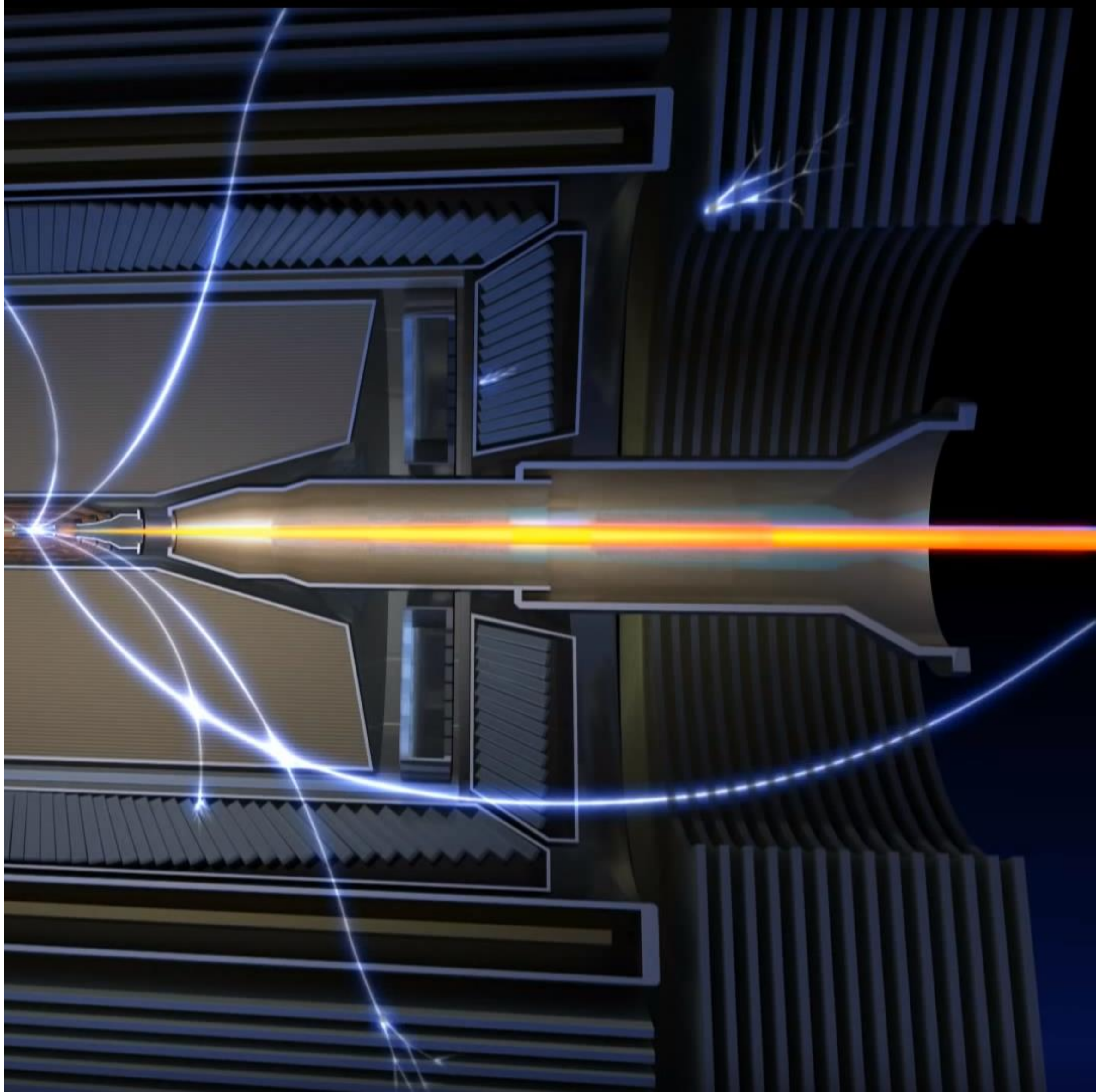
Pacific Northwest NATIONAL LABORATORY

Belle II Overview

Apr 25, 2022

Bryan Fulsom (PNNL)

Workshop on Muon Detection and Quarkonium Reconstruction at the EIC

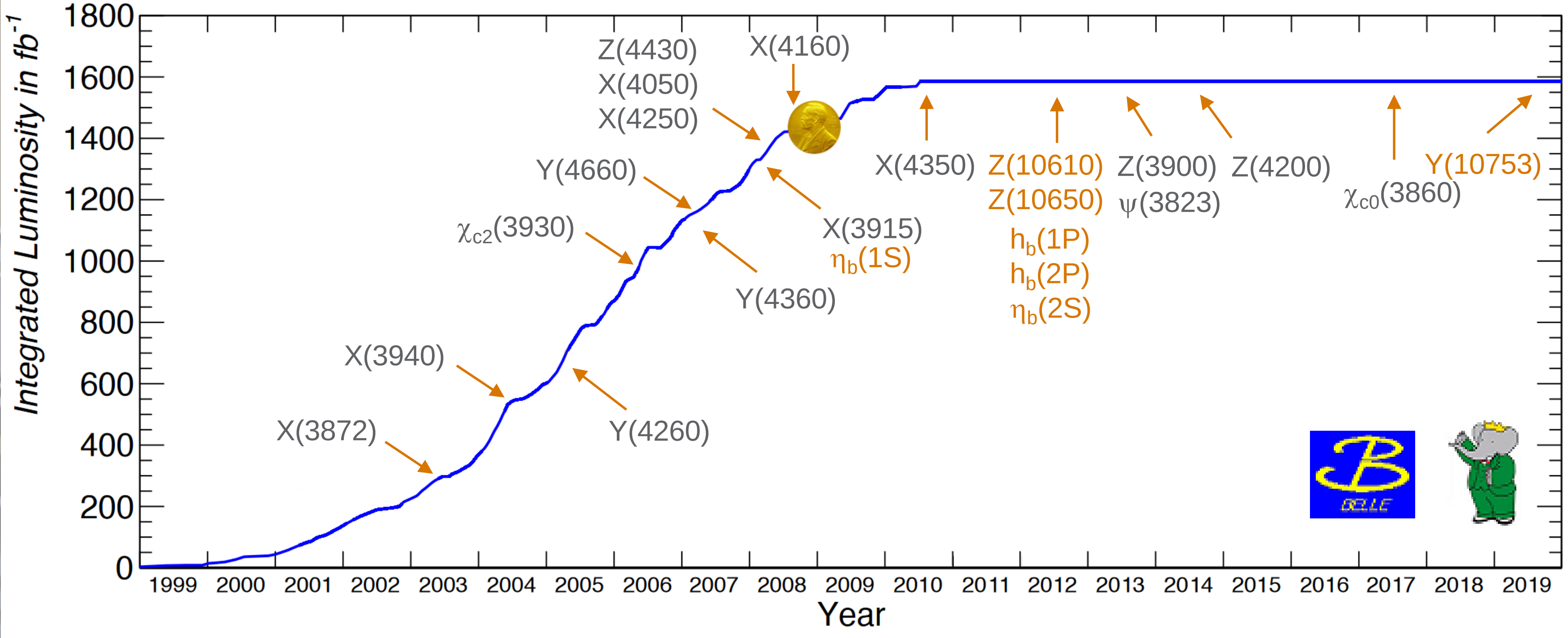


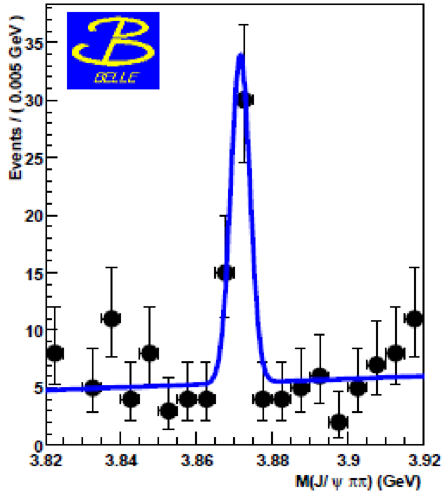
U.S. DEPARTMENT OF ENERGY BATTELLE

B-Factories Legacy

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

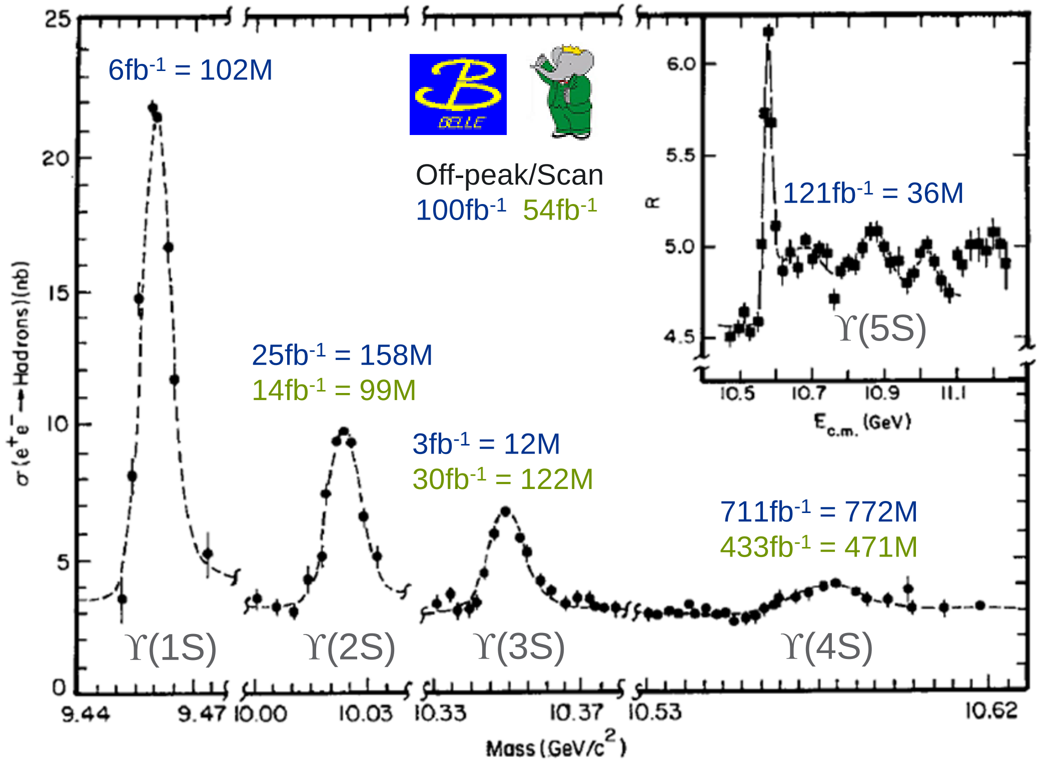
- 1999~2010 : BaBar (SLAC) & Belle (KEK)
- Flavor physics: CKM/UT, CPV in B decays
- Hints for NP in rare processes
- New particle discoveries: “XYZ” states





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

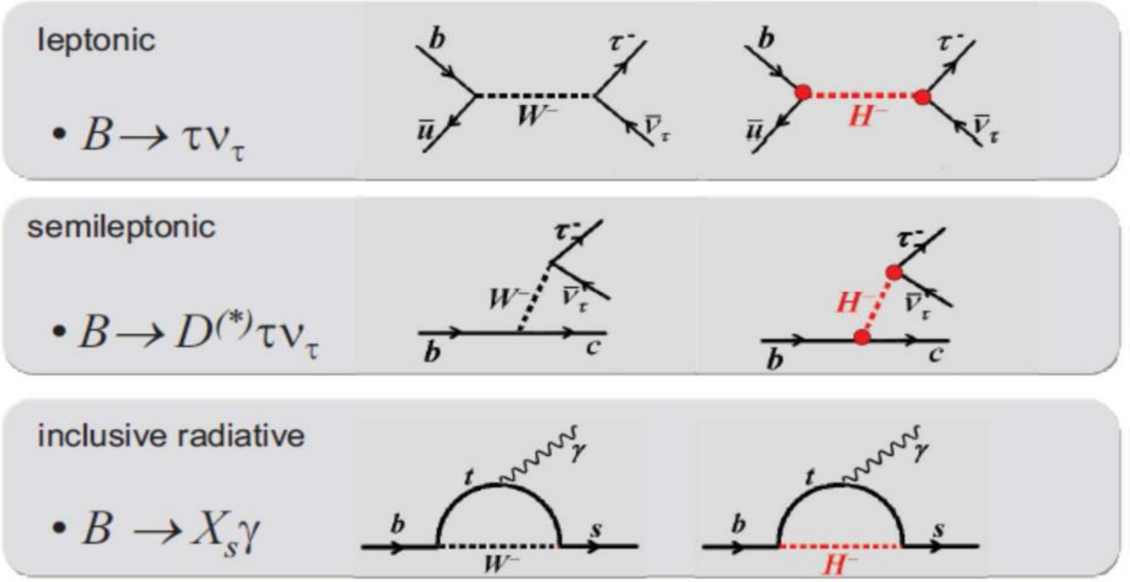
PRL 91, 262001 (2003)



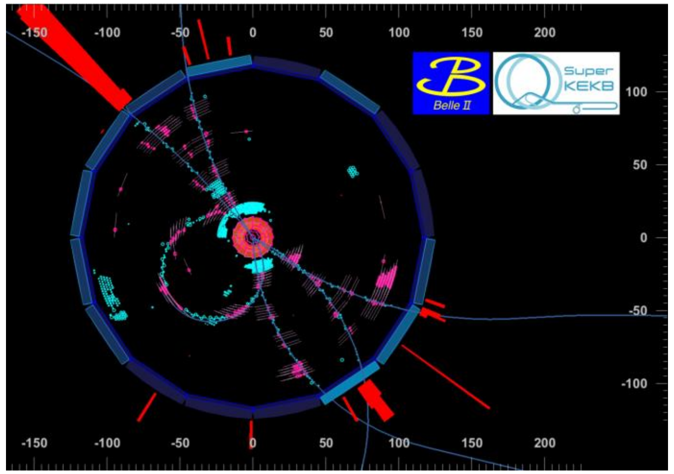
Motivations for a next-generation B Factory

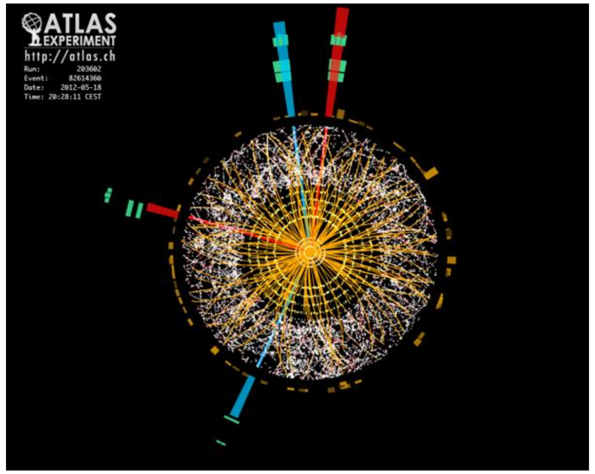
- Broad physics program
  - New Physics in precision/rare B meson decays
  - Dark sector particle searches
  - Spectroscopy of exotic QCD
  - …and more

"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)



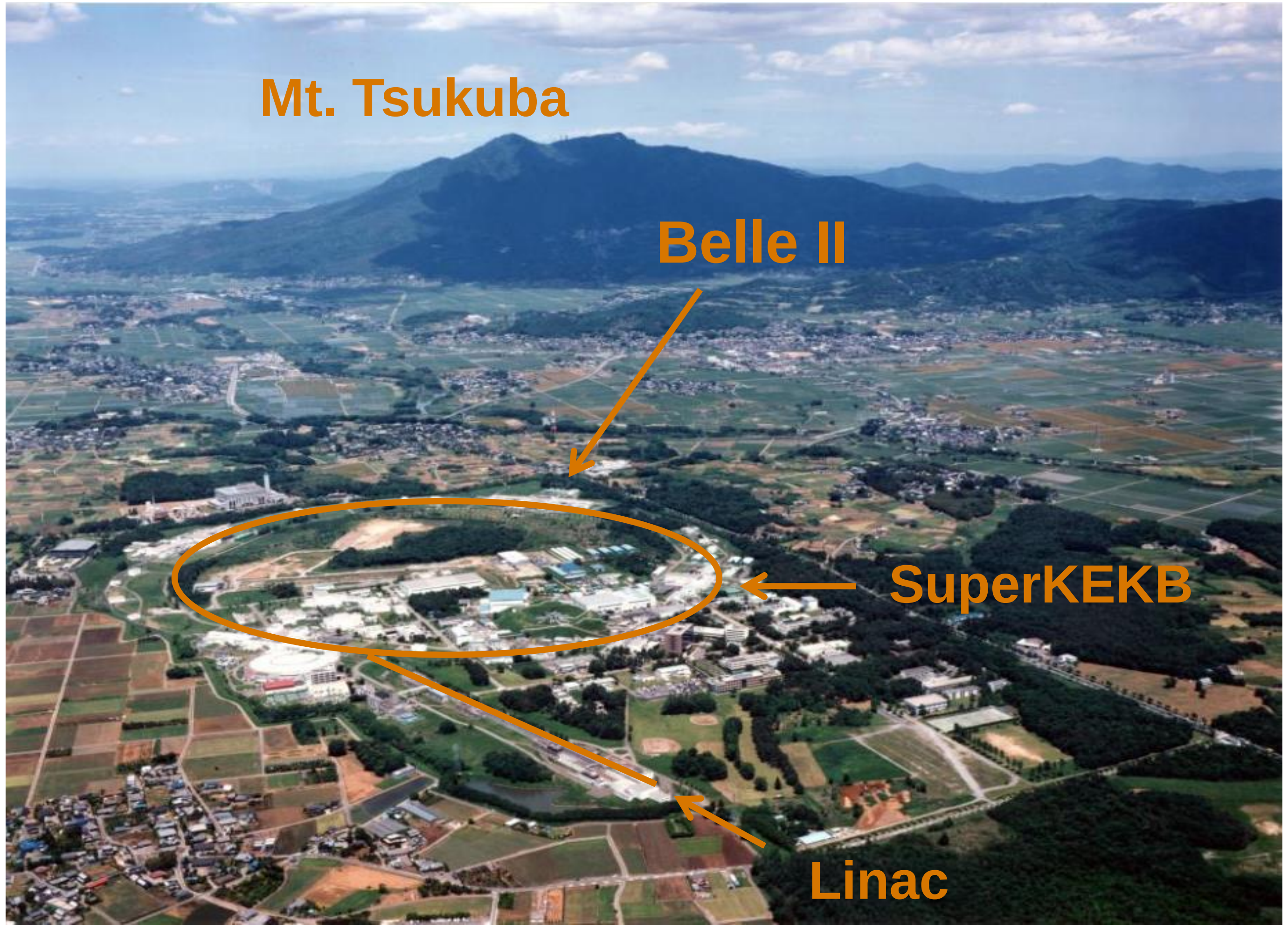
- Advantages of the Belle II
  - "Clean" environment
  - Full event reconstruction
  - Decay with neutrals (γ, π^o, K_L, ν) in final state
  - Large statistics
  - Complementary to LHC

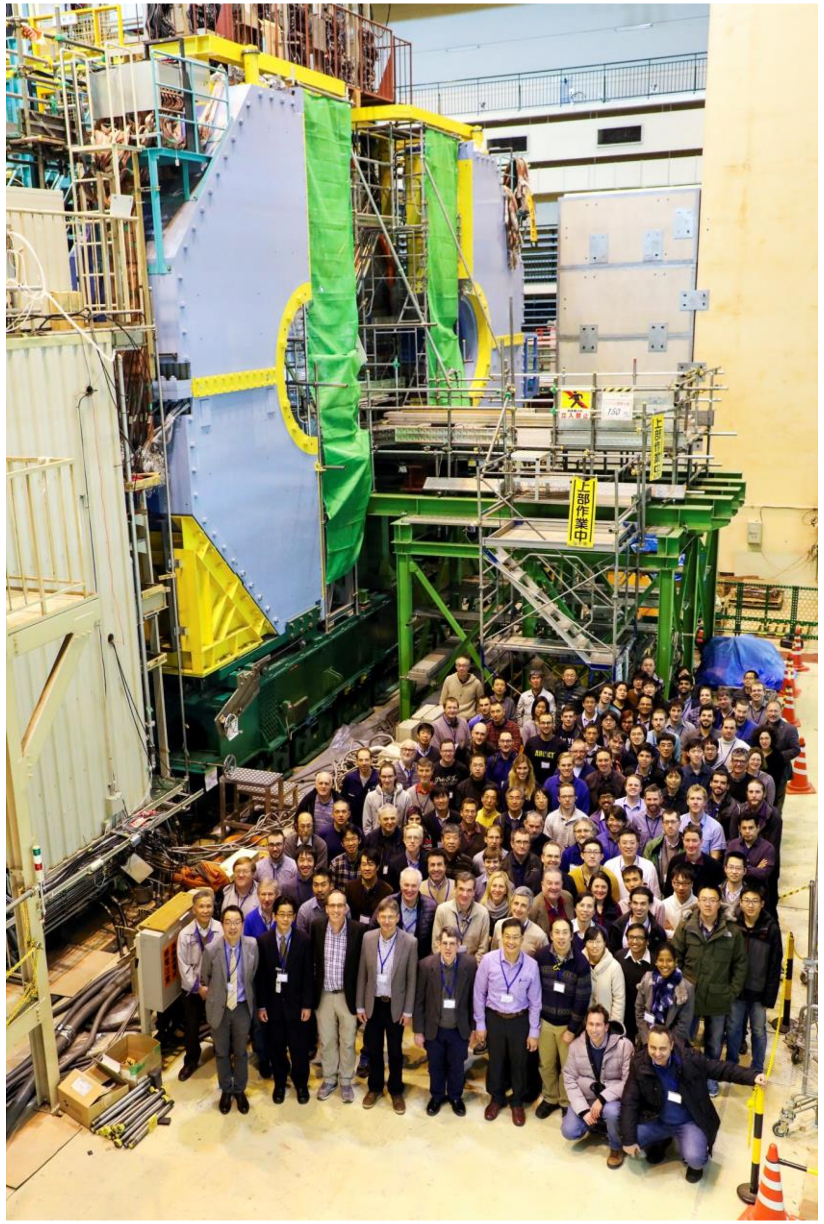




The Belle II Collaboration

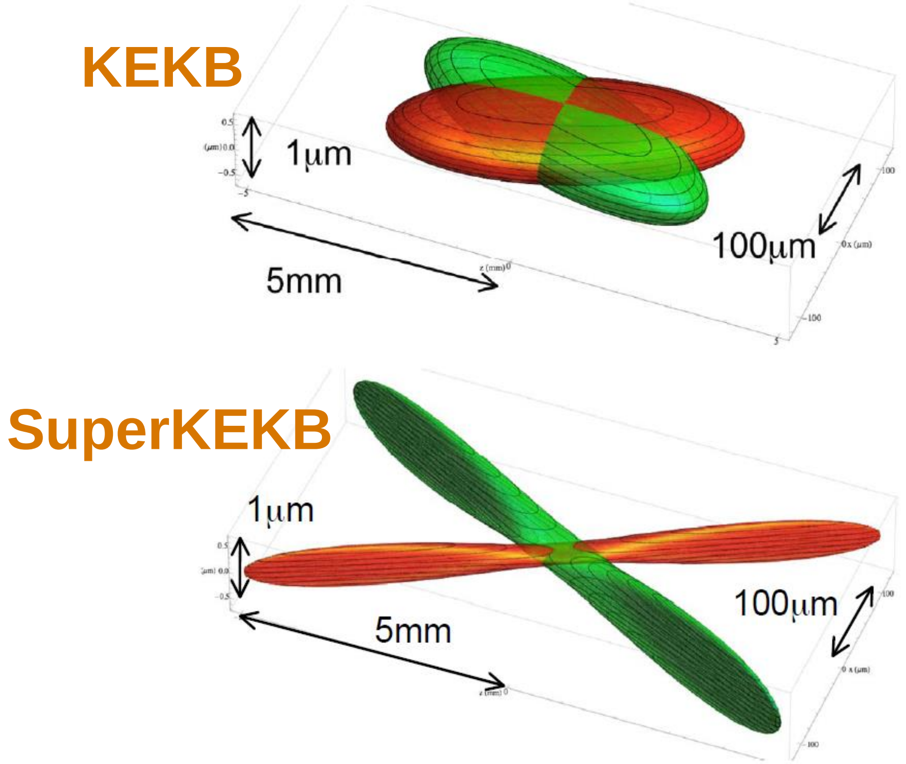
- Experiment located at KEK in Tsukuba, Japan
- 1100+ members, 123 institutions, 26 nations

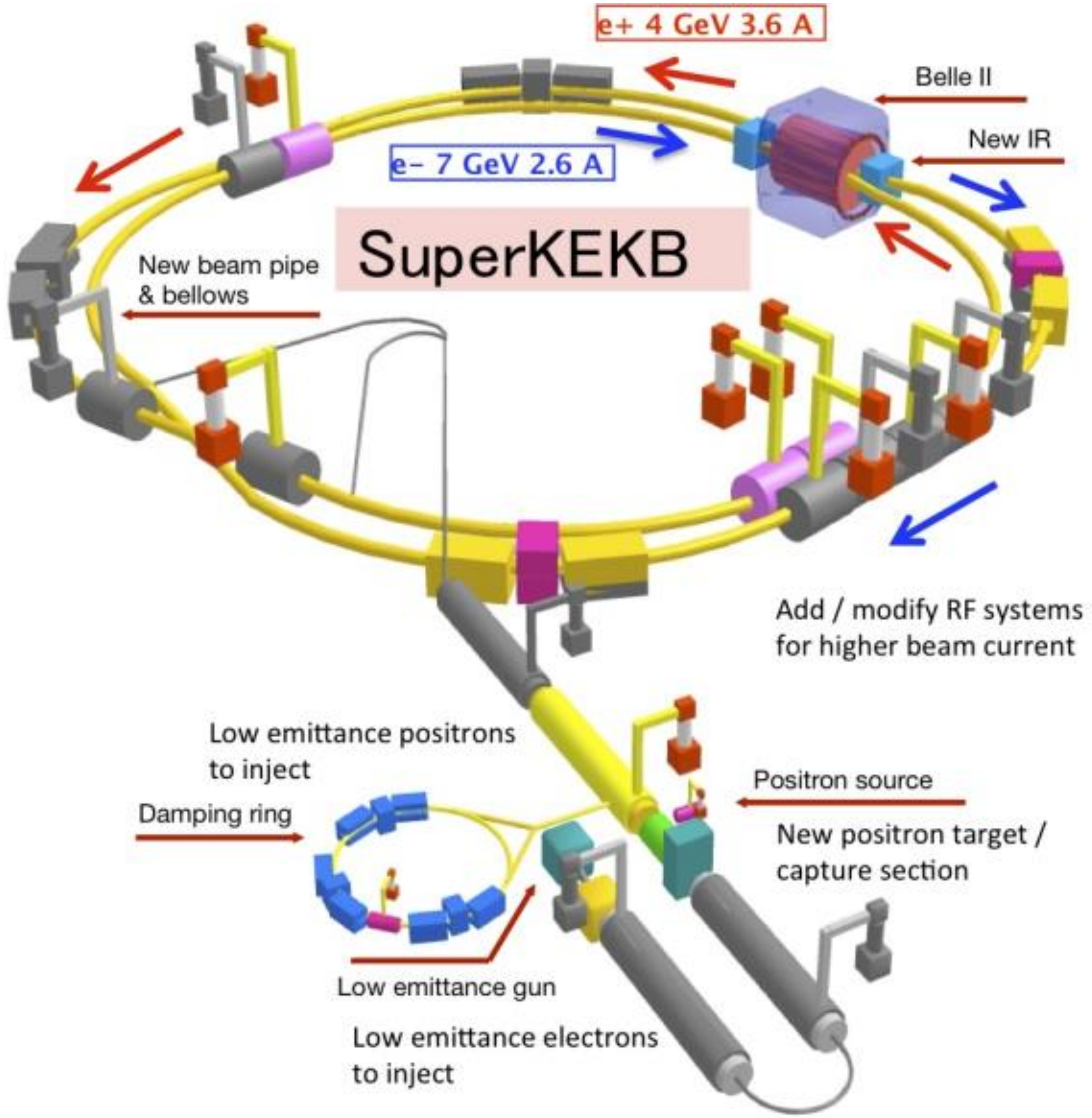




Accelerator Upgrade

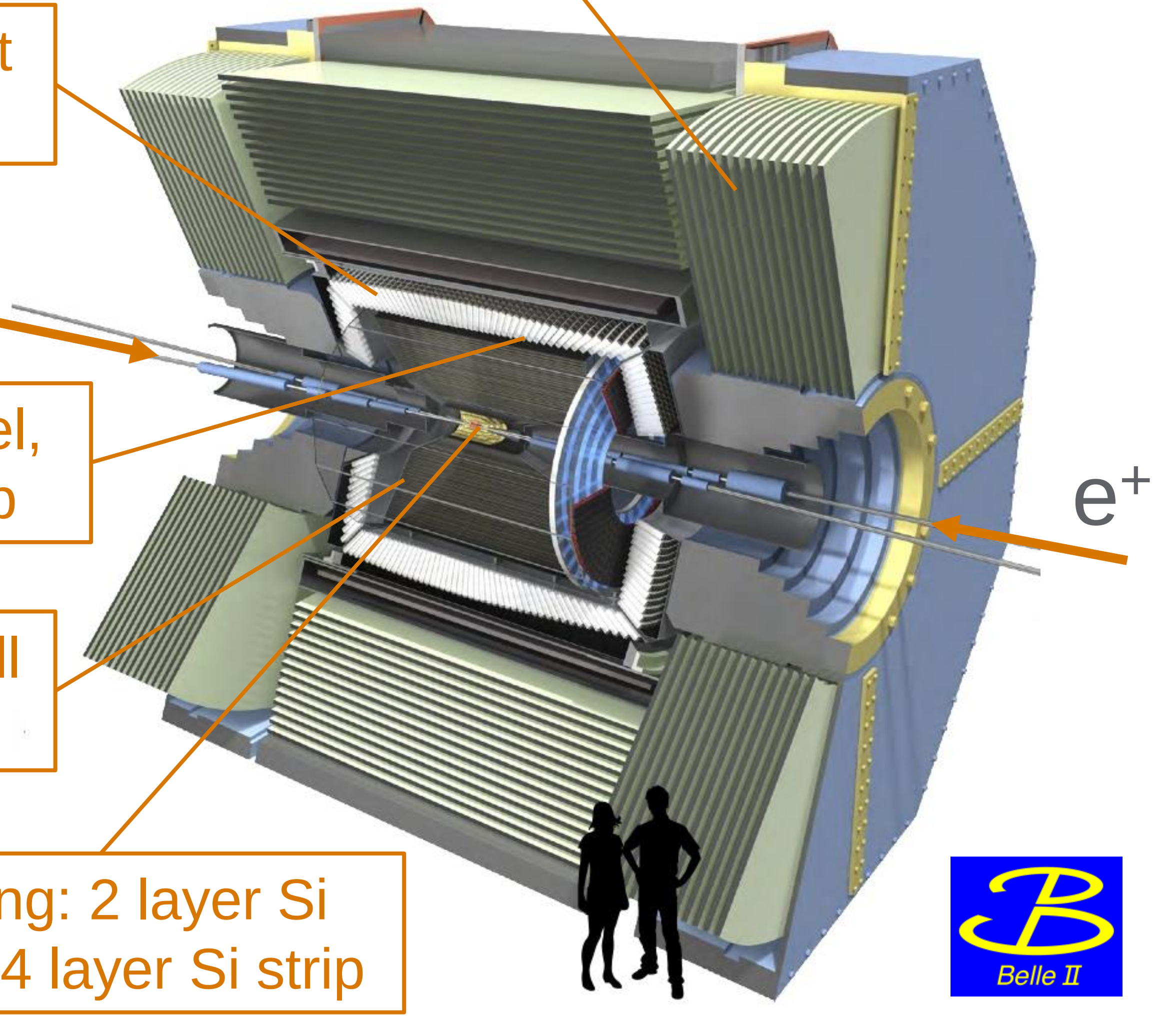
- SuperKEKB Upgrade
  - "Nano-beam" interaction point
  - Increase in current
  - Goal: factor of 40x increase in luminosity
  - Nominal energy: e^- (7 GeV) e^+ (4 GeV)





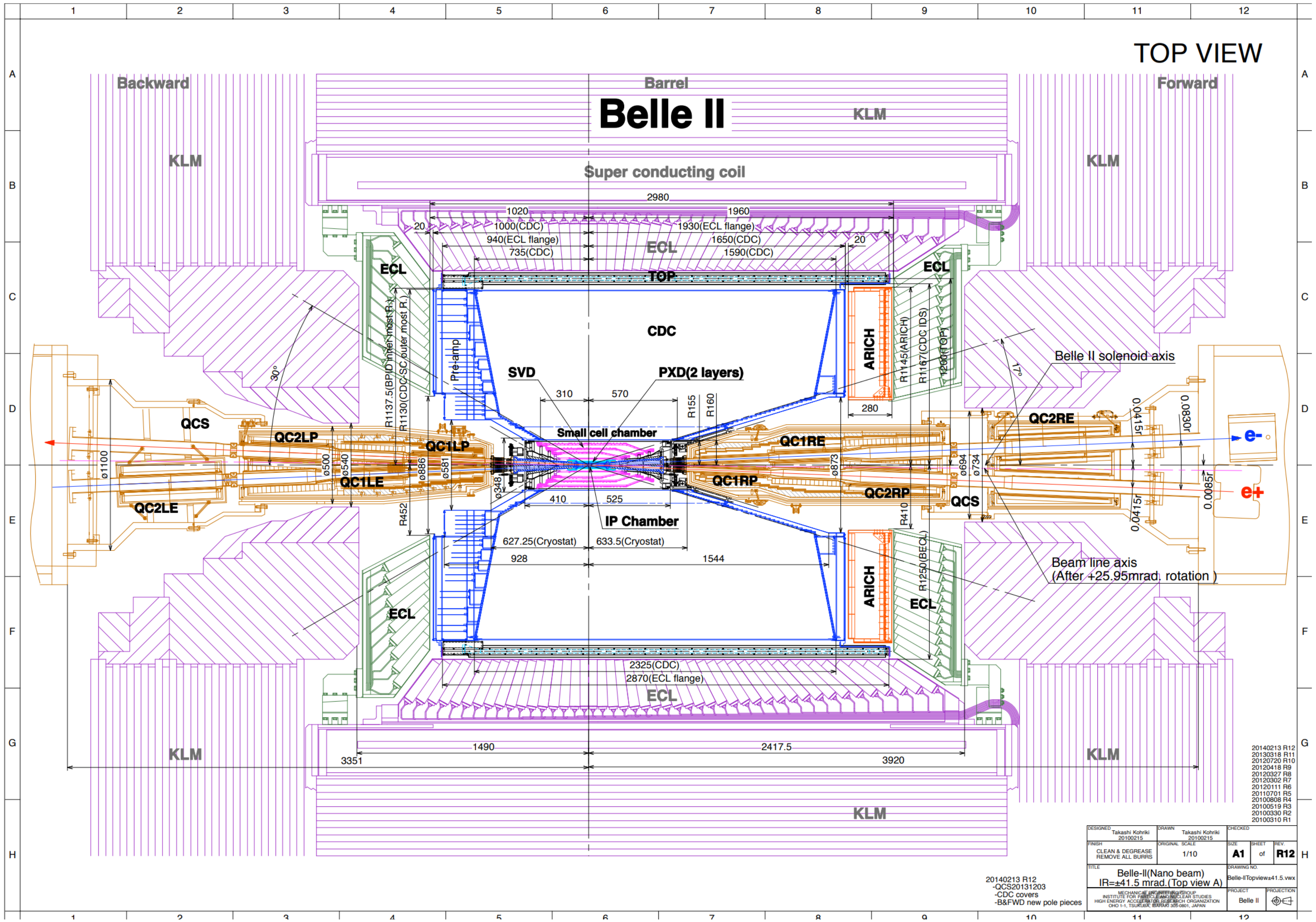
Belle II Detector Rebuild

- 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

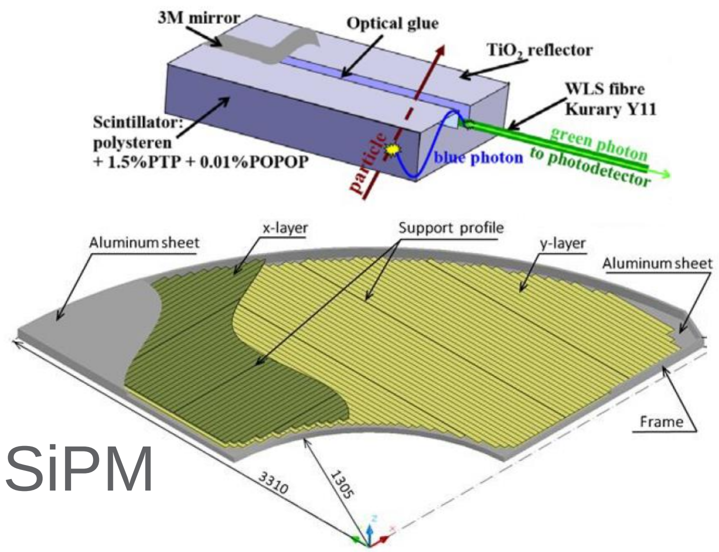


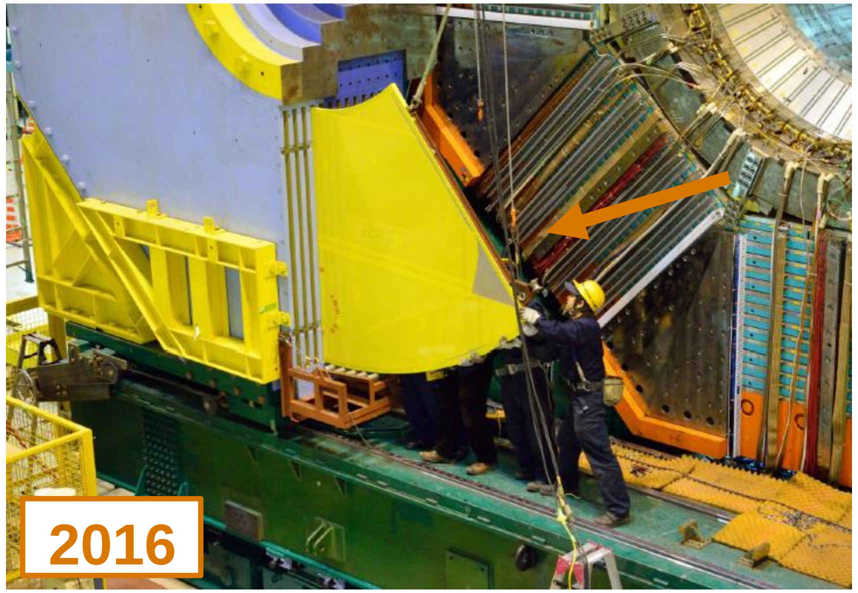
arXiv:1011.0352 (2011)

Belle II Detector

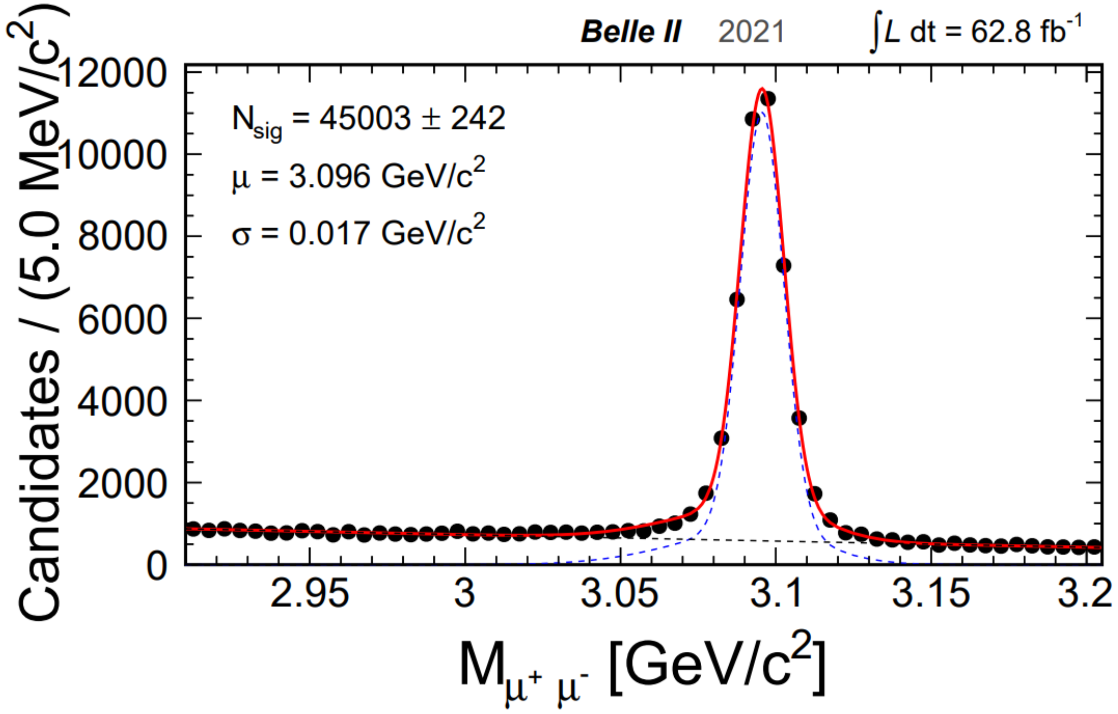


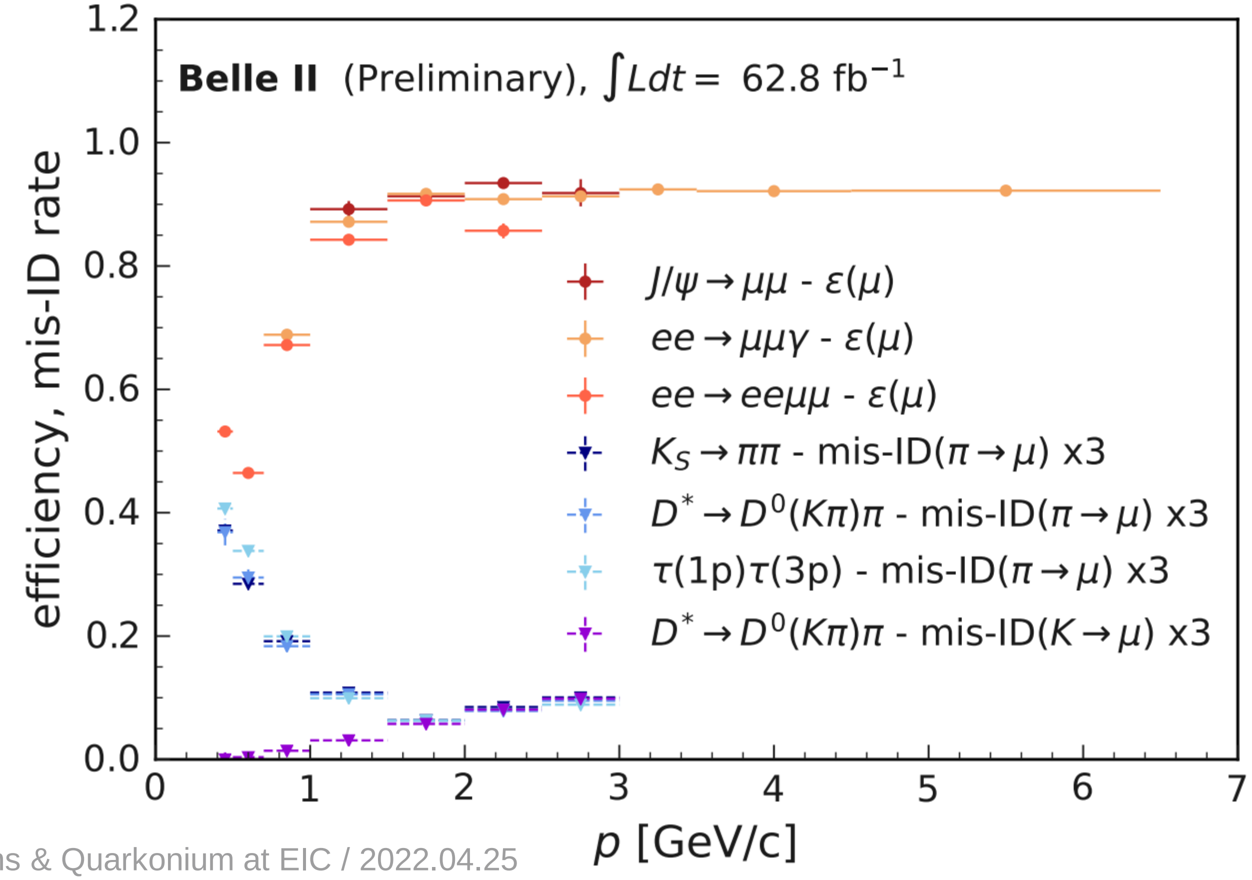
KLong and Muon detector



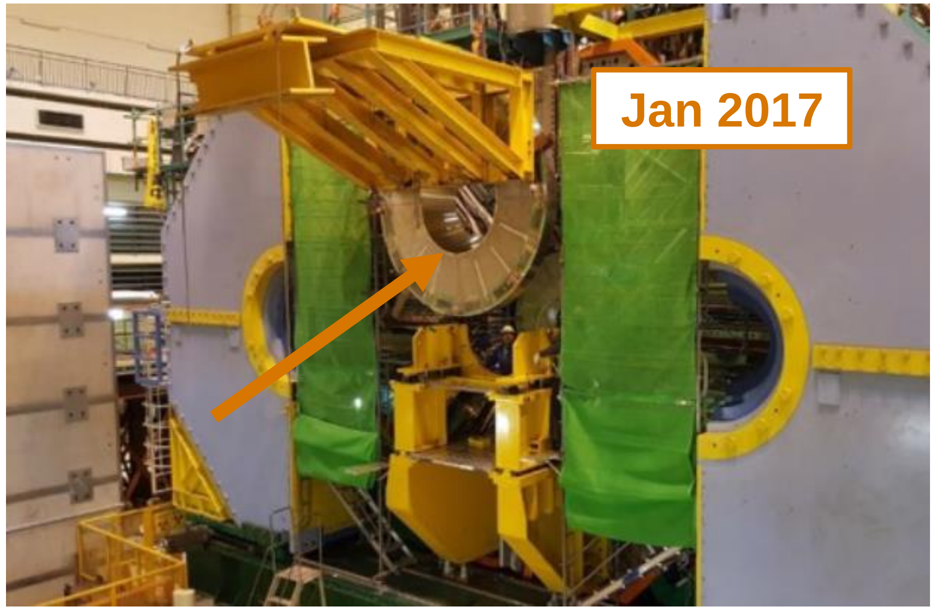


- Alternating iron / active layers
  - Barrel: 2 scintillator + 13 RPCs
  - Endcap: 14 scintillator
  - New for Belle II: PS strips + WLS + SiPM
- Preliminary performance

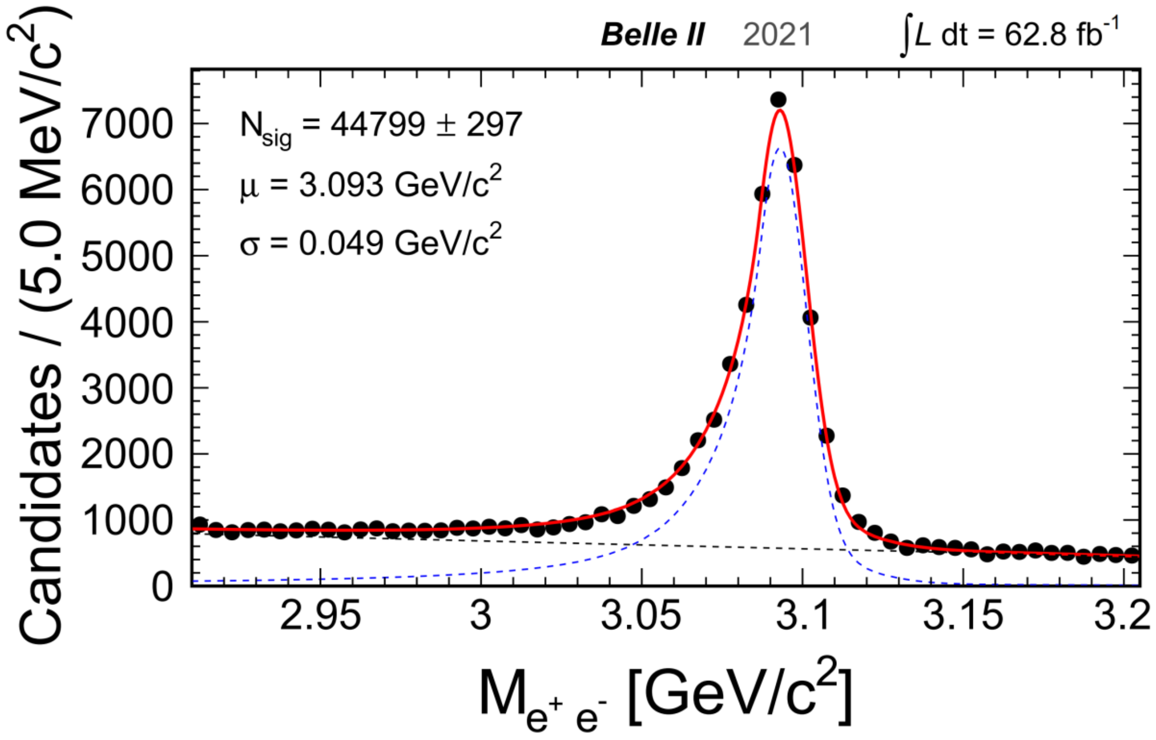


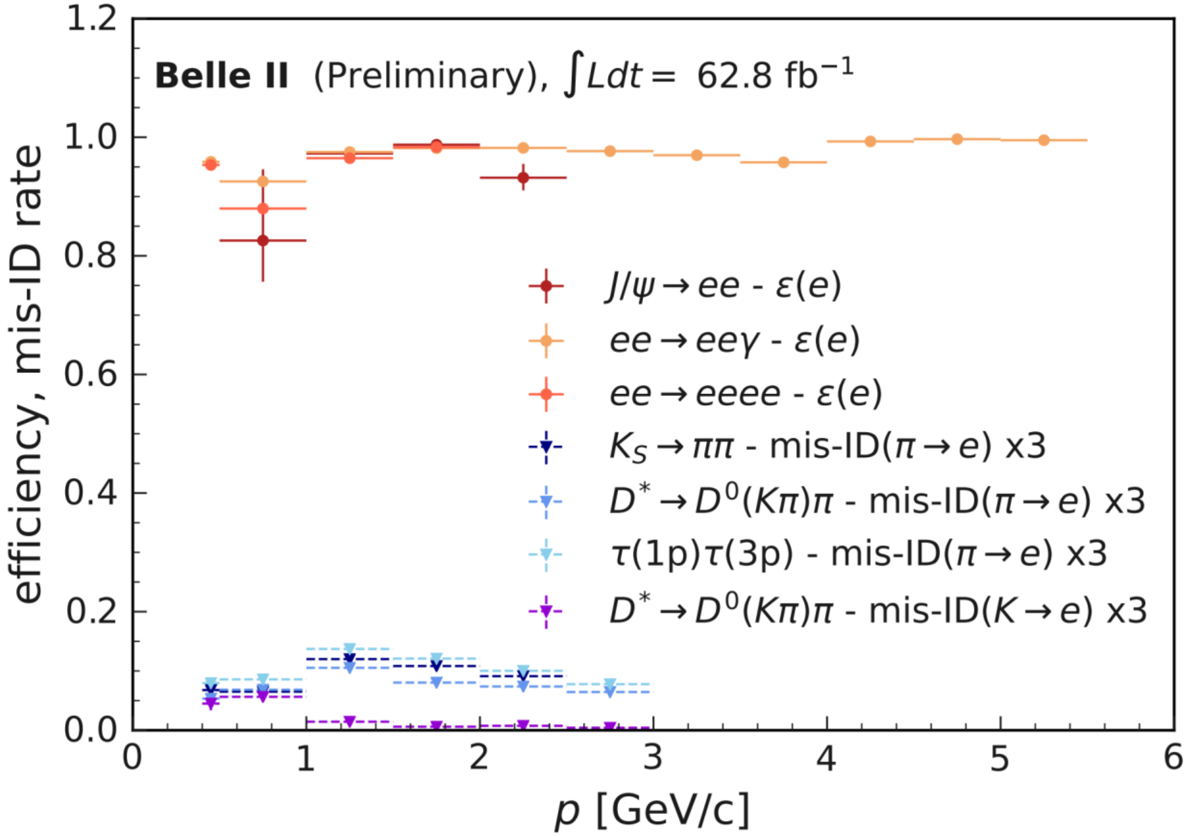


Electromagnetic CaLorimeter



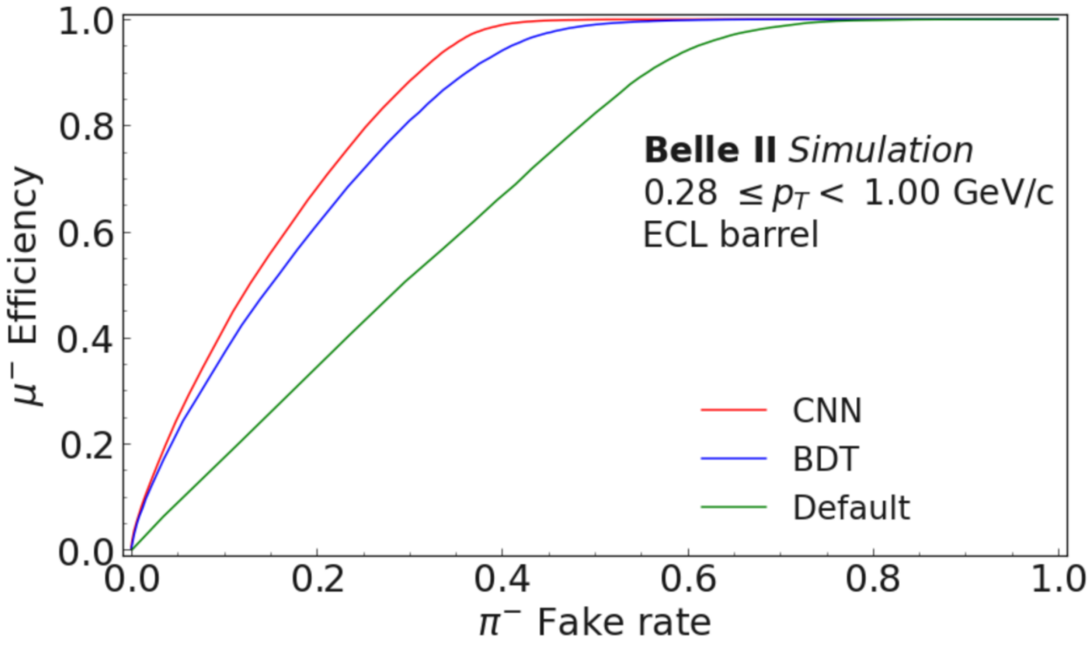
- CsI(Tl) crystals
  - Reused from Belle detector
  - Electronics upgrade
  - Waveform readout for hadron/electron discrimination
- Preliminary performance





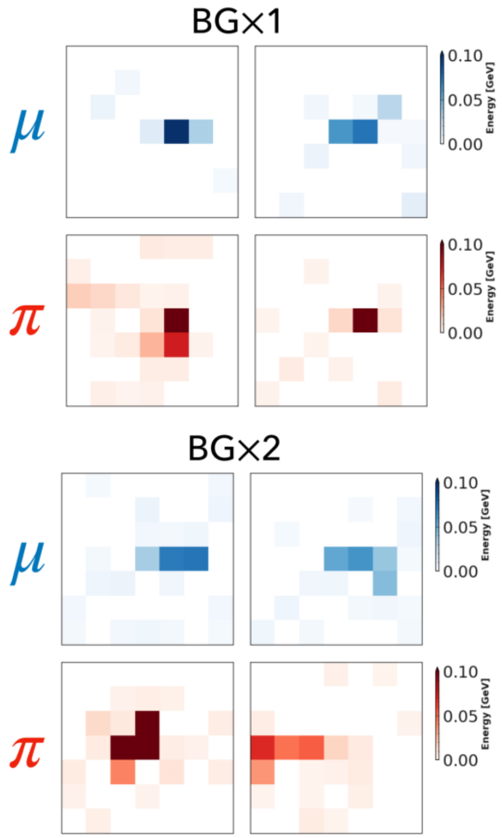
Future Developments

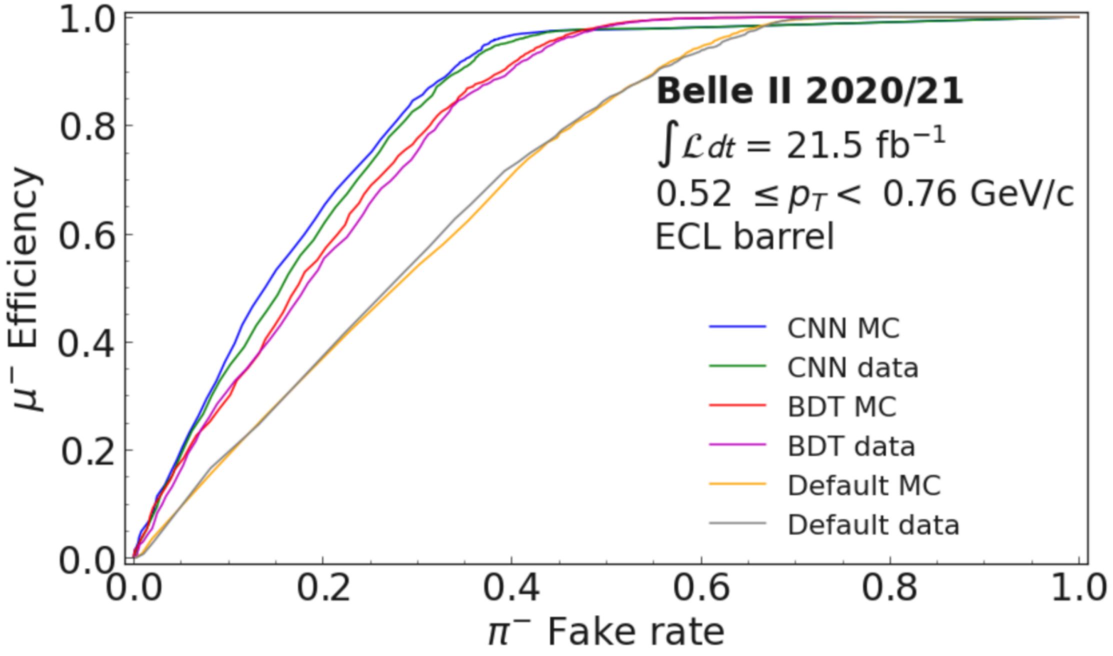
- Low-momentum μ reconstruction
  - Muons do not reach KLM
  - Use tracking and/or ECL information
  - BDT and CNN of variables/shape



Variable	Range	Description
E/p [c]	–	Ratio of cluster energy over track momentum.
$E_{cluster}$ [GeV]	–	Cluster energy.
E_1/E_9	–	Ratio of the energy of the seed crystal over the energy sum of the 9 surrounding crystals.
E_9/E_{21}	–	Ratio of the energy sum of 9 crystals surrounding the seed over the energy sum of the 25 surrounding crystals (minus 4 corners).
$\|Z_{40}\|$	–	Zernike moment $n = 4$, $m = 0$, calculated in a plane orthogonal to the EM shower direction.
$\|Z_{51}\|$	–	Zernike moment $n = 5$, $m = 1$, calculated in a plane orthogonal to the EM shower direction.
Z_{MVA}	–	Score of BDT trained on 11 Zernike moments.
ΔL [mm]	–	Projection on the extrapolated track direction of the distance between the track entry point in the ECL and the cluster centroid.
$\Delta \log \mathcal{L}(\ell/\pi)_{CDC}$	–	Log-likelihood difference between $\ell - \pi$ hypothesis in the CDC.
$\Delta \log \mathcal{L}(\ell/\pi)_{TOP}$	ECL barrel	Log-likelihood difference between $\ell - \pi$ hypothesis in the TOP.
$\Delta \log \mathcal{L}(\ell/\pi)_{ARICH}$	ECL FWD endcap	Log-likelihood difference between $\ell - \pi$ hypothesis in the ARICH.
$\Delta \log \mathcal{L}(\mu/\pi)_{KLM}$	$p > 0.6$ GeV/c	Log-likelihood difference between $\mu - \pi$ hypothesis in the KLM.

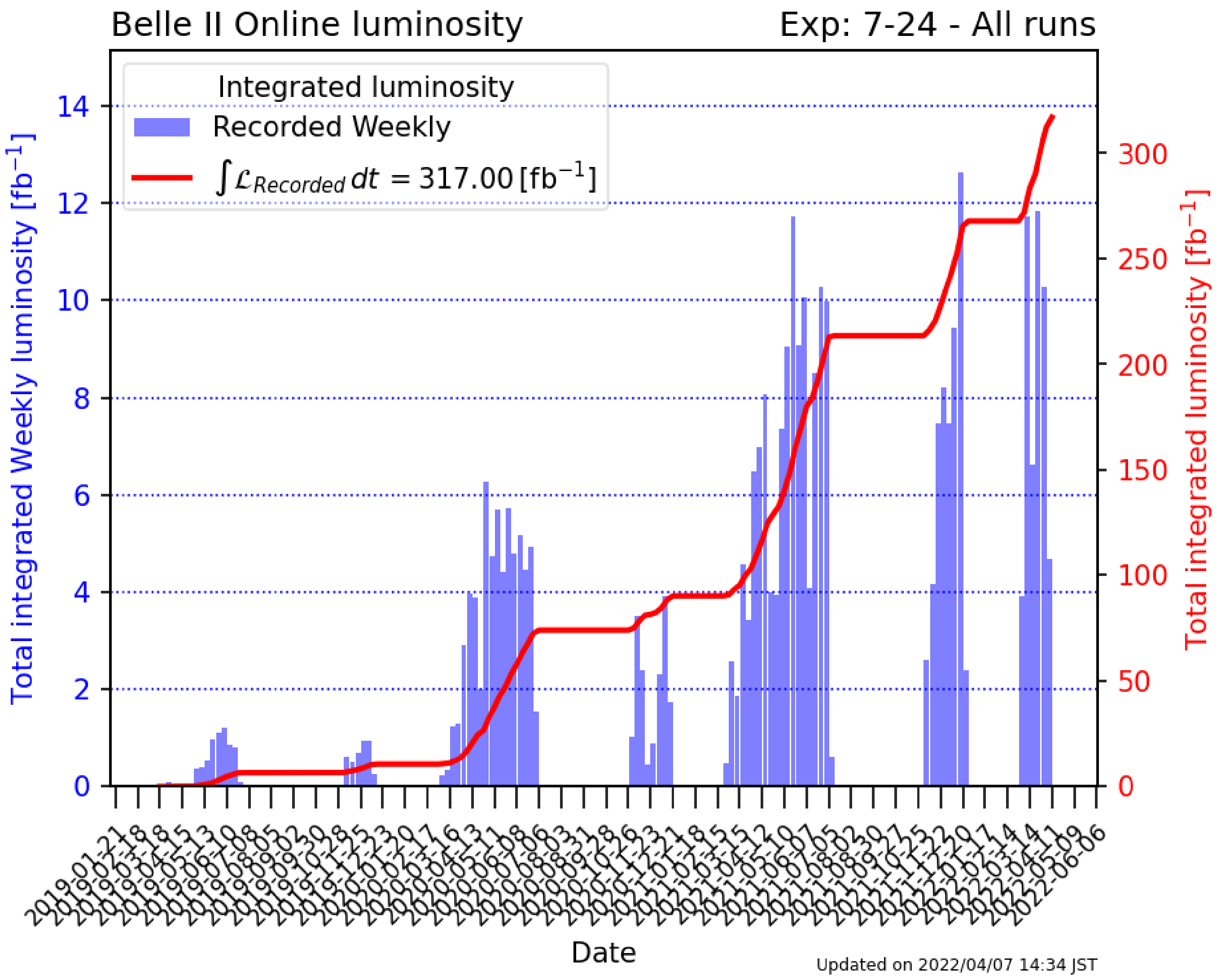
EPJ Web Conf., 245 (2020) 06023





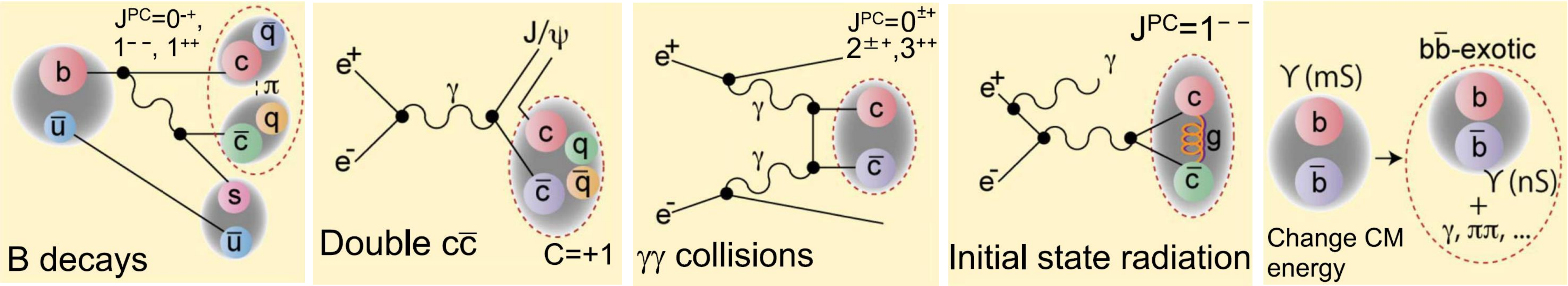
Belle II Timeline

- 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: >3.8x10^{-34}cm^{-2}s^{-1}
  - 2021: Non-Υ(4S) Energy scan
- 2022-2023: “Long Shutdown 1”
  - Detector/accelerator upgrades
- 2023~2027: Resume operations, target: 1.5-4 ab^{-1}
- 2028+: “Long Shutdown 2” upgrade (?), continue up to 50 ab^{-1}



How do we study quarkonium experimentally? Production Mechanisms

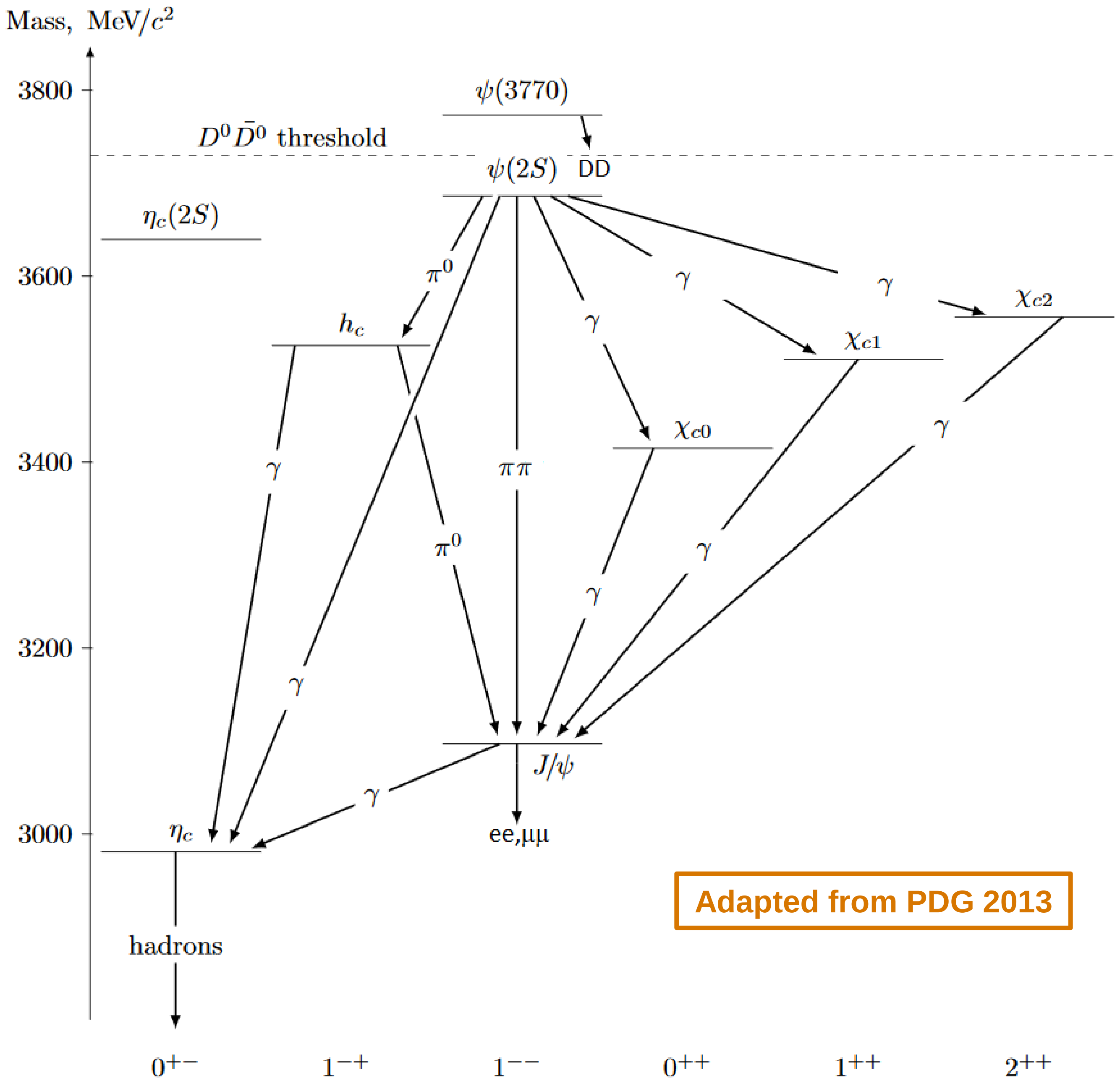
- Multiple methods to produce quarkonium/exotics at Belle II
- Production mode provides important information (e.g. J^{PC}, type)



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

How do we study quarkonium experimentally? Decay Modes

- Search for transitions between states
  - Radiative (γ) and hadronic (ππ, π^0, η, …)
  - ~Governed by selection rules
- Below-threshold
  - ee/μμ : low rate but clean, ψ/ϒ, QED bkd
  - hadronic: low efficiency for N particles
- Above-threshold
  - Strong decays to $D\bar{D}/B\bar{B}$ dominate

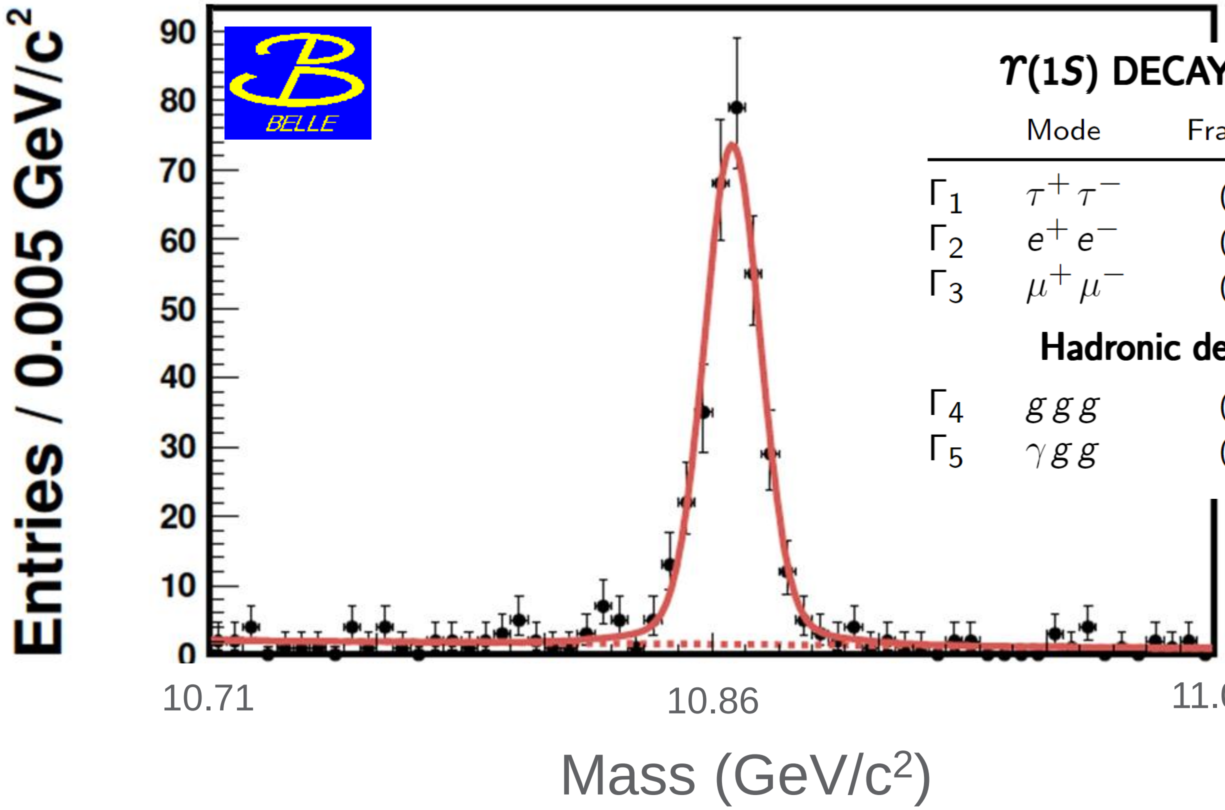


Adapted from PDG 2013

How do we study quarkonium experimentally? Exclusive Analysis

- Reconstruct a complete final state ("bottom-up")
  - E.g.: $e^+e^- \to \pi^+\pi^-\Upsilon(pS) \to \mu^+\mu^-$
- Potential advantages
  - Low background
  - Few combinations, "clean" final state
  - Complete understanding of event
- Potential disadvantages
  - Efficiency loss
  - Low branching fractions

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



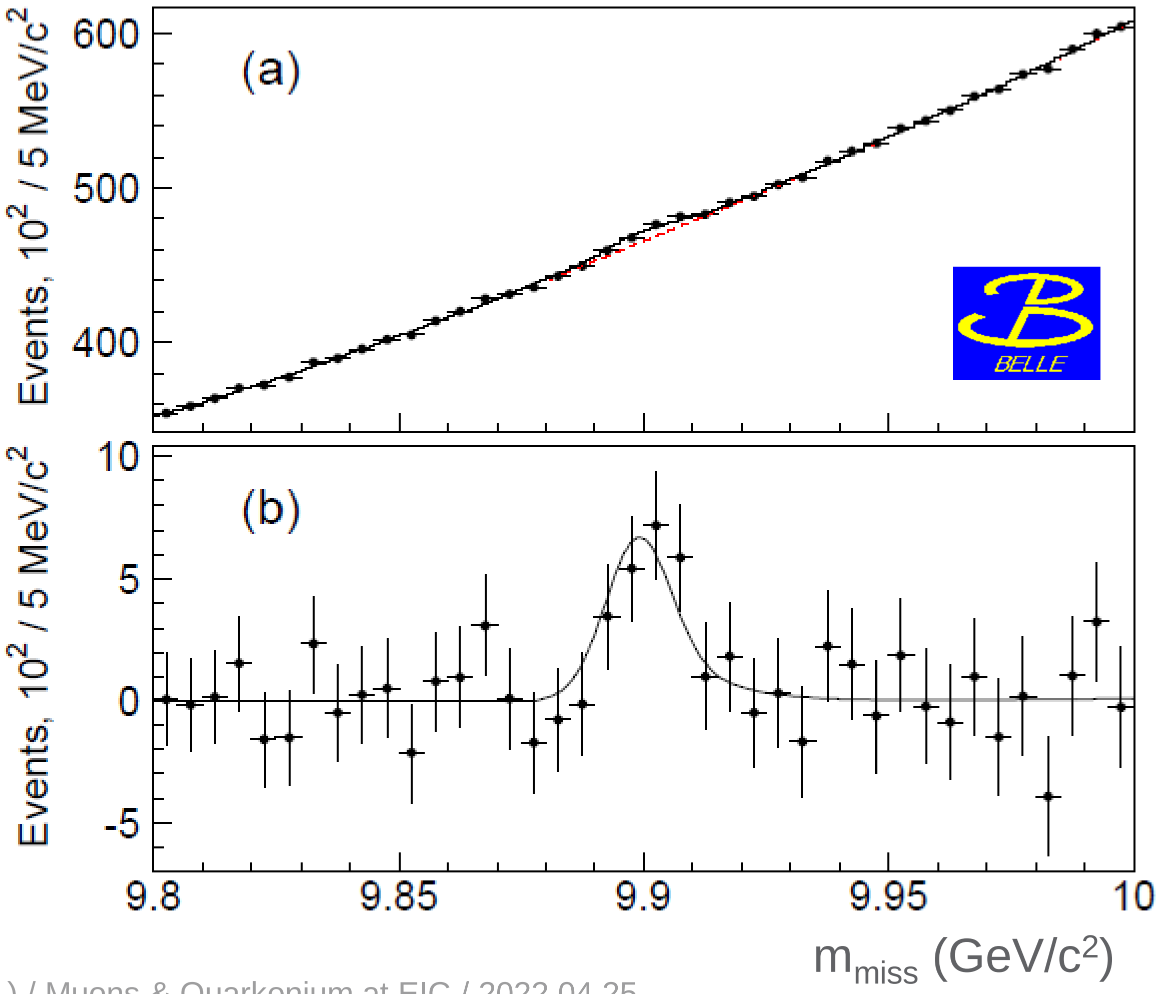
Υ(1S) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\tau^+\tau^-$	(2.60 ±0.10) %
Γ_2	e^+e^-	(2.38 ±0.11) %
Γ_3	$\mu^+\mu^-$	(2.48 ±0.05) %
	Hadronic decays	
Γ_4	ggg	(81.7 ±0.7) %
Γ_5	γgg	(2.2 ±0.6) %

How do we study quarkonium experimentally? Inclusive Analysis

- Reconstruct only part of the event (“top down”)
  - E.g.: $e^+e^- \to \pi^+\pi^- X$
  - E.g.: $m_X = m_{miss} = \mathrm{sqrt}[(p_{ee} - p_{\pi\pi})^2]$
- Potential advantages:
  - Large statistics
  - Good resolution
  - Do not need to reconstruct X
- Potential disadvantages:
  - High background
  - Combinatorics
  - Other peaking decays

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



$h_b(1P)$ DECAY MODES

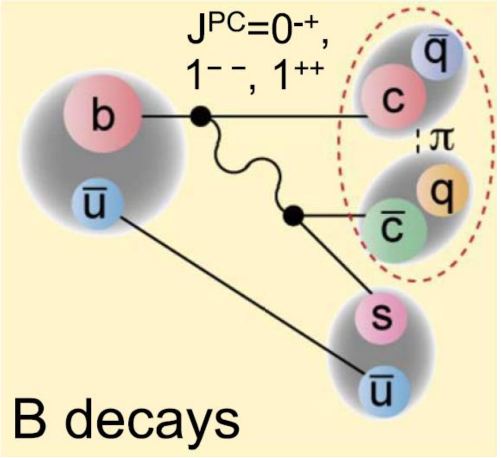
	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta_b(1S)\gamma$	(52^{+6}_{-5}) %

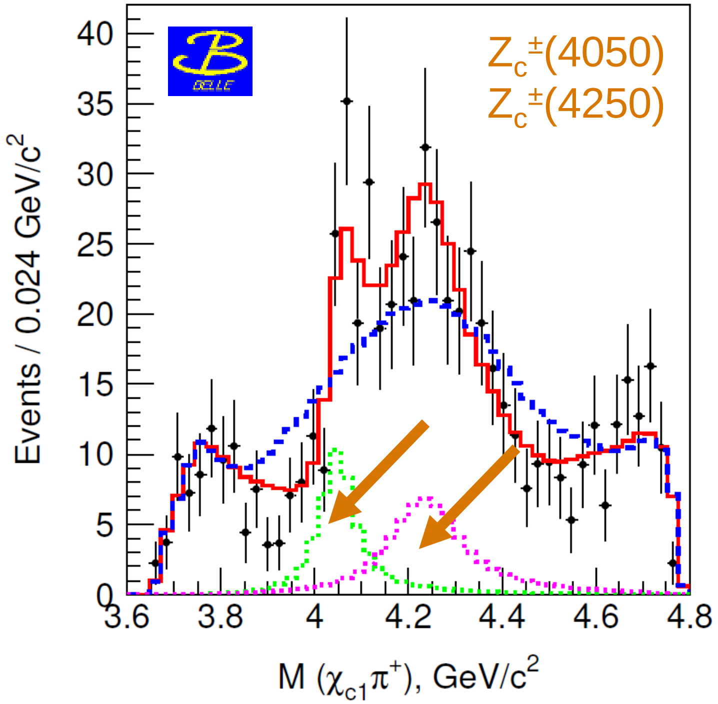
$\eta_b(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	hadrons	seen
Γ_2	$3h^+3h^-$	not seen
Γ_3	$2h^+2h^-$	not seen
Γ_4	$4h^+4h^-$	not seen
Γ_5	$\gamma\gamma$	not seen
Γ_6	$\mu^+\mu^-$	$<9 \times 10^{-3}$
Γ_7	$\tau^+\tau^-$	<8 %

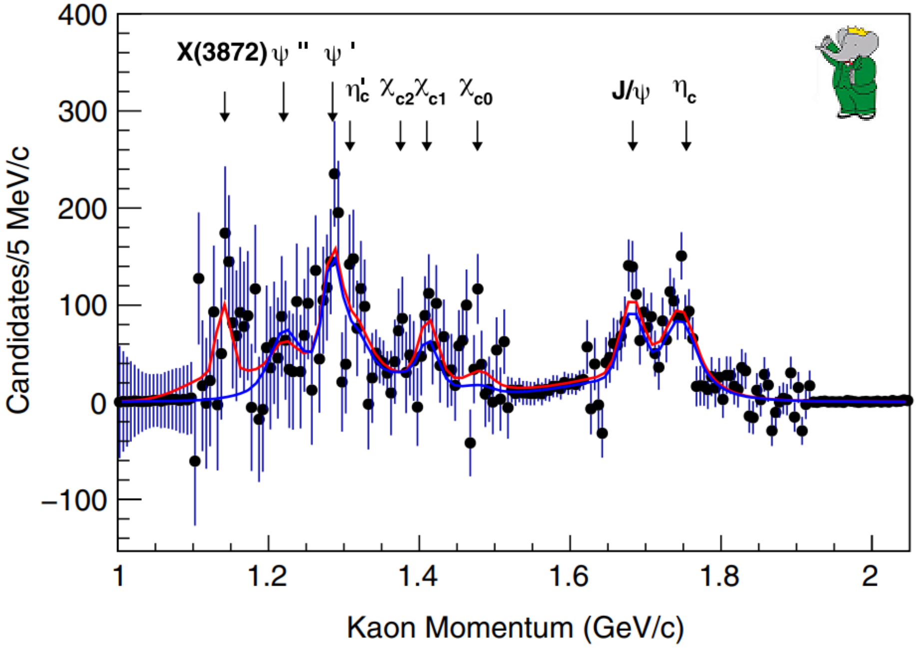
Belle II Potential – B Decay

- 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 $B \to X(3872,3915)\,K$
  - Confirmation of X(3872) width measurement with $D^0\bar{D}^0\pi^0$

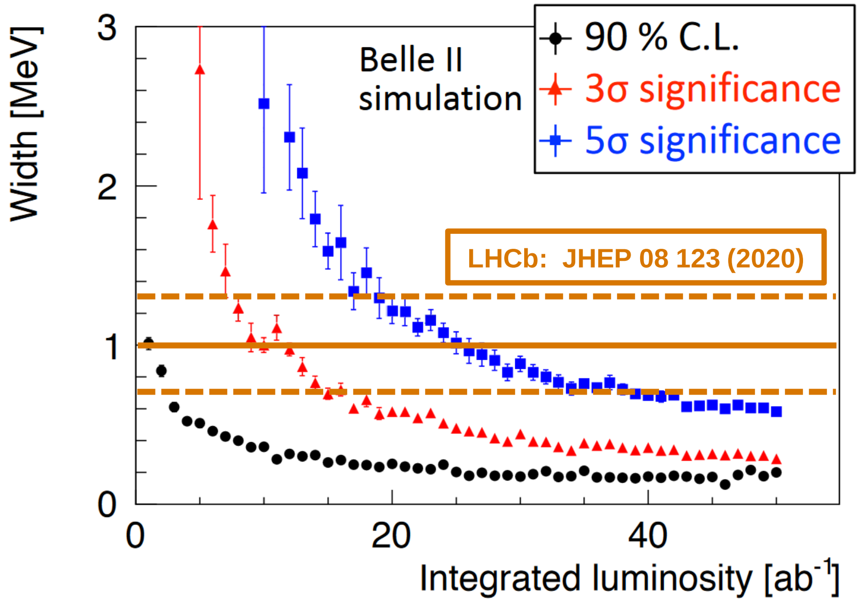




PRD 78, 072004 (2008)

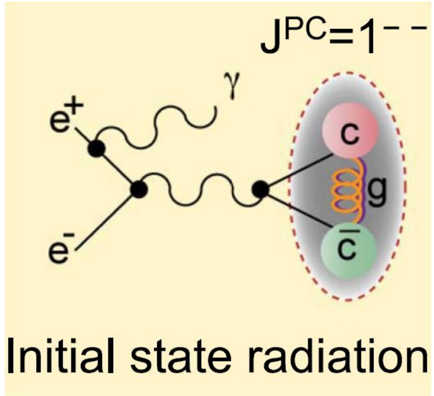


PRL 124, 152001 (2020)

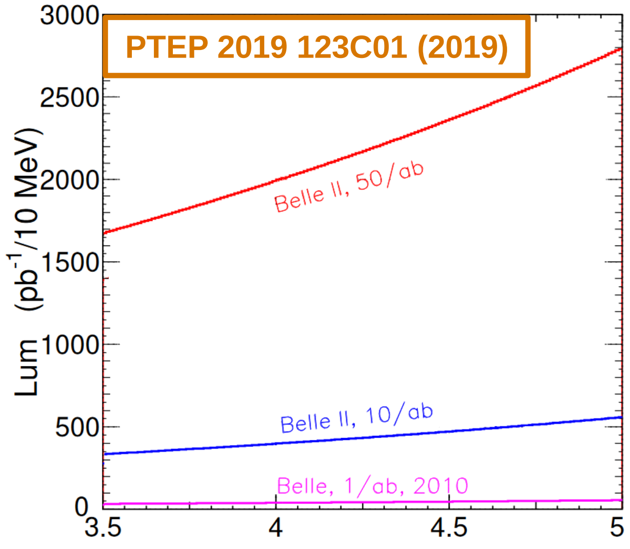


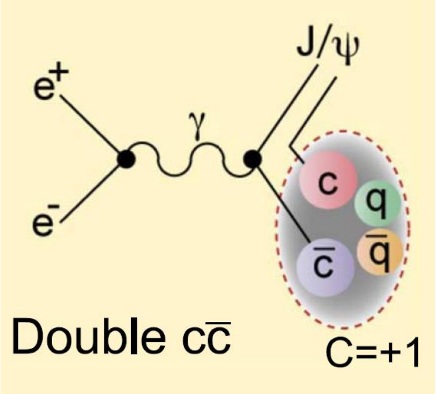
H. Hirata (KMI/Nagoya), MSc Thesis (2019)

Belle II Potential – Other Processes

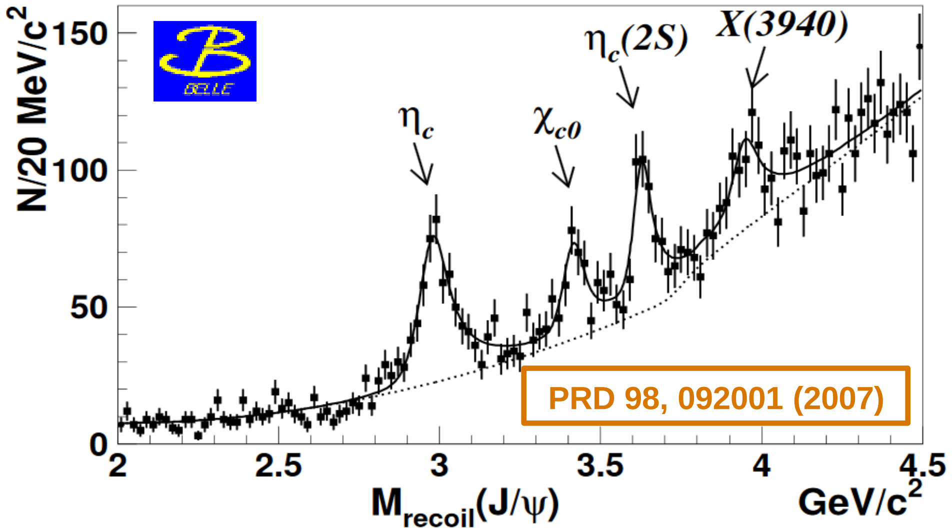


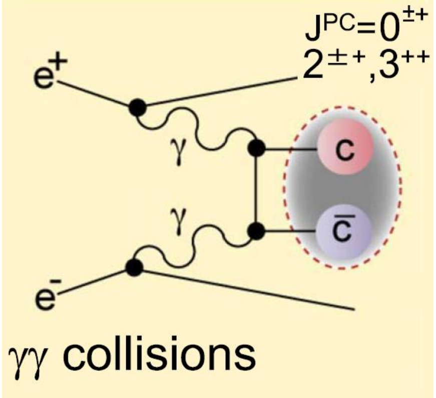
- ISR
  - Continuous mass range >4.6 GeV/c^2
  - Higher masses/channels (e.g. $\gamma_{ISR}\Sigma_c\bar{\Sigma}_c$)
  - Confirm Z_c states (e.g. $e^+e^- \to h_c\pi\pi$)



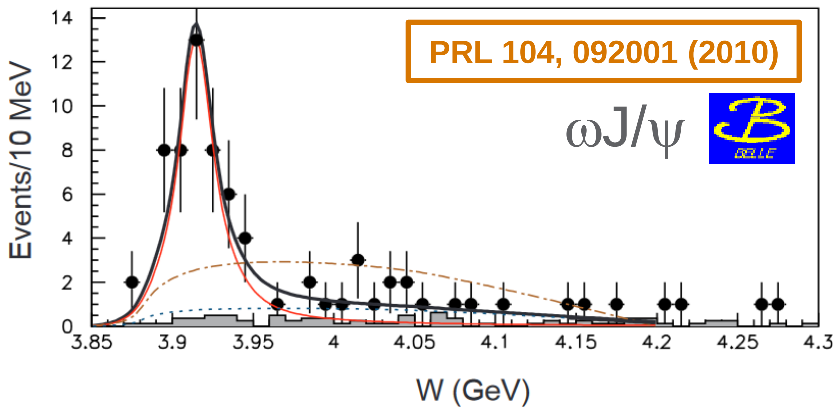


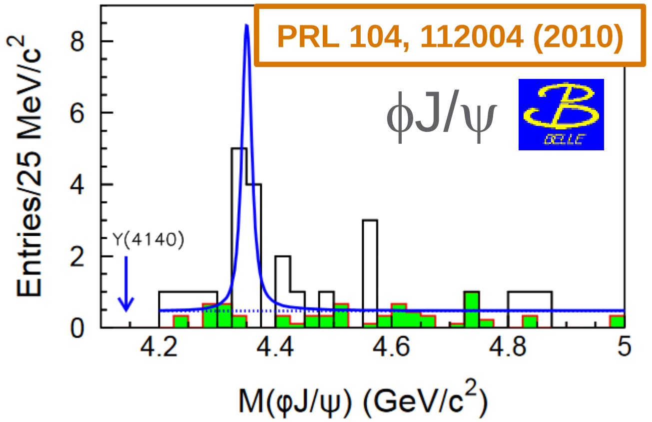
- Double-$c\bar{c}$
  - $e^+e^- \to (c\bar{c})_{J=1}(c\bar{c})_{J=0}$ production rule
  - Discovery of X(3940, 4160)
  - Expand to other $c\bar{c}$, search for new states





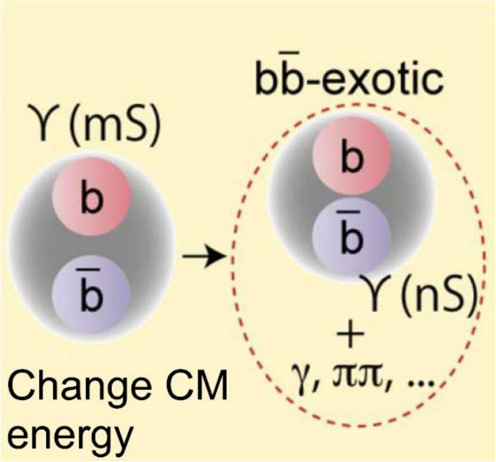
- Two-Photon
  - J^{PC} of X(3915)
  - Confirm $\phi J/\psi$ state?
  - $D^{(*)}\bar{D}^{(*)}$ final states

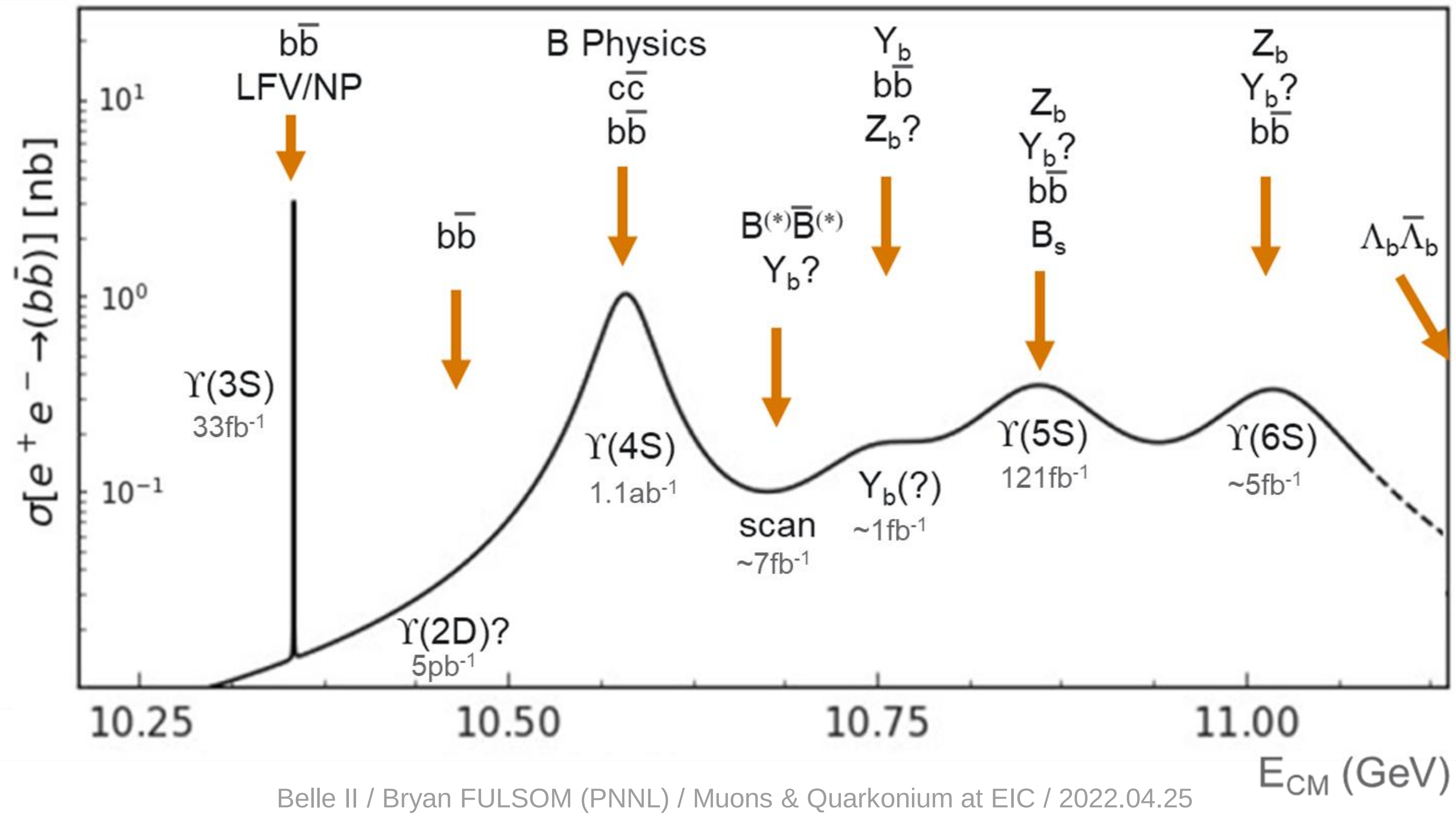




Belle II Potential – Non-ϒ(4S) Energies

- B-Factories extended their physics programs with non-ϒ(4S) data
  - BaBar ϒ(3S): discovery of $\eta_b(1S)$
  - Belle ϒ(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)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

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

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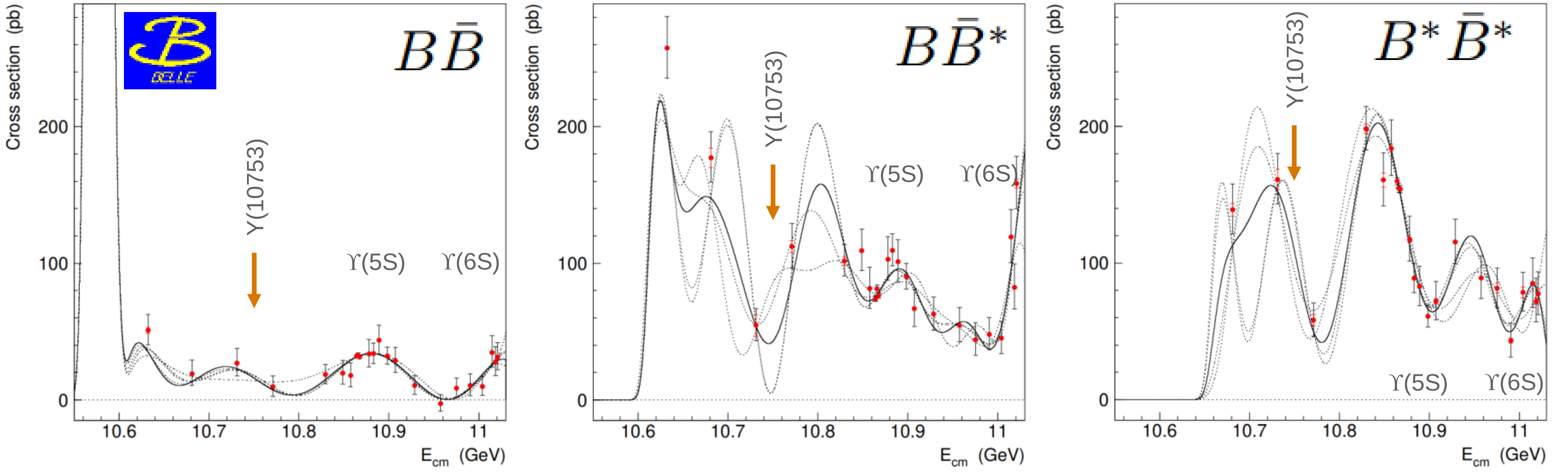
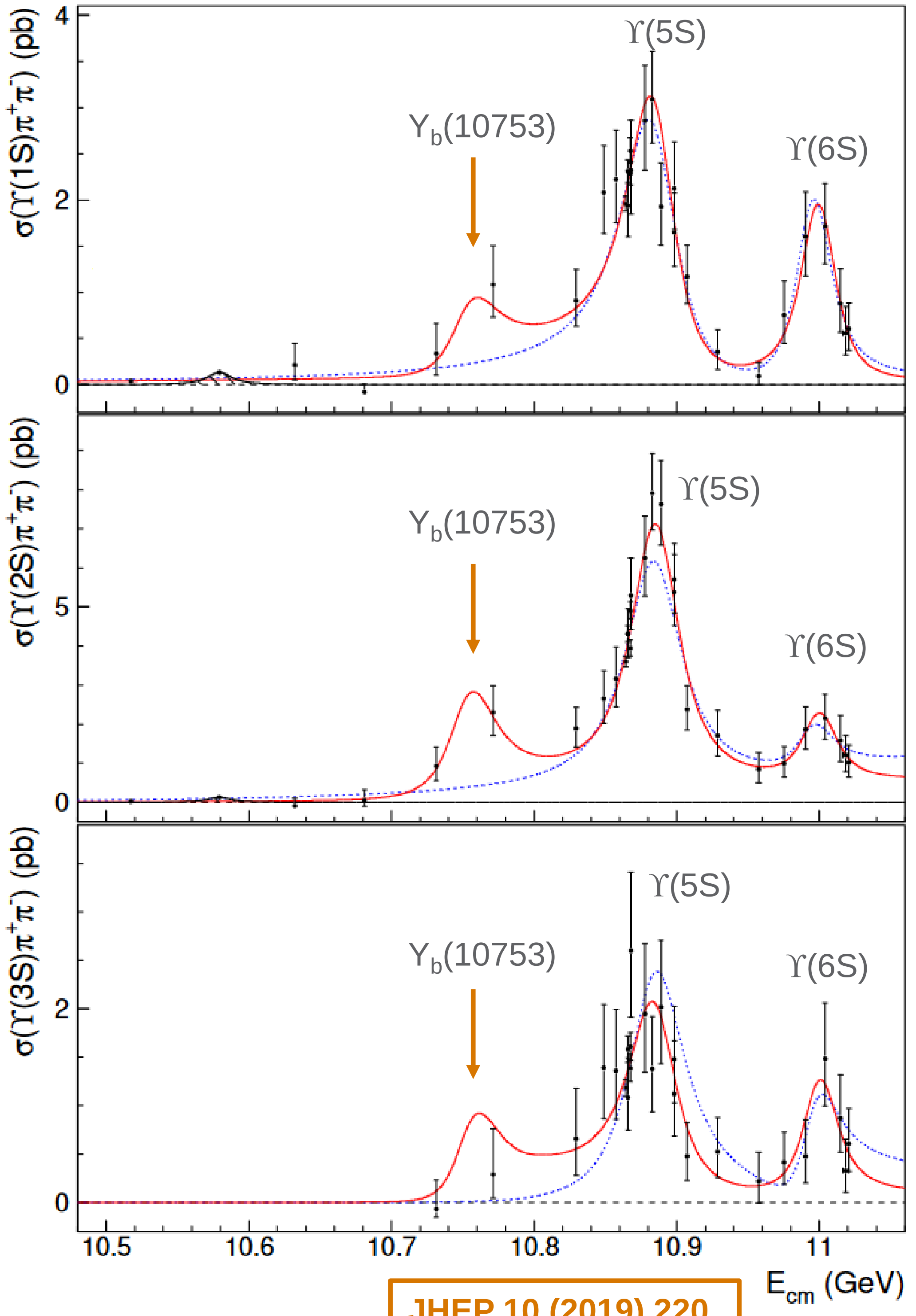


- Revisit this energy region with greater statistics



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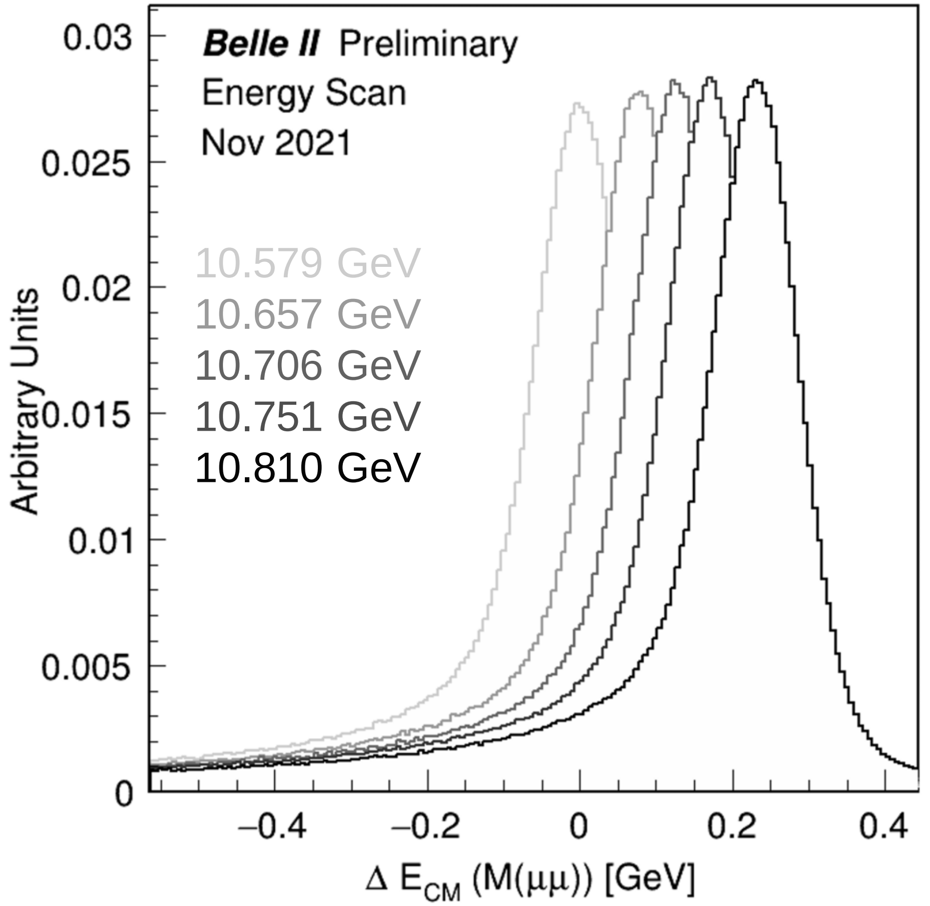
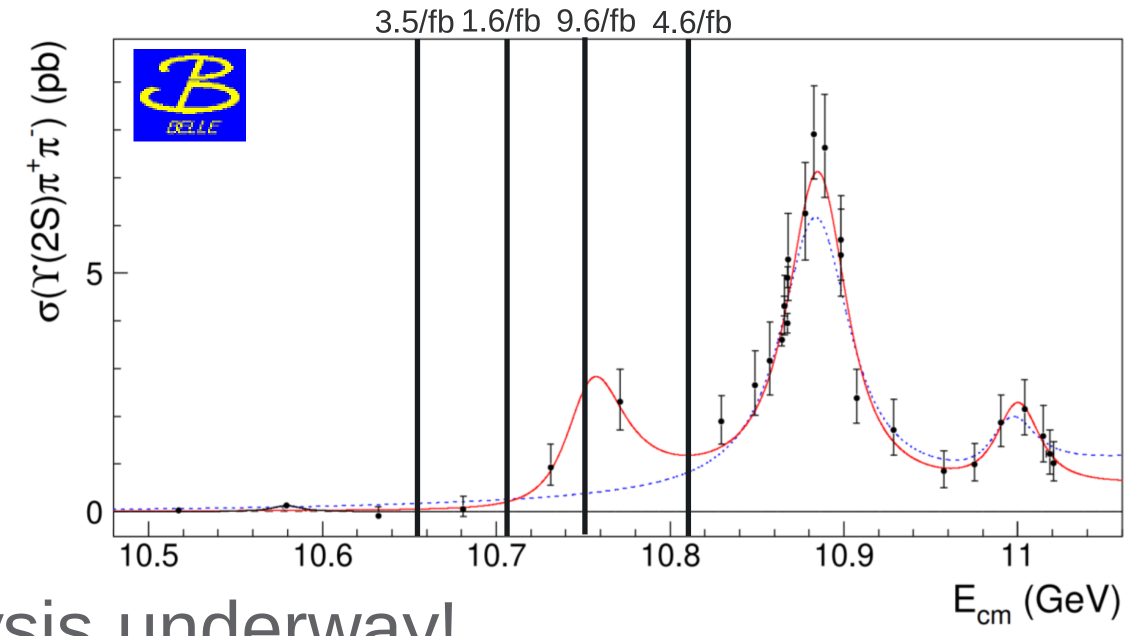
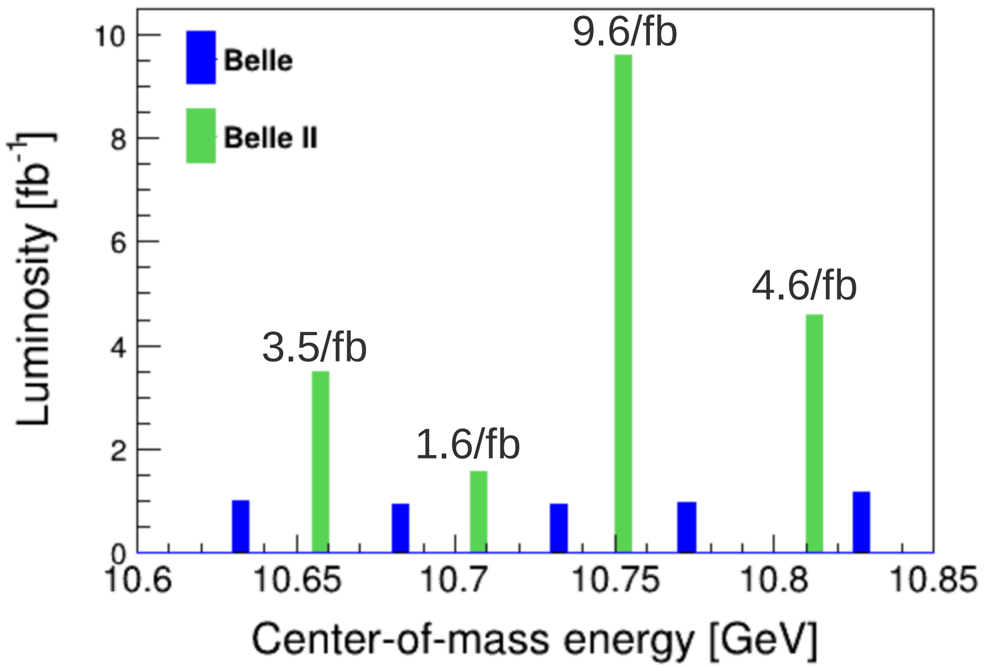
Belle II Energy Scan Nov. 10-29, 2021 (JST)



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



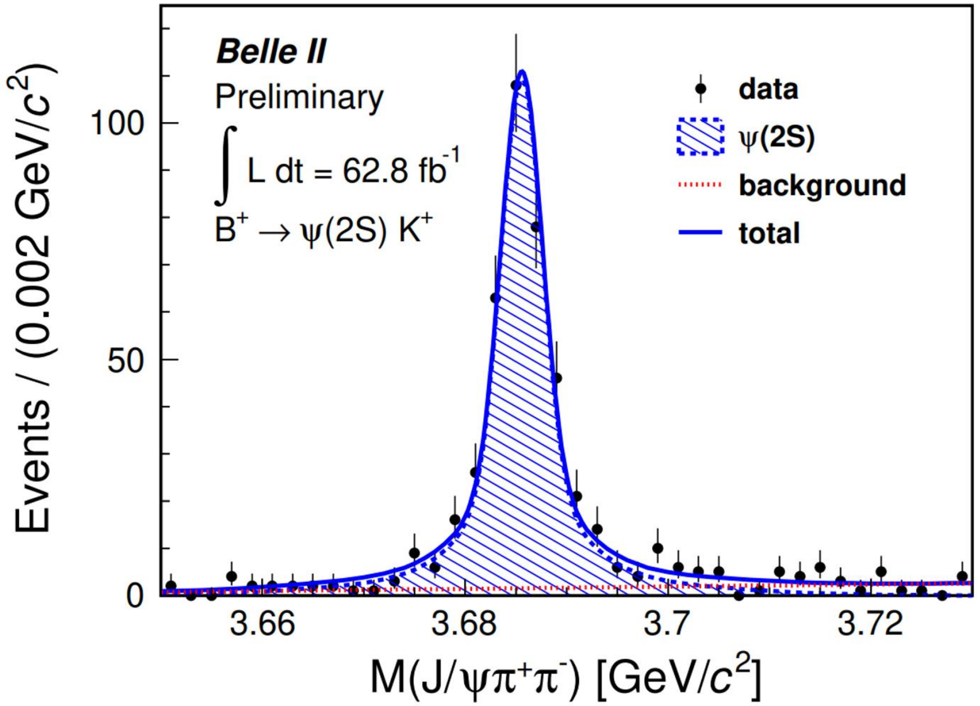


- Data analysis underway!

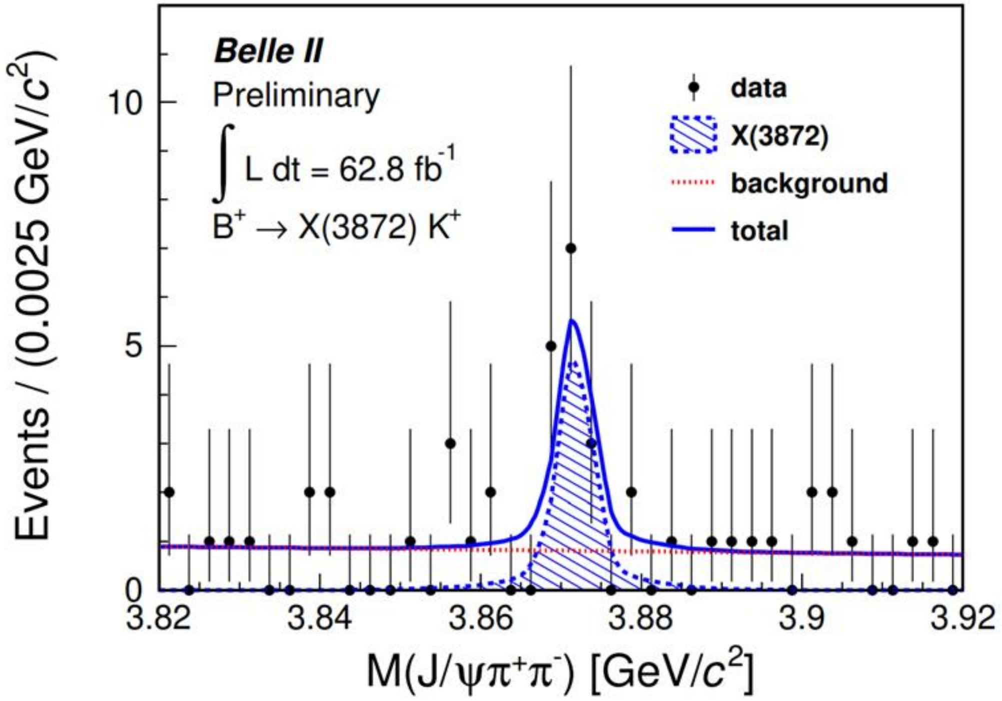
Belle II Progress – Charmonium/X(3872)

- "Rediscoveries" of several expected signal modes

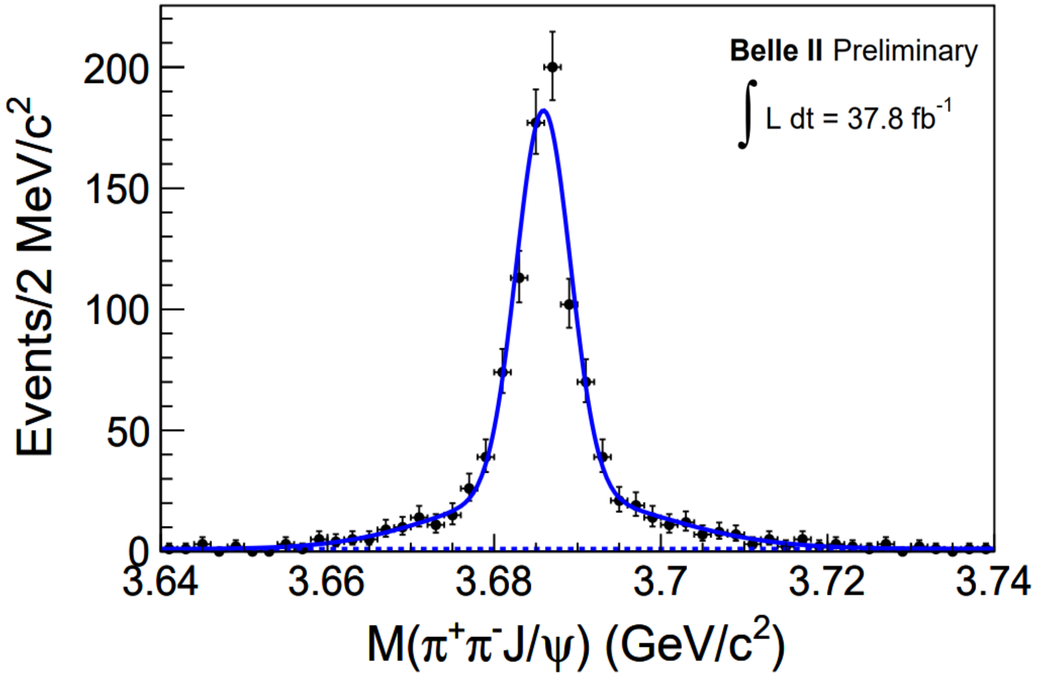
$B^+ \to \psi(2S) K^+$



$B^+ \to X(3872) K^+$



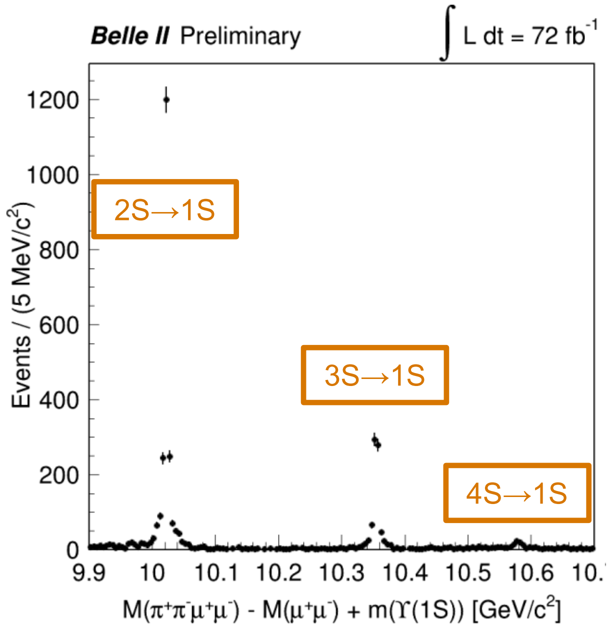
$e^+e^- \to \psi(2S) \to \mu^+\mu^-$

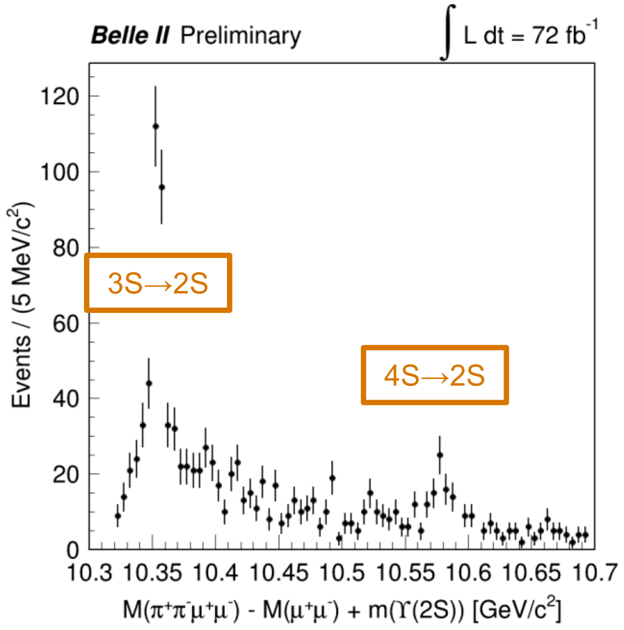


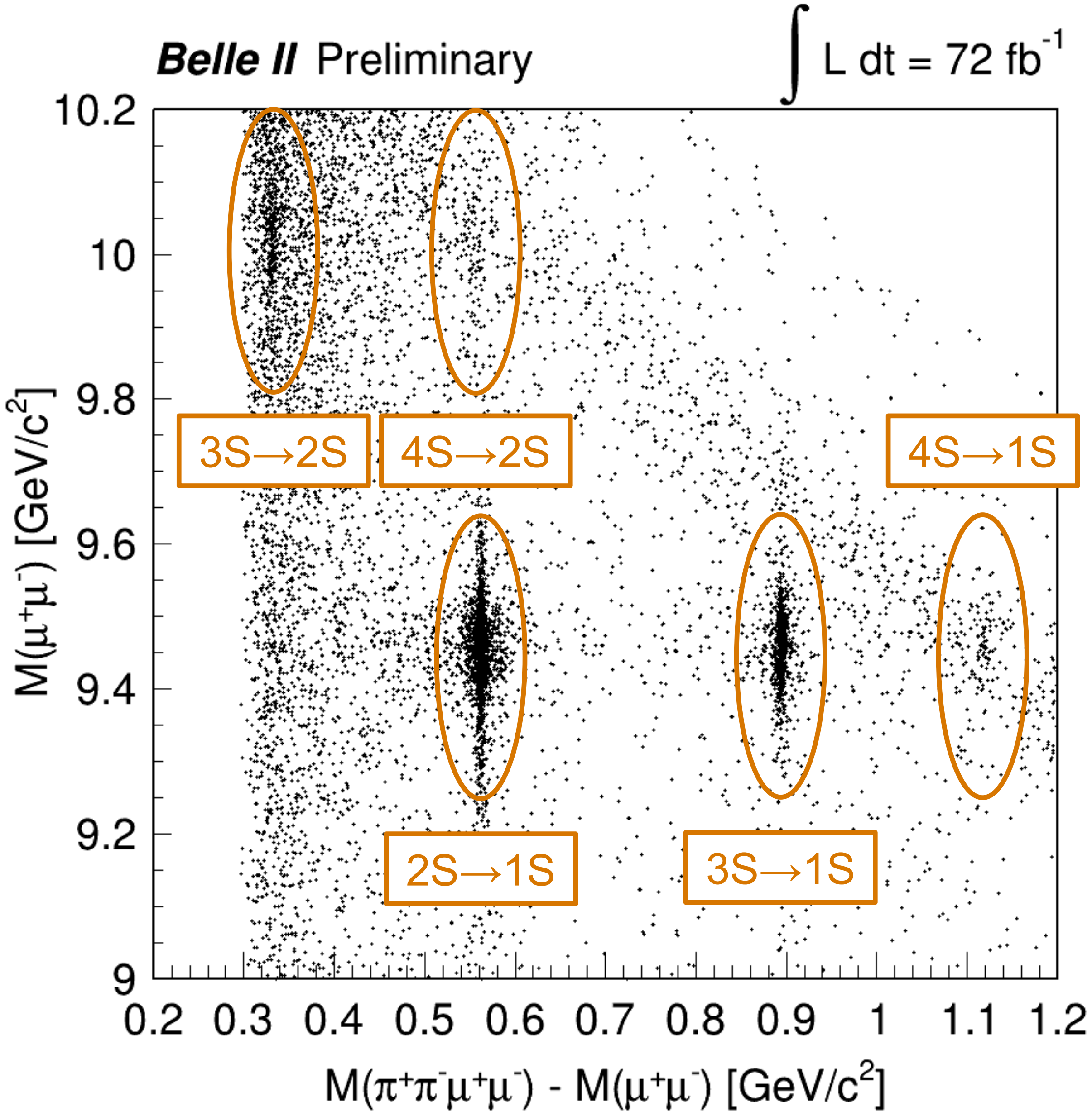
- Verification of reconstruction, efficiencies, etc.
- More results to come with increased luminosity

Belle II Progress – Bottomonium

- Initial State Radiation production:
  - $\gamma_{ISR}\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)(\ell^+\ell^-)$
  - $\gamma_{ISR}\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S,2S)(\ell^+\ell^-)$
- Direct transitions: $\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S,2S)$
- All signals observed in early Belle II data







- Prelude to energy scan analysis

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