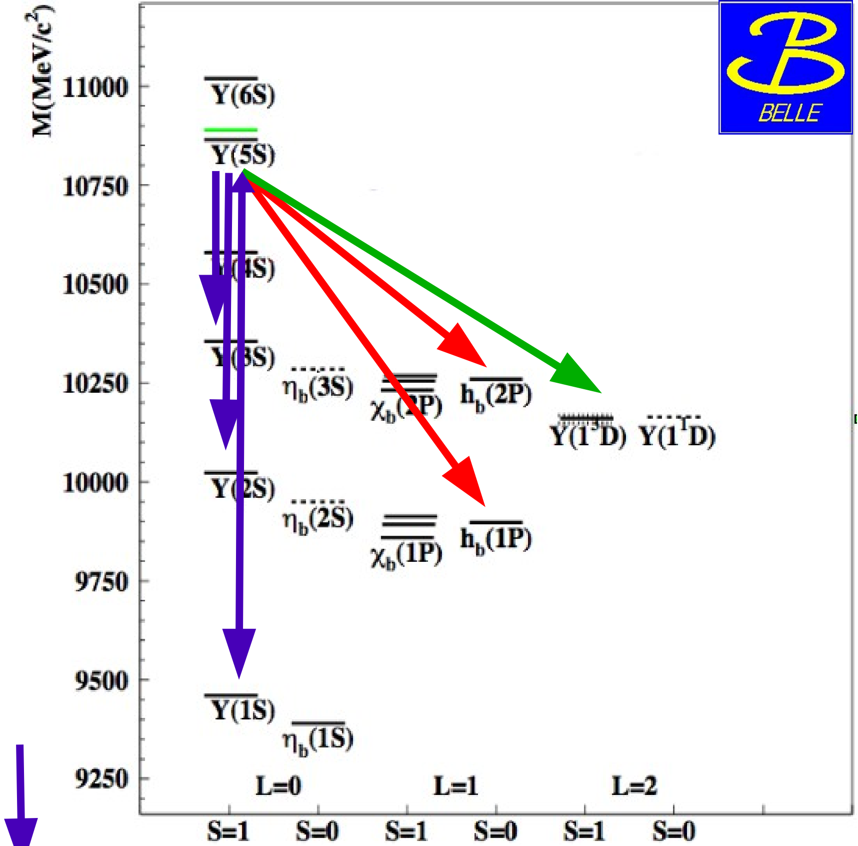
$$M(miss) = (E_{c.m.} - E^*_{\pi+\pi-})^2 - p^2_{\pi+\pi-}$$

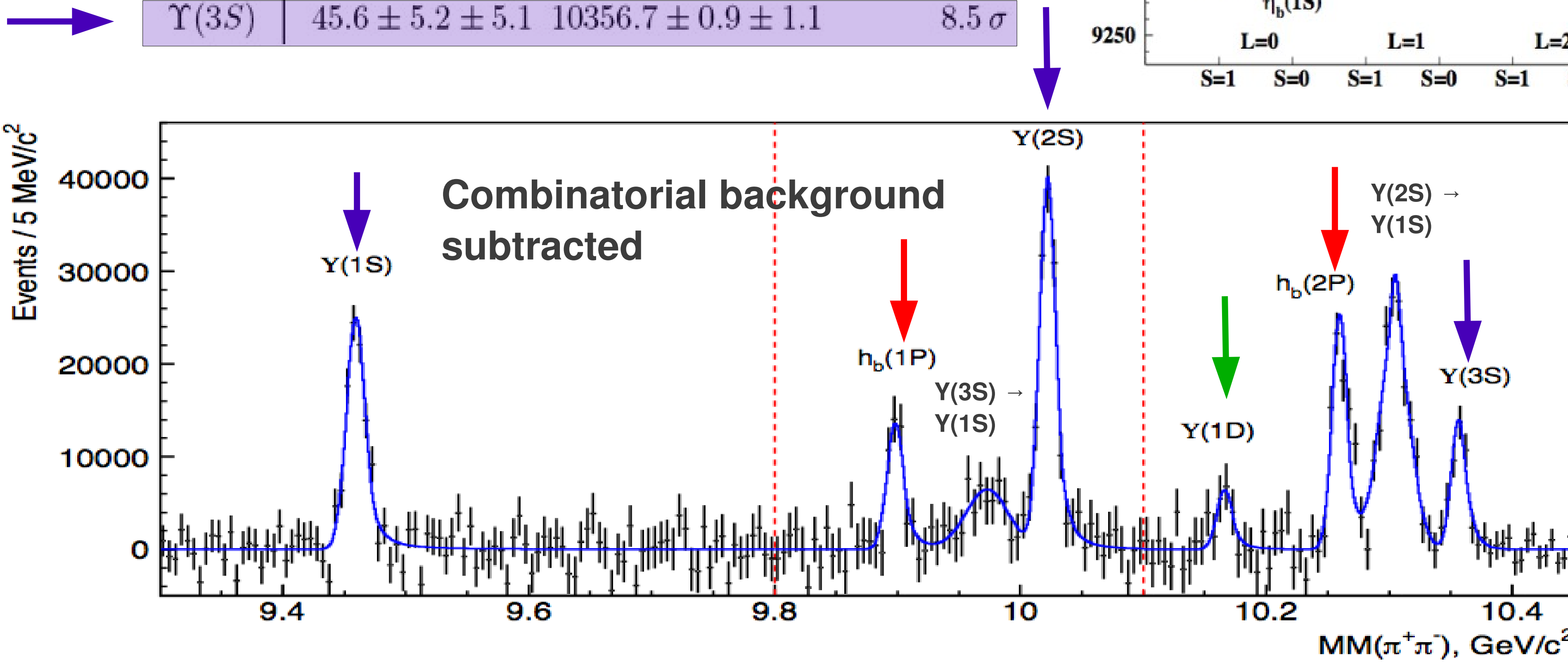
In Di-pion transition: M(miss) = M(lower state)

$h_b(1,2P)$ from $\Upsilon(5S)$

PRL108,032001

	Yield, 10^3	Mass, MeV$/c^2$	Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.0}_{-1.1}$	$6.2\,\sigma$
$3S \to 1S$	56 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.5 \pm 8.7 \pm 6.8$	$10022.3 \pm 0.4 \pm 1.0$	$16.6\,\sigma$
$\Upsilon(1D)$	22.0 ± 7.8	10166.2 ± 2.6	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.4\,\sigma$
$2S \to 1S$	$151.7 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\,\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\,\sigma$

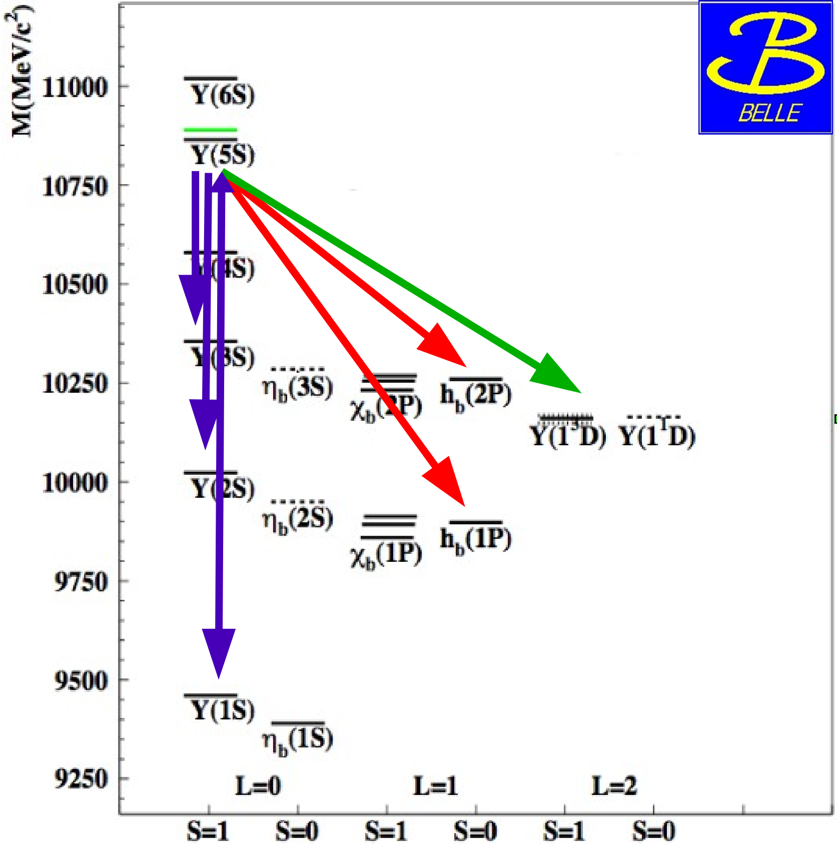




$h_b(1,2P)$ from $\Upsilon(5S)$

PRL108,032001

$h_b(nP)$ is the singlet partner of $\chi(nP)$



Hyperfine Splitting: M(singlet) – M(triplet)

$$\Delta M_{HF}(nP) = M(h_b(nP)) - M_{AVG}(\chi(nP))$$

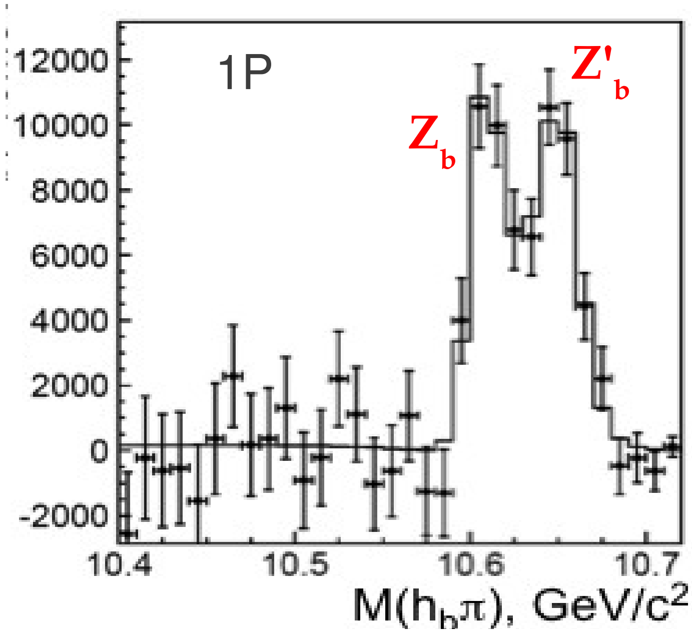
$$M_{AVG}(\chi(1P)) = (M\chi_{b0} + 3\,M\chi_{b1} + 5\,M\chi_{b2}) / 9$$

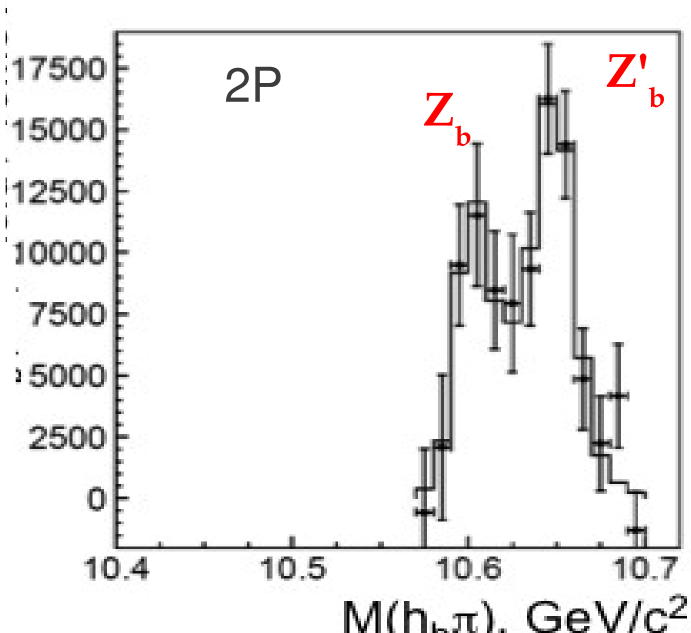
Spin-averaged mass

$\Delta M_{HF}(1P) = \mathbf{0.8 \pm 1.1}$ MeV/c^2	Precise measurement
	Study
$\Delta M_{HF}(2P) = \mathbf{0.5 \pm 1.2}$ MeV/c^2	**of spin effects in QCD**

$\pi\, h_b(1,2P)$ mass: Z_b

PRL108,122001





The heavy quark spin flip is predicted to suppress the $\pi\pi h_b$ transition

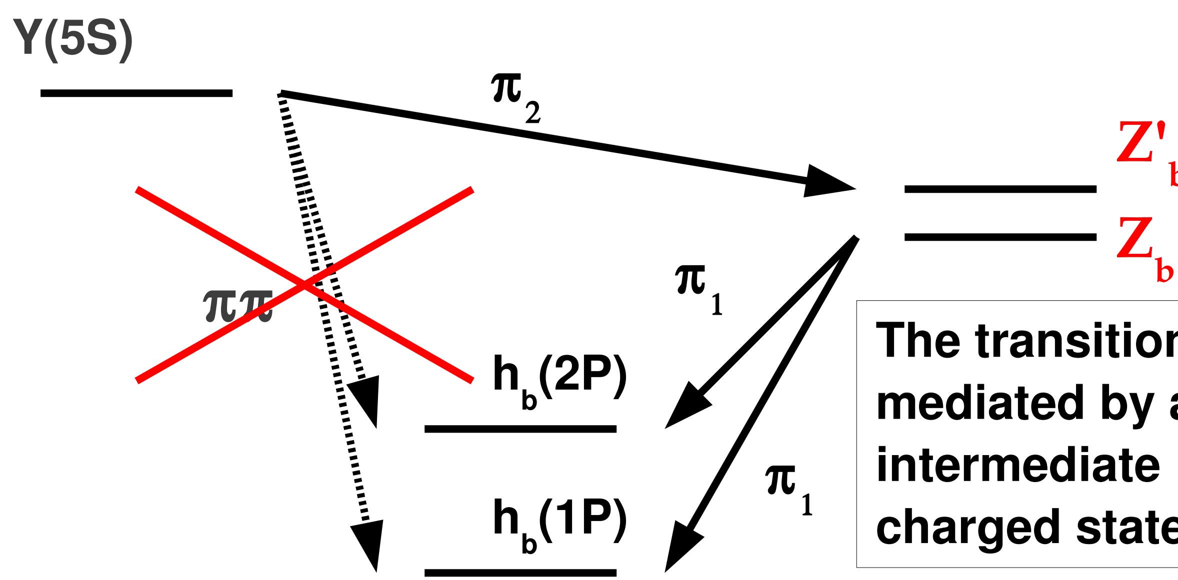
spin-flip

$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-]} = \begin{cases} 0.46 \pm 0.08^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

no spin-flip

No suppression

Intermediate state? Look at h_b yield in bins of $M(\pi_1 h_b)$ (Missing mass from π_2)

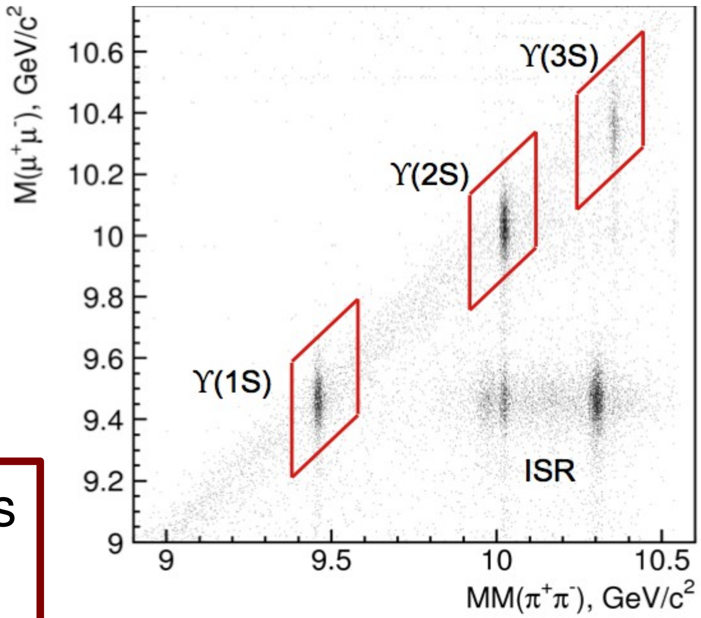


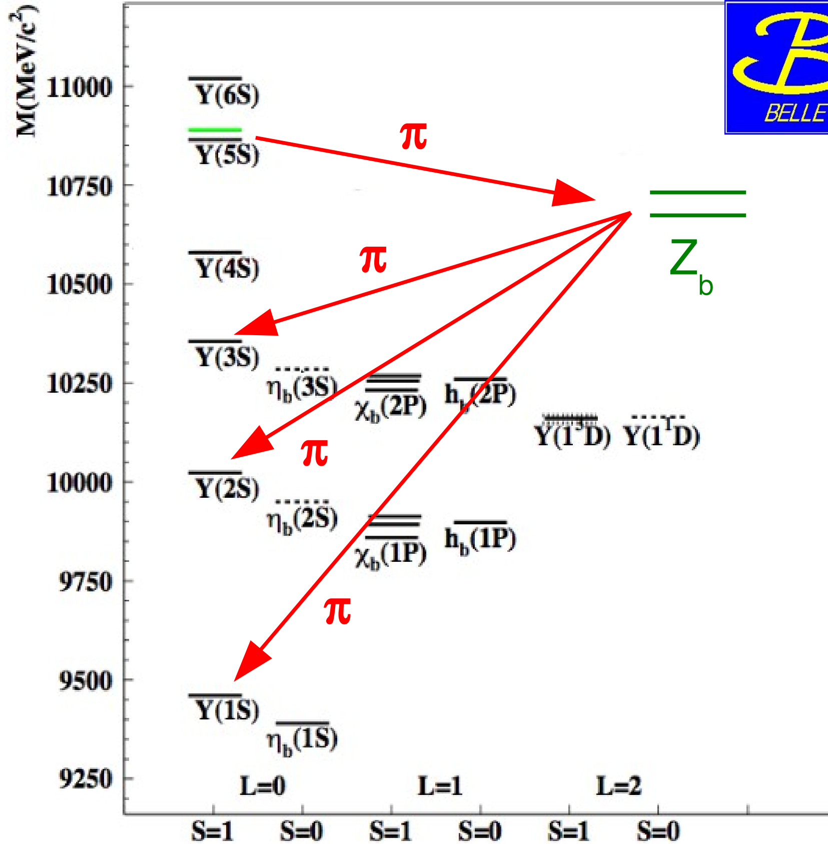
The transition is mediated by an intermediate charged state

Z_b in Y(nS) final states

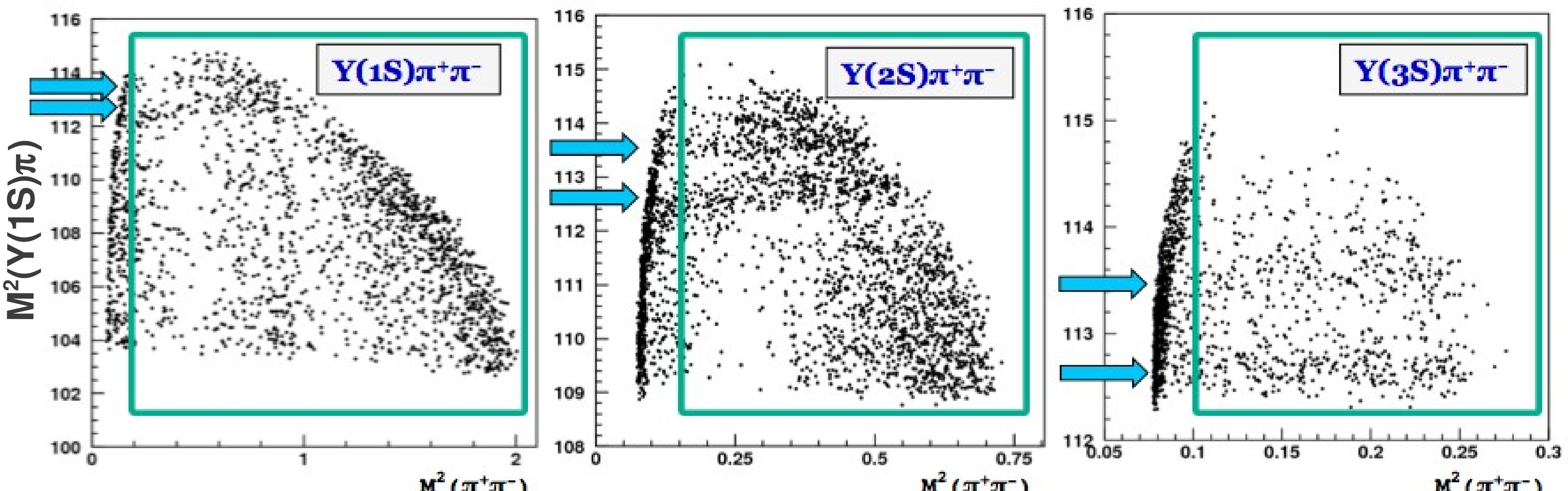
PRL108,122001

Y(nS) → $\mu^+\mu^-$
- Clean final state
- Pure Y(nS) sample
- $\pi^+\pi^-$ recoil tag



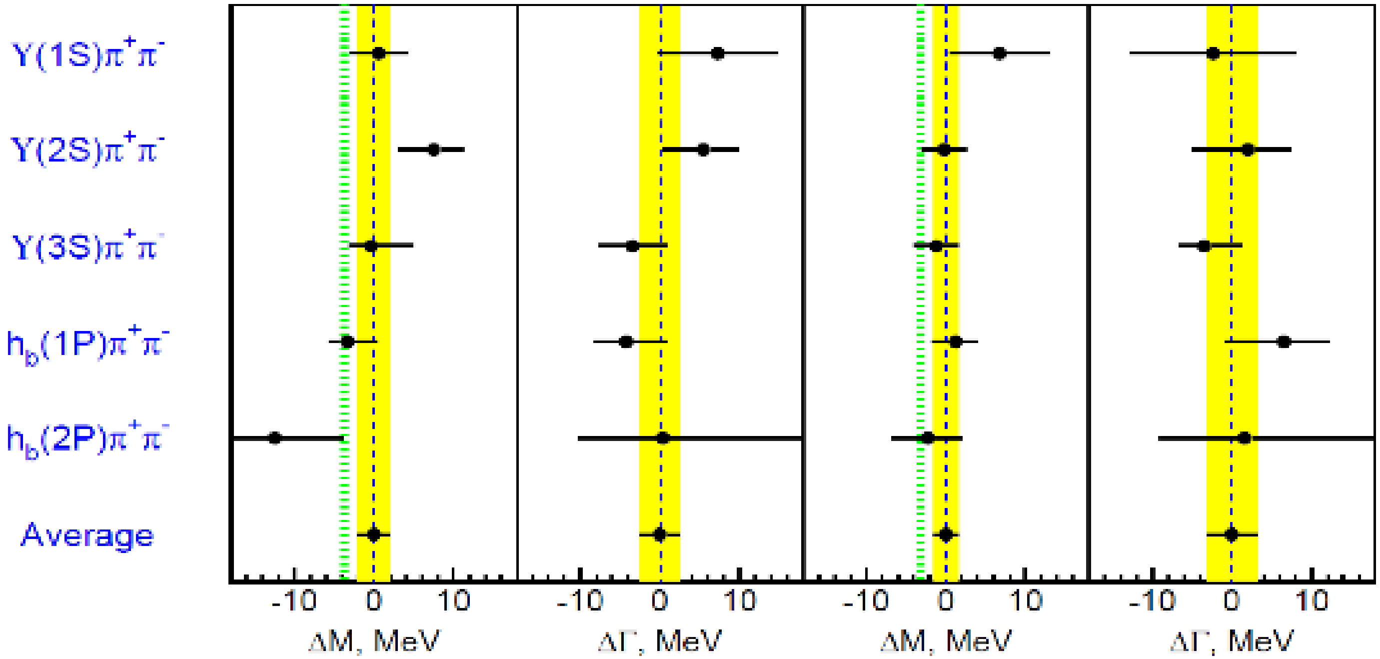


3 other observations of Z_b's !



Z_b Summary

PRL108,122001



Mass and Γ measured in 5 different final states agree

Angular analysis suggests **$J^P = 1^+$**

Z_b(10610)
M = 10608 ± 2.0 MeV
Γ = 15.6 ± 2.5 MeV
Z_b(10650)
M = 10653 ± 1.5 MeV
Γ = 14.4 ± 3.2 MeV

The Di Pion transitions from the Υ(5S) proceed via the intermediate charged state Z_b

The transition does not imply spin flip

Masses are close to B*B and B*B* theresholds
Molecules?

The Υ(5S) is an unexpected source of h_b

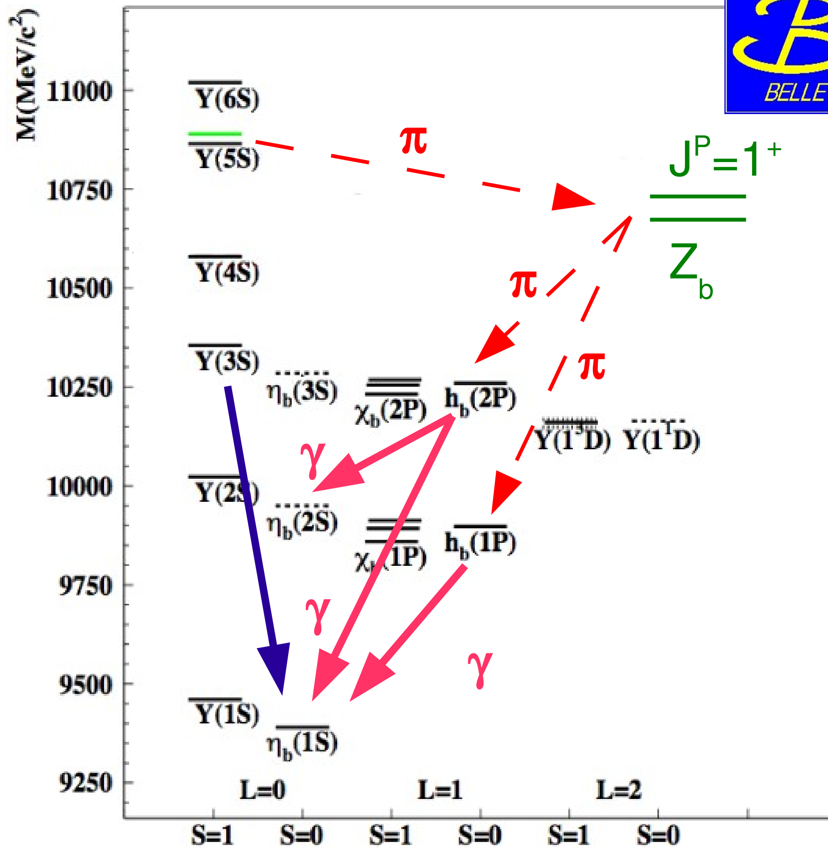
h_b (1P,2P)→ $\gamma\,\eta_b$ (1S,2S)

arXiv:1205.6351

h_b(1,2P) is predicted to have large BF for radiative decays to η_b

BF[h_b(1P) → $\gamma\,\eta_b$(1S)] = **41%**
BF[h_b(2P) → $\gamma\,\eta_b$(1S)] = **13%**
BF[h_b(2P) → $\gamma\,\eta_b$(2S)] = **19%**

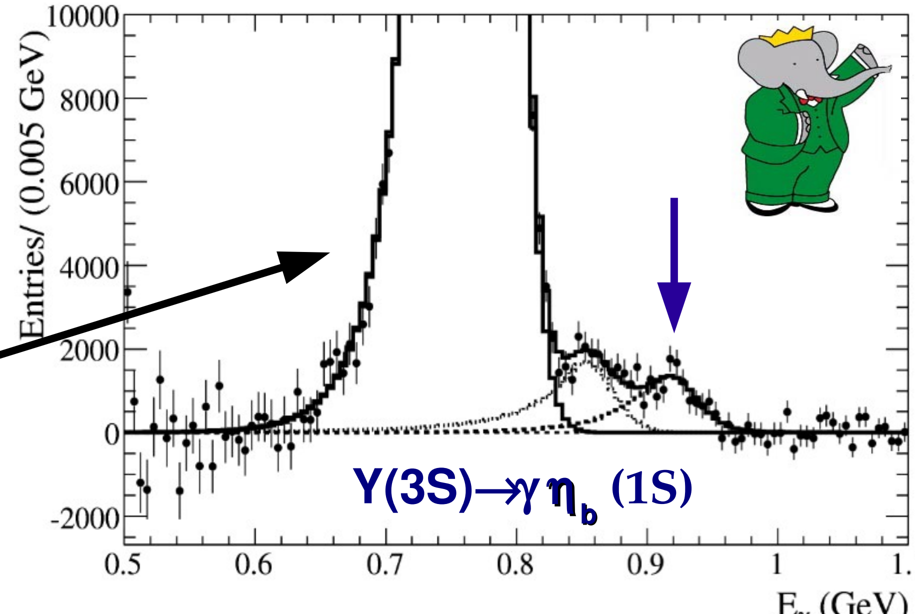
O(**10^4**) larger than in the Y(nS) system



Clean experimental signature with the h_b(1,2P) and Z_b tagging

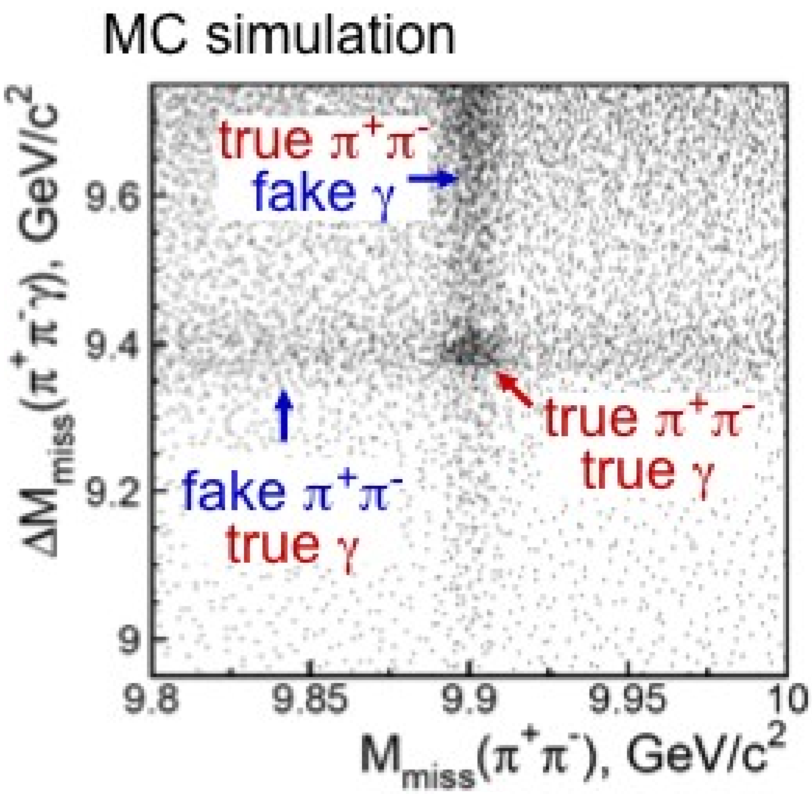
Means

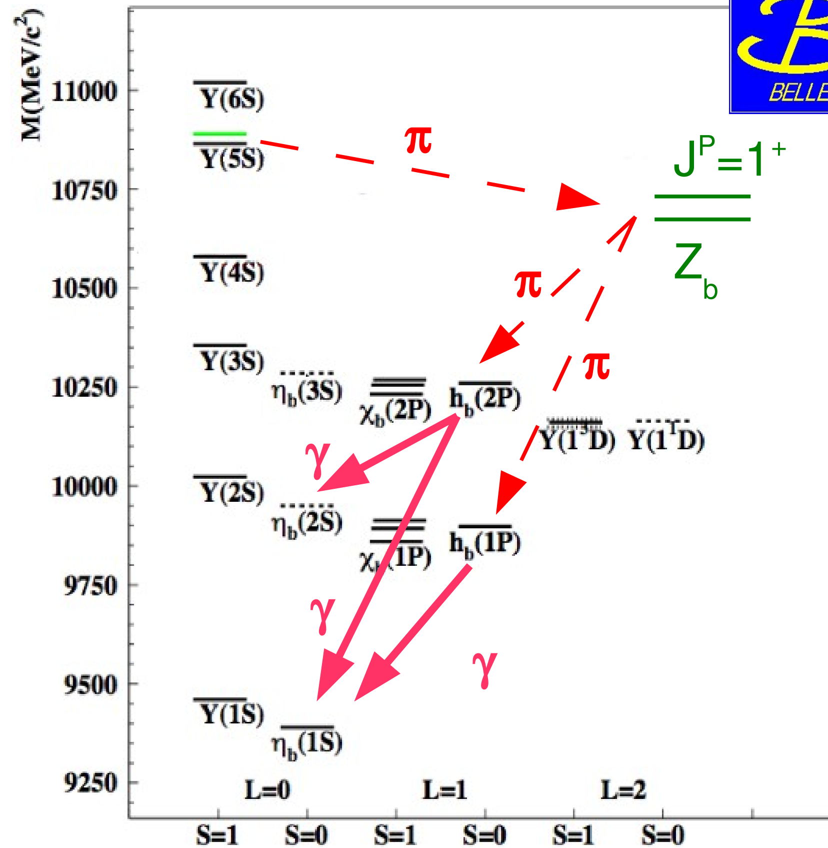
Less background than in the inclusive searches from Y(2,3S)



Search for the η_b (1,2S)

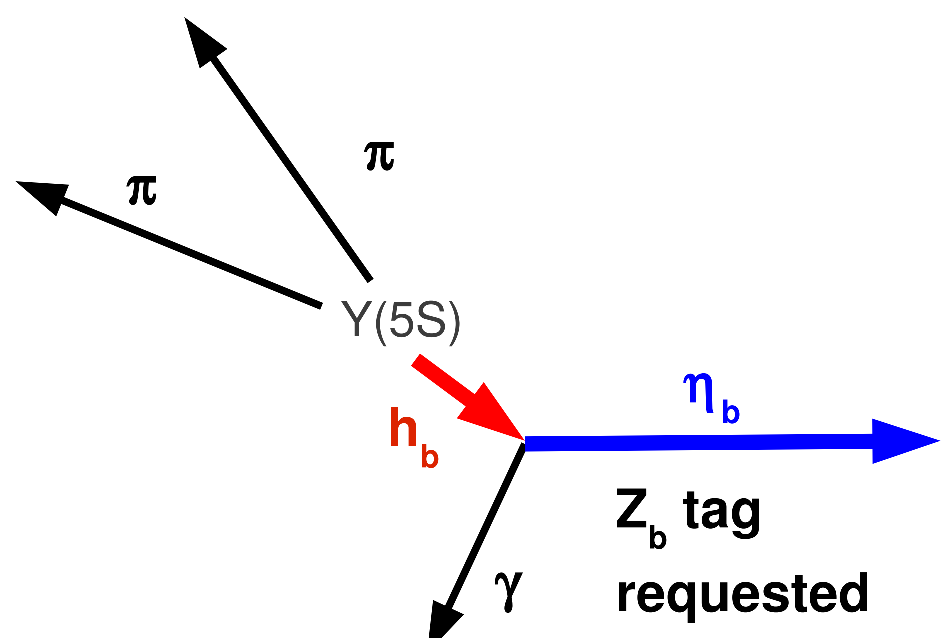
arXiv:1205.6351





h_b not reconstructed →
Missing mass analysis:

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



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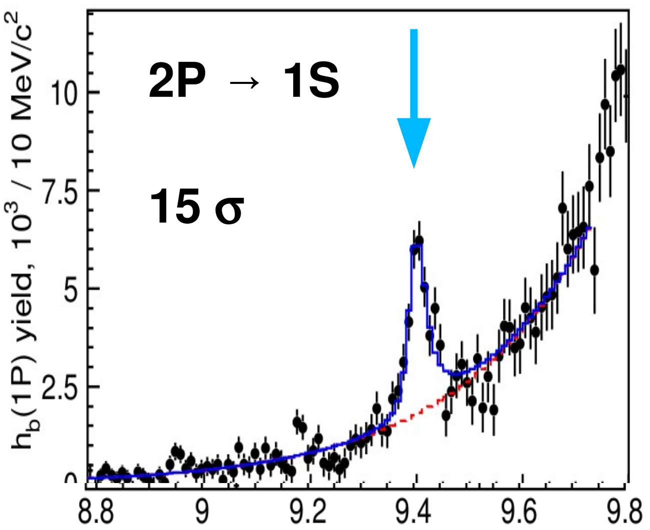
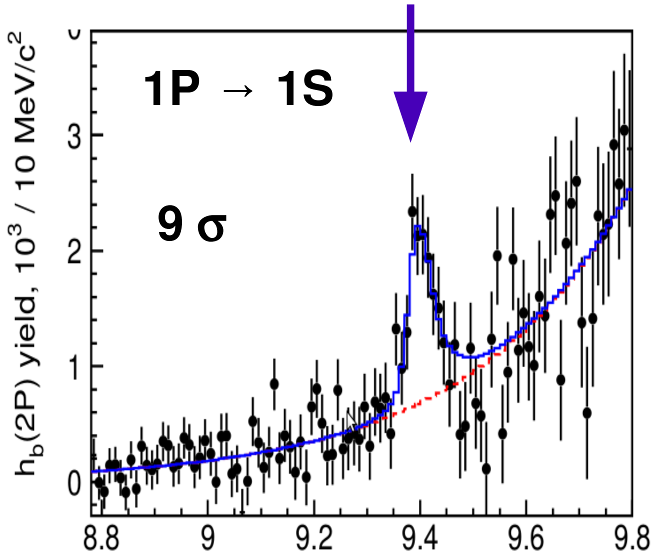
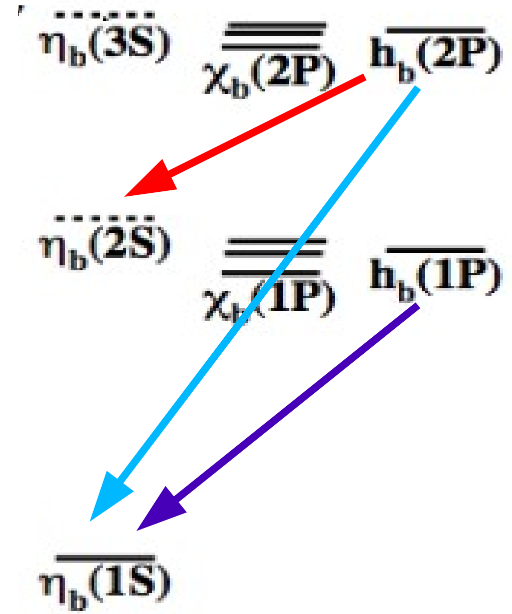
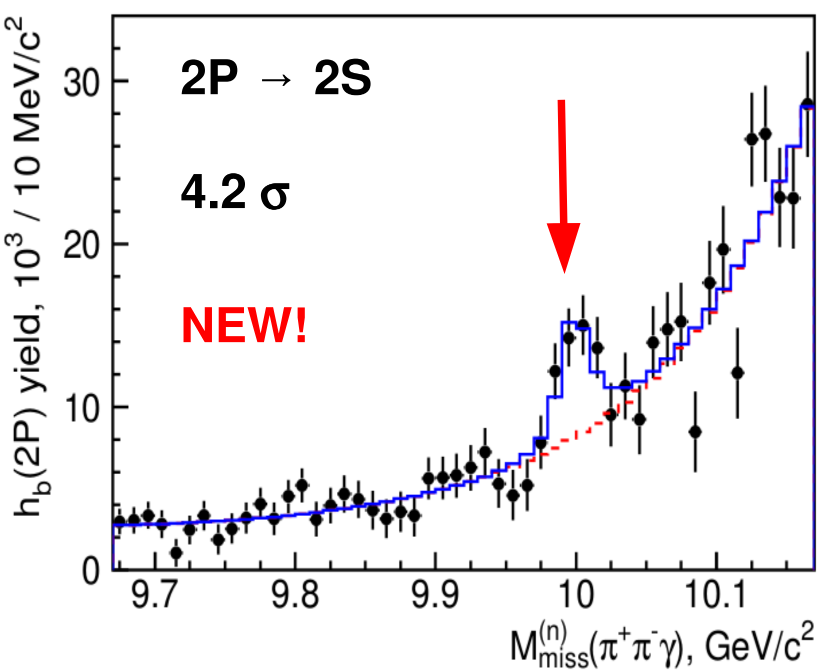








M[η_b(1S)] = (**9402.4** ± 1.5 ± 1.8)MeV

Γ[η_b(1S)] = (**10.8** +4.0 -3.7 +4.5 -2.0)MeV

B[h_b(1S) → γ η_b(1S)] = 49.2 ± 5.7 %

B[h_b(1S) → γ η_b(2S)] = 22.3 ± 3.8 %

M[η_b(2S)] = (**9999.0** ± 3.5 +2.8 -1.9)MeV

Γ[η_b(2S)] < **24** MeV

B[h_b(2S) → γ η_b(2S)] = 47.1 ± 10.5 %

Hyperfine splitting in 1S and 2S

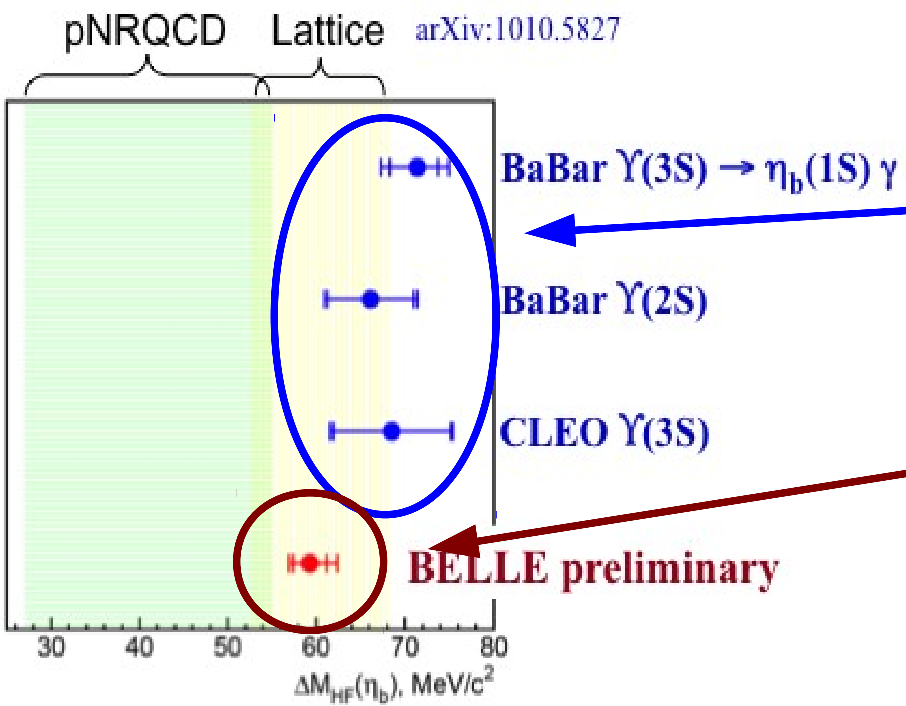
arXiv:1205.6351

1S hyperfine splitting was measured by CLEO and BaBar to be higher than theoretical predictions.

$$\Delta M_{HF}(\eta_b) = M(\eta_b) - M(\Upsilon(1S))$$

Belle measured a lower value with increased precision:

$\mathbf{\Delta M_{HF}(1S) = 57.9 \pm 2.3}$ **MeV**



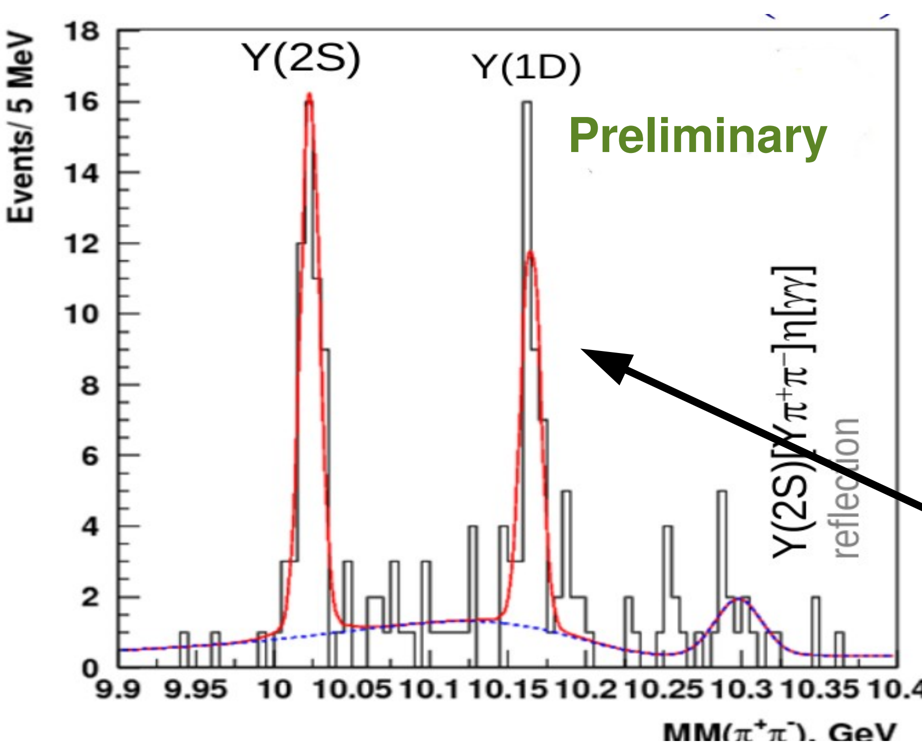
Hyperfine splitting slightly above the lattice prediction

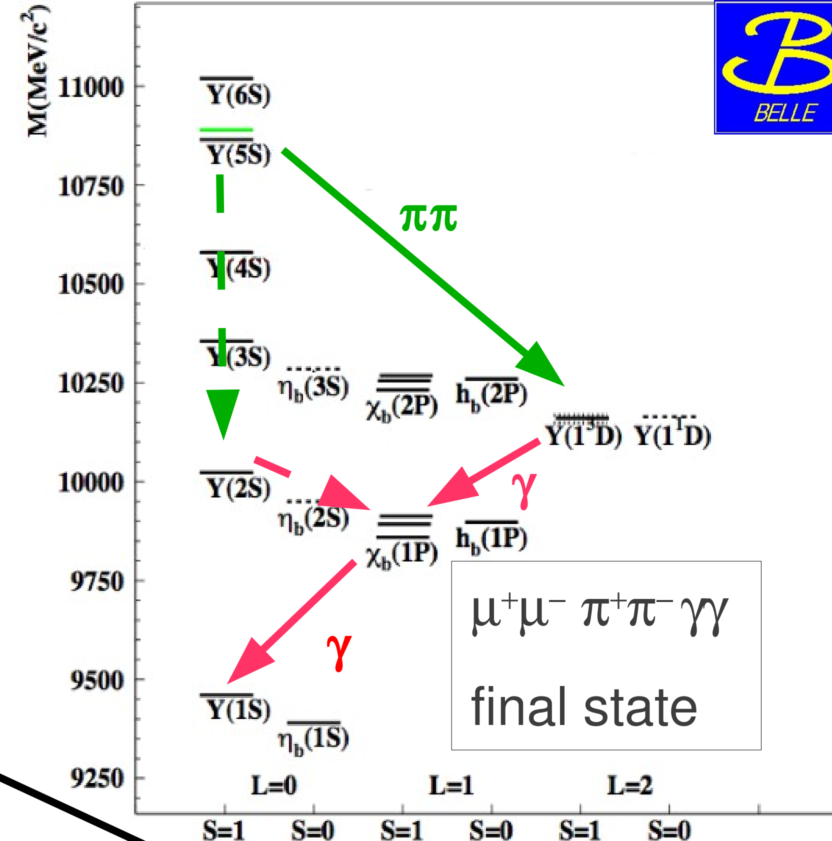
Agreement with lattice, still above NRQCD

First 2S measurement: $\mathbf{\Delta M_{HF}(2S) = 23.4^{+4.0}_{-4.5}}$ **MeV**

Agreement with theory

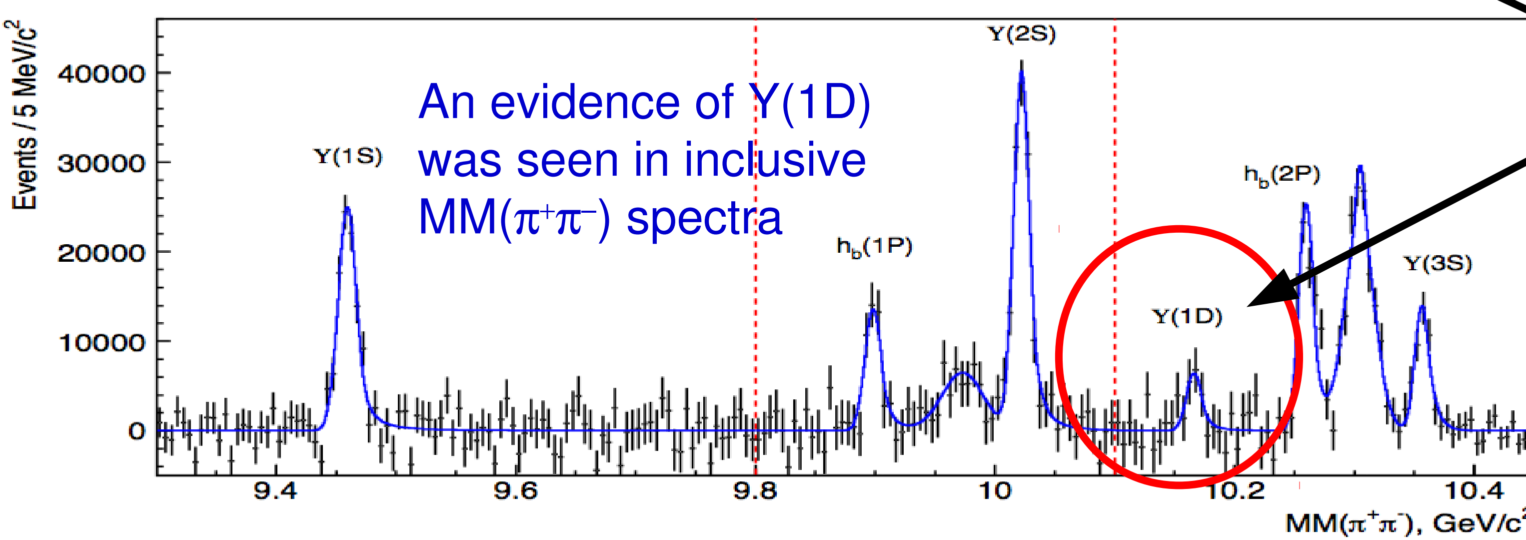
$\Upsilon(5S) \to \Upsilon(1D)\pi^+\pi^-$





Significance 9 σ

Significance 2.4 σ



$B[\Upsilon(5S) \to \Upsilon(1D)\pi^+\pi^-]\, B[\Upsilon(1D) \to \chi_b(1P)\gamma \to \Upsilon(1S)\gamma\gamma] = (2.0 \pm 0.4 \pm 0.3)\, 10^{-4}$ Preliminary

Part II

Transitions with η meson

$\Upsilon(nS) \to \eta\Upsilon(mS)$

E1E1 transition

$\Upsilon(nS) \to \pi\ \pi\ \Upsilon(mS)$

No Spin Flip

E1M2 transition

$\Upsilon(nS) \to \eta,\ \pi^0\ \Upsilon(mS)$

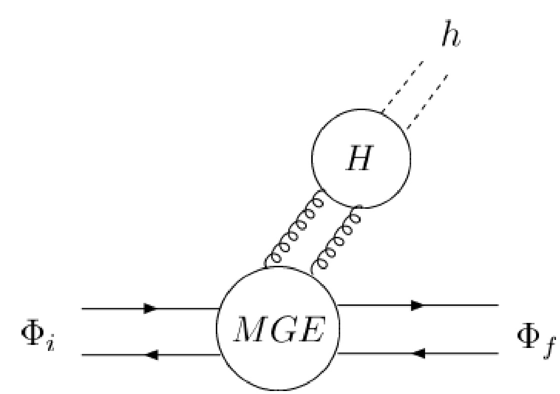
Spin Flip

The η transition is predicted to be suppressed with respect to the di pion one

The η transition requires a spin flip

QCD **multipole expansion**: spin flip amplitude proportional to $(m_b)^{-2}$

Kuang Front.Phys.China 1, 19 (2006)



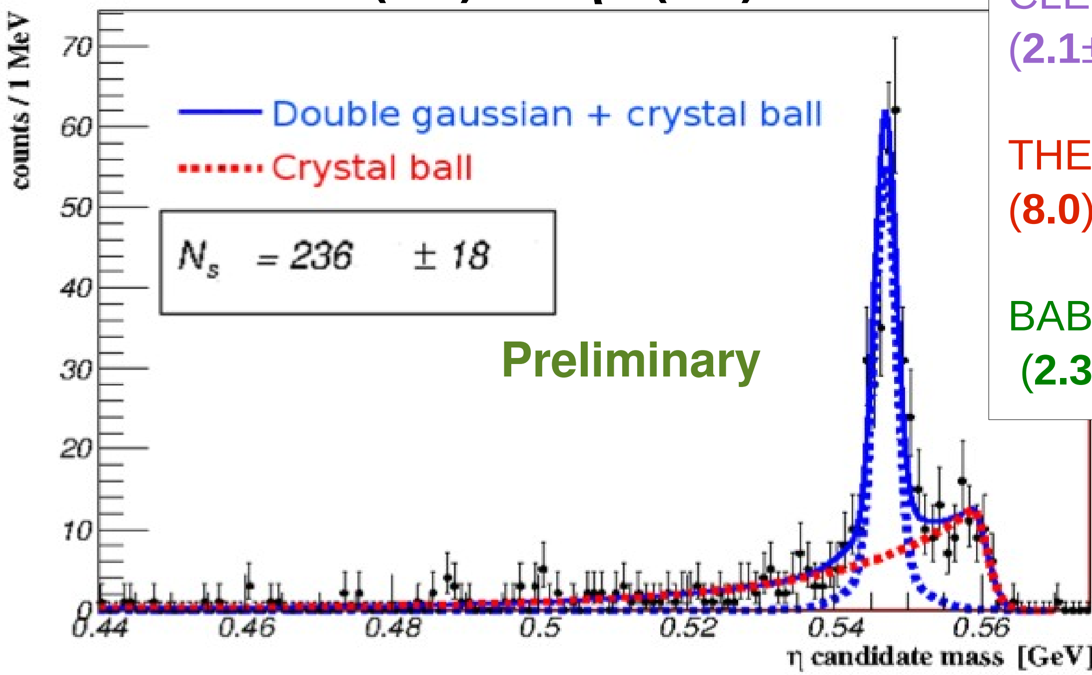
BF(2S → 1S) = 2.1 x 10^{-4} [CLEO], 2.39 x 10^{-4} [BaBar] ~8 x 10^{-4} [Theory]

BF(3S → 1S) < 1 x 10^{-4} [BaBar], ~6 x 10^{-4} [Theory]

BF(4S → 1S) = 1.96 x 10^{-4} [BaBar] Orders of magnitude higher (2.5x $\pi\pi$ transition)

$\Upsilon(2S) \rightarrow \eta, \pi^0\ \Upsilon(1S)$

$\Upsilon(2S) \rightarrow \eta\Upsilon(1S)$



CLEO: (PRL101:192001,2008)
$(\mathbf{2.1} \pm 0.7 \pm 0.4)\times10^{-4}$)

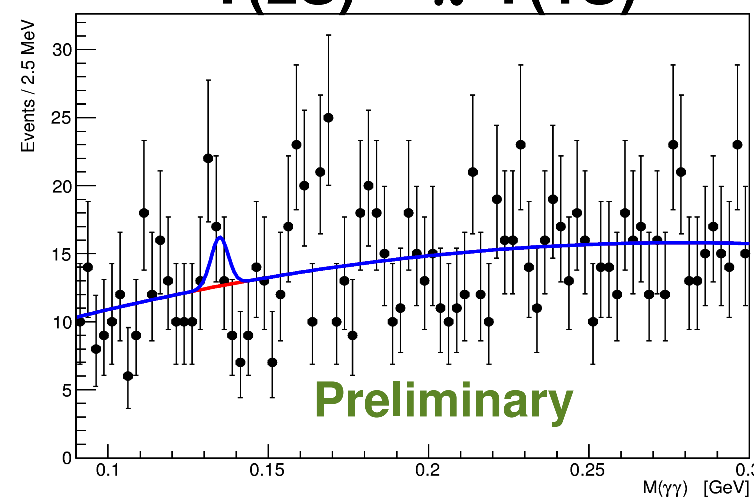
THEORY:
$(\mathbf{8.0})\times10^{-4}$)

BABAR: (PRD 84, 092003)
$(\mathbf{2.39} \pm 0.31 \pm 0.14)\times10^{-4}$

- Blind analysis
- Exclusive reconstruction:

$\Upsilon(1S) \rightarrow \mu\mu$ or ee
$\pi^0 \rightarrow \gamma\gamma$
$\eta \rightarrow \gamma\gamma$ or $\pi^+\pi^-\pi^0$

$\Upsilon(2S) \rightarrow \pi^0\Upsilon(1S)$



Higher than the other measurements, still ½ of th. prediction

$B(\Upsilon(2S) \rightarrow \eta\Upsilon(1S)) = (\mathbf{3.41} \pm 0.28(\text{stat.}) \pm 0.35(\text{syst.})) \times 10^{-4}$ **Preliminary**

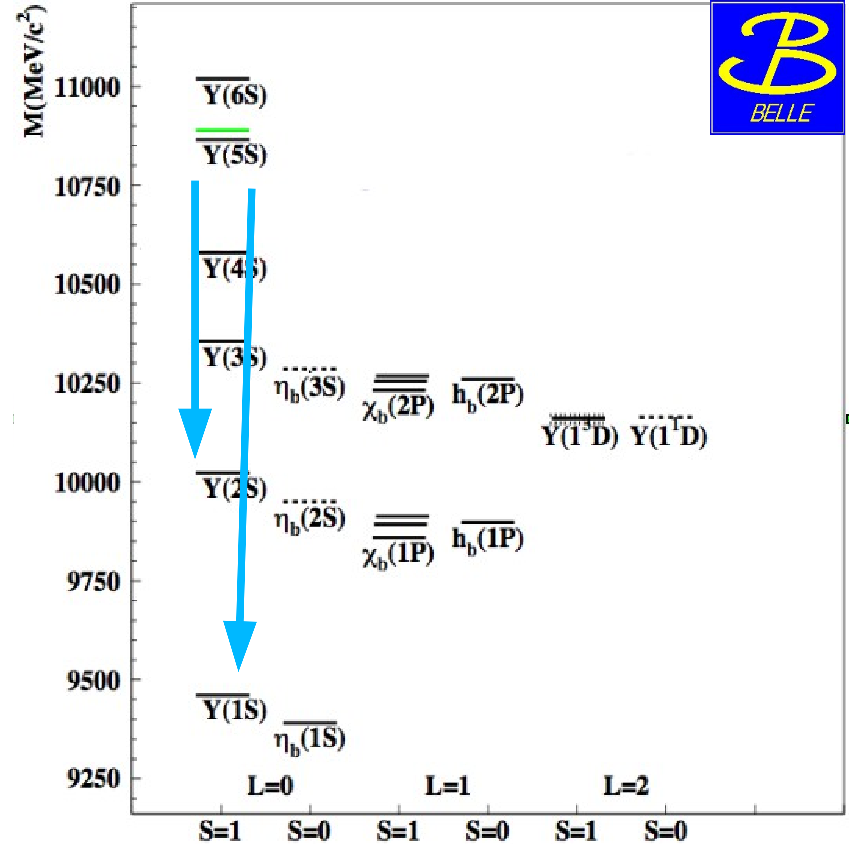
$B(\Upsilon(2S) \rightarrow \pi\Upsilon(1S)) < 0.43 \times 10^{-4}$ (90% CL) **Preliminary**

Normalization sample
$\Upsilon(2S) \rightarrow \pi^+\pi^-\ \Upsilon(1S)$

$\Upsilon(5S) \to \eta\ \Upsilon(1,2S)$

Exclusive reconstruction

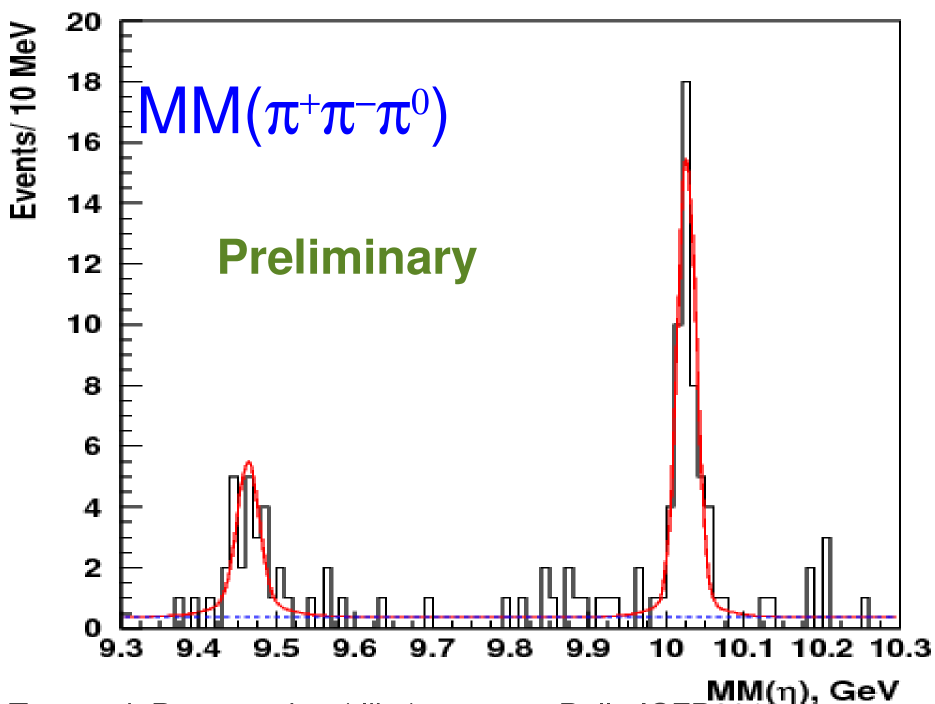
- $\Upsilon(1,2S) \to \mu^+\mu^- + \eta \to \pi^+\pi^-\pi^0$
- $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^- + \eta \to \gamma\gamma$

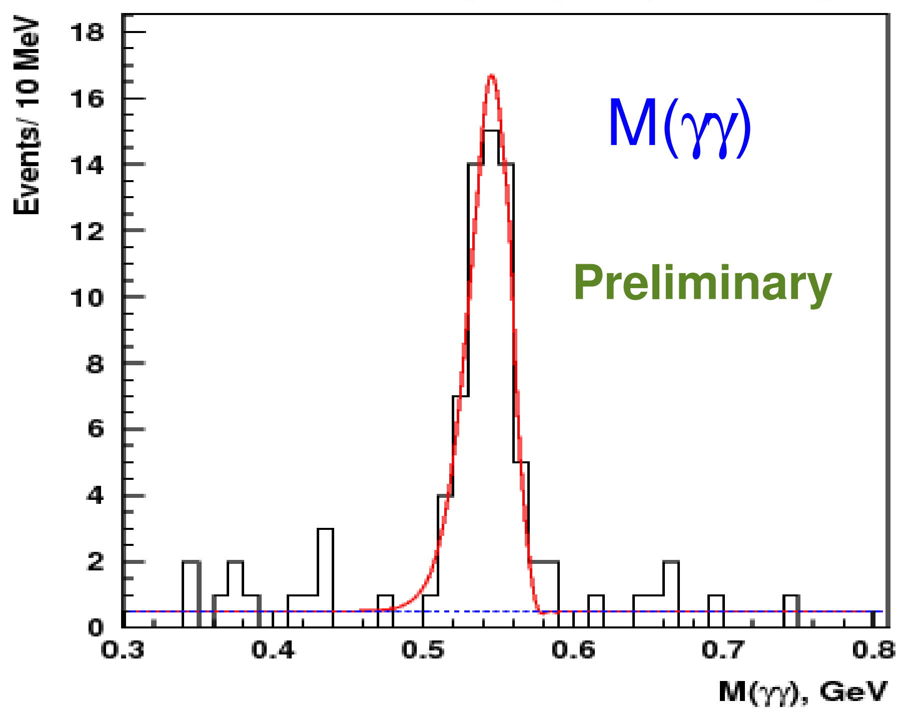


$B[\Upsilon(5S) \to \Upsilon(1S)\eta] = (7.3 \pm 1.6 \pm 0.8)\ 10^{-4}$

$B[\Upsilon(5S) \to \Upsilon(2S)\eta] = (38 \pm 4 \pm 5)\ 10^{-4}$

Preliminary





Part III

Bottomonium decays

$\Upsilon(1,2S) \to$ light hadrons

arXiv:1205.1246v1

$$Q_c = \frac{B[\psi' \to \text{hadrons}]}{B[J/\psi \to \text{hadrons}]} = \frac{B[\psi' \to e^+e^-]}{B[J/\psi \to e^+e^-]} = 12\%$$

12% rule in charmonium: violated in some VT and VP final states ($\rho\pi$ puzzle)

$$Q_\Upsilon = \frac{B[\Upsilon(2S) \to \text{hadrons}]}{B[\Upsilon(1S) \to \text{hadrons}]} = \frac{B[\Upsilon(2S) \to e^+e^-]}{B[\Upsilon(1S) \to e^+e^-]} = 77\%$$

From non-relativistic QCD. Expected to be precise but to be tested

$\phi f_2'$, ωf_2, ρa_2, $K^{*0}\bar{K}_2^{*0}$ — Vector-Tensor

$K_1(1270)^+K^-$, $K_1(1400)^+K^-$, $b_1(1235)^+\pi^-$ — Axial-Pseudoscalar

ϕK^+K^-, $\omega\pi^+\pi^-$, $K^{*0}K^-\pi^+$ — 3 body decays

→ Y(2S) and Y(1S) samples

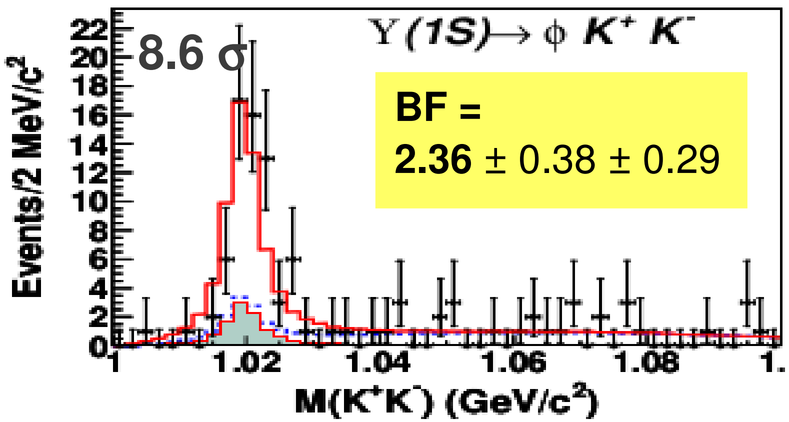
→ Complete event reconstruction

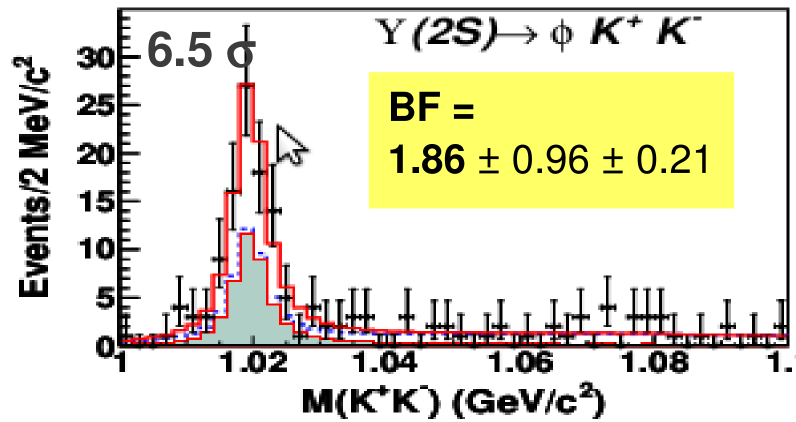
10 (x2) channels, 5 with observation

Y(1,2S)→ 3 bodies (observations)

arXiv:1205.1246v1

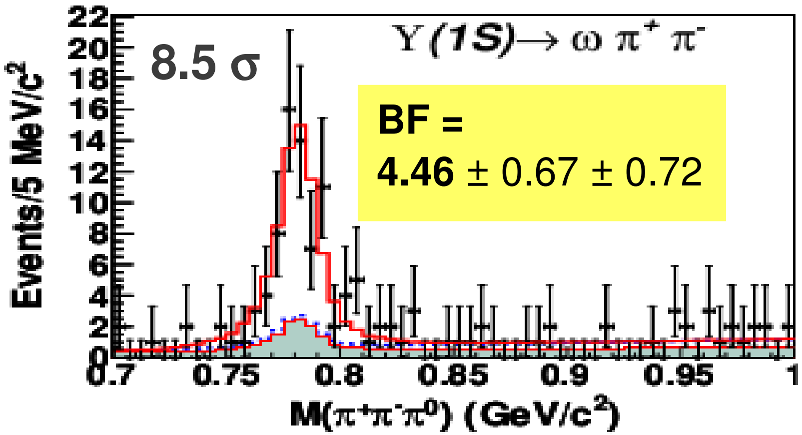
BF X 10^{-6}

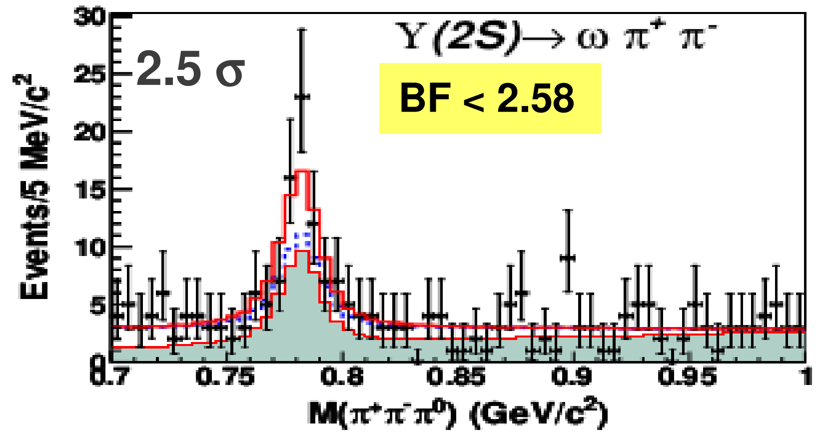




Q =
0.79 ± 0.54 ± 0.13

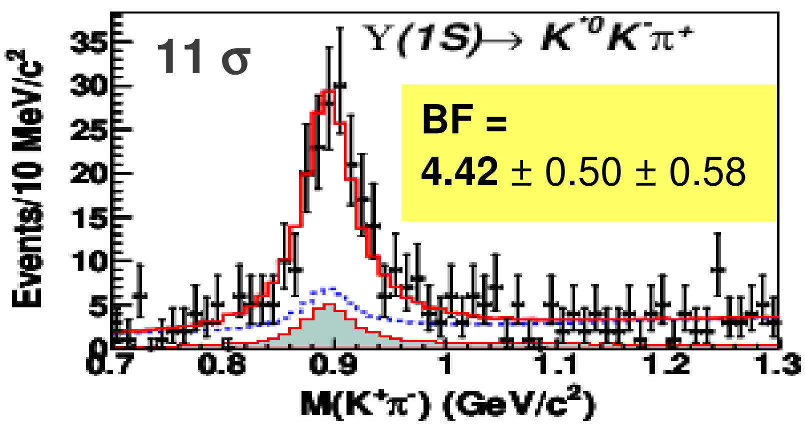
consistent

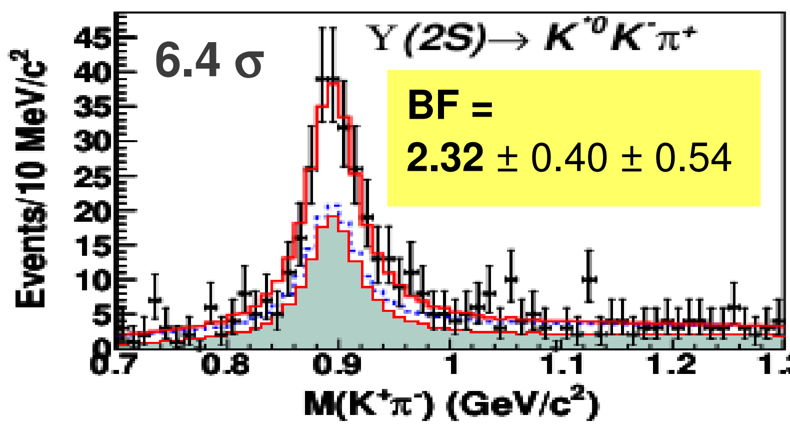




Q < 0.55

2.6 σ
lower than
prediction





Q =
0.52 ± 0.11 ± 0.14

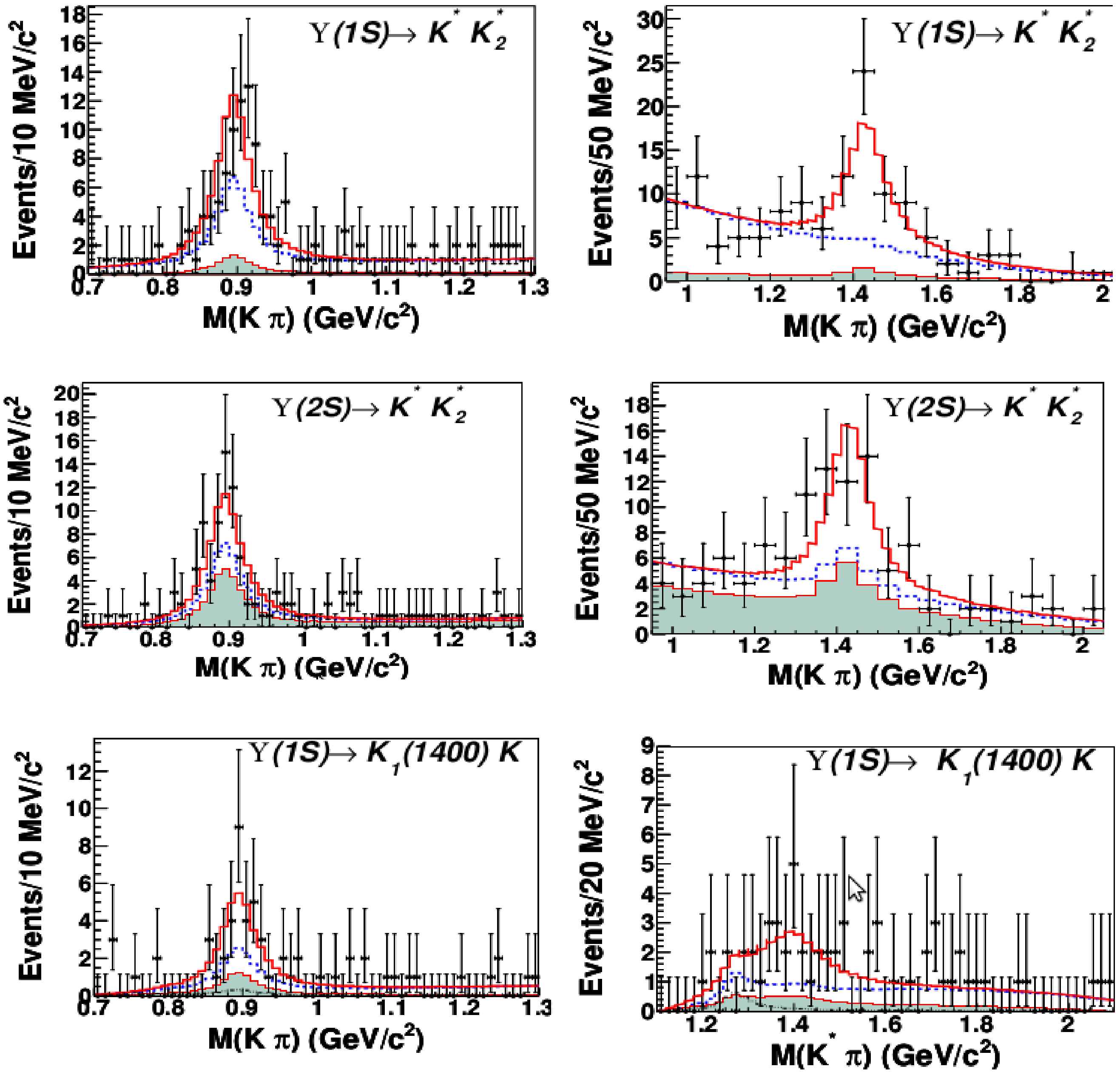
consistent

Υ(1,2S)→ 2 bodies (observations)

arXiv:1205.1246v1

BF X 10^{-6}

Signal from 2D fit of M(V,A) vs M(T) Dalitz plot → 1D projections



BF(1S) = 3.02 ± 0.68 ± 0.34

Q=0.50 ± 0.21 ± 0.07

consistent

BF(2S) = 1.53 ± 0.52 ± 0.19

BF(1S) = 1.02 ± 0.35 ± 0.22

BF(2S) < 0.86

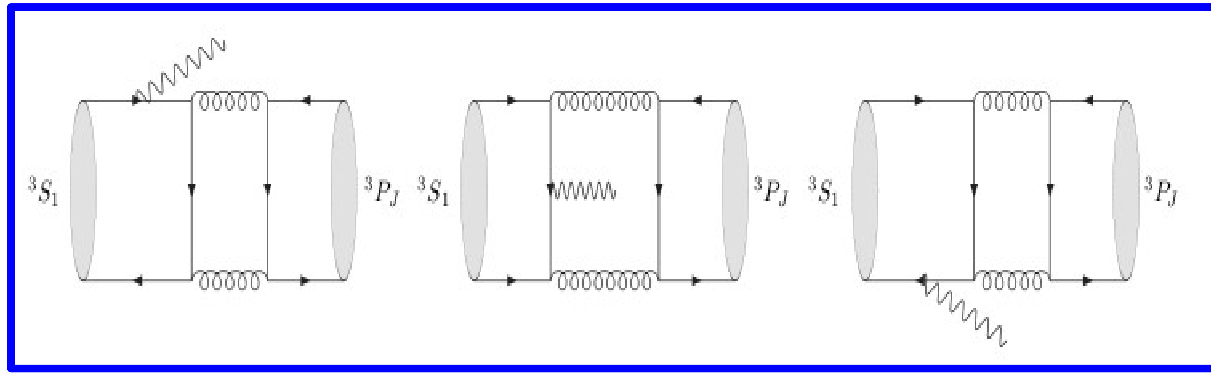
Q < 0.77 **consistent**

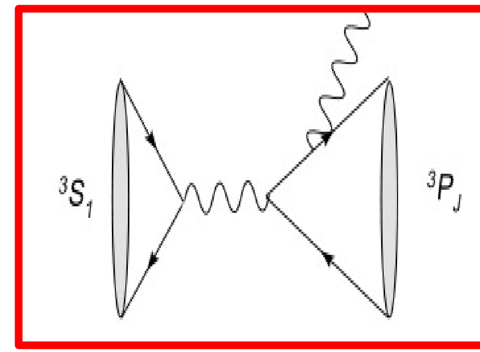
X 10^{-6}

$\Upsilon(1,2S) \rightarrow \gamma$ charmonium

PRD 82(2010),051504R

KT Chao et al, (hep-ph/0701009) provides a very large set of NRQCD predictions on many processes





Theoretical prediction (x 10^{-6}):

	QCD	QCD+QED
$\Upsilon(1S) \rightarrow \gamma\chi_{c0}$	**4.0**	**3.2**
$\Upsilon(1S) \rightarrow \gamma\chi_{c1}$	**4.5**	**9.8**
$\Upsilon(1S) \rightarrow \gamma\chi_{c2}$	**5.1**	**5.6**
$\Upsilon(1S) \rightarrow \gamma\eta_c$	**2.9**	**4.9**

Significant corrections are expected from interference between QCD and QED amplitudes.

Similar rates are expected for Y(2S)

Upper limits on $\Upsilon(1,2S) \to \gamma$ charmonium

PRD 82(2010),051504R

Charmonium $\times 10^{-6}$

Channel	90% CL U.L.
$\Upsilon(2S) \to \gamma\chi_{c0}$	**650**
$\Upsilon(2S) \to \gamma\chi_{c0}$	**23**
$\Upsilon(2S) \to \gamma\chi_{c0}$	**7.6**
$\Upsilon(2S) \to \gamma\eta_c$	**57**

Channel	90% CL U.L.
$\Upsilon(2S) \to \gamma\chi_{c0}$	**650**
$\Upsilon(2S) \to \gamma\chi_{c0}$	**23**
$\Upsilon(2S) \to \gamma\chi_{c0}$	**7.6**
$\Upsilon(2S) \to \gamma\eta_c$	**57**

Exotic charmonium $\times 10^{-6}$

Channel	90% CL U.L.
$\Upsilon(1S) \to \gamma$ X3872 $\to \gamma\, \pi^+\pi^- J/\psi$	**1.6**
$\Upsilon(1S) \to \gamma$ X3872 $\to \gamma\, \pi^+\pi^-\pi^0 J/\psi$	**2.8**
$\Upsilon(1S) \to \gamma$ X3915 $\to \gamma\, \omega J/\psi$	**3.0**
$\Upsilon(1S) \to \gamma$ Y4140 $\to \gamma\, \varphi J/\psi$	**2.2**

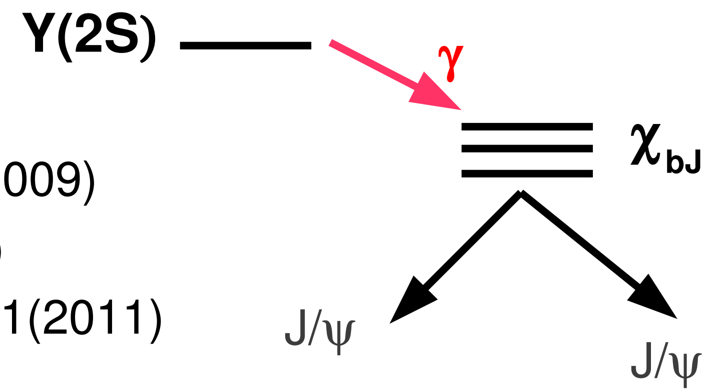
Channel	90% CL U.L.
$\Upsilon(2S) \to \gamma$ X3872 $\to \gamma\, \pi^+\pi^- J/\psi$	**0.8**
$\Upsilon(2S) \to \gamma$ X3872 $\to \gamma\, \pi^+\pi^-\pi^0 J/\psi$	**2.4**
$\Upsilon(2S) \to \gamma$ X3915 $\to \gamma\, \omega J/\psi$	**2.8**
$\Upsilon(2S) \to \gamma$ Y4140 $\to \gamma\, \varphi J/\psi$	**1.2**
$\Upsilon(2S) \to \gamma$ X4350 $\to \gamma\, \varphi J/\psi$	**1.3**

No signal observed.
UL in agreement with theory

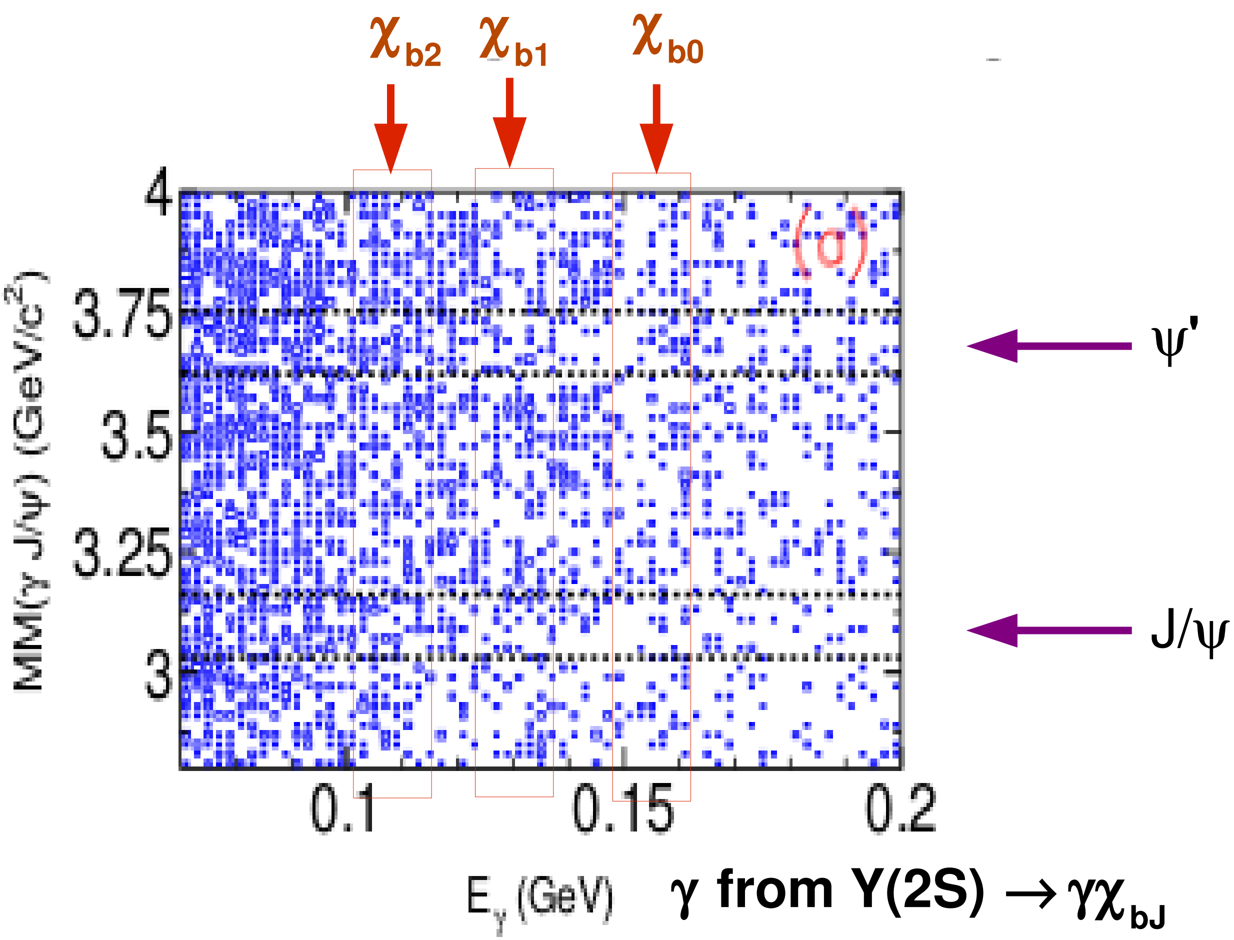
$\chi_b(1P) \to$ double charmonium New!

arXiv:1203.0368

Chance to compare different predictions:



Light Cone formalism (LC): Phys. Rev. D 80, 094008 (2009)
Potential QCD (pQCD) : Phys. Rev. D 72, 094018 (2005)
Non relativistic QCD (NRQCD): Phys. Rev. D 84,094031(2011)

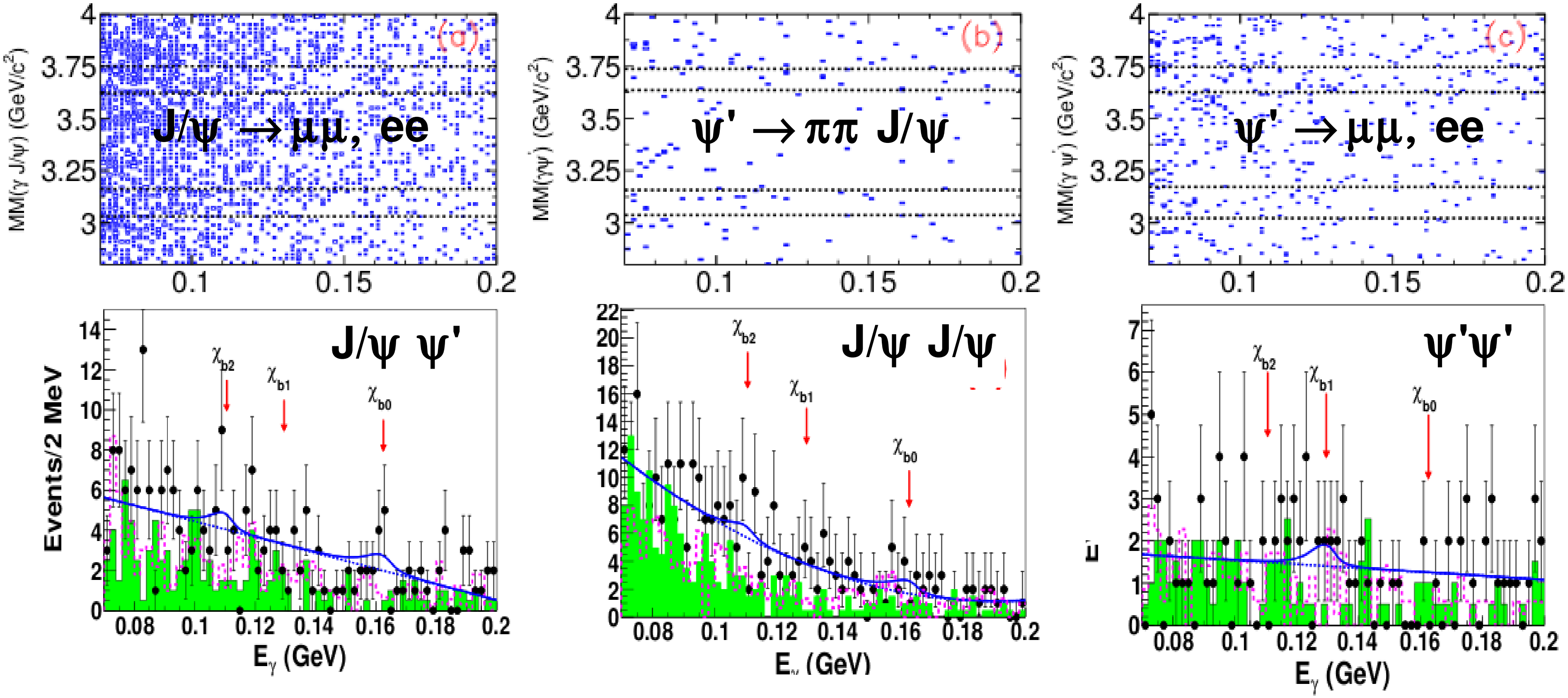


$\chi_{bJ} \to J/\psi\ J/\psi$
$\chi_{bJ} \to \psi'\psi'$
$\chi_{bJ} \to J/\psi\ \psi'$

Missing mass technique: clusters in $MM(\gamma J/\psi)$ versus $E(\gamma)$ with:

$J/\psi \to \mu^+\mu^-, e^+e^-$
$\psi' \to \pi^+\pi^- J/\psi,\ \mu^+\mu^-, e^+e^-$

$\chi_b(1P) \to$ double charmonium New!



Channel	n^{up}	$\varepsilon(\%)$	$\sigma_{\text{sys}}(\%)$	$\mathcal{B}_R$
$\chi_{b0} \to J/\psi J/\psi$	21	5.8	16	7.1×10^{-5}
$\chi_{b1} \to J/\psi J/\psi$	13	6.3	30	2.7×10^{-5}
$\chi_{b2} \to J/\psi J/\psi$	22	5.9	27	4.5×10^{-5}
$\chi_{b0} \to J/\psi \psi'$	20	3.4	17	1.2×10^{-4}
$\chi_{b1} \to J/\psi \psi'$	5.8	3.8	15	1.7×10^{-5}
$\chi_{b2} \to J/\psi \psi'$	17	3.5	16	4.9×10^{-5}
$\chi_{b0} \to \psi' \psi'$	3.0	2.1	20	3.1×10^{-5}
$\chi_{b1} \to \psi' \psi'$	12	2.2	17	6.2×10^{-5}
$\chi_{b2} \to \psi' \psi'$	3.3	2.1	12	1.6×10^{-5}

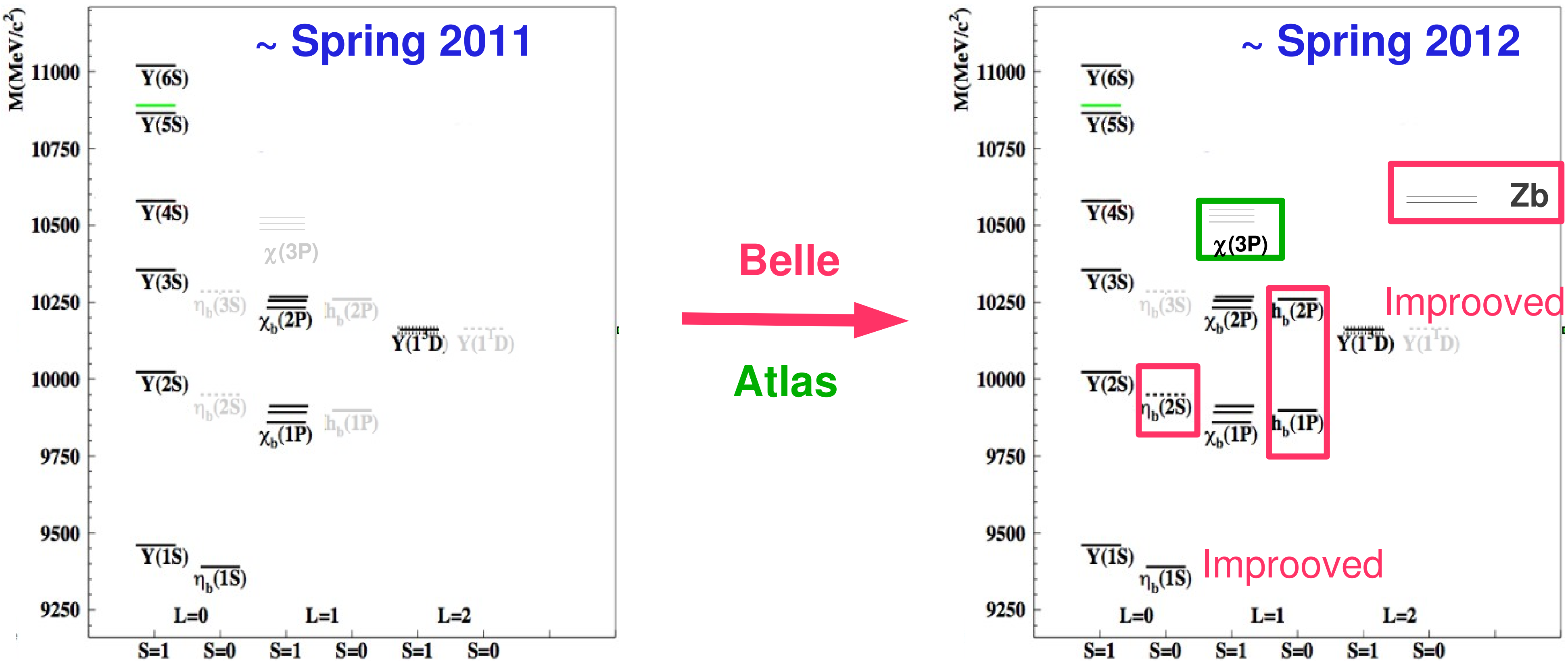
A set of **Preliminary** **Upper Limits**

- Below (~70% discrepancy) the Light Cone formalism and potential QCD predictions
- **In agreement with NRQCD predictions**

arXiv:1203.0368

Summary

~ 1.5 Year of results from Y(1,2,5 S)



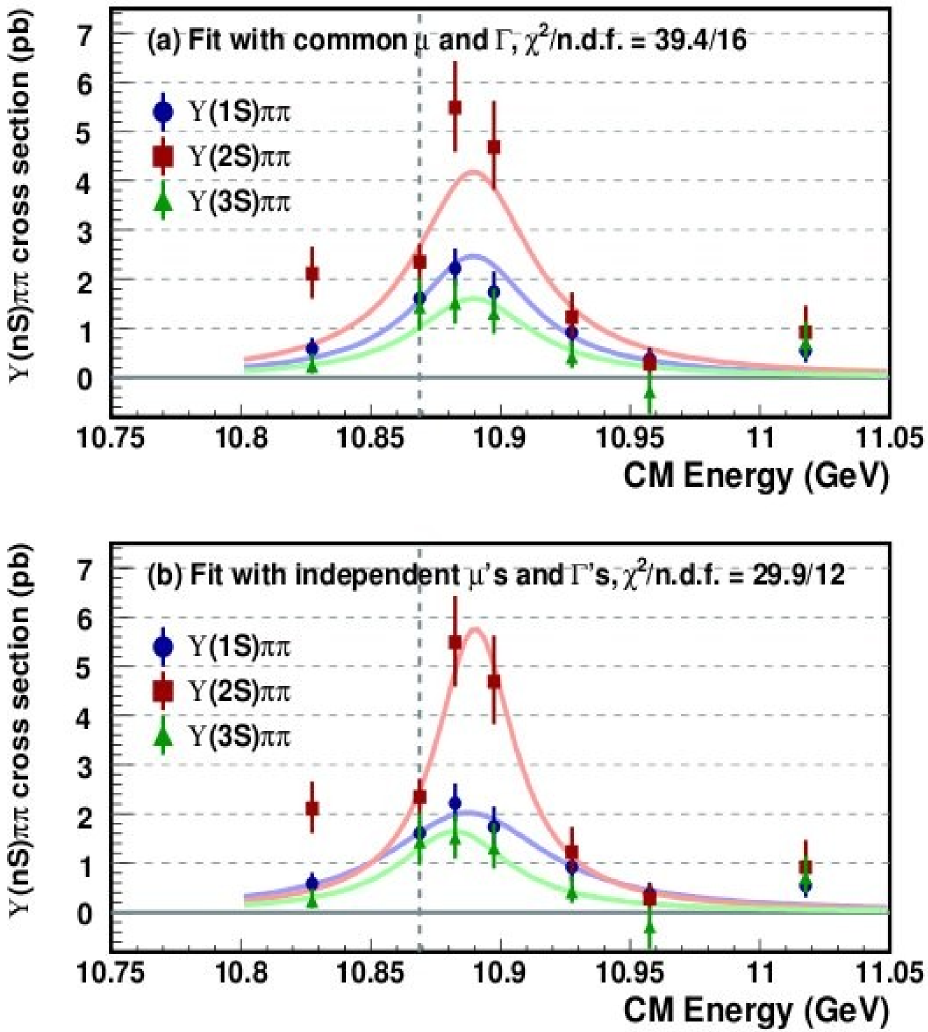
Y(1,2S) → light hadrons (first observation!)
Y(1,2S) → γ charmonium
χ(1P) → double charmonium

NRQCD seems to be a good model

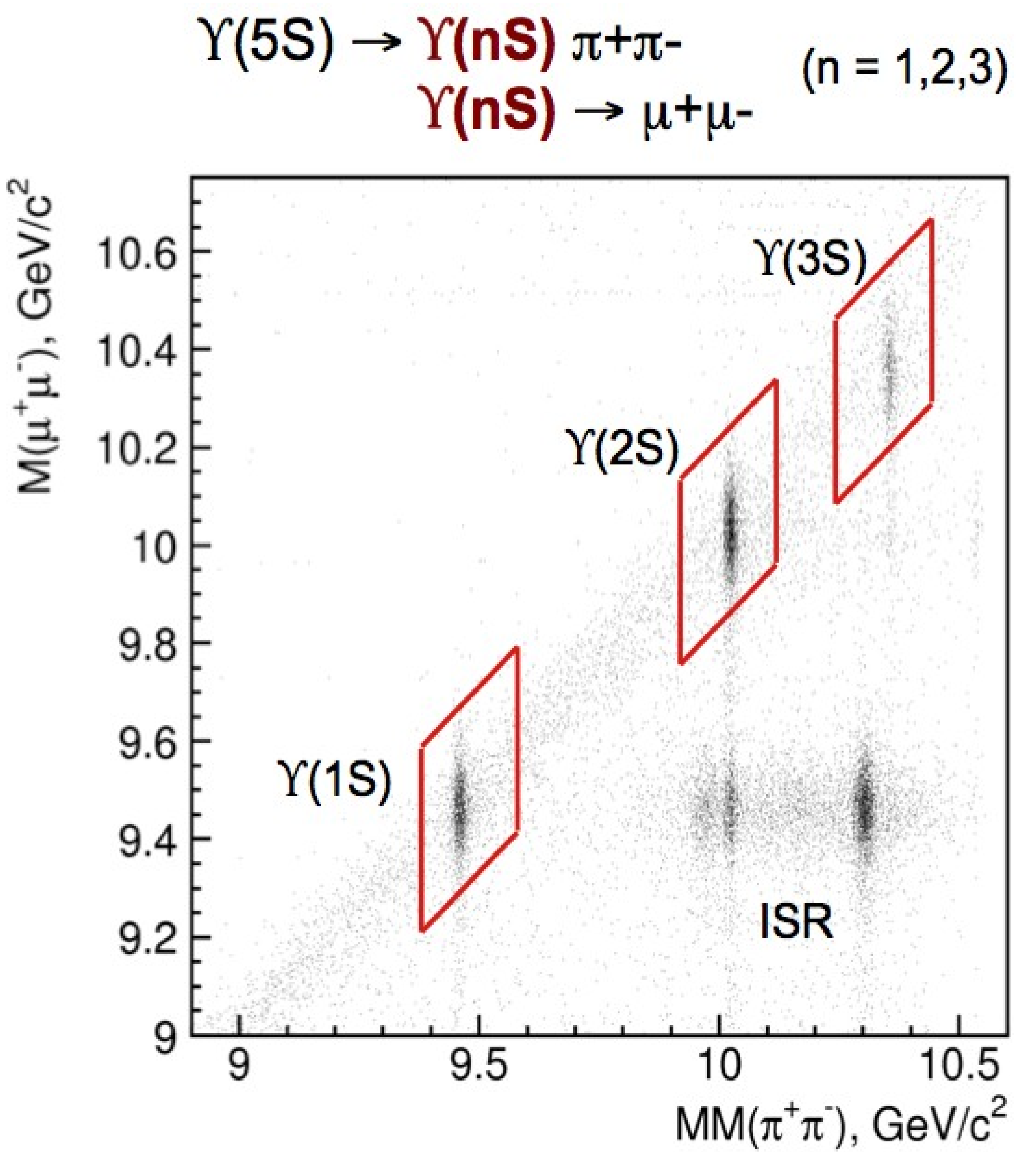
Y(nS)→η Y(mS) : a puzzle still to be solved

Backup

$\pi^+\pi^-$ transitions @ Y(5S)



PRD82(2010),091106R

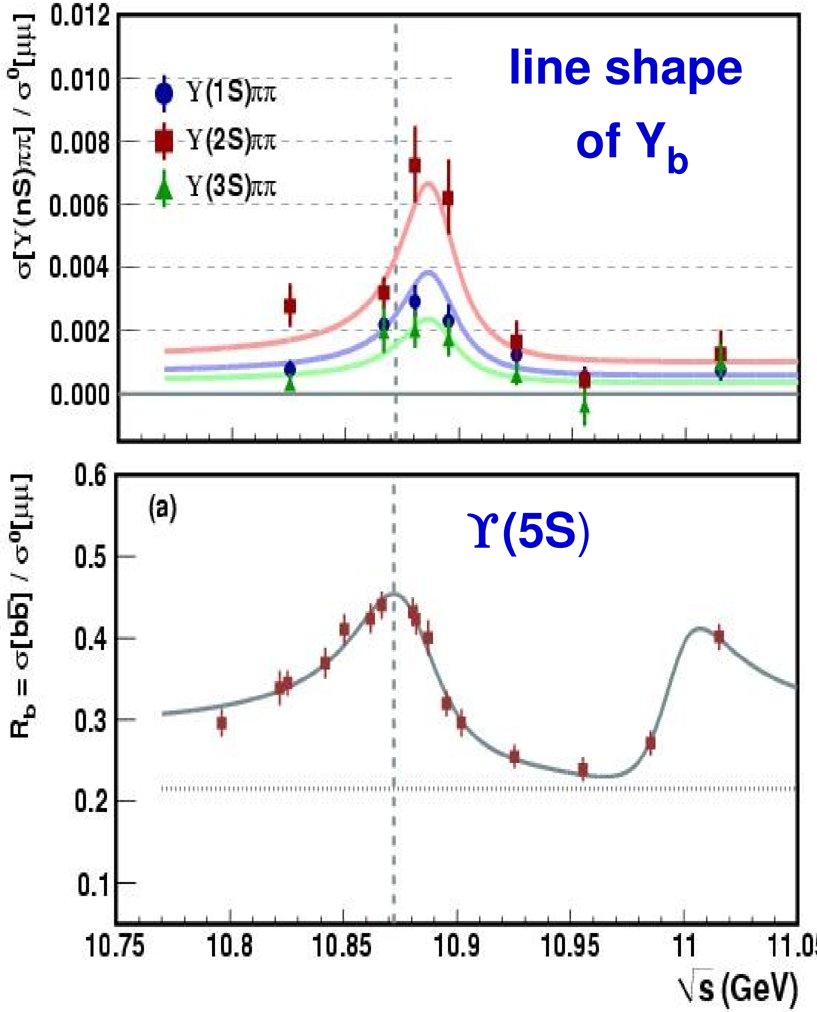


$\pi^+\pi^-$ transitions @ Y(5S)

PRL100,112001(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

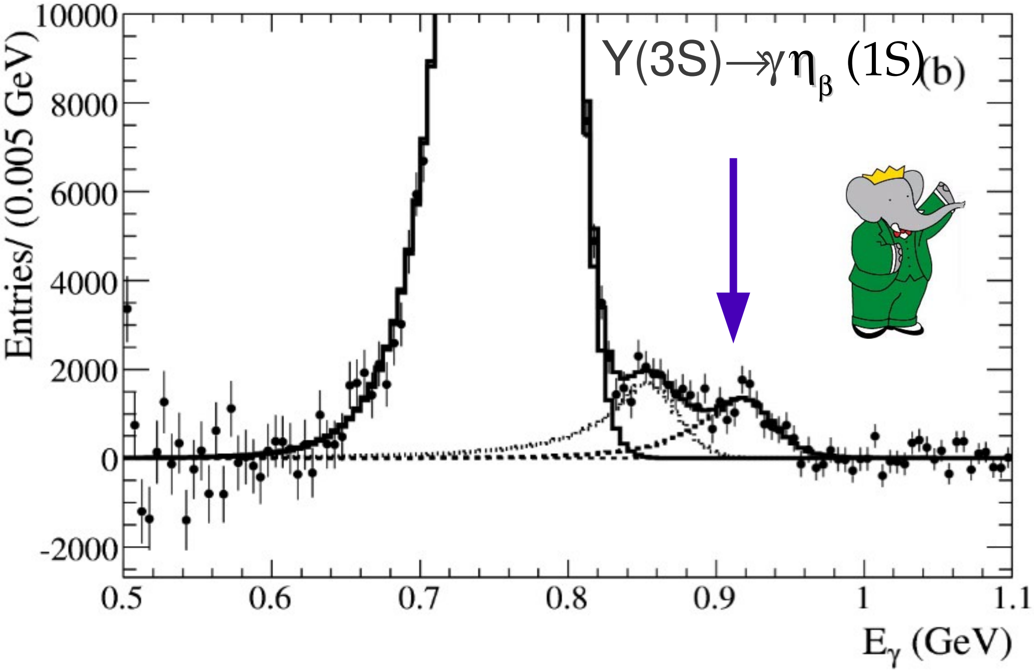
PRD82,091106R(2010)

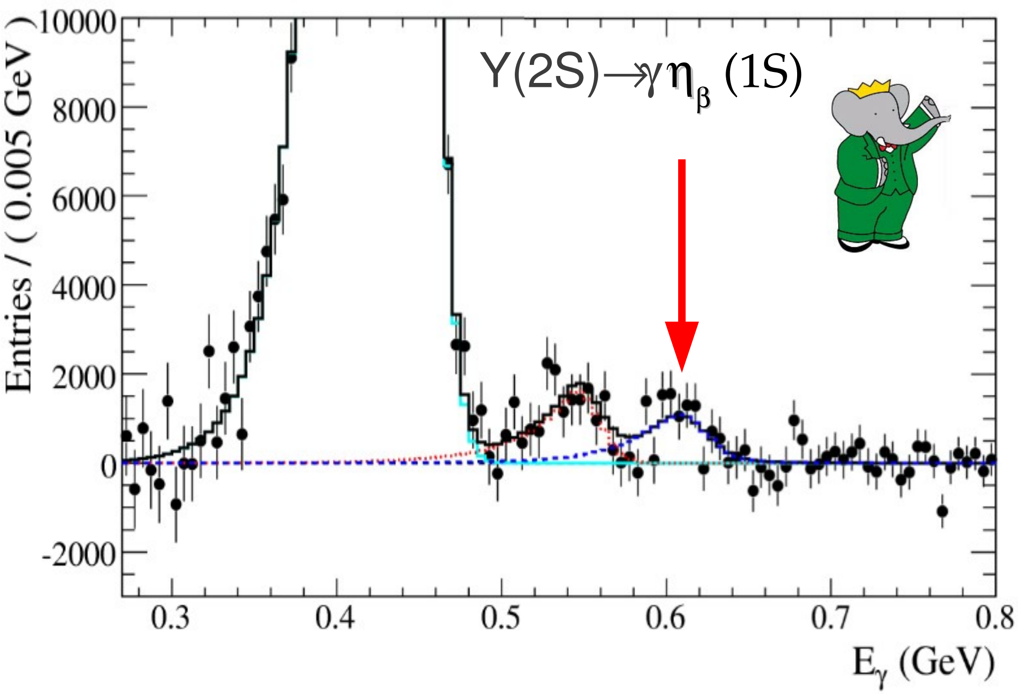


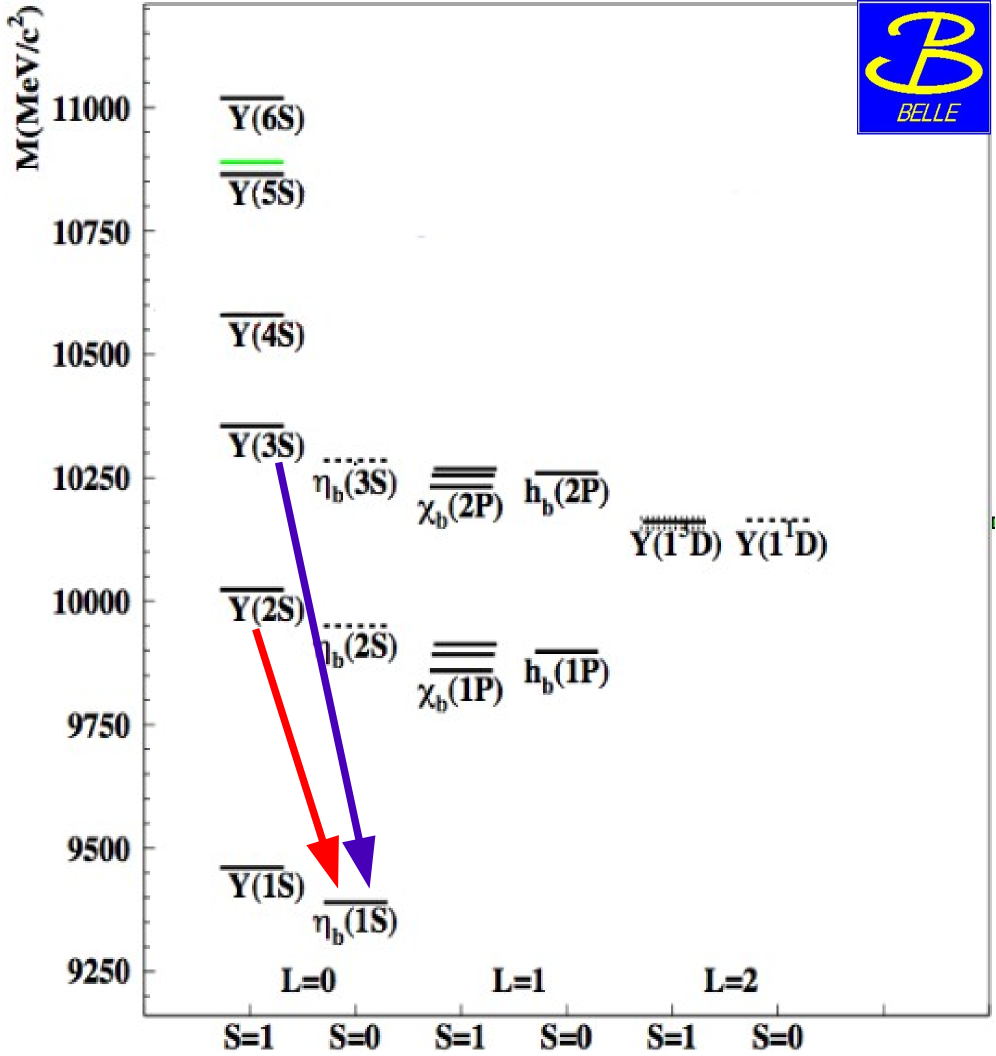
Simonov JETP Lett 87,147(2008)

Rescattering Y(5S) → BBππ → Y(nS)?

η_b(1S) at BaBar

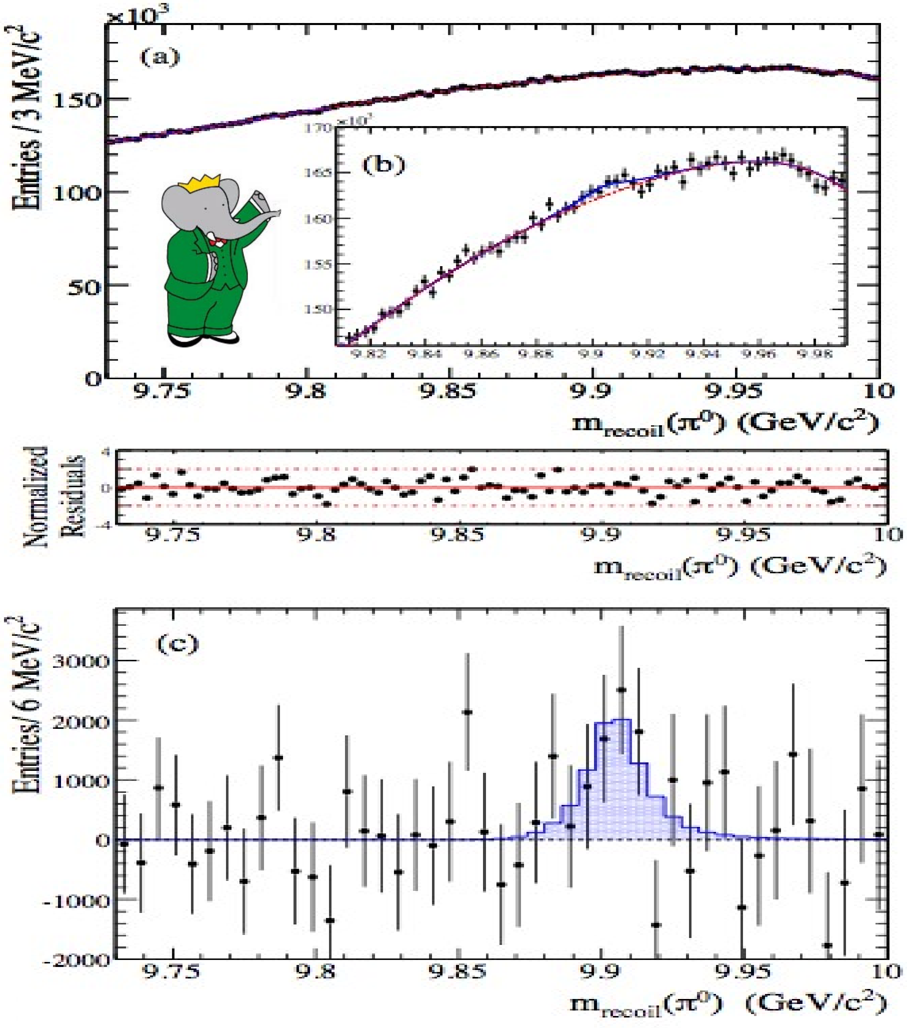




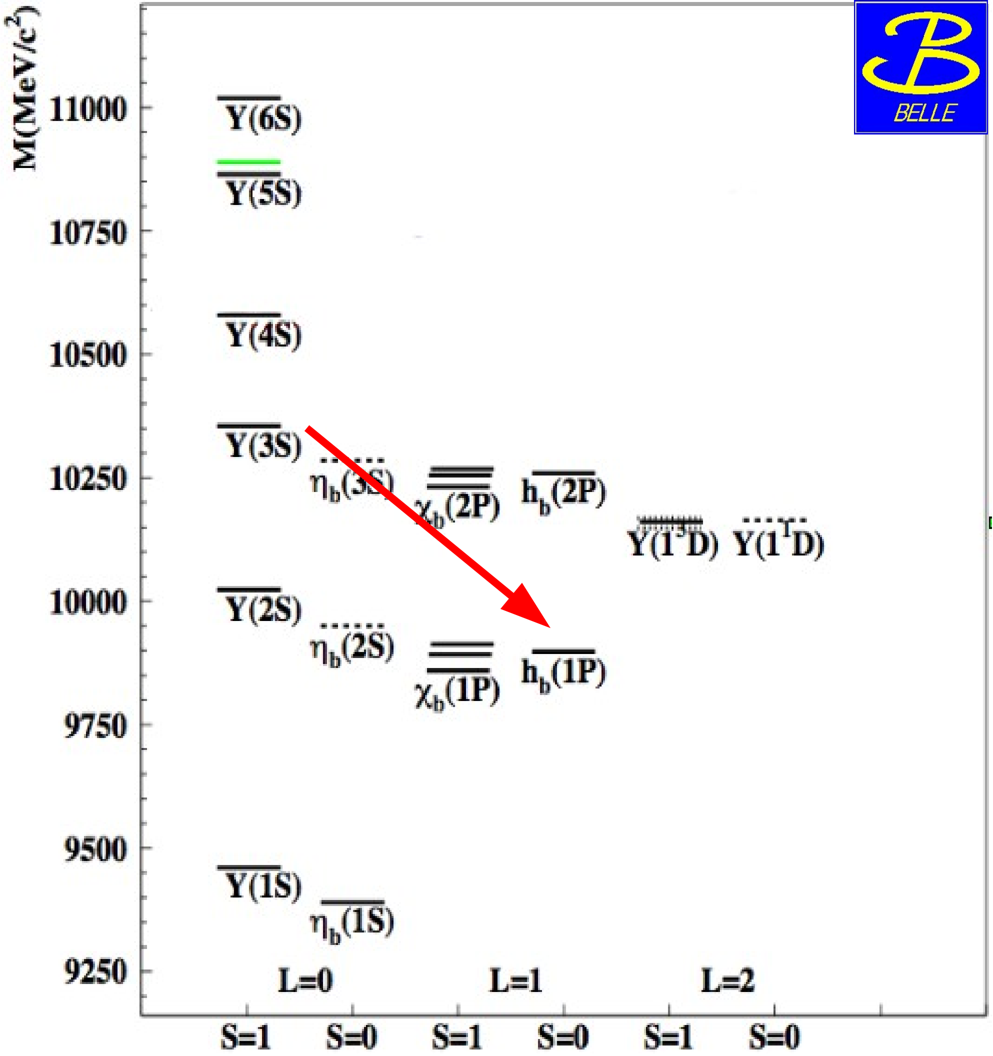


$h_b(1P)$ at BaBar

3 sigma evidence:
$e^+e^- \rightarrow \Upsilon(3S) \rightarrow \pi^0 h_b$



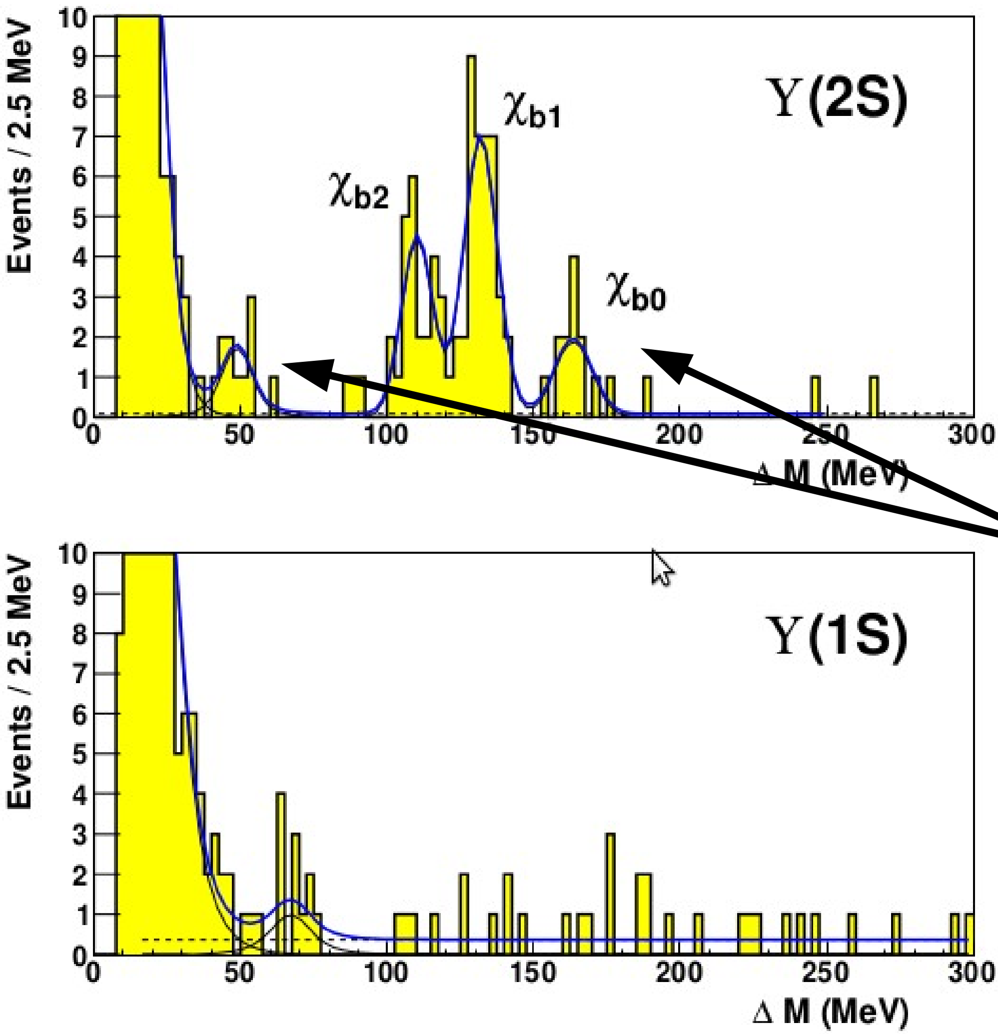
π⁰ recoil mass (GeV/c²)



Phys.Rev.D 84 091101(R)

η_b(2S) claim

arxiv:1204.4205



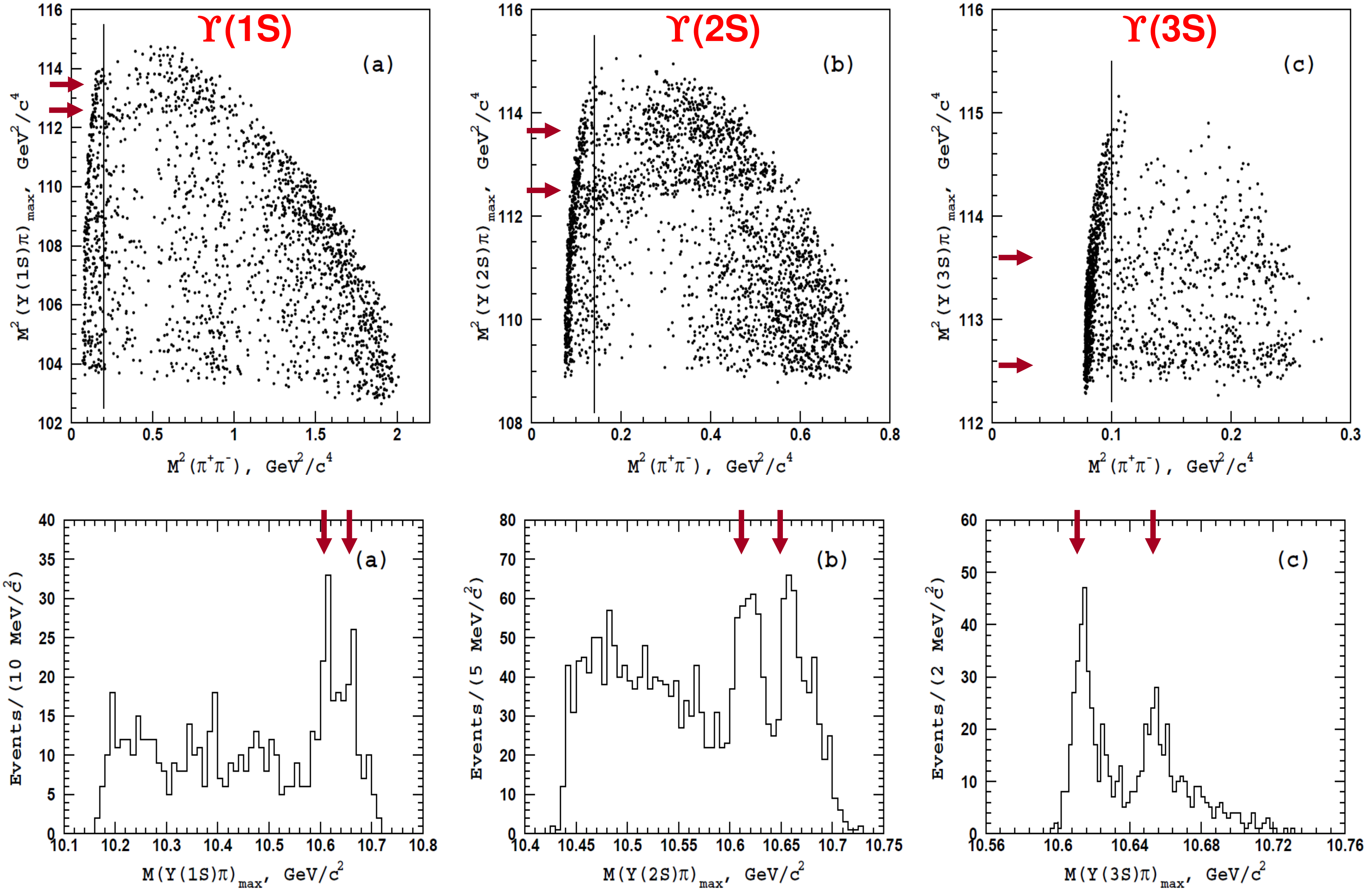
Belle: $\Delta M_{HF}(2S) = 23.4 ^{+4.0}_{-4.5}$ MeV

Dobbs et al.: $\Delta M_{HF}(2S) = 48.7$ MeV

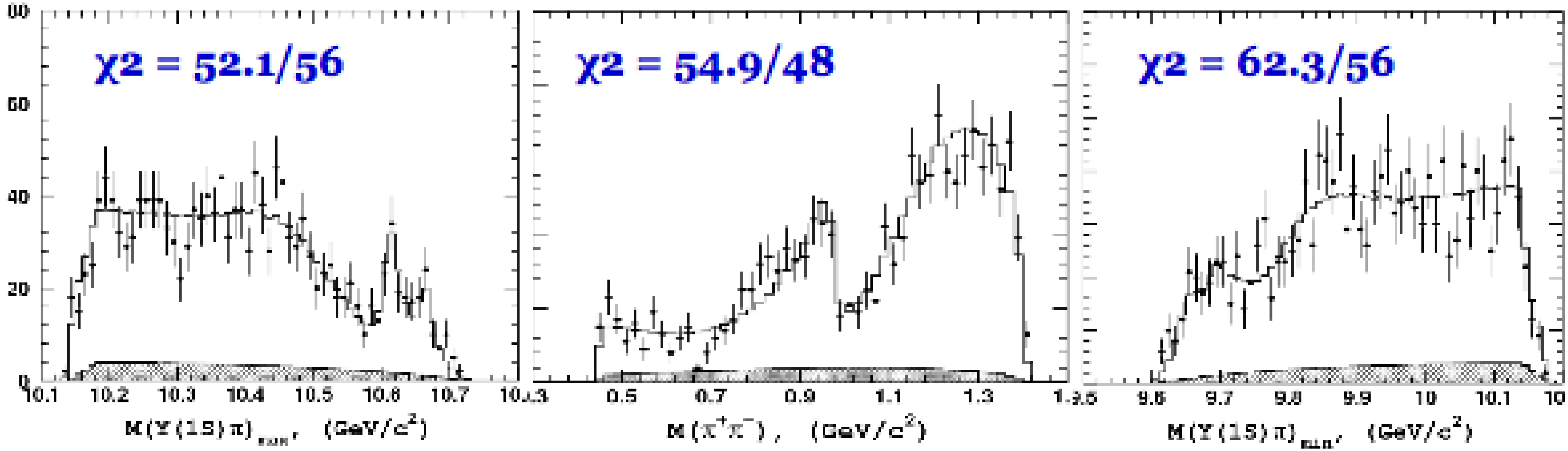
- ΔM_{HF}(2S) too high
- Anomalous production rate

	N	$\Delta M_{\rm hf}$ (MeV)	M (MeV)	$\chi^2/d.o.f.$	signif. (σ)	$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^6$
$\eta_b(2S)$	$11.4^{+4.3}_{-3.5}$	$48.7 \pm 2.3 \pm 2.1$	$9974.6 \pm 2.3 \pm 2.1$	$91.8/103$	4.9	$46.2^{+29.7}_{-14.2} \pm 10.6$
$\eta_b(1S)$	$10.3^{+4.9}_{-4.1}$	$67.1 \pm 3.4 \pm 2.3$	$9393.2 \pm 3.4 \pm 2.3$	$114.6/107$	3.1	$30.1^{+33.5}_{-7.4} \pm 7.5$

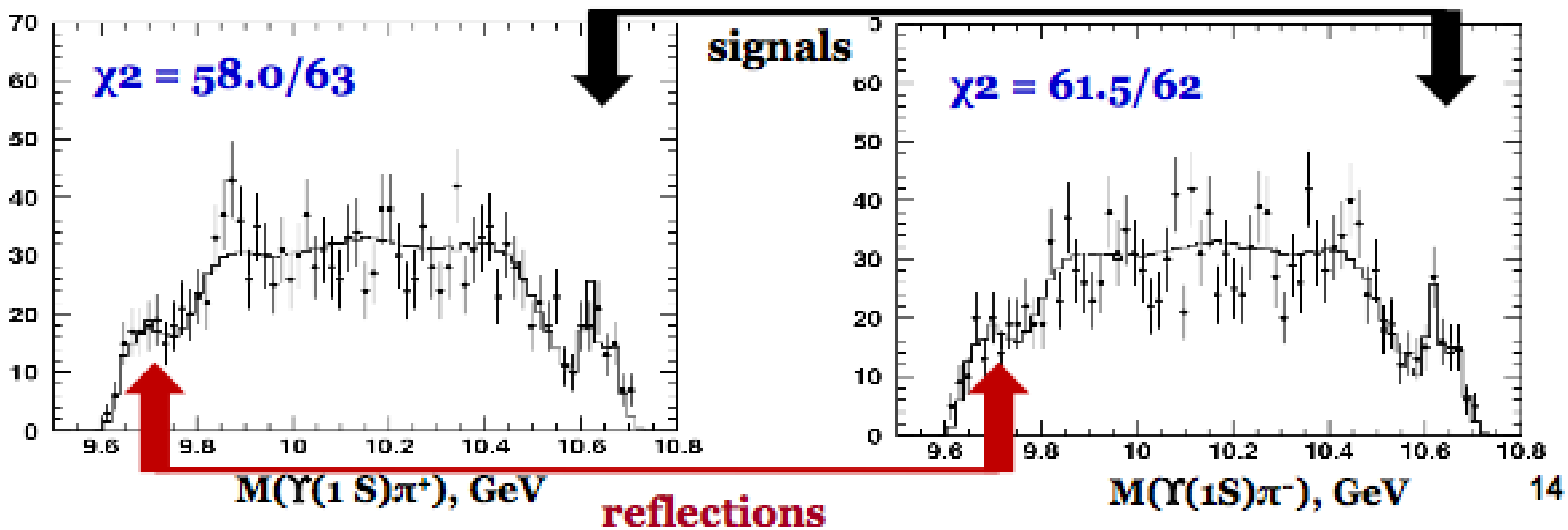
Z_b in Y(nS) final state



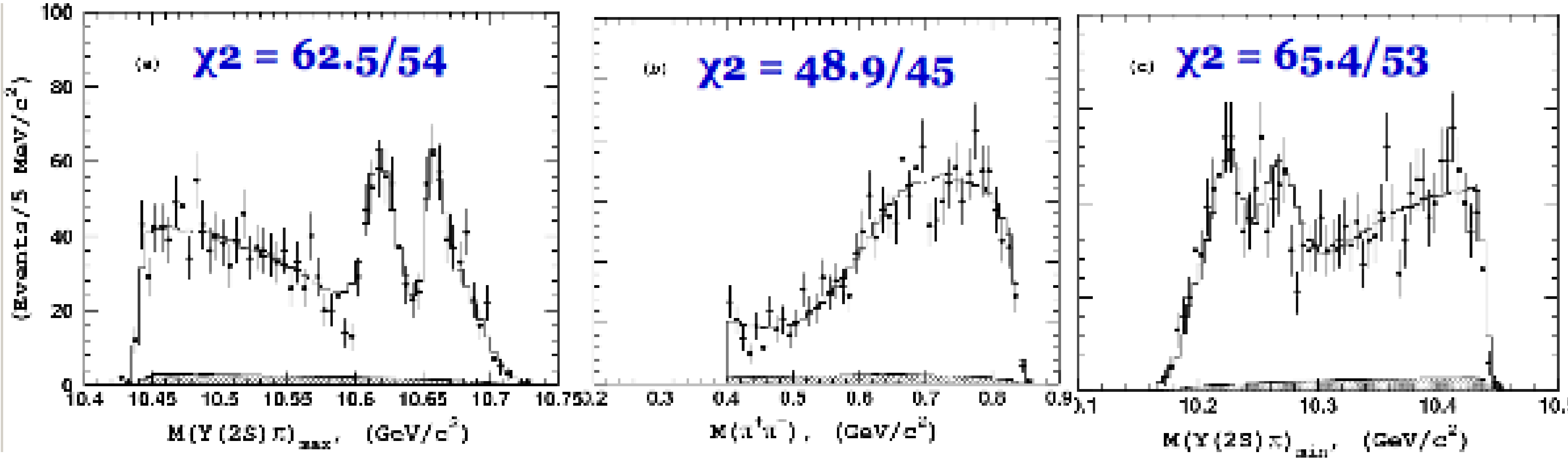
Z_b in Υ(1S) final state



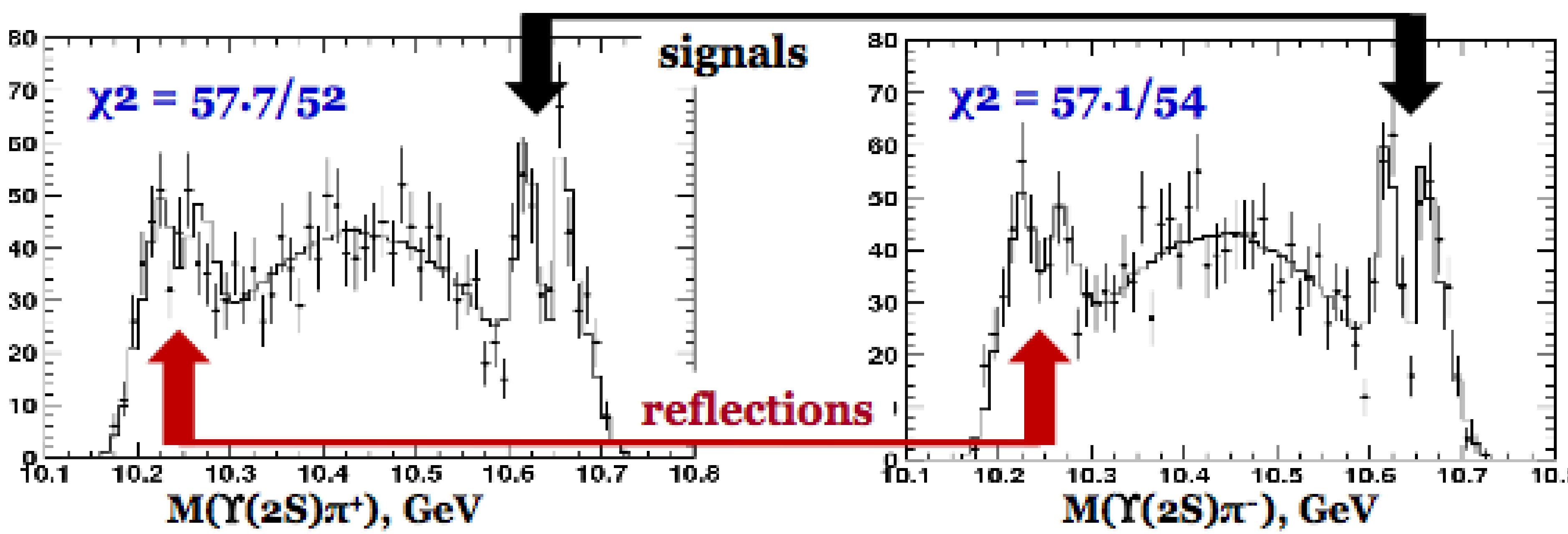
M(Υ(1S)π⁺) and M(Υ(1S)π⁻) projections:



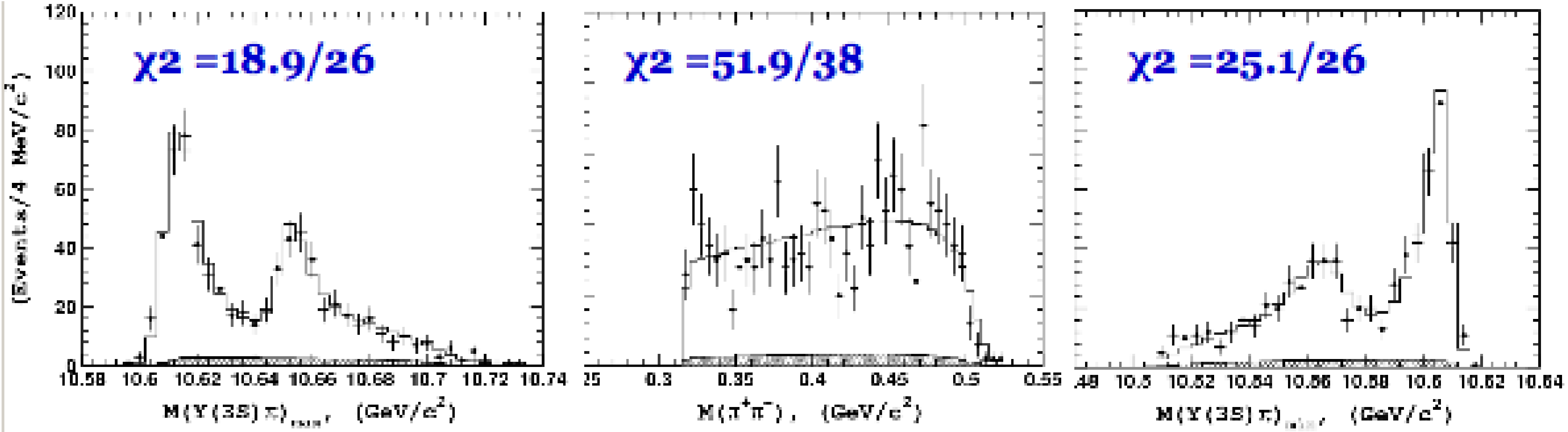
Z_b in Υ(2S) final state



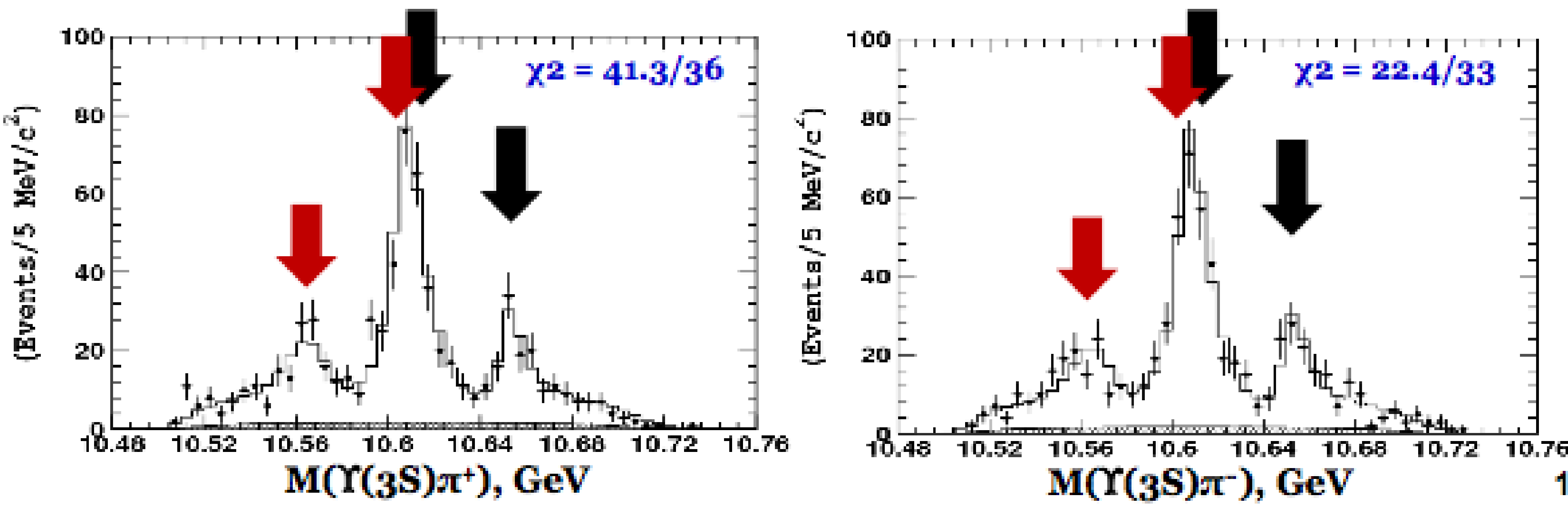
M(Υ(2S)π⁺) and M(Υ(2S)π⁻) projections:



Z_b in Y(3S) final state



M(ϒ(3S)π⁺) and M(ϒ(3S)π⁻) projections:



Z_b angular analysis

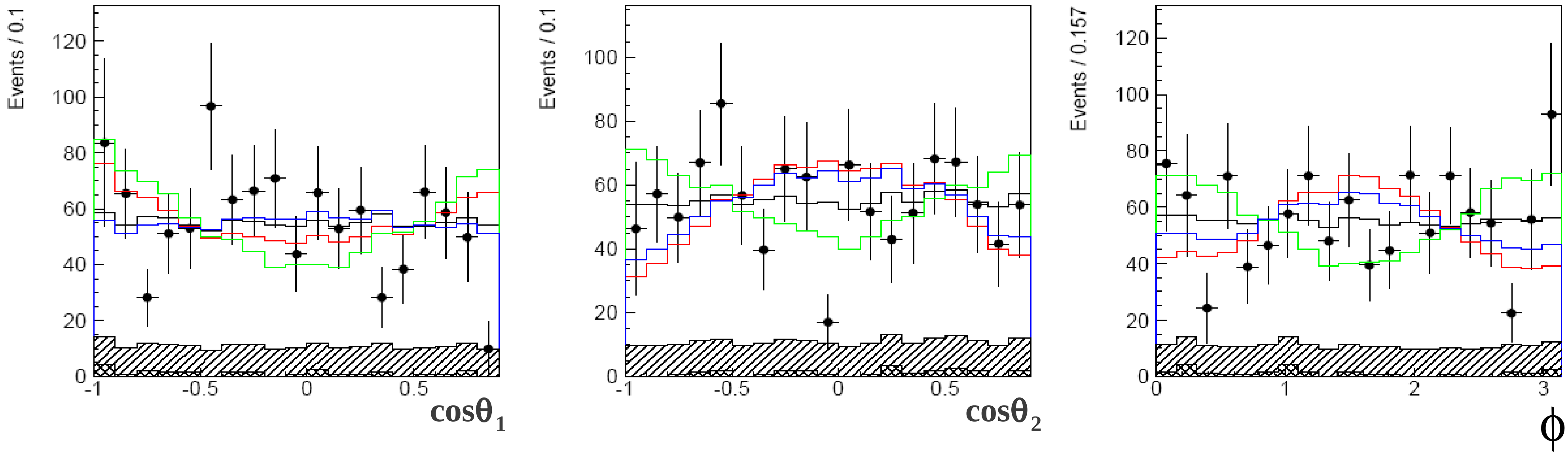
$\theta_i = \angle(\pi_i, e^+)$

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

e^+ → incoming positron beam

Color coding: J^P= 1^+ 1^- 2^+ 2^-

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



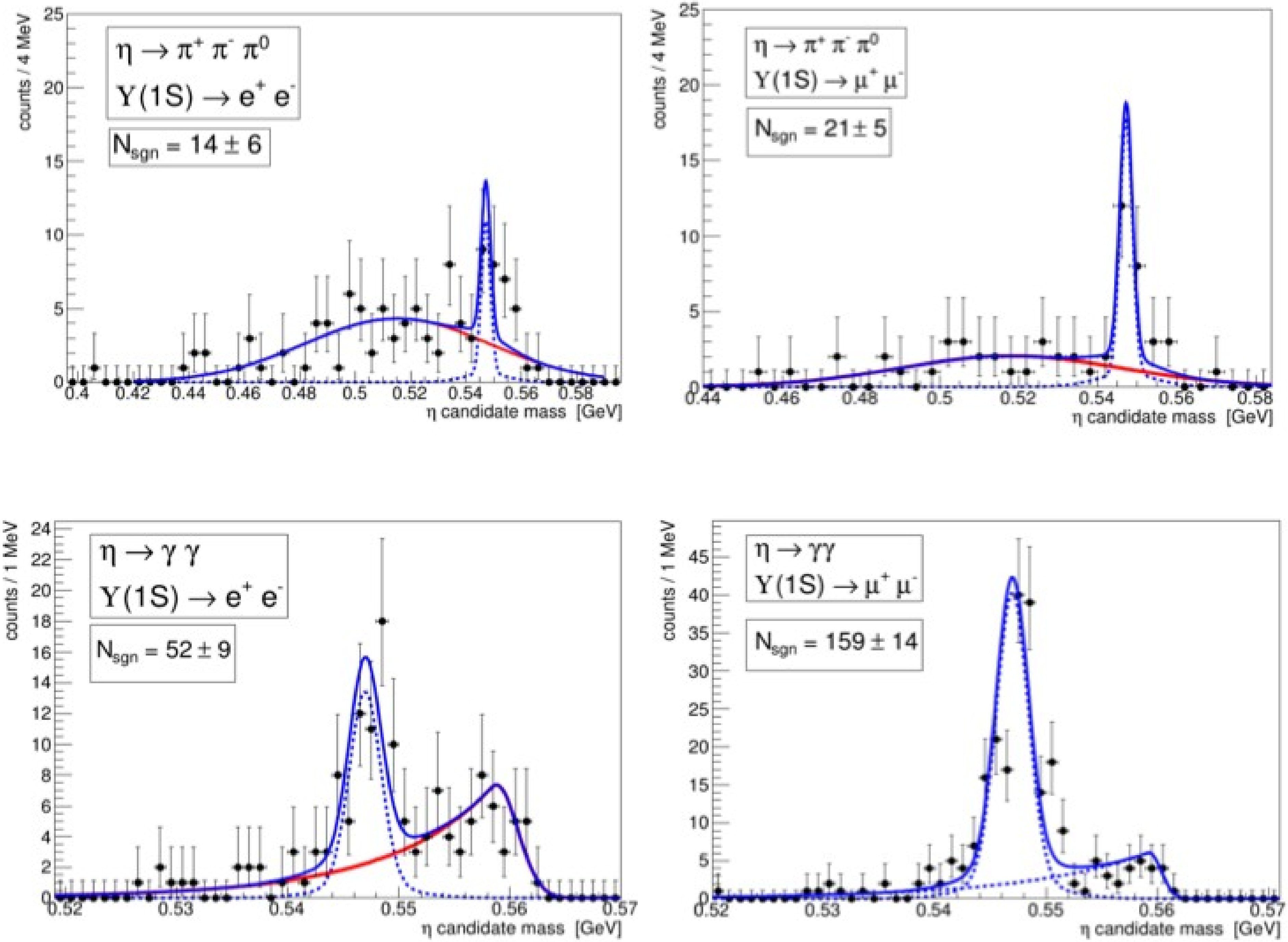
Probabilities at which different J^P hypotheses are disfavored compared to 1^+

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

Y(2S)→ η Y(1S)

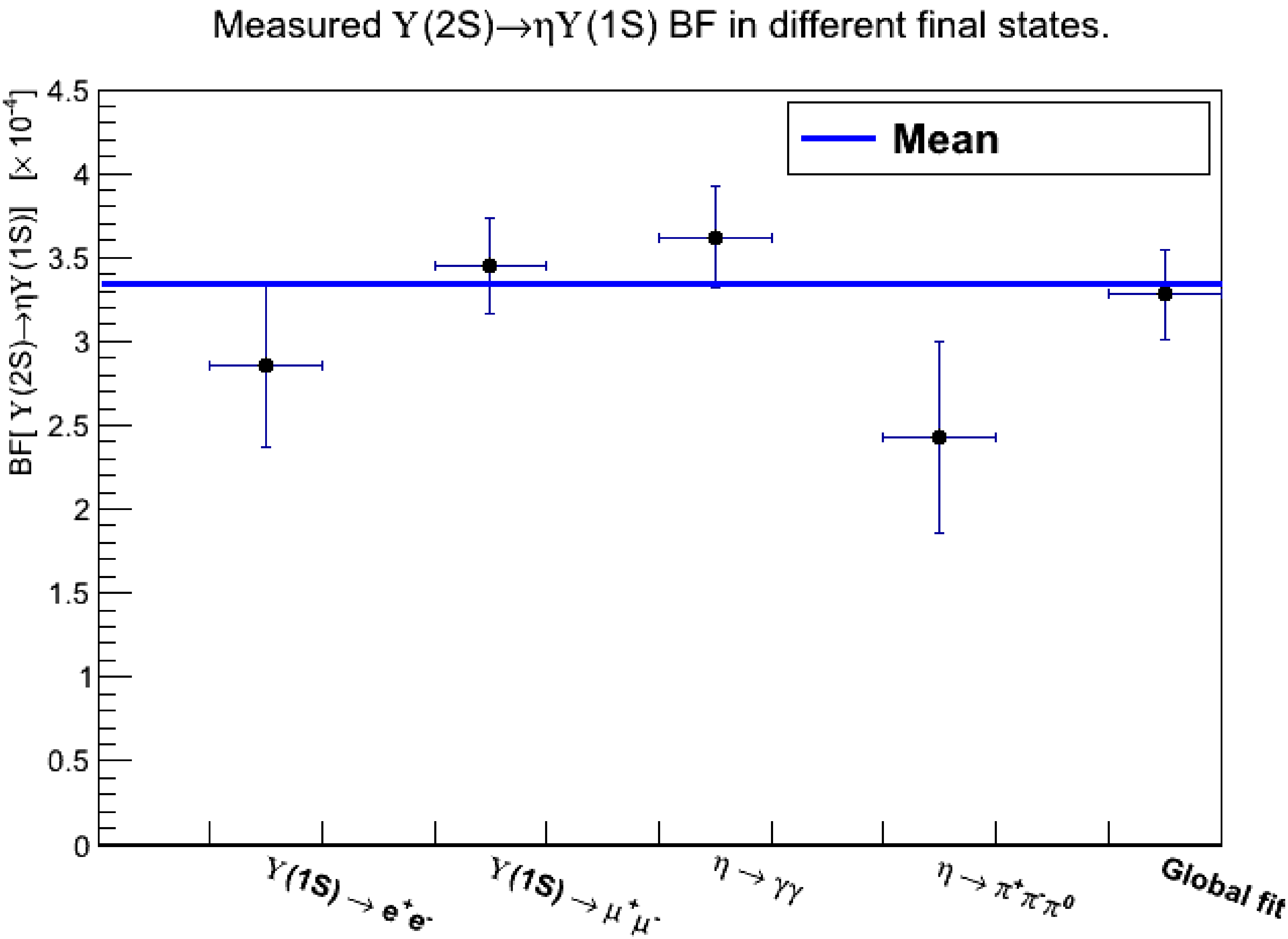
- $\Upsilon(2S) \to \eta\Upsilon(1S)$:
  -$\mathcal{B}_{theo} \approx 8.0 \times 10^{-4}$.
  -$\mathcal{B}_{CLEO} = (2.1^{+0.7}_{-0.6} \pm 0.3) \times 10^{-4}$ (5.3σ with 1.3 fb^{-1}, PRL101,192001).
- $\Upsilon(3S) \to \eta\Upsilon(1S)$:
  -$\mathcal{B}_{theo} \approx 6.5 \times 10^{-4}$.
  -$\mathcal{B}_{CLEO} < 1.8 \times 10^{-4}$ (PRL101,192001).
- $\Upsilon(4S) \to \eta\Upsilon(1S)$:
  -$\mathcal{B}_{BaBar} \approx 2.5 \times \mathcal{B}(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-)$, PRD78,112002.
- Event Reconstruction: $\eta \to \gamma\gamma/\pi^+\pi^-\pi^0$, and $\Upsilon(1S) \to e^+e^-/\mu^+\mu^-$.
- Backgrounds:
  - $\Upsilon(2S) \to \Upsilon(1S)\pi^0\pi^0$ ($\mathcal{B} = 9.0\%$)
  - $\Upsilon(2S) \to \gamma\chi_{bJ} \to \gamma\gamma\Upsilon(1S)$ ($\mathcal{B} = 4.0\%$)
  - Radiative Bhabha scattering

Υ(2S)→ η Υ(1S)

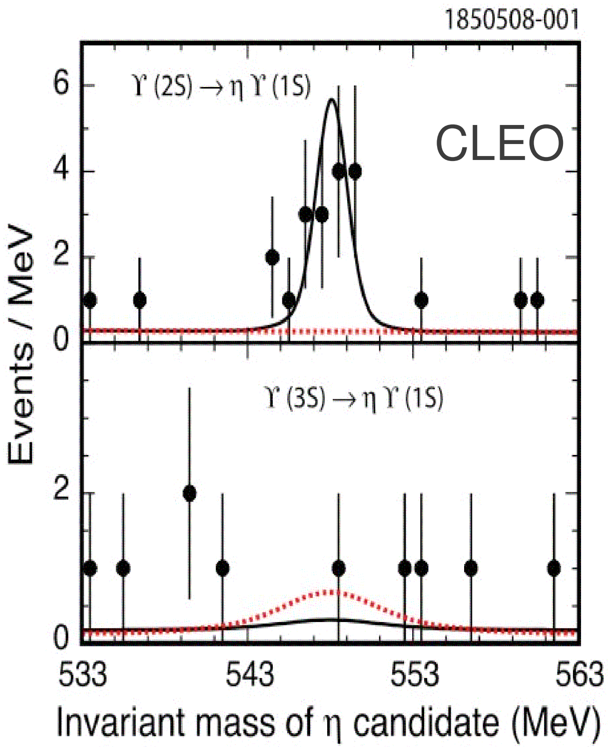


η → π⁺ π⁻ π⁰
Υ(1S) → e⁺ e⁻
N_sgn = 14 ± 6
η → π⁺ π⁻ π⁰
Υ(1S) → μ⁺ μ⁻
N_sgn = 21 ± 5
η → γ γ
Υ(1S) → e⁺ e⁻
N_sgn = 52 ± 9
η → γγ
Υ(1S) → μ⁺ μ⁻
N_sgn = 159 ± 14
counts / 4 MeV
counts / 1 MeV
η candidate mass [GeV]

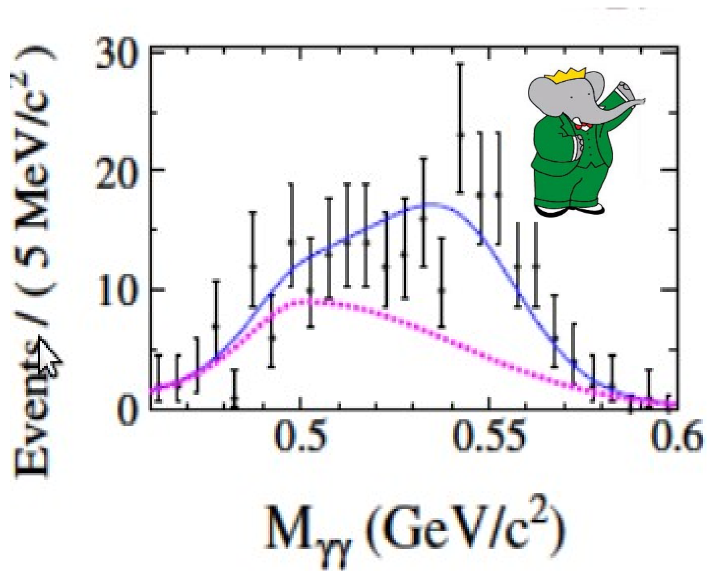
$\Upsilon(2S) \to \eta\ \Upsilon(1S)$

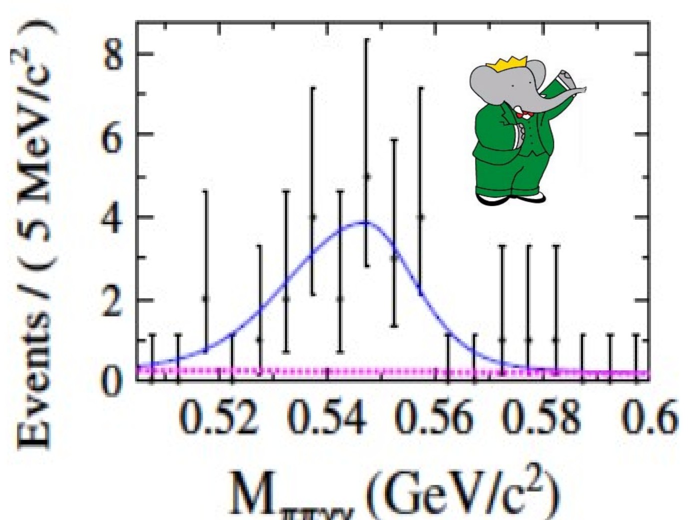


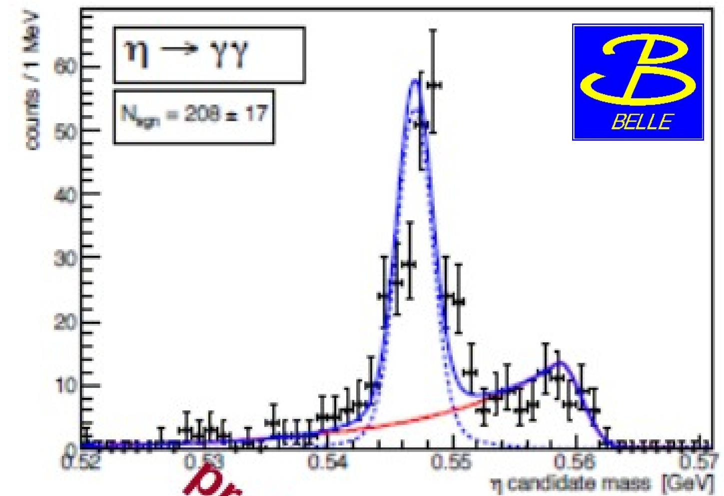
Υ(2S)→ η Υ(1S) @ BaBar and CLEO



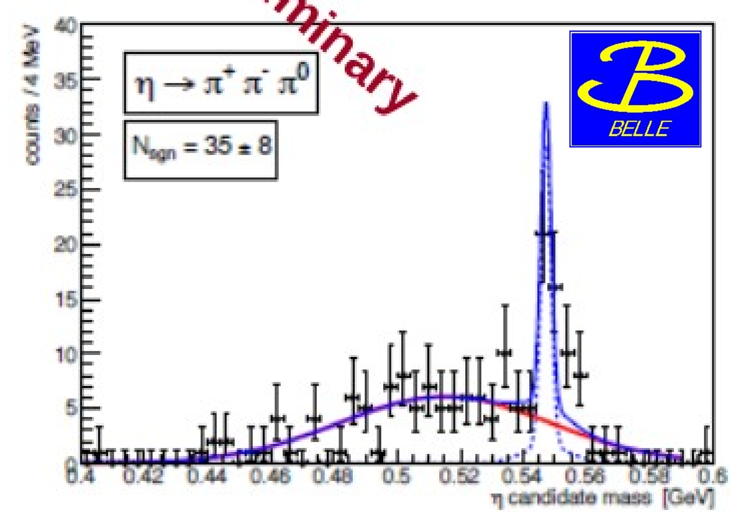
All modes summed







preliminary



BF = (2.39 ± 0.31 ±0.14)×10^{-4}

Υ(1,2S)→ light hadrons

arXiv:1205.1246v1

$$Q_C = \frac{B[\psi' \to \text{hadrons}]}{B[J/\psi \to \text{hadrons}]} = \frac{B[\psi' \to e^+e^-]}{B[J/\psi \to e^+e^-]} = 12\%$$

$$Q_\Upsilon = \frac{B[\Upsilon(2S) \to \text{hadrons}]}{B[\Upsilon(1S) \to \text{hadrons}]} = \frac{B[\Upsilon(2S) \to e^+e^-]}{B[\Upsilon(1S) \to e^+e^-]} = 77\%$$

Channel	$\Upsilon(1S)$					$\Upsilon(2S)$						
	$N^{\rm sig}$	$N^{\rm UP}_{\rm sig}$	Σ	$\mathcal{B}$	$\mathcal{B}^{\rm UP}$	$N^{\rm sig}$	$N^{\rm UP}_{\rm sig}$	Σ	$\mathcal{B}$	$\mathcal{B}^{\rm UP}$	Q_Υ	$Q^{\rm UP}_\Upsilon$
ϕK^+K^-	56.3 ± 9.0		8.6	$2.36 \pm 0.38 \pm 0.29$		69 ± 36		6.5	$1.86 \pm 0.96 \pm 0.21$		$0.79 \pm 0.54 \pm 0.13$	
$\omega\pi^+\pi^-$	63.6 ± 9.5		8.5	$4.46 \pm 0.67 \pm 0.72$		29 ± 12	51	2.5	$1.32 \pm 0.54 \pm 0.45$	2.58	$0.30 \pm 0.13 \pm 0.11$	0.55
$K^{*0}K^-\pi^+$	173 ± 20		11	$4.42 \pm 0.50 \pm 0.58$		135 ± 23		6.4	$2.32 \pm 0.40 \pm 0.54$		$0.52 \pm 0.11 \pm 0.14$	
$\phi f'_2$	6.9 ± 3.9	15	2.1	$0.64 \pm 0.37 \pm 0.14$	1.63	8.3 ± 6.0	18	1.6	$0.50 \pm 0.36 \pm 0.19$	1.33	$0.77 \pm 0.70 \pm 0.33$	2.54
ωf_2	5.2 ± 4.0	13	1.5	$0.57 \pm 0.44 \pm 0.13$	1.79	-0.4 ± 3.3	6.1		$-0.03 \pm 0.24 \pm 0.01$	0.57	$-0.06 \pm 0.42 \pm 0.02$	1.22
ρa_2	29 ± 11	49	2.7	$1.15 \pm 0.47 \pm 0.18$	2.24	10 ± 11	30	0.9	$0.27 \pm 0.28 \pm 0.14$	0.88	$0.23 \pm 0.26 \pm 0.12$	0.82
$K^{*0}\bar{K}_2^{*0}$	42.2 ± 9.5		5.4	$3.02 \pm 0.68 \pm 0.34$		32 ± 11		3.3	$1.53 \pm 0.52 \pm 0.19$		$0.50 \pm 0.21 \pm 0.07$	
$K_1(1270)^+K^-$	3.7 ± 4.9	13	0.8	$0.54 \pm 0.72 \pm 0.21$	2.41	11.0 ± 4.4	26	1.2	$1.06 \pm 0.42 \pm 0.32$	3.22	$1.96 \pm 2.71 \pm 0.84$	4.73
$K_1(1400)^+K^-$	23.8 ± 8.2		3.3	$1.02 \pm 0.35 \pm 0.22$		9.2 ± 8.2	24	0.5	$0.26 \pm 0.23 \pm 0.09$	0.83	$0.26 \pm 0.25 \pm 0.10$	0.77
$b_1(1235)^+\pi^-$	14.4 ± 6.9	28	2.4	$0.47 \pm 0.22 \pm 0.13$	1.25	1.2 ± 3.5	13	0.2	$0.02 \pm 0.07 \pm 0.01$	0.40	$0.05 \pm 0.16 \pm 0.03$	0.35