# Bottomonium Transitions at Belle

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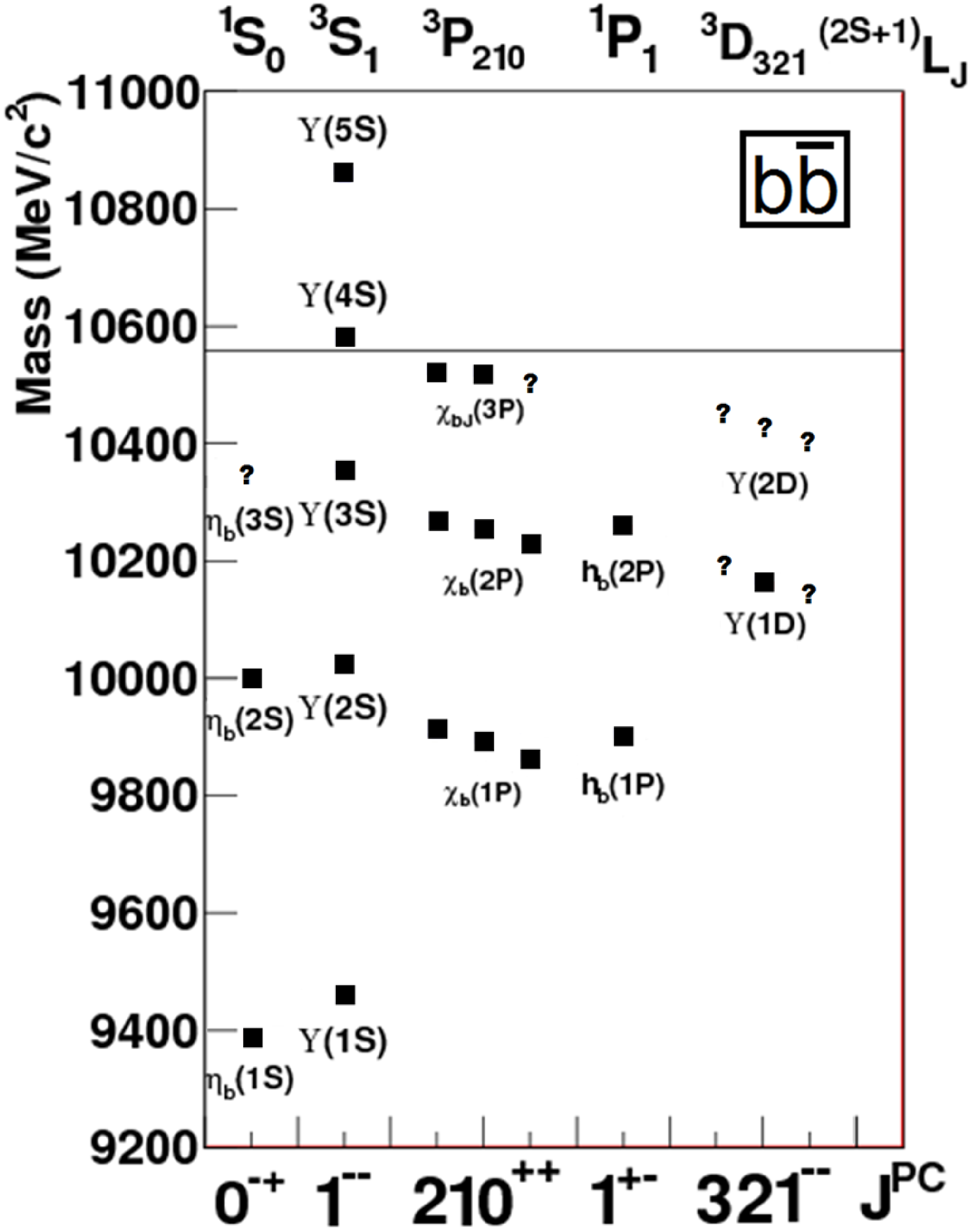
# Overview

- $\eta$ hadronic transitions
  - Observed with enhanced rates
  - Spectroscopic search for states
- Measurement of $\eta'$ transitions
  - $\eta$ observed, no past results for $\eta'$
  - 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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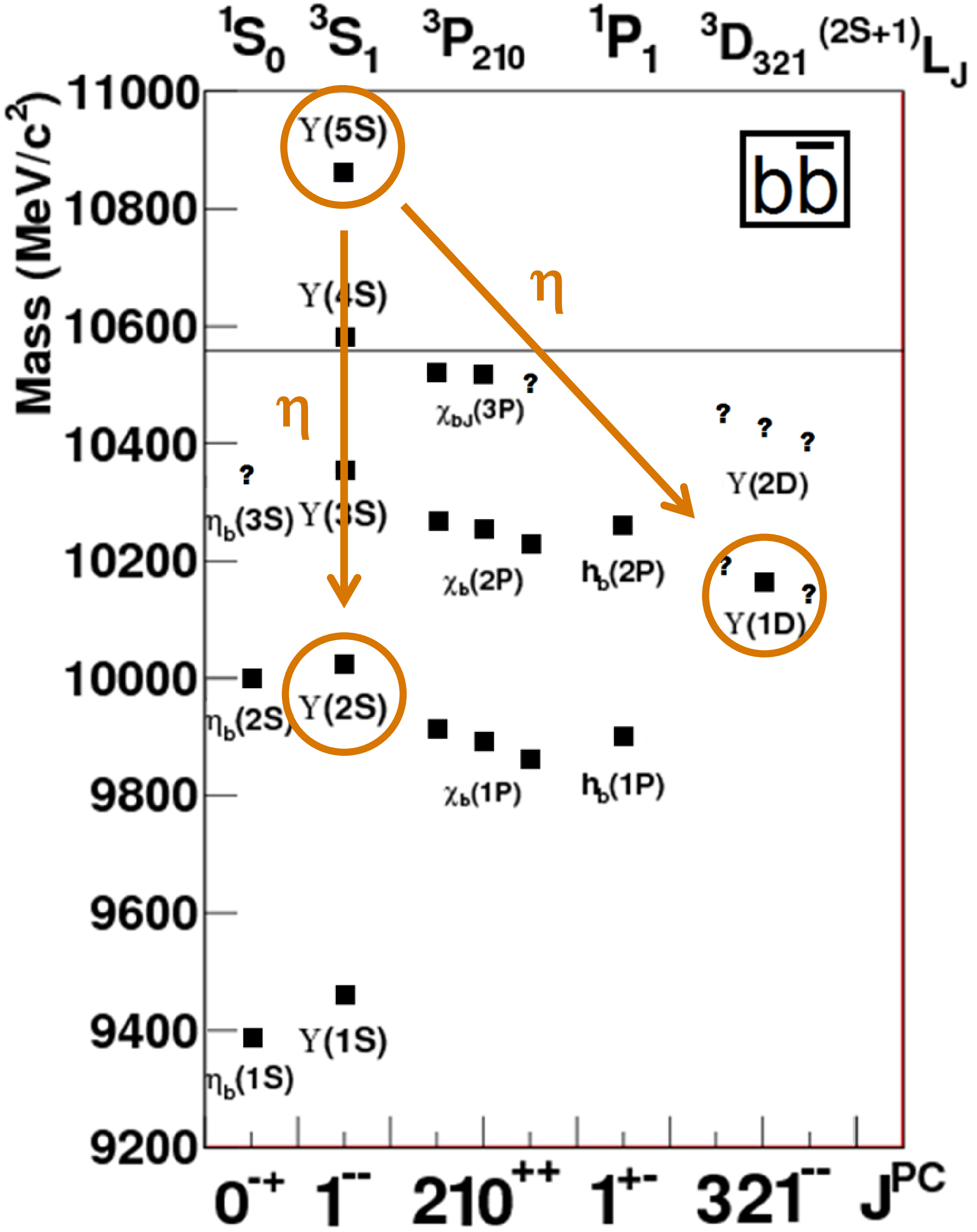

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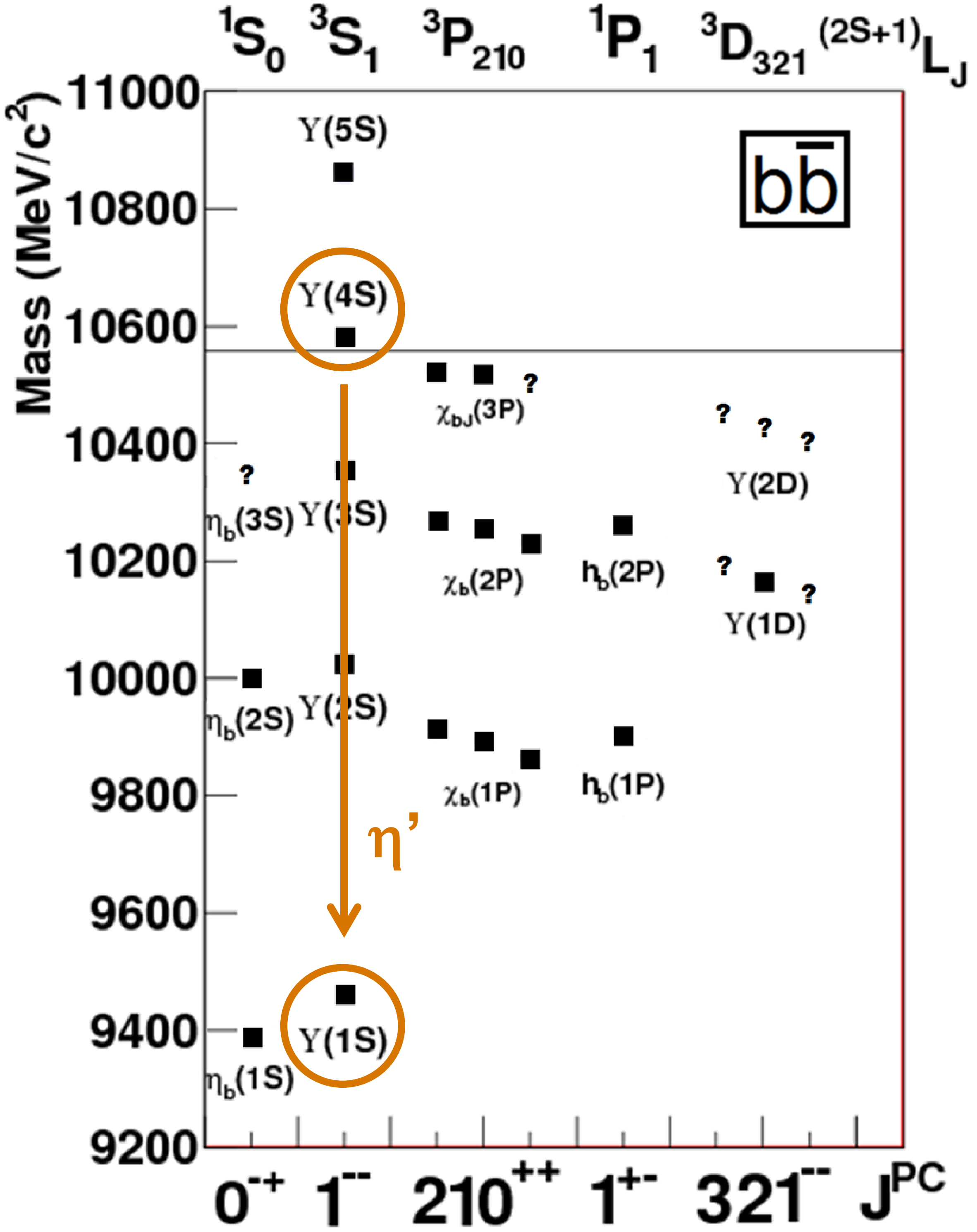

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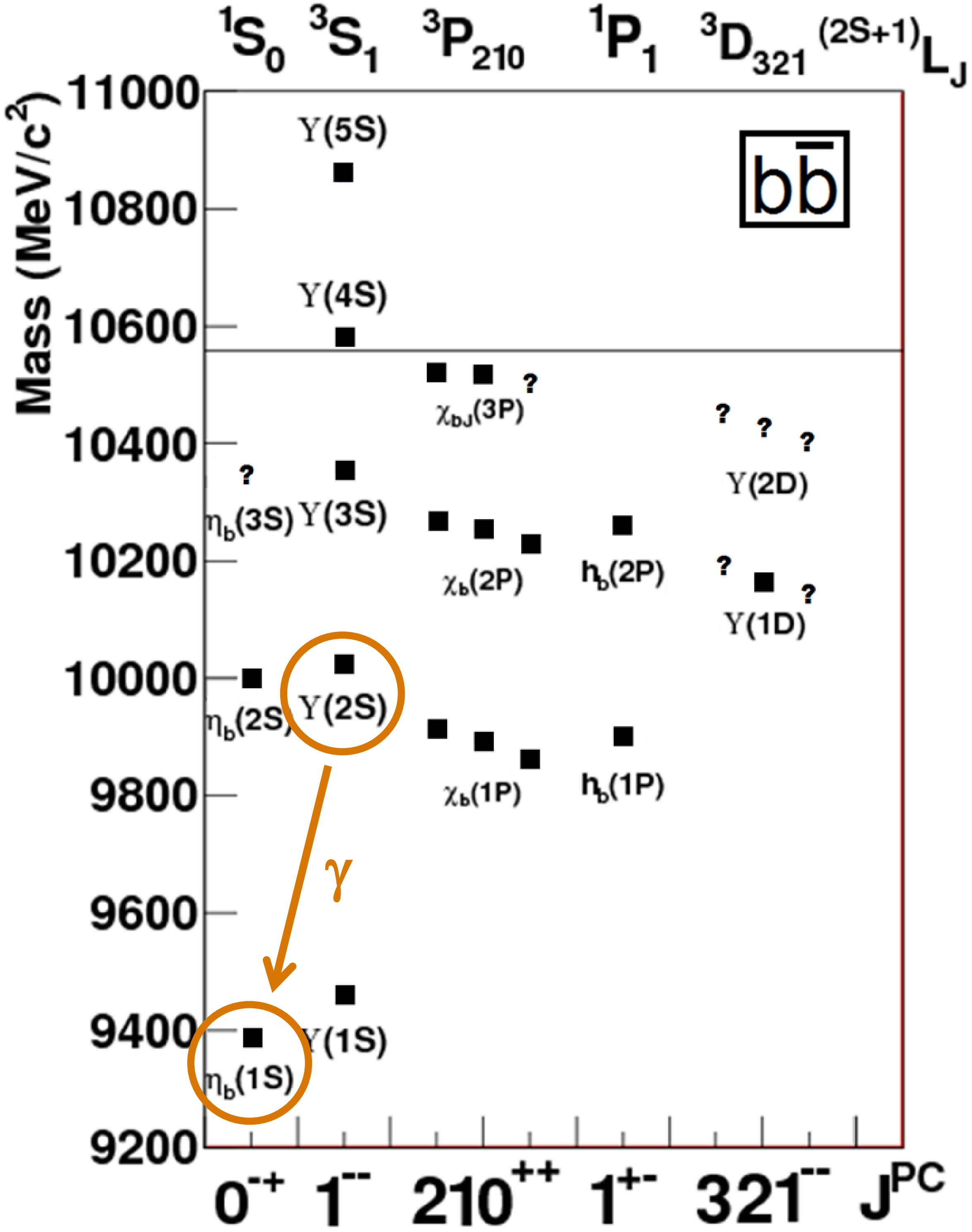
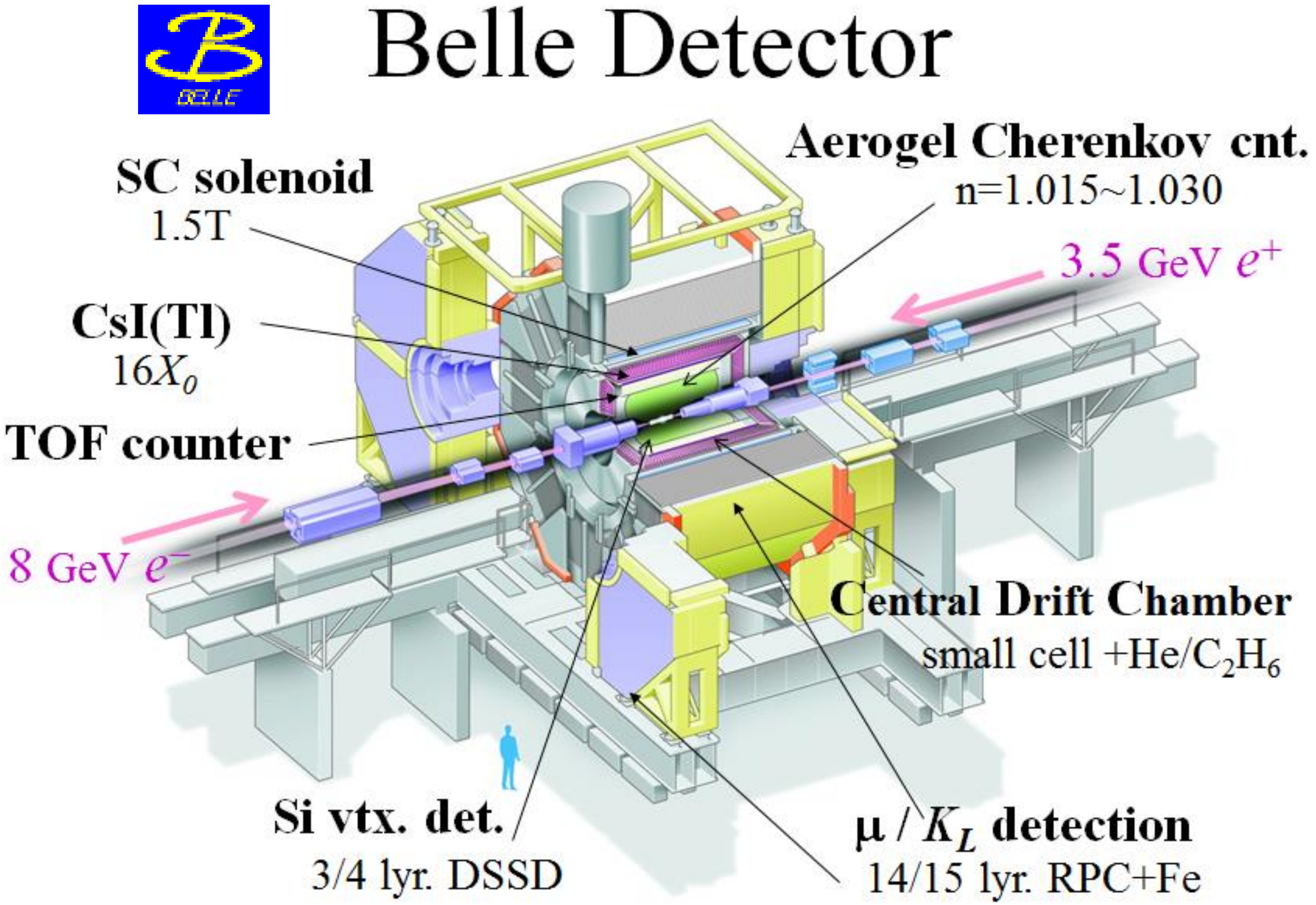


# The Belle Experiment

- Vital statistics
  - KEK, Tsukuba, Japan
  - Operated 1999-2010
  - ~1 $ab^{-1}$ collected
  - ~500 members, 21 countries
  - >500 publications




- Many contributions to $q\bar{q}$ study
  - Charmonium states (Vinokurova)
  - Energy scan results (Mizuk)
  - Bottomonium decays (Yin)

- Now upgraded to Belle II, at the next generation B-Factory

# $\Upsilon(5S) \to \eta\, b\bar{b}$

EPJC 78, 633 (2018)

# $\Upsilon(5S)\to\eta b\bar{b}$: Analysis Motivation

- Decays
  - Heavy Quark Spin Symmetry expected to be reliable
  - QCD Multipole Expansion predicts dominance of $\pi\pi$ transitions over $\eta$

$$\mathcal{R}^{\eta S}_{\pi\pi S}(n,m) = \frac{\mathcal{B}[\Upsilon(nS)\to\eta\Upsilon(mS)]}{\mathcal{B}[\Upsilon(nS)\to\pi^+\pi^-\Upsilon(mS)]} \approx 10^{-3}$$

**Kuang, FPC 1, 19 (2006)**
**Voloshin, PPNP 61, 455 (2008)**

  - Confirmed for $\Upsilon(2S)$ and $\Upsilon(3S)$
  - Violated in $\Upsilon(4S)\to\eta h_b(1P)$ and $\Upsilon(5S)\to\pi\pi\ h_b(nP)$

**Belle, PRL 115, 142001 (2015)**

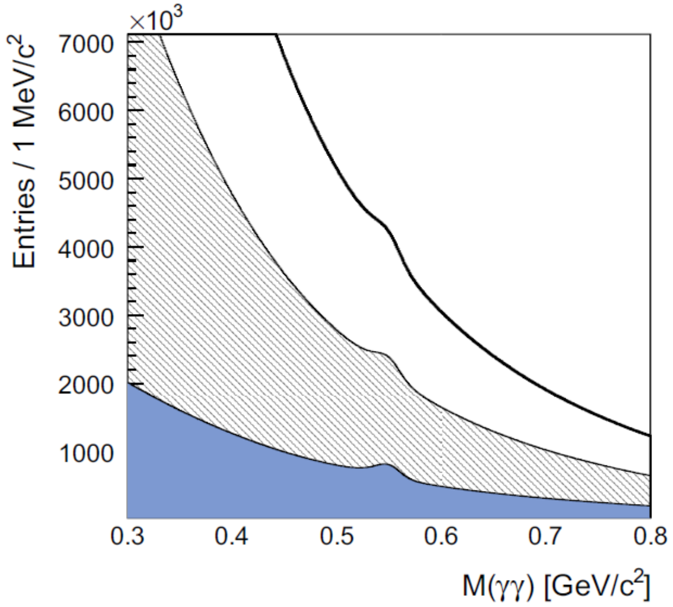
- Spectroscopy
  - $\Upsilon(1D)$ triplet: only J=2 has been observed
  - Enhanced $\eta$ transitions could be a pathway to discovery

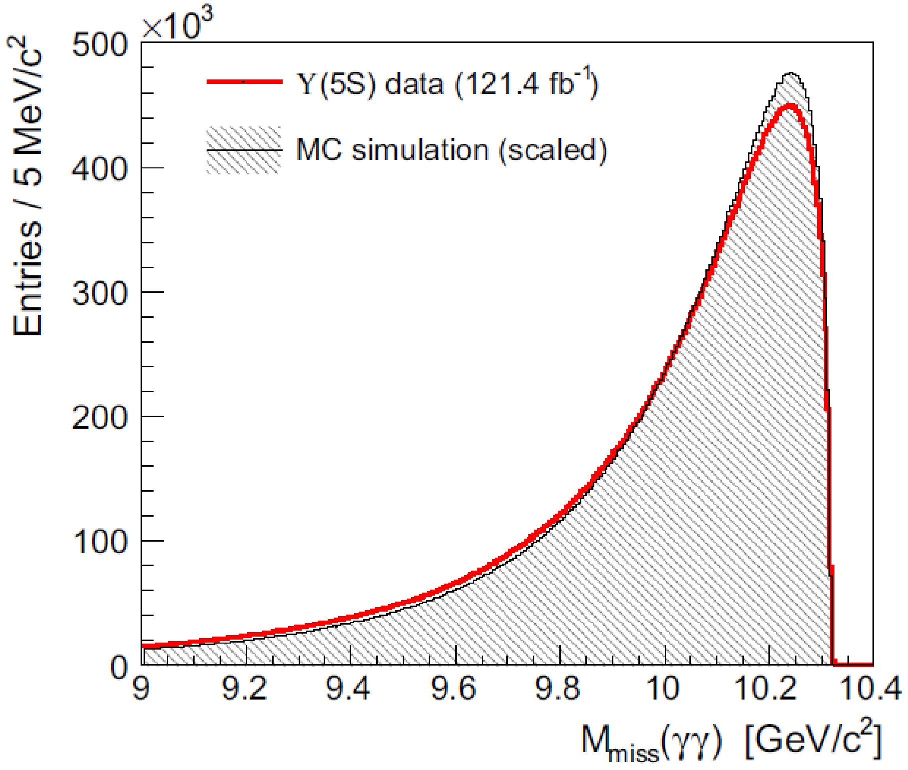
# $\Upsilon(5S) \to \eta b\bar{b}$: Analysis Overview

- Dataset: 121.4 $fb^{-1}$ = 36M $\Upsilon(5S)$
- Reconstruct $\eta \to \gamma\gamma$
  - $E_\gamma > 75 / 50 / 60$ MeV (bkd/bar/fwd)
  - $E_9/E_{25} > 0.9$
  - Veto $\pi^0$ within $m(\pi^0) \pm 17$ MeV
  - Photon helicity angle $\cos\theta < 0.94$
- Remove continuum background: $R_2 < 0.3$
- Fit $\eta$ missing mass spectrum

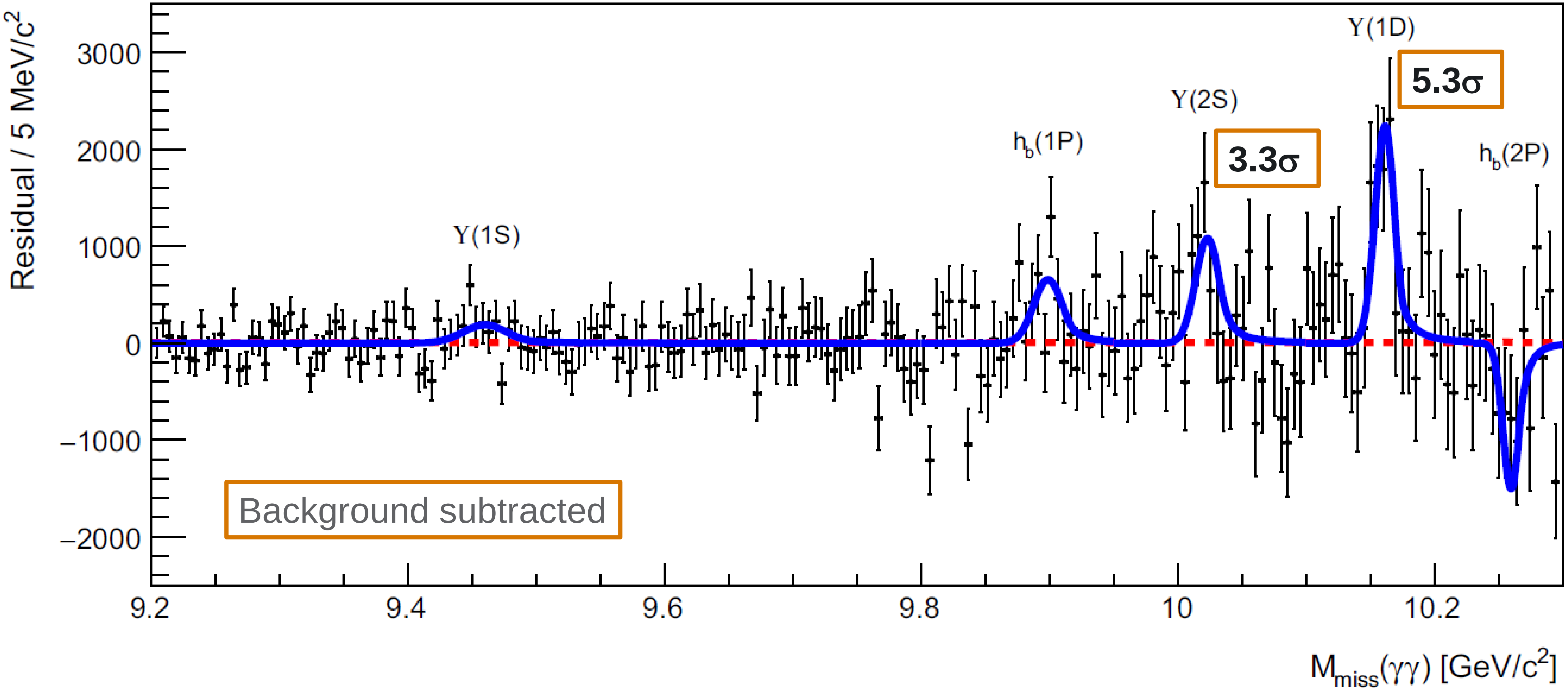
$$M_{\rm miss}(\eta) = \sqrt{(P_{e^+e^-} - P_\eta)^2}$$

- Signal peaks: Crystal Ball functions ($\sigma$ ~6-14 MeV)
- Background: ARGUS + $7^{th}$ order polynomial



# $\Upsilon(5S)\to\eta b\bar{b}$: Data Fit



# $\Upsilon(5S)\to\eta b\bar{b}$: Fit Results

- Observe $\Upsilon(5S) \to \eta\ \Upsilon(1D)$

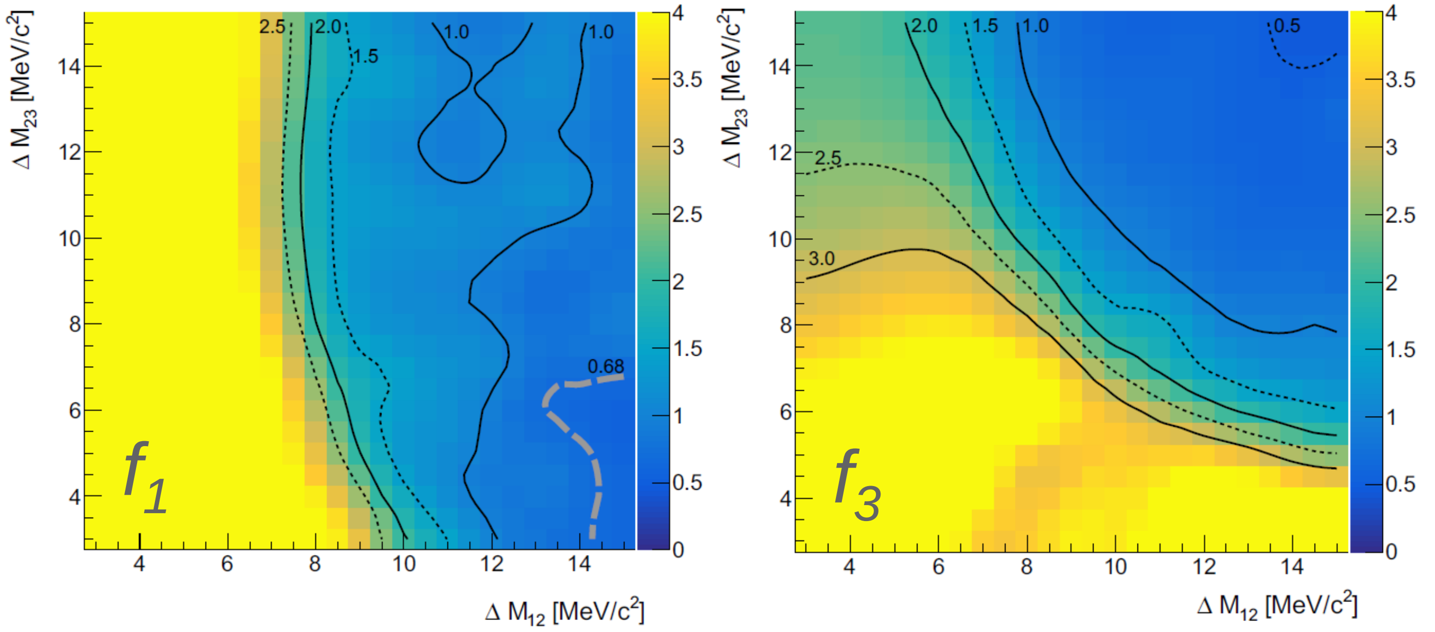
$$\mathcal{B}[\Upsilon(5S) \to \eta \Upsilon_J(1D)] = (4.82 \pm 0.92 \pm 0.67) \times 10^{-3}$$

- Evidence for $\Upsilon(5S) \to \eta\ \Upsilon(2S)$
- Measure/set limits on $\sigma_B$

| Process | $\Sigma$ | $N_{\rm meas}[10^3]$ | $\epsilon$ (%) | $\sigma_B$ (pb) |
|---|---|---|---|---|
| $e^+e^- \to \eta\Upsilon(1S)$ | $1.5\sigma$ | $1.7 \pm 1.0$ | 20.1 | $< 0.49$ |
| $e^+e^- \to \eta h_b(1P)$ | $2.7\sigma$ | $3.9 \pm 1.5$ | 22.2 | $< 0.76$ |
| $e^+e^- \to \eta\Upsilon(2S)$ | $3.3\sigma$ | $5.6 \pm 1.6$ | 16.5 | $1.02 \pm 0.30 \pm 0.17$ |
| $e^+e^- \to \eta\Upsilon(1D)$ | $5.3\sigma$ | $9.3 \pm 1.8$ | 17.2 | $1.64 \pm 0.31 \pm 0.21$ |
| $e^+e^- \to \eta h_b(2P)$ | – | $-5.2 \pm 3.6$ | 16.7 | $< 0.64$ |

- Attempt to understand $\Upsilon(1D)$ triplet
  - Fit dominated by J=2 assumption
  - Limit scan over mass splitting range

| Fraction | Fitted value |
|---|---|
| $f_1$ | $0.23 \pm 1.42$ |
| $f_3$ | $-0.31 \pm 0.53$ |



# $\Upsilon(5S)\to\eta b\bar{b}$: Systematic Uncertainties

| Source | $\sigma_B[\eta\Upsilon(1S)]$ | $\sigma_B[\eta\Upsilon(2S)]$ | $\sigma_B[\eta\Upsilon_J(1D)]$ | $\sigma_B[\eta h_b(1P)]$ | $\sigma_B[\eta h_b(2P)]$ |
|---|---|---|---|---|---|
| Luminosity | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 |
| Reconstruction efficiency | 6.6 | 6.6 | 6.6 | 6.6 | 6.6 |
| $\gamma$ energy calibration | 1.5 | 2.3 | 2.8 | 2.1 | 2.2 |
| Background fit | 4.0 | 15 | 7.1 | 4.6 | 8.7 |
| Signal model | 3.2 | 2.5 | 8.2 | 2.5 | 5.5 |
| Radiative correction | 0.6 | 0.6 | 0.6 | 0.6 | 0.8 |
| $\mathcal{B}[\eta\to\gamma\gamma]$ | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Total | 8.6 | 16.8 | 13.1 | 8.8 | 12.5 |

- Dominant uncertainty from background shape model
  - Change polynomial order (5-9), fit ranges, bin width
  - Varied background model and attempted sideband fits to ensure robustness of result
- Secondary contribution: $\gamma$ reconstruction efficiency

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

PRL 121, 062001 (2018)

# $\Upsilon(4S) \to \eta'\Upsilon(1S)$: Analysis Potential

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

**BaBar, PRD 78, 112002 (2008)**
**Belle, PRD 96, 052005 (2017)**

- Input from charm sector
  - Null searches for $\psi(4160)/Y(4260) \to \eta' J/\psi$ by CLEO

**CLEO, PRL 96, 162003 (2006)**

  - Observation of e+e- $\to \eta' J/\psi$ (4.226/4.258 GeV) by BESIII

**BESIII, PRD 94, 032009 (2016)**

  - Theory prediction: $BR(\psi(4160) \to \eta' J/\psi)$ ~ 6% x $BR(\psi(4160) \to \eta J/\psi)$

**Chen et al., PRD 87, 054006 (2013)**

  - By analogy: $BR(\Upsilon(4S) \to \eta\Upsilon(1S)) \sim 2 \times 10^{-4}$, $BR(\Upsilon(4S) \to \eta'\Upsilon(1S)) \sim O(10^{-5})$

# $\Upsilon(4S)\to\eta'\Upsilon(1S)$: Analysis Overview

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

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

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

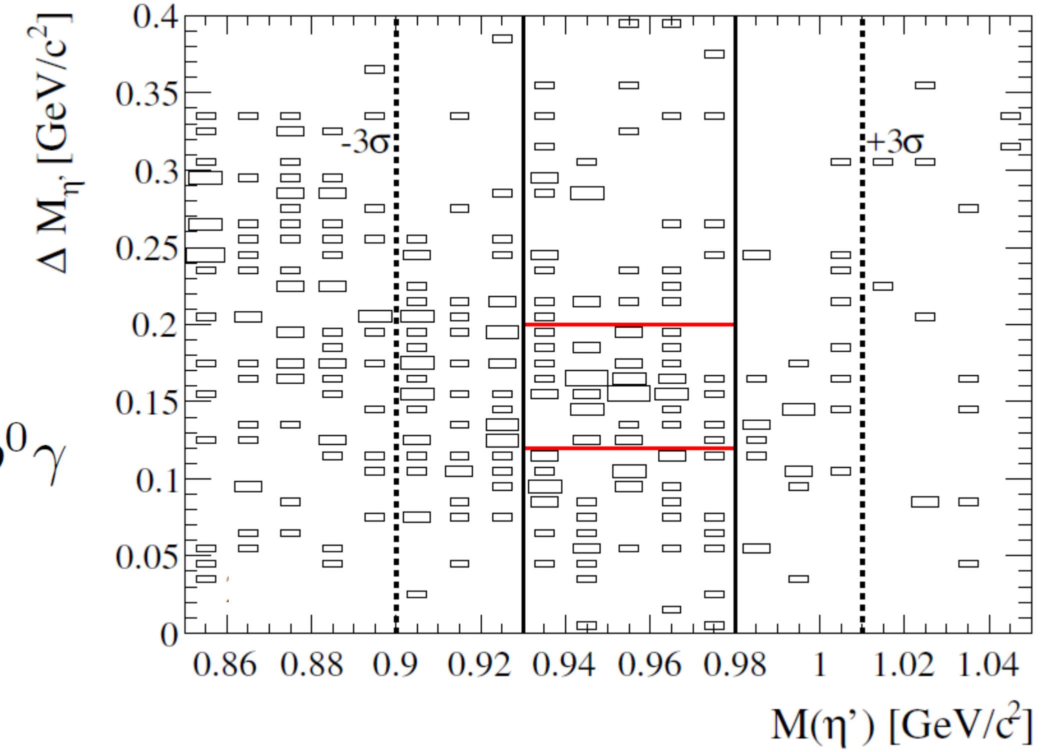
- Kinematic Bound: remove continuum

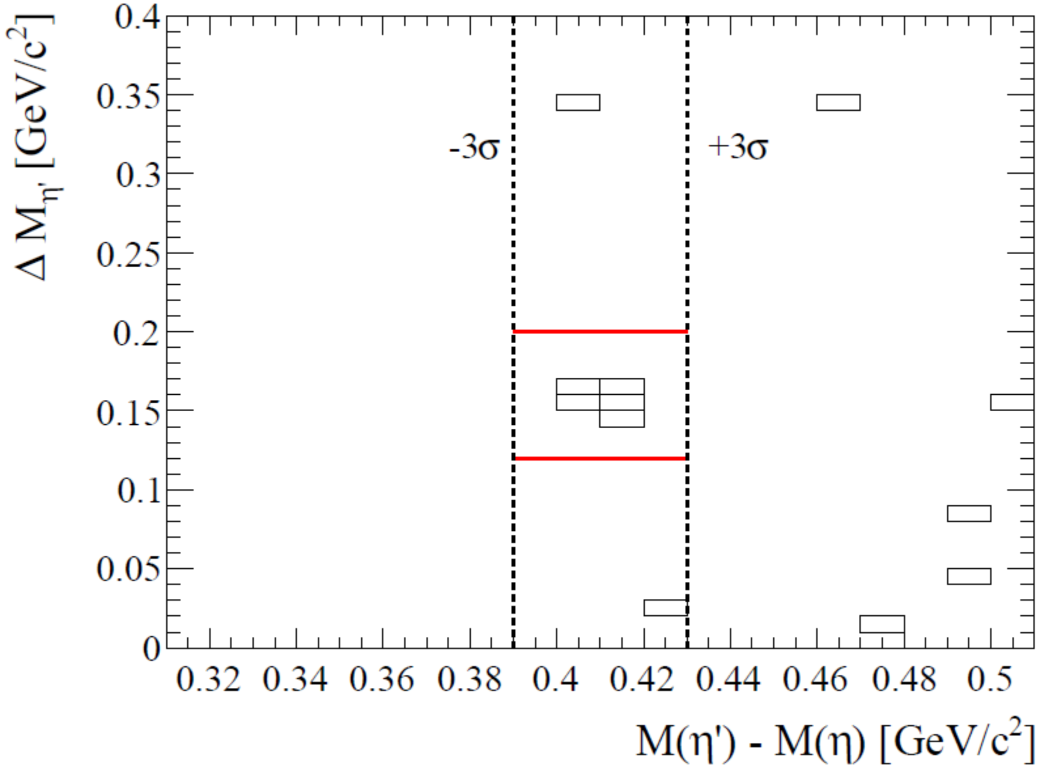
$$\mathrm{KB} = p(\mu^+\mu^-)_{CM} - \frac{1}{2}\frac{(s - m(\mu^+\mu^-)^2)}{\sqrt{s}}$$

- BDT: remove ISR and extra $\gamma$
  - Use $\Delta M_{\pi\pi}$=M(μμππ)-M(μμ) and M(μμππγ)

# $\Upsilon(4S)\to\eta'\Upsilon(1S)$: Application of Selection Criteria

$\eta' \to \rho^0\gamma$

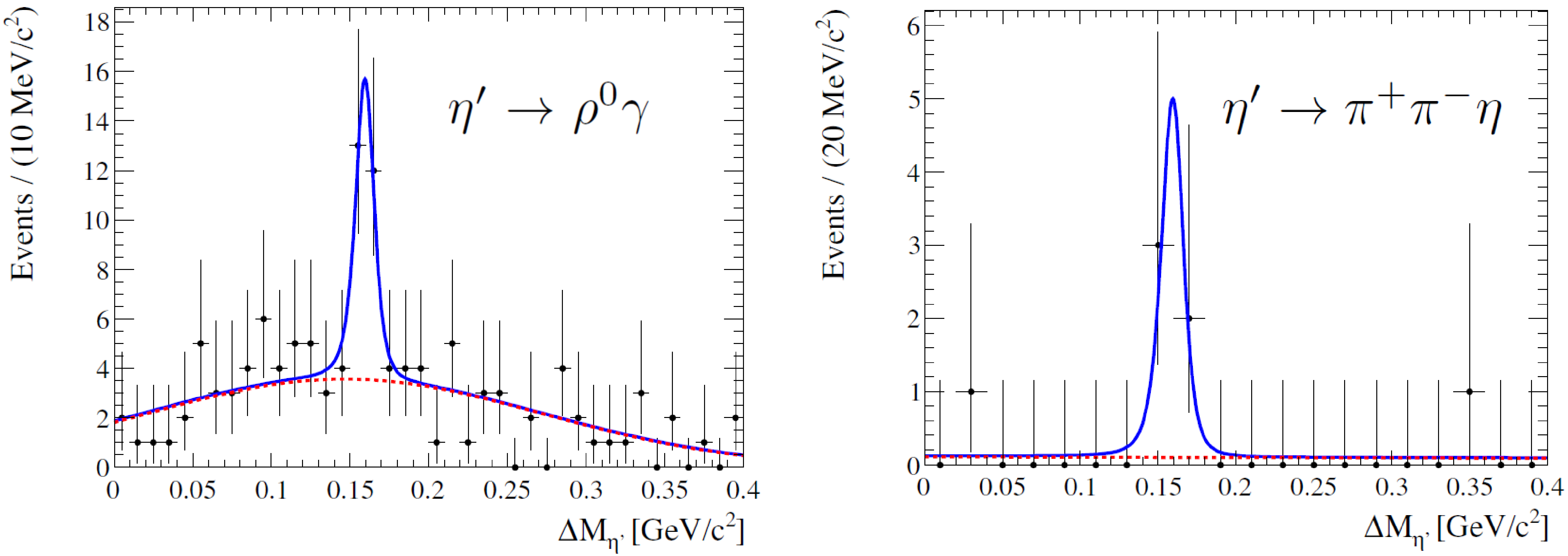



$\eta' \to \pi^+\pi^-\eta$

- Main fit variable: $\Delta M_{\eta'} = M(\Upsilon(4S)) - M(\Upsilon(1S)) - M(\eta')$
- Signal fit function: $\mathcal{F}(x) = \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2_{\mathrm{L,R}} + \alpha_{\mathrm{L,R}}(x-\mu)^2}\right\}$
- Backgrounds: Gaussian ($\rho^0\gamma$), linear ($\pi^+\pi^-\eta$)

# $\Upsilon(4S)\to\eta'\Upsilon(1S)$: Fit Results




$$N_{\rm sig} = 22 \pm 7 \quad (4.2\sigma)$$
$$N_{\rm bkg} = 96 \pm 11$$

$$N_{\rm sig} = 5.0 \pm 2.3 \quad (4.1\sigma)$$
$$N_{\rm bkg} = 2.0 \pm 1.6$$

# $\Upsilon(4S) \rightarrow \eta' \Upsilon(1S)$: Systematic Uncertainties

| Source | $\eta' \rightarrow \rho\gamma$ | $\eta' \rightarrow \eta\pi^+\pi^-$, $\eta \rightarrow \gamma\gamma$ |
|---|---|---|
| $\Upsilon(4S)$ | $\pm1.4$ | $\pm1.4$ |
| Tracking | $\pm1.4$ | $\pm1.4$ |
| $\mu$-id | $\pm1.1$ | $\pm1.1$ |
| BRs from PDG | $\pm2.7$ | $\pm2.6$ |
| $\eta' \rightarrow \rho\gamma$ model | $-1.9$ | - |
| Fit procedure | $\pm6.8$ | $\pm2.0$ |
| Total on $\mathcal{B}$ | $\pm7.6$ | $\pm3.5$ |

- 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

$$\mathcal{B} = \frac{N_{\text{sig}}}{\epsilon \times N_{\Upsilon(4S)} \times \mathcal{B}_{\text{secondary}}} \qquad R_{\eta'/h} = \frac{\mathcal{B}(\Upsilon(4S) \to \eta'\Upsilon(1S))}{\mathcal{B}(\Upsilon(4S) \to h\Upsilon(1S))}$$

- Branching fraction results
  - $\pi^+\pi^-\eta$ = $(3.19\pm0.96\pm0.24) \times 10^{-5}$
  - $\rho^0\gamma$ = $(4.53\pm2.12\pm0.16) \times 10^{-5}$
  - Combined = $(3.43\pm0.88\pm0.21) \times 10^{-5}$

**Combined significance = 5.7$\sigma$**
**First observation of this decay!**

- Ratio of branching fractions
  - $R_{\eta'/\eta}$ = $0.20\pm0.06$
  - $R_{\eta'/\pi\pi}$ = $0.42\pm0.11$
  - Indicative of light quark contributions?

**Voloshin, MPLA 26, 773 (2011)**

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

PRL 121, 232001 (2018)

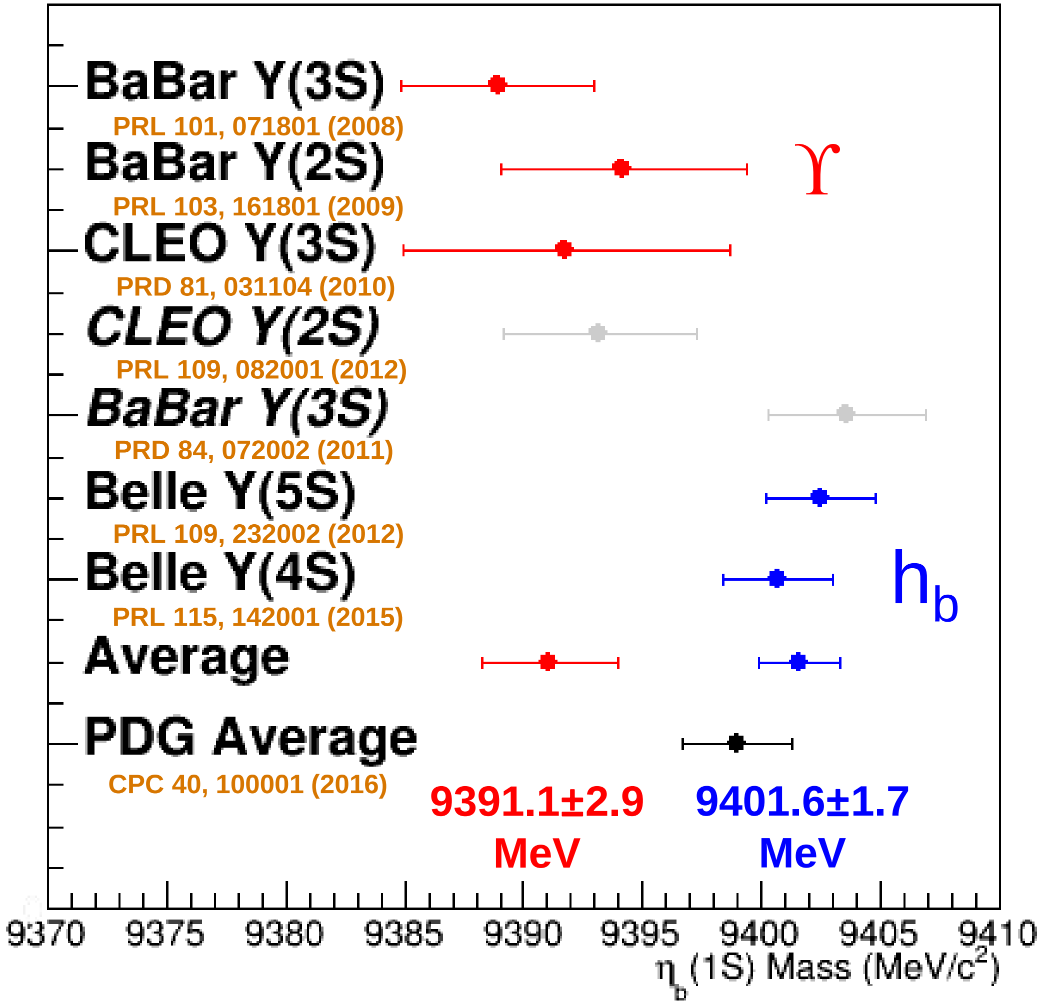
# $\Upsilon(2S)\to\gamma\eta_b(1S)$: Analysis potential

- $\eta_b(1S)$ mass
  - Past measurements inconsistent
  - Many theoretical predictions

**See e.g.: Burns, PRD 87, 034022 (2013)**

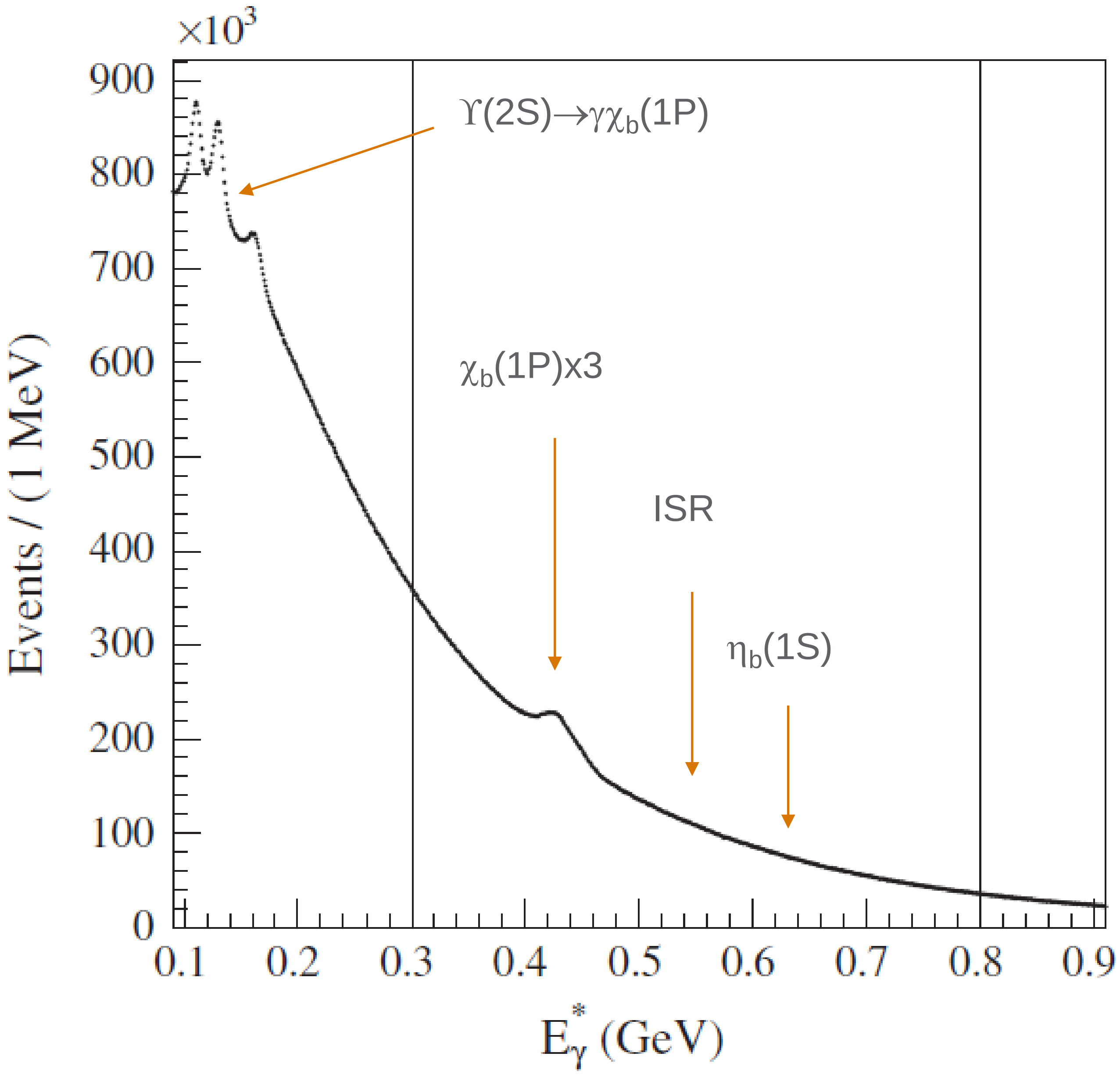
- Decay rate predictions vary
  - $BR(\Upsilon(2S)\to\gamma\eta_b(1S)) = (2 – 20) \times 10^{-4}$
- BaBar analysis had ~92M $\Upsilon(2S)$
  - Statistical significance 3.7$\sigma$
  - $B(\Upsilon(2S)\to\gamma\ \eta_b(1S)) = (3.9\pm1.5) \times 10^{-4}$
- Belle has ~158M $\Upsilon(2S)$ (24.7 $fb^{-1}$)
  - Should reach >5$\sigma$ significance

$\eta_b(1S)$ Mass

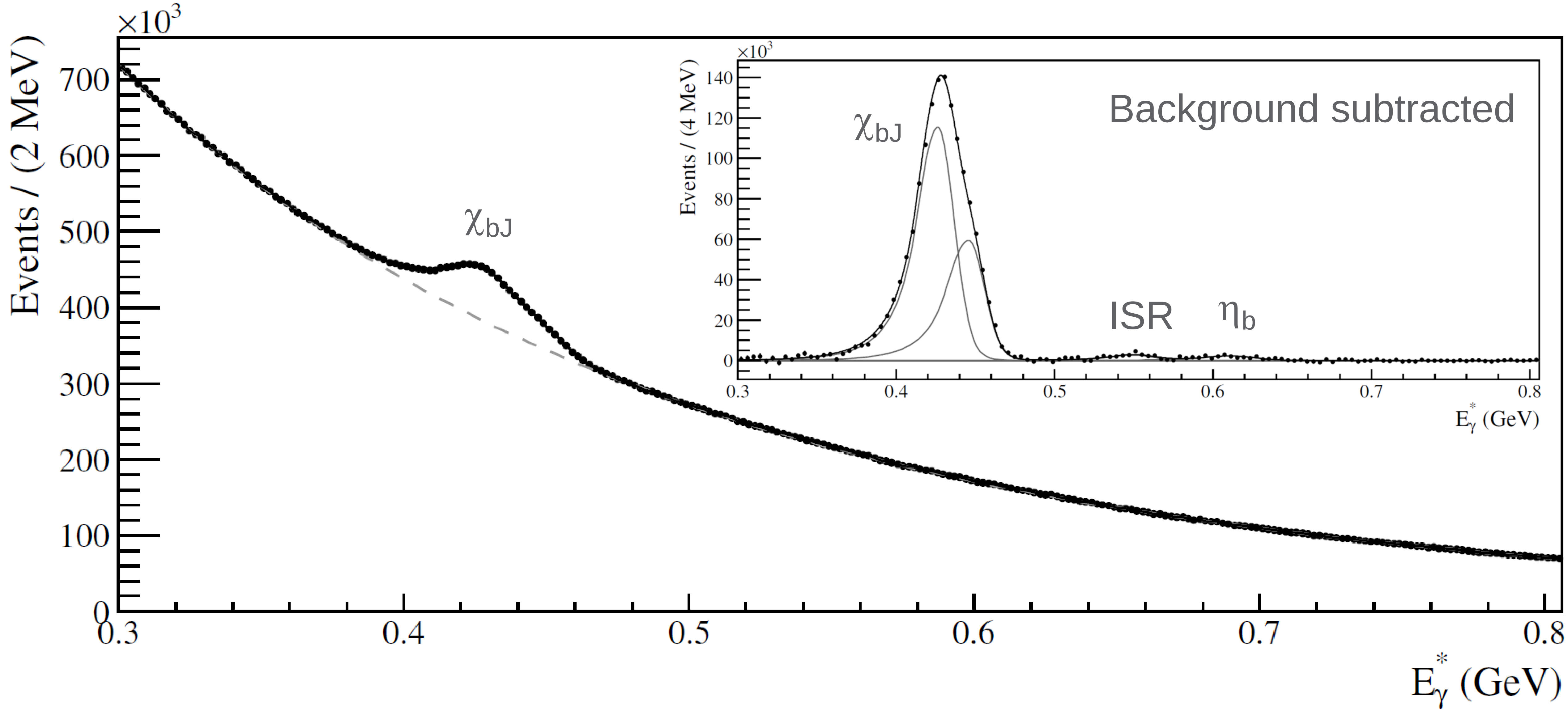


# $\Upsilon(2S) \to \gamma\eta_b(1S)$: Analysis Overview

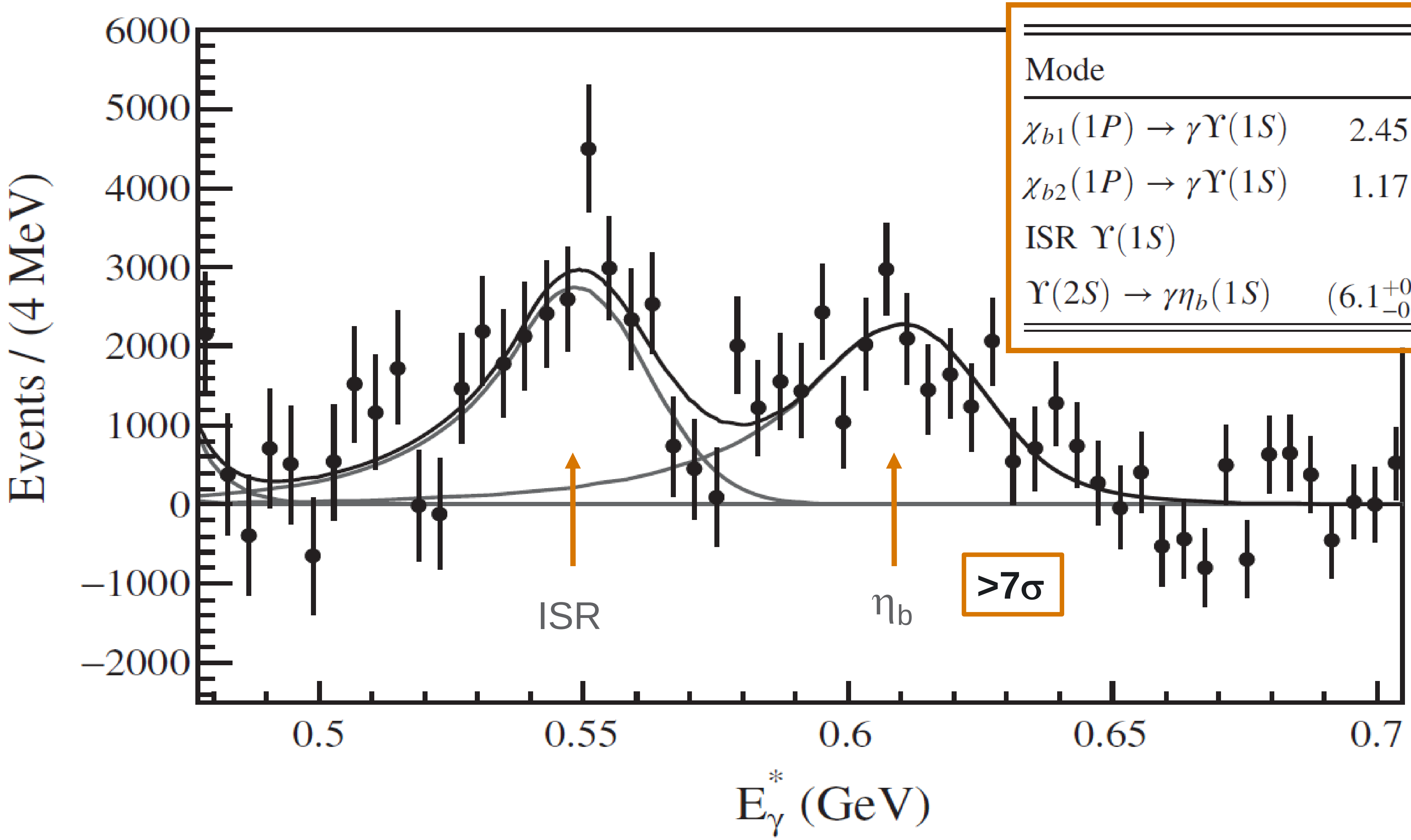
- Fit to inclusive photon spectrum
  - $\Upsilon(2S) \to \gamma\ \eta_b(1S)$ : ~610 MeV
  - $e^+e^-\ \gamma_{ISR} \to \Upsilon(1S)$ : ~547 MeV
  - $\chi_{bJ}(1P) \to \gamma\ \Upsilon(1S)$ : 391,424,442 MeV
  - Huge smooth inclusive background
- Optimized selection criteria
  - Photons in calorimeter barrel
  - e9oe25 > 0.925
  - Reject $|m_{\gamma\gamma}-m_{\pi 0}|$ < 15 MeV
  - $|\cos\theta_T|$ < 0.9
- Efficiency: $\varepsilon$ ~ 26 – 32 %
- Lineshapes:
  - Crystal Ball variants (signal)
  - exp(poly) (background)
- Resolution: $\sigma$ ~8 – 12 MeV



# $\Upsilon(2S) \rightarrow \gamma\eta_b(1S)$: Fit results



# $\Upsilon(2S) \to \gamma\eta_b(1S)$: Fit results in signal region




| Mode | $\mathcal{B}$ (%) | $E^*_\gamma$ (MeV) |
|---|---|---|
| $\chi_{b1}(1P) \to \gamma\Upsilon(1S)$ | $2.45 \pm 0.02^{+0.11}_{-0.15}$ | $423.1 \pm 0.1 \pm 0.5$ |
| $\chi_{b2}(1P) \to \gamma\Upsilon(1S)$ | $1.17 \pm 0.01^{+0.06}_{-0.07}$ | $442.1 \pm 0.2^{+0.5}_{-0.6}$ |
| ISR $\Upsilon(1S)$ | $\cdots$ | $547.2^{+0.6+1.3}_{-2.3-3.2}$ |
| $\Upsilon(2S) \to \gamma\eta_b(1S)$ | $(6.1^{+0.6+0.9}_{-0.7-0.6}) \times 10^{-2}$ | $606.1^{+2.3+3.6}_{-2.4-3.4}$ |

# $\Upsilon(2S) \to \gamma\eta_b(1S)$: Systematic Uncertainties

| | $E_\gamma^*$ (MeV) | | | | Branching fraction (%) | | | |
|---|---|---|---|---|---|---|---|---|
| Effect | $\chi_{b1}(1P)$ | $\chi_{b2}(1P)$ | ISR | $\eta_b(1S)$ | $\chi_{b1}(1P)$ | $\chi_{b2}(1P)$ | ISR | $\eta_b(1S)$ |
| $E_\gamma^*$ calibration | $\pm 0.5$ | $\pm 0.5$ | $^{+1.2}_{-2.2}$ | $\pm 2.5$ | $^{+0.1}_{-0.0}$ | $^{+0.1}_{-0.0}$ | $^{+1.9}_{-0.0}$ | $^{+1.1}_{-0.0}$ |
| $\Gamma_{\eta_b(1S)}$ | $\pm 0.0$ | $\pm 0.0$ | $^{+0.2}_{-0.0}$ | $\pm 0.3$ | $^{+0.2}_{-0.1}$ | $^{+0.0}_{-0.2}$ | $^{+1.1}_{-0.0}$ | $^{+9.9}_{-4.5}$ |
| Signal shape | $\pm 0.0$ | $\pm 0.0$ | $^{+0.3}_{-0.4}$ | $^{+2.6}_{-1.0}$ | $^{+0.0}_{-0.1}$ | $^{+0.0}_{-0.1}$ | $^{+1.2}_{-0.2}$ | $^{+10.6}_{-0.1}$ |
| Background shape | $^{+0.1}_{-0.0}$ | $^{+0.2}_{-0.0}$ | $^{+0.1}_{-2.0}$ | $^{+0.0}_{-2.1}$ | $^{+0.7}_{-0.1}$ | $^{+0.1}_{-0.2}$ | $^{+18.6}_{-1.7}$ | $^{+7.5}_{-2.2}$ |
| Bin/range | $^{+0.0}_{-0.2}$ | $^{+0.0}_{-0.4}$ | $^{+0.4}_{-0.5}$ | $^{+0.0}_{-0.5}$ | $^{+0.0}_{-1.3}$ | $^{+2.7}_{-0.0}$ | $^{+1.6}_{-0.0}$ | $^{+0.0}_{-4.9}$ |
| $N[\Upsilon(2S)]$ | ... | ... | ... | ... | $\pm 2.3$ | $\pm 2.3$ | $\pm 2.3$ | $\pm 2.3$ |
| $\gamma$ efficiency | ... | ... | ... | ... | $\pm 2.8$ | $\pm 2.8$ | $\pm 2.8$ | $\pm 2.8$ |
| Selection criteria | ... | ... | ... | ... | $^{+2.4}_{-4.8}$ | $^{+2.4}_{-4.8}$ | $^{+2.4}_{-4.8}$ | $^{+2.4}_{-4.8}$ |
| Total | $\pm 0.5$ | $^{+0.5}_{-0.6}$ | $^{+1.3}_{-3.2}$ | $^{+3.6}_{-3.4}$ | $^{+4.4}_{-6.1}$ | $^{+5.1}_{-6.0}$ | $^{+18.7}_{-5.7}$ | $^{+15.3}_{-9.2}$ |

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

# $\Upsilon(2S)\to\gamma\eta_b(1S)$: Summary of Results

- Branching Fractions / Yields
  - $\chi_b$ 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)

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

  - $\eta_b$ branching fraction corresponds with lattice

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

- All mass results ($\chi_b$, ISR, $\eta_b$) consistent with PDG (9399.0±2.3 MeV)

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

  - Consistent with $h_b$ (1.2$\sigma$) and $\Upsilon$ (0.7$\sigma$) results
  - Width not inconsistent with existing measurements

# CONCLUSIONS

# Conclusions

- Belle continues to make important contributions to the study of the bottomonium system

- Hadronic transitions
  - First observation of $\Upsilon(5S) \to \eta\Upsilon(1D)$
  - First observation of $\Upsilon(4S) \to \eta'\Upsilon(1S)$
- Radiative transitions
  - First observation of $\Upsilon(2S) \to \gamma\eta_b(1S)$

EPJC 78, 633 (2018)

PRL 121, 062001 (2018)

PRL 121, 232001 (2018)

- Future results expected from both Belle and high-statistics Belle II experiment

# Thank you