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Observation of $\Upsilon(4S) \rightarrow \eta' \Upsilon(1S)$ and $\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$ at Belle

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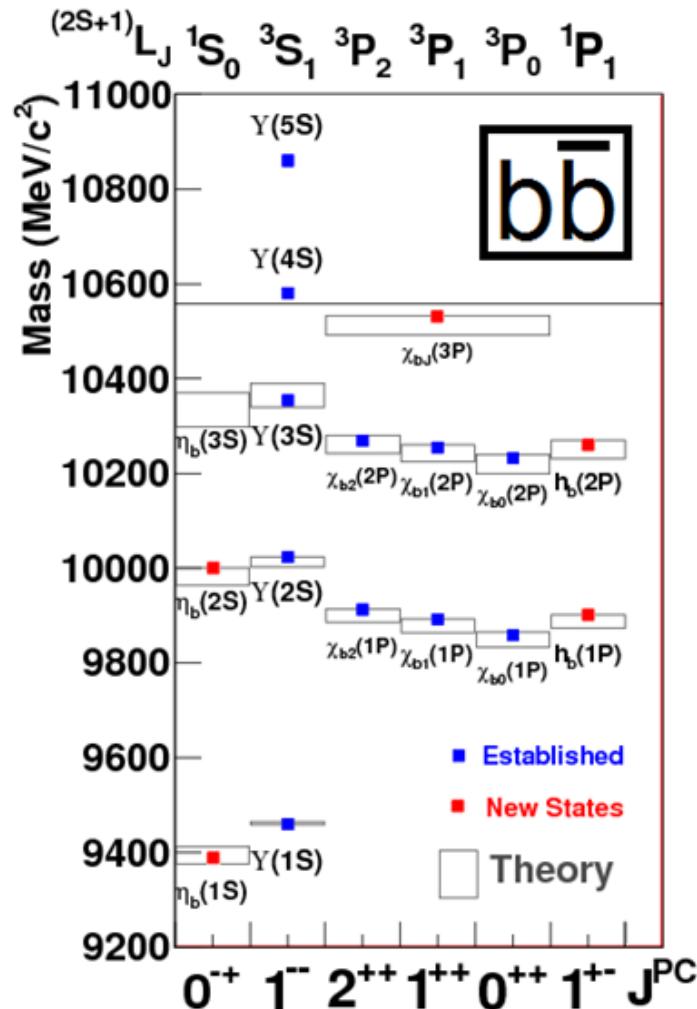
Introduction



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- ▶ Study of $b\bar{b}$ bound states
- ▶ Measurement of hadronic transitions
 - η observed, no past results for η'
 - Enhanced rates
 - No clear theoretical predictions
- ▶ Radiative decays
 - Well-studied, many theoretical predictions
 - Hyperfine splitting: $\Delta(m(\Upsilon(1S))-m(\eta_b(1S)))$



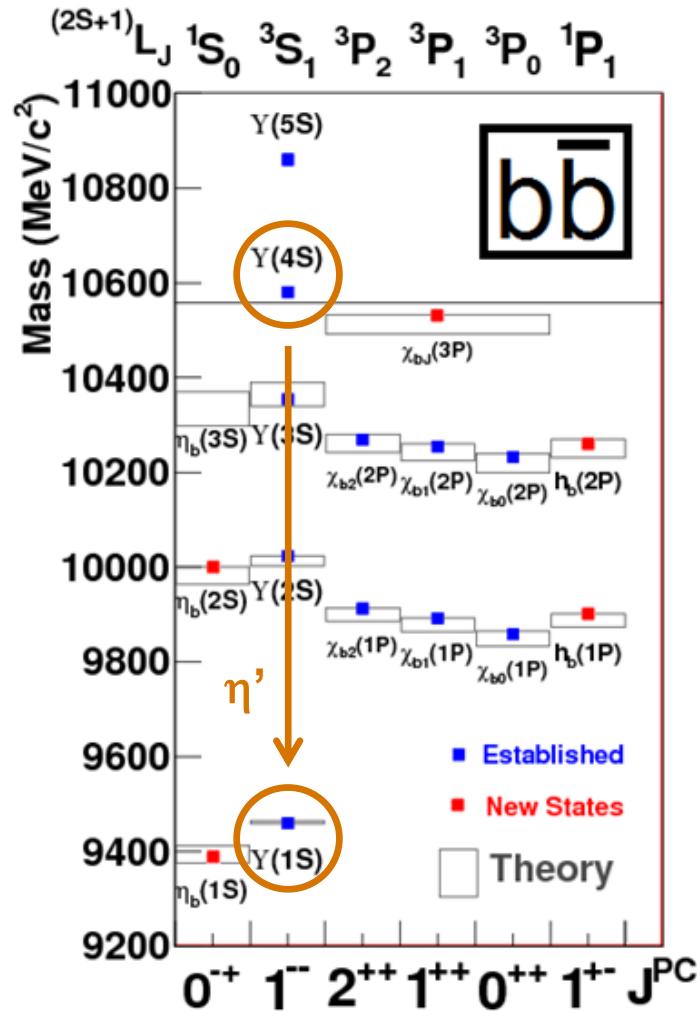
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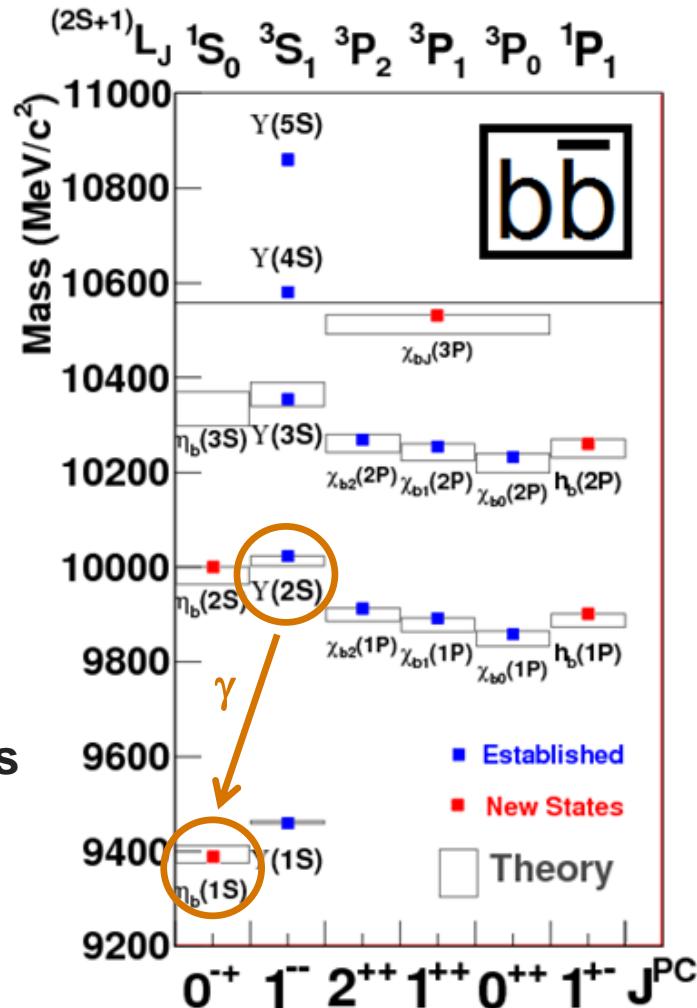
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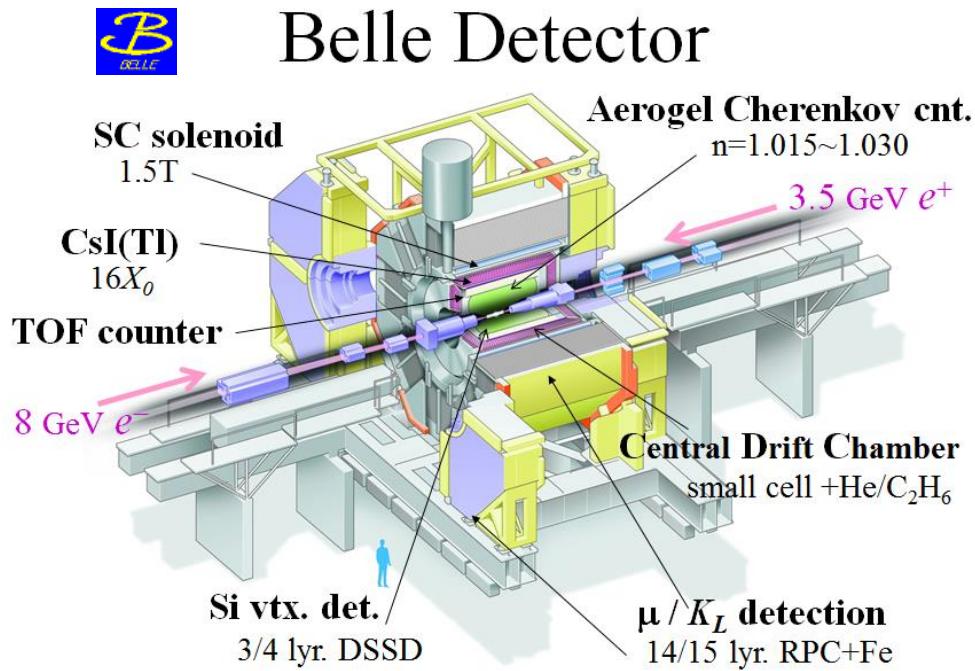
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The Belle Experiment

- ▶ Vital statistics
 - KEK, Tsukuba, Japan
 - Operated 1999-2010
 - $\sim 1 \text{ ab}^{-1}$ collected
 - ~ 400 members, 18 countries
 - >500 publications
- ▶ Many contributions to $b\bar{b}$ study
 - Discovery of $\eta_b(2S)$, $h_b(1P,2P)$
 - Discovery of $Z_b^{\pm}(10610/50)$
 - Measurements of decay modes
- ▶ Now upgraded to Belle II, at the next generation B-Factory





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$$\Upsilon(4S) \rightarrow \eta' \Upsilon(1S)$$

arXiv:1803.10303
Submitted to PRL

$\Upsilon(4S) \rightarrow \eta' \Upsilon(1S)$

Analysis potential

► Motivations

- Non- $B\bar{B}$ decays of $\Upsilon(4S) < 4\%$
- $\Upsilon(4S) \rightarrow X + \Upsilon(1S)$ (<0.4%) not saturated by known decay modes
- Recent experimental results indicate enhanced η rates
- Search for $\Upsilon(4S) \rightarrow \eta' \Upsilon(1S)$ not yet attempted

► Input from charm sector

- Null searches for $\psi(4160)/\Upsilon(4260) \rightarrow \eta' J/\psi$ by CLEO

CLEO, PRL 96, 162003 (2006)
- Observation of $e^+e^- \rightarrow \eta' J/\psi$ (4.226/4.258 GeV) by BESIII

BESIII, PRD 94, 032009 (2016)
- Theory prediction: $BR(\psi(4160) \rightarrow \eta' J/\psi) \sim 6\% \times BR(\psi(4160) \rightarrow \eta J/\psi)$

Chen et al., PRD 87, 054006 (2013)
- By analogy: $BR(\Upsilon(4S) \rightarrow \eta \Upsilon(1S)) \sim 2 \times 10^{-4}$, $BR(\Upsilon(4S) \rightarrow \eta' \Upsilon(1S)) \sim O(10^{-5})$

$\Upsilon(4S) \rightarrow \eta' \Upsilon(1S)$

Analysis Overview



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- ▶ Reconstruct $\Upsilon(1S) \rightarrow \mu^+ \mu^-$ with two η' final states
 - $\rho^0 \gamma$ ("2 π 1 γ ") : higher rate (~30%) but also higher background
 - $\pi^+ \pi^- \eta$ ("2 π 2 γ) : lower rate (~17%) but background-free
 - $\pi^0 \pi^0 \eta$: excluded due to high backgrounds
- ▶ Dataset: $496 \text{ fb}^{-1} = (538 \pm 8) \times 10^6 \Upsilon(4S)$

| Selection criteria: | |
|---|---|
| $\eta' \rightarrow \rho^0 \gamma$ | $\eta' \rightarrow \pi^+ \pi^- \eta$ |
| "2 charged" skim | "2 charged" skim |
| PID on μ^\pm | PID on μ^\pm |
| 2 pion and 1 γ candidates | 2 pion and 2 γ candidates |
| $\text{KB} < 0$ | $\text{KB} < 0$ |
| $BDT > 0.15$ | |
| $9.3 < M(\mu\mu) < 9.6 \text{ GeV}/c^2$ | $9.3 < M(\mu\mu) < 9.6 \text{ GeV}/c^2$ |
| $ \cos \theta(\pi\pi)_{\text{CM}} < 0.9$ | |

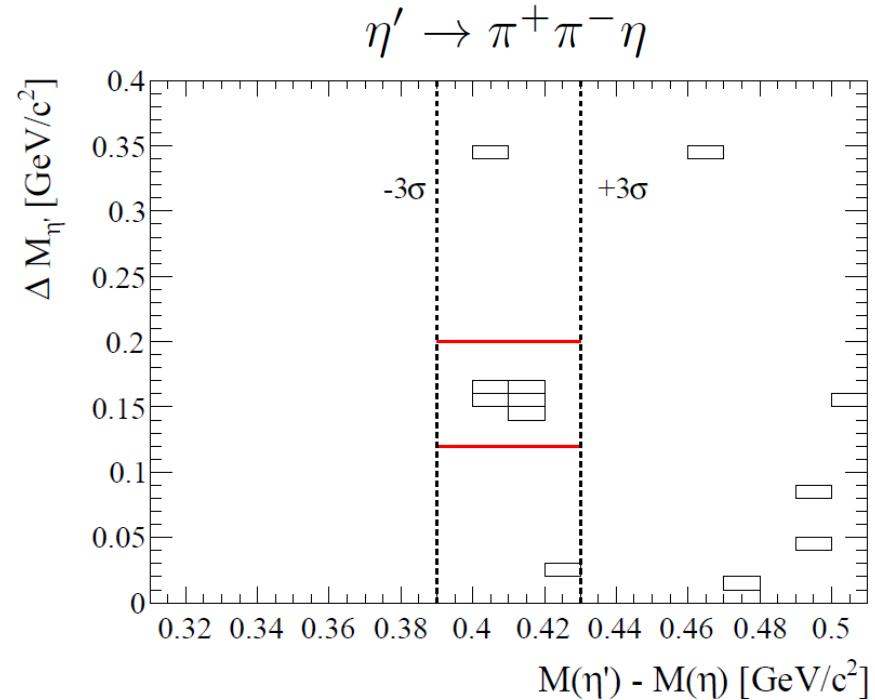
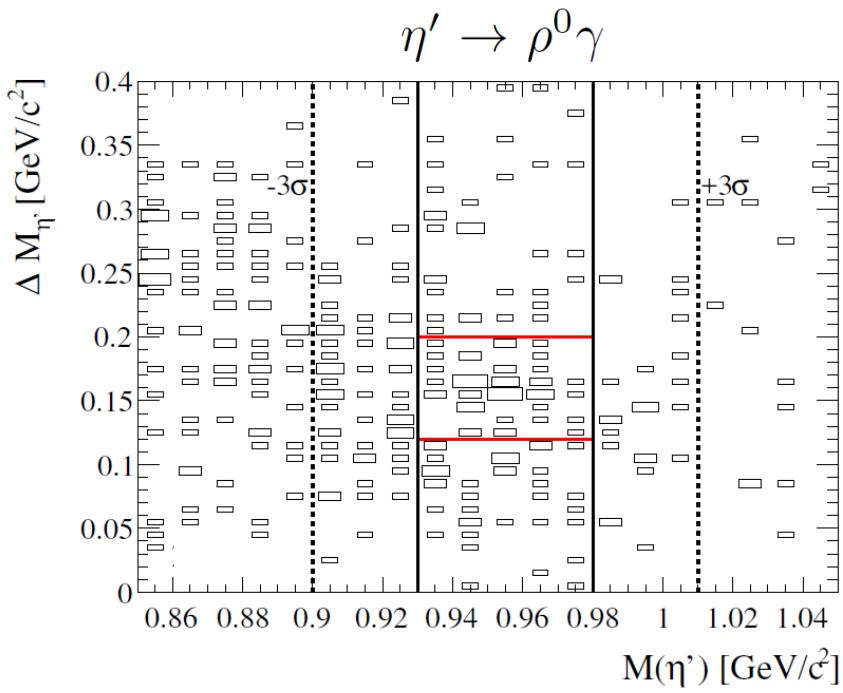
$$\epsilon = (17.64 \pm 0.05)\% \quad \epsilon = (5.02 \pm 0.03)\%$$

- ▶ KB: remove continuum

$$\text{KB} = p(\mu^+ \mu^-)_{CM} - \frac{1}{2} \frac{(s - m(\mu^+ \mu^-)^2)}{\sqrt{s}}$$
- ▶ BDT: remove ISR and extra γ
 - Use $\Delta M_{\pi\pi} = M(\mu\mu\pi\pi) - M(\mu\mu)$ and $M(\mu\mu\pi\gamma)$

$\Upsilon(4S) \rightarrow \eta' \Upsilon(1S)$

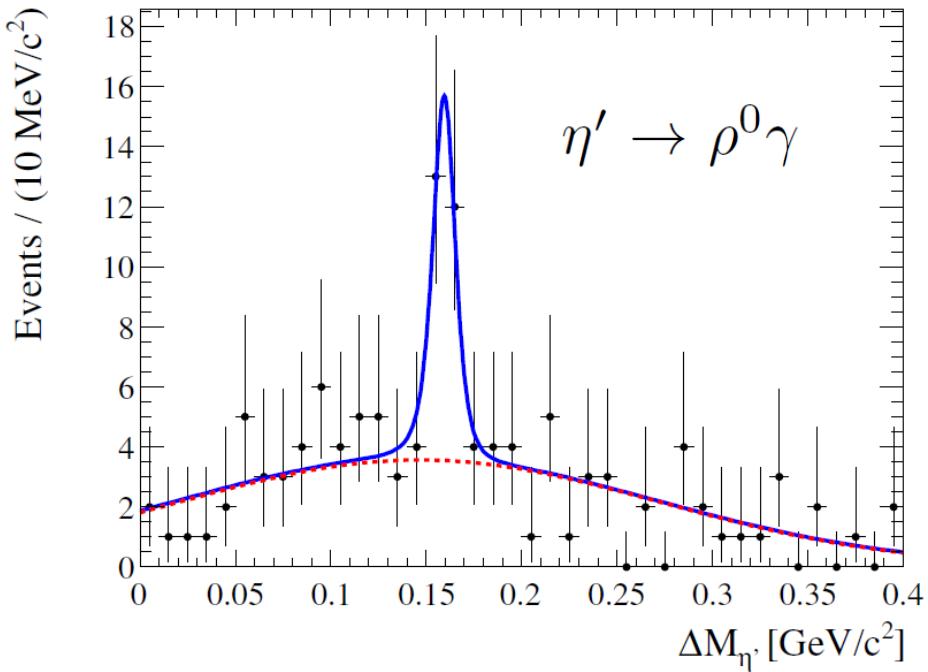
Application of Selection Criteria



- ▶ Main fit variable: $\Delta M_{\eta'} = M(\Upsilon(4S)) - M(\Upsilon(1S)) - M(\eta')$
- ▶ Signal fit function:
$$\mathcal{F}(x) = \exp \left\{ -\frac{(x - \mu)^2}{2\sigma_{L,R}^2 + \alpha_{L,R}(x - \mu)^2} \right\}$$
- ▶ Backgrounds: Gaussian ($2\pi 1\gamma$), linear ($2\pi 2\gamma$)

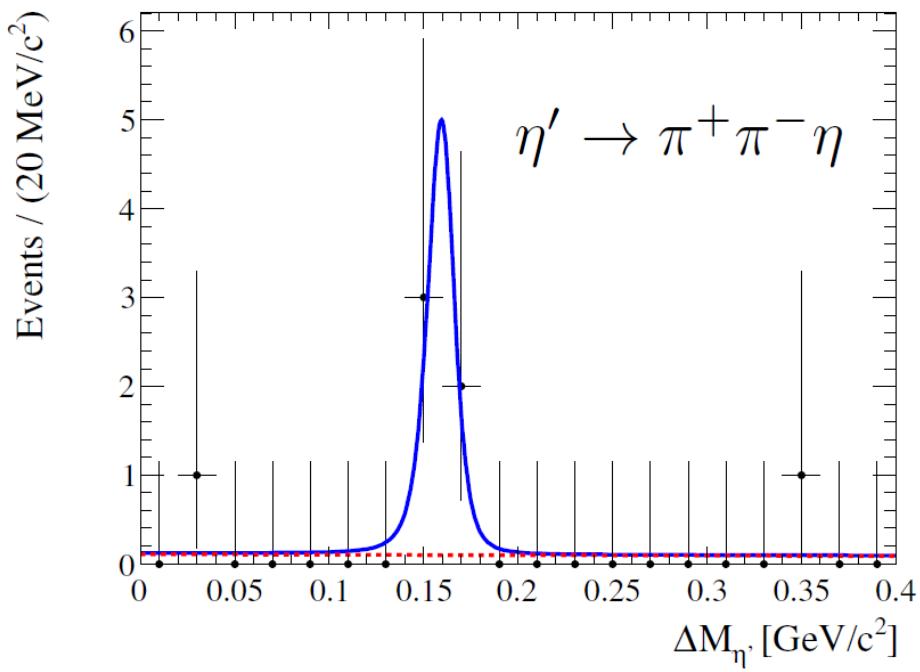
$\Upsilon(4S) \rightarrow \eta' \Upsilon(1S)$

Fit Results



$$N_{\text{sig}} = 22 \pm 7 \quad (4.2\sigma)$$

$$N_{\text{bkg}} = 96 \pm 11$$



$$N_{\text{sig}} = 5.0 \pm 2.3 \quad (4.1\sigma)$$

$$N_{\text{bkg}} = 2.0 \pm 1.6$$

$\Upsilon(4S) \rightarrow \eta' \Upsilon(1S)$

Systematic Uncertainties

| Source | $\eta' \rightarrow \rho\gamma$ | $\eta' \rightarrow \eta\pi^+\pi^-$, $\eta \rightarrow \gamma\gamma$ |
|--------------------------------------|--------------------------------|--|
| $\Upsilon(4S)$ | ± 1.4 | ± 1.4 |
| Tracking | ± 1.4 | ± 1.4 |
| μ -id | ± 1.1 | ± 1.1 |
| BRs from PDG | ± 2.7 | ± 2.6 |
| $\eta' \rightarrow \rho\gamma$ model | -1.9 | - |
| Fit procedure | ± 6.8 | ± 2.0 |
| Total on \mathcal{B} | ± 7.6 | ± 3.5 |

- ▶ Largest sources
 - Modeling of lineshapes
 - Secondary branching fractions (beyond scope of this analysis)
- ▶ Dominated by statistical uncertainty (~30-40%)

$\Upsilon(4S) \rightarrow \eta' \Upsilon(1S)$

Summary of Results

- Derivation of branching fractions and ratio with other hadronic decays

$$\mathcal{B} = \frac{N_{\text{sig}}}{\epsilon \times N_{\Upsilon(4S)} \times \mathcal{B}_{\text{secondary}}}$$

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

- Branching fraction results

- $\pi^+ \pi^- \eta = (3.19 \pm 0.96 \pm 0.24) \times 10^{-5}$
- $\rho^0 \gamma = (4.53 \pm 2.12 \pm 0.16) \times 10^{-5}$
- Combined = $(3.43 \pm 0.88 \pm 0.21) \times 10^{-5}$

Combined significance = 5.7σ
First observation of this decay!

- Ratio of branching fractions

- $R_{\eta'/\eta} = 0.20 \pm 0.06$
- $R_{\eta'/\pi\pi} = 0.42 \pm 0.11$

- Indicative of light quark contributions?

Voloshin, MPLA 26, 773 (2011)



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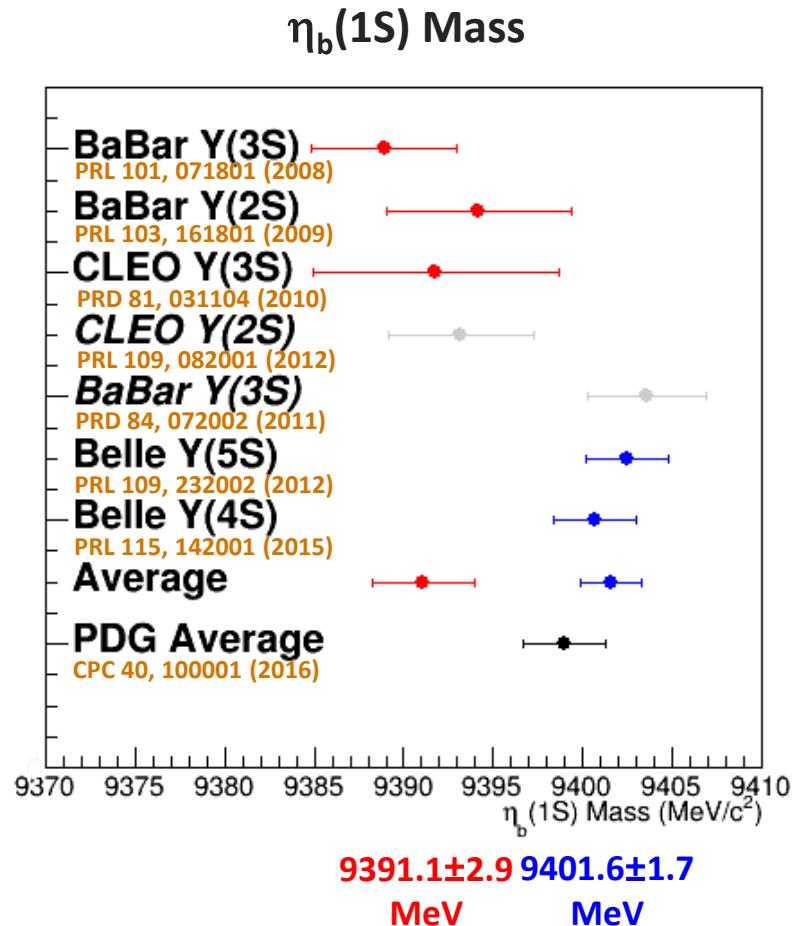
$$\Upsilon(2S) \rightarrow \gamma\eta_b(1S)$$

arXiv:1807.01201
Submitted to PRL

$\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$

Analysis potential

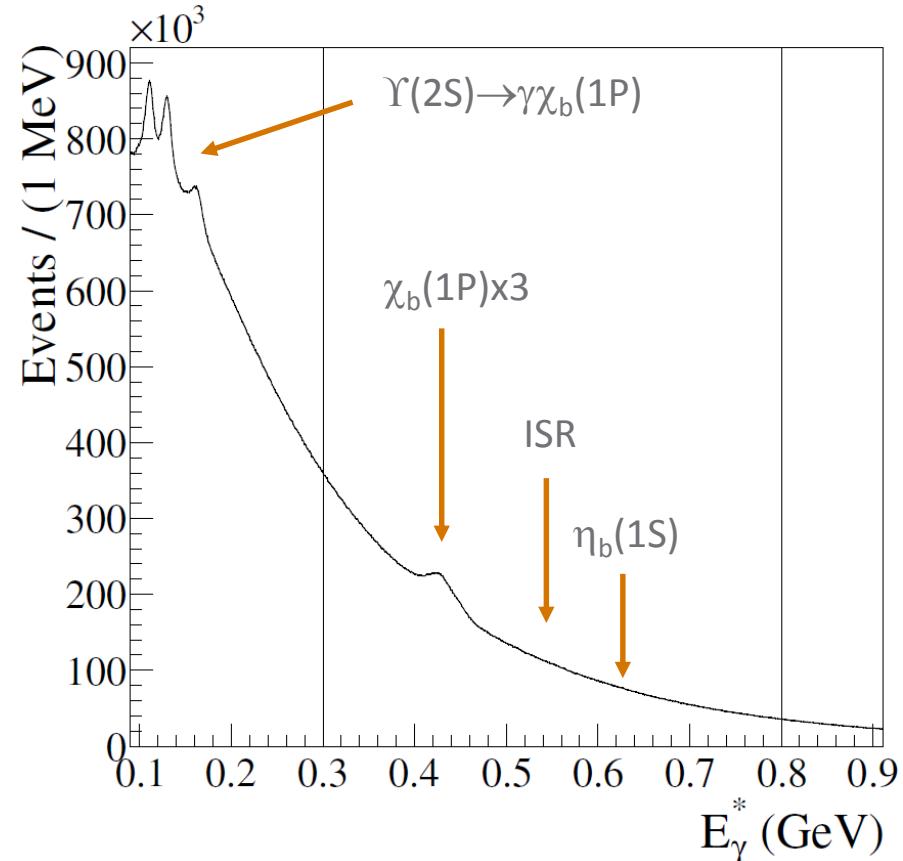
- ▶ $\eta_b(1S)$ mass
 - Past measurements inconsistent
 - Many theoretical predictions
- See e.g.: Burns, PRD 87, 034022 (2013)
- ▶ Decay rate predictions vary
 - $BR(\Upsilon(2S) \rightarrow \gamma \eta_b(1S)) = (2 - 20) \times 10^{-4}$
- ▶ BaBar analysis had $\sim 92M$ $\Upsilon(2S)$
 - Statistical significance 3.7σ
 - $B(\Upsilon(2S) \rightarrow \gamma \eta_b(1S)) = (3.9 \pm 1.5) \times 10^{-4}$
- ▶ Belle has $\sim 158M$ $\Upsilon(2S)$ (24.7 fb^{-1})
 - Should reach $>5\sigma$ significance



$\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$

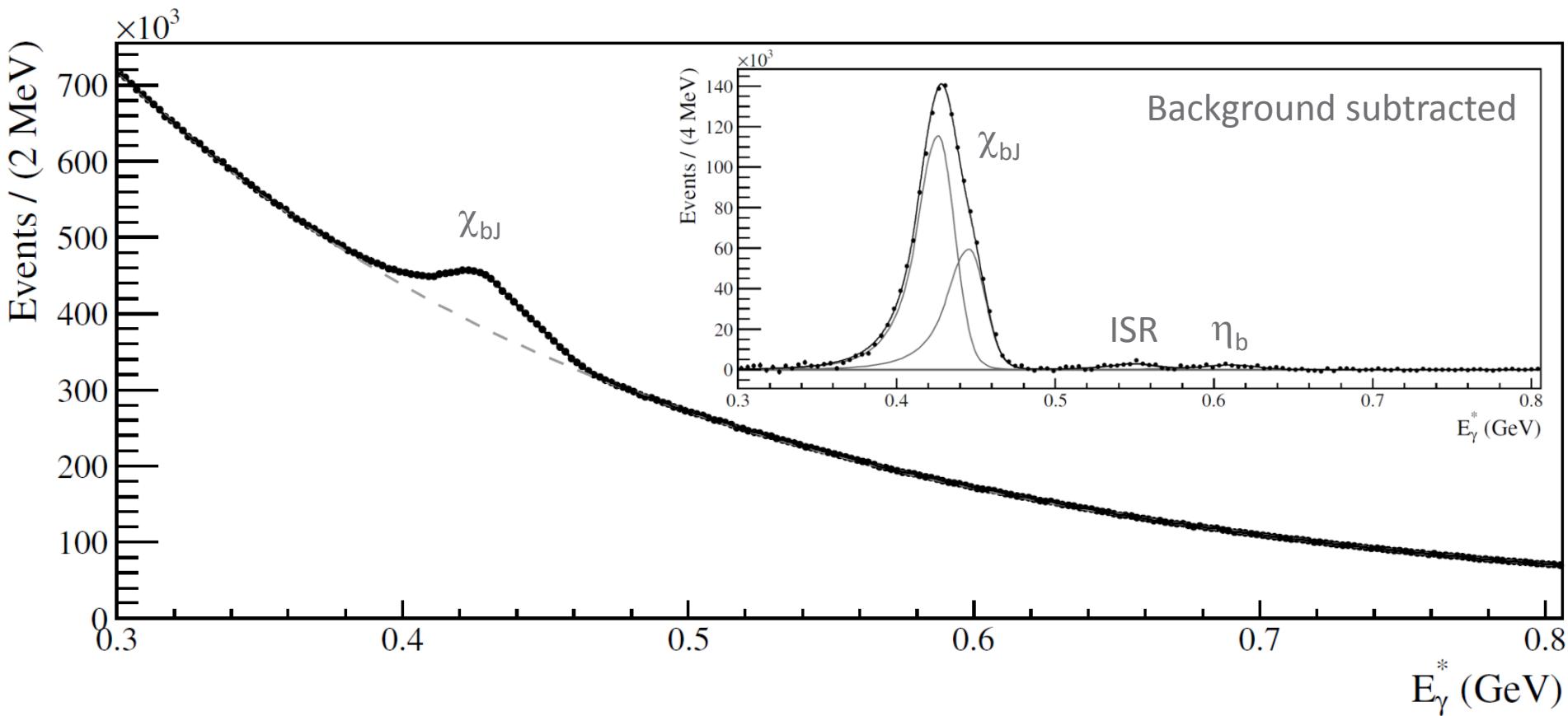
Analysis Overview

- ▶ Fit to inclusive photon spectrum
 - $\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$: ~610 MeV
 - $e^+e^- \gamma_{ISR} \rightarrow \Upsilon(1S)$: ~547 MeV
 - $\chi_{bJ}(1P) \rightarrow \gamma \Upsilon(1S)$: 391,424,442 MeV
 - Huge smooth inclusive background
- ▶ Optimized selection criteria
 - Photons in calorimeter barrel
 - $e9oe25 > 0.925$
 - Reject $|m_{\gamma\gamma} - m_{\pi^0}| < 0.15$ MeV
 - $|\cos\theta_T| < 0.9$
- ▶ Efficiency: $\varepsilon \sim 26 - 32\%$
- ▶ Lineshapes: Crystal Ball variants (signal), $\exp(\text{poly})$ (background)
- ▶ Resolution: $\sigma \sim 8 - 12$ MeV



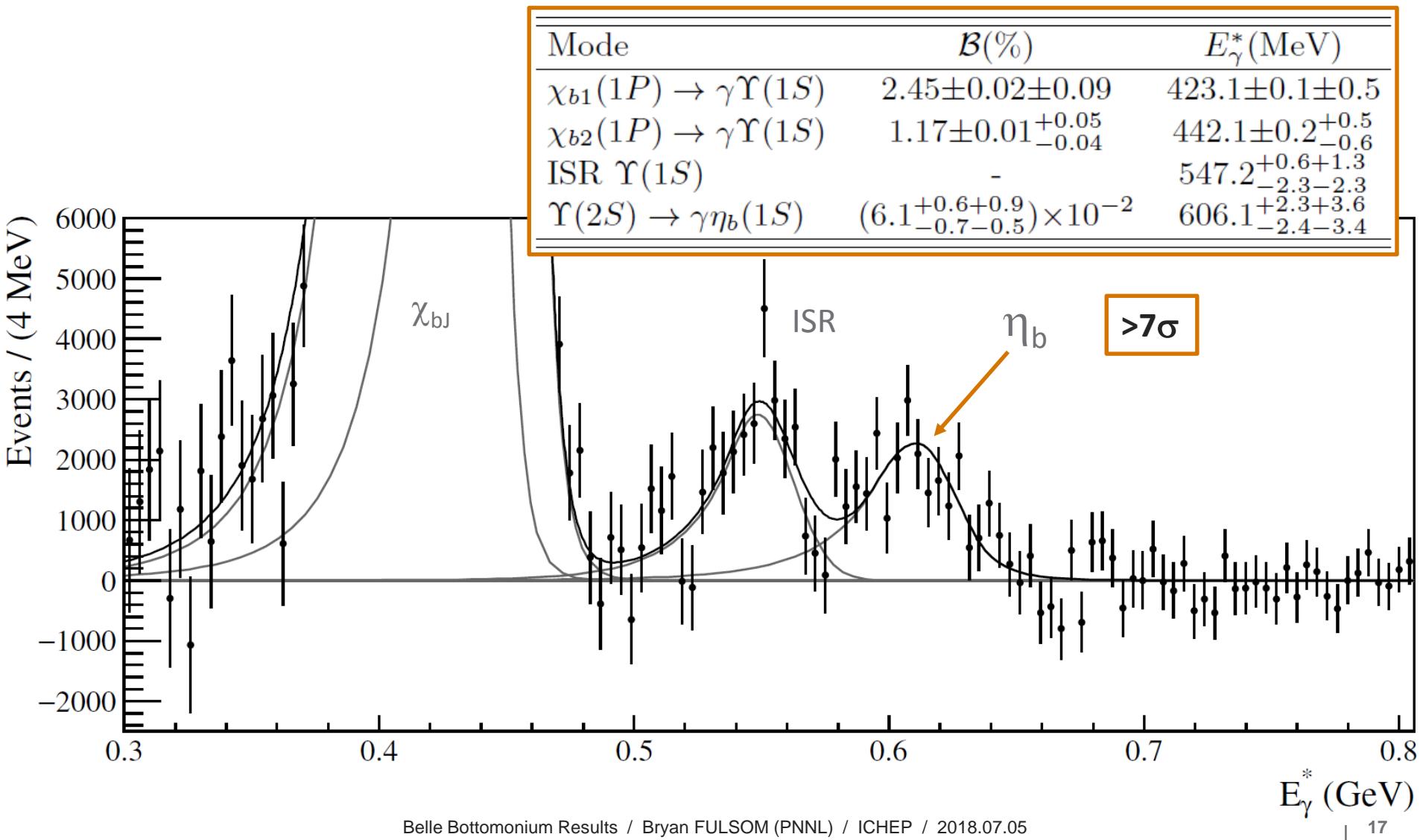
$\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$

Fit results



$\Upsilon(2S) \rightarrow \gamma\eta_b(1S)$

Fit results: signal region



$\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$

Systematic Uncertainties

| Effect | E_γ^* (MeV) | | | | Yield (%) | | | | |
|--------------------------|--------------------|-----------------|--------|--------------|-----------------|-----------------|-----------|--------------|---------|
| | $\chi_{b1}(1P)$ | $\chi_{b2}(1P)$ | ISR | $\eta_b(1S)$ | $\chi_{b1}(1P)$ | $\chi_{b2}(1P)$ | ISR | $\eta_b(1S)$ | |
| E_γ^* calibration | ± 0.5 | ± 0.5 | $+1.2$ | -2.2 | ± 2.5 | $+0.1$ | $+0.1$ | $+1.9$ | $+1.1$ |
| $\Gamma_{\eta_b(1S)}$ | ± 0.0 | ± 0.0 | $+0.2$ | -0.0 | ± 0.3 | $+0.2$ | $+0.0$ | $+1.1$ | $+9.9$ |
| Signal shape | ± 0.0 | ± 0.0 | $+0.3$ | $+2.6$ | $+0.0$ | $+0.0$ | $+0.0$ | $+1.2$ | $+10.6$ |
| Background shape | $+0.1$ | $+0.2$ | $+0.1$ | $+0.0$ | $+0.7$ | $+0.1$ | $+18.6$ | $+7.5$ | |
| | -0.0 | -0.0 | -2.0 | -2.1 | -0.1 | -0.2 | -1.7 | -2.2 | |
| Bin/range | $+0.0$ | $+0.0$ | $+0.4$ | $+0.0$ | $+0.0$ | $+2.7$ | $+1.6$ | $+0.0$ | |
| | -0.2 | -0.4 | -0.5 | -0.5 | -1.3 | -0.0 | -0.0 | -4.9 | |
| $N(\Upsilon(2S))$ | - | - | - | - | ± 2.3 | ± 2.3 | ± 2.3 | ± 2.3 | |
| γ efficiency | - | - | - | - | ± 2.8 | ± 2.8 | ± 2.8 | ± 2.8 | |
| Total | ± 0.5 | $+0.5$ | $+1.3$ | $+3.6$ | $+3.7$ | $+4.5$ | $+18.6$ | $+15.1$ | |
| | | -0.6 | -3.2 | -3.4 | -3.8 | -3.6 | -3.2 | -7.9 | |

- ▶ Energy calibration: maximum uncertainty from two methods and ISR
 - E_γ^* extrapolation from $\Upsilon(2S) \rightarrow \gamma \chi_{b0,1,2}(1P)$ and $\chi_{b1,2}(1P) \rightarrow \gamma \Upsilon(1S)$
 - E_γ control modes: $D^{*0} \rightarrow D^0(K^\pm \pi^\mp) \gamma$, $\eta \rightarrow \gamma \gamma$, $\chi_{b1,2}(1P) \rightarrow \gamma \Upsilon(1S)(\mu^+ \mu^-)$
- ▶ Lineshape:
 - Signal lineshape from theoretical M1 transition predictions
 - Description of background composition

$\Upsilon(2S) \rightarrow \gamma \eta_b(1S)$

Summary of Results

► Branching Fractions / Yields

- χ_b match CLEO/BaBar measurements
- ISR consistent with theory

CLEO, PRD 83, 054003 (2011)

BaBar, PRD 84, 072002 (2011), PRD 90, 112010 (2014)

Benayoun et al., MPLA 14, 2605 (1999)

$$\mathcal{B}(\Upsilon(2S) \rightarrow \gamma \eta_b(1S)) = (6.1^{+0.6+0.9}_{-0.7-0.5}) \times 10^{-4}$$

- η_b branching fraction corresponds with lattice

Hughes et al., PRD 92, 094501 (2015)

► All mass results (χ_b , ISR, η_b) consistent with PDG (9399.0 ± 2.3 MeV)

$$m_{\eta_b(1S)} = 9394.8^{+2.7+4.5}_{-3.1-2.7} \text{ MeV}/c^2$$

- Consistent with h_b (1.2σ) and Υ (0.7σ) results
- Width not inconsistent with predictions



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CONCLUSIONS

Conclusions



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- ▶ Belle continues to make important contributions to the study of the bottomonium system
- ▶ Hadronic transitions
 - First observation of $\Upsilon(4S) \rightarrow \eta'\Upsilon(1S)$ arXiv:1803.10303
- ▶ Radiative transitions
 - First observation of $\Upsilon(2S) \rightarrow \gamma\eta_b(1S)$ arXiv:1807.01201
- ▶ Stay tuned for results as the high-statistics Belle II experiment begins!