Quarkonium Decays at Belle

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Zachary S. Stottler, Virginia Tech

14th International Workshop on Heavy Quarkonium

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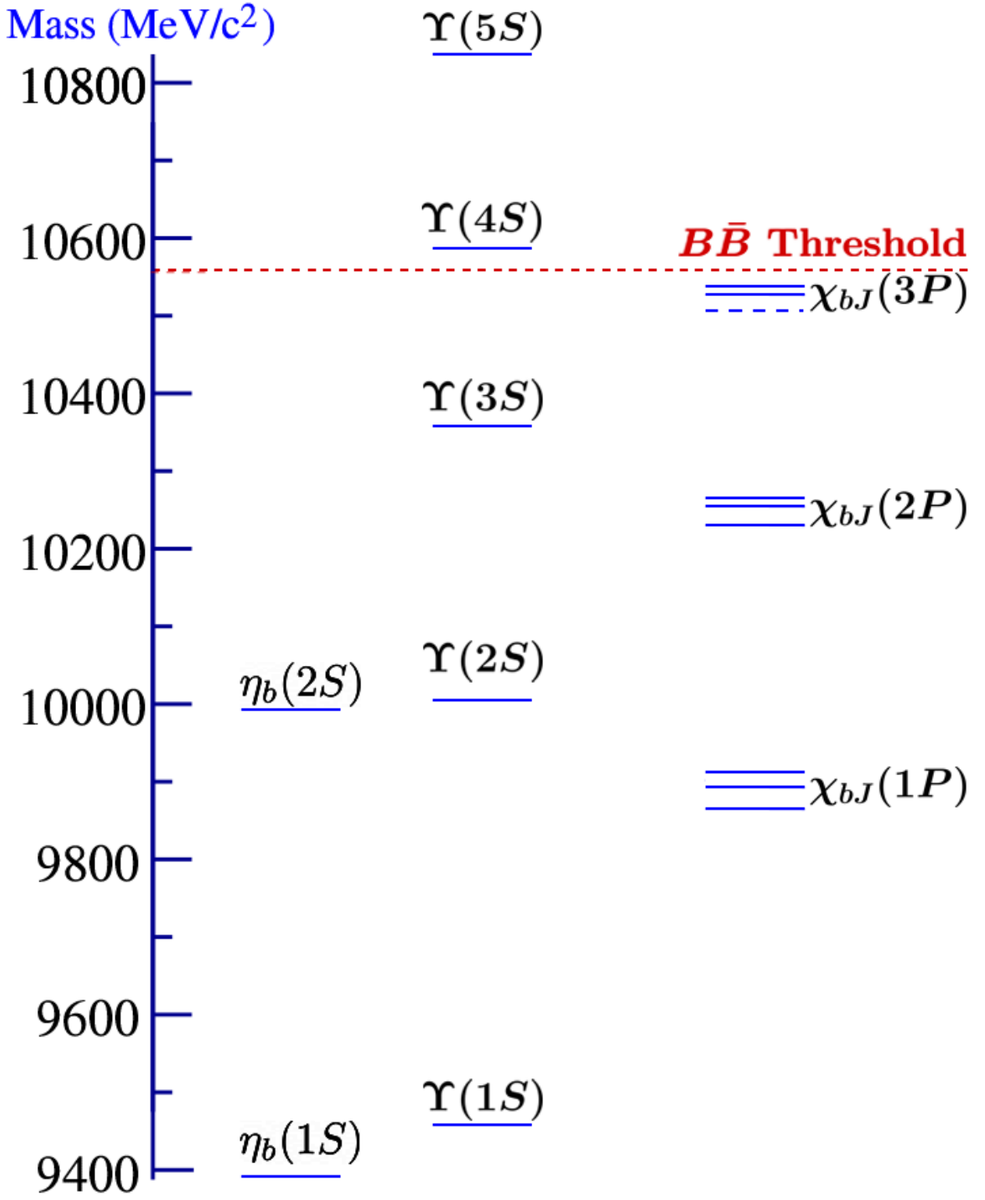
Overview

- Radiative decays of $\Upsilon(1S)$ to $(c\bar{c})_{res}$
  - 1st Observation of $\Upsilon(1S) \to \gamma\chi_{c1}$
  - Spectroscopic search for states
- Search for $\Upsilon(nS) \to \omega\eta_b(mS)$
  - 3 transitions accessible; No significant signals seen
  - Order of magnitude smaller than $\Upsilon(4S) \to \eta h_b(1P)$ (90% CL)
- Search for $\chi_{bJ}(nP) \to \omega\Upsilon(1S)$
  - No significant $3P$ signal seen
  - Measurement of $J = 1,2$



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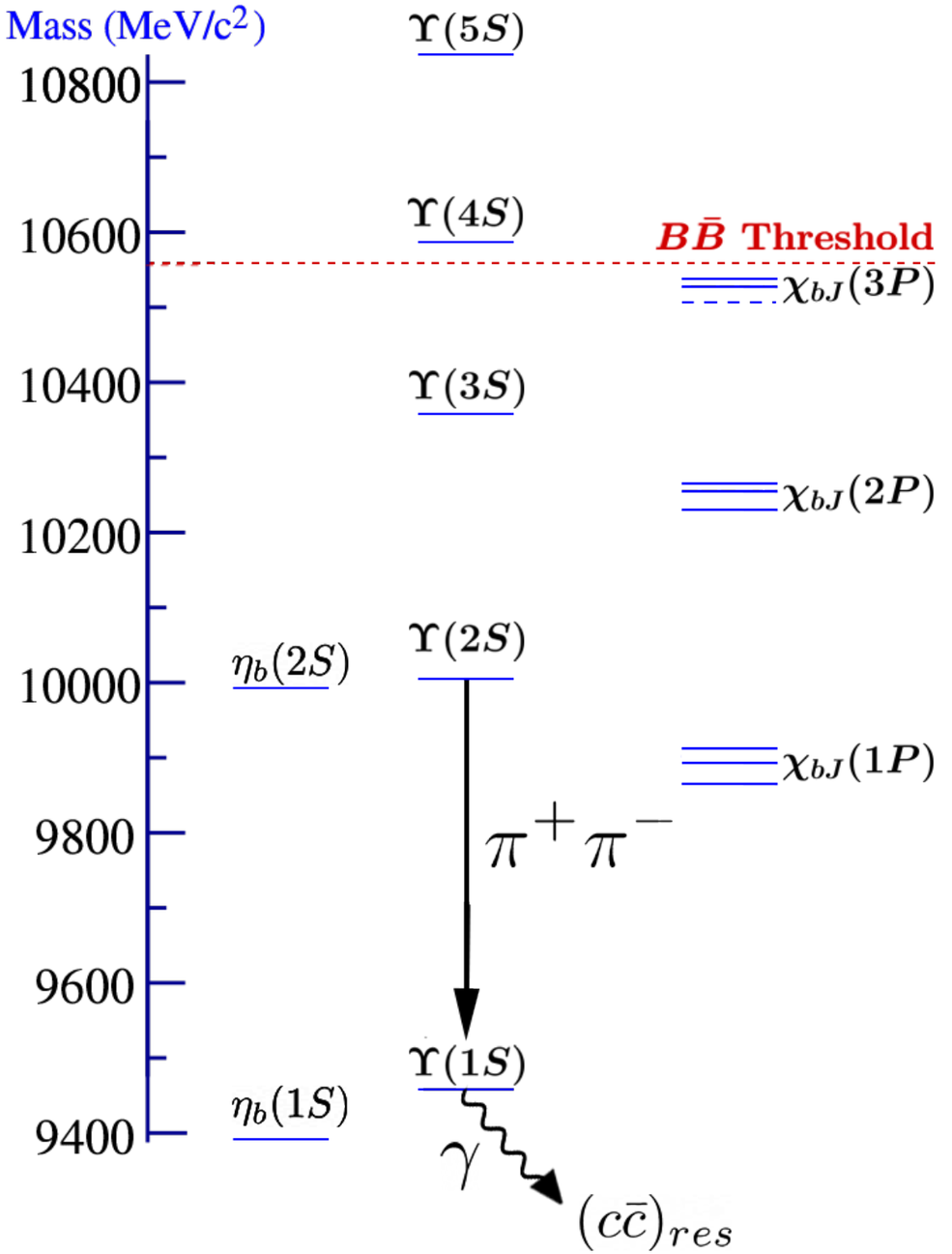

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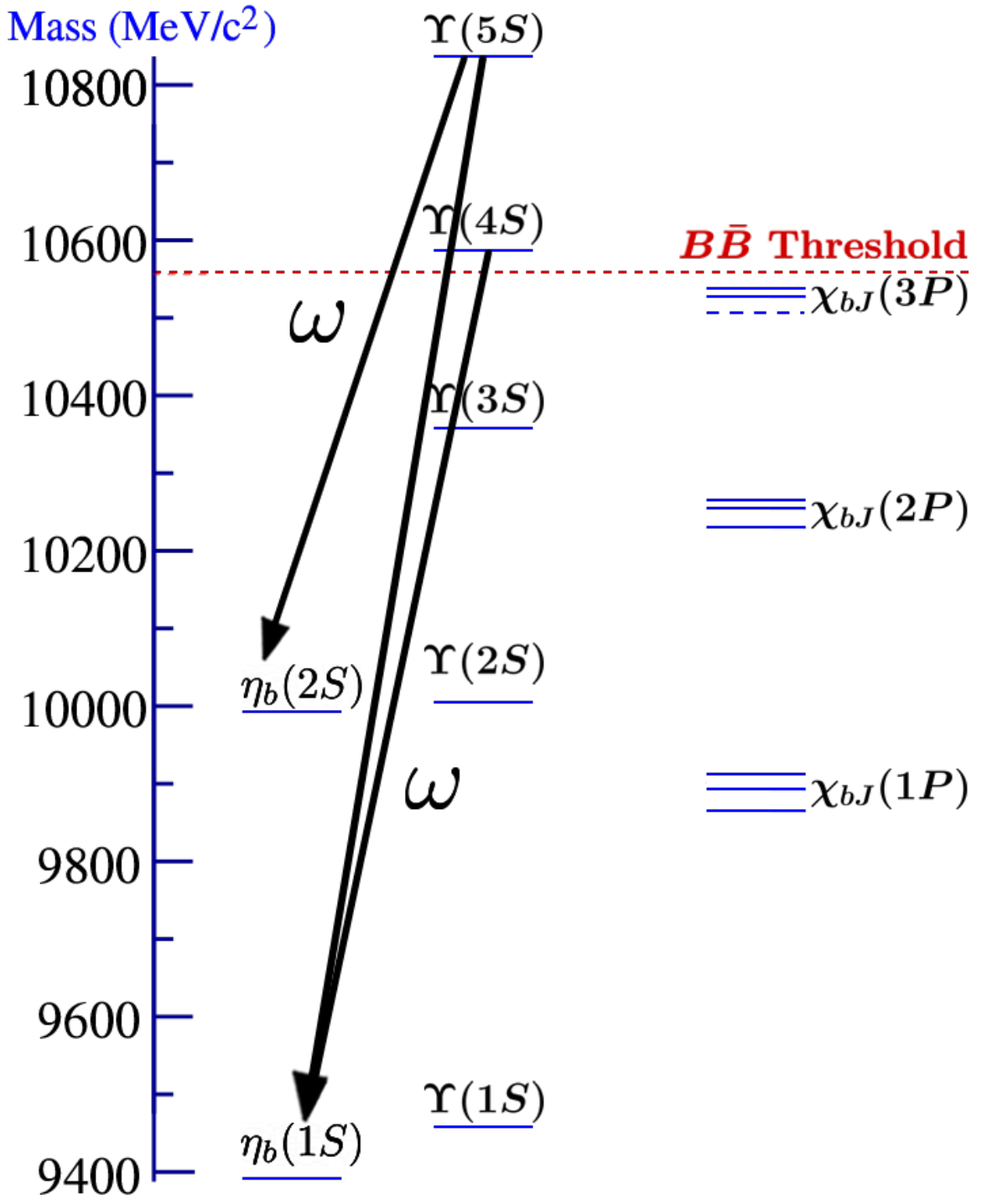

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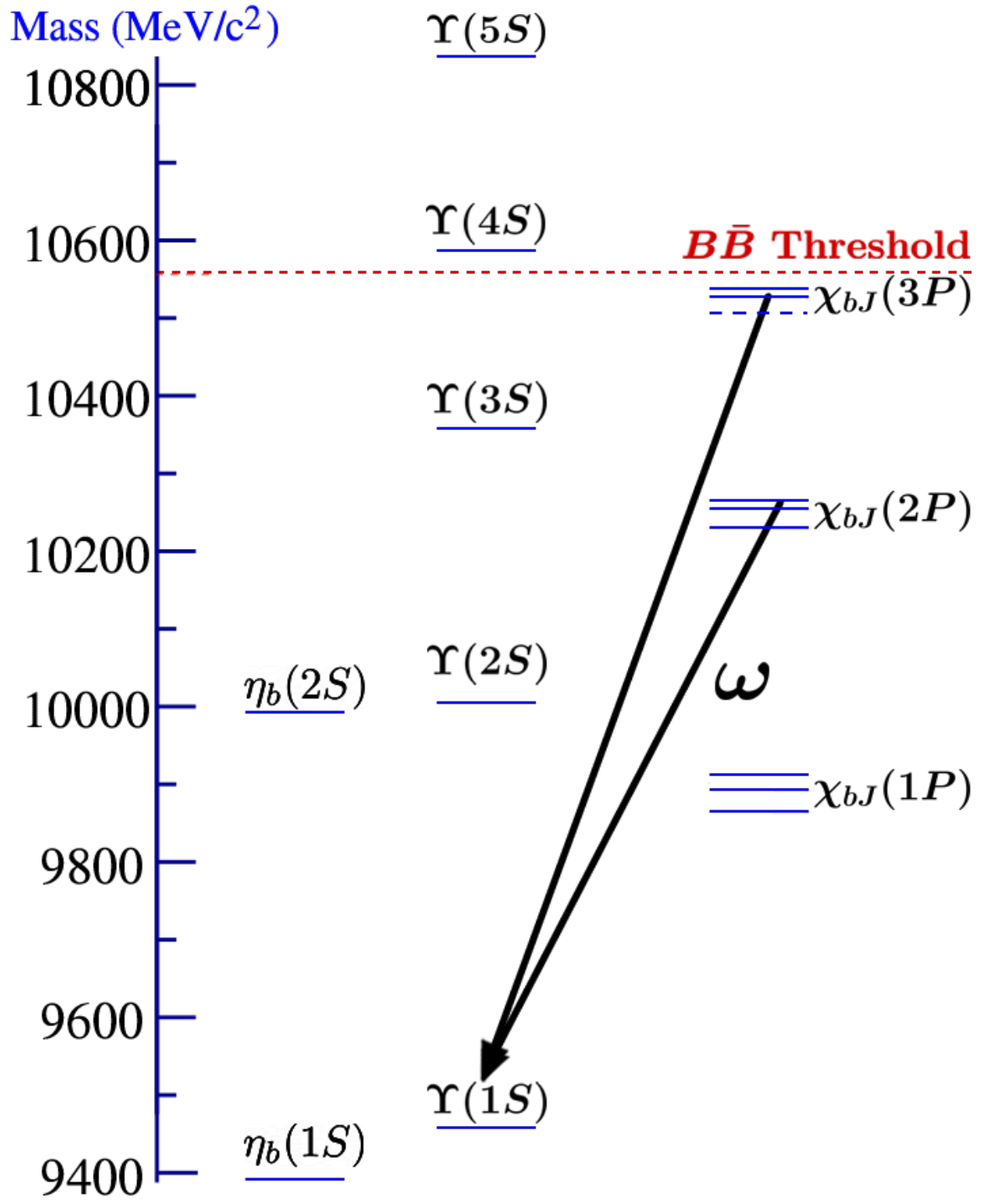
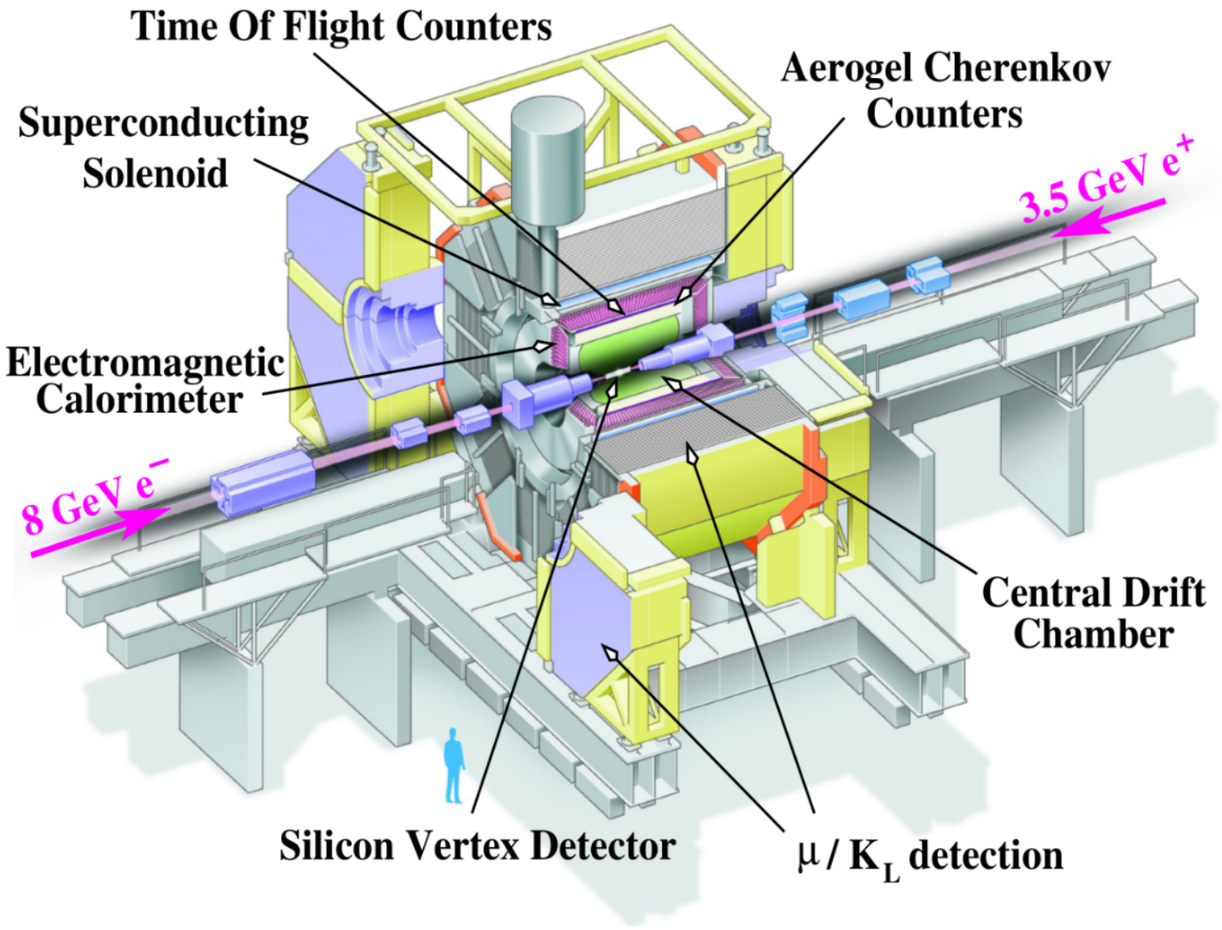
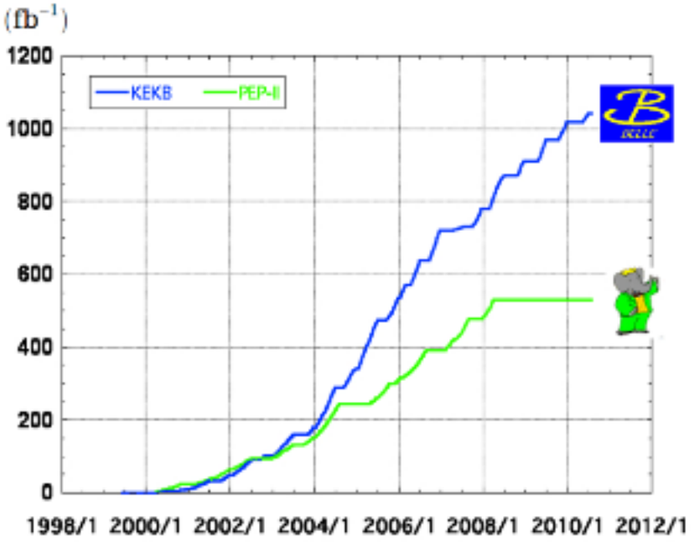


The Belle Experiment



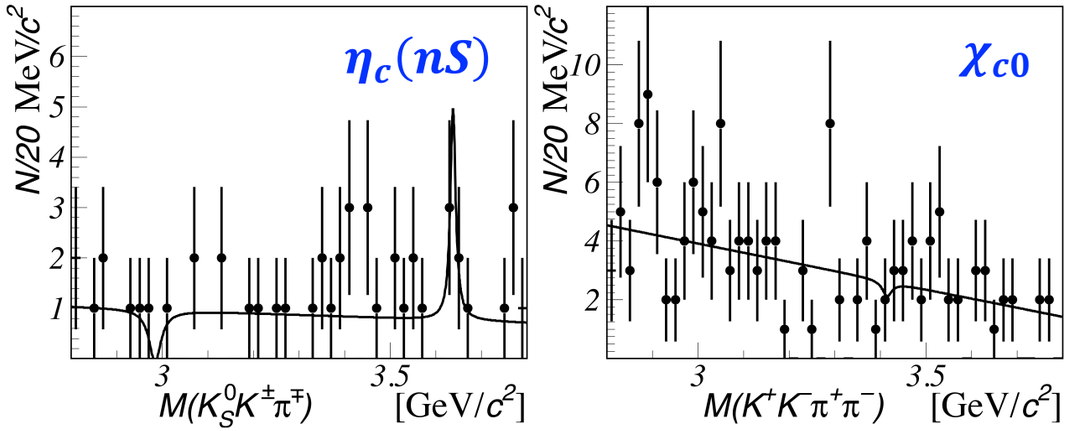


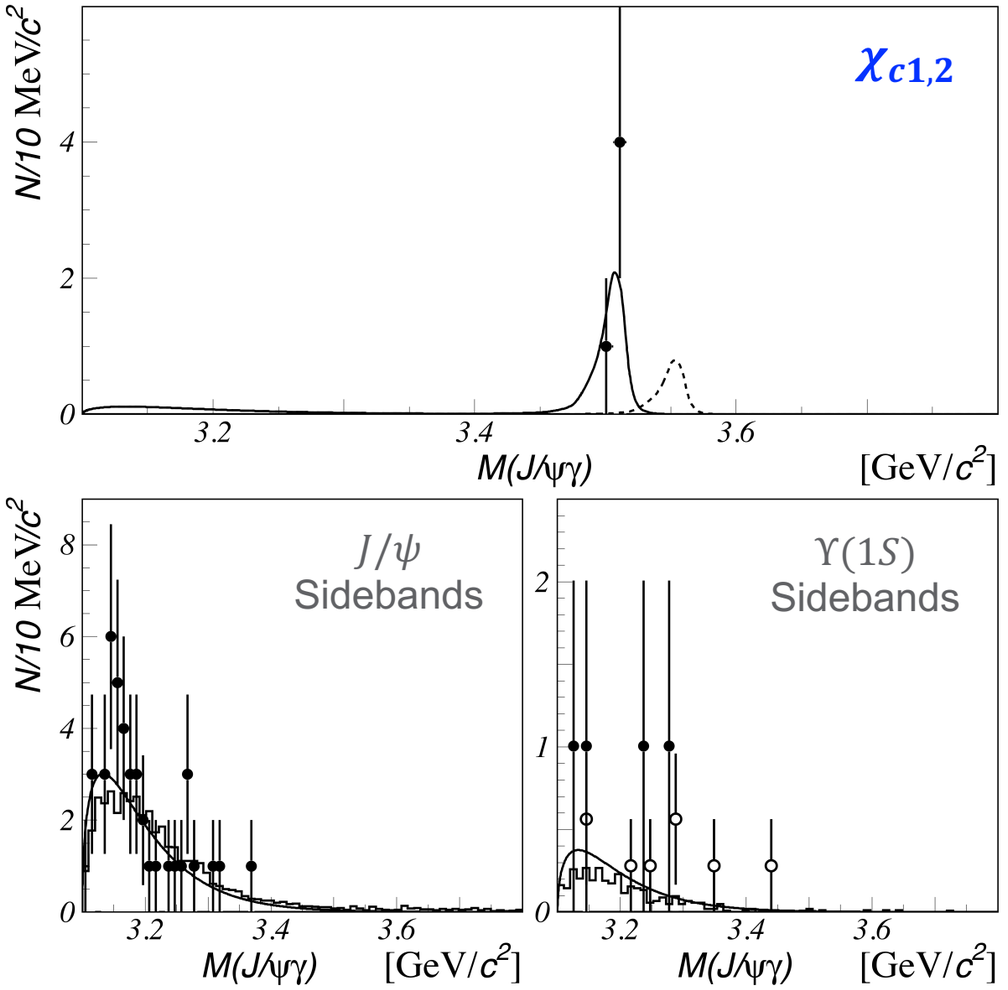
- **Highlights**
  - KEK, Tsukuba, Japan
  - Operation 1999-2010
  - Collected $\mathcal{L}\sim 1\ \mathrm{ab}^{-1}$
  - 500 members, 21 countries
  - More than 500 publications
- **Many contributions to $Q\bar{Q}$ study**
  - Charmonium(like) States (Li)
  - Vector Bottomonium States (Mizuk)
  - Bottomonium decays (this talk)

Observation of the Radiative Decays of $\Upsilon(1S)$ to χ_{c1}

- **Reconstruct $\Upsilon(1S) \to \gamma(c\bar{c})_{res}$**
  - Exclusively reconstruct final states:
    - ✓ $\chi_{c1,2} \to \gamma\, J/\psi(\mu^+\mu^-)$
    - ✓ $\chi_{c0} \to K^+K^-\pi^+\pi^-$
    - ✓ $\eta_c(1S, 2S) \to K^0_S K^\pm \pi^\mp$
- **Novel approach using $\Upsilon(2S)$ data**
  - $(157.3 \pm 3.6)\times 10^6$ $\Upsilon(2S)$
  - Tag $\Upsilon(1S)$ events with $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$
    - ✓ Substantial reduction in backgrounds:

      Ex. beam-related, ISR, FSR, continuum





P. Katrenko et al., Phys.Rev.Lett. 124, 122001 (2020)

Observation of the Radiative Decays of $\Upsilon(1S)$ to χ_{c1}

P. Katrenko et al., Phys.Rev.Lett. 124, 122001 (2020)

Significance: 6.3σ

Mode	Result (10^{-5})	Previous UL	Prediction
χ_{c1}	$4.7^{+2.4+0.4}_{-1.8-0.5}$	< 2.3	$0.45 - 0.9$
χ_{c2}	< 3.3	< 0.76	$0.51 - 0.56$
χ_{c0}	< 6.6	< 65	$0.32 - 0.4$
$\eta_c(1S)$	< 2.9	< 5.7	$2.9 - 4.9$
$\eta_c(2S)$	< 40	–	–

Previous UL (Belle): C.-P. Shen et al., Phys.Rev. D82, 051504 (2010)

- Used data collected near the $\Upsilon(1S)$ resonance → higher backgrounds

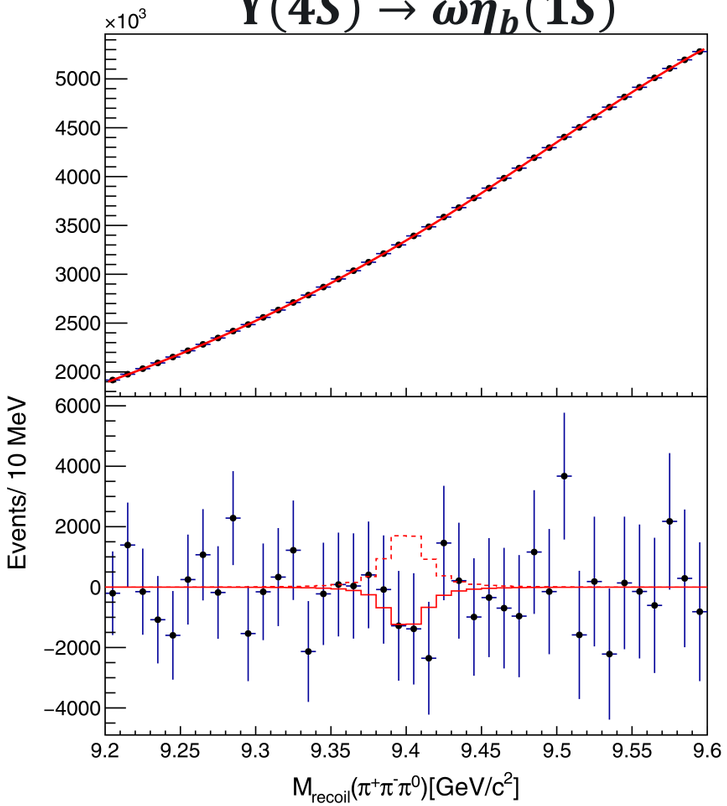
Prediction: Y.-l. Gao et al., hep-ph 0701009

Search for Transitions from $\Upsilon(4S)$ and $\Upsilon(5S)$ to $\eta_b(1S)$ and $\eta_b(2S)$ with Emission of an ω Meson

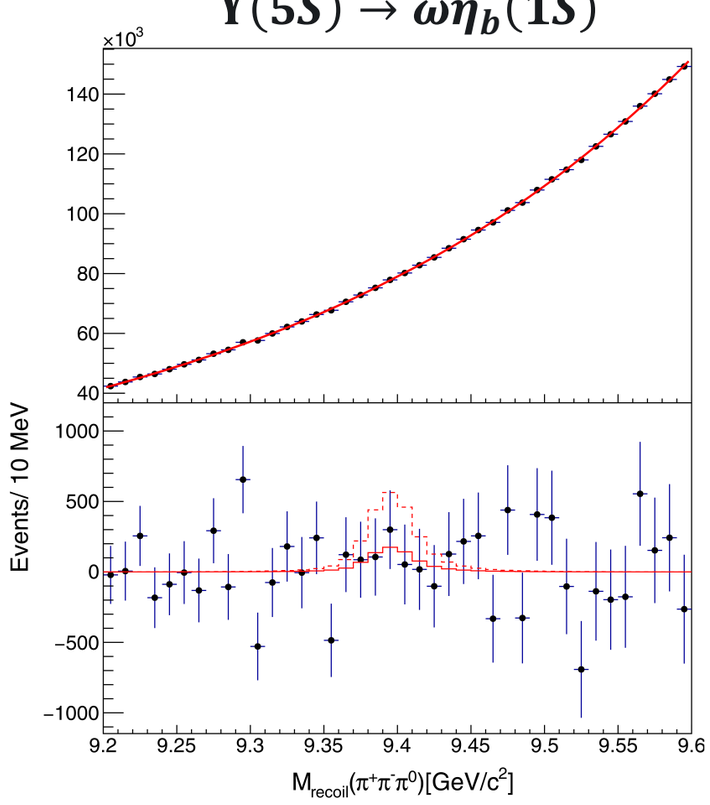
P. Oskin et al., Phys.Rev.D 102, 092011 (2020)

- **Inclusively search** for $\eta_b(mS)$ in the **mass recoiling against the** ω $\left(M_{recoil}(\pi^+\pi^-\pi^0)\right)$
  - Reconstruct $\omega \to \pi^+\pi^-\pi^0(\gamma\gamma)$
- Binned χ^2 fits: binning artificially enlarged for visualization.

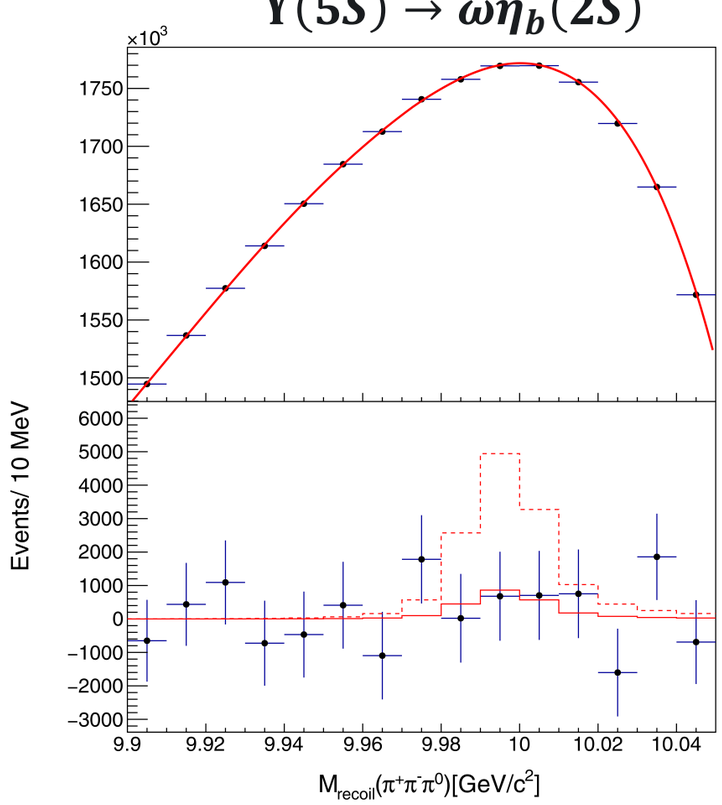
$\Upsilon(4S) \to \omega\eta_b(1S)$



$\Upsilon(5S) \to \omega\eta_b(1S)$



$\Upsilon(5S) \to \omega\eta_b(2S)$



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- In total, 711fb^{-1} of $\Upsilon(4S)$ data and 121fb^{-1} of $\Upsilon(5S)$ data were used
- 90% CL upper limits are set on:
  - Visible cross sections
  - Branching Ratios
  - Ratio with $\eta h_b(1P)$ transition (Phys. Rev. Lett. 115, 142001 (2015))

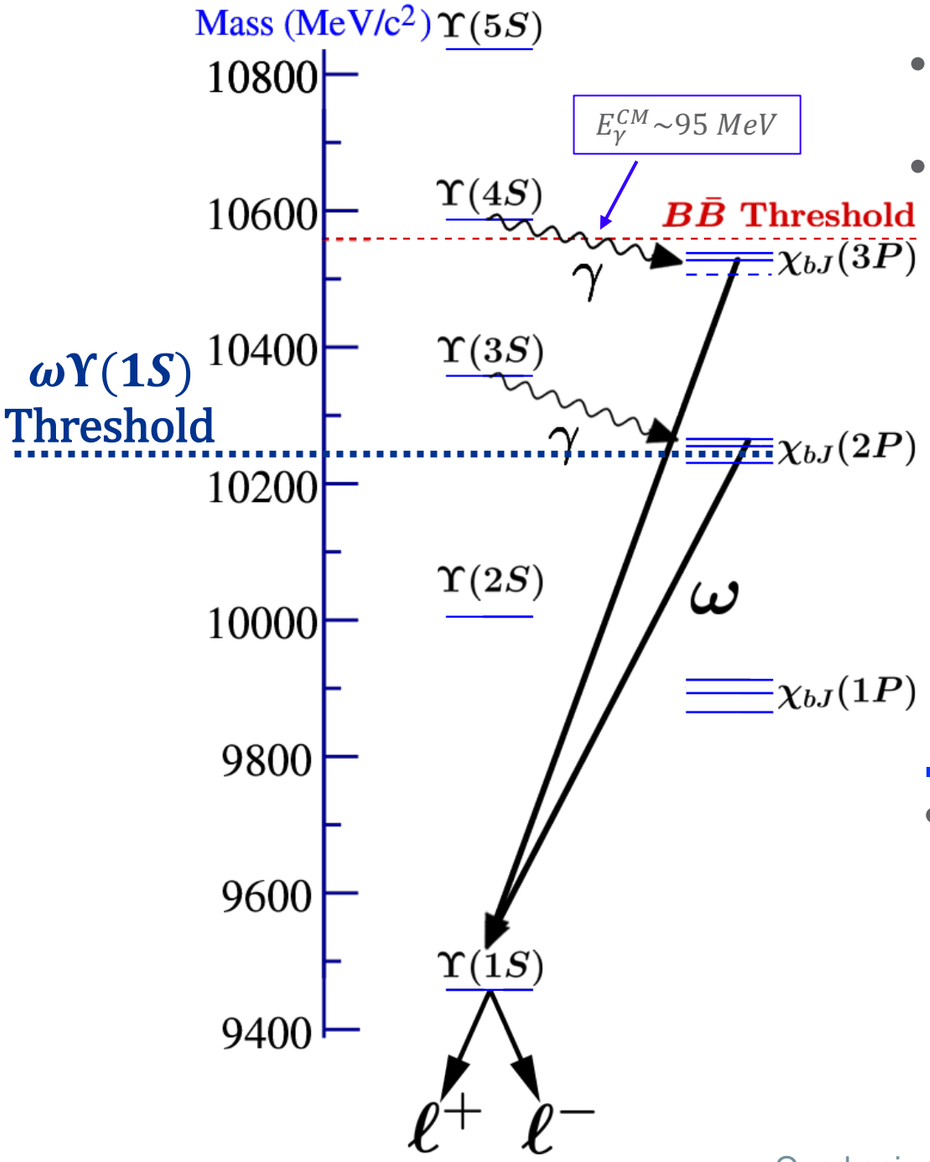
$$\sigma_{\text{vis}}[e^+e^- \to \eta_b(mS)\omega] = \frac{N}{\epsilon \cdot \mathcal{B}[\omega \to \pi^+\pi^-\pi^0] \cdot L_{\Upsilon(nS)}}$$

	Visible cross section	Upper limit
$e^+e^- \to \eta_b(1S)\omega$ at $\Upsilon(4S)$	$-0.14^{+0.19}_{-0.20}$	0.2 (pb)
$e^+e^- \to \eta_b(1S)\omega$ at $\Upsilon(5S)$	$0.13^{+0.18}_{-0.17}$	0.4 (pb)
$e^+e^- \to \eta_b(2S)\omega$ at $\Upsilon(5S)$	$0.3^{+0.9}_{-1.7}$	1.9 (pb)

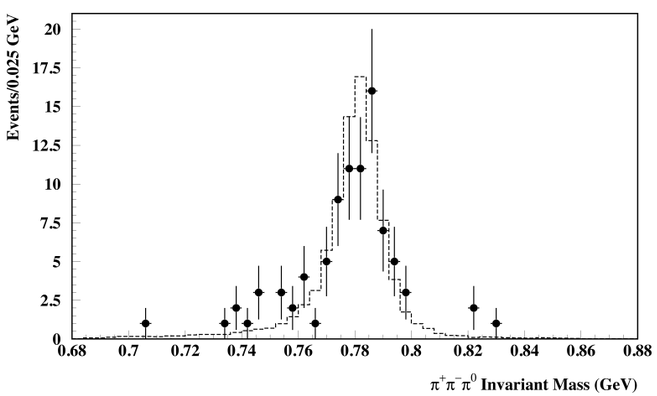
	Branching fraction	Upper limit
$\Upsilon(4S) \to \eta_b(1S)\omega$	$(-1.3^{+1.8}_{-1.9}) \times 10^{-4}$	1.8×10^{-4}
$\Upsilon(5S) \to \eta_b(1S)\omega$	$(3.7^{+5.4}_{-5.1}) \times 10^{-4}$	1.3×10^{-3}
$\Upsilon(5S) \to \eta_b(2S)\omega$	$(1.0^{+2.7}_{-5.1}) \times 10^{-3}$	5.6×10^{-3}

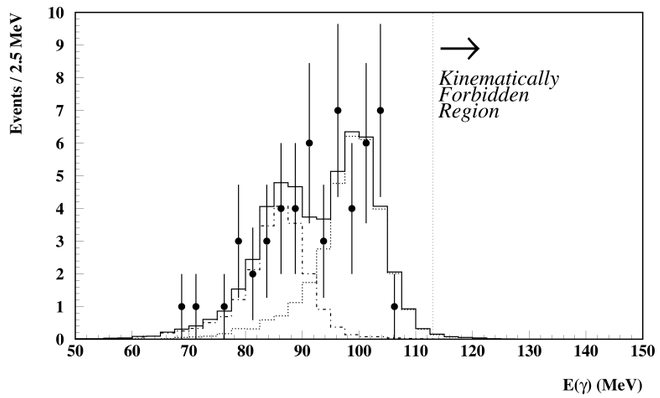
$$\frac{\mathcal{B}[\Upsilon(4S) \longrightarrow \eta_b(1S)\omega]}{\mathcal{B}[\Upsilon(4S) \to h_b(1P)\eta]} < 8.4 \times 10^{-2} \ (90\%\ CL)$$

Analysis Strategy: Search for $\Upsilon(4S) \to \gamma\chi_{bJ}(nP)$



- $\chi_{b(0),1,2}(3P)$ and $\chi_{b1,2}(2P)$ states are kinematically accessible
- $\mathcal{B}\left(\chi_{b1,2}(2P) \to \omega\Upsilon(1S)\right)$ ~1.0%
  - Discovered by CLEO [Phys.Rev.Lett. 92 (2004) 222002]





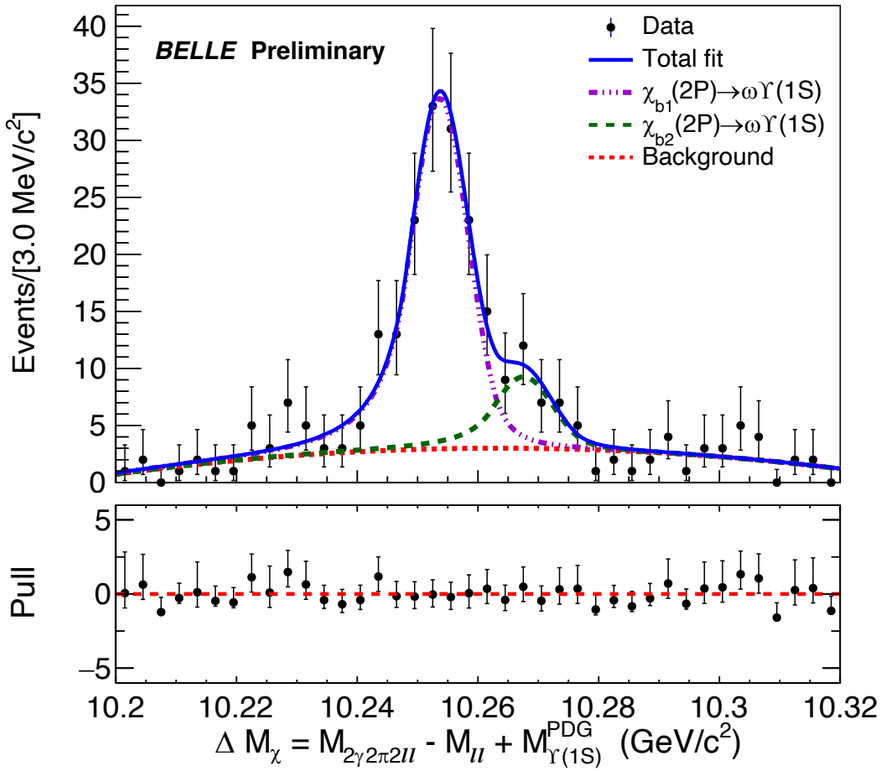
- **We reconstruct the exclusive final state**:

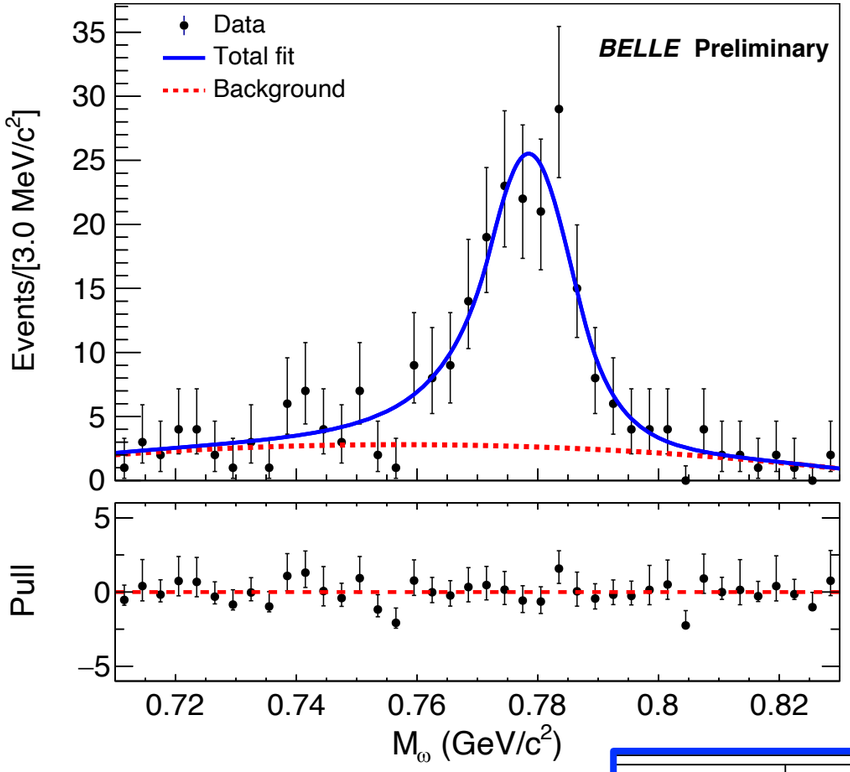
  $\chi_{bJ} \to \omega[\Upsilon(1S)] \to \pi^+\pi^-\pi^0[\ell^+\ell^-]$

  - High backgrounds for low energy photons make reconstruction of $\Upsilon(3S) \to \gamma\chi_{bJ}(nP)$ suboptimal

Search for $\chi_{bJ}(nP) \to \omega\Upsilon(1S)$

Perform a Simultaneously Fit of M_ω and ΔM_χ n 3.0 fb^{-1} of $\Upsilon(3S)$ data





Data Sample: 3.0 fb^{-1} of **on-resonance $\Upsilon(3S)$ data**

$-$ $\Upsilon(3S)$ Population $-$

$(12.7 \pm 0.1 \pm 0.4) \cdot 10^6$

Results

Calculate Branching Fractions as ratio with $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)[\ell^+\ell^-]$

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

Channel	$\mathcal{B}(\chi_{bJ}(2P) \to \omega\Upsilon(1S))$	Significance
J=1	$\left(2.20^{+0.24}_{-0.23} \pm 0.22\right)$ %	12.2σ
J=2	$\left(0.44^{+0.16}_{-0.15} \pm 0.06\right)$ %	3.3σ

Compare with PDG

Channel	Branching Fraction	Consistency
J=1	$\left(1.63^{+0.35+0.12}_{-0.31-0.11}\right)$ %	1.3σ
J=2	$\left(1.10^{+0.32+0.08}_{-0.28-0.07}\right)$ %	2.0σ

Search for $\chi_{bJ}(nP) \to \omega\Upsilon(1S)$

[Mod. Phys. Lett. A18 (2003) 1067]

In QCD Multipole Expansion, the heavy quark spin decouples from the partial width → independent of spin

Voloshin Calculates:

$$r_{2/1} = \frac{\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{b2}(2P) \to \omega\Upsilon(1S))}{\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{b1}(2P) \to \omega\Upsilon(1S))}$$

Estimated from $\mathcal{B}\left(\chi_{bJ}(nP) \to \gamma\Upsilon(mS)\right)$

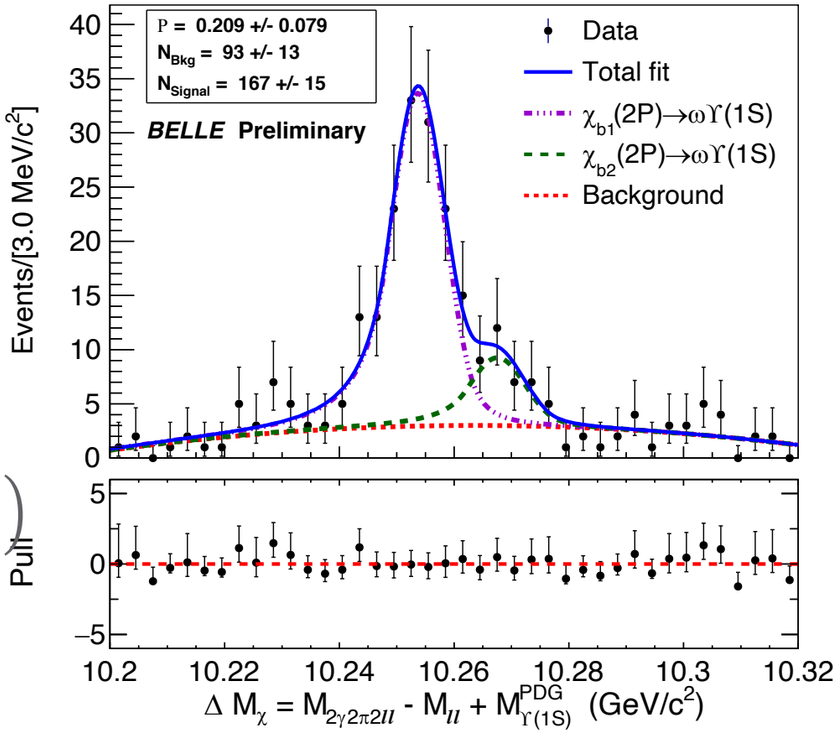
$$= \frac{\Gamma(\Upsilon(3S) \to \gamma\chi_{b2}(2P))}{\Gamma(\Upsilon(3S) \to \gamma\chi_{b1}(2P))} \frac{\Gamma(\chi_{b2}(2P) \to \omega\Upsilon(1S))}{\Gamma(\chi_{b1}(2P) \to \omega\Upsilon(1S))} \frac{\Gamma(\chi_{b1}(2P))}{\Gamma(\chi_{b2}(2P))}$$

Using vintage world averages (circa 2004):

$$r_{2/1} \approx 1.3 \pm 0.3$$

- B-Factories measured many radiative $\mathcal{B}$ precisely!
- **Recalculation with current world averages yields:**

$$r_{2/1} = 0.51 \pm 0.09$$



Reparameterize fit:

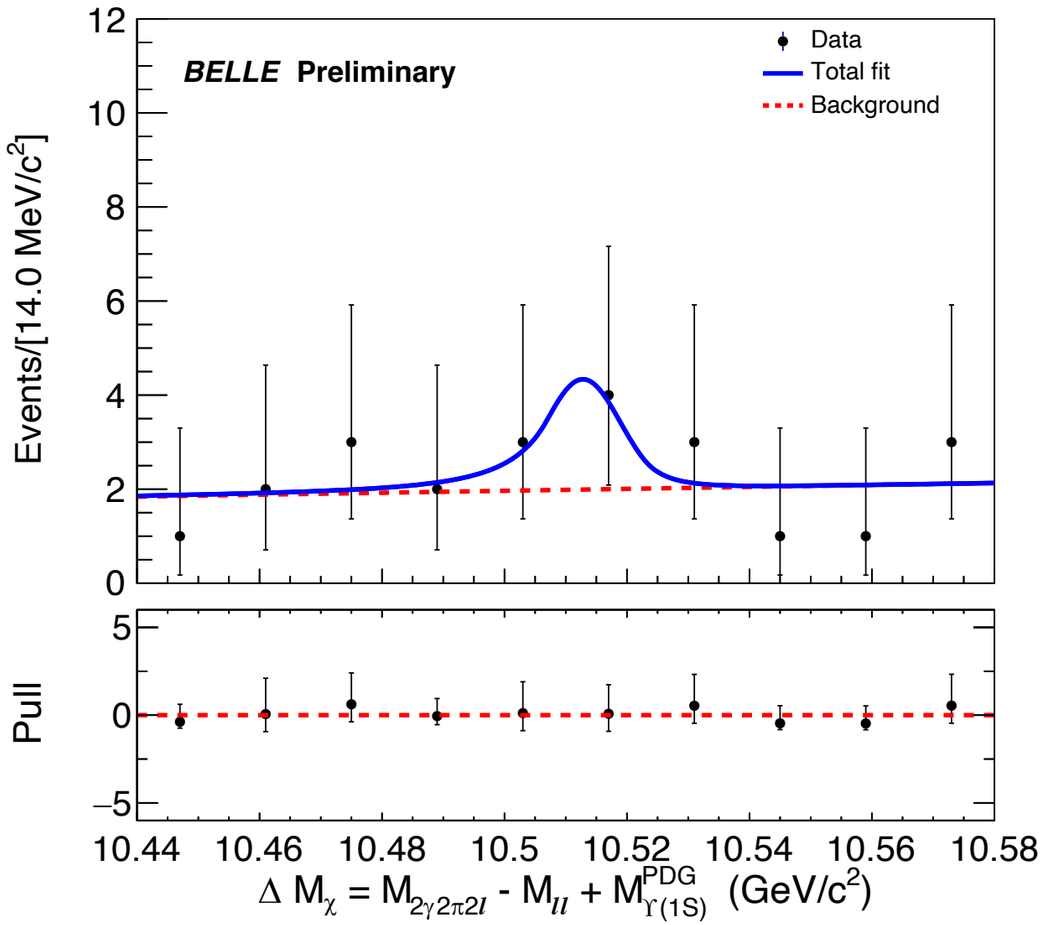
$$N_{Signal} = N_{\chi 1} + N_{\chi 2}$$

$$\mathrm{P} = \frac{N_{\chi 2}}{N_{\chi 1}}$$

$$r_{2/1} = \mathrm{P} \times \frac{\epsilon_{\chi 1}}{\epsilon_{\chi 2}} = 0.209^{+0.090}_{-0.074} \pm 0.013$$

Consistent with QCDME at 2.3σ

Search for $\chi_{bJ}(3P)$



$513\ \text{fb}^{-1}$ of **on-resonance $\Upsilon(4S)$ data** analyzed

[*Phys.Rev.D* 92 (2015) 5, 054034]

Initial state	Final state	M_f (GeV)	$\mathcal{M}$	Predicted Width (keV)	Predicted BR (%)	Predicted Width (keV)
$\Upsilon(4^3S_1)$	$\ell^+\ell^-$		0.459	0.39	1.8×10^{-3}	0.32 ± 0.04^a
10.579^a	ggg		0.459	15.1	0.0686	
	γgg		0.459	0.40	1.8×10^{-3}	
	$\gamma\gamma\gamma$		0.459	6.0×10^{-6}	2.7×10^{-8}	
	$\chi_{b2}(3^3P_2)\gamma$	10.528^d	−3.223	0.82	3.7×10^{-3}%	
	$\chi_{b1}(3^3P_1)\gamma$	10.516^d	−3.072	0.84	3.8×10^{-3}%	
	$\chi_{b0}(3^3P_0)\gamma$	10.500^d	−2.869	0.48	2.2×10^{-3}%	

Can estimate conservative upper limit on expected on

$$\mathcal{B}(\Upsilon(4S)\to\gamma\chi_{b1}(3P)\to\gamma\omega\Upsilon(1S))$$

- *Assume* $\mathcal{B}(\chi_{b1}(3P)\to\omega\Upsilon(1S))\simeq\mathcal{B}(\chi_{b1}(2P)\to\omega\Upsilon(1S))$
  - Overestimate, as $\Gamma(\chi_{b1}(3P))>\Gamma(\chi_{b1}(2P))$
- **Estimate: $\mathcal{B}\sim 8.4\times10^{-7}$**

From the fit, a 90% CL upper limit is determined:

$$\mathcal{B}(\Upsilon(4S)\to\gamma\chi_{b1}(3P)\to\gamma\omega\Upsilon(1S))<1.4\times10^{-5}$$

Summary

- Belle remains productive in $Q\bar{Q}$ spectroscopy!

- Radiative Transitions
  - **First Observation:**
    - ✓ $\Upsilon(1S) \to \gamma\chi_{c1}$ [Phys.Rev.Lett. 124, 122001 (2020)]
- Hadronic Transitions:
  - **New Limits Set:**
    - ✓ $\Upsilon(4S) \to \omega\eta_b(1S)$
    - ✓ $\Upsilon(5S) \to \omega\eta_b(1S, 2S)$

    [Phys.Rev.D 102, 092011 (2020)]
  - **Preliminary results:**
    - ✓ **First measurement of $\chi_{bJ}(2P) \to \omega\Upsilon(1S)$ *since discovery in 2004***
    - ✓ **New Limit set on $\Upsilon(4S) \to \gamma\chi_{b1}(3P) \to \gamma\omega\Upsilon(1S)$**
- The future is bright for Quarkonium at Belle and high luminosity Belle II

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Thank you