Studies of hadron spectroscopy at Belle and Belle II

Stefan Wallner for the Belle and Belle II collaborations
(swallner@mpp.mpg.de)

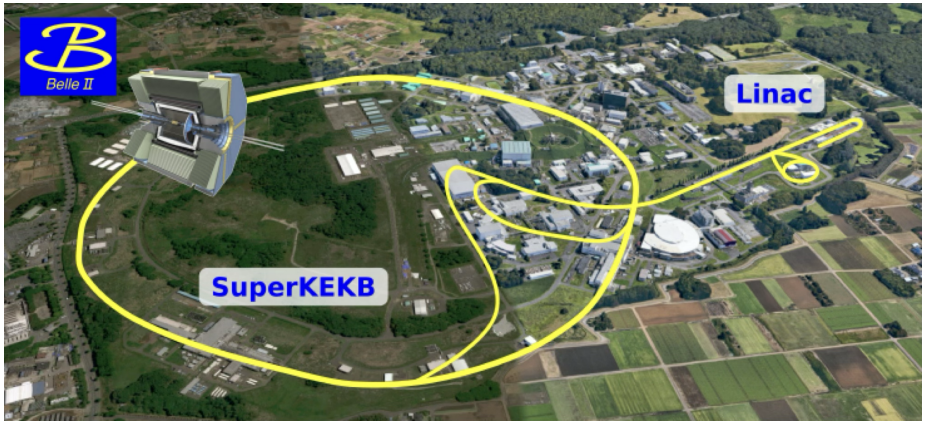
Max Planck Institute for Physics

EPS-HEP 2025
July 9, 2025

MAX PLANCK INSTITUTE
FOR PHYSICS

The Belle and Belle II Experiments

- B factories at KEK (Tsukuba/Japan): e^+e^- collider at E_{CM} around $\Upsilon(4S)$ mass

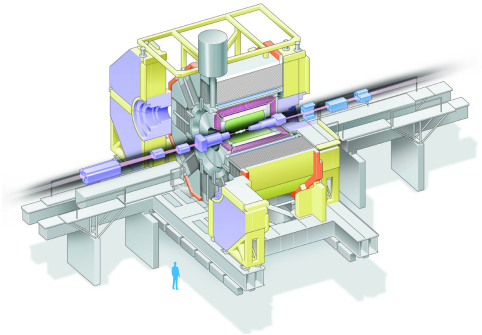


The Belle and Belle II Experiments

- B factories at KEK (Tsukuba/Japan): e^+e^- collider at E_{CM} around $\Upsilon(4S)$ mass

Belle at KEKB accelerator (1999–2010)

- Collected integrated luminosity of about 1000 fb^{-1}
  - 711 fb^{-1} at $\Upsilon(4S)$
  - 6 fb^{-1} at $\Upsilon(1S)$
  - 25 fb^{-1} at $\Upsilon(2S)$
  - 3 fb^{-1} at $\Upsilon(3S)$
  - 121 fb^{-1} at $\Upsilon(5S)$
  - $\approx$ 100 fb^{-1} off-Υ/scan

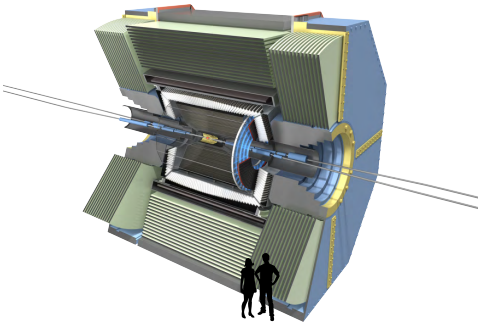


The Belle and Belle II Experiments

- B factories at KEK (Tsukuba/Japan): e^+e^- collider at E_{CM} around $\Upsilon(4S)$ mass

Belle II at SuperKEKB accelerator (2019–)

- Goals
  - $50\times$ Belle data-sample size by increasing luminosity
  - Renewed detector, trigger, analysis techniques, ...
- Run 1 (2019–2022)
  - Collected about $1/2\times$ Belle data-sample size
    $1\times$ BaBar data-sample size
- Run2 started in spring 2024
  - Upgraded detector
  - World-record luminosity: $5.1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

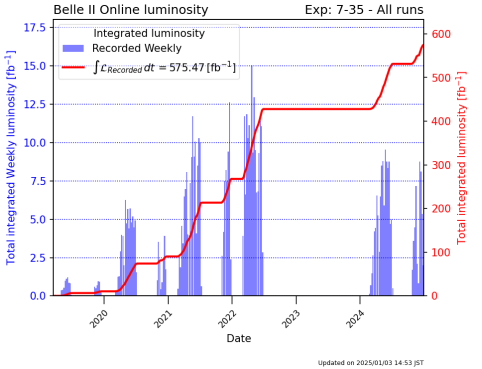


The Belle and Belle II Experiments

- B factories at KEK (Tsukuba/Japan): e^+e^- collider at E_{CM} around $\Upsilon(4S)$ mass

Belle II at SuperKEKB accelerator (2019–)

- Goals
  - $50\times$ Belle data-sample size by increasing luminosity
  - Renewed detector, trigger, analysis techniques, ...
- Run 1 (2019–2022)
  - Collected about $1/2\times$ Belle data-sample size
    $1\times$ BaBar data-sample size
- Run2 started in spring 2024
  - Upgraded detector
  - World-record luminosity: $5.1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

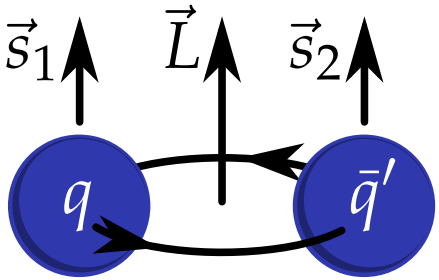


- Explore the nature of the $\Upsilon(10753)$ [see A. Bondar's EPS-HEP talk]
- Search for $h_b(1P, 2P)$ decays to $\Upsilon(1S)$, χ_{bJ} (this talk)
- Search for $P_{c\bar{c}s}$ states in $\Upsilon(1S, 2S)$ decays (this talk)
- Precision measurement of the B^0 and B^+ mass difference (in progress)
- Search for resonances in $e^+e^- \to J/\psi h\bar{h}$ $(h = p, \pi, K)$ (in progress)
- ...

Search for $h_b(1P, 2P)$ Decays to $\Upsilon(1S)$, χ_{bJ}

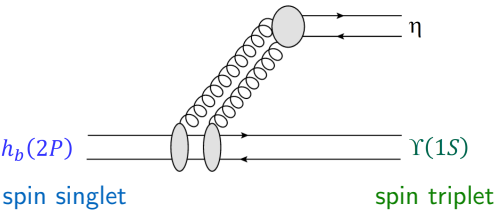
Motivation: Spin-Singlet to Spin-Triplet Transitions

- Bottomonium: bound $b\bar{b}$ system
  - Quark spins S_j can couple to
    - $S_{b\bar{b}} = 0$ spin singlet
    - $S_{b\bar{b}} = 1$ spin triplet
  - Orbital angular momentum L
- Study transitions between bottomonia
  - Probe inner structure
  - Test effective field theories
- Transitions from spin-singlet to spin-triplet state suppressed by heavy-quark spin symmetry
- Suppression may be lifted by hadron loops
- $\mathcal{B}[\Upsilon(3S) \to h_b(1P)\pi^0] \approx 10^{-3}$ (significance 3.1σ)
  [BaBar PRD 84 (2011) 091101]
  - Prediction $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\eta] \approx 10\,\%$
    [Li and Voloshin PRD 86 (2012) 094013]



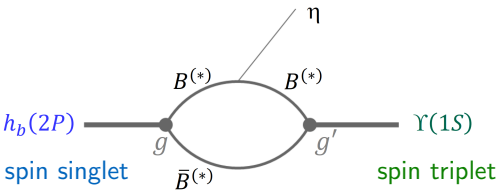
Motivation: Spin-Singlet to Spin-Triplet Transitions

- Bottomonium: bound $b\bar{b}$ system
  - Quark spins S_j can couple to
    - $S_{b\bar{b}} = 0$ spin singlet
    - $S_{b\bar{b}} = 1$ spin triplet
  - Orbital angular momentum L
- Study transitions between bottomonia
  - Probe inner structure
  - Test effective field theories
- Transitions from spin-singlet to spin-triplet state suppressed by heavy-quark spin symmetry
- Suppression may be lifted by hadron loops
- $\mathcal{B}[\Upsilon(3S) \to h_b(1P)\pi^0] \approx 10^{-3}$ (significance 3.1σ)
  [BaBar PRD 84 (2011) 091101]
  - Prediction $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\eta] \approx 10\,\%$
    [Li and Voloshin PRD 86 (2012) 094013]



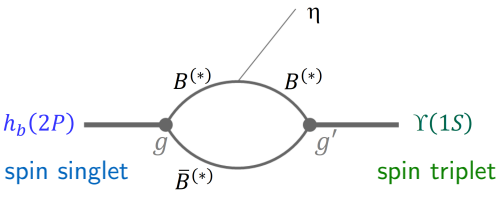
Motivation: Spin-Singlet to Spin-Triplet Transitions

- Bottomonium: bound $b\bar{b}$ system
  - Quark spins S_j can couple to
    - $S_{b\bar{b}} = 0$ spin singlet
    - $S_{b\bar{b}} = 1$ spin triplet
  - Orbital angular momentum L
- Study transitions between bottomonia
  - Probe inner structure
  - Test effective field theories
- Transitions from spin-singlet to spin-triplet state suppressed by heavy-quark spin symmetry
- Suppression may be lifted by hadron loops
- $\mathcal{B}[\Upsilon(3S) \to h_b(1P)\pi^0] \approx 10^{-3}$ (significance 3.1σ) [BaBar PRD 84 (2011) 091101]
  - Prediction $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\eta] \approx 10\,\%$ [Li and Voloshin PRD 86 (2012) 094013]



Motivation: Spin-Singlet to Spin-Triplet Transitions

- Bottomonium: bound $b\bar{b}$ system
  - Quark spins S_j can couple to
    - $S_{b\bar{b}} = 0$ spin singlet
    - $S_{b\bar{b}} = 1$ spin triplet
  - Orbital angular momentum L
- Study transitions between bottomonia
  - Probe inner structure
  - Test effective field theories
- Transitions from spin-singlet to spin-triplet state suppressed by heavy-quark spin symmetry
- Suppression may be lifted by hadron loops
- $\mathcal{B}[\Upsilon(3S) \to h_b(1P)\pi^0] \approx 10^{-3}$ (significance 3.1σ)
  [BaBar PRD 84 (2011) 091101]
  - Prediction $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\eta] \approx 10\,\%$
    [Li and Voloshin PRD 86 (2012) 094013]



Evidence of $h_b(2P) \to \Upsilon(1S)\eta$ Decay

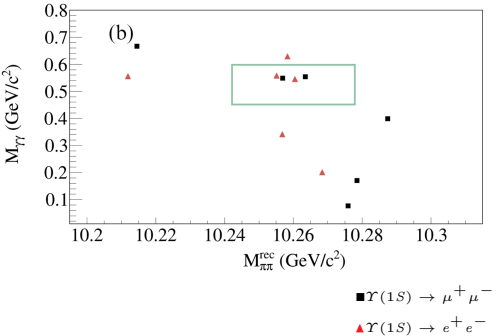
[PRL 133 (2024) 26]

Measurement

- Full reconstruction in $\Upsilon(5S)$ decays ($121\,\text{fb}^{-1}$)

$$\Upsilon(5S) \to Z_b^+ \pi^- \to h_b(2P)\,\pi^+\pi^- \to \Upsilon(1S)\,\eta \to \gamma\gamma,\ \ell^+\ell^-$$

- Define signal in 2D plane $M_{\gamma\gamma}$ and $M^{\text{rec}}_{\pi\pi}$
- Extract signal yield from 2D fit
- Signal with 3.5σ significance
- $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\eta] = (7.1^{+3.7}_{-3.2} \pm 0.8) \times 10^{-3}$
  - $10\times$ lower than expected based on $\mathcal{B}[\Upsilon(3S) \to h_b(1P)\pi^0]$
  - Disfavors large loop contributions
- No evidence for isospin violating decay: $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$



Evidence of $h_b(2P) \to \Upsilon(1S)\eta$ Decay

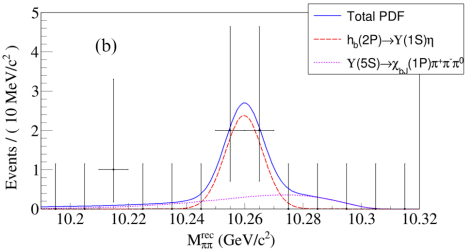
[PRL 133 (2024) 26]

Measurement

- Full reconstruction in $\Upsilon(5S)$ decays ($121\,\text{fb}^{-1}$)

$$\Upsilon(5S) \to Z_b^+ \pi^- \to h_b(2P)\,\pi^+\pi^- \to \Upsilon(1S)\,\eta \to \gamma\gamma,\ \ell^+\ell^-$$

- Define signal in 2D plane $M_{\gamma\gamma}$ and $M^{\text{rec}}_{\pi\pi}$
- Extract signal yield from 2D fit
- Signal with 3.5σ significance
- $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\eta] = (7.1^{+3.7}_{-3.2} \pm 0.8) \times 10^{-3}$
  - $10\times$ lower than expected based on $\mathcal{B}[\Upsilon(3S) \to h_b(1P)\pi^0]$
  - Disfavors large loop contributions
- No evidence for isospin violating decay: $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$



Evidence of $h_b(2P) \to \Upsilon(1S)\eta$ Decay

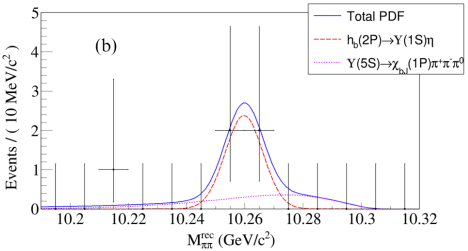
[PRL 133 (2024) 26]

Measurement

- Full reconstruction in $\Upsilon(5S)$ decays ($121\,\text{fb}^{-1}$)

$$\Upsilon(5S) \to Z_b^+ \pi^- \to h_b(2P)\,\pi^+\pi^- \to \Upsilon(1S)\,\eta \to \gamma\gamma,\ \ell^+\ell^-$$

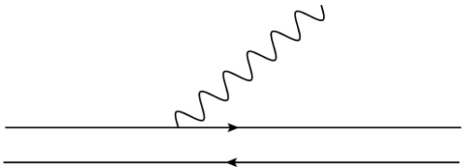
- Define signal in 2D plane $M_{\gamma\gamma}$ and $M_{\pi\pi}^{\text{rec}}$
- Extract signal yield from 2D fit
- Signal with 3.5σ significance
- $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\eta] = (7.1^{+3.7}_{-3.2} \pm 0.8) \times 10^{-3}$
  - $10\times$ lower than expected based on $\mathcal{B}[\Upsilon(3S) \to h_b(1P)\pi^0]$
  - Disfavors large loop contributions
- No evidence for isospin violating decay: $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$



Search for $h_b(2P) \to \chi_{bJ}(1P)\gamma$

Motivation

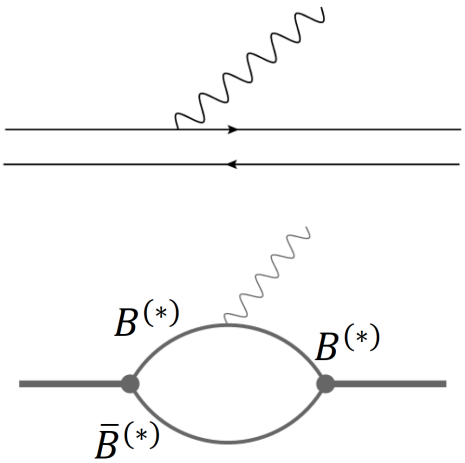
- Search for spin-singlet to spin-triplet transitions $h_b(2P) \to \chi_{bJ}(1P)\gamma$ with $J = 0, 1, 2$
- Direct radiative $M1$ transition suppressed ($\mathcal{B} = 10^{-6}$–10^{-5})
  [Godfrey Isgur PRD 32 (1985) 189]
- May be enhanced by hadron loops ($\mathcal{B} = 10^{-2}$–10^{-1})
  [K.-F. Guo et al. PLB 760 (2016) 417]



Search for $h_b(2P) \to \chi_{bJ}(1P)\gamma$

Motivation

- Search for spin-singlet to spin-triplet transitions $h_b(2P) \to \chi_{bJ}(1P)\gamma$ with $J = 0, 1, 2$
- Direct radiative $M1$ transition suppressed ($\mathcal{B} = 10^{-6}$–10^{-5})
  [Godfrey Isgur PRD 32 (1985) 189]
- May be enhanced by hadron loops ($\mathcal{B} = 10^{-2}$–10^{-1})
  [K.-F. Guo et al. PLB 760 (2016) 417]



Search for $h_b(2P) \to \chi_{bJ}(1P)\gamma$

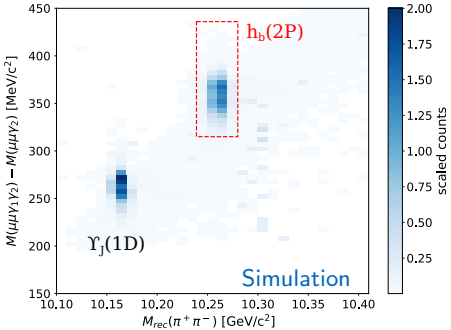
[PRD 111 (2025) 1]

Measurement

- Full reconstruction in $\Upsilon(5S)$ decays ($121\,\text{fb}^{-1}$)

$$\Upsilon(5S) \longrightarrow Z_b^+ \pi^- \longrightarrow h_b(2P)\,\pi^+\pi^- \hookrightarrow \chi_{bJ}(1P)\,\gamma \hookrightarrow \Upsilon(1S)\,\gamma_2 \hookrightarrow \mu^+\mu^-$$

- 2D signal region
  - $M_{\text{rec}}(\pi^+\pi^-)$ corresponding to $M(h_b(2P))$
  - $M(\mu\mu\gamma\gamma) - M(\mu\mu\gamma_2)$ corresponding to $M(h_b(2P)) - M(\chi_{bJ}(1P))$
- Region of $\Upsilon_J(1D)$ signal from $\Upsilon(5S) \to \Upsilon_J(1D)\pi^+\pi^-$ excluded in analysis
  - Dedicated analysis ongoing



Search for $h_b(2P) \to \chi_{bJ}(1P)\gamma$

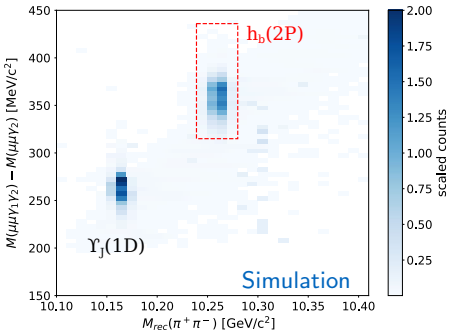
[PRD 111 (2025) 1]

Measurement

- Full reconstruction in $\Upsilon(5S)$ decays ($121\,\text{fb}^{-1}$)

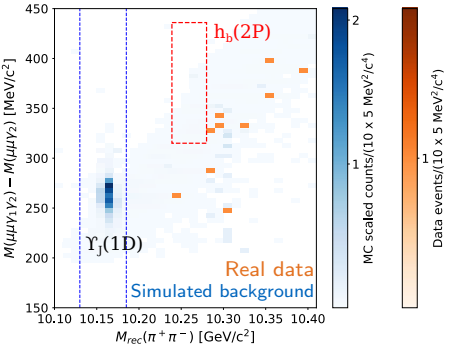
$$\Upsilon(5S) \longrightarrow Z_b^+ \pi^- \longrightarrow h_b(2P)\,\pi^+\pi^- \hookrightarrow \chi_{bJ}(1P)\,\gamma \hookrightarrow \Upsilon(1S)\,\gamma_2 \hookrightarrow \mu^+\mu^-$$

- 2D signal region
  - $M_{\text{rec}}(\pi^+\pi^-)$ corresponding to $M(h_b(2P))$
  - $M(\mu\mu\gamma\gamma) - M(\mu\mu\gamma_2)$ corresponding to $M(h_b(2P)) - M(\chi_{bJ}(1P))$
- Region of $\Upsilon_J(1D)$ signal from $\Upsilon(5S) \to \Upsilon_J(1D)\pi^+\pi^-$ excluded in analysis
  - Dedicated analysis ongoing



Results

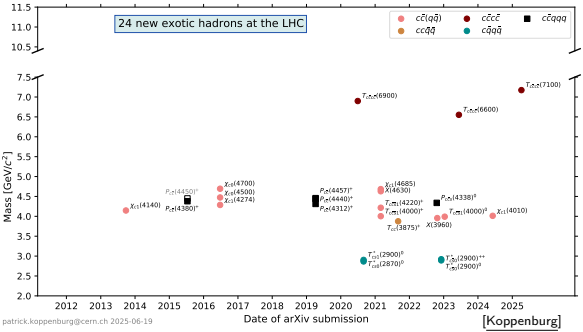
- No events in signal region
- First upper limits on branching fraction
  - $\mathcal{B}[h_b(2P) \to \chi_{b0}(1P)\gamma] < 2.7 \times 10^{-1}$
  - $\mathcal{B}[h_b(2P) \to \chi_{b1}(1P)\gamma] < 5.4 \times 10^{-3}$
  - $\mathcal{B}[h_b(2P) \to \chi_{b2}(1P)\gamma] < 1.3 \times 10^{-2}$
- Upper limits consistent with predictions from relativistic quark-model
- Limits in the range sensitive to hadronic loops



Search for $P_{c\bar{c}s}(4459)^0$ and $P_{c\bar{c}s}(4338)^0$

Search for $P_{c\bar{c}s}(4459)^0$ and $P_{c\bar{c}s}(4338)^0$ in $\Upsilon(1S, 2S)$ Inclusive Decays

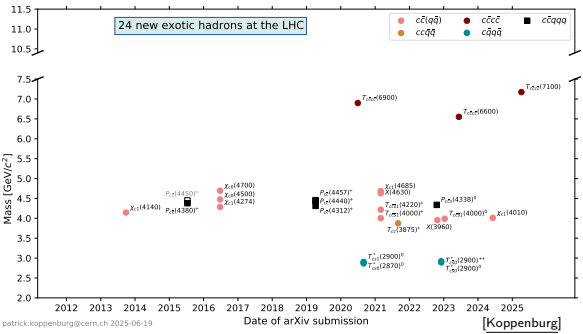
- QCD allows for complex configurations than $q\bar{q}$ and qqq, so-called exotics
- LHCb, Belle, and others discovered a new zoo of exotics: Tetraquark ($qq\bar{q}\bar{q}$), pentaquark ($qqqq\bar{q}$)
- Pentaquarks with $c\bar{c}$ and strangeness ($P_{c\bar{c}s}$)
  - $P_{c\bar{c}s}(4338)^0$ with 15σ significance
  - $P_{c\bar{c}s}(4459)^0$ with 3.1σ significance
  - Both in $P_{c\bar{c}s} \to J/\psi\Lambda$ decays



- Baryon and deuteron production in $\Upsilon(1S, 2S)$ decays enhanced
  - World's largest samples at Belle: 6 fb^{-1} at $\Upsilon(1S)$ [102M]; 25 fb^{-1} at $\Upsilon(2S)$ [158M]
  - Search of $\Upsilon(1S, 2S) \to P_c X$ decays
    - No pentaquark signal in $\Upsilon(1S, 2S) \to P_{c\bar{c}} X \to (J/\psi p) X$ [arXiv:2403.04340]
    - Search for $P_{c\bar{c}s}$ in $\Upsilon(1S, 2S) \to P_{c\bar{c}s} X \to (J/\psi\Lambda) X$

Search for $P_{c\bar{c}s}(4459)^0$ and $P_{c\bar{c}s}(4338)^0$ in $\Upsilon(1S, 2S)$ Inclusive Decays

- QCD allows for complex configurations than $q\overline{q}$ and qqq, so-called exotics
- LHCb, Belle, and others discovered a new zoo of exotics: Tetraquark ($qq\bar{q}\bar{q}$), pentaquark ($qqqq\bar{q}$)
- Pentaquarks with $c\bar{c}$ and strangeness ($P_{c\bar{c}s}$)
  - $P_{c\bar{c}s}(4338)^0$ with 15σ significance
  - $P_{c\bar{c}s}(4459)^0$ with 3.1σ significance
  - Both in $P_{c\bar{c}s} \to J/\psi\Lambda$ decays



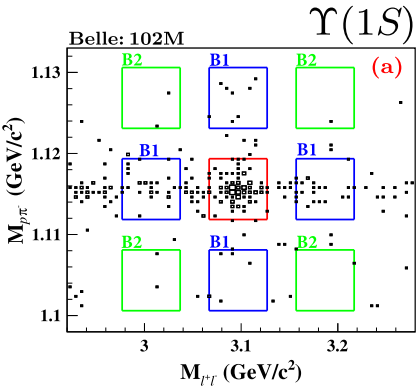
- Baryon and deuteron production in $\Upsilon(1S, 2S)$ decays enhanced
  - ➥ World's largest samples at Belle: 6 fb^{-1} at $\Upsilon(1S)$ [102M]; 25 fb^{-1} at $\Upsilon(2S)$ [158M]
  - ➥ Search of $\Upsilon(1S, 2S) \to P_c X$ decays
    - No pentaquark signal in $\Upsilon(1S, 2S) \to P_{c\bar{c}} X \to (J/\psi p)X$ [arXiv:2403.04340]
    - Search for $P_{c\bar{c}s}$ in $\Upsilon(1S, 2S) \to P_{c\bar{c}s} X \to (J/\psi\Lambda)X$

Search for $P_{c\bar{c}s}(4459)^0$ and $P_{c\bar{c}s}(4338)^0$ in $\Upsilon(1S, 2S)$ Inclusive Decays

[arXiv:2502.09951]

Measurement of $\Upsilon(1S, 2S) \to J/\psi\Lambda + X$

- 2D signal region in $M_{l^+l^-}$ and $M_{p\pi^-}$
- Subtract continuum background estimated from off-Υ data
- Subtract background from 2D sidebands
  - False J/ψ or Λ
  - Combinatorial background
- Measure the total inclusive branching fraction
  - $\mathcal{B}[\Upsilon(1S) \to J/\psi\Lambda/\bar{\Lambda} + X] = (36.9 \pm 5.3 \pm 2.4) \times 10^{-6}$
  - $\mathcal{B}[\Upsilon(2S) \to J/\psi\Lambda/\bar{\Lambda} + X] = (22.3 \pm 5.7 \pm 3.1) \times 10^{-6}$

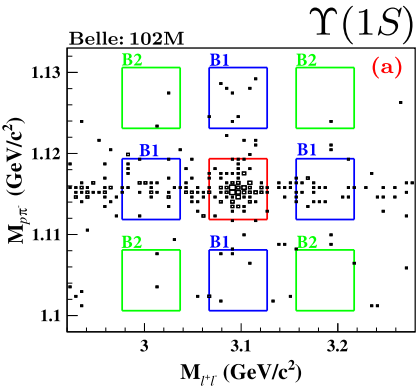


Search for $P_{c\bar{c}s}(4459)^0$ and $P_{c\bar{c}s}(4338)^0$ in $\Upsilon(1S, 2S)$ Inclusive Decays

[arXiv:2502.09951]

Measurement of $\Upsilon(1S, 2S) \to J/\psi\Lambda + X$

- 2D signal region in $M_{l^+l^-}$ and $M_{p\pi^-}$
- Subtract continuum background estimated from off-Υ data
- Subtract background from 2D sidebands
  - False J/ψ or Λ
  - Combinatorial background
- Measure the total inclusive branching fraction
  - $\mathcal{B}[\Upsilon(1S) \to J/\psi\Lambda/\bar{\Lambda} + X] = (36.9 \pm 5.3 \pm 2.4) \times 10^{-6}$
  - $\mathcal{B}[\Upsilon(2S) \to J/\psi\Lambda/\bar{\Lambda} + X] = (22.3 \pm 5.7 \pm 3.1) \times 10^{-6}$

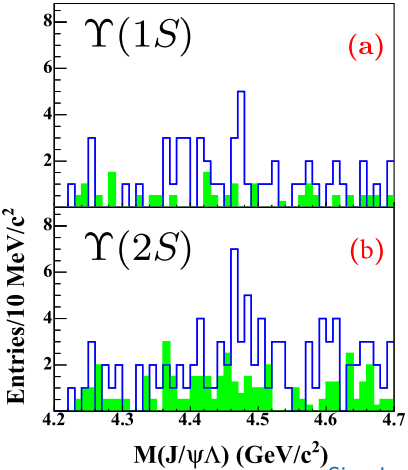


Search for $P_{c\bar{c}s}(4459)^0$ and $P_{c\bar{c}s}(4338)^0$ in $\Upsilon(1S, 2S)$ Inclusive Decays

[arXiv:2502.09951]

$M(J/\psi\Lambda)$ Spectrum

- Measure yields in $M(J/\psi\Lambda)$ bins
- Enhancement near $P_{c\bar{c}s}(4459)^0$ mass
- Combined fit to $\Upsilon(1S)$ and $\Upsilon(2S)$ data
  - Background polynomial constrained by simultaneous fit to 2D sideband data
  - $P_{c\bar{c}s}(4459)^0$ mass and width constrained to LHCb measurement

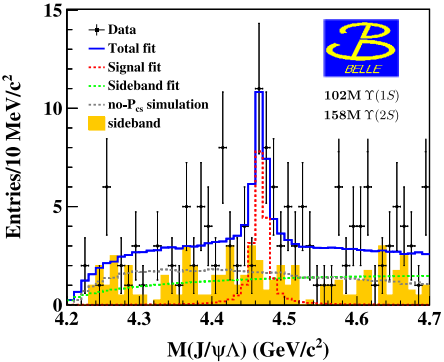


Search for $P_{c\bar{c}s}(4459)^0$ and $P_{c\bar{c}s}(4338)^0$ in $\Upsilon(1S, 2S)$ Inclusive Decays

[arXiv:2502.09951]

$M(J/\psi\Lambda)$ Spectrum

- Measure yields in $M(J/\psi\Lambda)$ bins
- Enhancement near $P_{c\bar{c}s}(4459)^0$ mass
- Combined fit to $\Upsilon(1S)$ and $\Upsilon(2S)$ data
  - Background polynomial constrained by simultaneous fit to 2D sideband data
  - $P_{c\bar{c}s}(4459)^0$ mass and width constrained to LHCb measurement

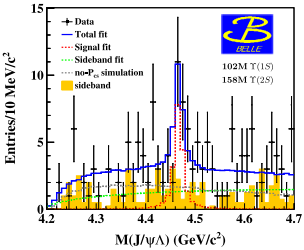


Search for $P_{c\bar{c}s}(4459)^0$ and $P_{c\bar{c}s}(4338)^0$ in $\Upsilon(1S, 2S)$ Inclusive Decays

[arXiv:2502.09951]

$P_{c\bar{c}s}(4459)^0$

- $P_{c\bar{c}s}(4459)^0$ significance 3.3σ including systematic uncertainties
  - $\mathcal{B}[\Upsilon(1S) \to P_{c\bar{c}s}(4459)^0 X \to J/\psi \Lambda X] = (3.5 \pm 2.0 \pm 0.2) \times 10^{-6}$
  - $\mathcal{B}[\Upsilon(2S) \to P_{c\bar{c}s}(4459)^0 X \to J/\psi \Lambda X] = (2.9 \pm 1.7 \pm 0.4) \times 10^{-6}$
- First evidence for $\Upsilon(1S, 2S)$ decays to exotic state
- $M = 4471.7 \pm 4.8 \pm 0.6\,\text{MeV}/c^2$, $\Gamma = 22 \pm 13 \pm 3\,\text{MeV}/c^2$
  - From separate fit omitting LHCb mass and width constraints



[arXiv:2502.09951]
accepted by PRL

$P_{c\bar{c}s}(4338)^0$

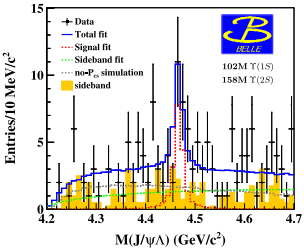
- No $P_{c\bar{c}s}(4338)^0$ signal observed
  - $\mathcal{B}[\Upsilon(1S) \to P_{c\bar{c}s}(4338)^0 X \to J/\psi \Lambda X] < 1.8 \times 10^{-6}$
  - $\mathcal{B}[\Upsilon(2S) \to P_{c\bar{c}s}(4338)^0 X \to J/\psi \Lambda X] < 1.6 \times 10^{-6}$

Search for $P_{c\bar{c}s}(4459)^0$ and $P_{c\bar{c}s}(4338)^0$ in $\Upsilon(1S, 2S)$ Inclusive Decays

[arXiv:2502.09951]

$P_{c\bar{c}s}(4459)^0$

- $P_{c\bar{c}s}(4459)^0$ significance 3.3σ including systematic uncertainties
  - $\mathcal{B}[\Upsilon(1S) \to P_{c\bar{c}s}(4459)^0 X \to J/\psi\Lambda X] = (3.5 \pm 2.0 \pm 0.2) \times 10^{-6}$
  - $\mathcal{B}[\Upsilon(2S) \to P_{c\bar{c}s}(4459)^0 X \to J/\psi\Lambda X] = (2.9 \pm 1.7 \pm 0.4) \times 10^{-6}$
- First evidence for $\Upsilon(1S, 2S)$ decays to exotic state
- $M = 4471.7 \pm 4.8 \pm 0.6\,\text{MeV}/c^2$, $\Gamma = 22 \pm 13 \pm 3\,\text{MeV}/c^2$
  - From separate fit omitting LHCb mass and width constraints



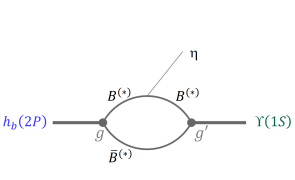
[arXiv:2502.09951]
accepted by PRL

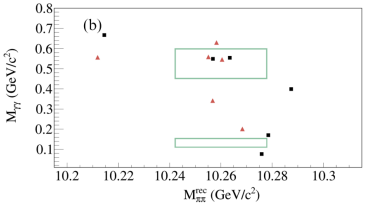
$P_{c\bar{c}s}(4338)^0$

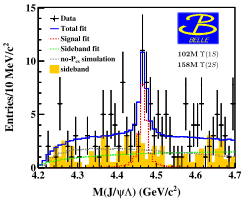
- No $P_{c\bar{c}s}(4338)^0$ signal observed
  - $\mathcal{B}[\Upsilon(1S) \to P_{c\bar{c}s}(4338)^0 X \to J/\psi\Lambda X] < 1.8 \times 10^{-6}$
  - $\mathcal{B}[\Upsilon(2S) \to P_{c\bar{c}s}(4338)^0 X \to J/\psi\Lambda X] < 1.6 \times 10^{-6}$

Summary

- Search bottomonium spin-singlet to spin-triplet transitions
  - First evidence for $h_b(2P) \to \Upsilon(1S)\eta$
    - Lower than expected from $\Upsilon(3S) \to h_b(1P)\pi^0$
    - Disfavors large hadronic loop contributions
  - No signal for $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$ and $h_b(2P) \to \chi_{bJ}(1P)\gamma$
- Evidence for $P_{c\bar{c}s}(4459) \to J/\psi\Lambda$ in inclusive $\Upsilon(1S, 2S)$ decays
  - First evidence for $\Upsilon(1S, 2S)$ decays to exotic state
- Belle II restarts data taking in November 2025







Backup

Outline

7 The Belle and Belle II Experiments
- Unique environment for high-precision measurements and New Physics searches

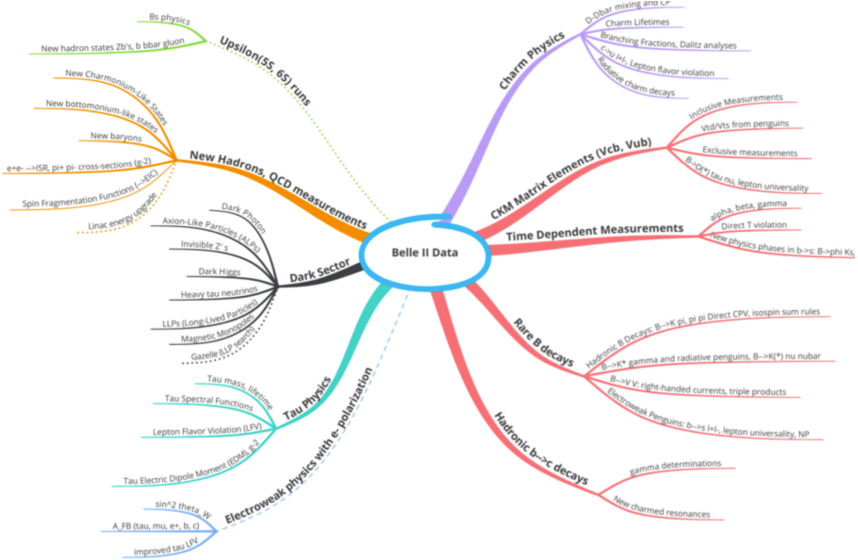
8 Search for $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$

9 Search for $h_b(2P) \to \chi_{bJ}(1P)\gamma$

The Belle and Belle II Experiments

Unique environment for high-precision measurements and New Physics searches

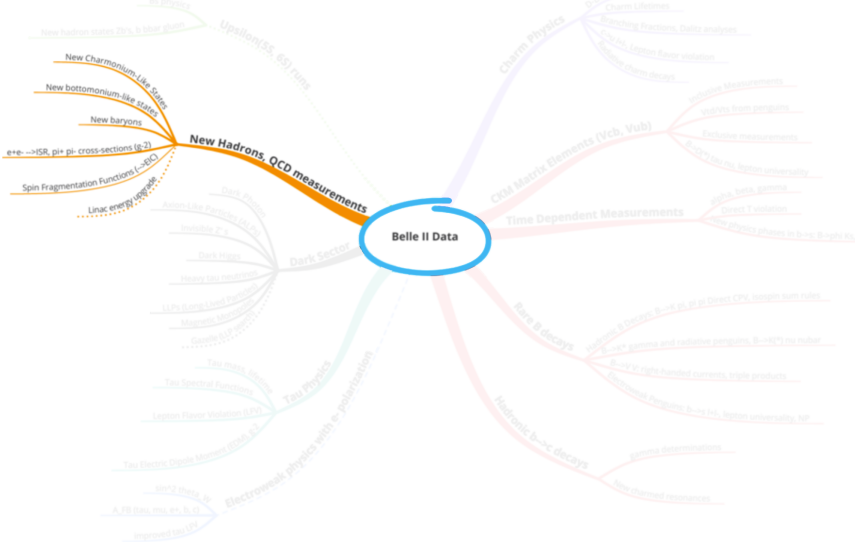
[Snowmass White Paper]



The Belle and Belle II Experiments

Unique environment for high-precision measurements and New Physics searches

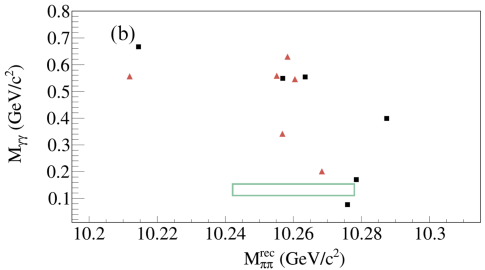
[Snowmass White Paper]



Search for $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$

[PRL 133 (2024) 26]

- Same final-state allows us to also search for $h_b(2P) \to \Upsilon(1S)\pi^0$
- Isospin-violating transition strongly suppressed
- No event in signal region
  - $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\pi^0] < 1.8 \times 10^{-3}$
- No event in signal region for $h_b(1P) \to \Upsilon(1S)\pi^0$
  - $\mathcal{B}[h_b(1P) \to \Upsilon(1S)\pi^0] < 1.8 \times 10^{-3}$

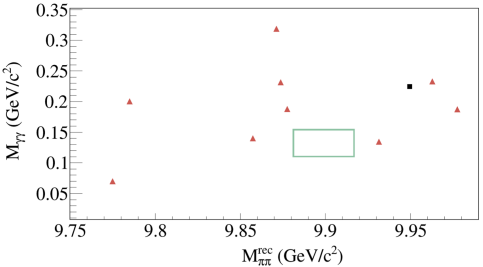


■ $\Upsilon(1S) \to \mu^+\mu^-$
▲ $\Upsilon(1S) \to e^+e^-$

Search for $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$

[PRL 133 (2024) 26]

- Same final-state allows us to also search for $h_b(2P) \to \Upsilon(1S)\pi^0$
- Isospin-violating transition strongly suppressed
- No event in signal region
  - $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\pi^0] < 1.8 \times 10^{-3}$
- No event in signal region for $h_b(1P) \to \Upsilon(1S)\pi^0$
  - $\mathcal{B}[h_b(1P) \to \Upsilon(1S)\pi^0] < 1.8 \times 10^{-3}$



Search for $h_b(2P) \to \chi_{bJ}(1P)\gamma$

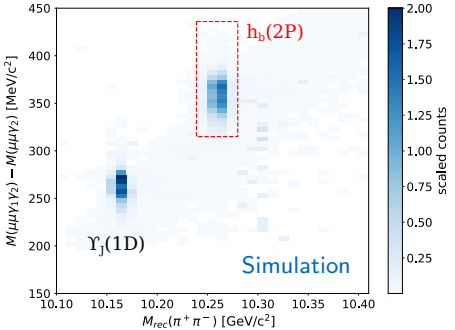
[PRD 111 (2025) 1]

Measurement

- Full reconstruction in $\Upsilon(5S)$ decays ($121\,\text{fb}^{-1}$)

$$\Upsilon(5S) \to Z_b^+ \pi^- \to h_b(2P)\,\pi^+\pi^- \to \chi_{bJ}(1P)\,\gamma \to \Upsilon(1S)\,\gamma_2 \to \mu^+\mu^-$$

- 2D signal region
  - $M_{\text{rec}}(\pi^+\pi^-)$ corresponding to $M(h_b(2P))$
  - $M(\mu\mu\gamma\gamma) - M(\mu\mu\gamma_2)$ corresponding to $M(h_b(2P)) - M(\chi_{bJ}(1P))$
- Region of $\Upsilon_J(1D)$ signal from $\Upsilon(5S) \to \Upsilon_J(1D)\pi^+\pi^-$ excluded in analysis
  - Dedicated analysis ongoing
- Systematics studied in analog $\Upsilon(3S) \to \gamma\chi_{bJ}(2P) \to \pi^+\pi^-\gamma\gamma\mu^+\mu^-$ decay
  - Good agreement between real data and simulation



Search for $h_b(2P) \to \chi_{bJ}(1P)\gamma$

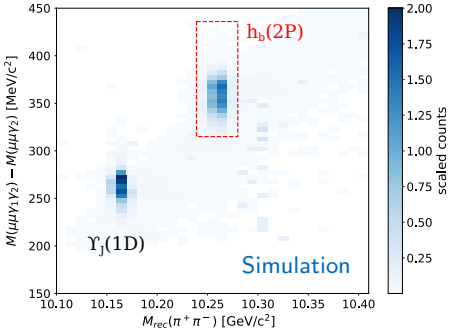
[PRD 111 (2025) 1]

Measurement

- Full reconstruction in $\Upsilon(5S)$ decays ($121\,\text{fb}^{-1}$)

$$\Upsilon(5S) \to Z_b^+ \pi^- \to h_b(2P)\,\pi^+\pi^- \to \chi_{bJ}(1P)\,\gamma \to \Upsilon(1S)\,\gamma_2 \to \mu^+\mu^-$$

- 2D signal region
  - $M_{\text{rec}}(\pi^+\pi^-)$ corresponding to $M(h_b(2P))$
  - $M(\mu\mu\gamma\gamma) - M(\mu\mu\gamma_2)$ corresponding to $M(h_b(2P)) - M(\chi_{bJ}(1P))$
- Region of $\Upsilon_J(1D)$ signal from $\Upsilon(5S) \to \Upsilon_J(1D)\pi^+\pi^-$ excluded in analysis
  - Dedicated analysis ongoing
- Systematics studied in analog $\Upsilon(3S) \to \gamma\chi_{bJ}(2P) \to \pi^+\pi^-\gamma\gamma\mu^+\mu^-$ decay
  - Good agreement between real data and simulation



Search for $h_b(2P) \to \chi_{bJ}(1P)\gamma$

[PRD 111 (2025) 1]

Measurement

- Full reconstruction in $\Upsilon(5S)$ decays ($121\,\text{fb}^{-1}$)

$$\Upsilon(5S) \to Z_b^+ \pi^- \to h_b(2P)\,\pi^+\pi^- \to \chi_{bJ}(1P)\,\gamma \to \Upsilon(1S)\,\gamma_2 \to \mu^+\mu^-$$

- 2D signal region
  - $M_{\text{rec}}(\pi^+\pi^-)$ corresponding to $M(h_b(2P))$
  - $M(\mu\mu\gamma\gamma) - M(\mu\mu\gamma_2)$ corresponding to $M(h_b(2P)) - M(\chi_{bJ}(1P))$
- Region of $\Upsilon_J(1D)$ signal from $\Upsilon(5S) \to \Upsilon_J(1D)\pi^+\pi^-$ excluded in analysis
  - Dedicated analysis ongoing
- Systematics studied in analog $\Upsilon(3S) \to \gamma\chi_{bJ}(2P) \to \pi^+\pi^-\gamma\gamma\mu^+\mu^-$ decay
  - Good agreement between real data and simulation