



Prospects of Quarkonium Studies at Belle II

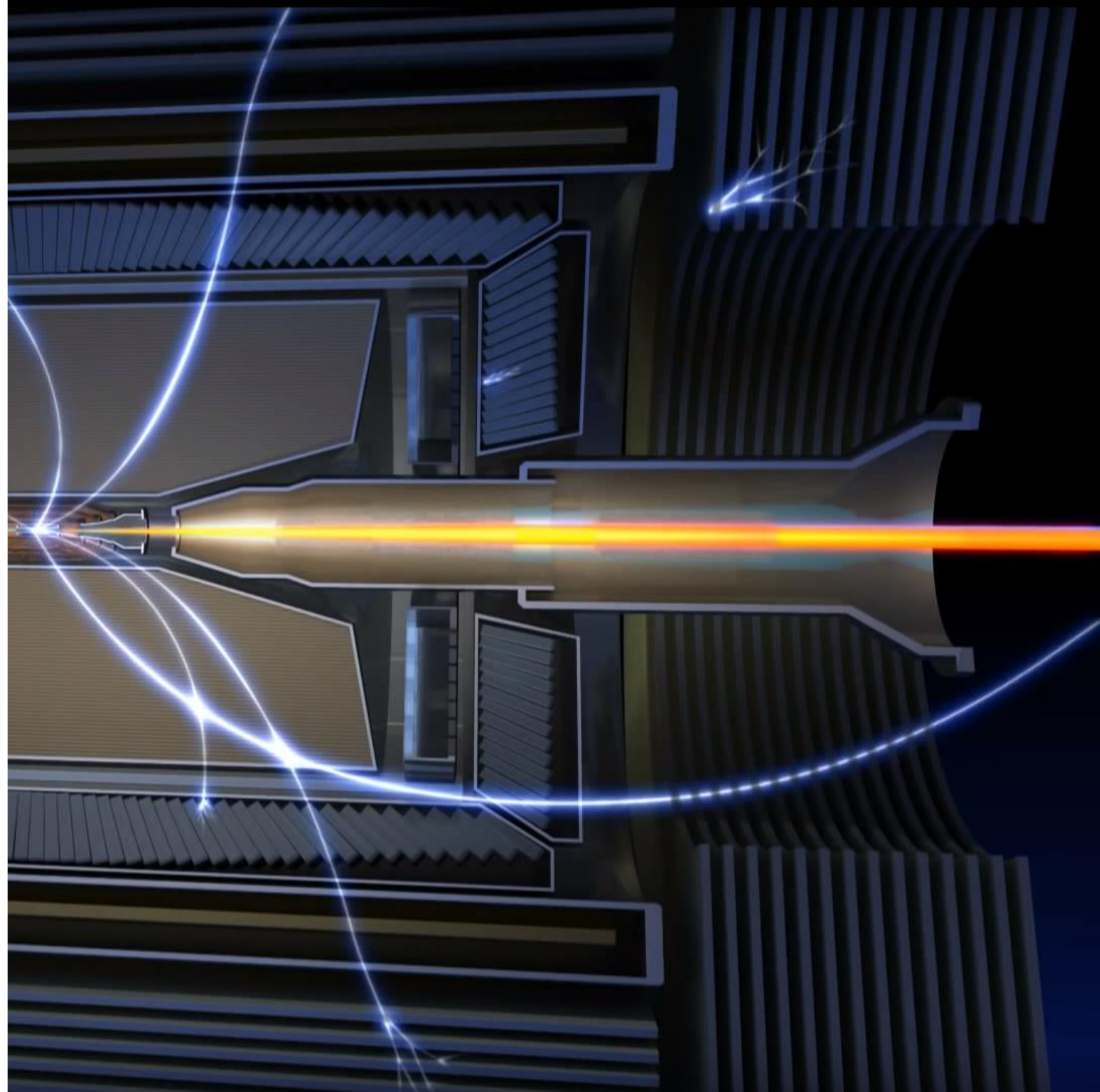
March 19, 2021

Bryan Fulsom (PNNL)
on behalf of the Belle II Collaboration

14th International Workshop on Heavy Quarkonium
UC Davis, CA, USA



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Introduction

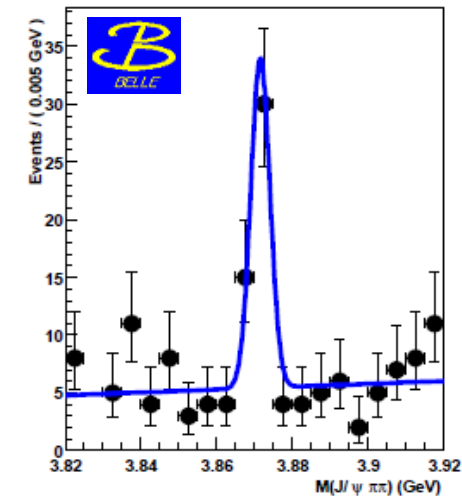
- Belle / Belle II Overview
- Physics Potential
 - B Decays
 - Initial State Radiation
 - Other processes
 - Non- $\Upsilon(4S)$ Energies
- New Results from Data

Overview

B-Factories Legacy

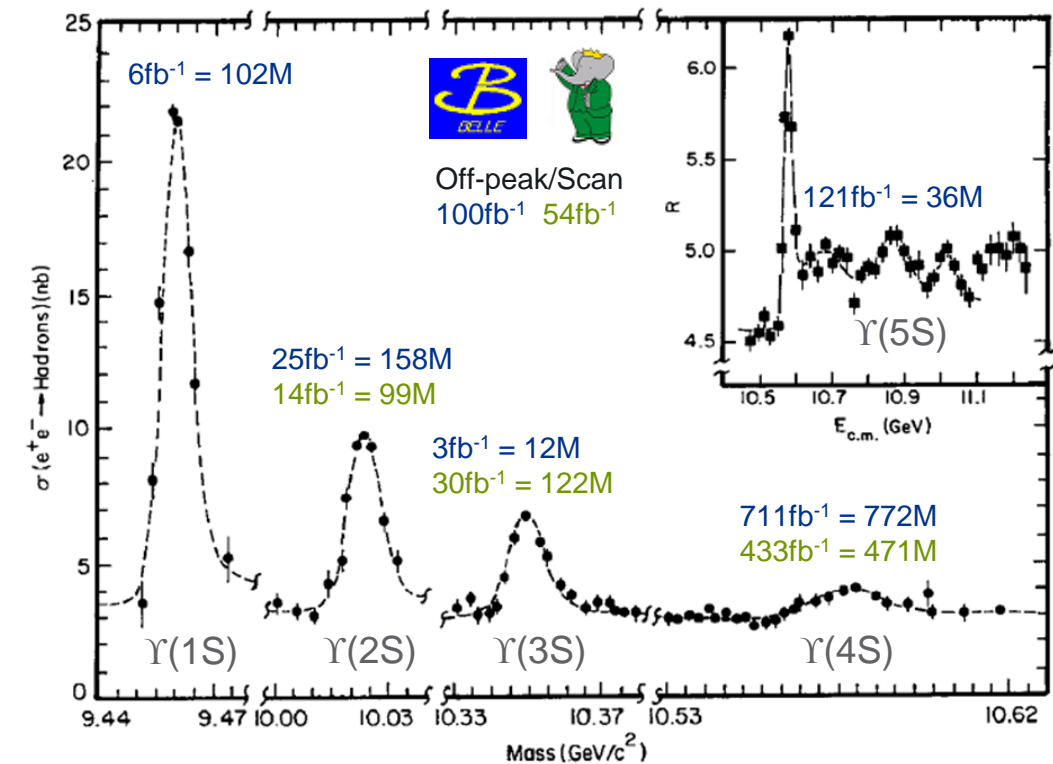
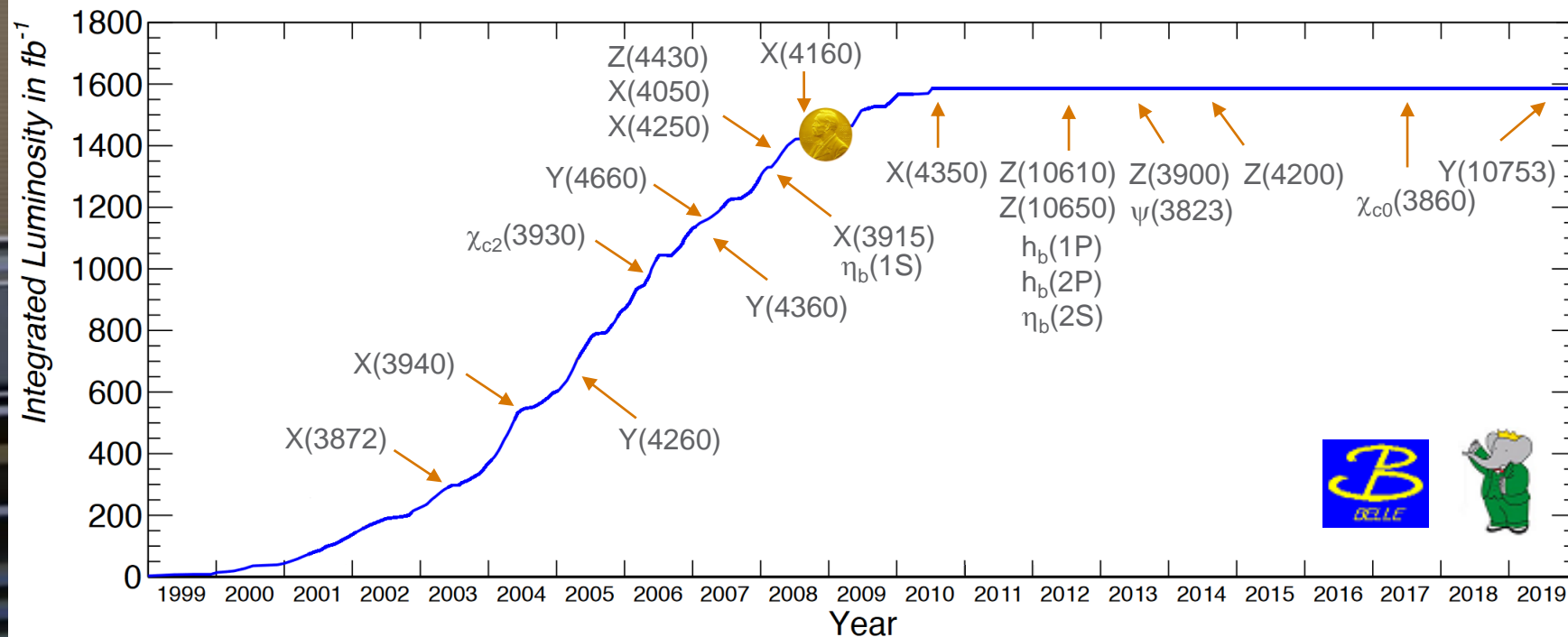
e.g.: “The Physics of the B Factories”, EPJC 74, 3026 (2014)

- ~2000 – 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)

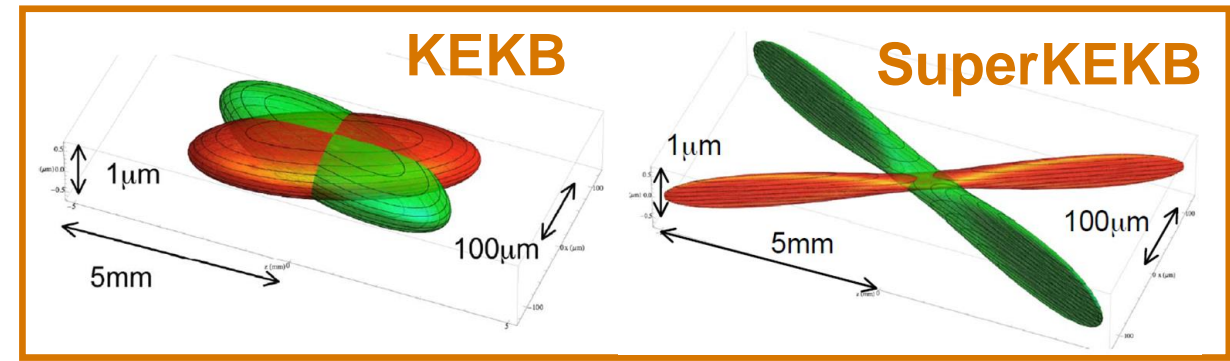
PRL 91, 262001 (2003)



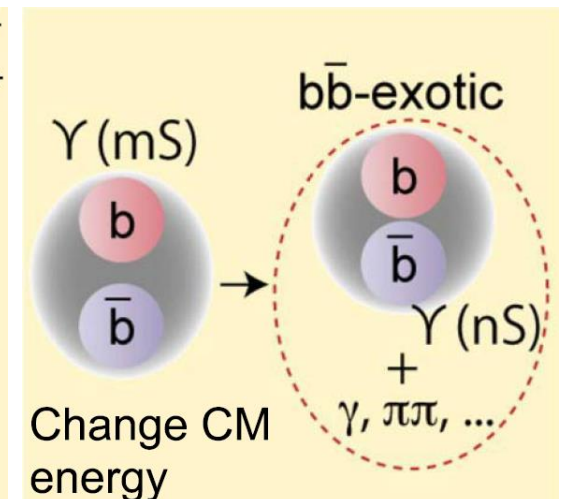
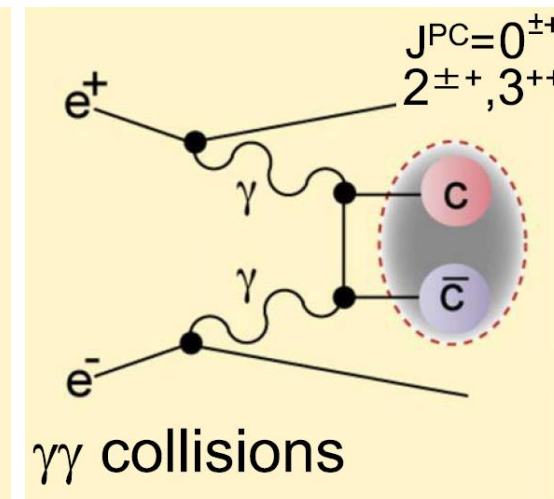
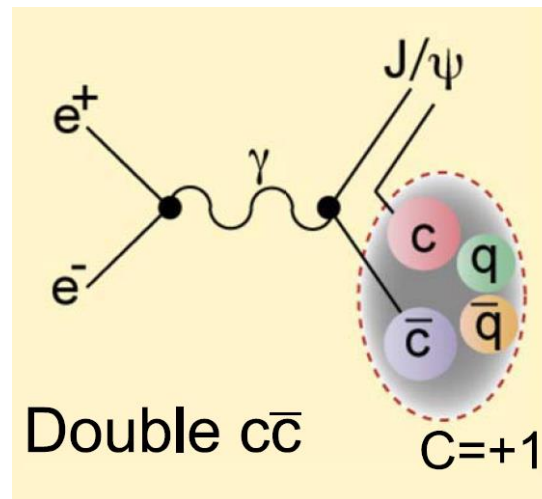
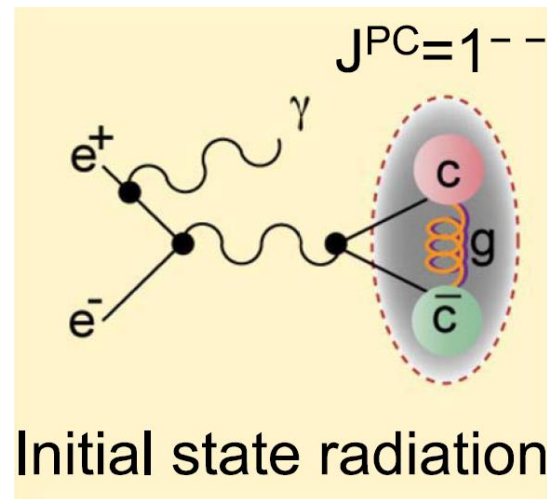
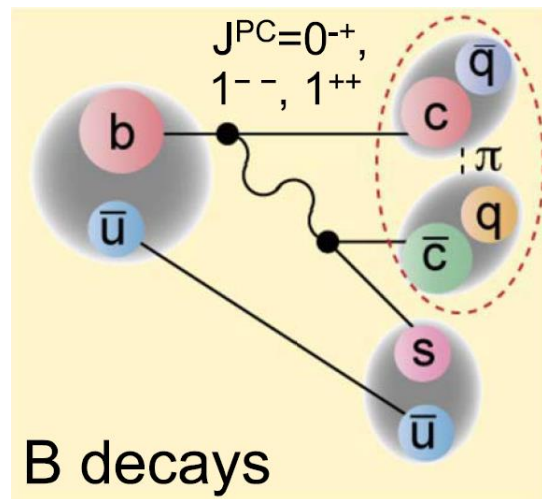
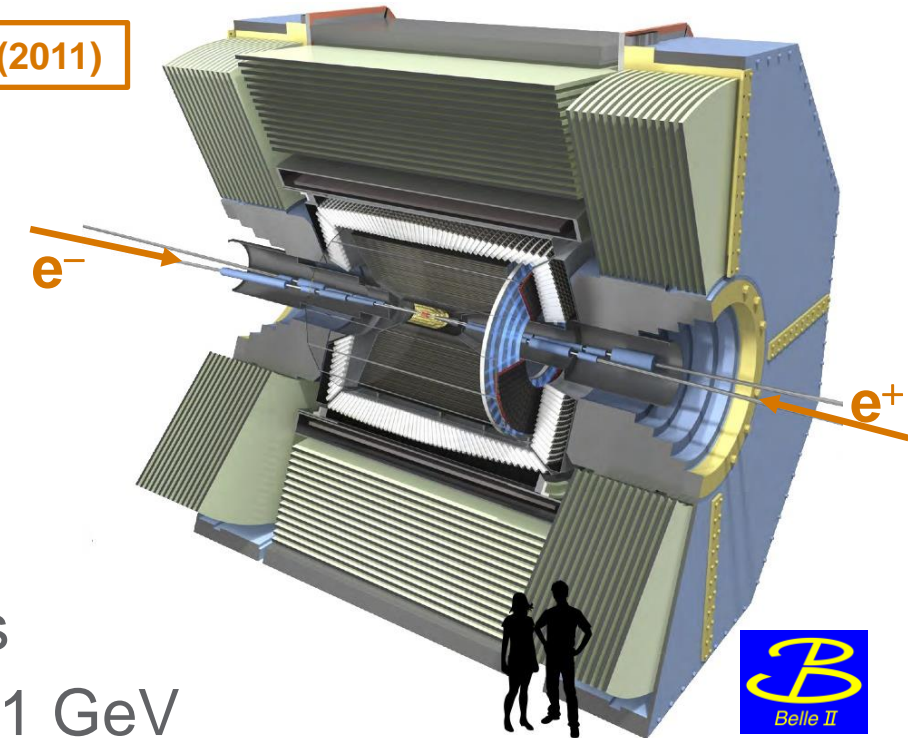
Belle II Capabilities

PTEP 2019 123C01 (2019)

- Belle II is the next generation B-Factory
 - Upgraded detector and accelerator
 - 1076 members, 121 institutions, 26 nations
 - ~10-year program ongoing since 2019
- Advantages
 - ~40x instantaneous and integrated luminosity
 - Full event reconstruction, decays with neutral/soft particles
 - Nominal $\sqrt{s} = 10.58 \text{ GeV} = m(\Upsilon(4S))$, potential to reach ~11 GeV



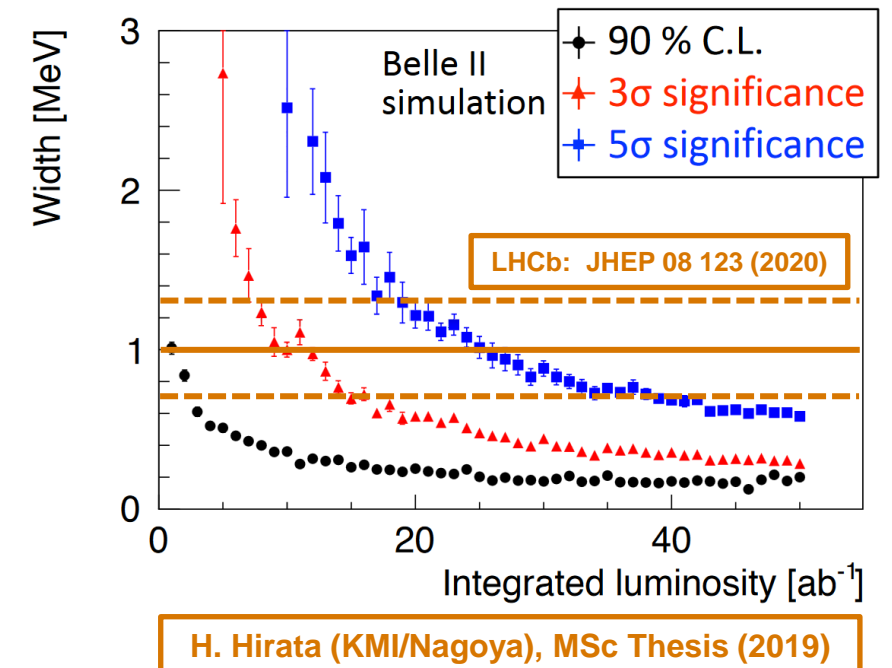
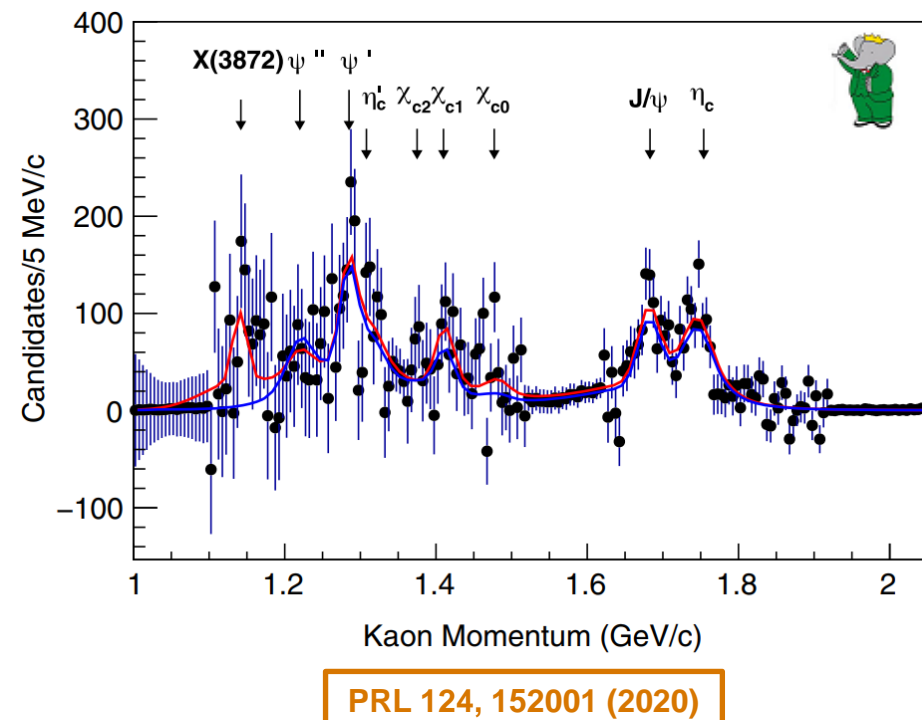
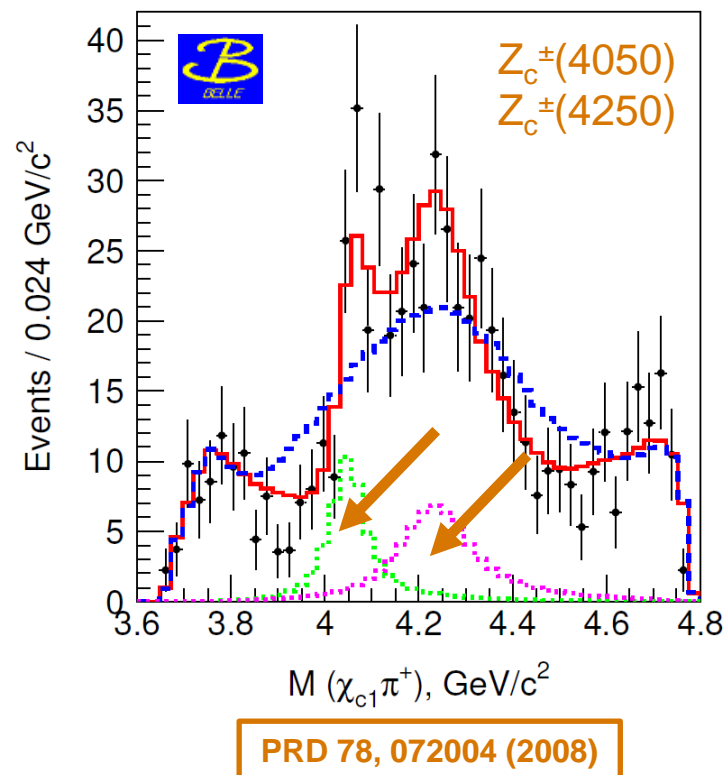
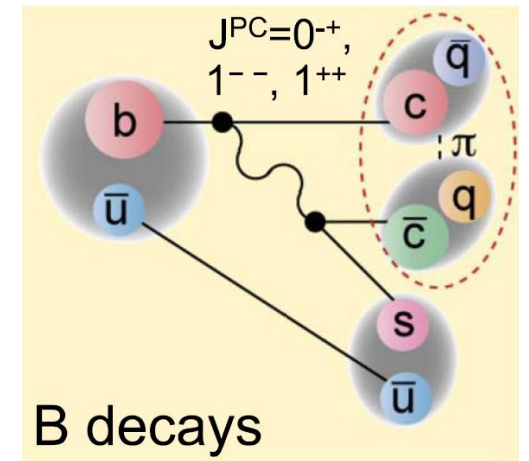
arXiv:1011.0352 (2011)



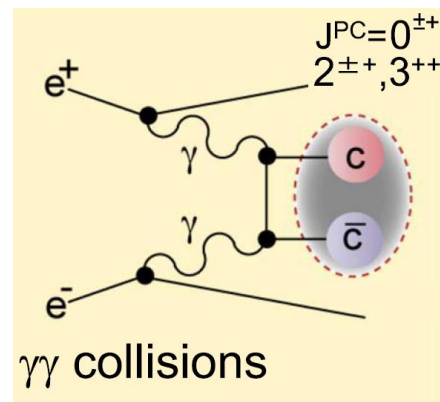
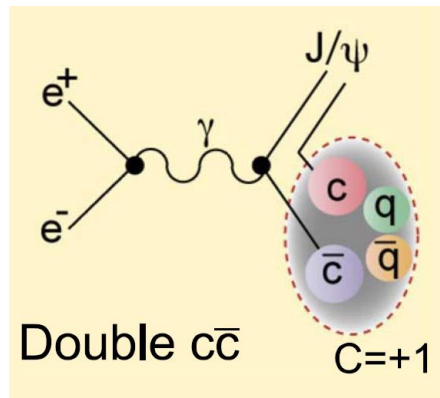
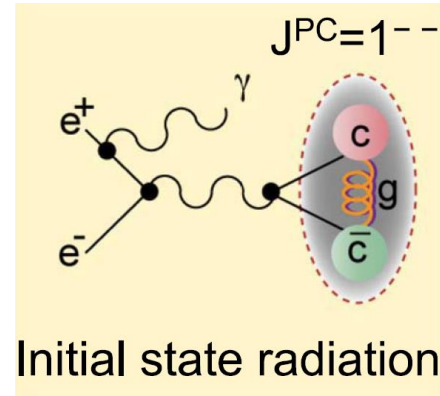
Physics Potential

Belle II Potential – B Decay

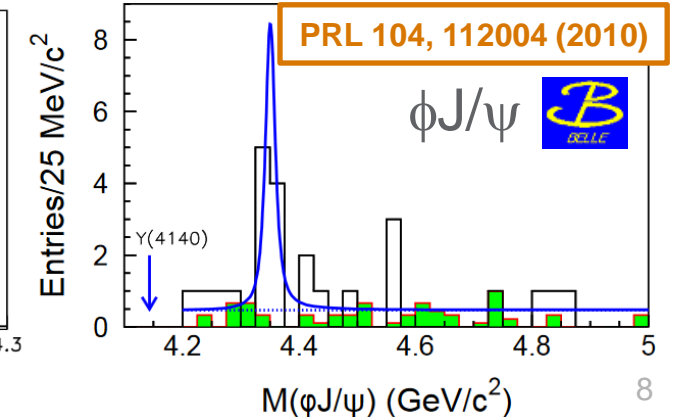
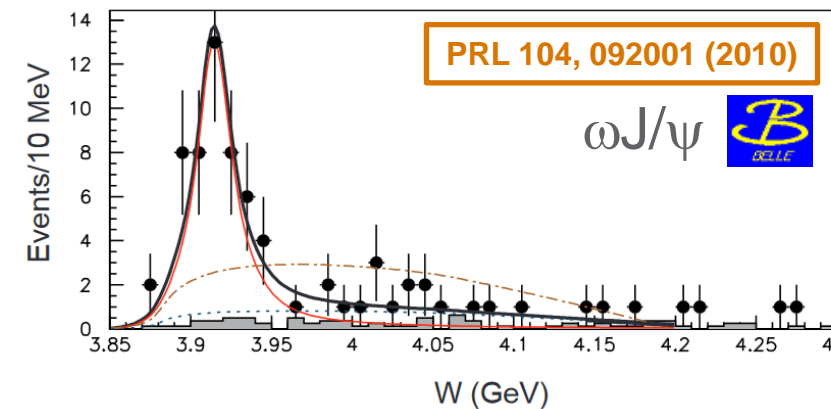
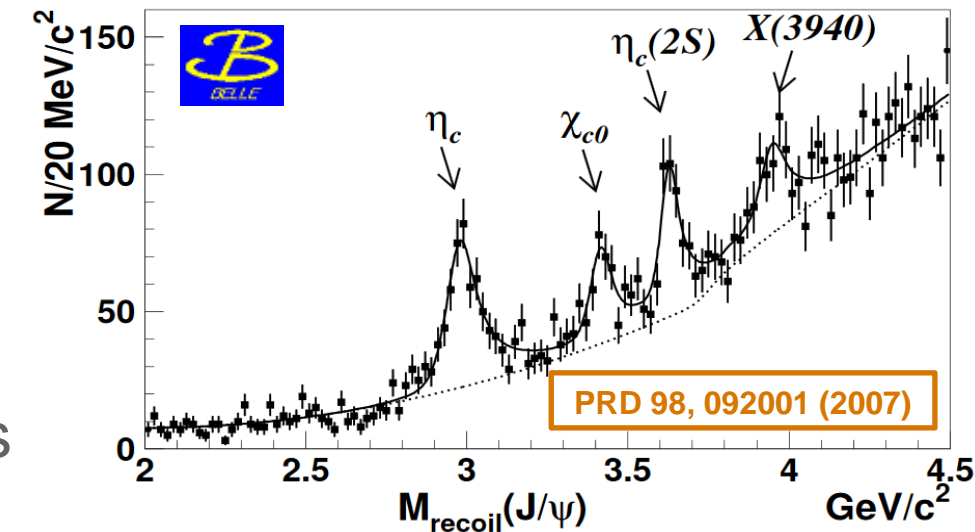
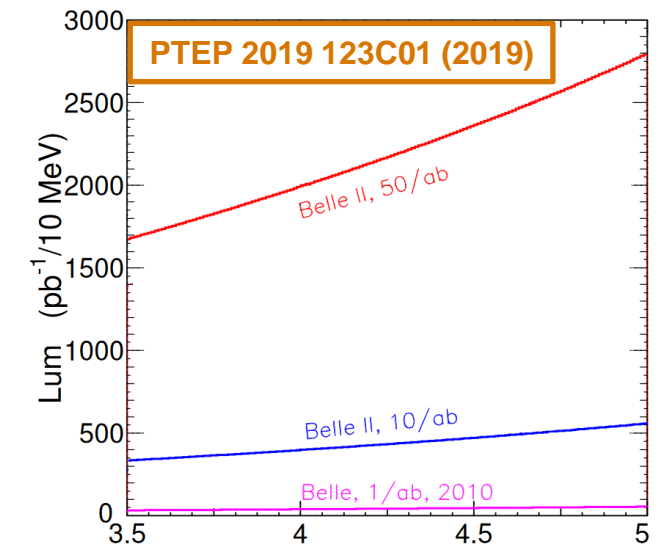
- High-statistics continuation from B-Factories
- Competition from LHCb, advantages for modes with neutrals
 - Confirm Z_c states and search for neutral partners
 - Absolute branching fractions $B \rightarrow X(3872,3915) K$
 - Confirmation of $X(3872)$ width measurement with $D^0 \bar{D}^0 \pi^0$



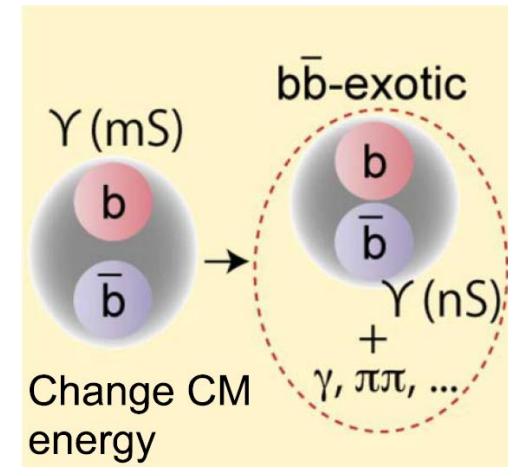
Belle II Potential – Other Processes



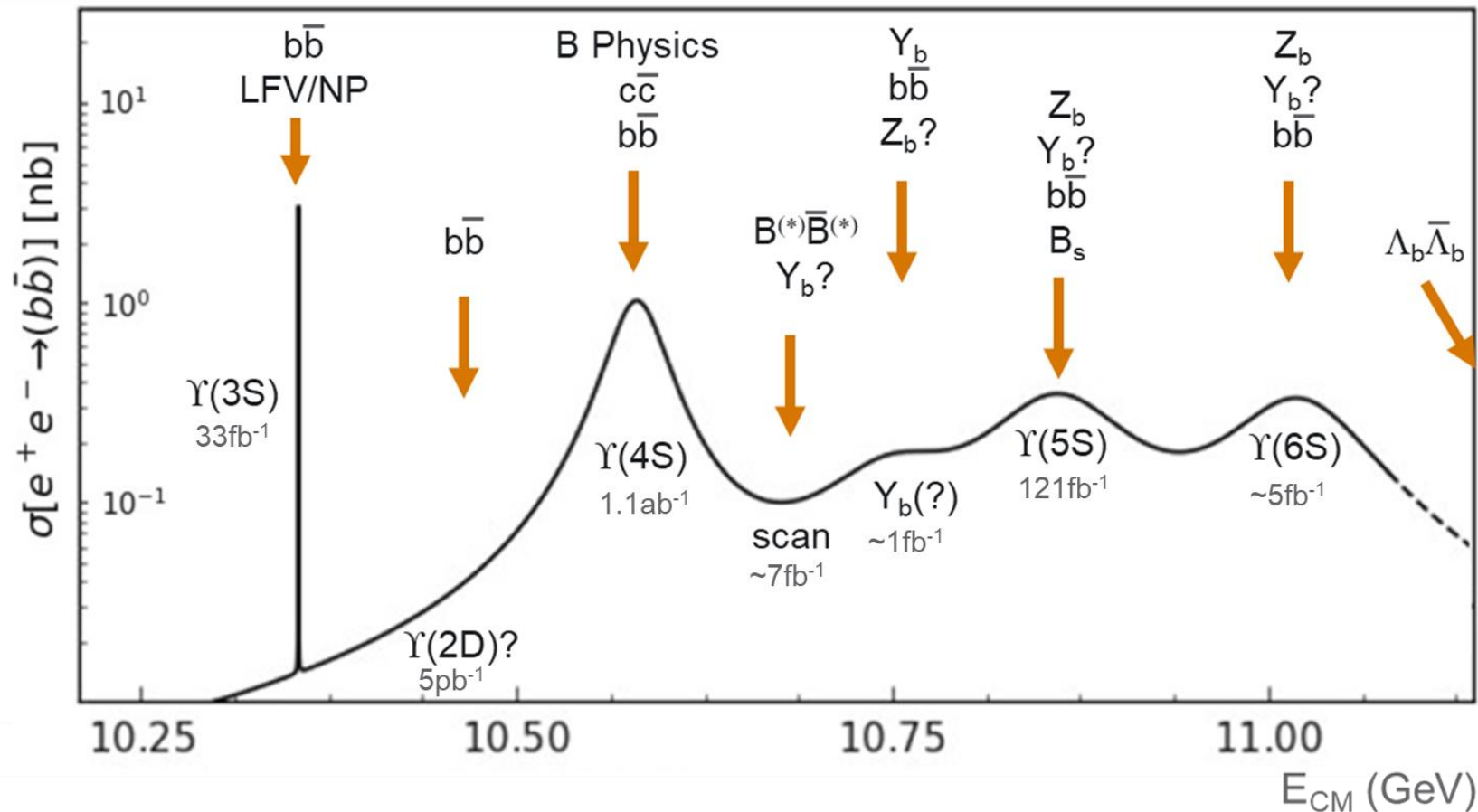
- ISR
 - Continuous mass range $>4.6 \text{ GeV}/c^2$
 - Higher masses/channels (e.g. $\gamma_{\text{ISR}}\Sigma_C\bar{\Sigma}_C$)
 - Confirm Z_c states (e.g. $e^+e^- \rightarrow h_c\pi\pi$)
- Double- $c\bar{c}$
 - $e^+e^- \rightarrow (c\bar{c})_{J=1}(c\bar{c})_{J=0}$ production rule
 - Discovery of 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 – Other 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 $h_b(1P, 2P)$, $\eta_b(2S)$, $Z_b^\pm(10610, 10650)$
 - KEKB/Belle energy scan data: $\Upsilon(6S)$, $Y_b(10753)$



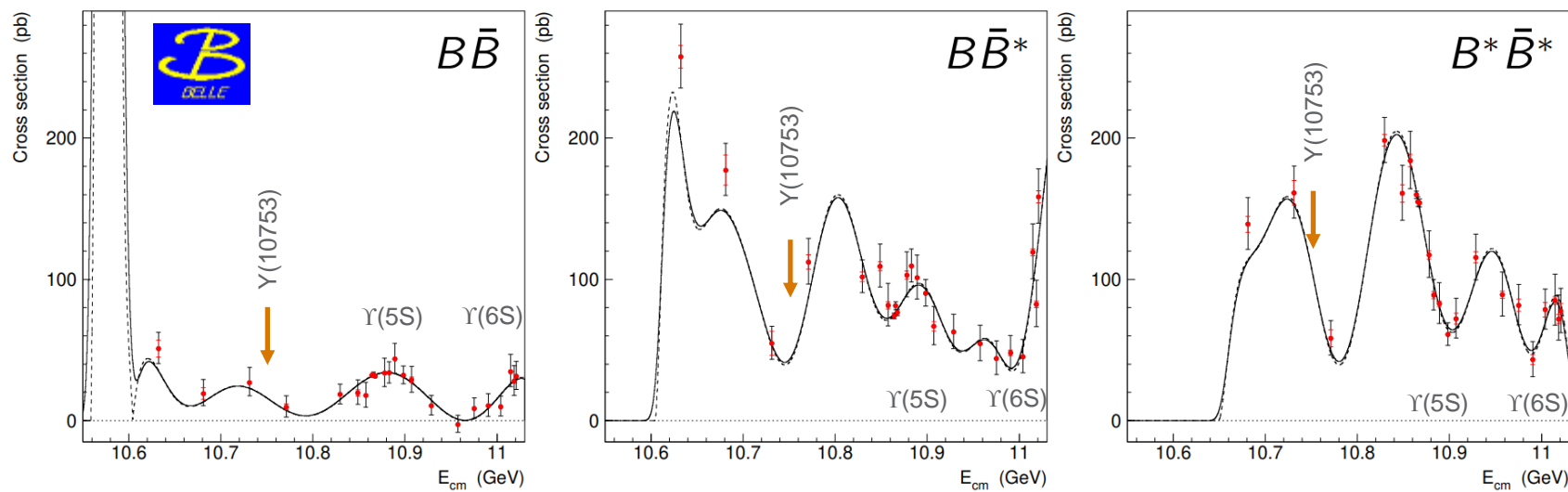
Belle II Potential – 10.75 GeV

- Seven $\sim 1\text{fb}^{-1}$ 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) | $36.6^{+4.5}_{-3.9} {}^{+0.5}_{-1.1}$ | $23.8^{+8.0}_{-6.8} {}^{+0.7}_{-1.8}$ | $35.5^{+17.6}_{-11.3} {}^{+3.9}_{-3.3}$ |

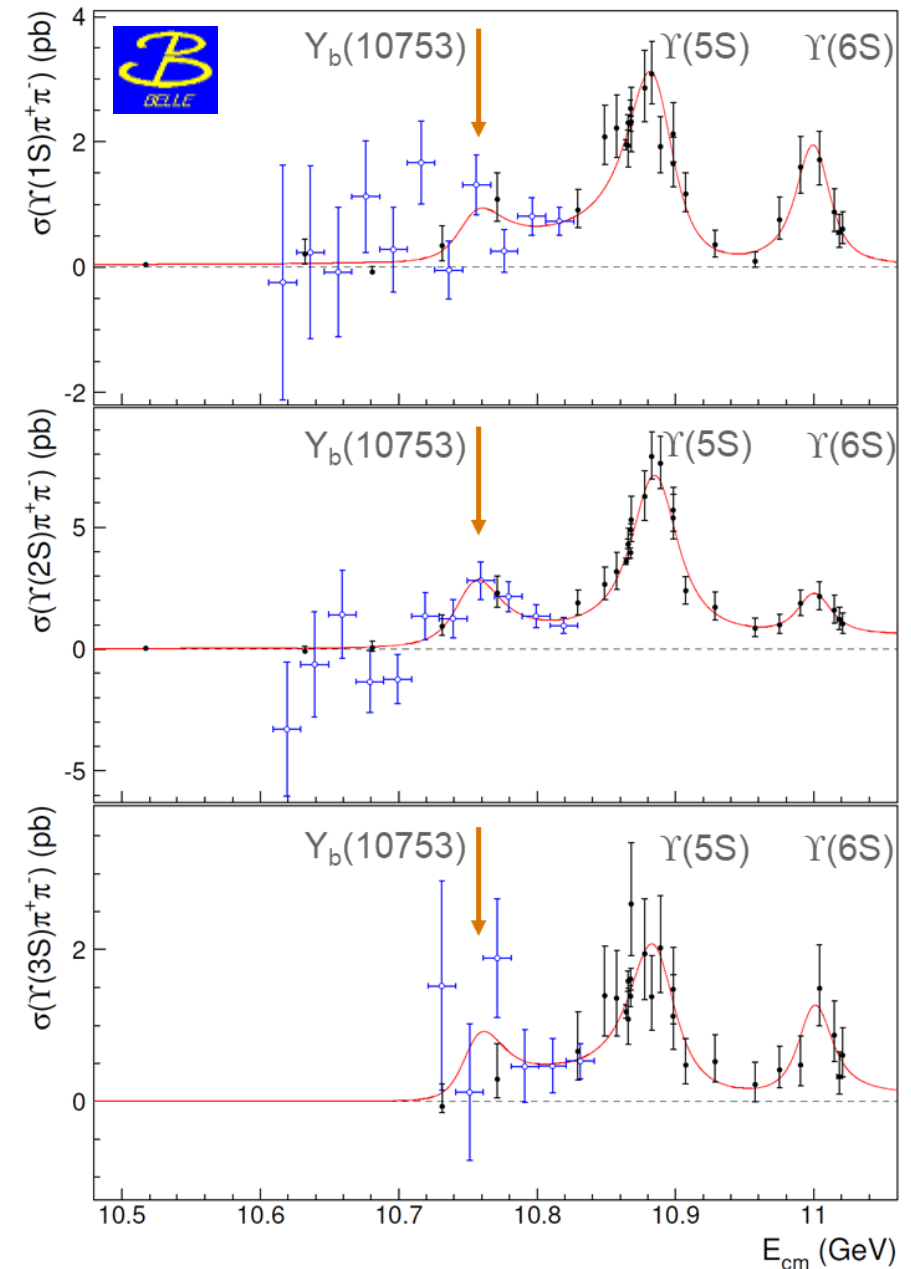
- New preliminary results this week

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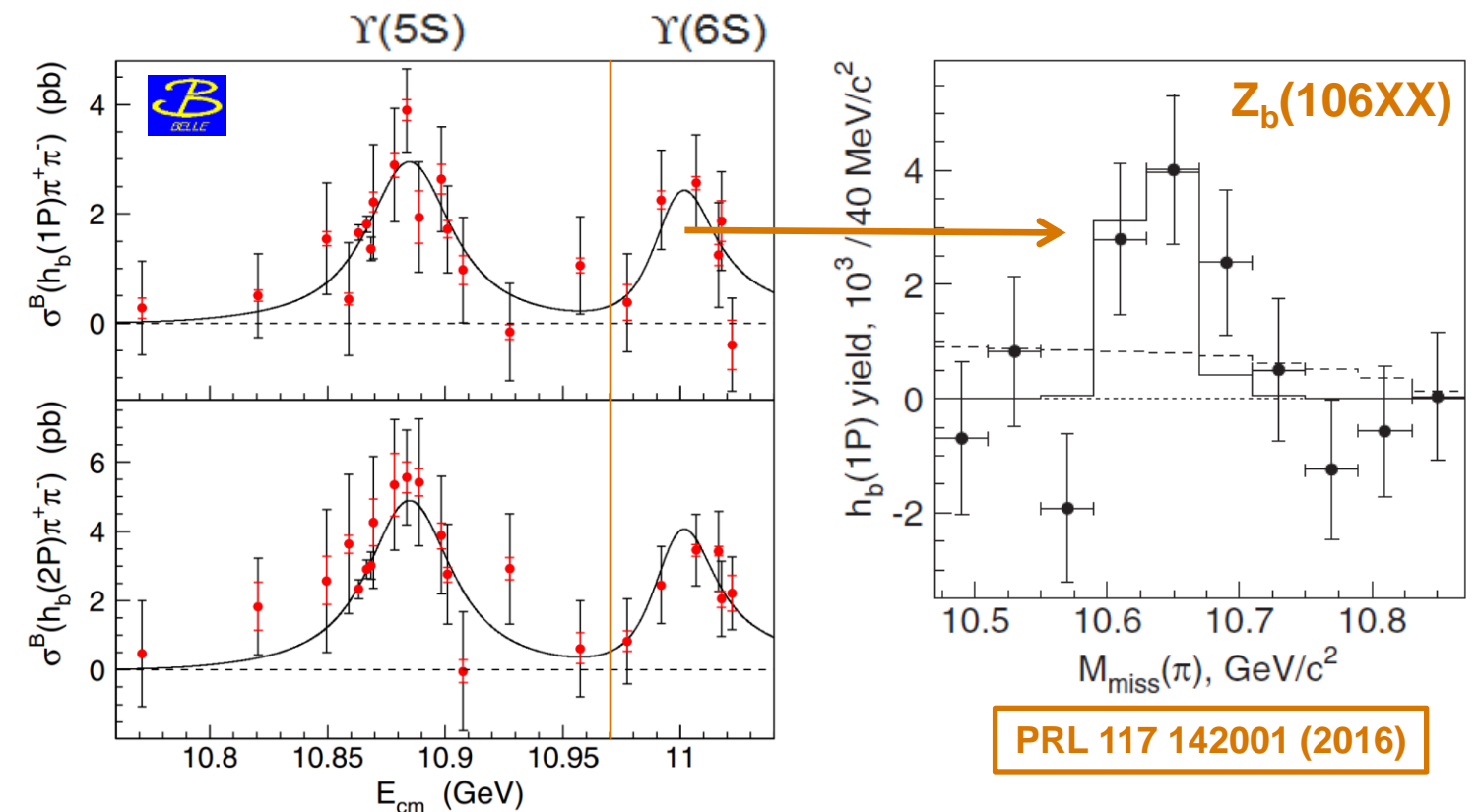
- Revisit this energy region with greater statistics

JHEP 10 (2019) 220



Belle II Potential – $\Upsilon(6S)$

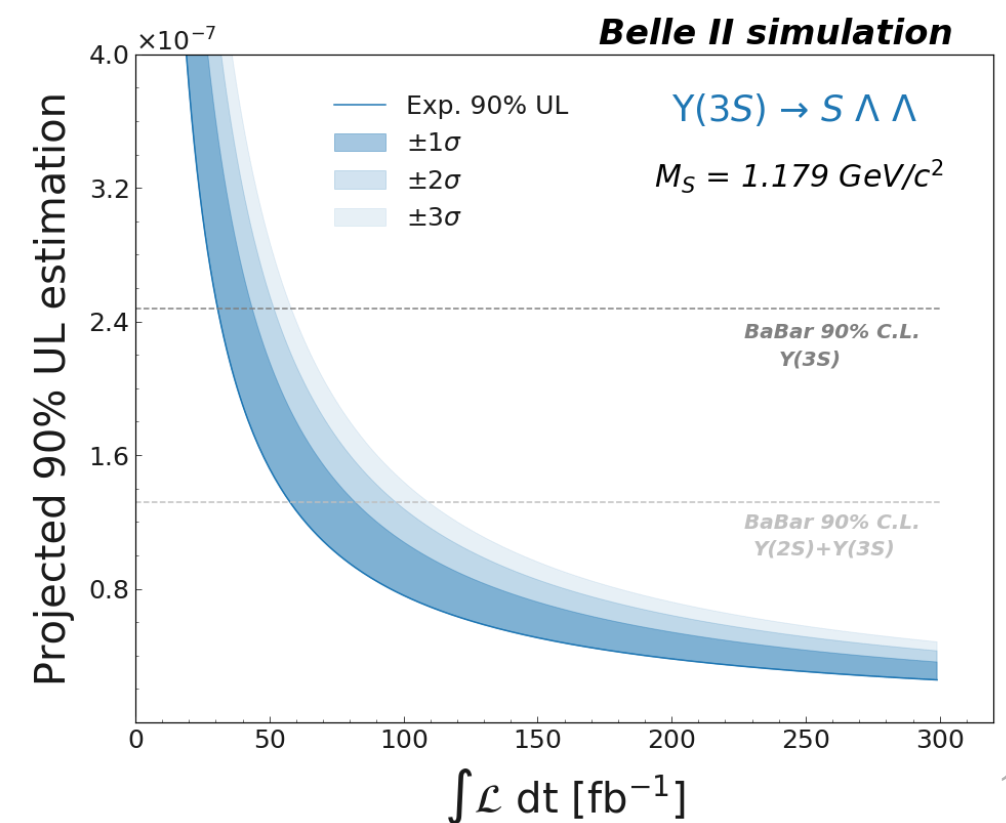
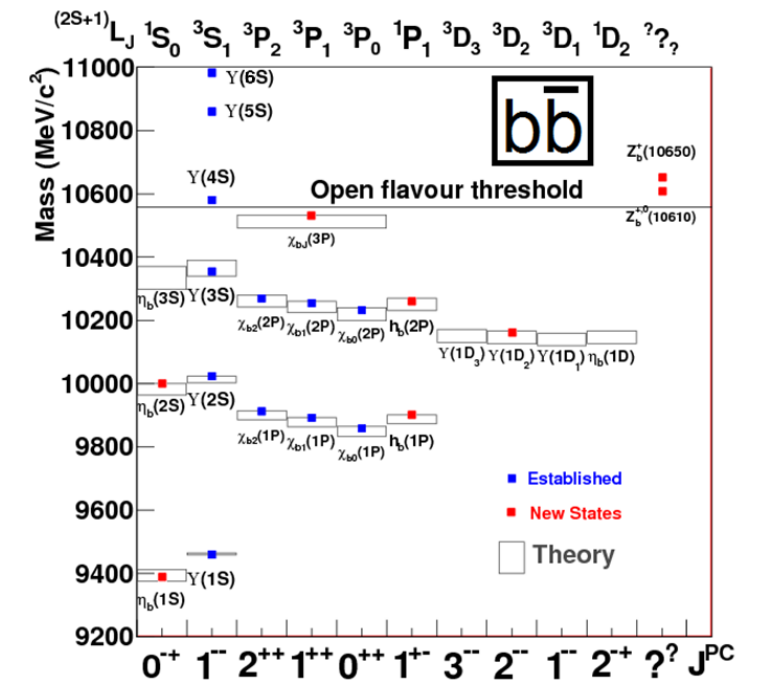
- Belle limited by statistics
- $<1 \text{ fb}^{-1}$ per scan point $\sim 4.6 \text{ fb}^{-1}$
- Not on σ peak, $L_{\text{eff}} \sim 3 \text{ fb}^{-1}$
- $\Upsilon(6S) \rightarrow \pi^+\pi^- X$
 - h_b : evidence for Z_b
 - $\Upsilon(pS)$: statistics needed
- Include other decay modes
- Pending questions:
 - Investigate nature of $\Upsilon(6S)$ and Z_b : how many states, neutral partners?
 - Potential pathway to other bottomonium states ($h_b(3P)$, $\Upsilon(D)$)?



Belle II Potential – $\Upsilon(4S)$ and Below

- Default $\Upsilon(4S)$
 - Transitions: $\pi\pi/\eta/\eta'$ transitions, radiative decays?
 - 16k h_b and 5k η_b tagged events / 100fb^{-1}
- Conventional quarkonium below $\Upsilon(4S)$
 - Rare decays: $\Upsilon(3S) \rightarrow \pi^0 h_b(1P)$, $\Upsilon(3S) \rightarrow \eta \Upsilon(1S)$, ...
 - D-wave: $\Upsilon(3S) \rightarrow \gamma\gamma \Upsilon(1D)$, scan for $e^+e^- \rightarrow \Upsilon(mD_1)$
 - Inclusive production (D, \bar{d}, \dots) in $b\bar{b}$ decay
- Beyond Standard Model below $\Upsilon(4S)$
 - $\Upsilon(1S) \rightarrow$ invisible with dipion tag
 - LFV search $b\bar{b} \rightarrow \ell\tau$, LFU $\Upsilon(nS) \rightarrow \tau\tau/\mu\mu$
 - $\Upsilon(3S) \rightarrow S\Lambda\Lambda(n\pi)$ 'sexaquark' search

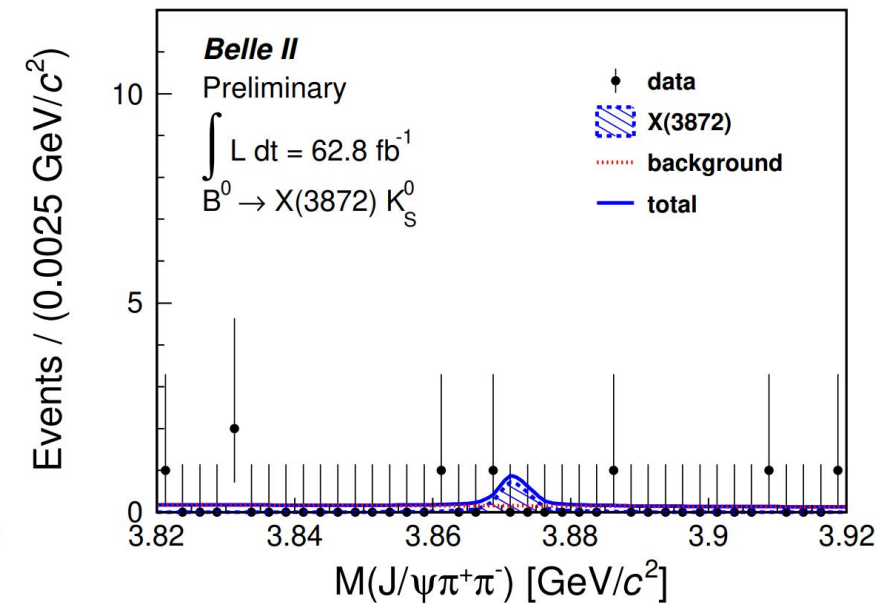
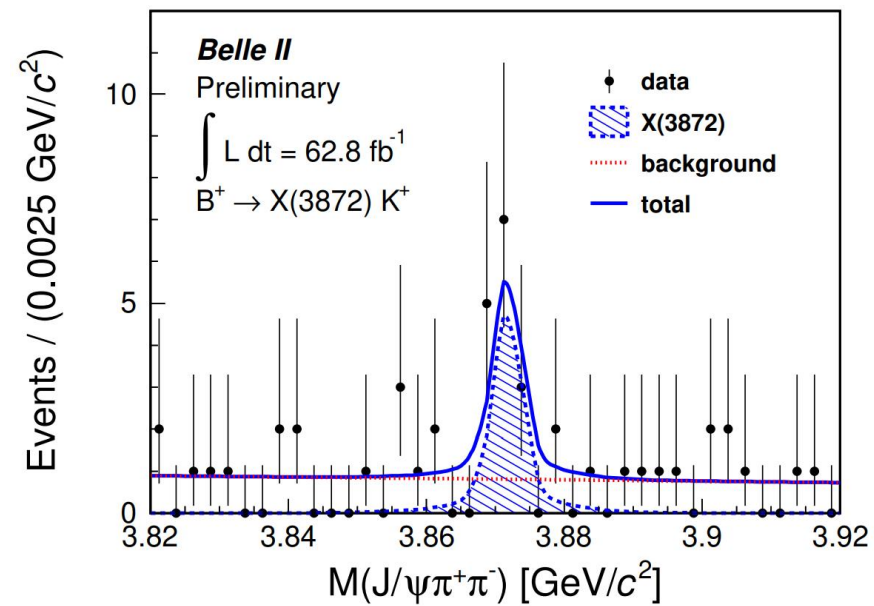
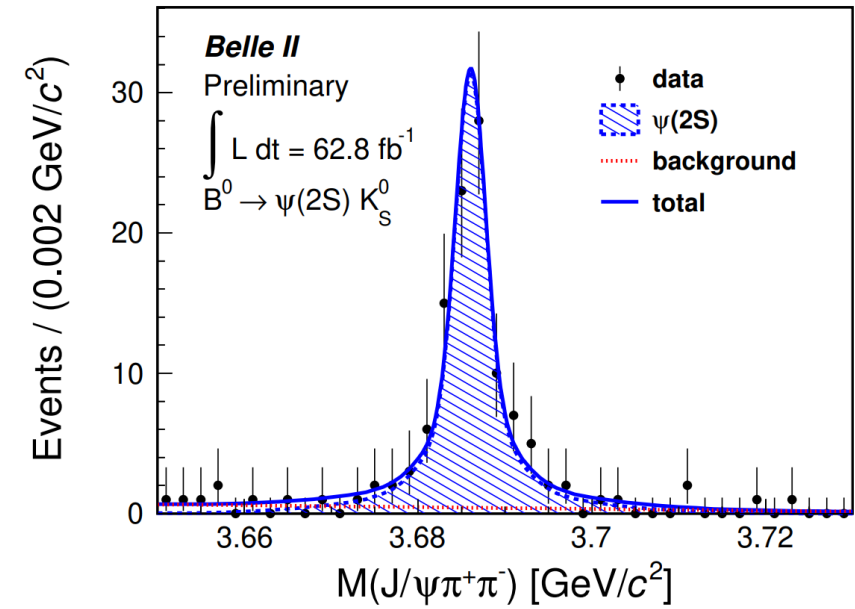
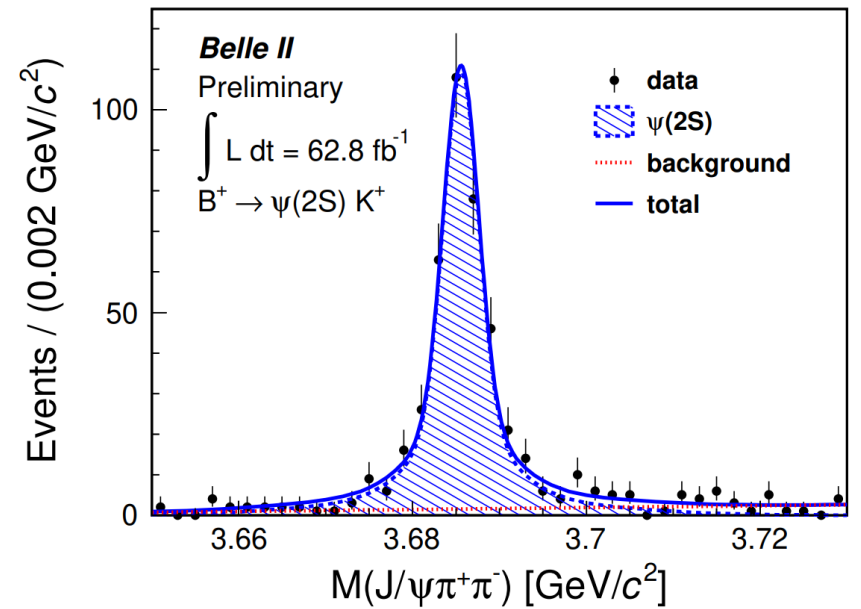
arXiv:1708.08951 (2018)



Latest Results

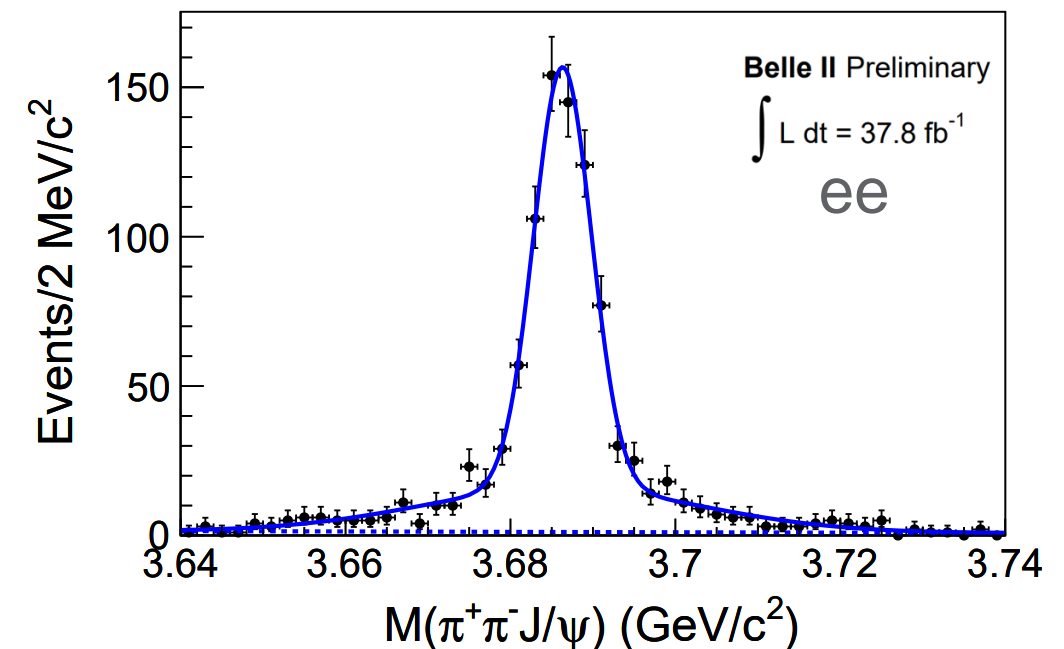
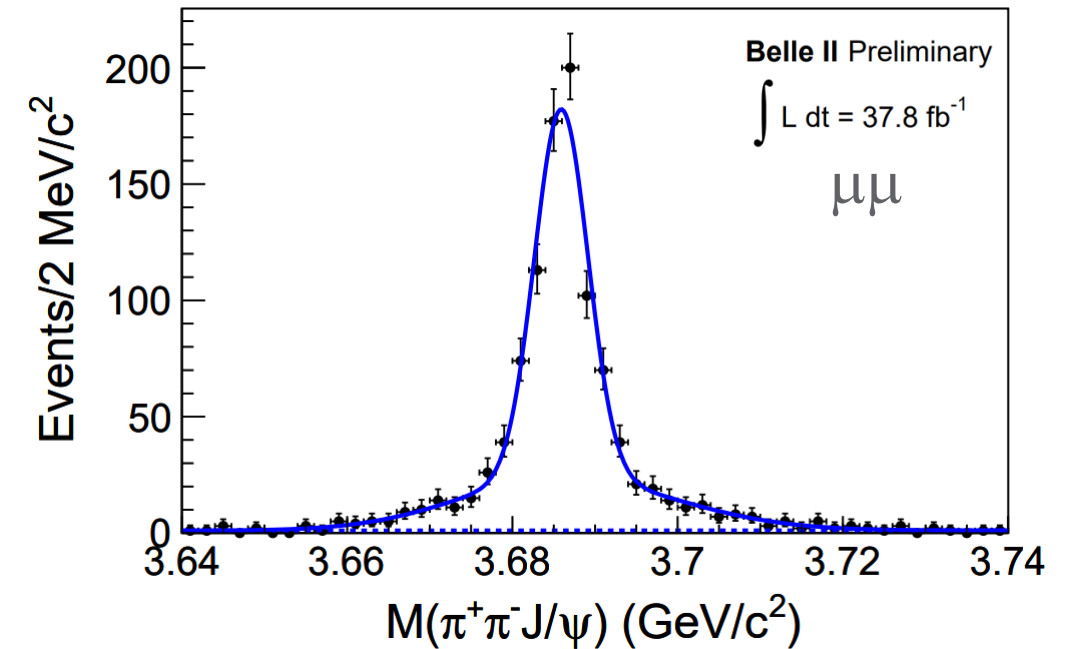
Belle II Progress – X(3872)

- Reconstruct final states:
 - $B^\pm \rightarrow \pi^+\pi^-J/\psi(\ell^+\ell^-) K^\pm$
 - $B^0 \rightarrow \pi^+\pi^-J/\psi(\ell^+\ell^-) K_S$
- “Standard” selection criteria
 - Particle identification
 - Continuum: nTracks, R_2
 - Kinematics: $M_{\pi^+\pi^-}$, M_{BC} , $|\Delta E|$
- Observe $B \rightarrow \psi(2S) K$
- First X(3872) at Belle II
 - 14.4 ± 4.6 events (4.6σ)



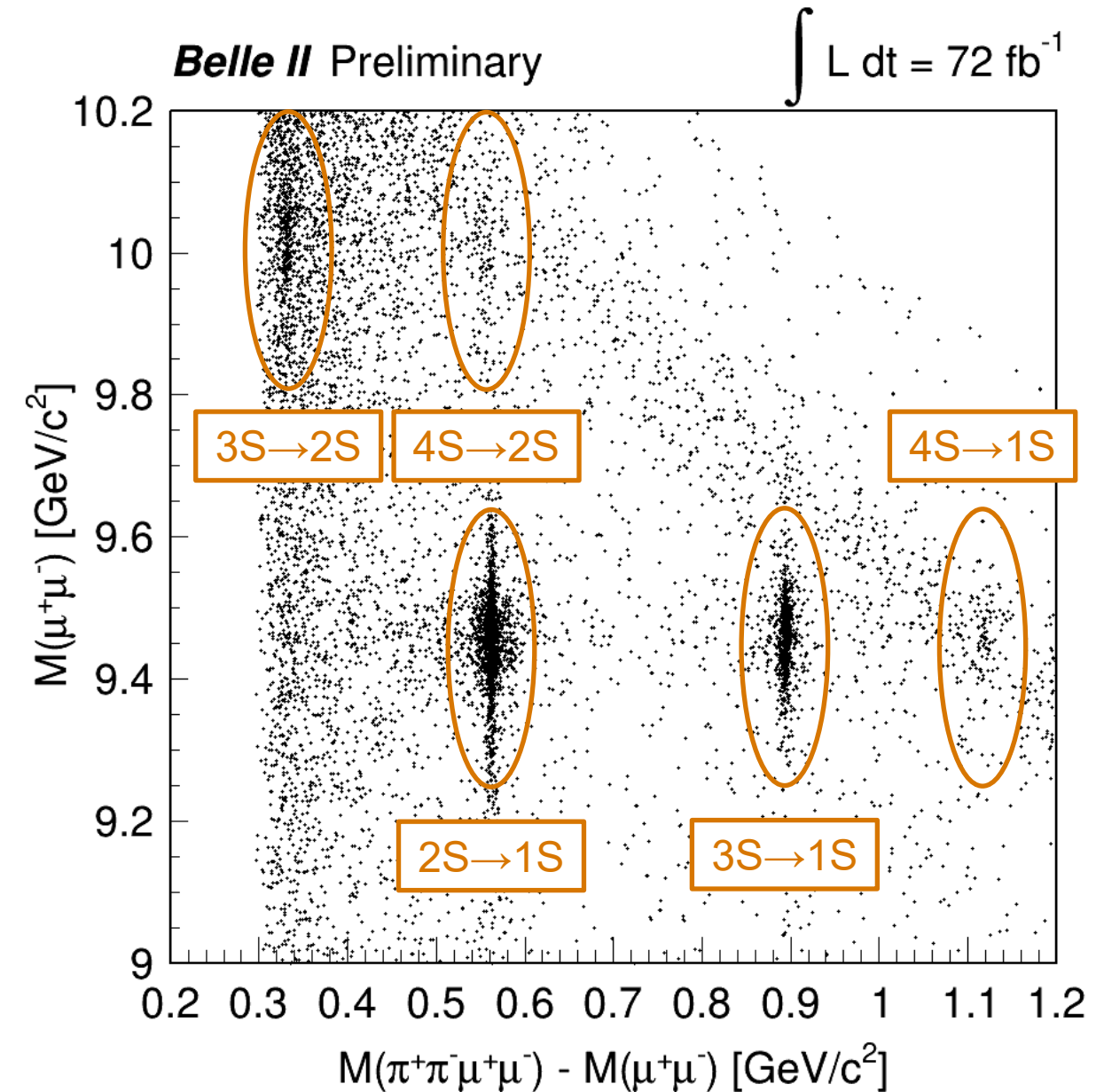
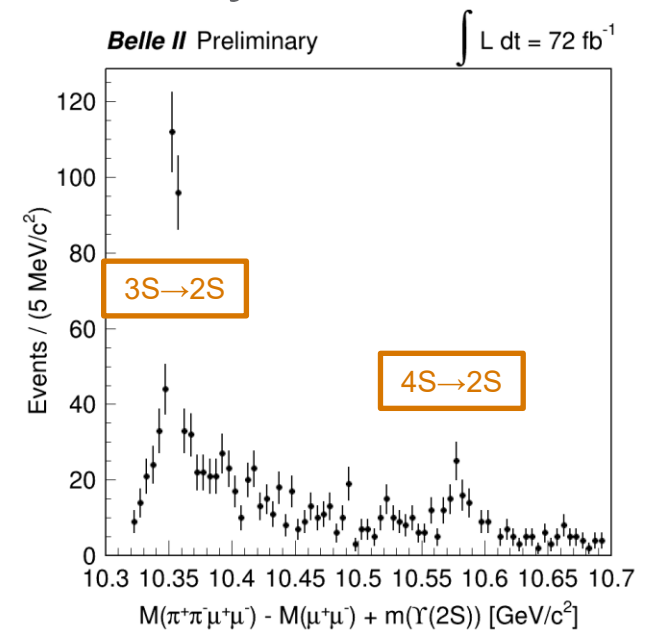
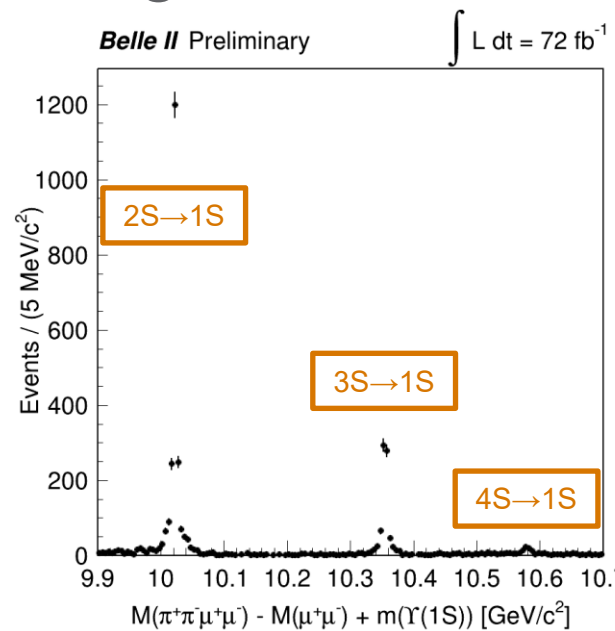
Belle II Progress – ISR $c\bar{c}$ Processes

- $e^+e^- \gamma_{\text{ISR}} \rightarrow \pi^+\pi^- J/\psi(\ell^+\ell^-)$ final states
 - Nominal PID requirements
 - $|M(J/\psi) - M(\text{PDG})| < 75 \text{ MeV}$
 - ISR photon not required (high efficiency)
 - $|MM^2(\pi^+\pi^- J/\psi)| < 2 \text{ GeV}^2$
- Clear observation of ISR $\psi(2S)$ signals
- Next step: “Y(4260)” rediscovery
 - Expect ~ 60 total events per 100 fb^{-1}



Belle II Progress – Bottomonium

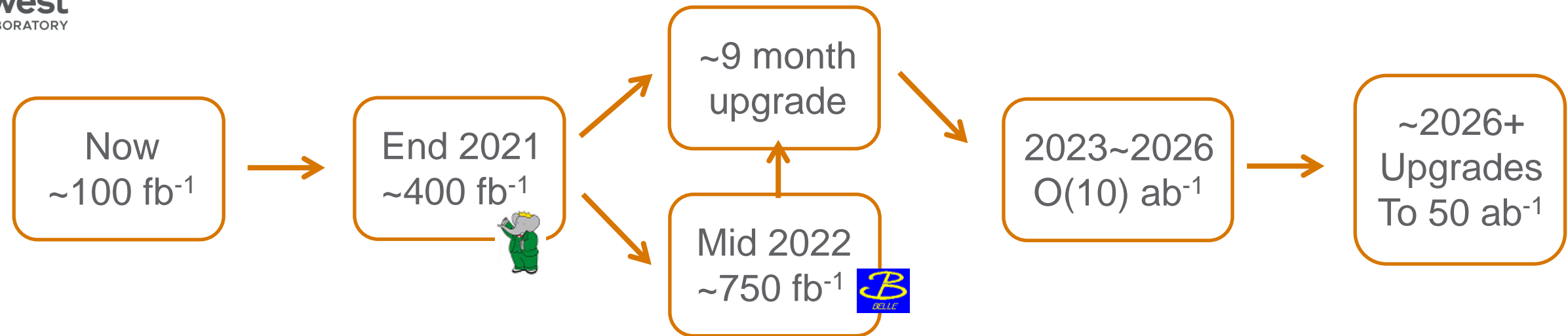
- Initial State Radiation production:
 - $\gamma_{\text{ISR}} \Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S) (\ell^+ \ell^-)$
 - $\gamma_{\text{ISR}} \Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S, 2S) (\ell^+ \ell^-)$
- Direct transitions: $\Upsilon(4S) \rightarrow \pi^+ \pi^- \Upsilon(1S, 2S)$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



- Future studies: $M(\pi^+ \pi^-)$ in $\Upsilon(4S)$ transitions

Conclusions

Future Plans



- Main focus to collect $\Upsilon(4S)$ on-peak data
- Near-term non- $\Upsilon(4S)$ proposals
 - **10.751 GeV (10 fb⁻¹)**: to study $Y_b(10753)$ on-peak
 - **10.657, 10.706, 10.810 (1+2+3 fb⁻¹)**: additional points for $B\bar{B}$ decomposition
 - **11 GeV (30+ fb⁻¹)**: post-upgrade to study $\Upsilon(6S)$ on-peak
- Beyond: options for larger $\Upsilon(6S)$, perhaps $\Upsilon(3S)$, $\Upsilon(5S)$, datasets...

Summary

- Belle II: next generation B-Factory
 - Quarkonium / XYZ is a main component of the physics program
 - Advantages with unique production, decay modes related to neutrals
 - Planning for non- $\Upsilon(4S)$ energies
- Analysis of early data
 - Rediscoveries of $1^{--} c\bar{c} / b\bar{b}$ states and X(3872)
 - Statistics soon comparable to BaBar/Belle
- **Input welcome from QWG community!**

Thank you

