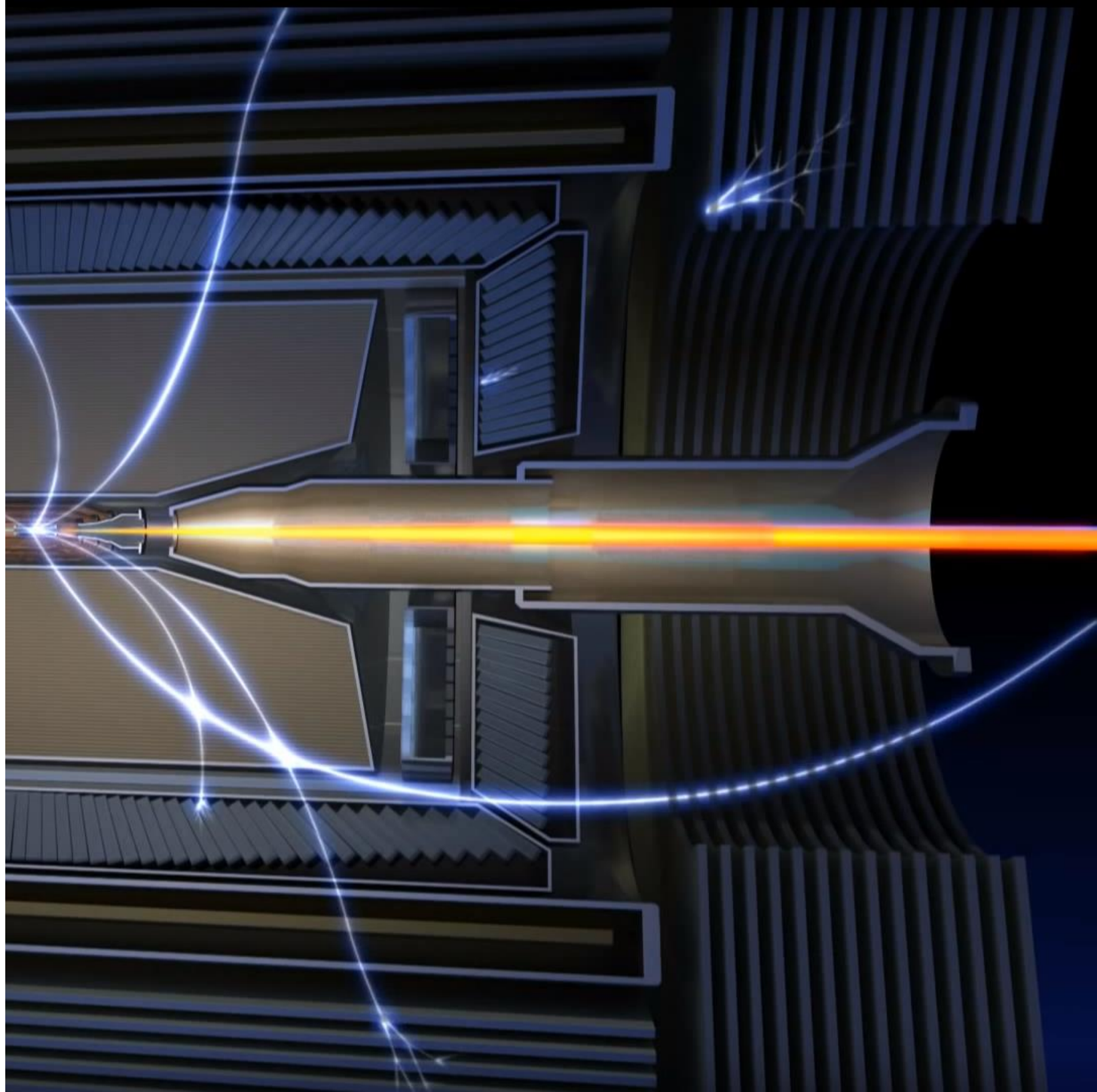
Pacific Northwest
NATIONAL LABORATORY

Belle II Results and Plans

Aug 15, 2022

Bryan Fulsom (PNNL)

Exotic heavy meson spectroscopy
and structure with EIC
Stony Brook, NY
Aug 15-19, 2022



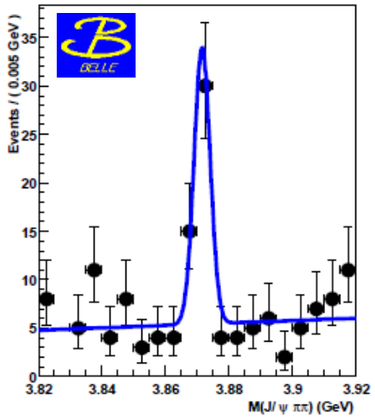
U.S. DEPARTMENT OF ENERGY BATTELLE

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

B-Factories Legacy

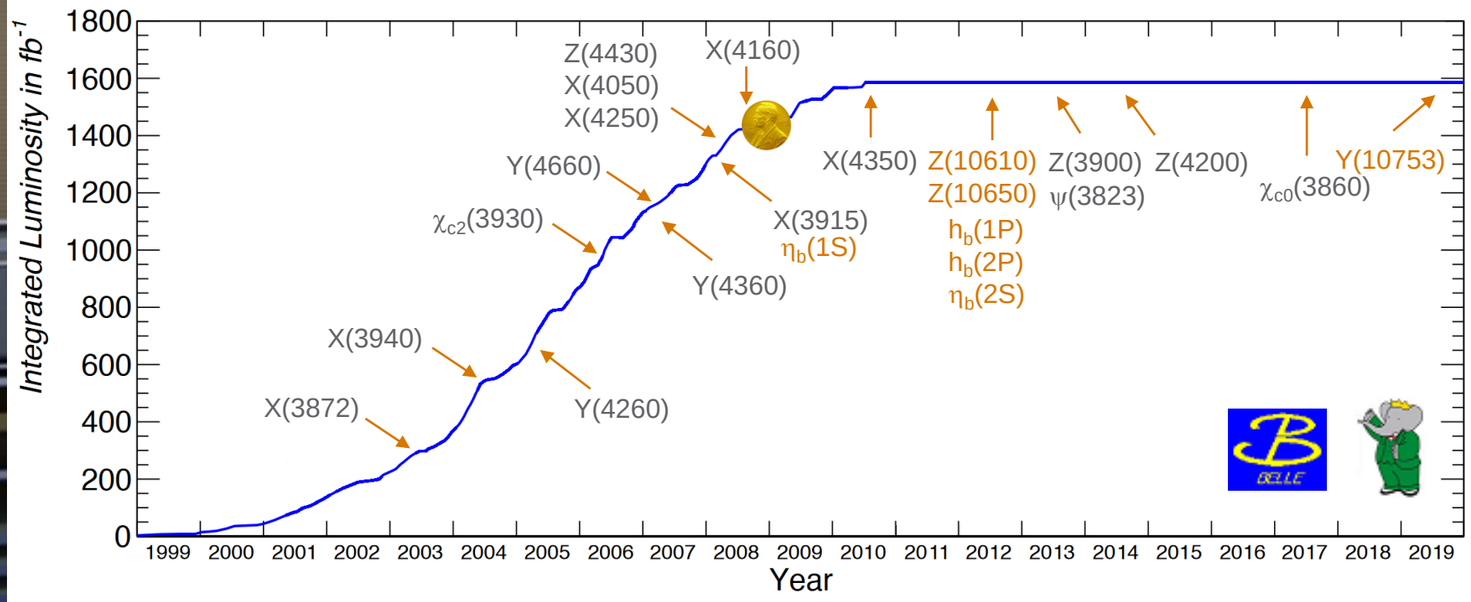
e.g.: “The Physics of the B Factories”, EPJC 74, 3026 (2014)

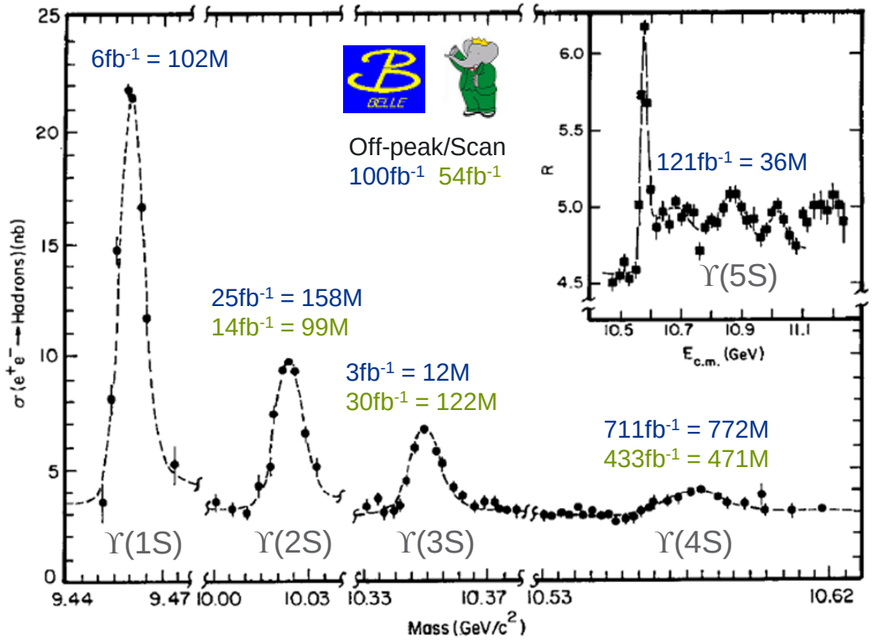
- 1999~2011 : BaBar (SLAC) & Belle (KEK)
- Flavor physics: CKM/UT, CPV in B decays
- Possible hints for NP in rare processes
- New particle discoveries: “XYZ” states



X(3872): Most cited Belle paper (~1900)

PRL 91, 262001 (2003)

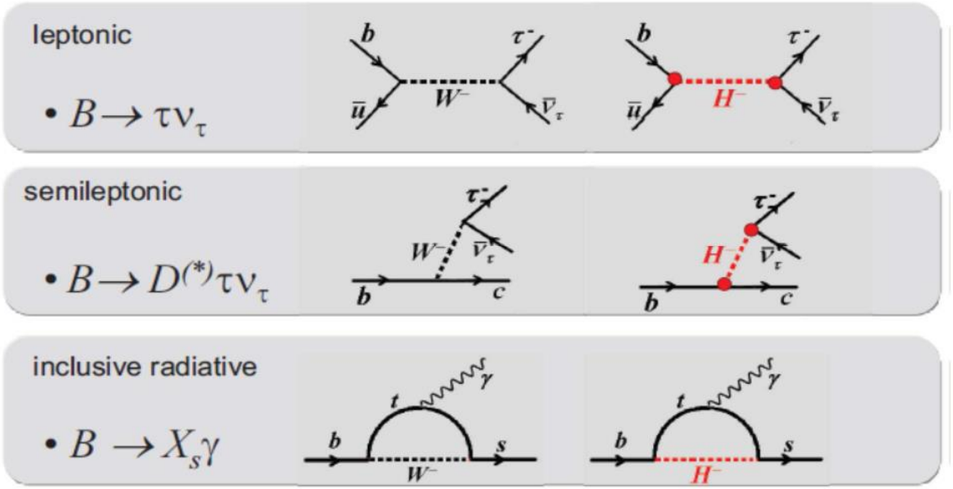




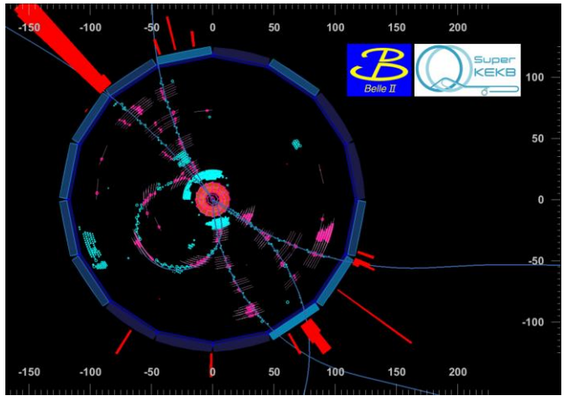
Motivations for a next-generation B Factory

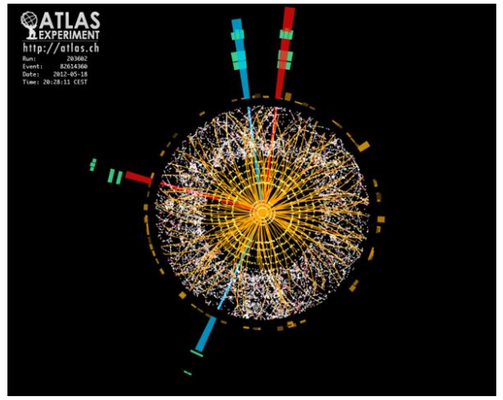
- Broad physics program
  - New Physics in precision/rare B meson decays
  - Dark sector particle searches
  - Spectroscopy of exotic QCD
  - …and more

"The Belle II Physics Book", PTEP 2019, 123C01 (2019)
"Belle II physics reach and plans for the next decade and beyond", SNOWMASS 2021 White Paper (2022)



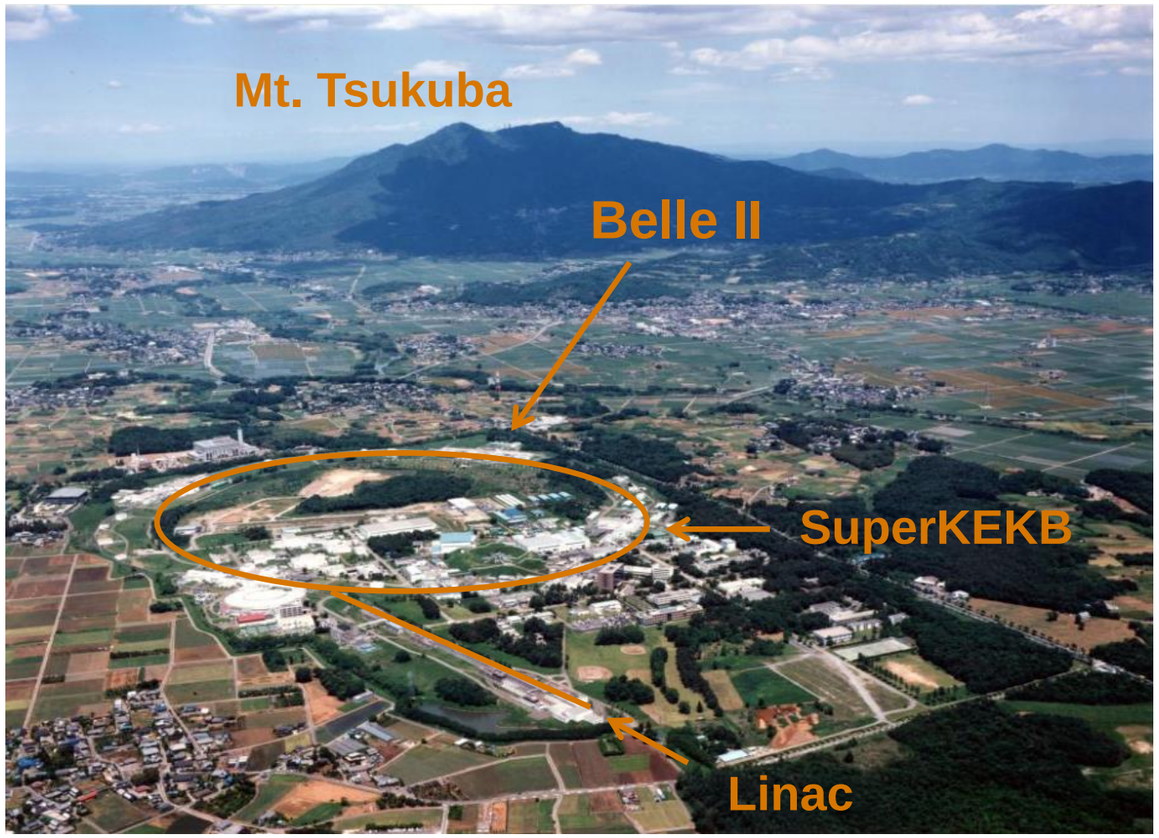
- Advantages of Belle II
  - "Clean" environment
  - Full event reconstruction
  - Decay with neutrals (γ, π^0, K_L, ν) in final state
  - Large statistics
  - Complementary to LHC





The Belle II Collaboration

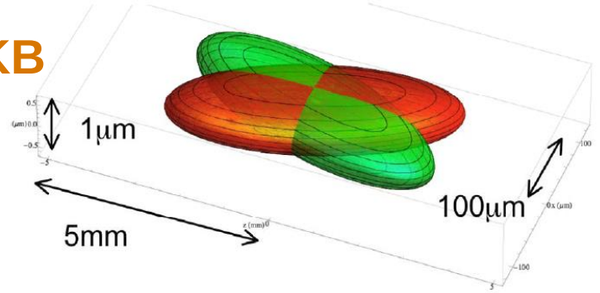
- Experiment located at KEK in Tsukuba, Japan
- 1100+ members, 123 institutions, 26 countries



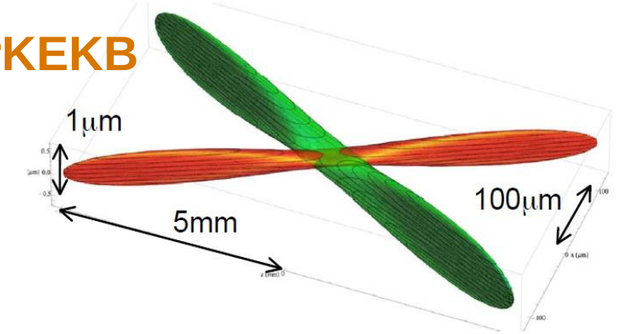
Accelerator Upgrade

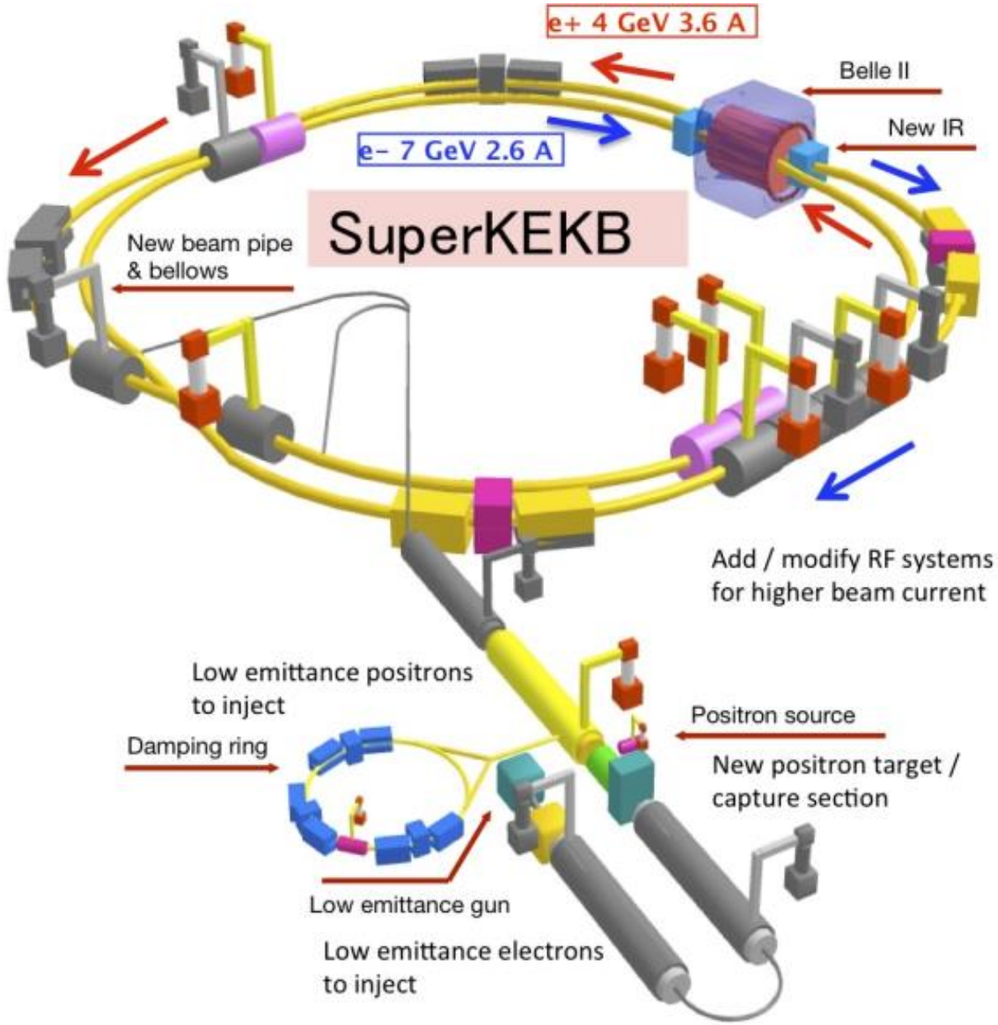
- SuperKEKB Upgrade
  - “Nano-beam” interaction point
  - Increase in current
  - Goal: factor of 40x increase in luminosity
  - Nominal energy: e^- (7 GeV) e^+ (4 GeV)

KEKB



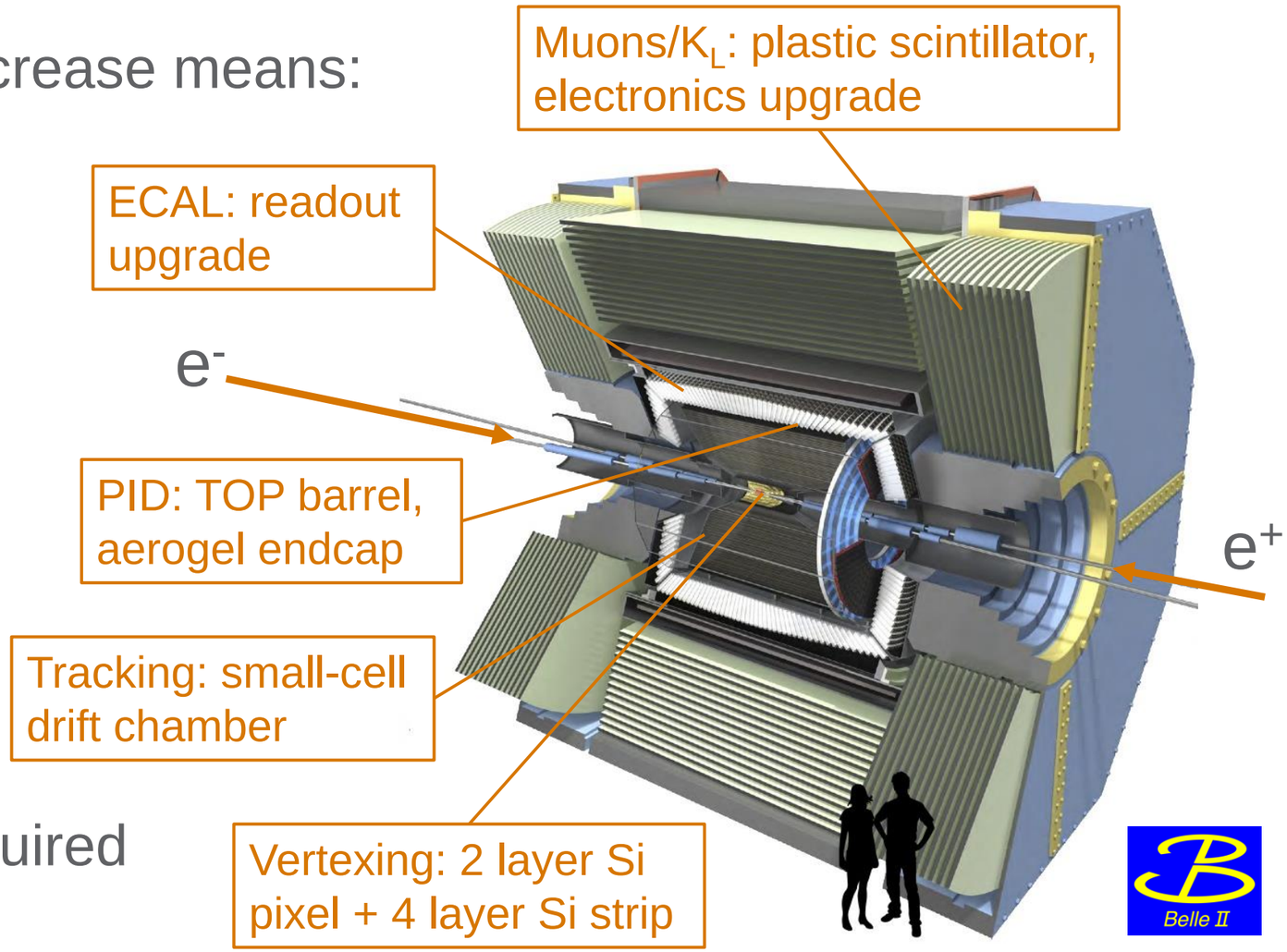
SuperKEKB





Belle II Detector Rebuild

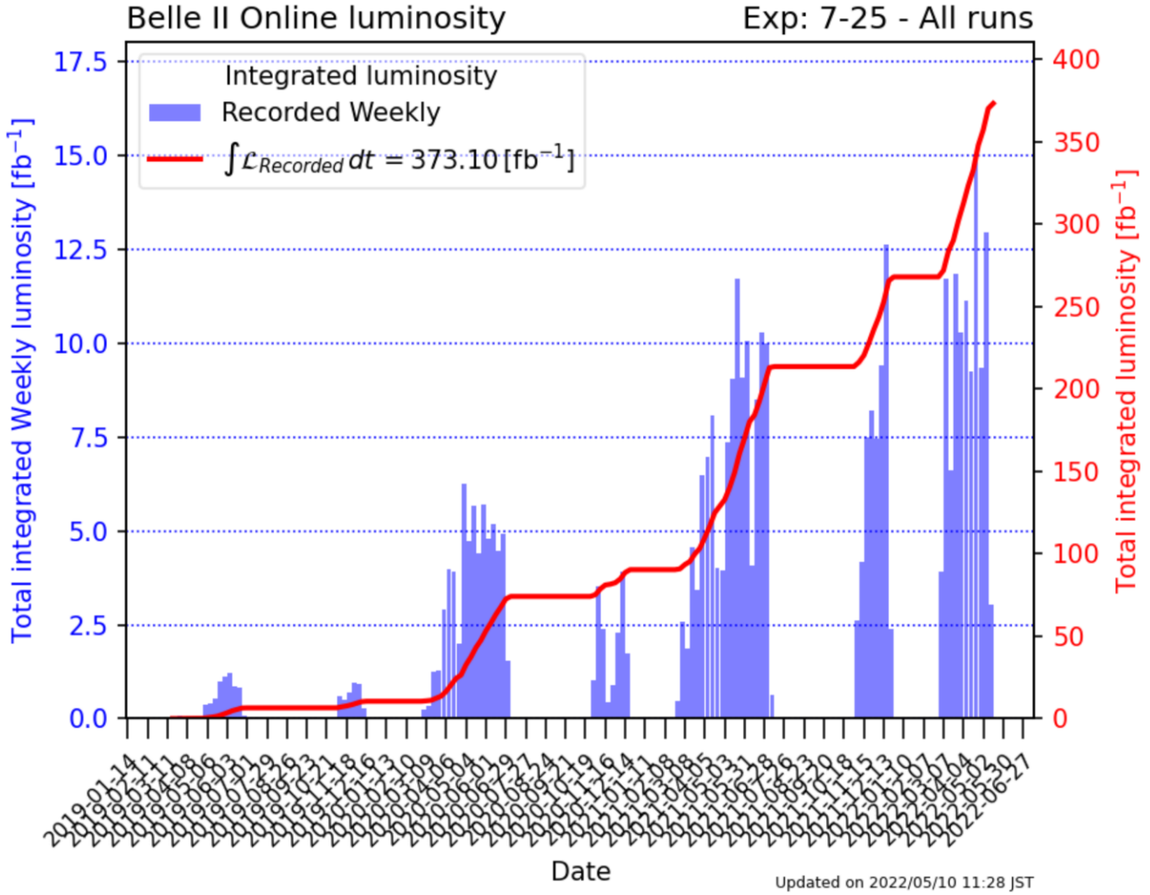
- Order of magnitude luminosity increase means:
  - Higher background
    - ✓ Radiation damage
    - ✓ Detector readout
  - Higher event rate
    - ✓ Trigger, DAQ, computing
  - Boost change
    - ✓ Improve vertexing
- Significant detector upgrades required



arXiv:1011.0352 (2011)

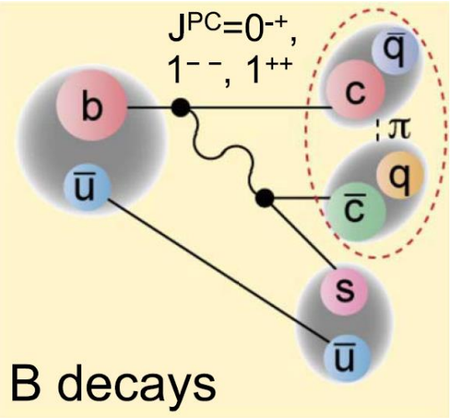
Belle II Timeline

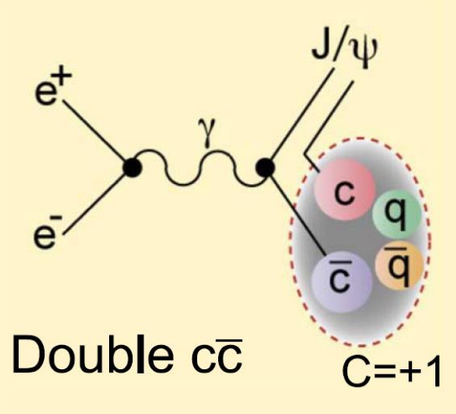
- 2016: “Phase 1”: Beam commissioning
- 2017: Detector roll-in
- 2018: “Phase 2”
  - Background study w. partial detector
  - First collisions/data
- 2019: “Phase 3”
  - Nominal start of operations
  - 2021: Inst. lumi. record: >4.7x$10^{34}$$cm^{-2}s^{-1}$
  - 2021: Non-Υ(4S) Energy scan
- 2022-2023: “Long Shutdown 1”
  - Detector/accelerator upgrades
- 2023~2027: Resume operations, target: 5 ab^{-1}
- 2027+: “Long Shutdown 2” upgrade (?), continue up to 50 ab^{-1}

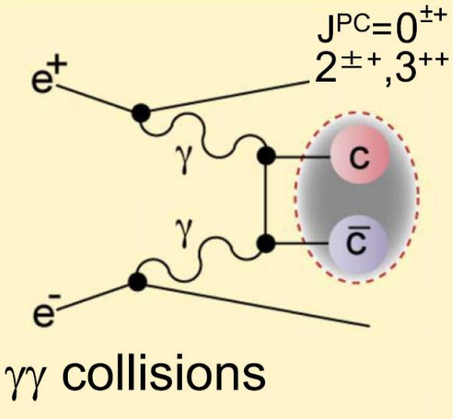


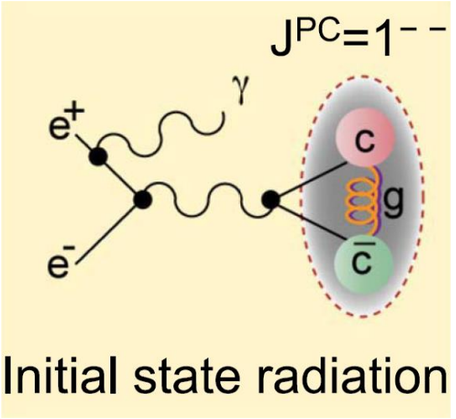
How do we study quarkonium experimentally? Production Mechanisms

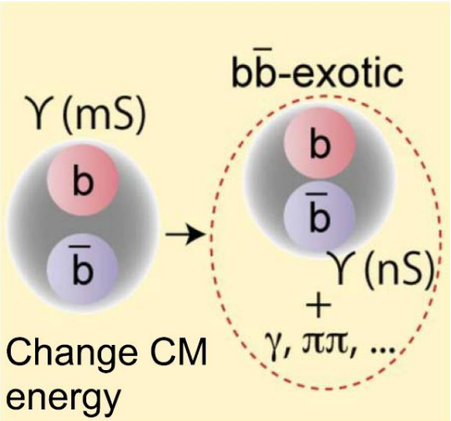
- Multiple methods to produce quarkonium/exotics at Belle II
- Production mode provides important information (e.g. J^{PC}, type)











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

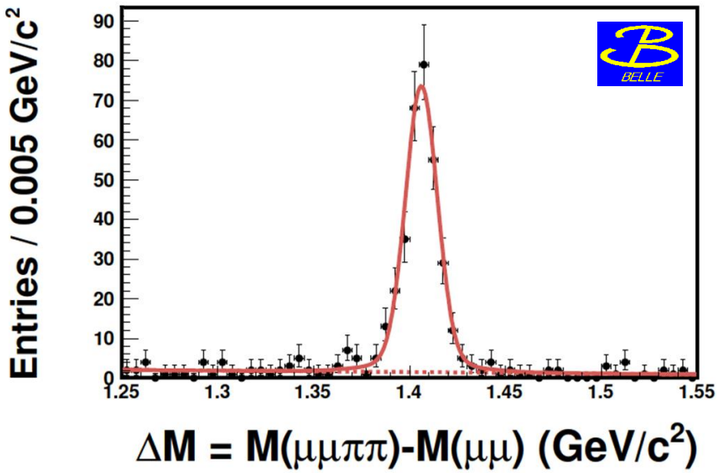
How do we study quarkonium experimentally? Decay Modes

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

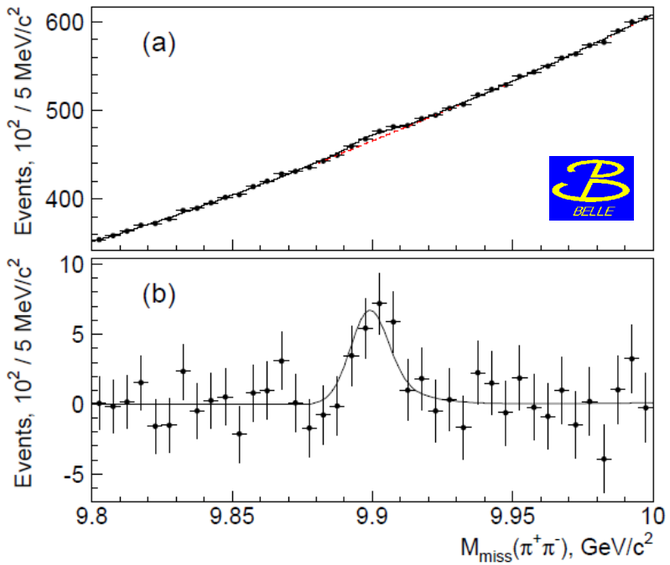
- Inclusive analyses (complete decay chain)
  - E.g.: $e^+e^- \to \pi^+\pi^-\Upsilon(pS) \to \mu^+\mu^-$
  - "Full Event Interpretation": collective B decays
  - Low statistics, but very clean

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

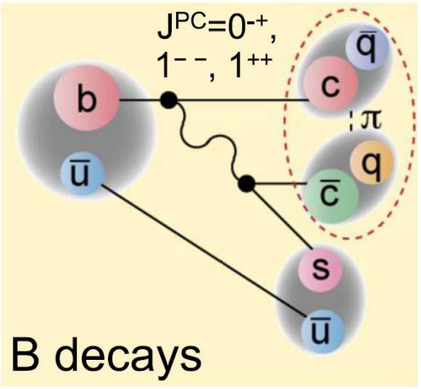


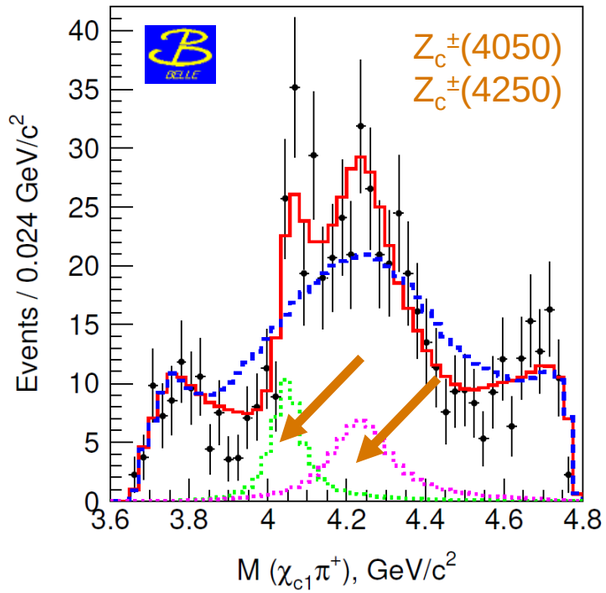
Inclusive $\Upsilon(5S) \to \pi^+\pi^- h_b(1P)$



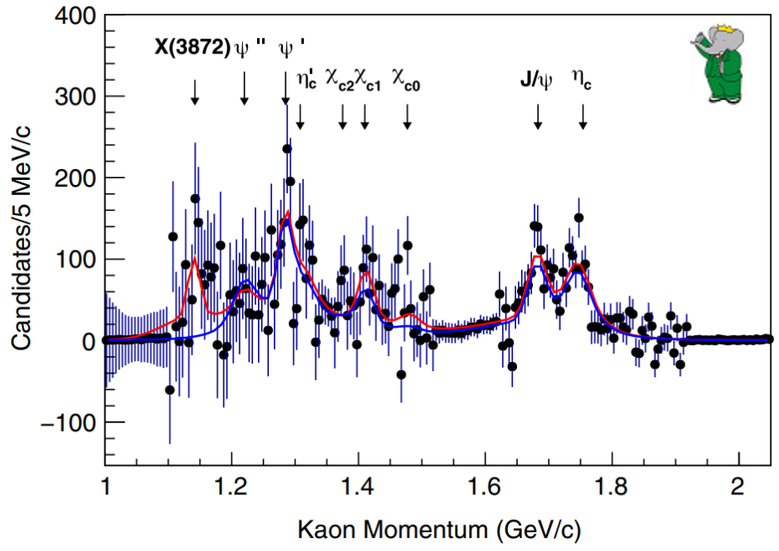
Belle II Potential – B Decay

- 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 → X(3872,3915) K
  - X(3872) width and lineshape measurement with $D^0\bar{D}^0\pi^0$

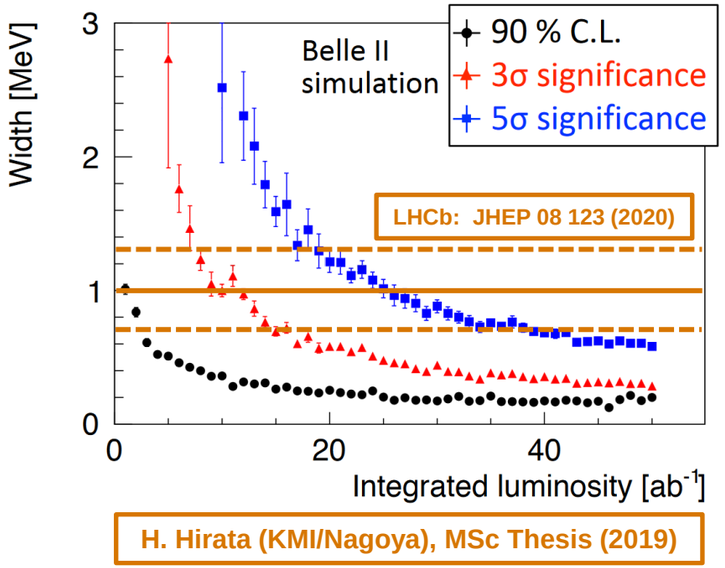




PRD 78, 072004 (2008)

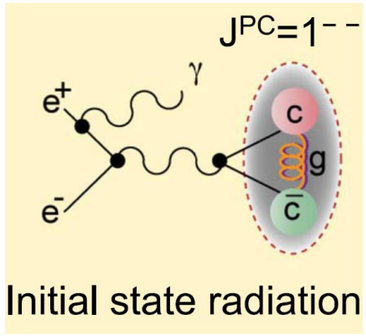


PRL 124, 152001 (2020)

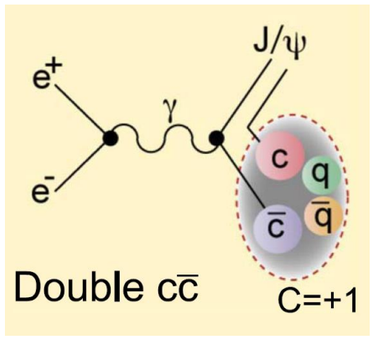


H. Hirata (KMI/Nagoya), MSc Thesis (2019)

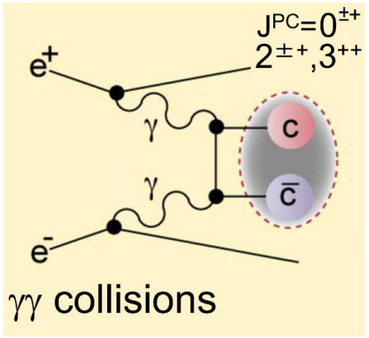
Belle II Potential – Other Processes



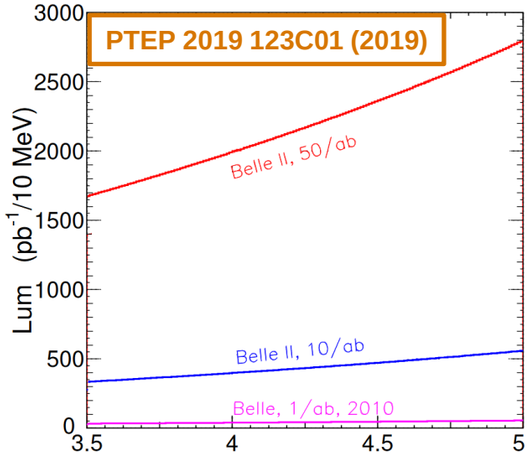
- ISR
  - Continuous mass range >4.9 GeV/c^2
  - Higher masses/channels (e.g. $\gamma_{ISR}\Sigma_c\bar{\Sigma}_c$)
  - Confirm Z_c states (e.g. $e^+e^- \rightarrow h_c\pi\pi$)

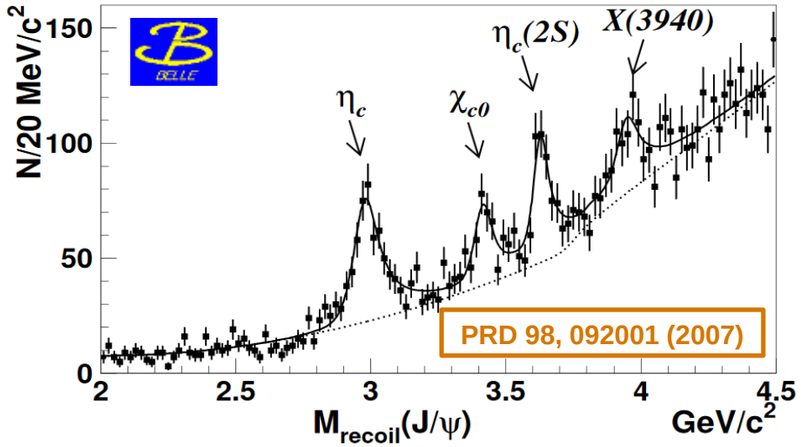


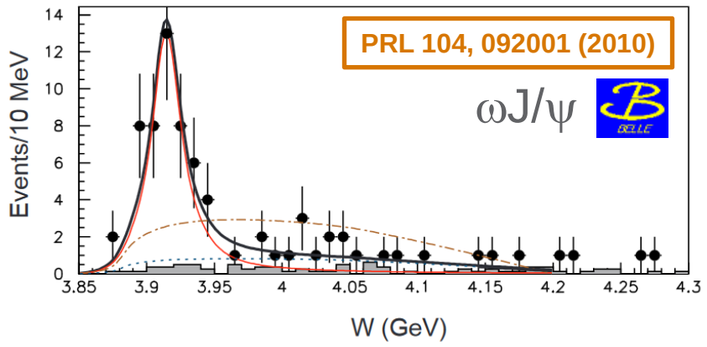
- Double-$c\bar{c}$
  - $e^+e^- \rightarrow (c\bar{c})_{J=1}(c\bar{c})_{J=0}$ production rule
  - Discovery of X(3940, 4160)
  - Expand to other $c\bar{c}$, search for new states

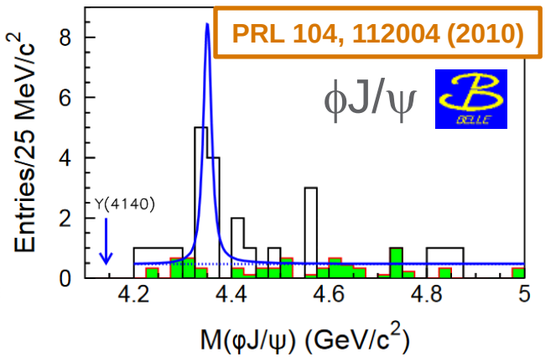


- Two-Photon
  - J^{PC} of X(3915)
  - Confirm $\phi J/\psi$ state?
  - $D^{(*)}\bar{D}^{(*)}$ final states



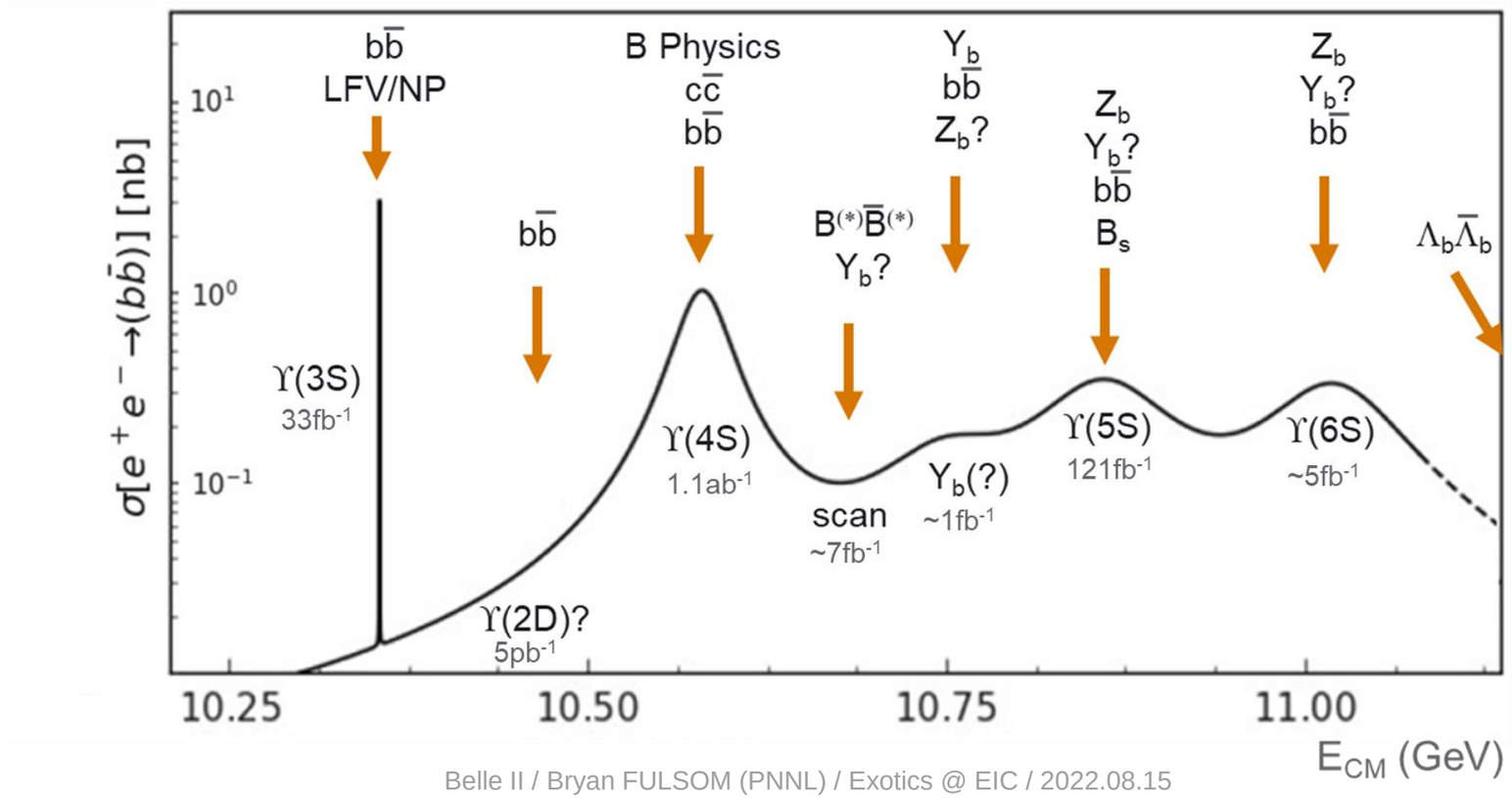


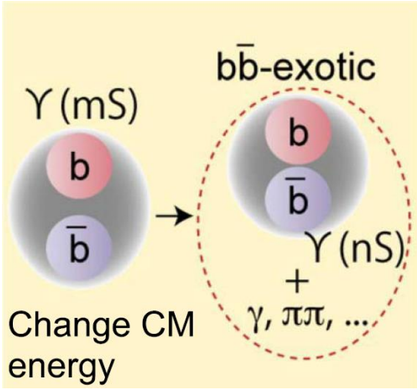




Belle II Potential – Non-$\Upsilon(4S)$ Energies

- 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)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0\,+1.0}_{-4.5\,-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (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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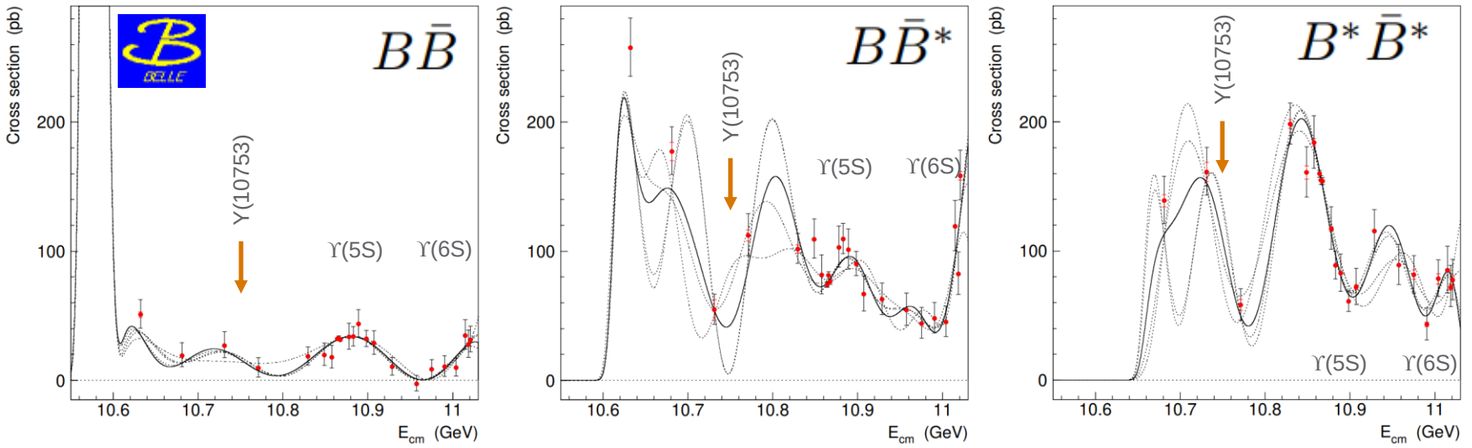
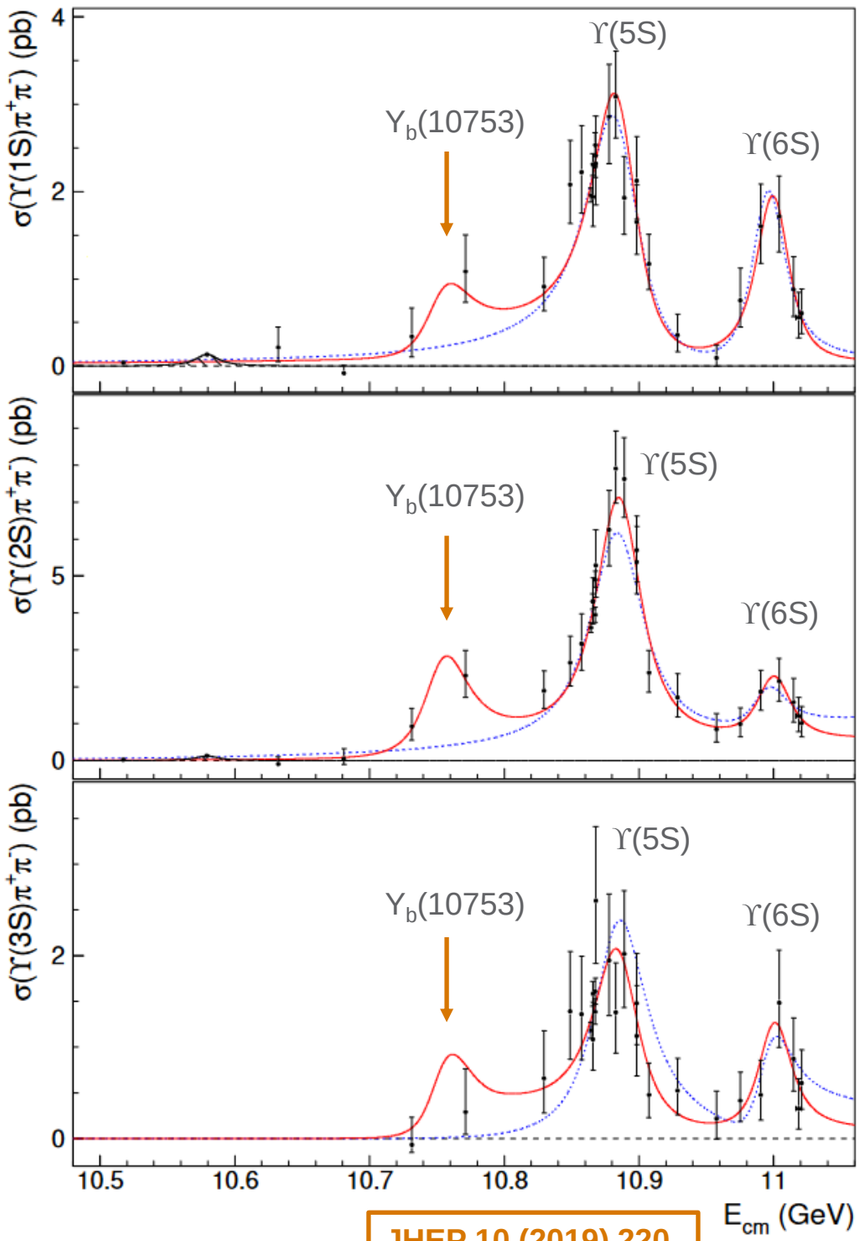


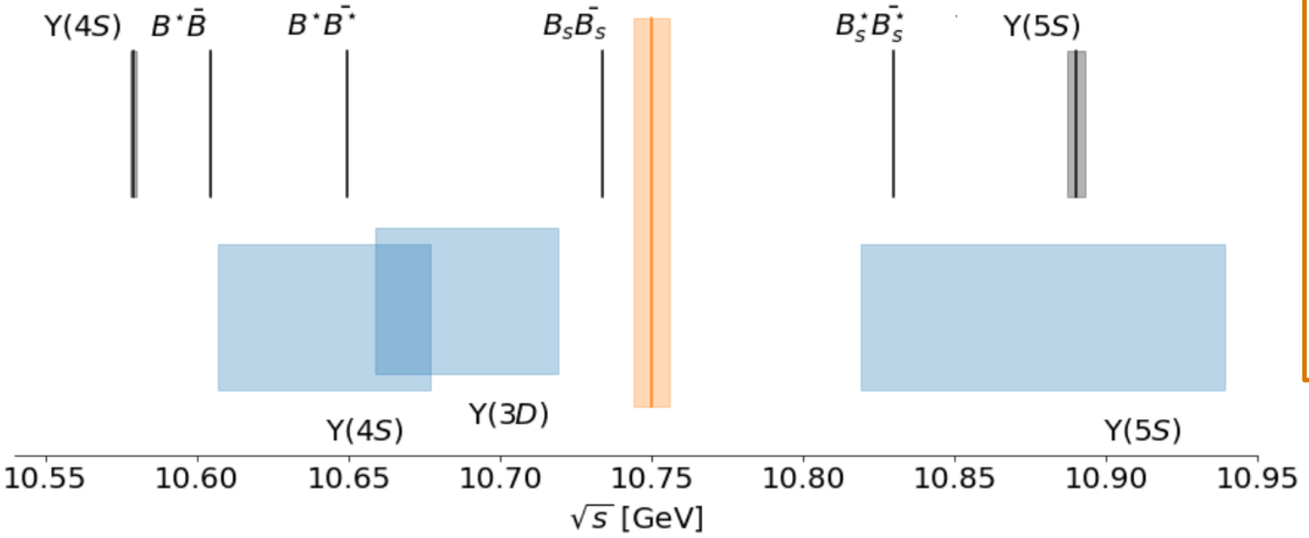
- Revisit this energy region with greater statistics



JHEP 10 (2019) 220

Why is the $Y_b(10753)$ important?

- Uncertain nature
  - Molecular interpretation? Does not coincide with a threshold...
  - No clear conventional bb candidate
  - Potential tetraquark?



Conventional interpretations:
Chen, Zhang & He, PRD 101, 014020 (2020)
Li et al., EPJC 80, 59 (2020)
Liang, Ikeno & Oset, PLB 803, 135340 (2020)

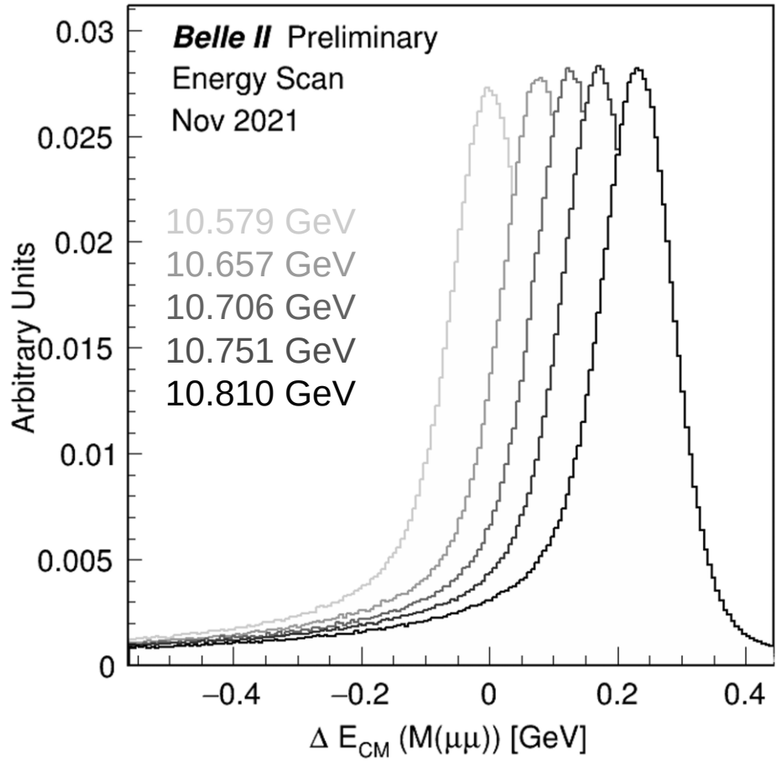
"Exotic" interpretations:
Wang, CPC 43, 123102 (2019)
Ali, Maiani, Parkhomenko & Wang, PLB 802, 135217 (2020)
Bicudo, Cardoso & Wagner, arXiv:2008.05605 (2020)
Giron & Lebed, PRD 102, 014036 (2020)

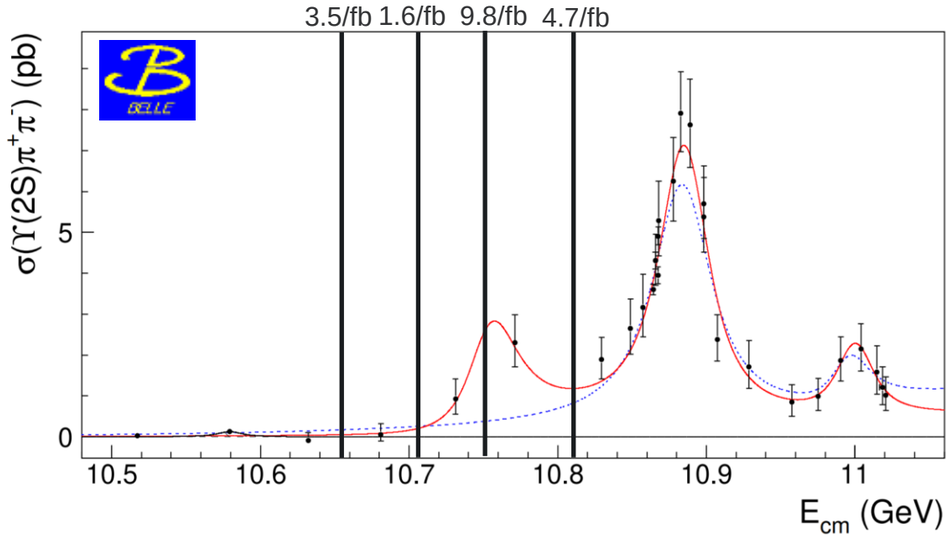
…

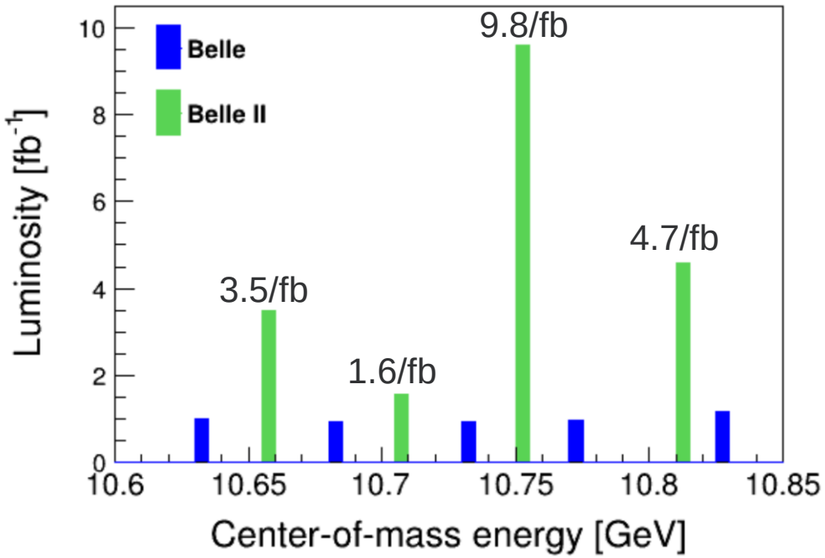
- Big picture: relationship to puzzles in XYZ/charmonium system

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

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

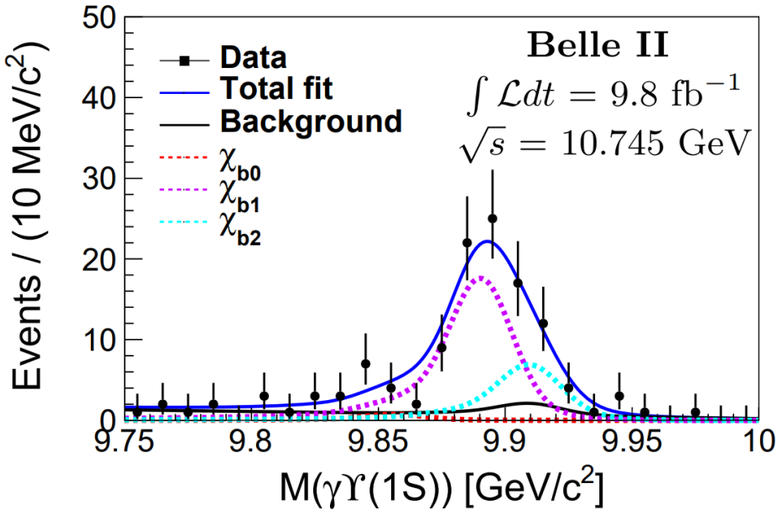


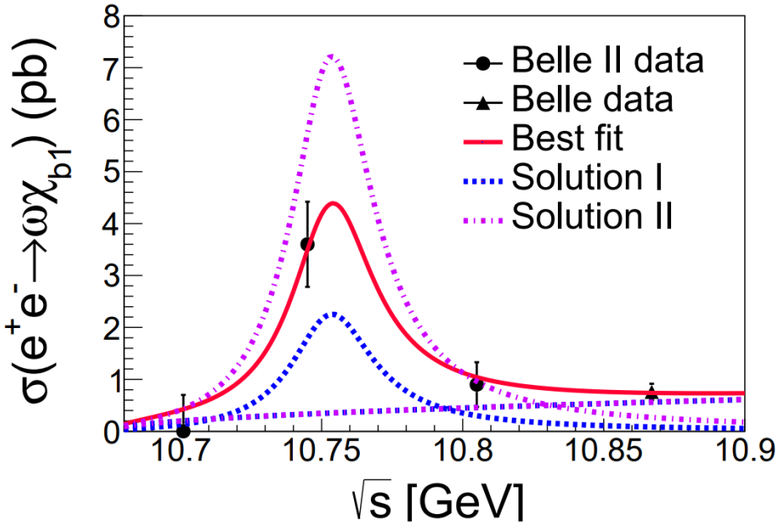


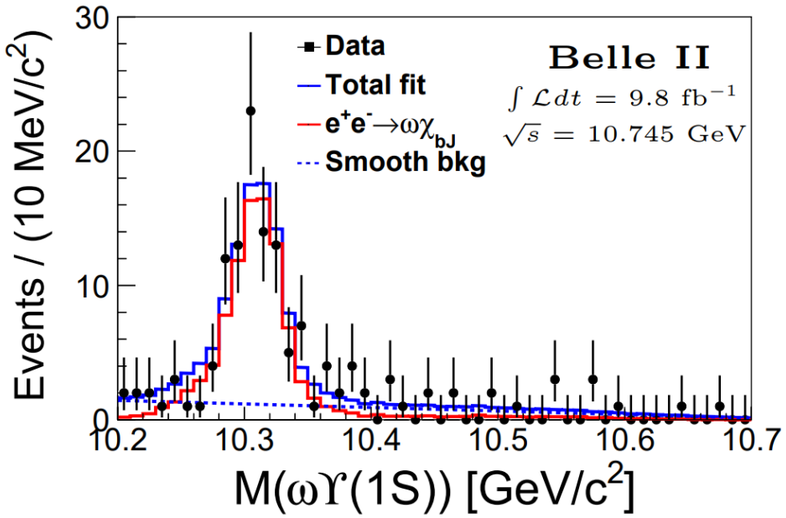


Belle II Energy Scan – First Results
Observation of $e^+e^- \to \omega\chi_{bJ}$ and search for $X_b \to \omega\,\Upsilon(1S)$

- Theoretical Predictions
  - $\mathcal{B}(\Upsilon(10753) \to \omega\chi_{bJ}) \sim 10^{-3}$ predicted for 4S-3D $b\bar{b}$ mixture
  - BESIII: $e^+e^- \to \Upsilon(4220) \to \pi\pi J/\psi$, $\gamma X(3872)$, $\omega\chi_{c0}$ …implies X(3872) partner "X_b"?
- Belle II Results







  - Observation of $\omega\chi_{b1,2}(\gamma\Upsilon(1S))$ decay in energy scan data
  - Born cross section consistent with Y(10753) enhancement
  - No evidence for $\gamma X_b \to \omega Y(1S)$

Belle II Energy Scan – Future Results

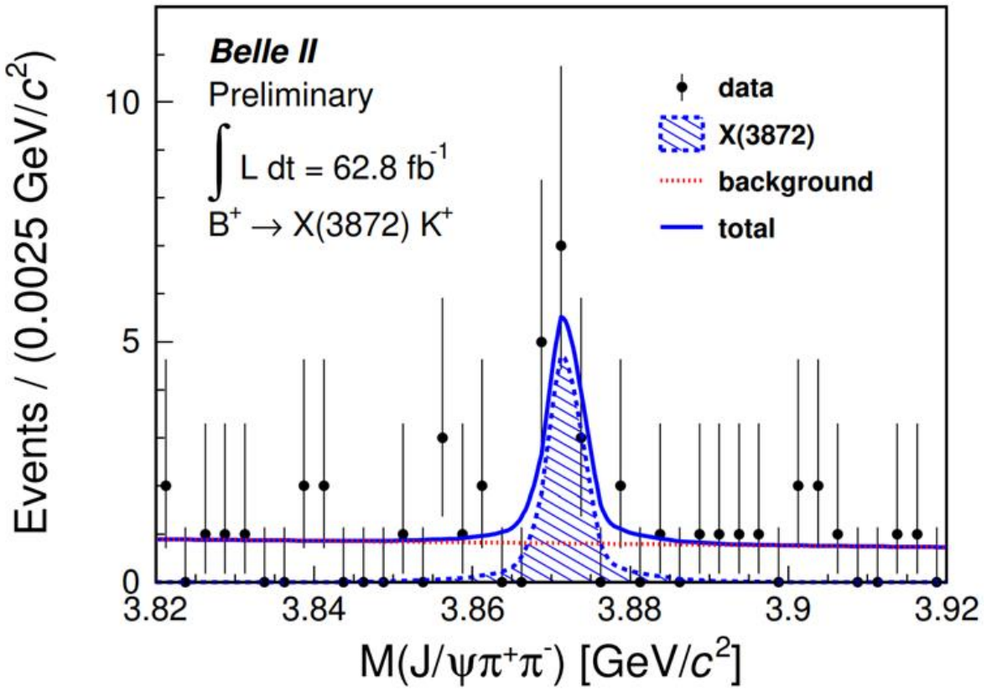
- Active analyses based on energy scan data
  - Quarkonium spectroscopy (conventional and exotic)
  - Hadronic and radiative transitions
  - Inclusive and exclusive final states
  - Precision study of vector bottomonium

- Data at Υ(6S)
  - Accelerator upgrades during “Long Shutdown”
  - 11 GeV will be accessible
  - Revisit this region with 10x statistics?

Golden Modes
$e^+e^- \to \pi^+\pi^-\Upsilon(pS)(\to \ell^+\ell^-)$
$B\overline{B}$ decomposition
$\pi^+\pi^-$ Dalitz
$Y_b \to \omega\eta_b(1S)$
$Y_b \to \omega\chi_{bJ}(1P)$
Silver Modes
$Y_b \to \pi^+\pi^- X$ (inclusive)
$Y_b \to \eta X$ (inclusive)
$Y_b \to \eta\Upsilon(1S, 2S)(\to \ell^+\ell^-)$
$Y_b \to \eta'\Upsilon(1S)(\to \ell^+\ell^-)$
$Y_b \to \Upsilon(1S)$ (inclusive)
Bronze Modes
$Y_b \to \gamma X_b$
$Y_b \to \pi^0\pi^0\Upsilon(pS)(\to \ell^+\ell^-)$
$Y_b \to KK(\phi)\Upsilon(pS)(\to \ell^+\ell^-)$
$Y_b \to \pi^0\pi^0 X$ (inclusive)
$Y_b \to \pi^0 X$ (incl. or excl.)
...

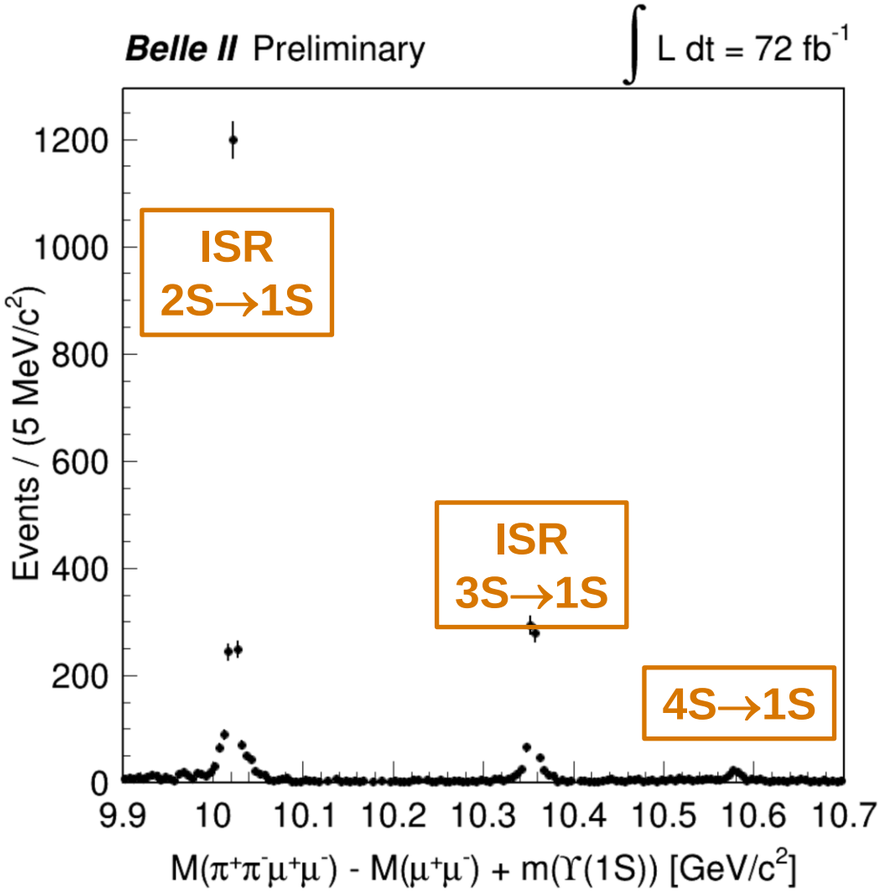
Other Belle II Quarkonium Progress

“Rediscovery” of the X(3872)



$\Upsilon(mS)\to\pi^+\pi^-\Upsilon(nS)$ decays in $\Upsilon(4S)$ data

prelude to $Y_b(10753)$ analysis



Belle II: 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, π^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

Belle II: 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 Υ, 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

- Belle II: next generation B-Factory
  - Advantages with clean event reconstruction, neutrals, unique production
  - Data collection underway since 2019, will continue through this decade
- Quarkonium / “XYZs” are a main component of the physics program
  - Belle II is poised to continue the successes of Belle
  - Energy scan recently performed to understand features near 10.75 GeV
  - Success serves as motivation for other non-$\Upsilon(4S)$ data: $\Upsilon(6S)$ and beyond
- Stay tuned for results at conferences this year

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Thank you