Pacific Northwest
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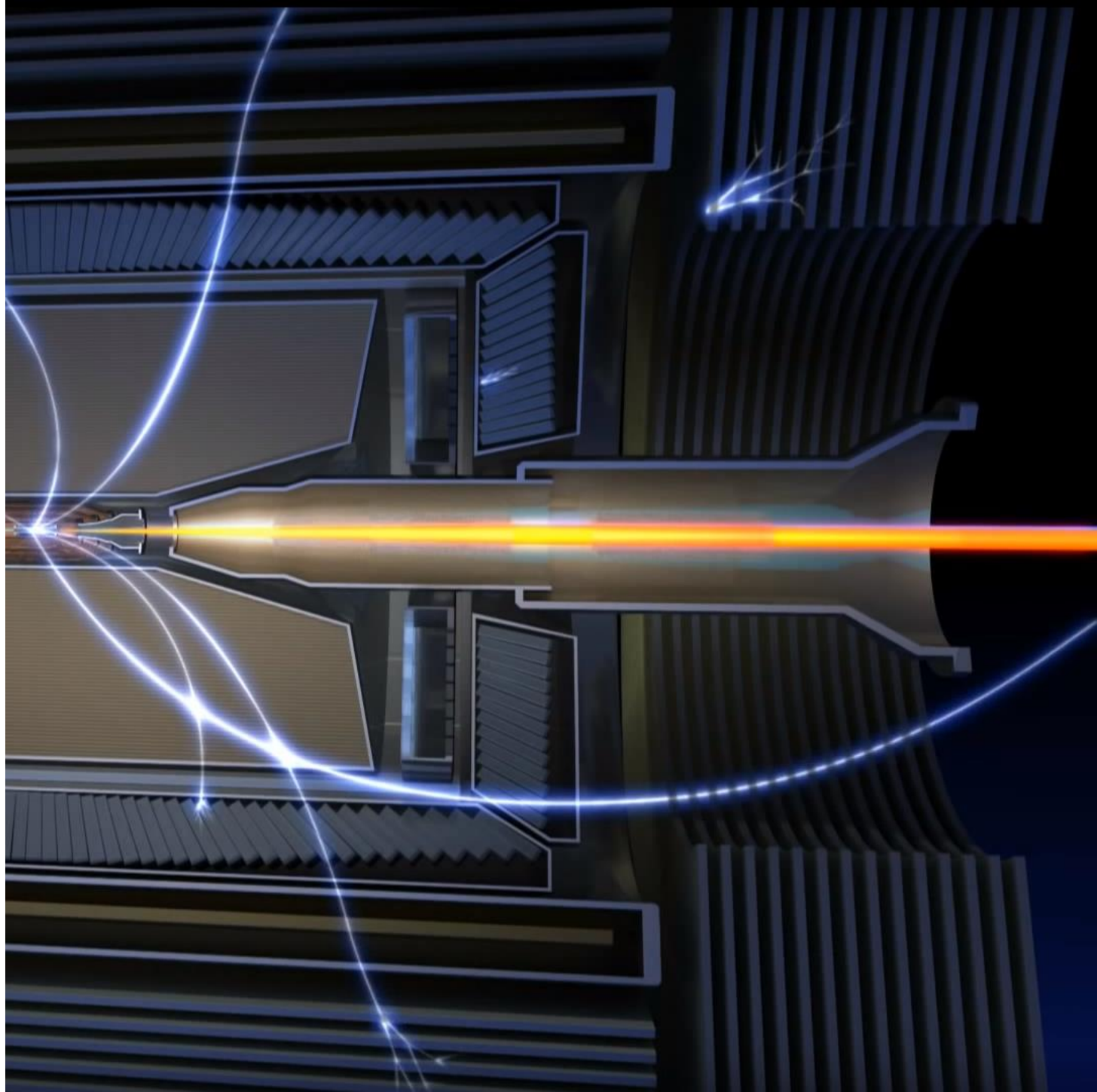
# Future of Hadron Spectroscopy at Belle II

May 17, 2022

**Bryan Fulsom (PNNL)**

Snowmass RPF Spring Meeting



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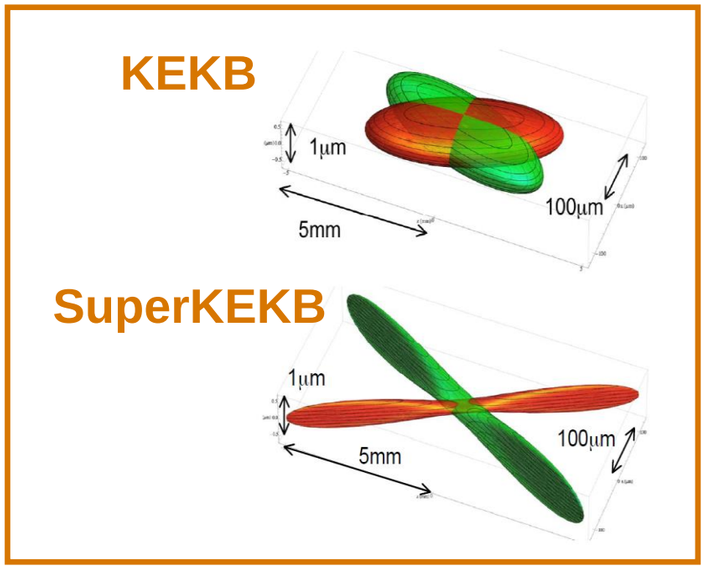
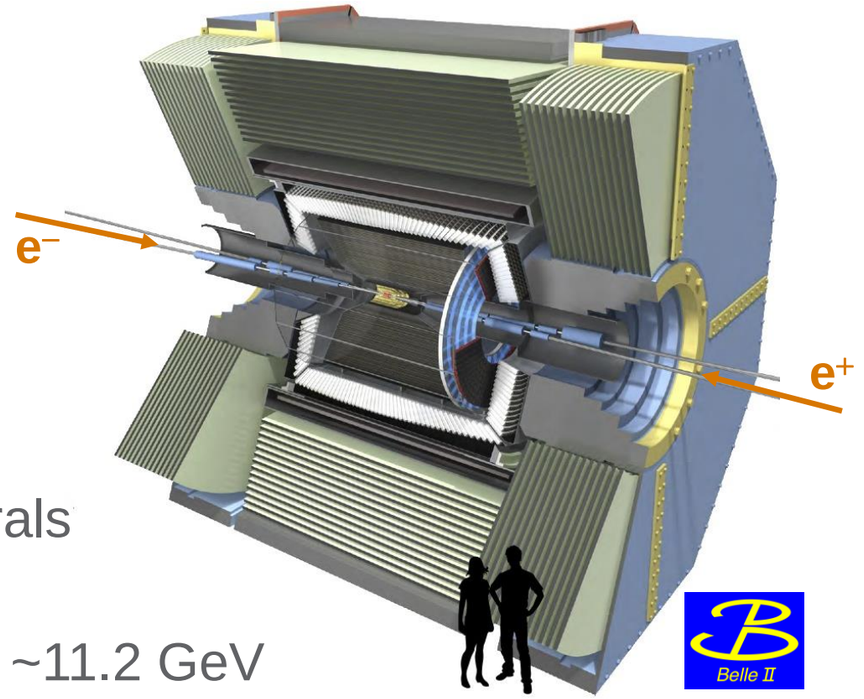
PNNL is operated by Battelle for the U.S. Department of Energy

# Belle II Capabilities




- Belle II is the next generation B-Factory
  - Flavor physics anomalies in B decays
  - NP in rare processes
  - DM searches in $e^+e^-$/B meson processes
  - Spectroscopy ("XYZ" states) and QCD studies
  - ~1000 members (~100 US @ 18 institutions)
  - ~10-year program ongoing since 2019
- Upgraded detector and accelerator
- Features
  - 30x instantaneous and integrated luminosity
  - Full event reconstruction and decays involving neutrals
  - Multiple production mechanisms for exotics
  - Nominal $\sqrt{s}$ = 10.58 GeV = $\Upsilon$(4S), potential to reach ~11.2 GeV



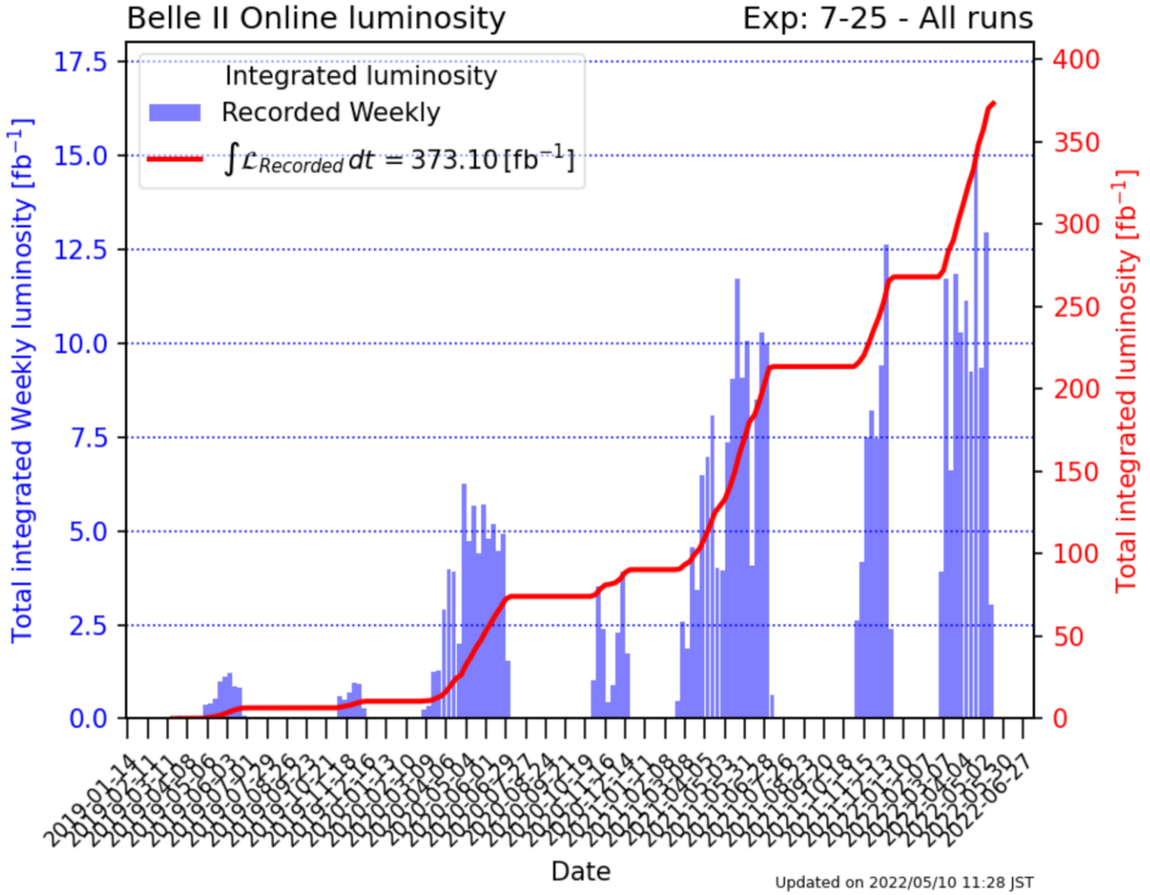

arXiv:1011.0352 (2011)

# Belle II in the Snowmass Process

- **Belle II Physics Program White Paper** (https://www.slac.stanford.edu/~mpeskin/Snowmass2021/BelleIIPhysicsforSnowmass.pdf)
  - **Chapter 8.1 Quarkonium, exotics, and hadron spectroscopy (RF07, EF06)**
- Opportunities for Precision QCD at Belle II (https://arxiv.org/abs/2204.02280)
- Charged Lepton Flavor Violation in the Tau Sector (https://arxiv.org/abs/2203.14919)
- Belle II Detector Upgrades White Paper (https://arxiv.org/abs/2203.11349)
- Belle II User-based GRID analysis (https://arxiv.org/abs/2203.07564)
- Beam Background Expectations for Belle II at SuperKEKB (http://arxiv.org/abs/2203.05731)
- SuperKEKB Electron Polarization Upgrade White Paper (in progress)
- Future HEP Computing Challenges (Belle II/DUNE joint paper, https://arxiv.org/abs/2203.07237)
- Physics reach of a long-lived particle detector at Belle II (https://arxiv.org/abs/2105.12962)

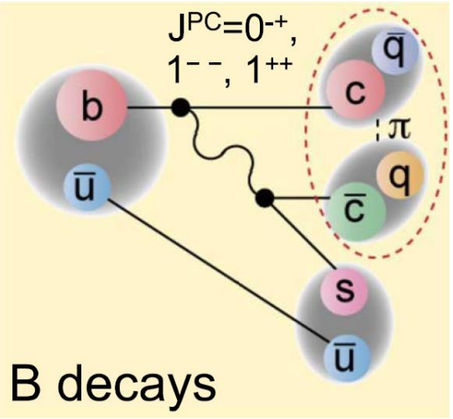
# Belle II Timeline

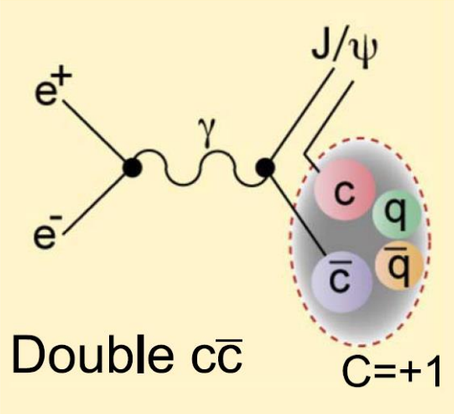
- 2016: “Phase 1”: Beam commissioning
- 2017: Detector roll-in
- 2018: “Phase 2”
  - Background study w. partial detector
  - First collisions/data
- 2019: “Phase 3”
  - Nominal start of operations
  - 2021: Non-$\Upsilon$(4S) Energy scan
  - 2022: Inst. lumi. record: >4.1x$10^{34}$$cm^{-2}s^{-1}$
- Jul 2022-Fall 2023: “Long Shutdown 1”
  - Detector/accelerator upgrades
- 2023~2026: Resume operations, target: 1.5-4 $ab^{-1}$
- 2027+: “Long Shutdown 2” upgrade (?), continue up to 50 $ab^{-1}$

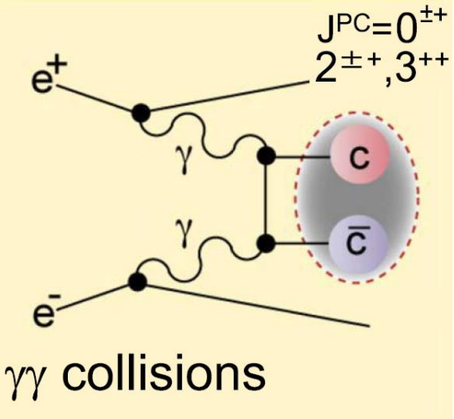


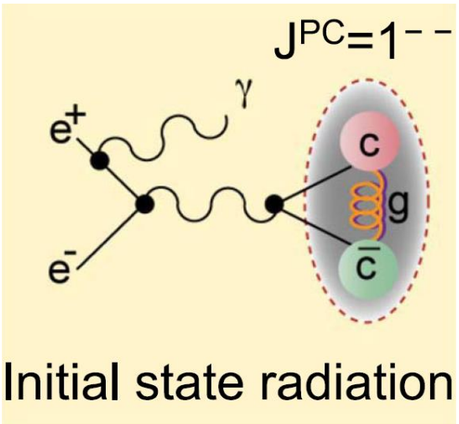
# How do we study quarkonium experimentally? Production Mechanisms

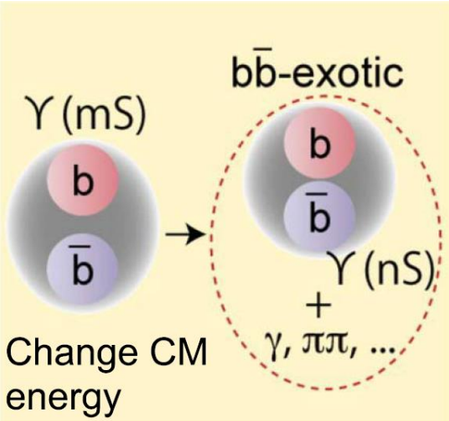
- Multiple methods to produce quarkonium/exotics at Belle II
- Production mode provides important information (e.g. $J^{PC}$, type)




- Several of these are **unique to Belle II**

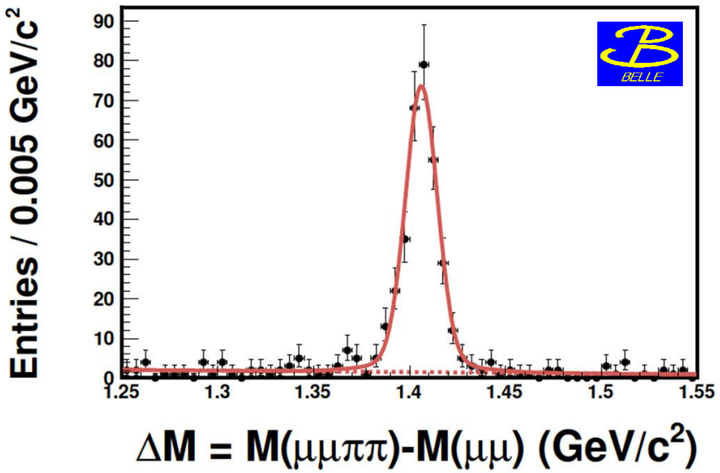
# How do we study quarkonium experimentally? Decay Modes

- Decay modes
  - Transitions: radiative ($\gamma$), hadronic ($\pi\pi$, $\pi^0$, $\eta$, …)
  - Below-threshold: ee/$\mu\mu$ and hadronic
  - Above-threshold: $D\bar{D}$/$B\bar{B}$ dominate

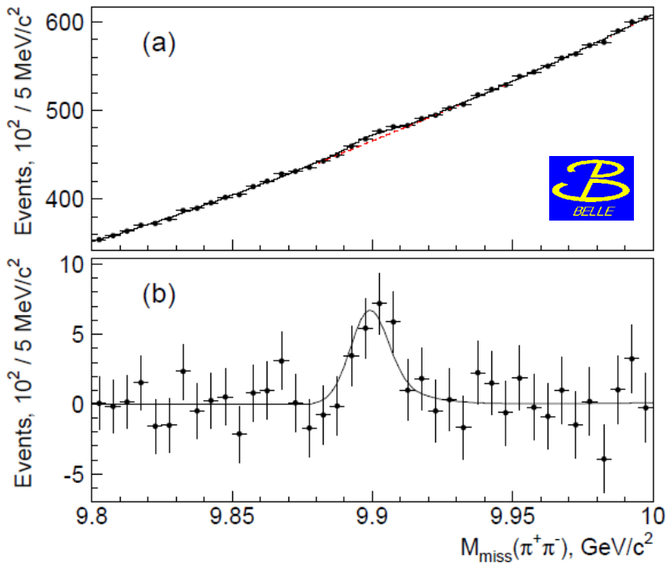
- Inclusive analyses (complete decay chain)
  - E.g.: $e^+e^- \to \pi^+\pi^-\Upsilon(pS) \to \mu^+\mu^-$
  - "Full Event Interpretation": collective B decays
  - Low statistics, but very clean

- Exclusive analyses ("missing" momentum)
  - E.g.: $e^+e^- \to \pi^+\pi^- X$
  - E.g.: $m_X = m_{miss} = \mathrm{sqrt}[(p_{ee} - p_{\pi\pi})^2]$
  - Knowledge of beam energy: full reconstruction not required

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

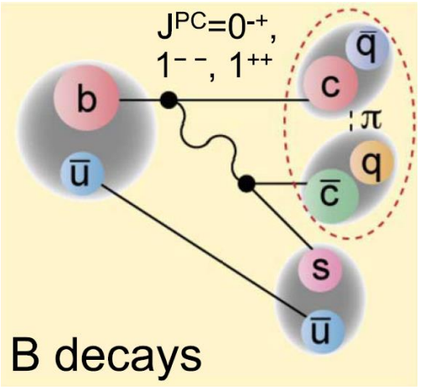


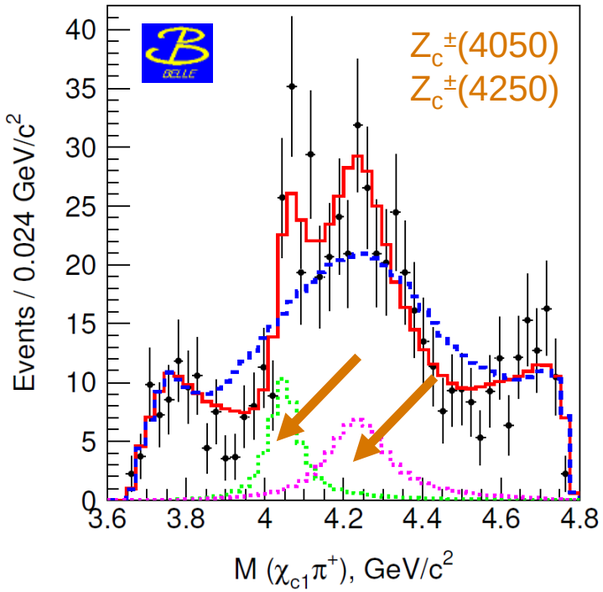

Inclusive $\Upsilon(5S) \to \pi^+\pi^- h_b(1P)$



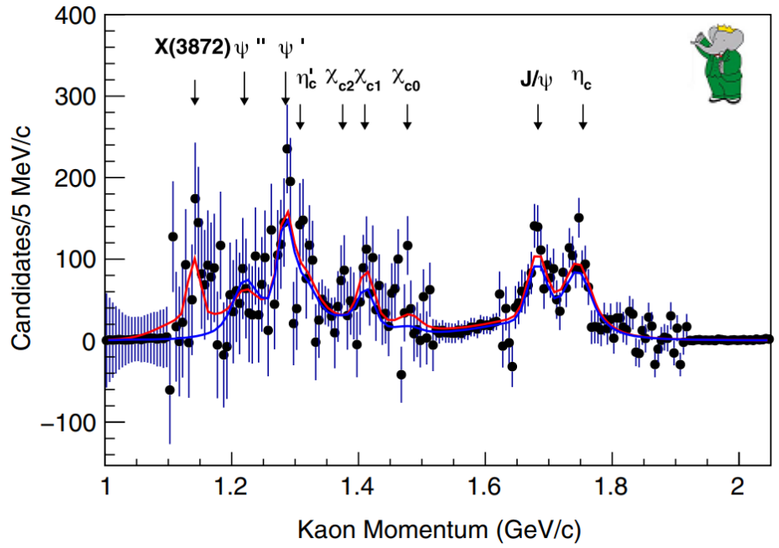
# Belle II Potential – B Decay

- High-statistics continuation from B-Factories
- Competition from LHCb, advantages for modes with neutrals
  - Confirm $Z_c$ states and search for neutral partners
  - Absolute branching fractions $B \to X(3872,3915)\, K$
  - X(3872) width and lineshape measurement with $D^0\bar{D}^0\pi^0$

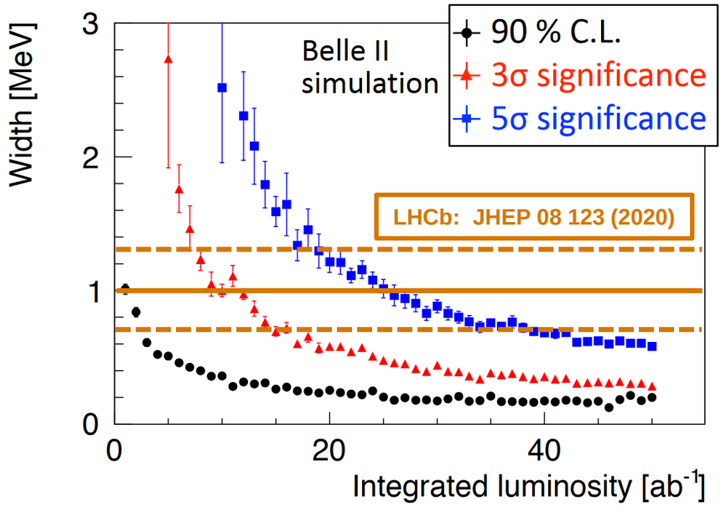



PRD 78, 072004 (2008)

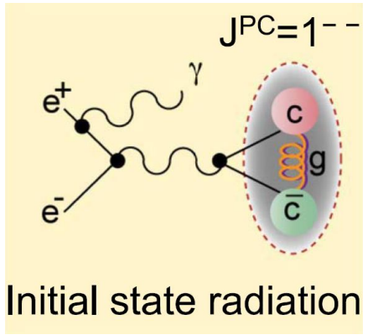



PRL 124, 152001 (2020)

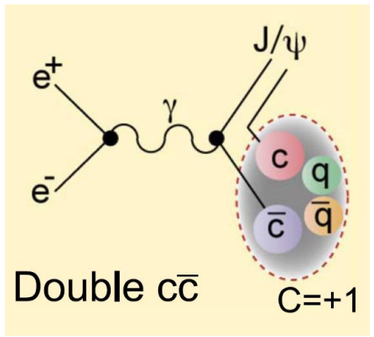



H. Hirata (KMI/Nagoya), MSc Thesis (2019)

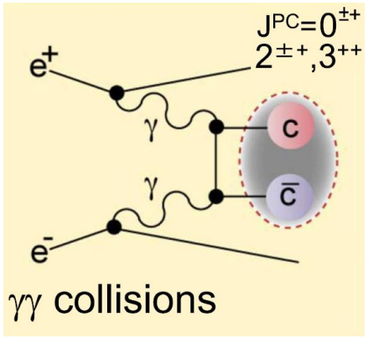
# Belle II Potential – Other Processes



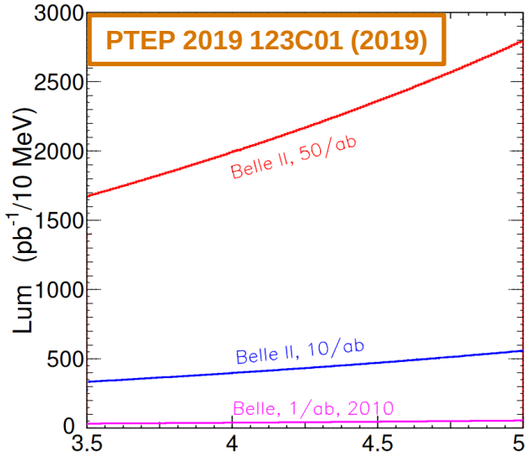

- ISR
  - Continuous mass range >4.9 GeV/$c^2$
  - Higher masses/channels (e.g. $\gamma_{ISR}\Sigma_c\bar{\Sigma}_c$)
  - Confirm $Z_c$ states (e.g. $e^+e^- \rightarrow h_c\pi\pi$)

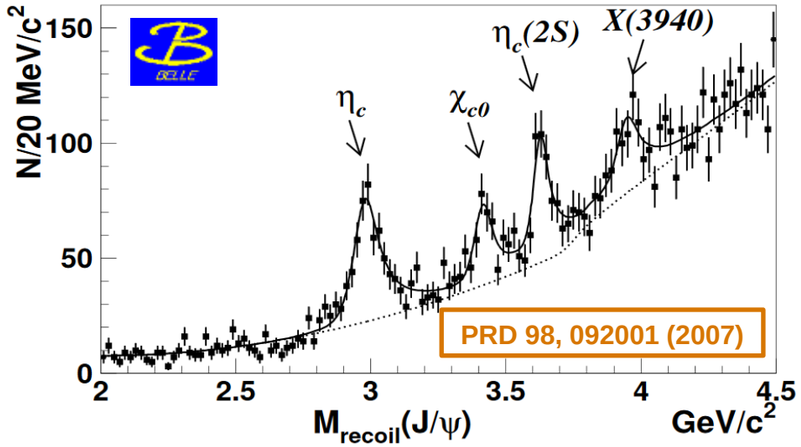


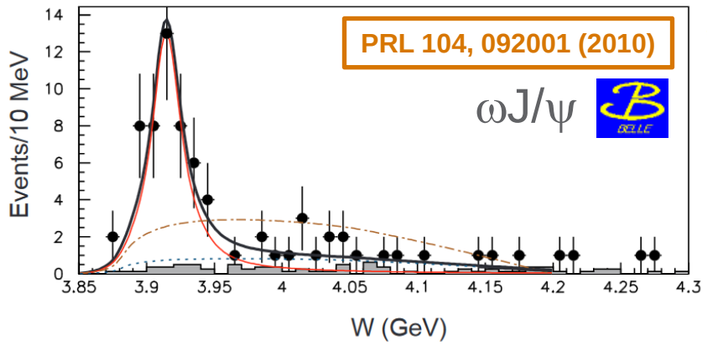

- Double-$c\bar{c}$
  - $e^+e^- \rightarrow (c\bar{c})_{J=1}(c\bar{c})_{J=0}$ production rule
  - Discovery of X(3940, 4160)
  - Expand to other $c\bar{c}$, search for new states

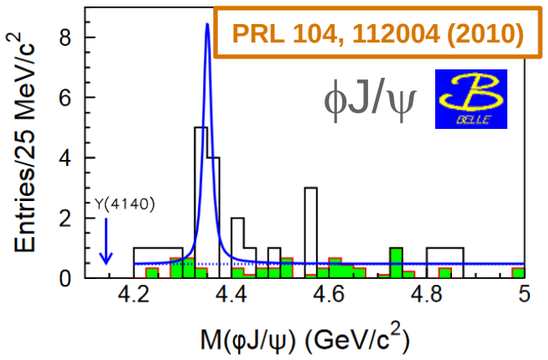



- Two-Photon
  - $J^{PC}$ of X(3915)
  - Confirm $\phi J/\psi$ state?
  - $D^{(*)}\bar{D}^{(*)}$ final states



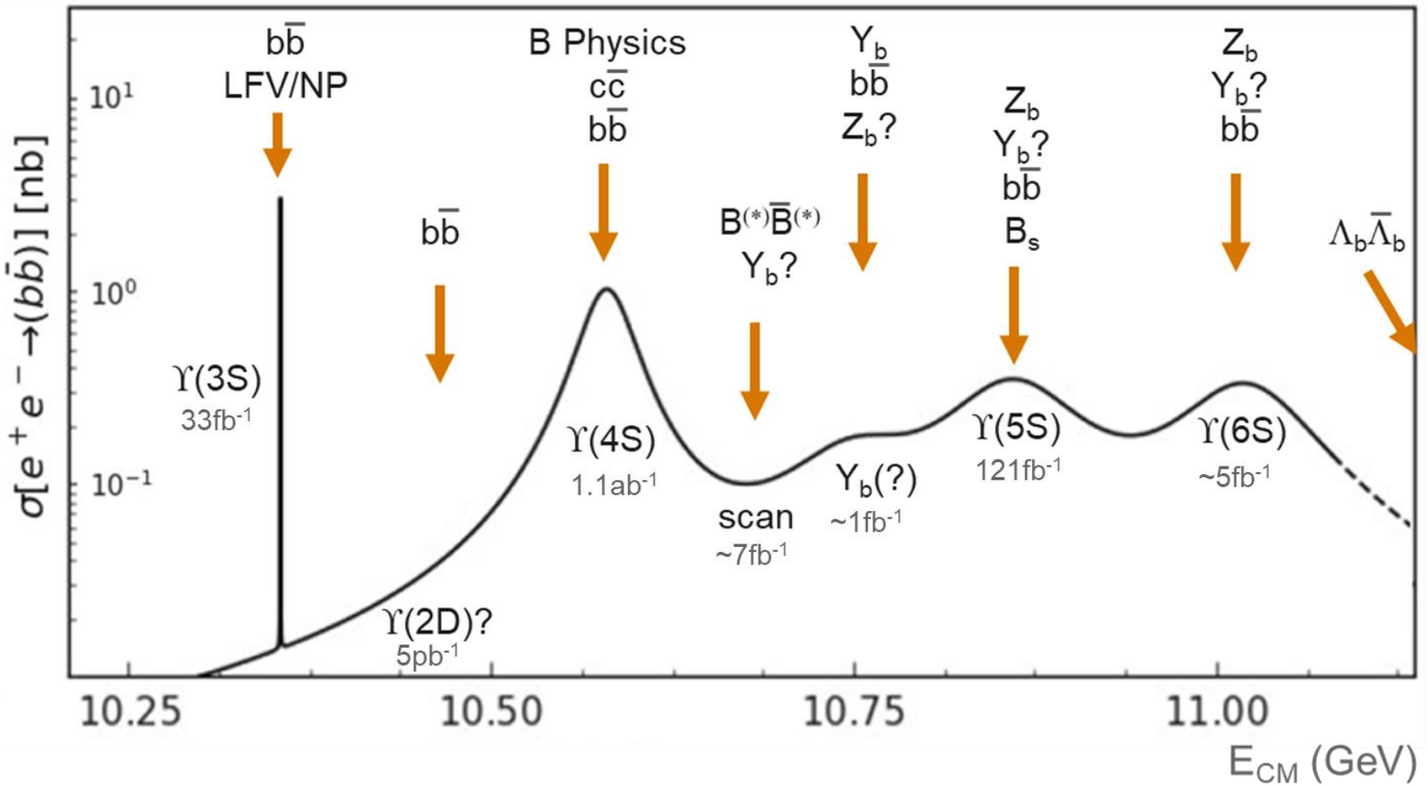



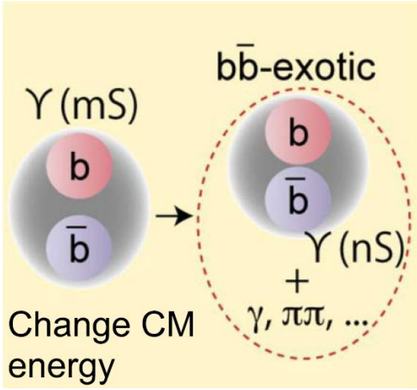



# Belle II Potential – Non-$\Upsilon(4S)$ Energies

- B-Factories extended their physics programs with non-$\Upsilon(4S)$ data
  - BaBar $\Upsilon(3S)$: discovery of $\eta_b(1S)$
  - Belle $\Upsilon(5S)$: discovery of $h_b(1P, 2P)$, $\eta_b(2S)$, $Z_b(10610, 10650)^{\pm}$
  - KEKB/Belle energy scan data: $Y_b(10753)$



# Belle II Potential – 10.75 GeV

- Belle: seven ~1fb$^{-1}$ scan points below $\Upsilon(5S)$
- New structure observed in $\pi^+\pi^-\Upsilon(\ell^+\ell^-)$ transitions

| | $\Upsilon(10860)$ | $\Upsilon(11020)$ | New structure |
|---|---|---|---|
| M (MeV/c$^2$) | $10885.3 \pm 1.5\,^{+2.2}_{-0.9}$ | $11000.0^{+4.0\,+1.0}_{-4.5\,-1.3}$ | $10752.7 \pm 5.9\,^{+0.7}_{-1.1}$ |
| $\Gamma$ (MeV) | $36.6^{+4.5\,+0.5}_{-3.9\,-1.1}$ | $23.8^{+8.0\,+0.7}_{-6.8\,-1.8}$ | $35.5^{+17.6\,+3.9}_{-11.3\,-3.3}$ |

- Varying $B\bar{B}$ cross sections

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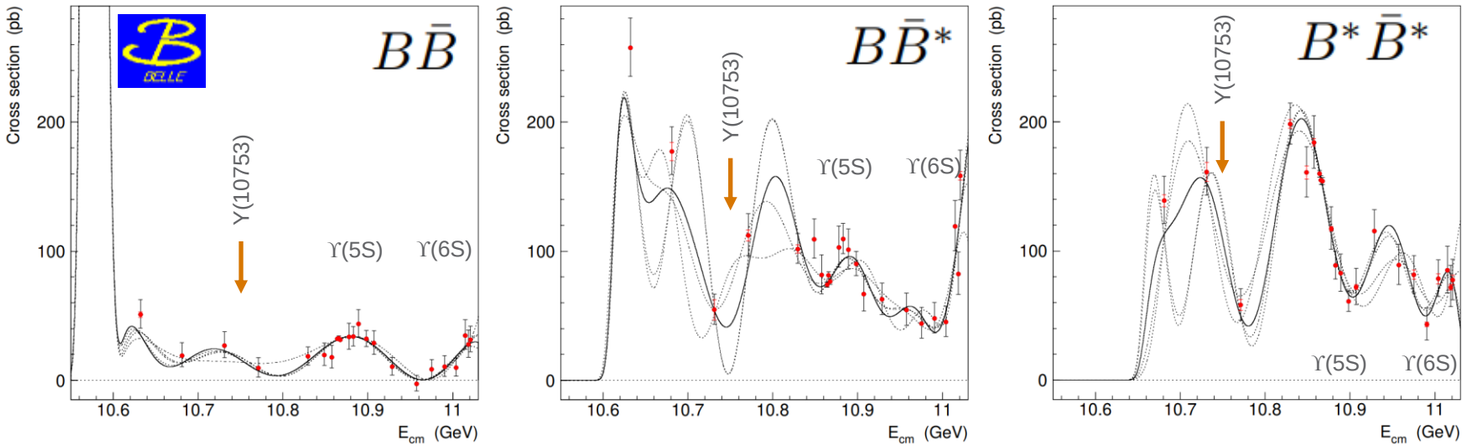
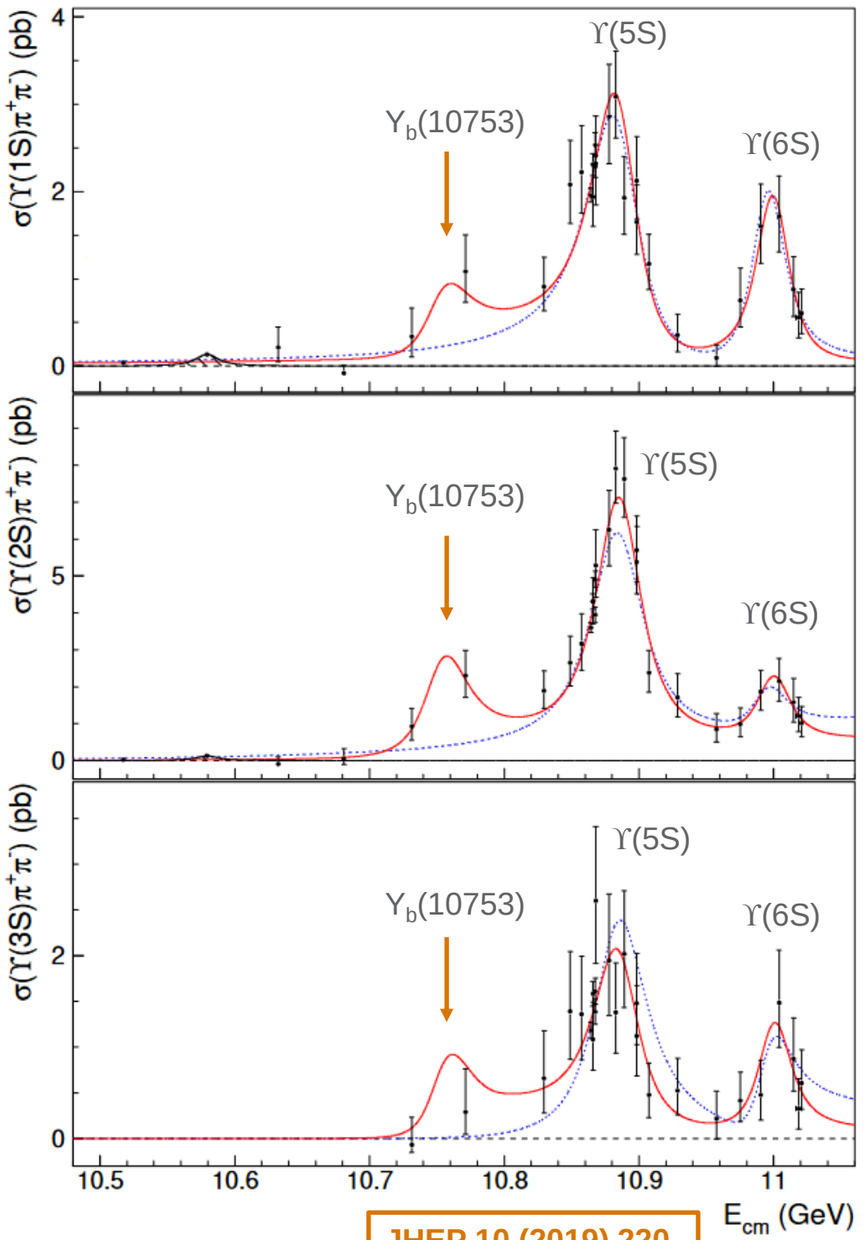



- Revisit this energy region with greater statistics

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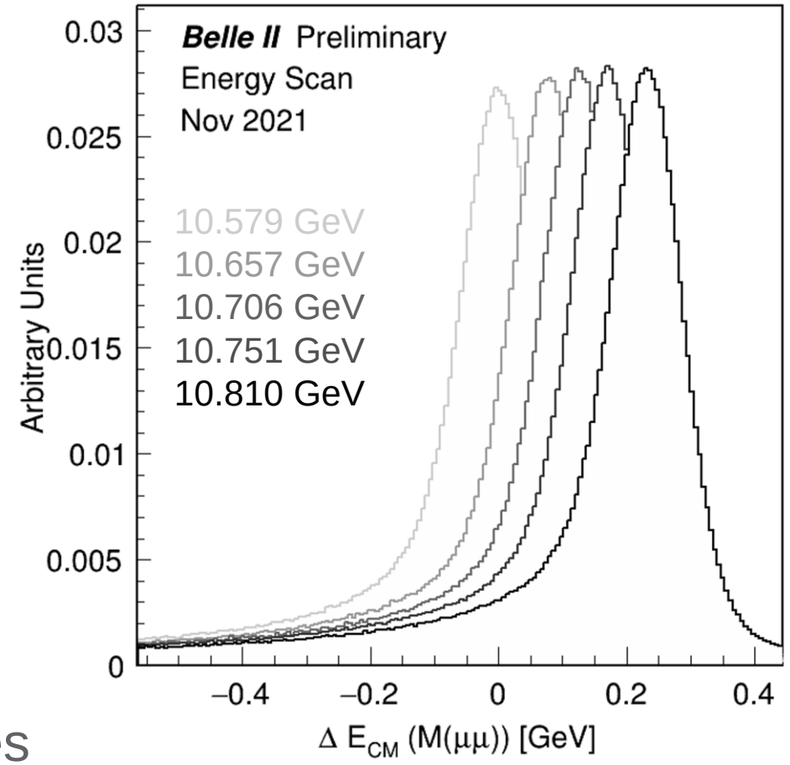
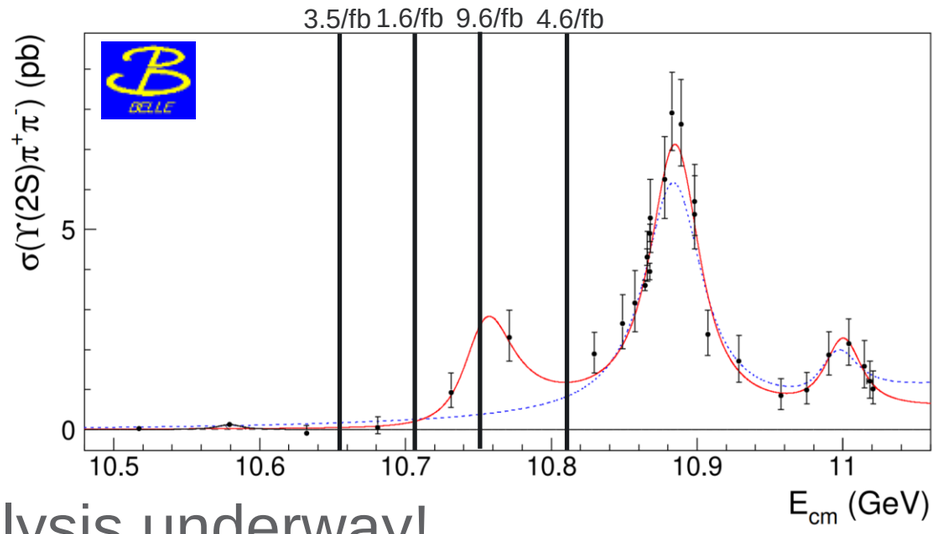
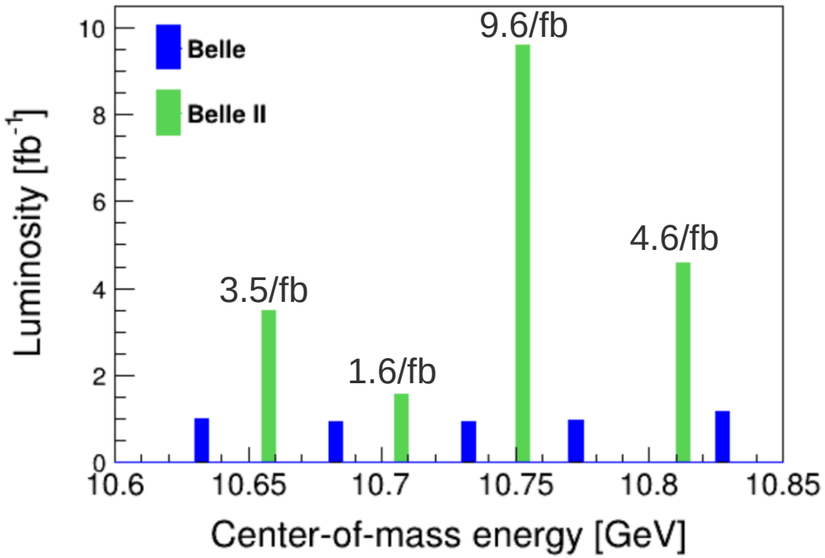
# Belle II Energy Scan
# Nov. 10-29, 2021 (JST)

- Considerations
  - Potential for early physics impact by Belle II
  - Limited luminosity requirement (O(15/fb))
  - $\Upsilon$(6S) requires accelerator infrastructure upgrade
- Energy scan operation was successful
  - Unique high stat. points between previous Belle energies
- Data analysis underway!



# Snowmass Context: Charmonium(-like) Future

- B-Factories started the XYZs…but do not hold a monopoly!
  - Many statistics dominated B-decay modes covered by LHCb
  - BES III energy scans extending range above 4.9 GeV
- Still well-known for this legacy (e.g., X(3872) still the most cited paper), and essential for full understanding of these new states

- Key future contributions
  - Modes with neutrals (e.g., neutral Z partners, $\pi^0$ transitions/decays)
  - Unique double-charmonium ($e^+e^- \to c\bar{c}\, c\bar{c}$) and two-photon ($e^+e^- \to e^+e^-\, c\bar{c}$) production
  - Statistics-dominated: results will come with additional luminosity

# Snowmass Context: Bottomonium(-like) Future

- Belle II holds a special advantage
  - Able to exploit tunable beam energy in 9.4 – 11.2 GeV energy region
  - Main possibility to study $\Upsilon$, $Y_b$, and $Z_b$ states
  - Understanding of relationship between c- and b-sector spectroscopy

- Ability to run at non-$\Upsilon(4S)$ energies has been demonstrated
- Opens multiple possibilities
  - Revisit $\Upsilon(6S)$ with 10x+ statistics
  - LFV/spectroscopy in $\Upsilon(2S,3S)$ decays
  - Higher statistics scan of entire region and $\Upsilon(5S)$
  - $E_{CM}$ to $\Lambda_b\bar{\Lambda}_b$ (beyond requires SuperKEKB upgrades)

# Summary

- Current Status
  - Initial quarkonium physics rediscoveries as performance benchmarks
  - Operation through the next 10 years with detector/accelerator upgrades
  - Above-$\Upsilon$(4S) scan available for spectroscopy studies

- Next Steps / Desired Outcomes
  - Use success of energy scan to promote $\Upsilon$(6S) and other runs
  - Focus on long-term luminosity goals for 10-year Snowmass process
  - Discoveries/precision measurements of quarkonium(-like) particles
  - Ensure continued support for US program

- Belle II is one of the experimental pillars of modern hadron spectroscopy

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# Thank you