Exploration of bottomonium states at Belle

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Introductory Remarks

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Bottom Meson Cross Sections above $\Upsilon(4S)$

Act II

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Act III

Observation of $\chi_{bJ}(2P) \to \omega\Upsilon(1S)$ and search for $\chi_{bJ}(3P)$

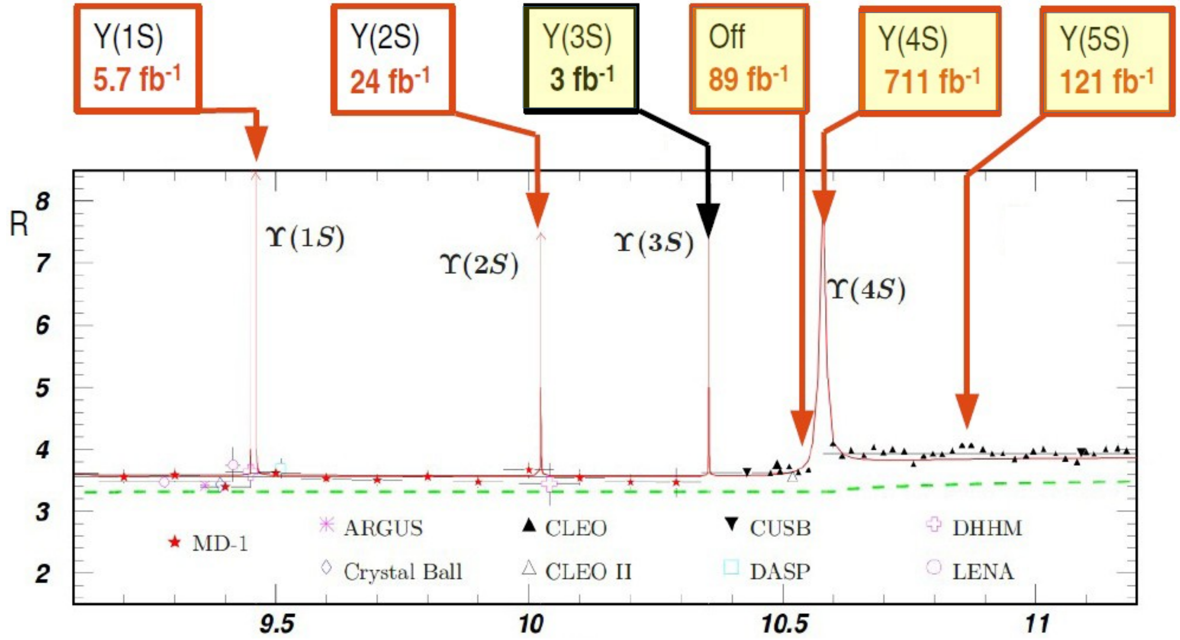
Prologue

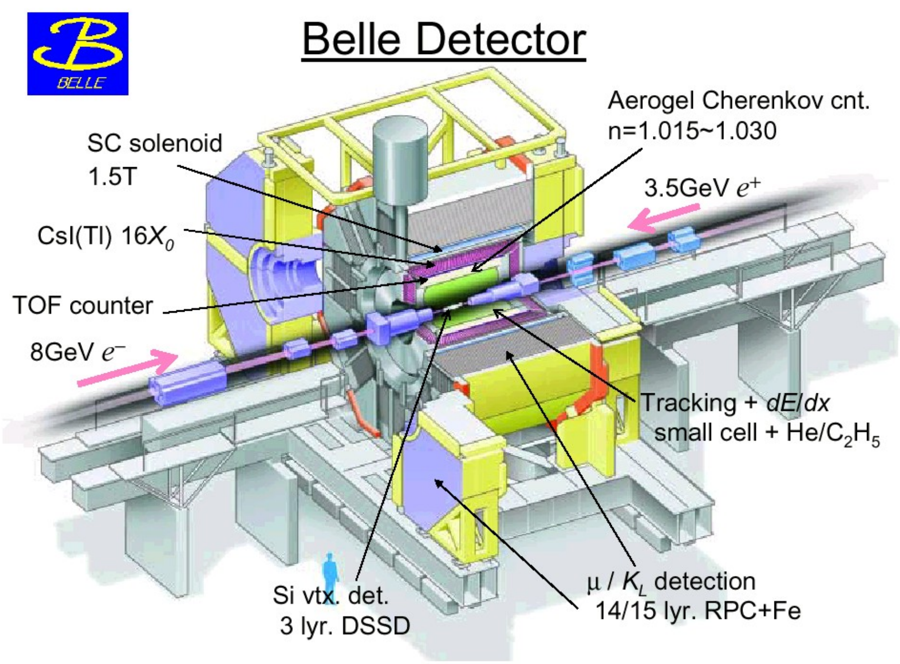
Introductory Remarks

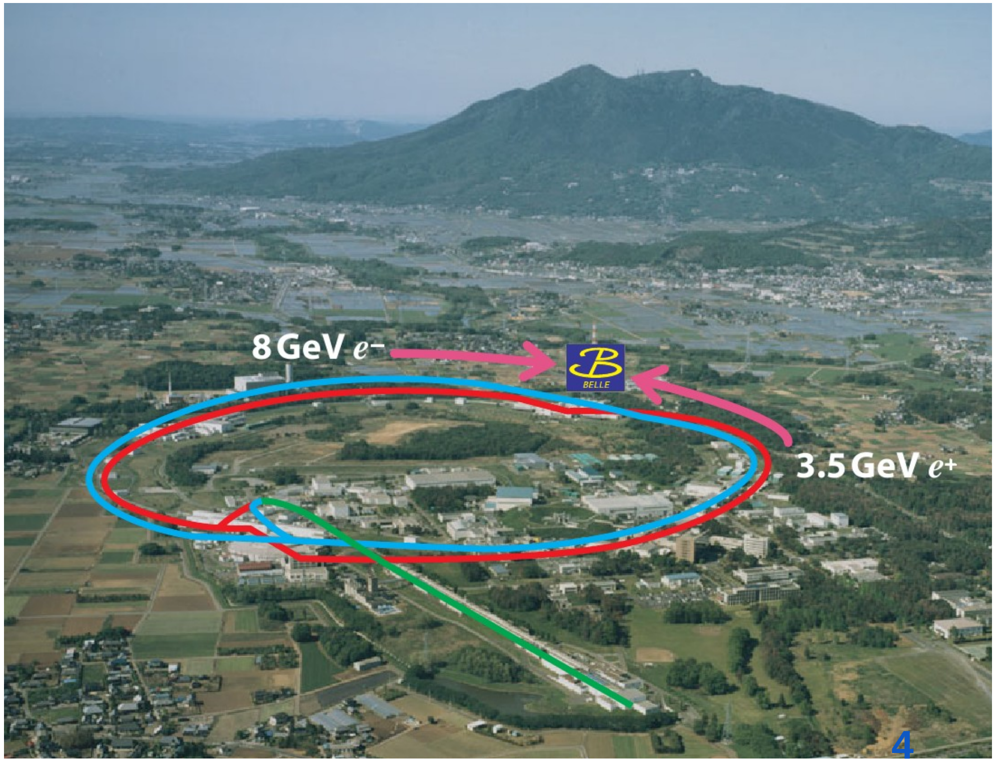
Belle @ KEK

Asymmetric e+e- collider that was mainly operated at $\Upsilon(4S)$

- World's largest data samples at most bottomonium S-wave resonances
- In addition - 20 fb^{-1} of scan data from about 10.6 to 11.0 GeV



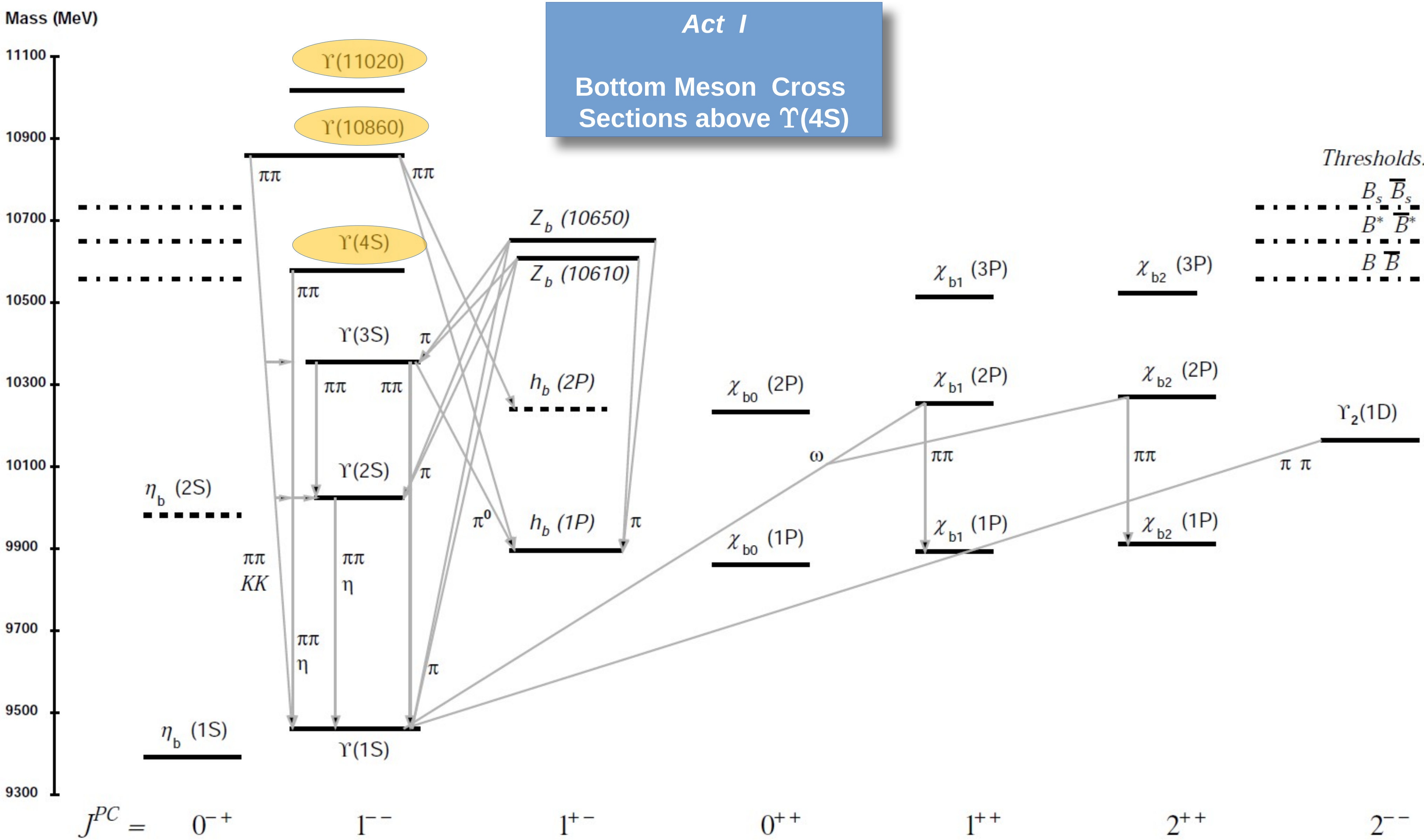




The Bottomonium Spectrum

Act I

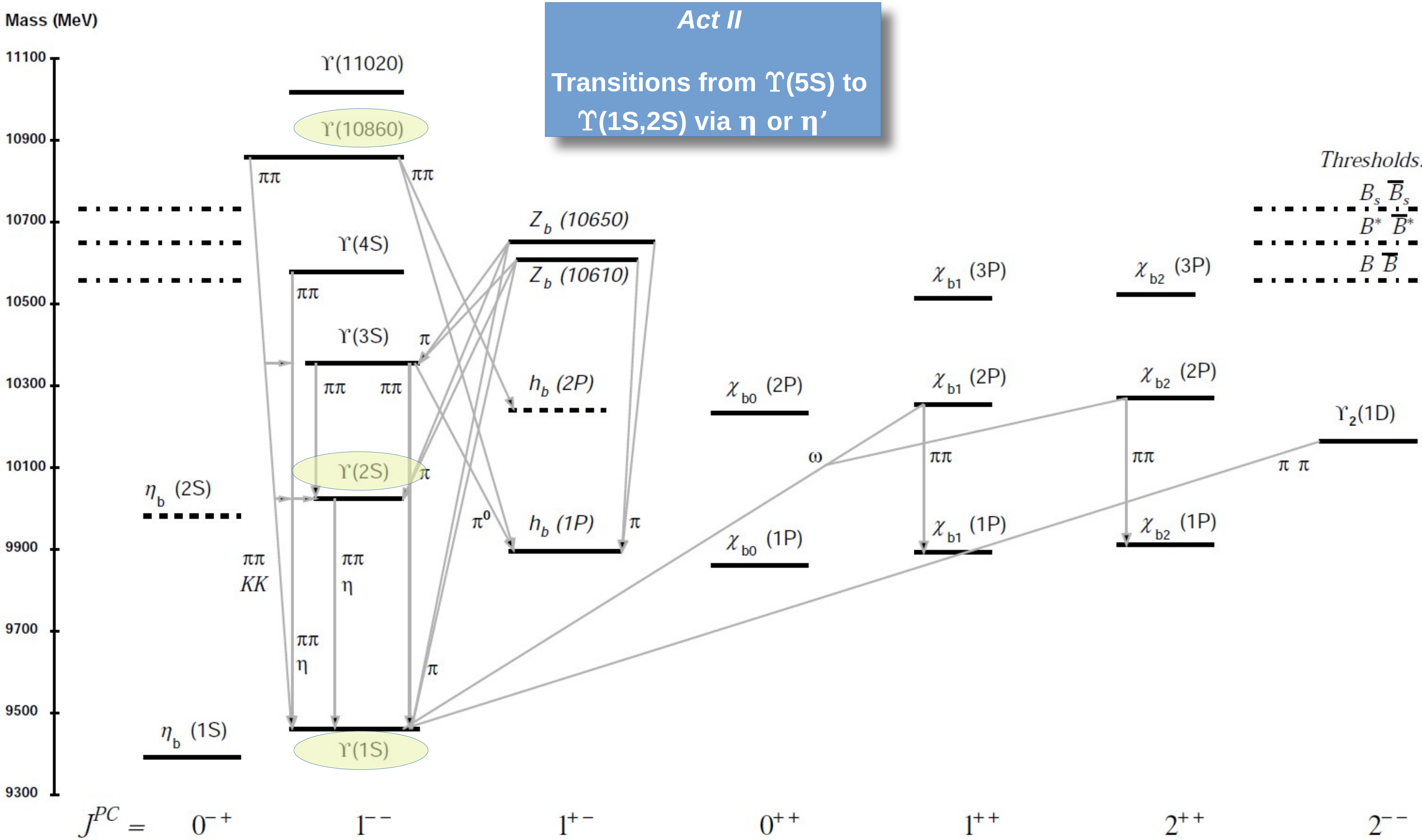
Bottom Meson Cross Sections above ϒ(4S)



The Bottomonium Spectrum

Act II

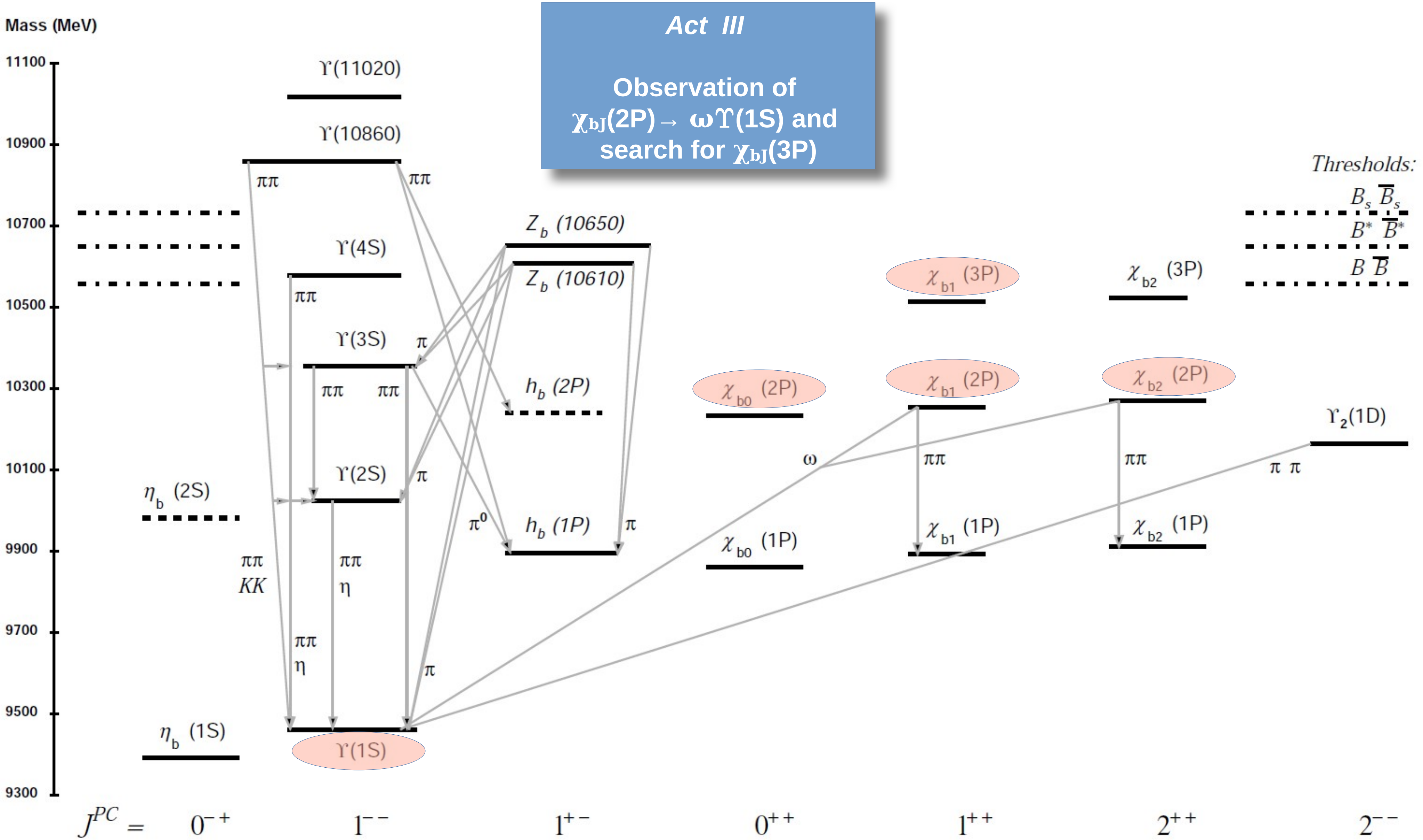
Transitions from Υ(5S) to Υ(1S,2S) via η or η'



The Bottomonium Spectrum

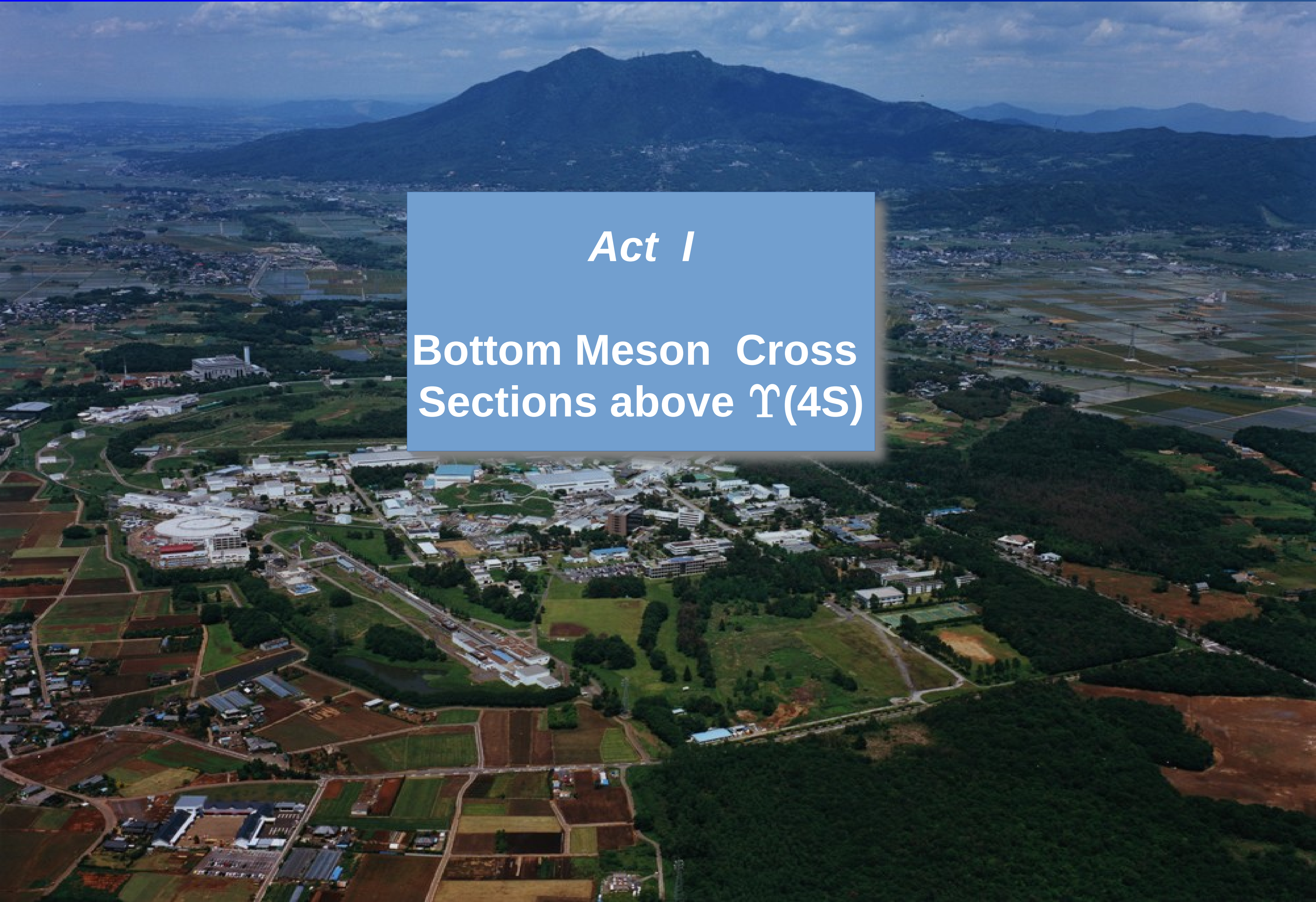
Act III

Observation of $\chi_{bJ}(2P) \to \omega\Upsilon(1S)$ and search for $\chi_{bJ}(3P)$

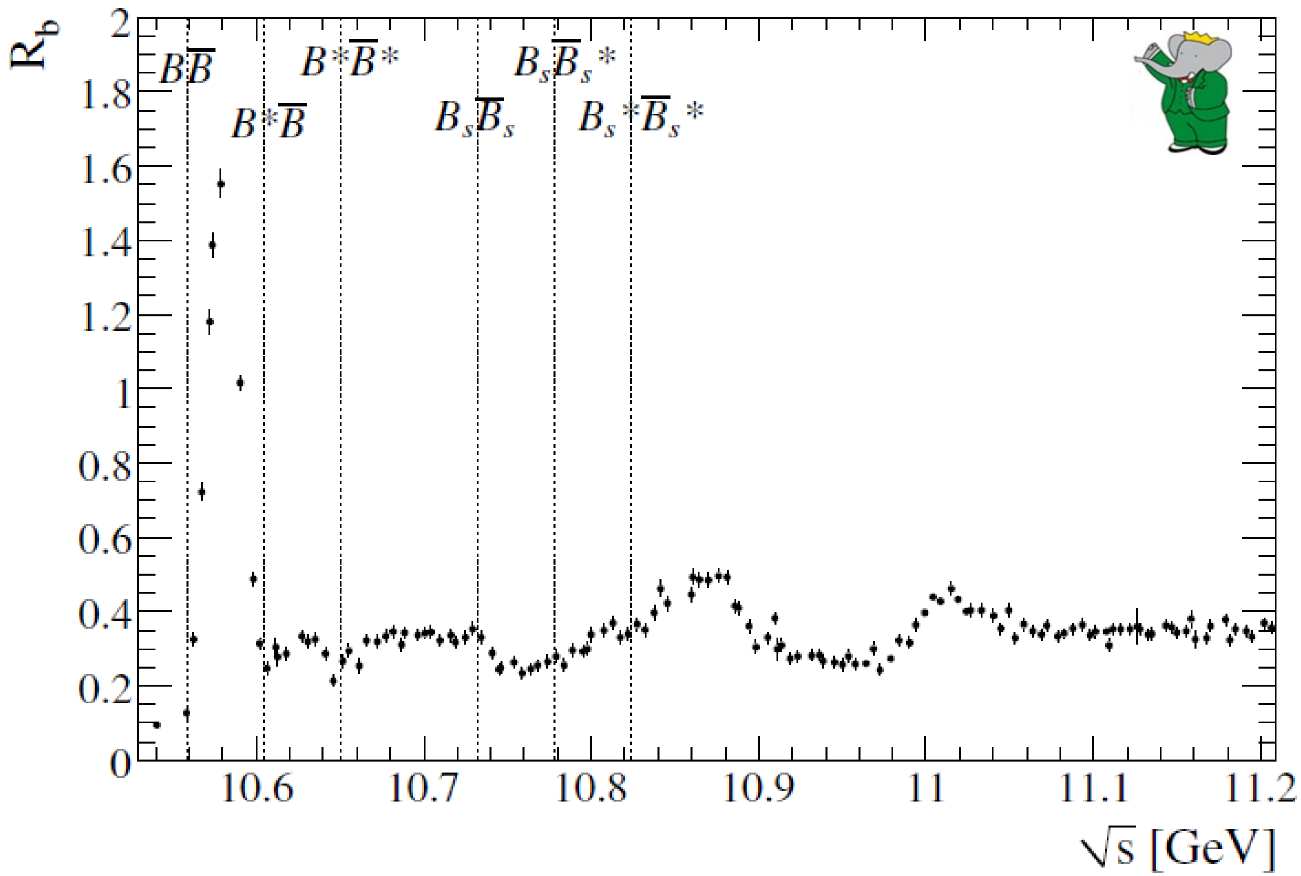


Act I

Bottom Meson Cross Sections above $\Upsilon(4S)$



PRL 102, 012001



- Above shows inclusive bb cross section from 10.54 GeV - 11.2 GeV
- Key features include the Υ(4S,5S,6S), and a few threshold effects
- An exclusive study of bottom meson pair cross sections is called for!

Data samples

121 fb^{-1} on Υ(5S)
571 fb^{-1} on Υ(4S)
16 fb^{-1} in a scan of [10.63 - 11.02] GeV

- Reconstruction of charged and neutral B mesons in charm and charmonium modes selected for particularly clean reconstruction
- MVA algorithms for signal selection and continuum suppression
- A single charged or neutral B meson per event is selected based on MVA

B and D meson decay modes utilized

$B^+ \to$	$B^0 \to$
$\bar{D}^0\pi^+$	$D^-\pi^+$
$\bar{D}^0\pi^+\pi^+\pi^-$	$D^-\pi^+\pi^+\pi^-$
$\bar{D}^{*0}\pi^+$	$D^{*-}\pi^+$
$\bar{D}^{*0}\pi^+\pi^+\pi^-$	$D^{*-}\pi^+\pi^+\pi^-$
$D_s^+\bar{D}^0$	$D_s^+D^-$
$D_s^{*+}\bar{D}^0$	$D_s^{*+}D^-$
$D_s^+\bar{D}^{*0}$	$D_s^+D^{*-}$
$D_s^{*+}\bar{D}^{*0}$	$D_s^{*+}D^{*-}$
$J/\psi\, K^+$	$J/\psi\, K_S^0$
$J/\psi\, K_S^0\,\pi^+$	$J/\psi\, K^+\pi^-$
$J/\psi\, K^+\pi^+\pi^-$	
$D^-\pi^+\pi^+$	$D^{*-}K^+K^-\pi^+$
$D^{*-}\pi^+\pi^+$	

$D^0 \to$	$D^+ \to$	$D_s^+ \to$
$K^-\pi^+$	$K^-\pi^+\pi^+$	$K^+K^-\pi^+$
$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	$K^+K_S^0$
$K^-\pi^+\pi^+\pi^-$	$K_S^0\,\pi^+$	$K^+K^-\pi^+\pi^0$
$K_S^0\,\pi^+\pi^-$	$K_S^0\,\pi^+\pi^0$	$K^+K_S^0\,\pi^+\pi^-$
$K_S^0\,\pi^+\pi^-\pi^0$	$K_S^0\,\pi^+\pi^+\pi^-$	$K^-K_S^0\,\pi^+\pi^+$
K^+K^-	$K^+K^-\pi^+$	$K^+K^-\pi^+\pi^+\pi^-$
$K^+K^-K_S^0$		$K^+\pi^+\pi^-$
		$\pi^+\pi^+\pi^-$

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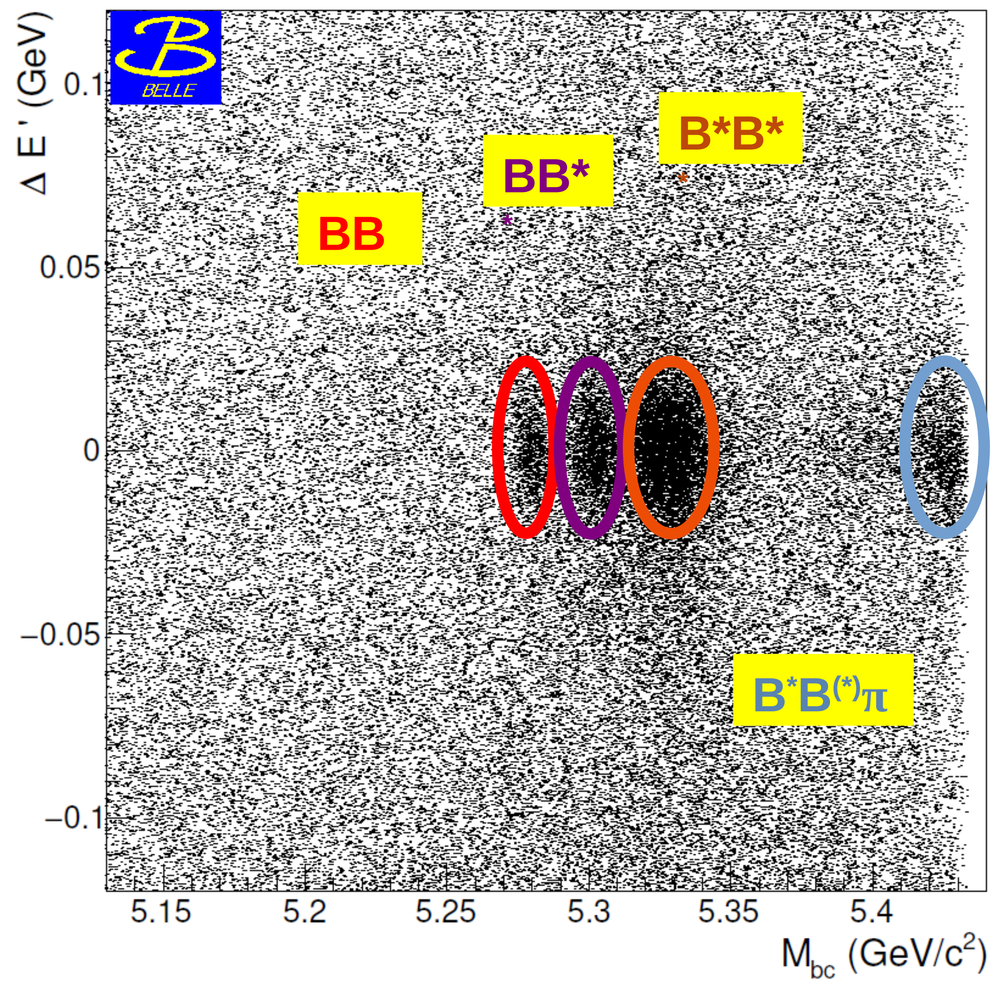
- At right, data taken at $\Upsilon(5S)$
- Key variables for analysis are

$$M_{bc} \equiv \sqrt{(E_{beam,CM})^2 - (p_{B,CM})^2}$$
$$\Delta E' \equiv \Delta E - M_{bc} + M_B$$

- Where as usual

$$\Delta E \equiv E_{B,CM} - E_{beam,CM}$$

- ΔE′ has improved resolution and allows all desired two-body decays to be selected with a common cut
- Populations of each can be studied by fitting the projections onto the M_{bc} axis for all energies at which data were accumulated



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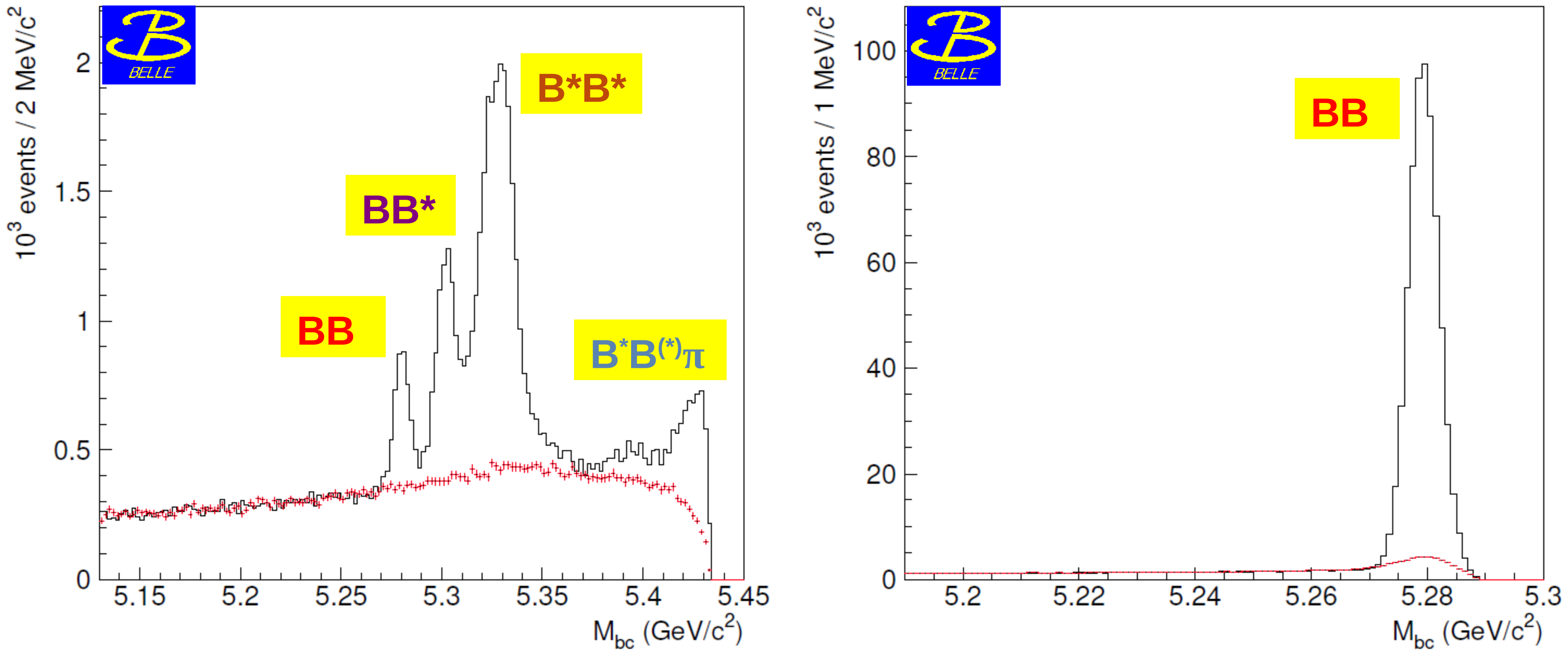

M_{bc} distributions, corresponding to the ΔE′ signal region (black histogram) and ΔE′ side-bands (red points) for (left) ϒ(5S) and (right) ϒ(4S)

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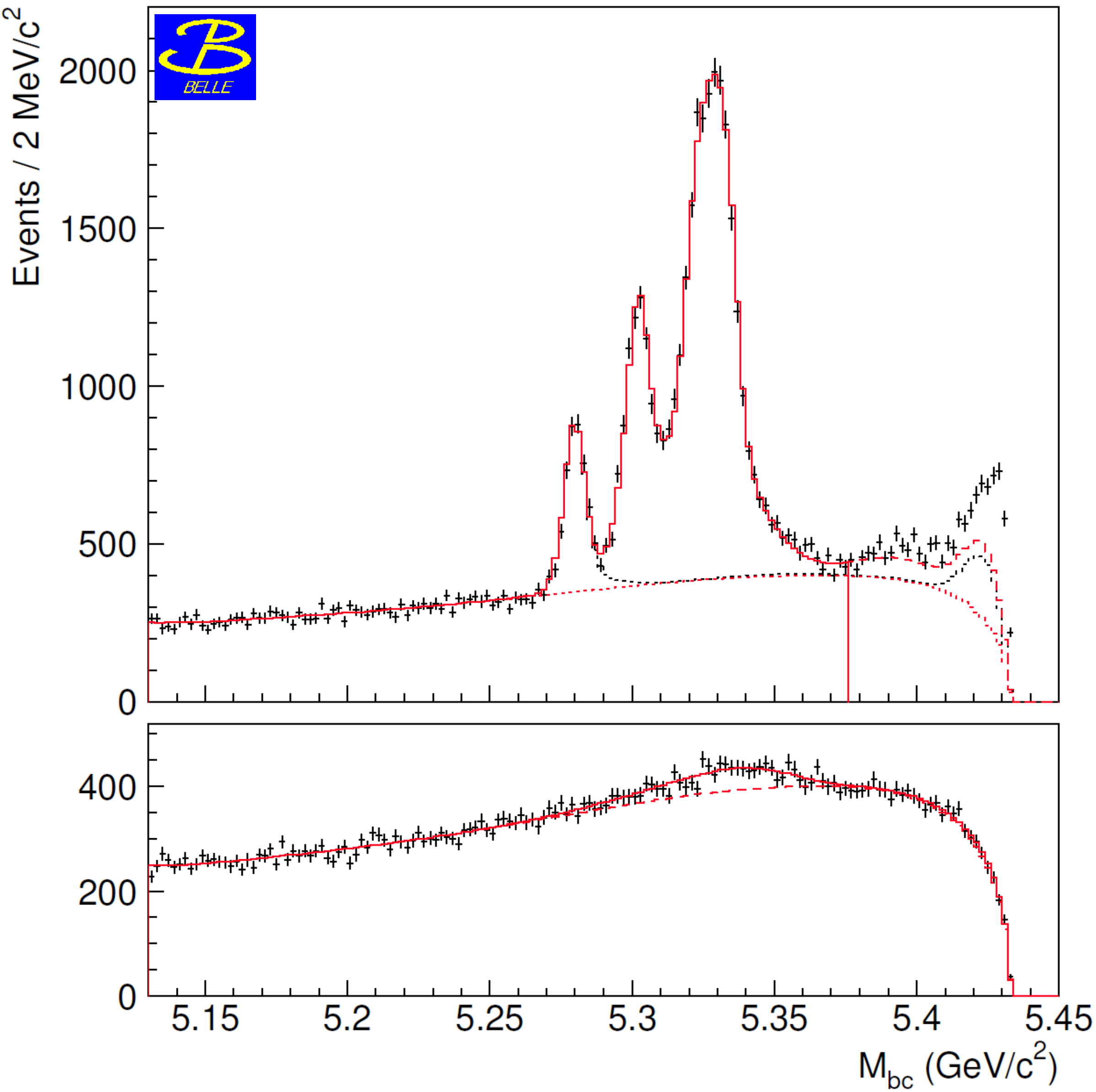

Example: M_{bc} fit from 121 fb^{-1} @Υ(5S)

ΔE′ signal region (upper)

ΔE′ side-bands (lower)

Yield breakdown at Υ(5S):

N_{total}	$(23.66 \pm 0.22 \pm 0.34) \times 10^3$
$N_{B\bar{B}} / N_{\text{total}}$	0.1121 ± 0.0030
$N_{B\bar{B}^*} / N_{\text{total}}$	0.3095 ± 0.0045
$N_{B^*\bar{B}^*} / N_{\text{total}}$	0.5784 ± 0.0048

Similar fits done for all 16 data points in the scan, to observe the energy dependence of the cross sections

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Sum of the two body cross sections compared to the previous full R_b scan

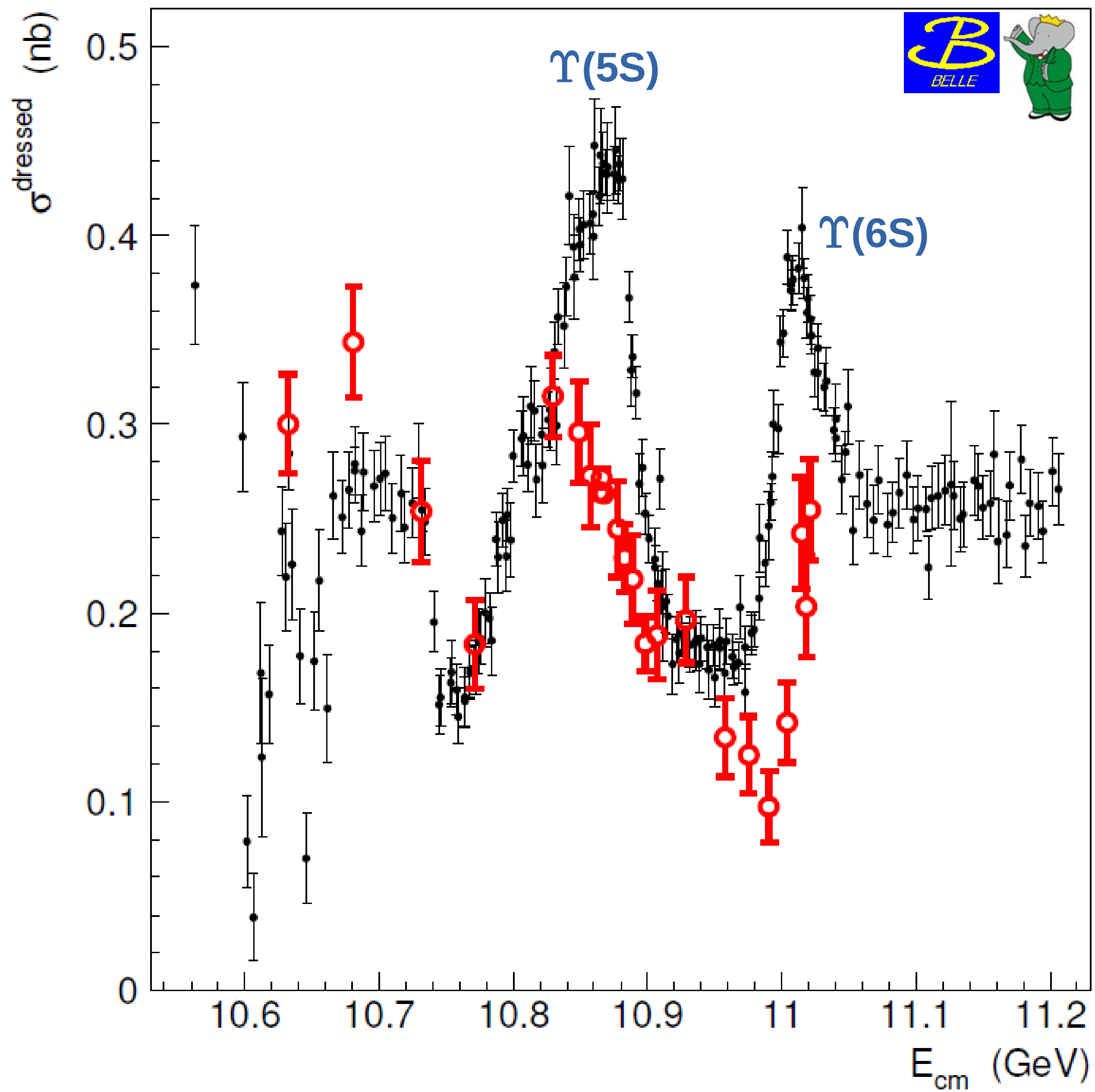
Note:

Rough agreement with R_b until the $B_S^{(*)}B_S^{(*)}$ threshold

The two-body sum of BB, BB* and B*B* does NOT peak at the ϒ(5S), contrary to expectations, e.g. PRD 34, 186

Further scan points called for in throughout the region and beyond ϒ(5S,6S) in Belle II!

(See the following Belle II talk by Bryan Fulsom)

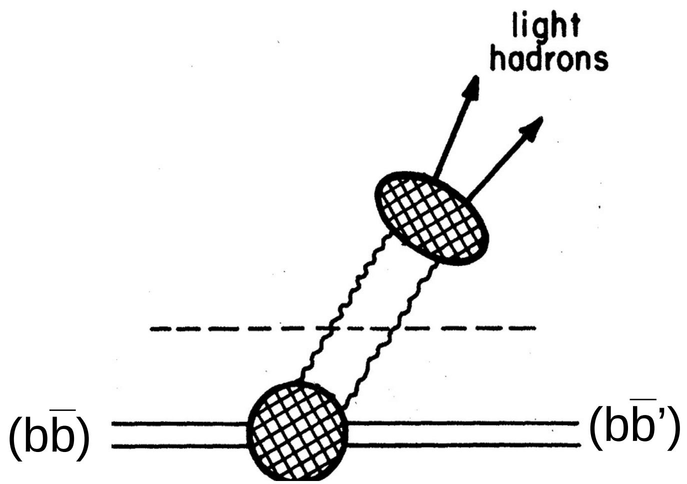


Act II

Transitions from $\Upsilon(5S)$ to $\Upsilon(1S,2S)$ via η or η'

Recent observations of hadronic transitions in bottomonium have yielded surprises

The QCDME model successfully explains such transitions involving states below open-bottom threshold, but seems unreliable for those originating above open-bottom threshold



Similarly, questions of the composition of the resonances above open-bottom threshold, and impact of the recently discovered exotic Z_b states which complicate the picture

In the context of this talk, the most critical questions arise from observations of large $\pi\pi$ transition rates from $\Upsilon(4S,5S)$, of η transition rates from $\Upsilon(4S)$ that are comparable to or larger than the $\pi\pi$ rates, and of the transition $\Upsilon(4S) \rightarrow \eta' \Upsilon(1S)$

Study of η and η' transitions from ϒ(5S)

In this analysis we have studied the following transitions, exclusively reconstructed

$$\Upsilon(5S) \to \eta\Upsilon(2S) \to [\gamma\gamma][\pi^+\pi^-\Upsilon(1S)] \to [\gamma\gamma][\pi^+\pi^-(\mu^+\mu^-)]$$
$$\Upsilon(5S) \to \eta\Upsilon(2S) \to [\pi^+\pi^-\pi^0][\mu^+\mu^-] \to [\pi^+\pi^-(\gamma\gamma)][\mu^+\mu^-]$$
$$\Upsilon(5S) \to \eta\Upsilon(1S) \to [\pi^+\pi^-\pi^0][\mu^+\mu^-] \to [\pi^+\pi^-(\gamma\gamma)][\mu^+\mu^-]$$

$$\Upsilon(5S) \to \eta'\Upsilon(1S) \to [\pi^+\pi^-\eta][\mu^+\mu^-] \to [\pi^+\pi^-(\gamma\gamma)][\mu^+\mu^-]$$
$$\Upsilon(5S) \to \eta'\Upsilon(1S) \to [\rho^0\gamma][\mu^+\mu^-] \to [(\pi^+\pi^-)\gamma][\mu^+\mu^-]$$

The data for these studies consists of a 118.3 fb^{-1} sample at ϒ(5S)

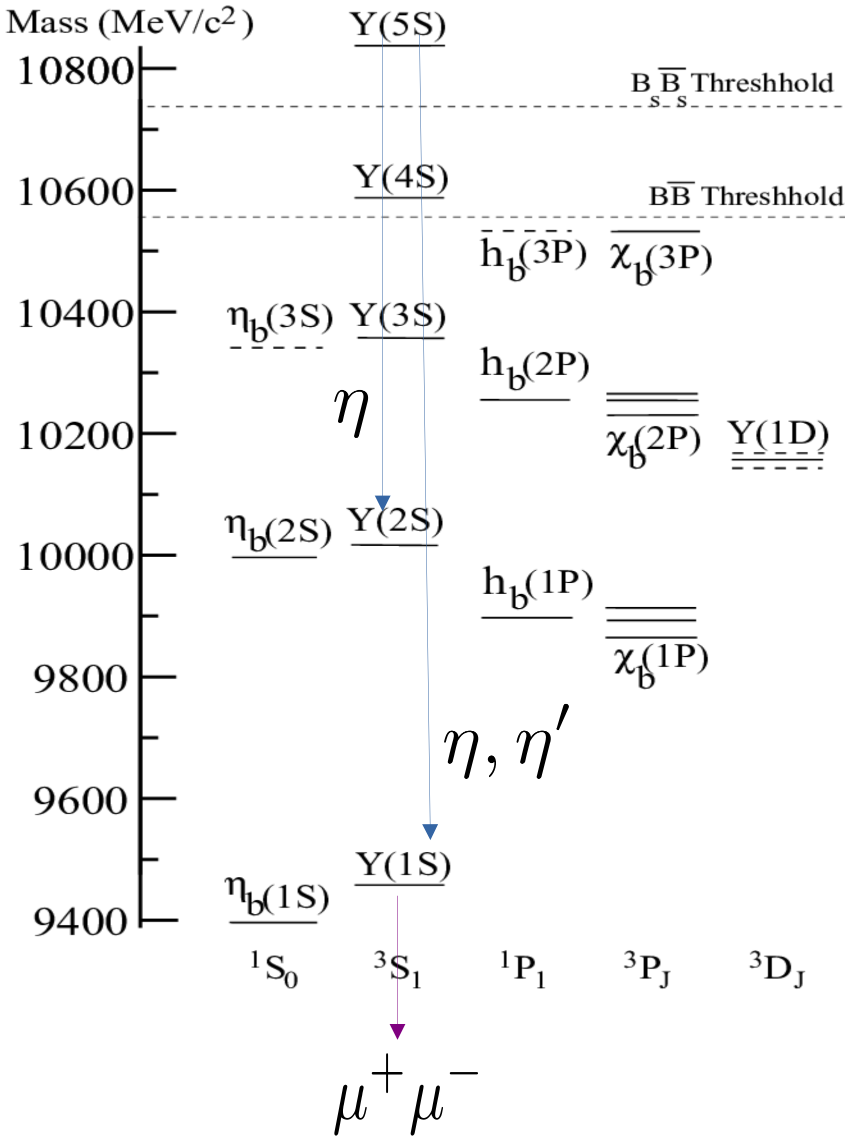
The final state observed for all these analyses is $\pi^+\pi^-\mu^+\mu^-\gamma(\gamma)$ arising from

- A muon pair from $\Upsilon(1S)$ or $\Upsilon(2S)$
- A charged pion pair, and
- Either a single photon or a photon pair consistent with π^0 or η

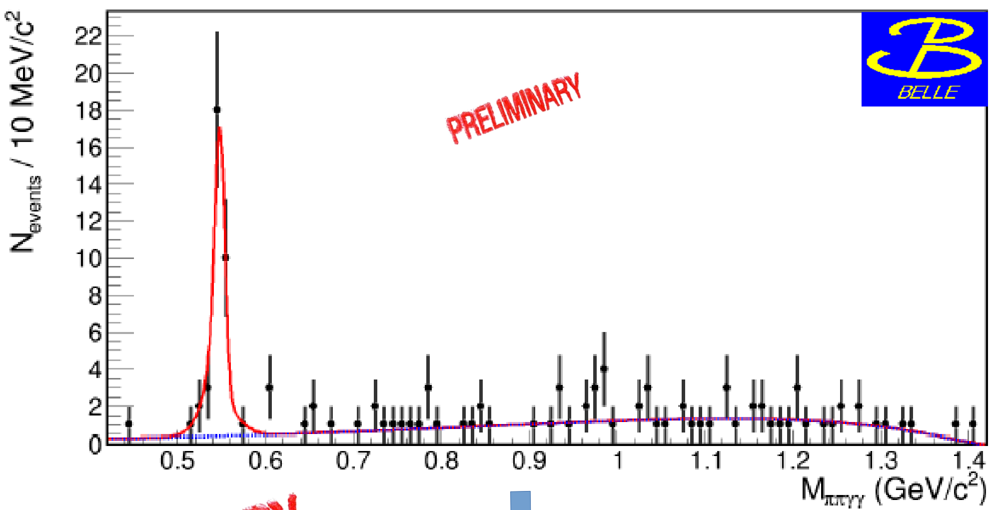
Further requirements include:

- Consistency w/total energy E_{tot} and collinearity
- Additional kinematic selections that reject particular ranges of mass differences $M(\pi\pi\gamma\gamma\mu\mu)-M(\mu\mu)$ or recoil mass ranges

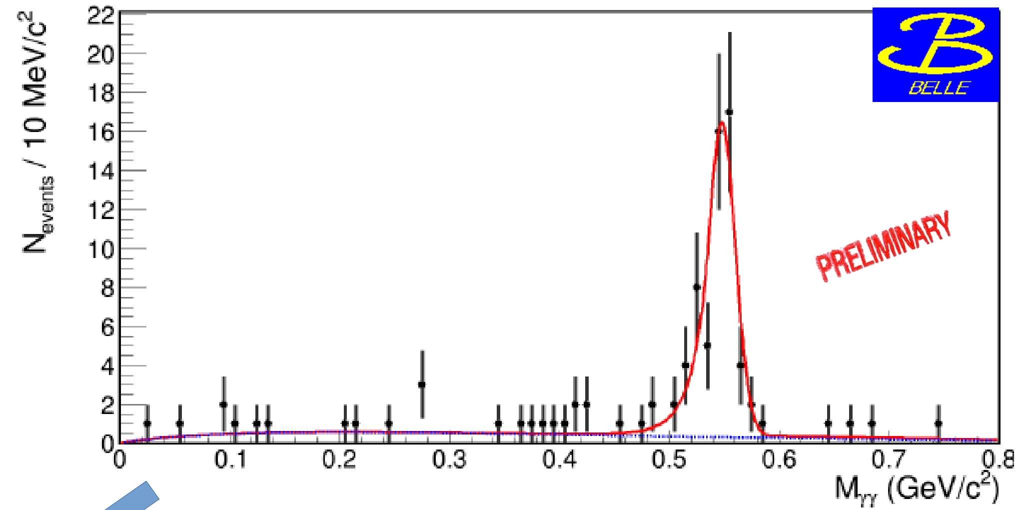
Favorable kinematics enable a very clean selection with high signal efficiency



$\Upsilon(5S) \to \eta\Upsilon(2S) \to [\gamma\gamma][\pi^+\pi^-\Upsilon(1S)] \to [\gamma\gamma][\pi^+\pi^-(\mu^+\mu^-)]$



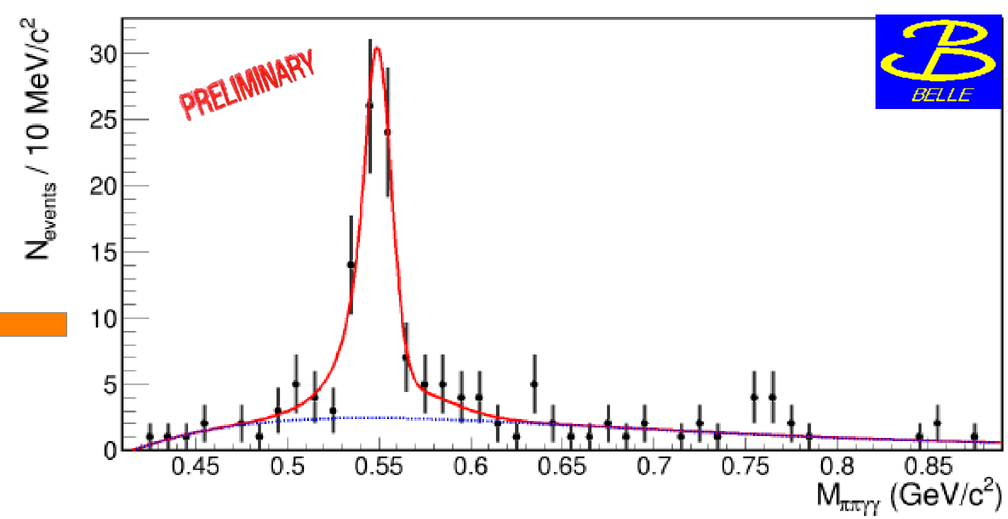
$\Upsilon(5S) \to \eta\Upsilon(2S) \to [\pi^+\pi^-\pi^0][\mu^+\mu^-] \to [\pi^+\pi^-(\gamma\gamma)][\mu^+\mu^-]$



PRELIMINARY

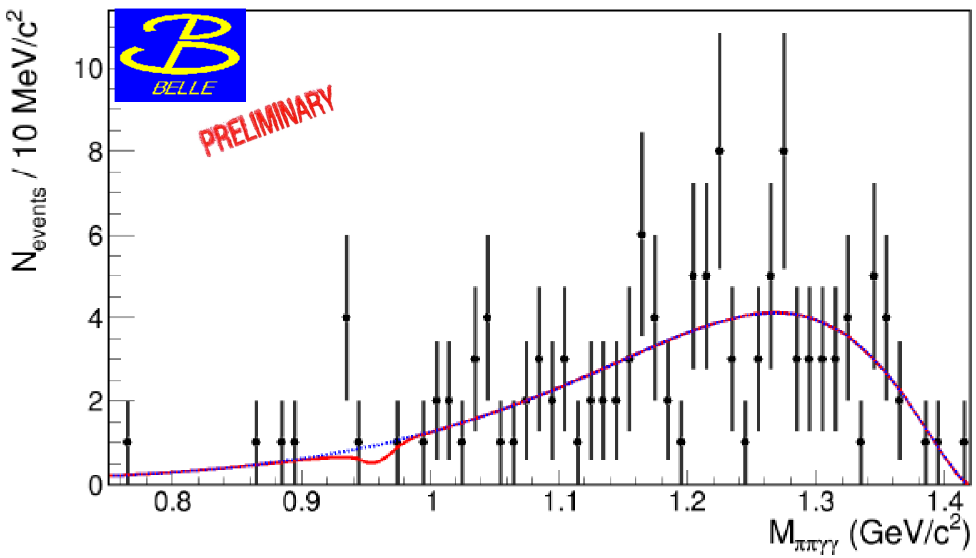
$$\mathcal{B}(\Upsilon(5\mathrm{S}) \to \Upsilon(2\mathrm{S})\eta) = (4.13 \pm 0.41 \pm 0.37) \times 10^{-3}$$

$\Upsilon(5S) \to \eta\Upsilon(1S) \to [\pi^+\pi^-\pi^0][\mu^+\mu^-] \to [\pi^+\pi^-(\gamma\gamma)][\mu^+\mu^-]$

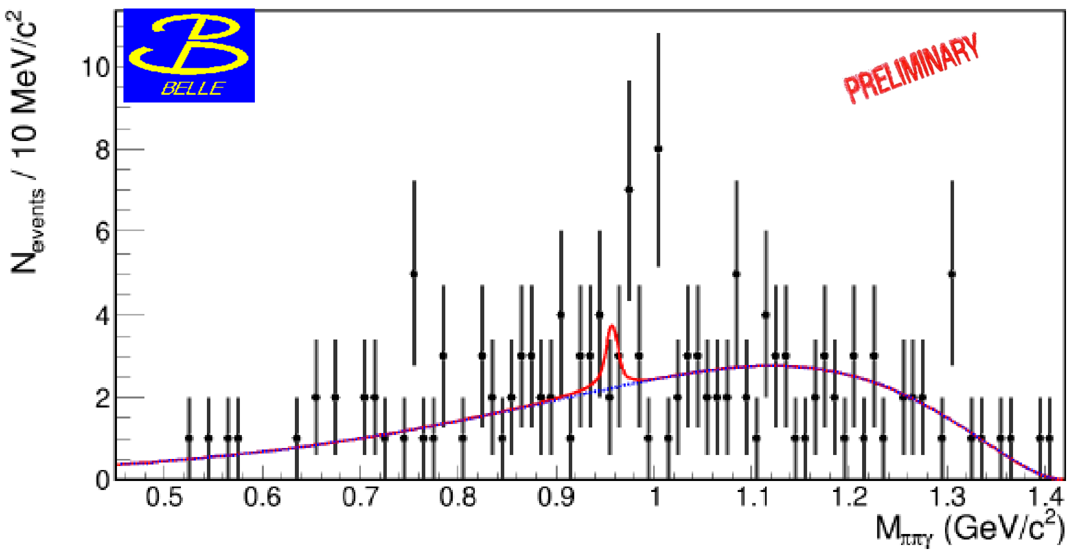


$$\mathcal{B}(\Upsilon(5\mathrm{S}) \to \Upsilon(1\mathrm{S})\eta) = (0.85 \pm 0.15 \pm 0.08) \times 10^{-3}$$

$\Upsilon(5S) \to \eta' \Upsilon(1S) \to [\pi^+\pi^-\eta][\mu^+\mu^-] \to [\pi^+\pi^-(\gamma\gamma)][\mu^+\mu^-]$



$\Upsilon(5S) \to \eta' \Upsilon(1S) \to [\rho^0\gamma][\mu^+\mu^-] \to [(\pi^+\pi^-)\gamma][\mu^+\mu^-]$



$$\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\eta') < 6.9 \times 10^{-5},\ CL = 90\%$$

PRELIMINARY

QCDME Predictions

Again, again, we find QCDME expectations challenged

PRELIMINARY

$$\frac{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\eta)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = 0.51 \pm 0.06 \pm 0.04$$ ~0.03

$$\frac{\Gamma(\Upsilon(5S) \to \Upsilon(1S)\eta)}{\Gamma(\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-)} = 0.19 \pm 0.04 \pm 0.01$$ ~0.005

$$\frac{\Gamma(\Upsilon(5S) \to \Upsilon(1S)\eta')}{\Gamma(\Upsilon(5S) \to \Upsilon(1S)\eta)} < 0.09 \ (CL = 90\%)$$ ~12

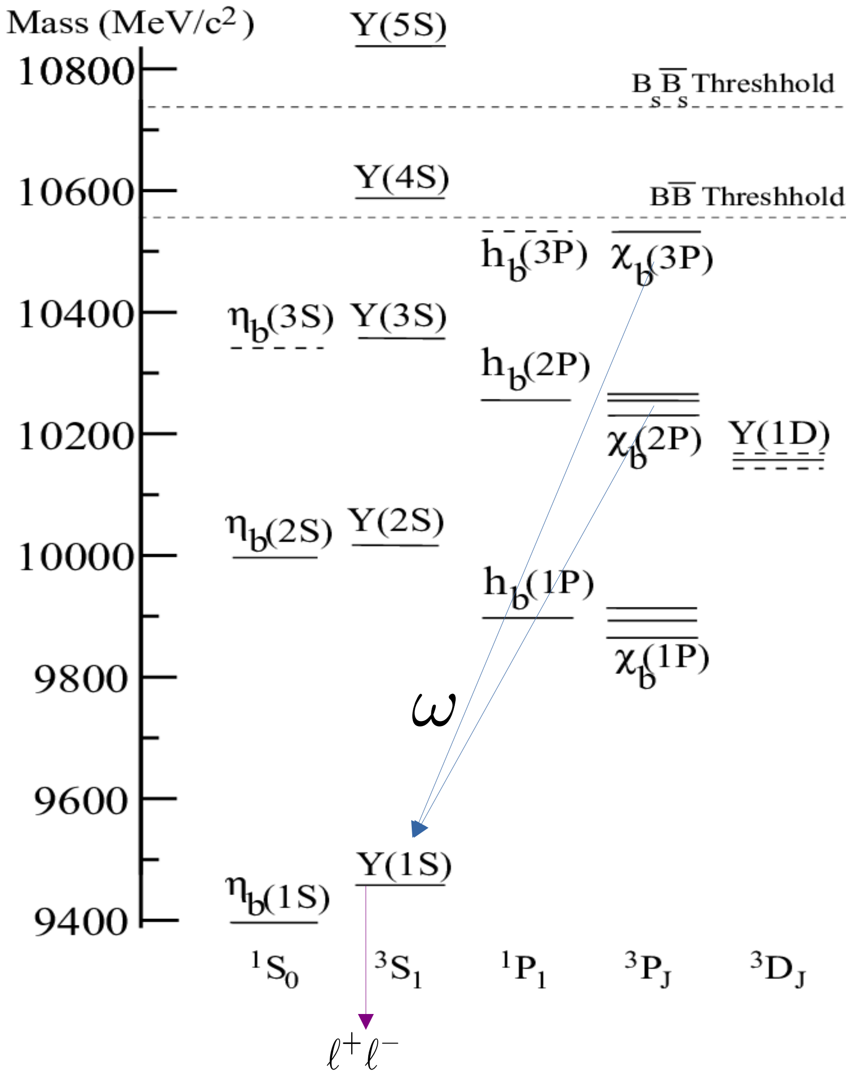
All these challenges to QCDME predictions are consistent with the need for an admixture of light-quark degrees of freedom to the $b\bar{b}$ state

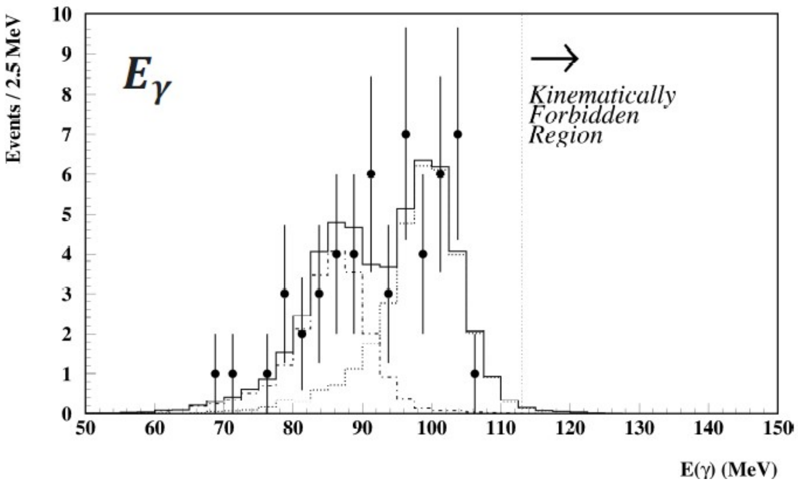
Act III

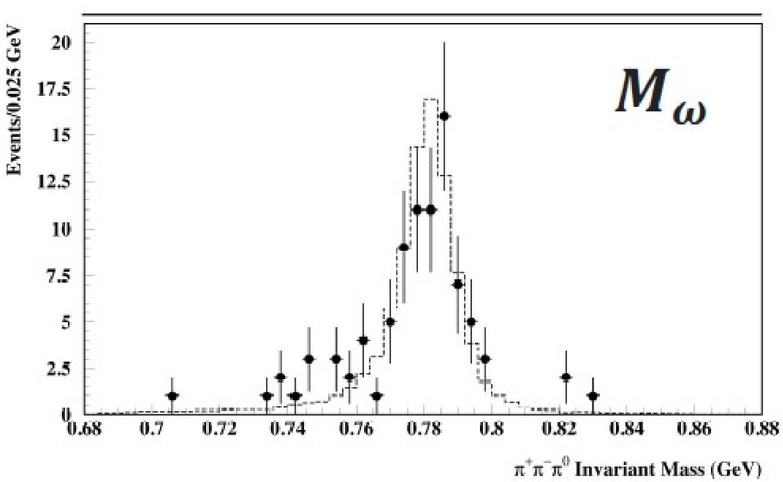
Observation of $\chi_{bJ}(2P) \rightarrow \omega\Upsilon(1S)$ and search for $\chi_{bJ}(3P)$

PRL 92, 222002

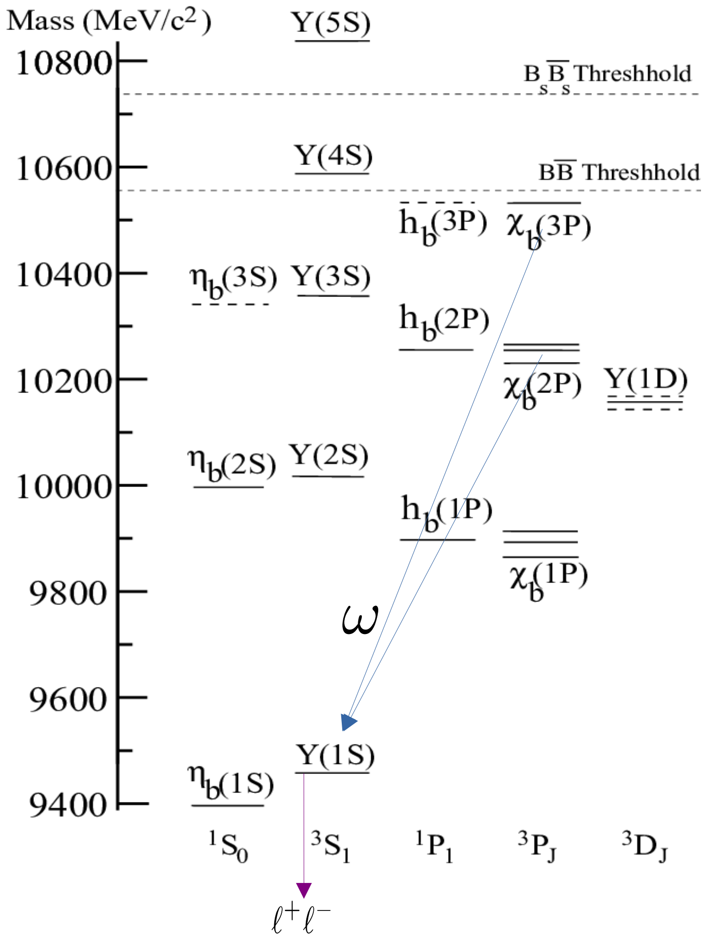
- CLEO announced in 2004 the observation of $\chi_{bJ}(2P)\to\omega\Upsilon(1S)$ in fully reconstructed events including the detection of the soft E1 transition photon from $\Upsilon(3S)\to\gamma\chi_{bJ}(2P)$, observing a large branching fraction for J=1 and 2







Channel	Branching Fraction
J=1	$(1.63^{+0.35+0.12}_{-0.31-0.11})$ %
J=2	$(1.10^{+0.32+0.08}_{-0.28-0.07})$ %



Sample	$\mathcal{L}(fb^{-1})$	$N(\Upsilon(3S)) \times 10^6$
$\Upsilon(4S)_{\rm on}$	513	13.4 ± 0.6
$\Upsilon(4S)_{\rm off}$	56	1.7 ± 0.1
$\Upsilon(3S)_{\rm on}$	3.0	12.7 ± 0.5
Total $\Upsilon(3S)$	N/A	28.0 ± 1.1

Event selection requires (in each event)

- Exactly one large invariant mass dilepton (dimuon only in the 3P search)
- Exactly one dipion candidate
- Exactly one kinematically fitted π^0 candidate (smallest χ^2)

Candidate yield is determined by studying the distributions of the mass of the $\pi^+\pi^-\pi^0$ combination and the quantity

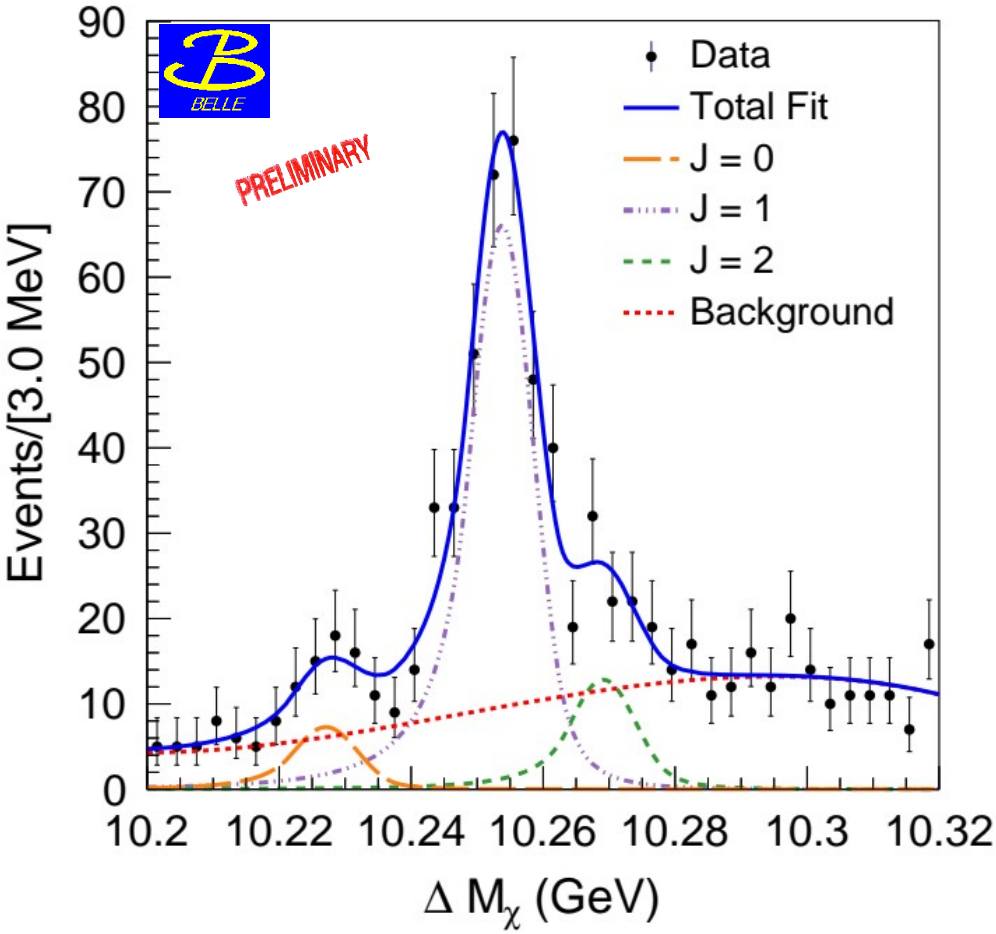
$$\Delta M_\chi \equiv M(\ell^+\ell^-\pi^+\pi^-\pi^0) - M(\ell^+\ell^-) + M_{PDG}(\Upsilon(1S))$$

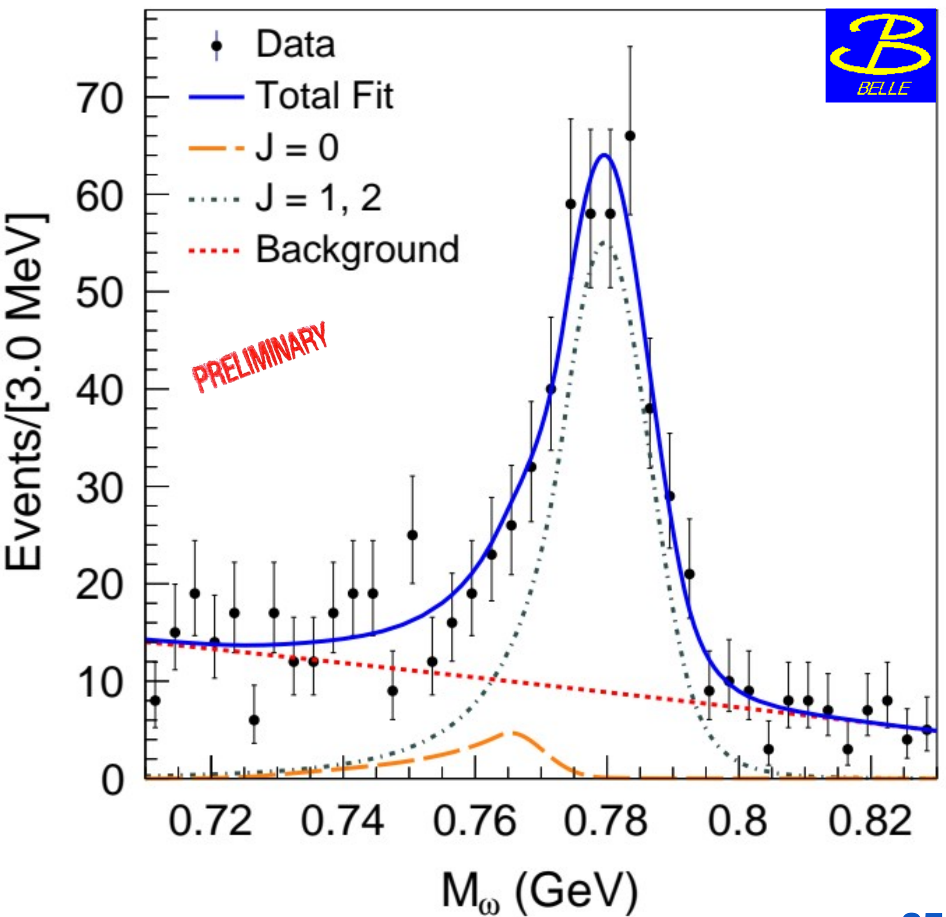
Branching fractions are normalized to $N(\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S))$

If I could turn back time, I'd tell you to attend Zach Stottler's presentation yesterday, but instead I must only suggest you seek out his slides for many more details

Result of a simultaneous fit to the variable ΔM_χ near the mass of the $\chi_{bJ}(2P)$ and to $M(\pi^+\pi^-\pi^0)$

Note the presence of all three $\chi_{bJ}(2P)$ in the ΔM_χ distribution



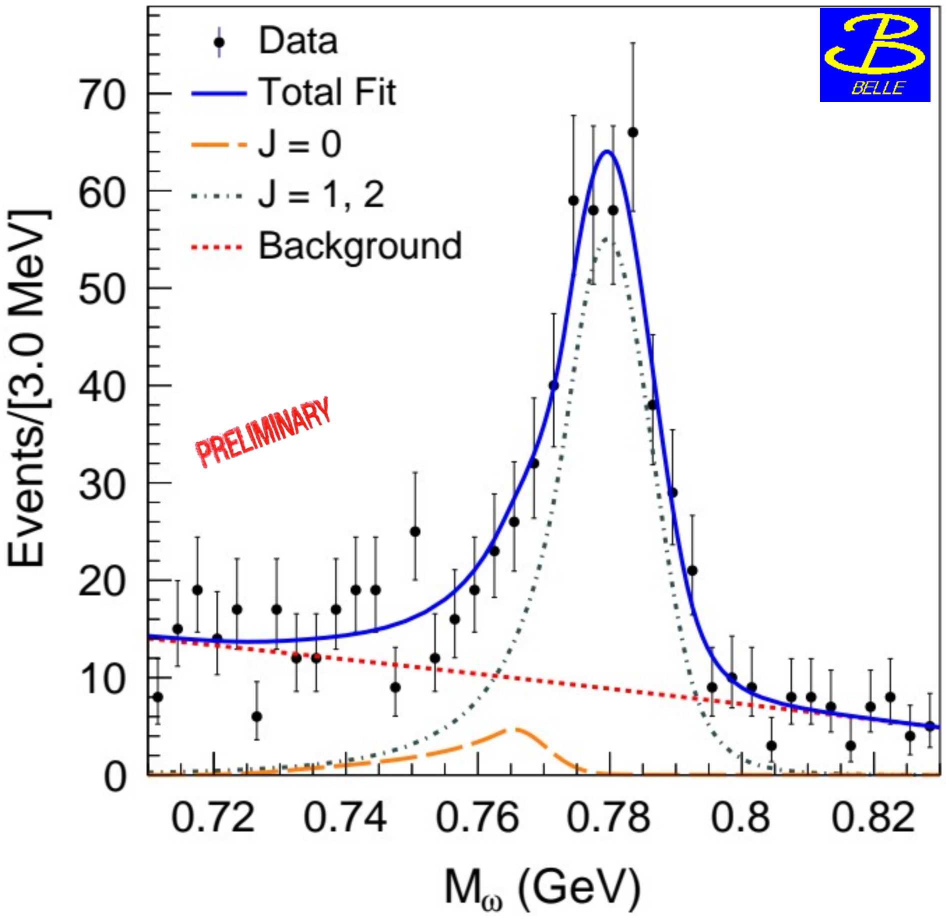


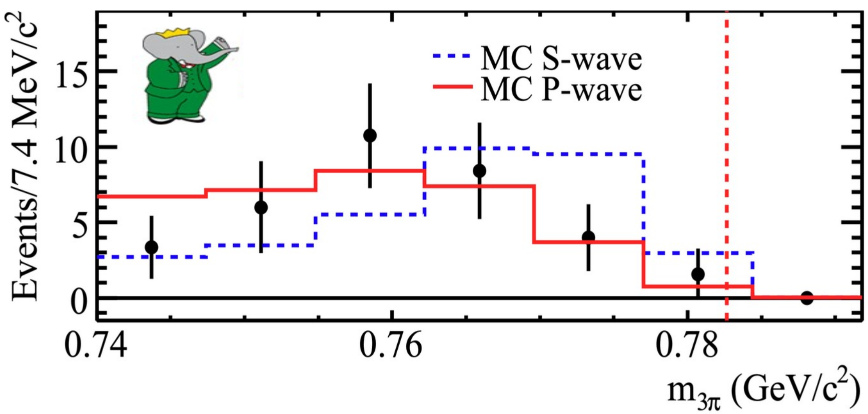
Things to note:

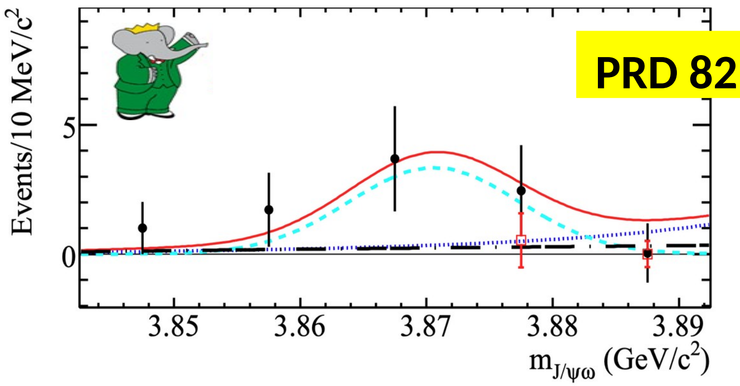
Distorted lineshape associated with the $\chi_{b0}(2P)\rightarrow\omega\Upsilon(1S)$ transition

The $\chi_{b0}(2P)\rightarrow\omega\Upsilon(1S)$ transition, 10.5 MeV below threshold, occurs through the tail of the ω meson, whose natural width is 8.7 MeV

A similar distortion of the ω lineshape by Babar was observed in $\chi_{c1}(2P)\rightarrow\omega J/\psi(1S)$, which is about 8 MeV below threshold.

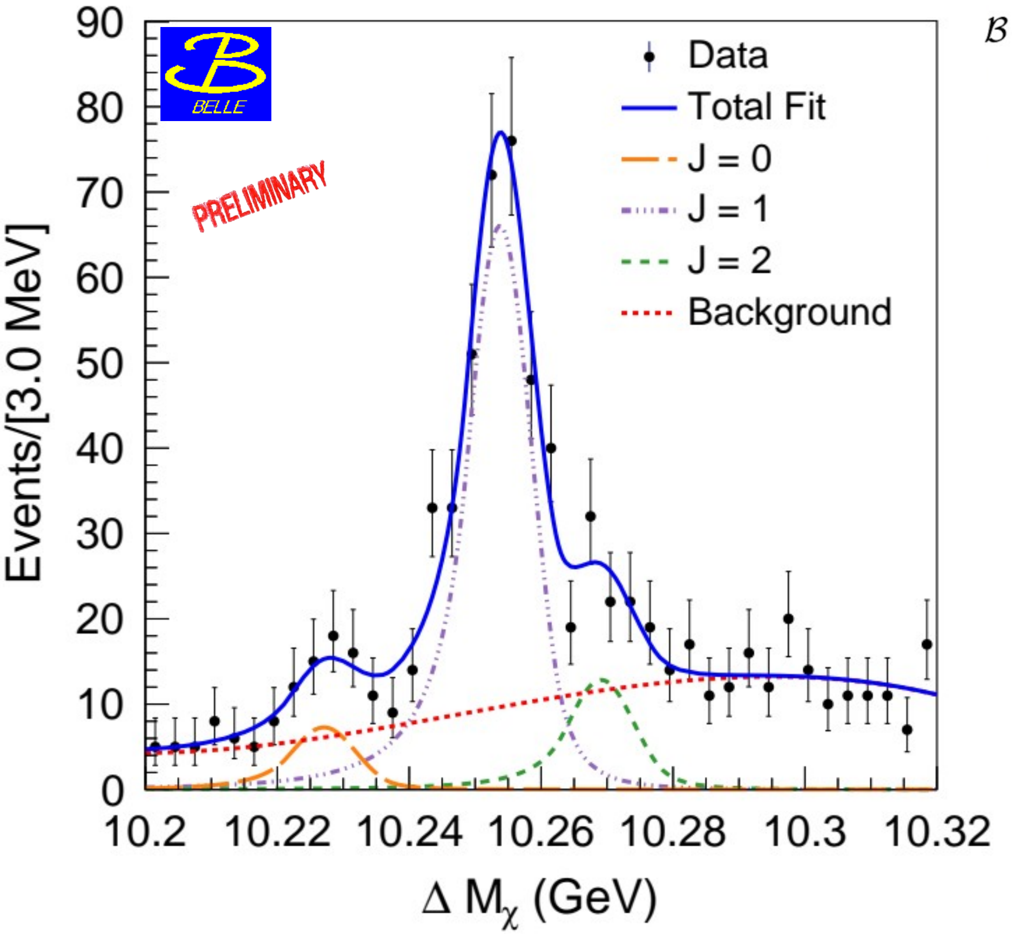






PRD 82, 011101

Yields for the three $\chi_{bJ}(2P)$ are determined, and normalized by the number of $\Upsilon(3S)$, (28.0±1.0) x 10^6, obtained by studying $\Upsilon(3S) \to \pi^+\pi^-$ $\Upsilon(1S)$ in the combined data samples.



$$\mathcal{B}(\chi_{bJ}(2P) \to \omega\Upsilon(1S)) = \frac{N_J}{N_{\pi\pi\Upsilon}} \frac{\epsilon_{\pi\pi\Upsilon}}{\epsilon_J} \frac{\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))}{\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{bJ}(2P))\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)\mathcal{B}(\pi^0 \to \gamma\gamma)}$$

Channel	$\mathcal{B}(\chi_{bJ}(2P) \to \omega\Upsilon(1S))$	Significance
$J=0$	$(0.56^{+0.19}_{-0.18} \pm 0.08)$ %	3.2σ
$J=1$	$(2.38 \pm 0.19^{+0.23}_{-0.24})$ %	15.0σ
$J=2$	$(0.46 \pm 0.12^{+0.06}_{-0.07})$ %	3.9σ

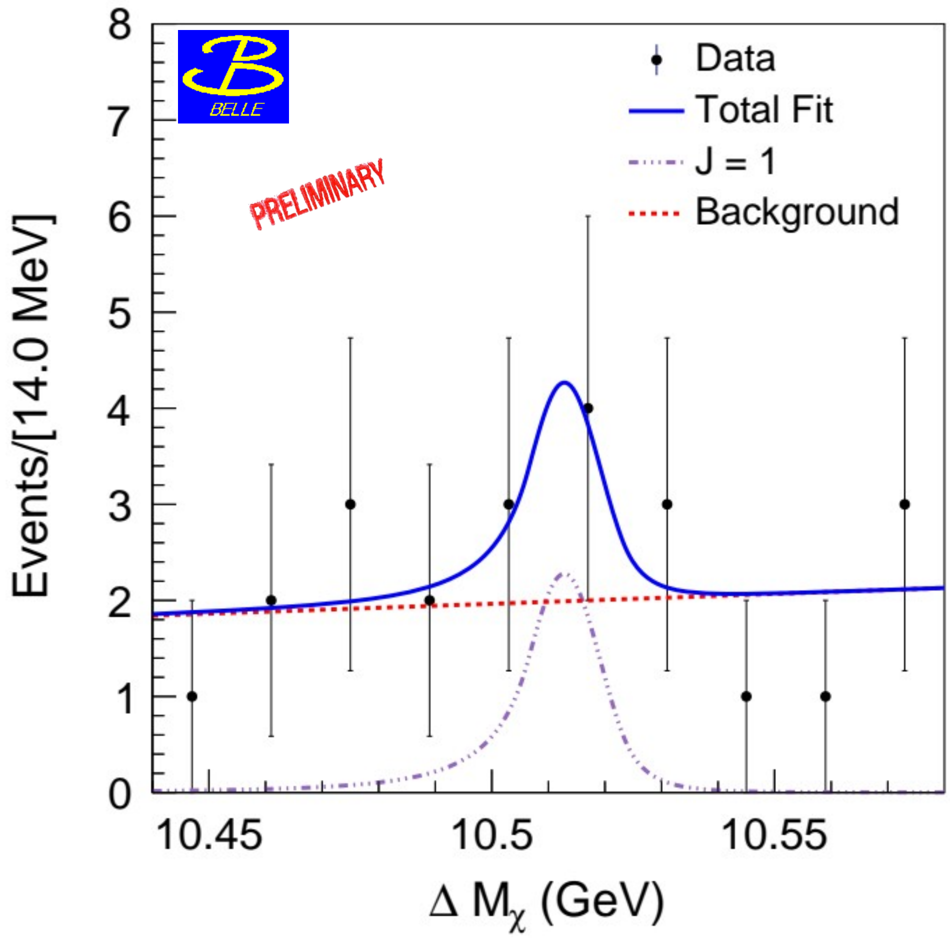
PRELIMINARY

First confirmation of the CLEO measurement, with new evidence for $\chi_{b0}(2P)$ giving another example of a sub-threshold transition involving the relatively broad ω

A similar analysis is conducted using $\Upsilon(4S)$ data, examining ΔM_χ near the mass of the $\chi_{bJ}(3P)$ reported by CMS and others

In this fit the mass is fixed to that reported by CMS for the $\chi_{b1}(3P)$, the dominant member of the multiplet in rate of decay to $\omega\Upsilon(1S)$

Yield is normalized to the number of $\Upsilon(4S)$ (number of BB pairs)



$$\mathcal{B}\left(\Upsilon(4S) \to \gamma\chi_{b1}(3P) \to \gamma\omega\Upsilon(1S)\right) < 1.4 \times 10^{-5}\ (90\%\ \mathrm{CL})$$

PRELIMINARY

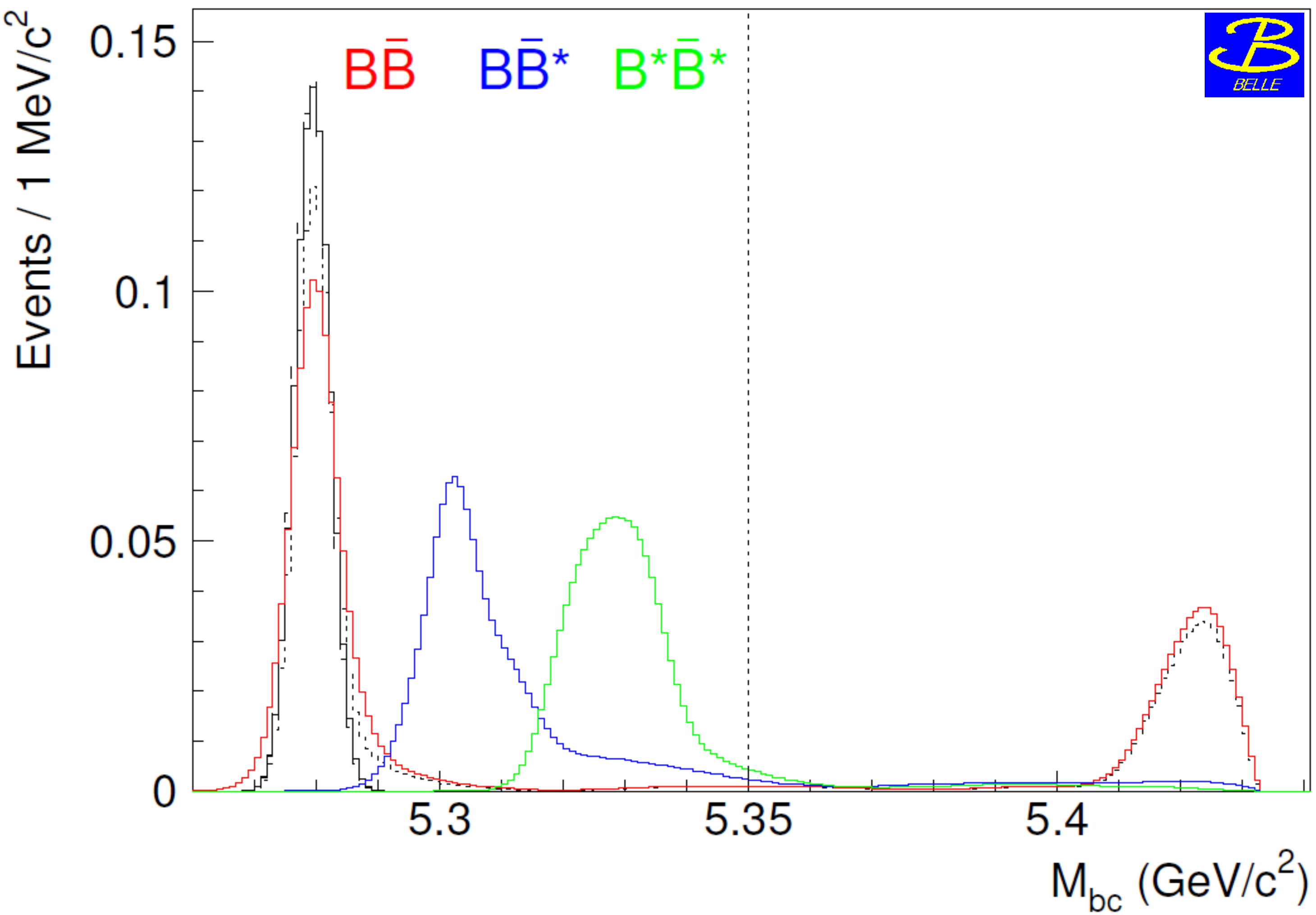
- We have reported:
  - First measurements of cross-sections for BB, BB*, B*B* in the range of 10.63 to 11.02 GeV. Interestingly the sum of these cross sections does not peak at $\Upsilon(5S)$ but instead decreases ~ linearly throughout the vicinity of 10.89 GeV.
  - First observations of $\Upsilon(5S) \rightarrow \eta\Upsilon(1S,2S)$ and search for $\Upsilon(5S) \rightarrow \eta'\Upsilon(1S)$
  - Confirmation of $\chi_{bJ}(2P) \rightarrow \omega\Upsilon(1S)$, including evidence for the sub-threshold process $\chi_{b0}(2P) \rightarrow \omega\Upsilon(1S)$. Also report the search for $\chi_{bJ}(3P)$ in transition to $\omega\Upsilon(1S)$. (See Zach Stottler's talk from yesterday in Analysis Tools 3)

Hadronic transitions in the bottomonium system, both above and below open bottom threshold continue to bear fruit! Stay tuned (next talk!) for Bryan Fulsom's account of the status and prospects of Belle II bottomonium studies

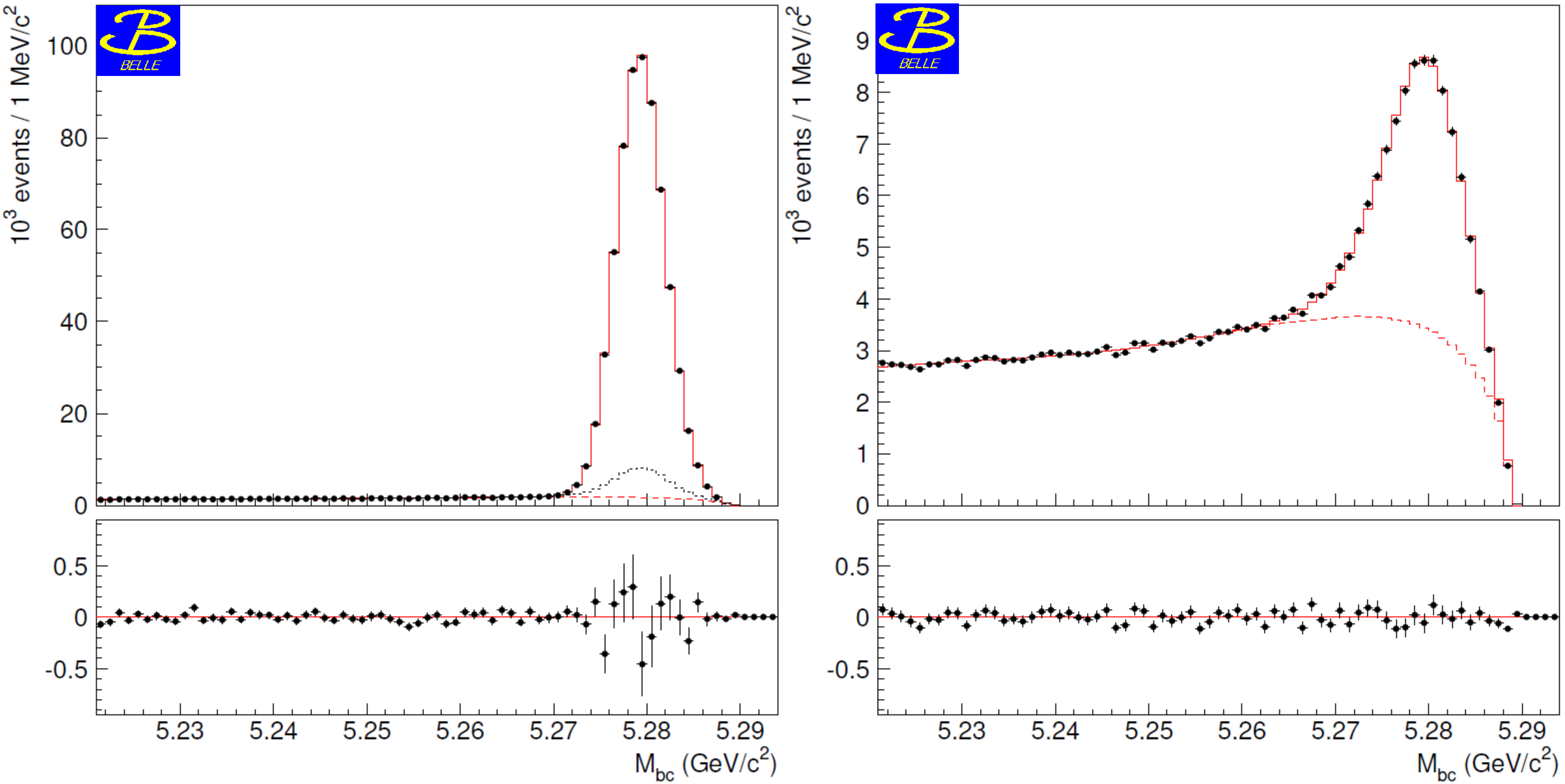

Tak
Obrigado
감사합니다
Gracias
Merci
شكرا لك
Thank you
謝謝
Danke
Grazie

Backup Slides

Beam-Constrained Mass Fit Function at ϒ(5S)

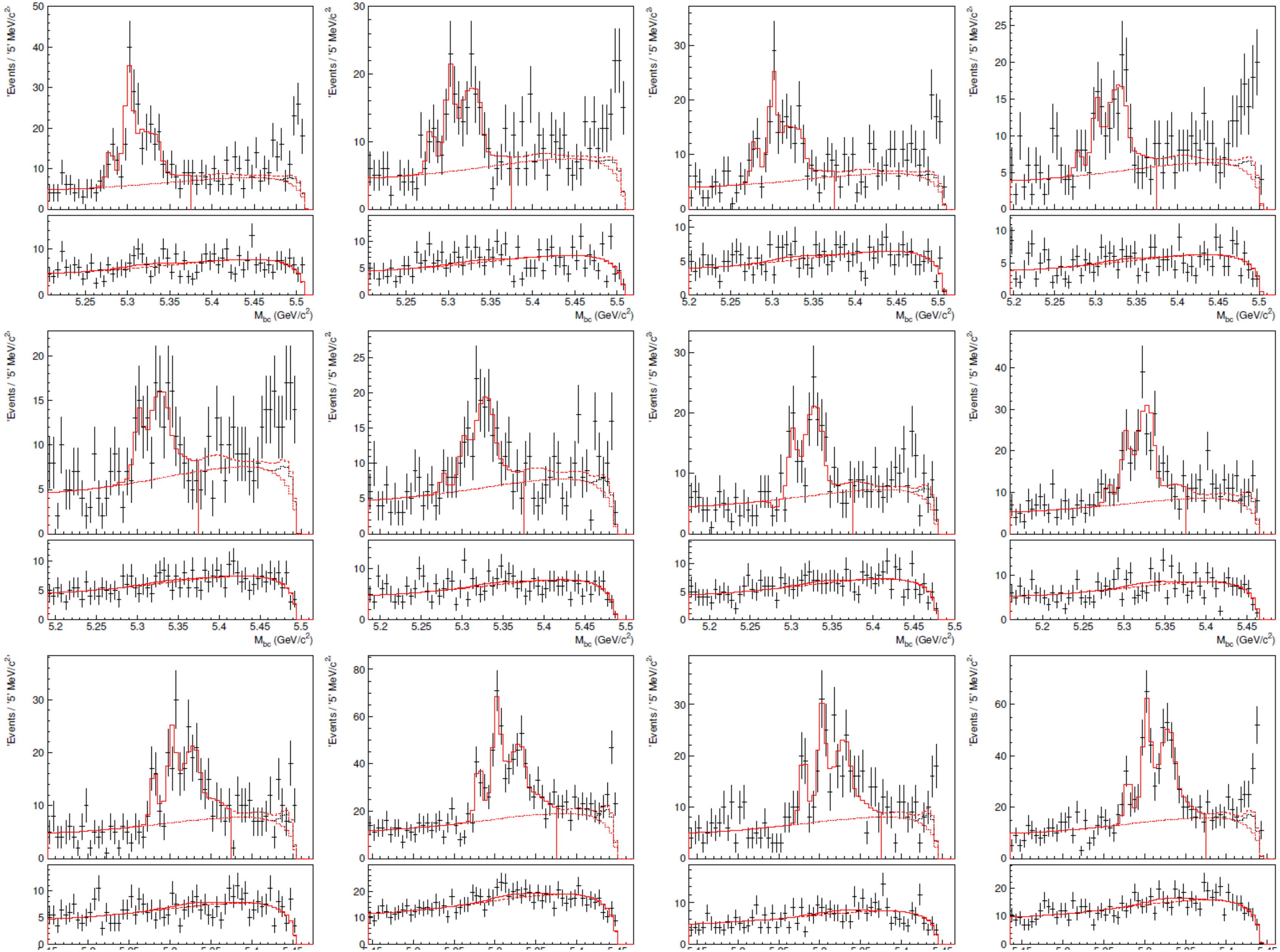


Fit to the Beam-Constrained Mass at ϒ(4S)

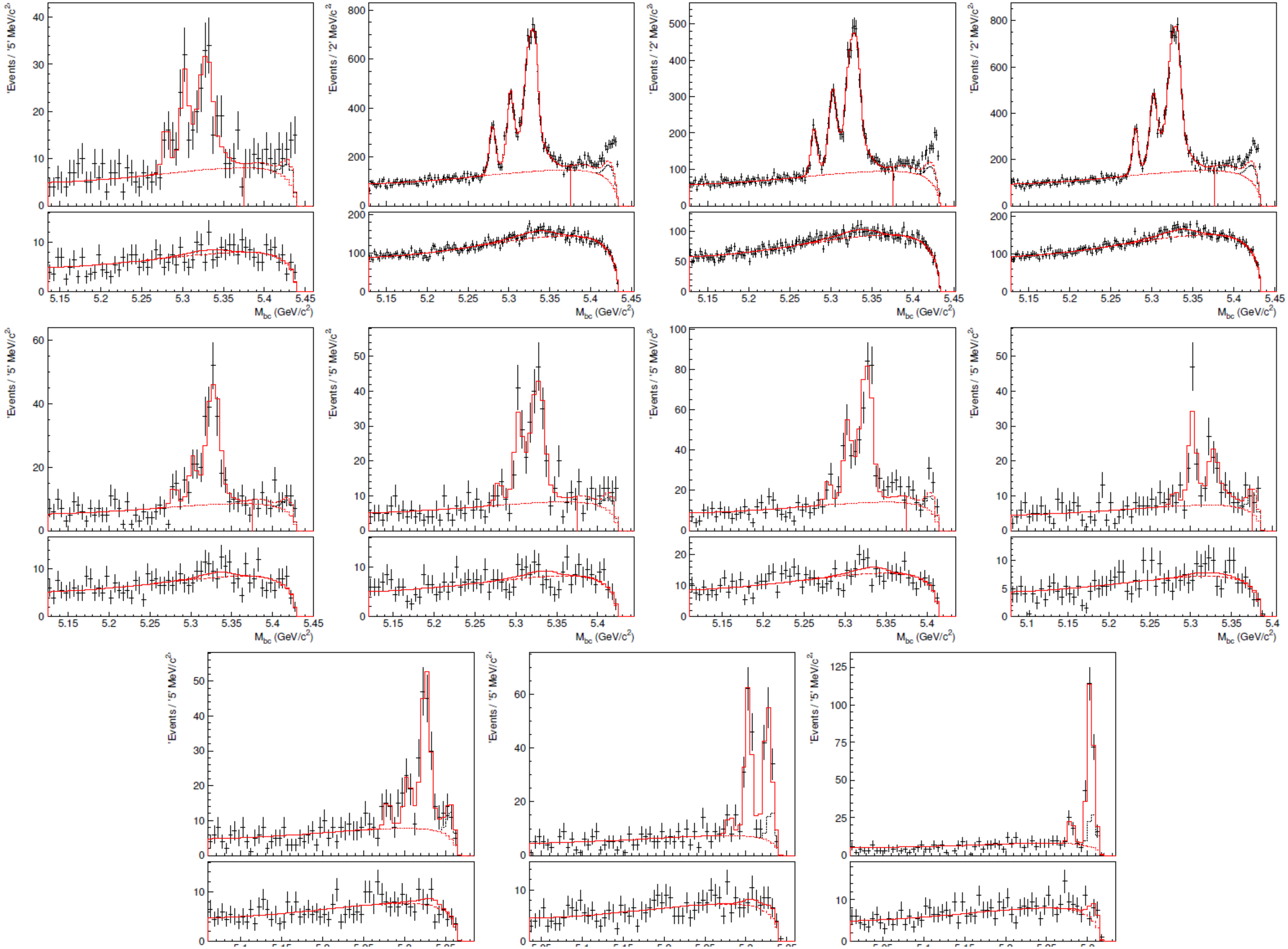


M_{bc} distributions, selected in ΔE′ signal region and ΔE′ side-bands, for data taken at ϒ(4S)

Fits to scan data (I)



Fits in scan data (II)



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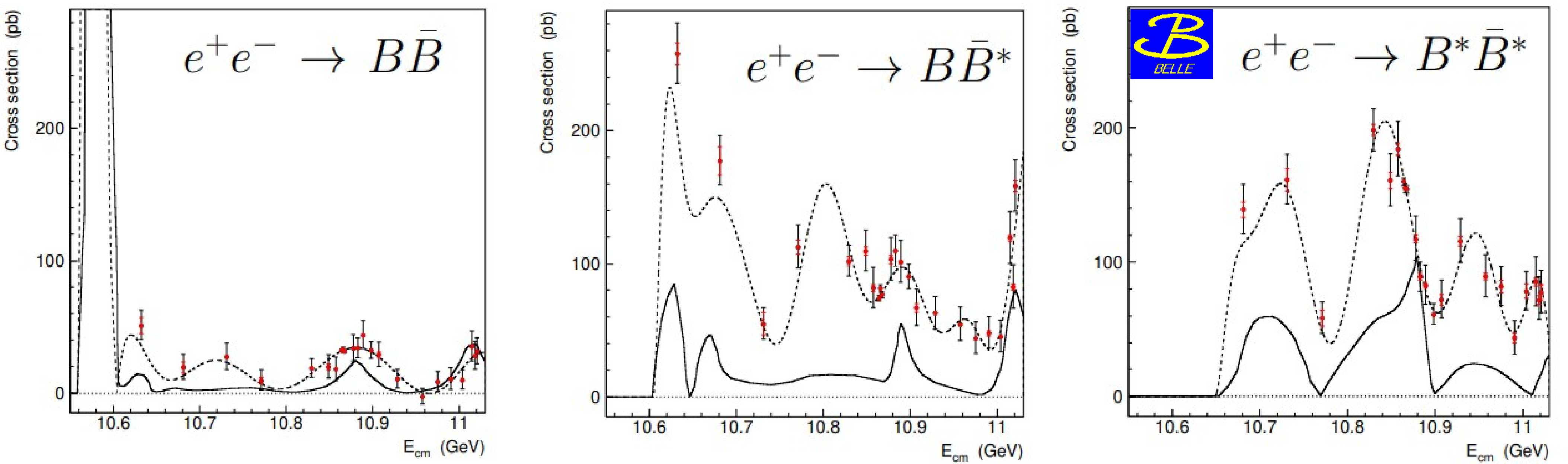
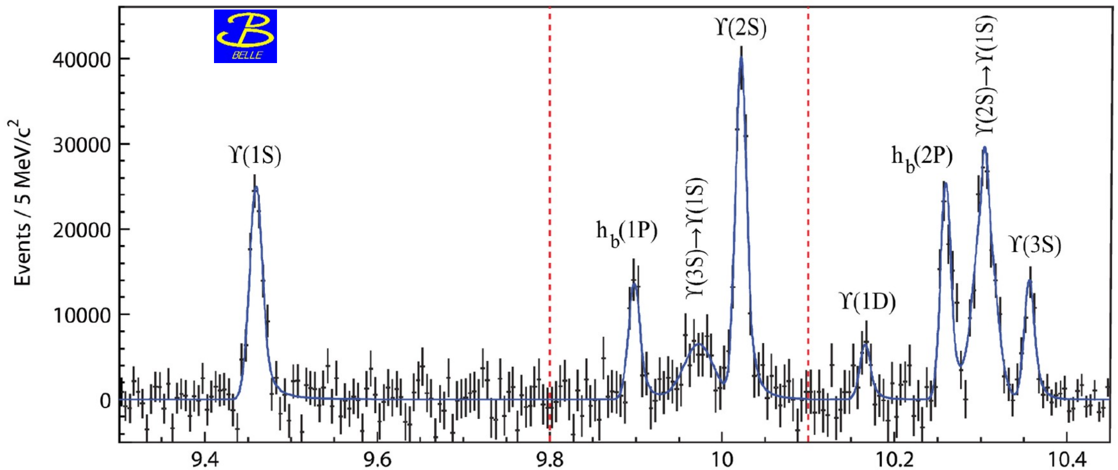


The resulting cross sections for each of the three two-body modes

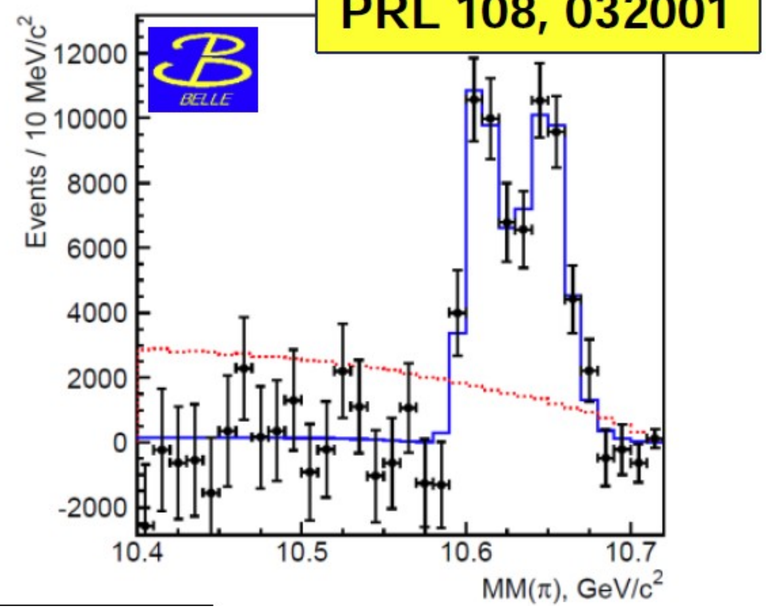
- Observations by Belle concerning hadronic transitions in the bottomonium system have yielded a number of significant surprises

PRL 108, 122001



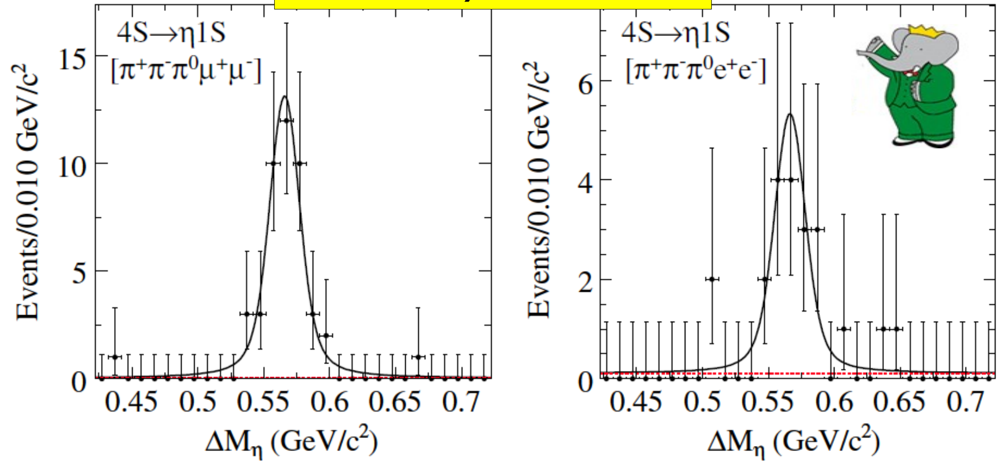
- Very large rates for Υ(5S), roughly two orders of magnitude larger than expected by QCDME models led to observation of $h_b(1P)$ in transitions.
-
- This led to the discovery of the exotic multi-quark Z states, and leads us to thinking about other hadronic transitions from states above open bottom threshold

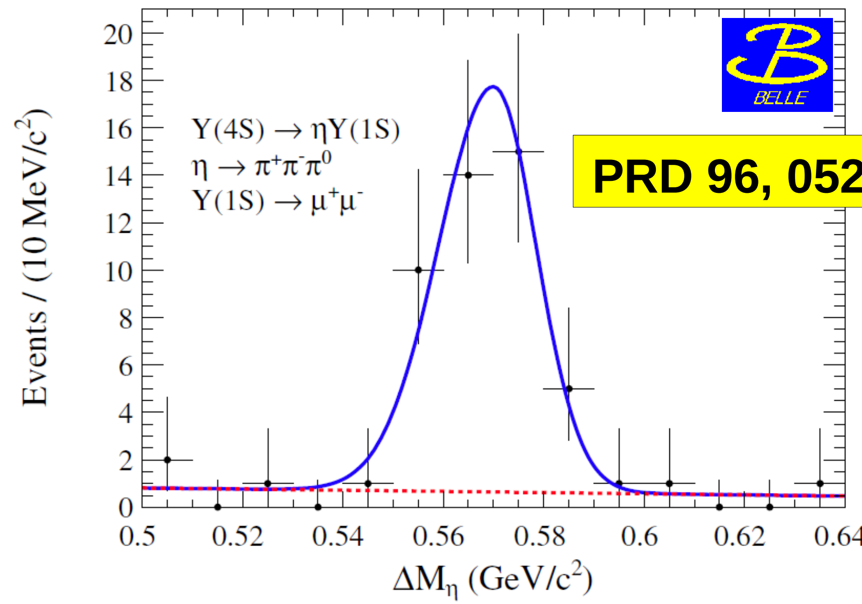
PRL 108, 032001



- BABAR discovered and Belle confirmed $\Upsilon(4S) \rightarrow \eta\Upsilon(1S)$, with a very large rate for the transition compared to $\Upsilon(4S) \rightarrow \pi\pi\Upsilon(1S)$
- Belle dicovered $\Upsilon(4S) \rightarrow \eta'\Upsilon(1S)$, again with large rate c.f. QCDME, but consistent with a possible light-quark object admixture at $\Upsilon(4S)$
- Meanwhile, $\Upsilon(2S)$ and $\Upsilon(3S)$ have rates for $\eta\Upsilon(1S)$ compared to $\pi\pi\Upsilon(1S)$ that are consistent with QCDME
- Belle discovers the most prolific production mechanism for $h_b(1P)$, namely $\Upsilon(4S) \rightarrow \eta h_b(1P)$
- Thus we now proceed to the study of η transitions exclusively reconstructed at $\Upsilon(5S)$

PRD 78, 112002





PRD 96, 052005

$$\mathcal{B}(\Upsilon(4S) \rightarrow \eta\Upsilon(1S)) = (1.81 \pm 0.18) \times 10^{-4}$$
$$cf \;\; \mathcal{B}(\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S)) = (8.2 \pm 0.4) \times 10^{-5}$$

PRL 121, 062001

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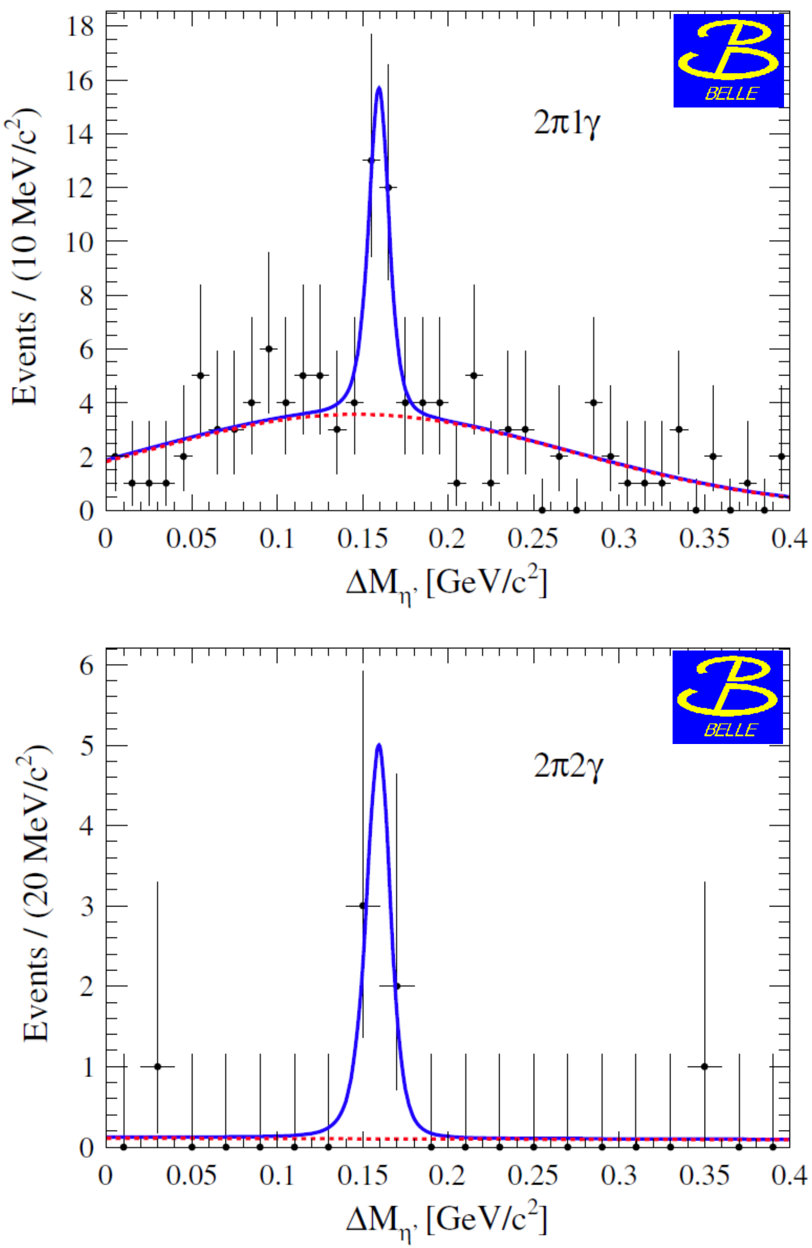

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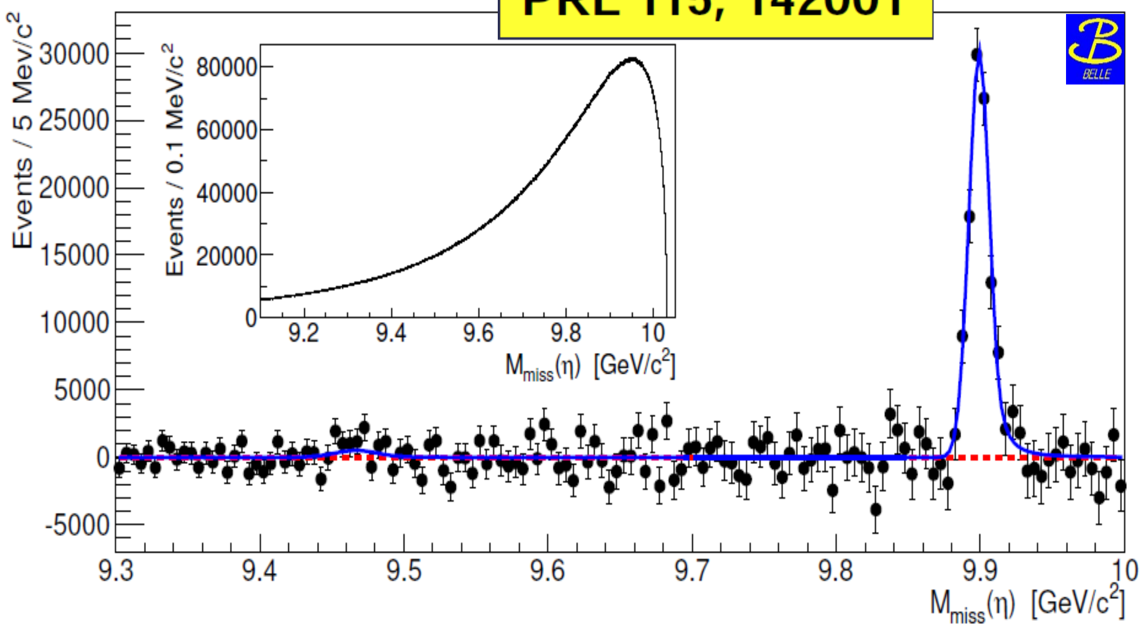
PRL 115, 142001

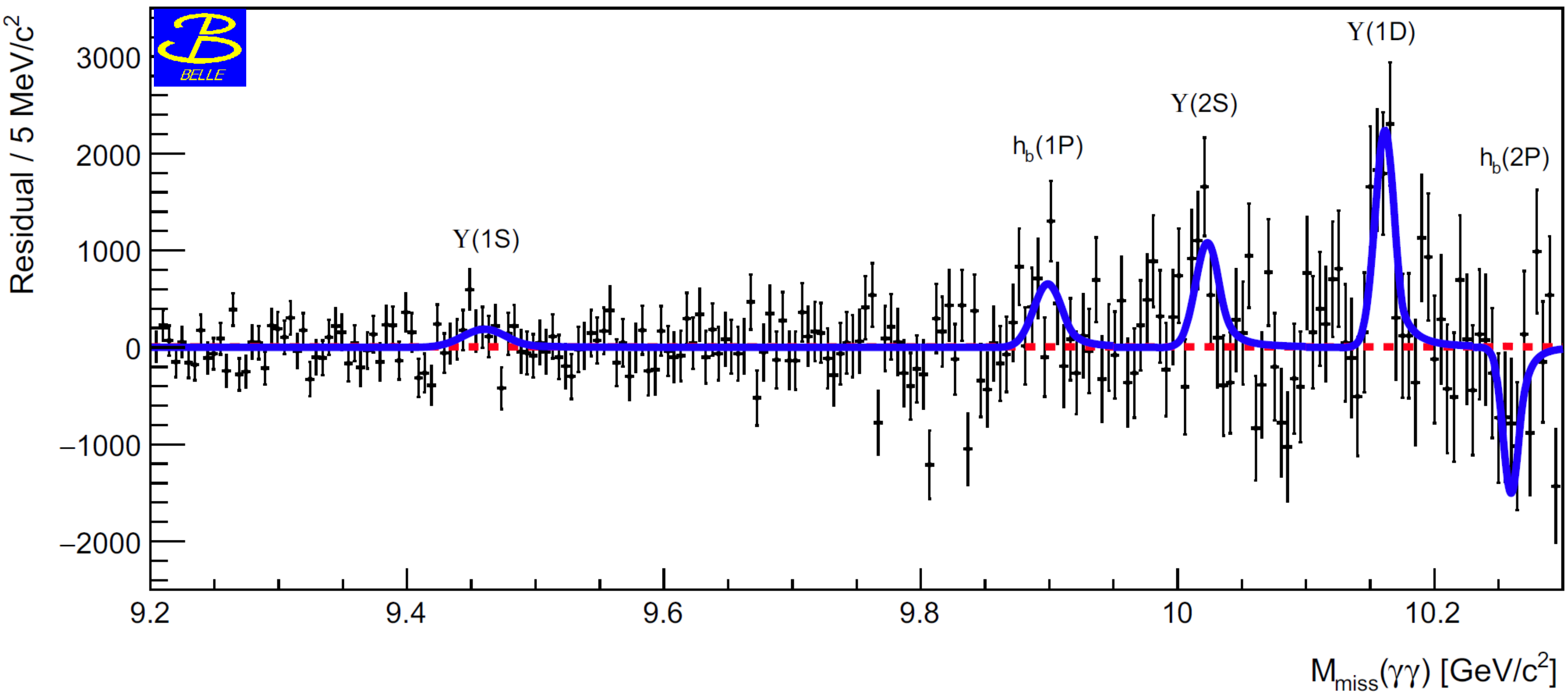


$$\mathcal{B}[\Upsilon(4S) \rightarrow \eta h_b(1P)] = (2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$$

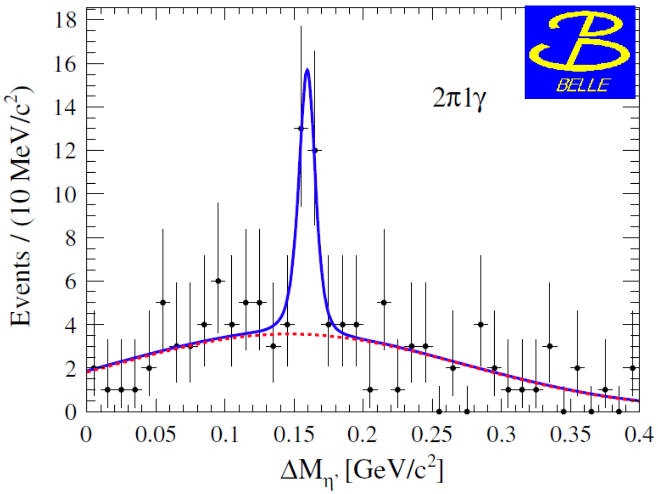
This is the single largest exclusive branching fraction for $\Upsilon(4S)$, and will serve as a tag mode for studying $h_b(1P)$ in Belle II

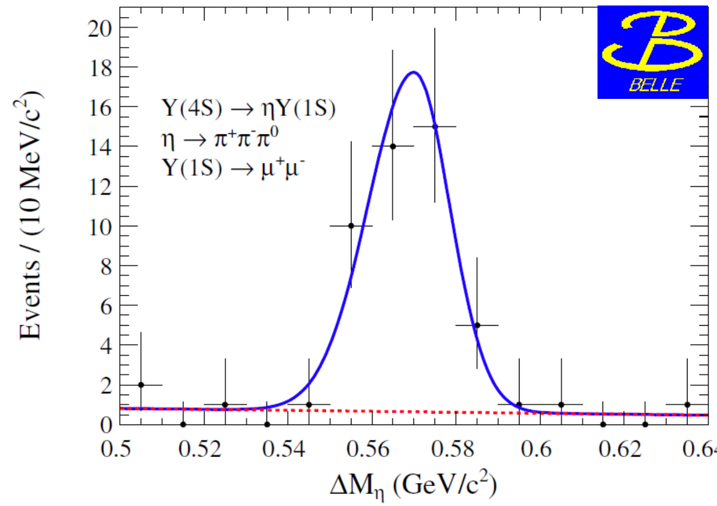
Previous Study by Belle of eta transitions from $\Upsilon(5S)$

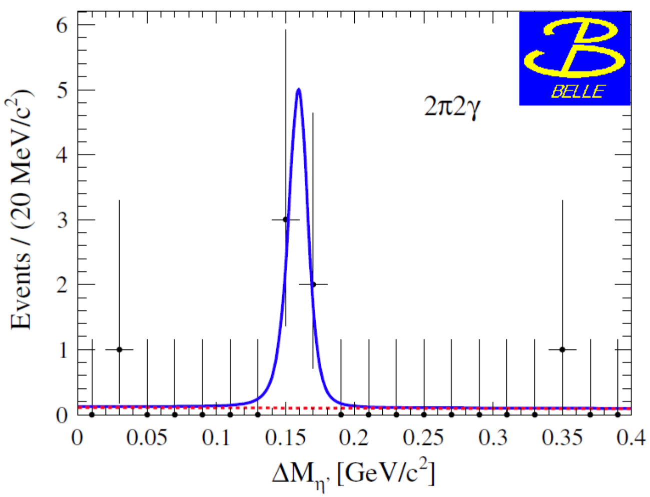
EPJC 78:633



Belle's first attempt to extend the study of eta decays to data taken at $\Upsilon(5S)$ used the missing mass recoiling against eta in $\Upsilon(5S)$ data indicates evidence for a number of transitions – including a first observation of the transition to $\Upsilon(5S)$. Other peaks are not statistically significant.







$$R_{\eta'/h} = \frac{\mathcal{B}(\Upsilon(4S) \to \eta'\Upsilon(1S))}{\mathcal{B}(\Upsilon(4S) \to h\Upsilon(1S))}$$

$$R_{\eta'/\pi^+\pi^-} = 0.42 \pm 0.11$$

$$R_{\eta'/\eta} = 0.20 \pm 0.06$$

$$\mathcal{B}(\Upsilon(4S) \to \eta'\Upsilon(1S)) = (3.43 \pm 0.88(\text{stat}) \pm 0.21(\text{syst})) \times 10^{-5}$$

These results follow the same pattern – much increased transition rates compared to the dipion. Consistent with a model of a mixture of light quark states together with the bottom quark pair in the Υ(4S) region (Voloshin, MPLA 26, 773)

- Υ(2S) and Υ(3S) have rates for $\eta\Upsilon$(1S) compared to $\pi\pi\Upsilon$(1S) that are consistent with QCDME, while that for Υ(4S) is not.

$$\frac{\Gamma(\Upsilon(2S)\to\Upsilon(1S)\eta)}{\Gamma(\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-)} = (1.64\pm0.25)\times10^{-3}$$

$$\frac{\Gamma(\Upsilon(3S)\to\Upsilon(1S)\eta)}{\Gamma(\Upsilon(3S)\to\Upsilon(1S)\pi^+\pi^-)} < 2.3\times10^{-3}$$

$$\frac{\Gamma(\Upsilon(4S)\to\eta\Upsilon(1S))}{\Gamma(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S))} = 2.41\pm0.42\ (\text{BaBar})$$

$$\frac{\Gamma(\Upsilon(4S)\to\eta\Upsilon(1S))}{\Gamma(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S))} = 2.07\pm0.30\pm0.11\ (\text{Belle})$$

To check the correlation of $\chi_{b0}(2P) \rightarrow \omega \Upsilon(1S)$ transition, we can project the values of ΔM_χ for ω masses above and below 0.78 GeV