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# Bottomonium results and prospects at Belle II

July 29, 2021

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

19th International Conference on Hadron Spectroscopy and Structure, in memoriam of Simon Eidelman
UNAM, Mexico City, MEXICO

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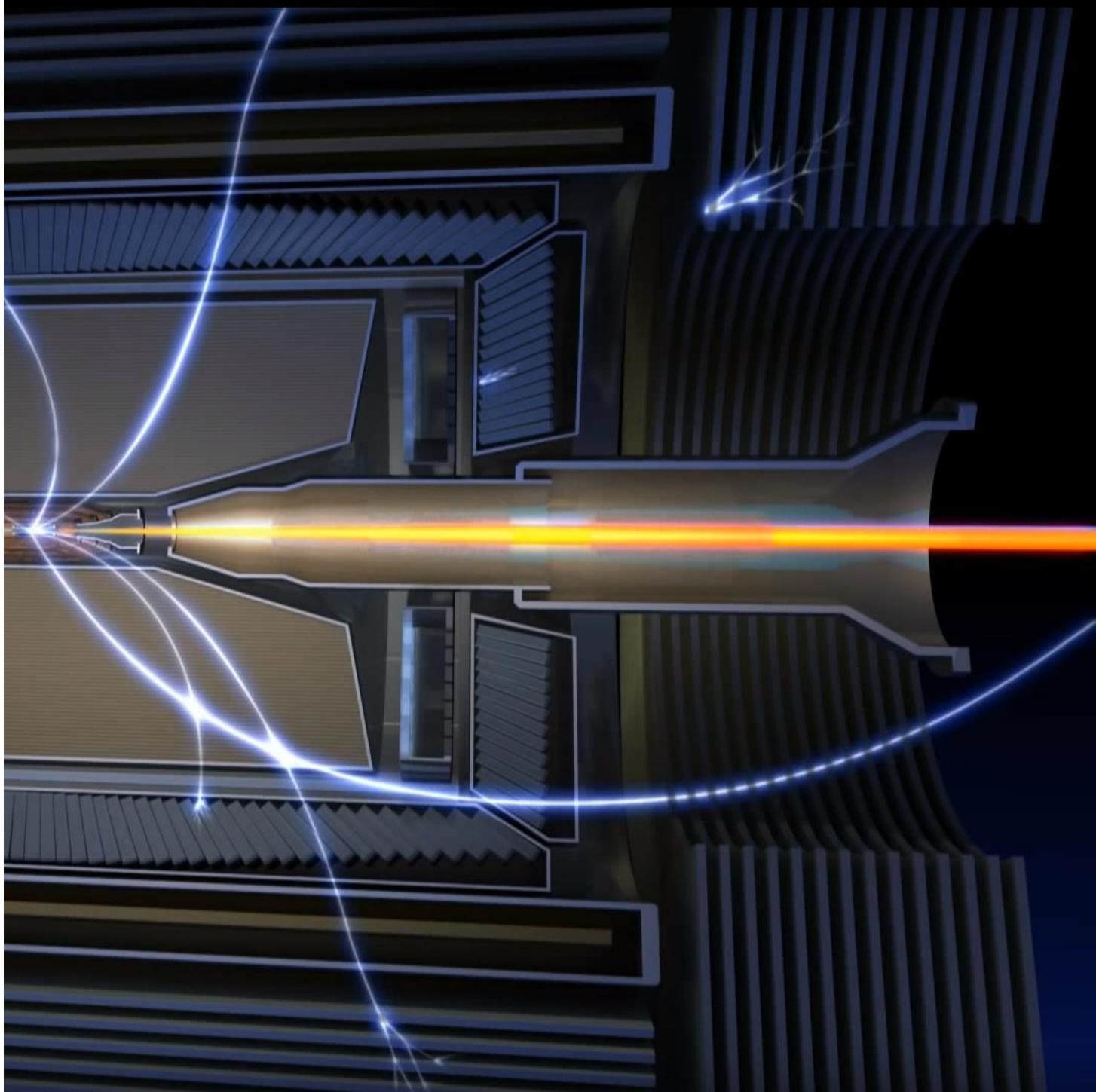

# Introduction

- Belle II Overview
- Bottomonium Physics Potential
- Results from Early Data
- Summary and Future Plans

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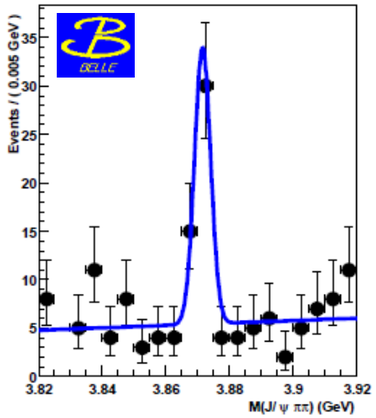
# Overview

# B-Factories Legacy

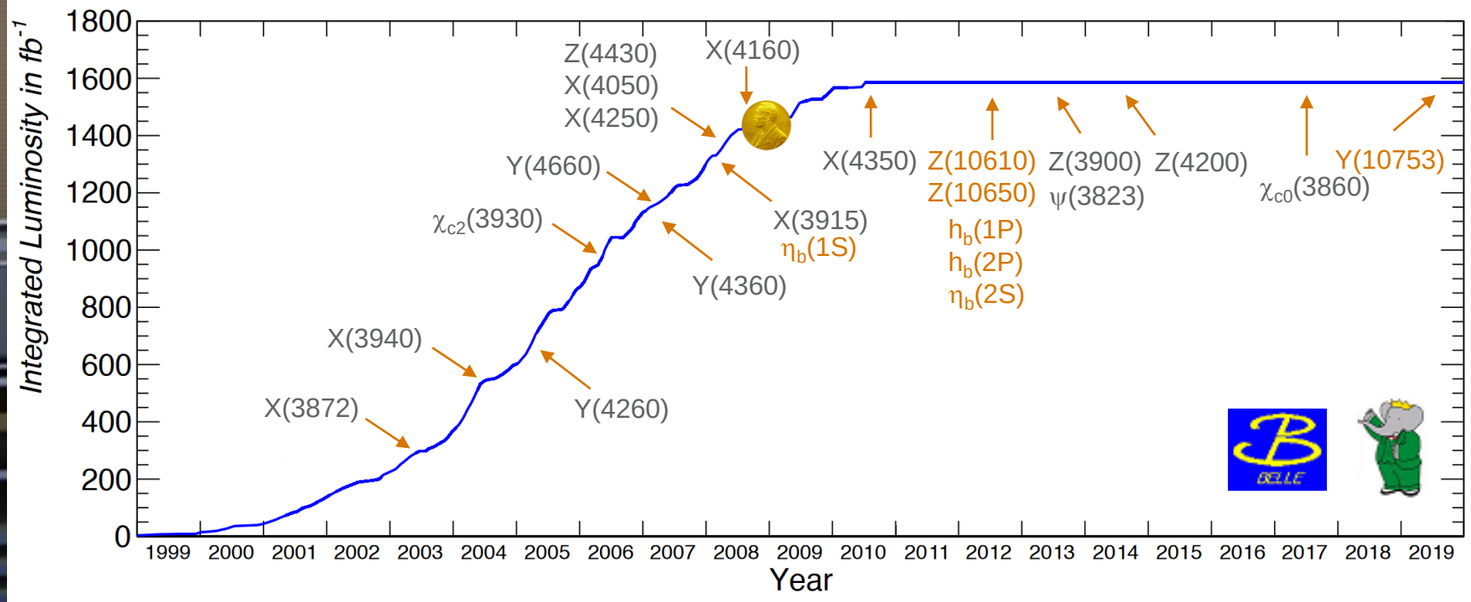
e.g.: “The Physics of the B Factories”, EPJC 74, 3026 (2014)

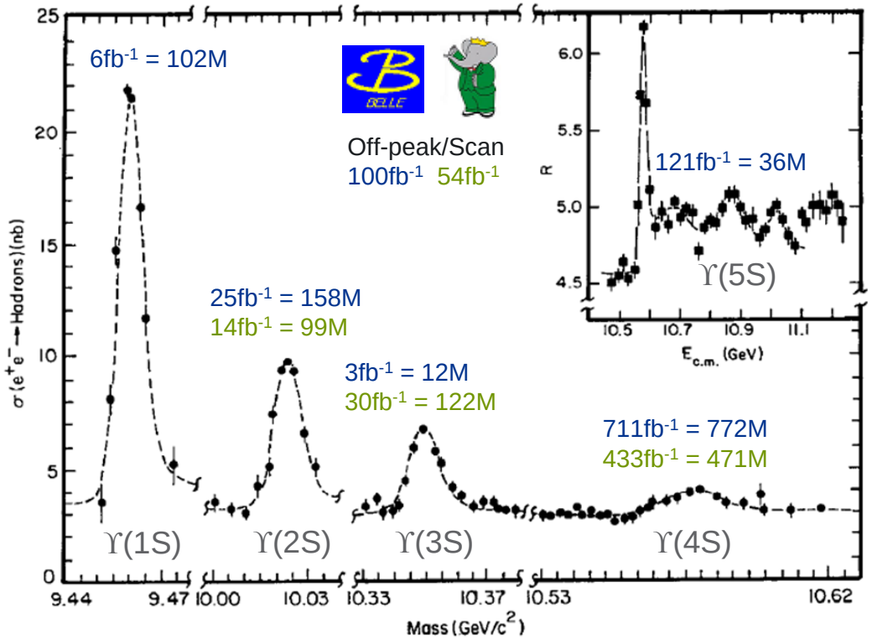
- ~2000 – 2010 : BaBar (SLAC) & Belle (KEK)
- Flavor physics: CKM/UT, CPV in B decays
- Hints for NP in rare processes
- New particle discoveries: “XYZ” states




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

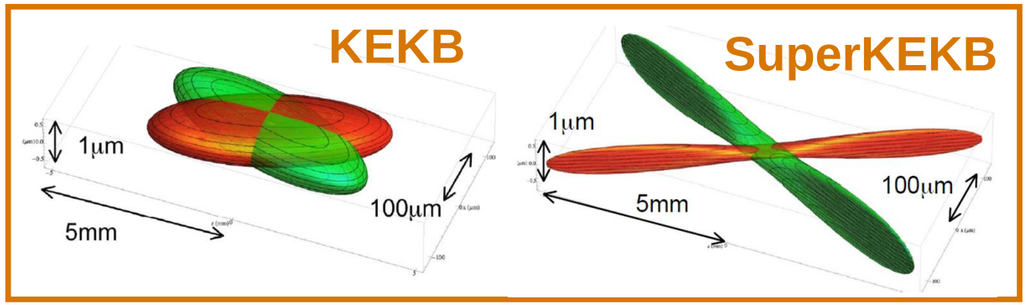
PRL 91, 262001 (2003)



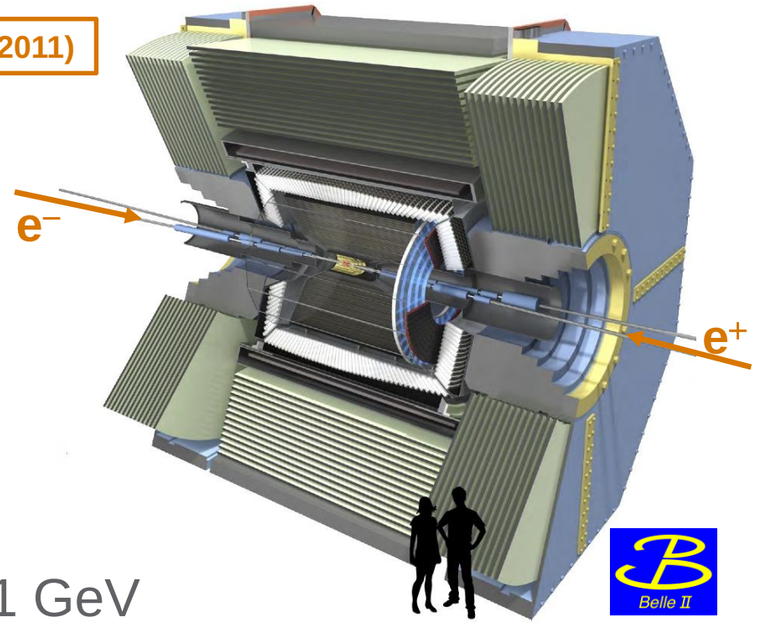



# Belle II Capabilities

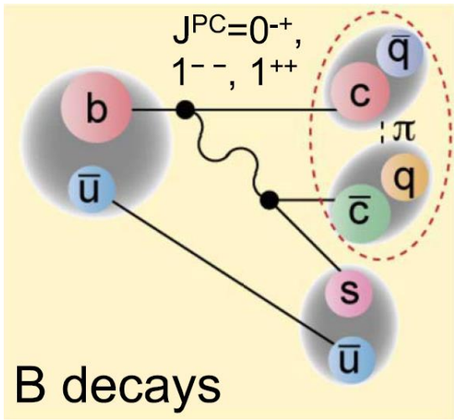
PTEP 2019 123C01 (2019)

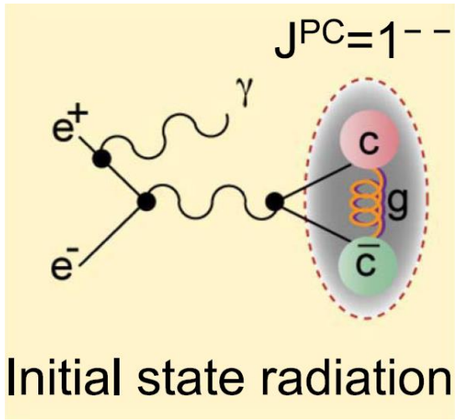


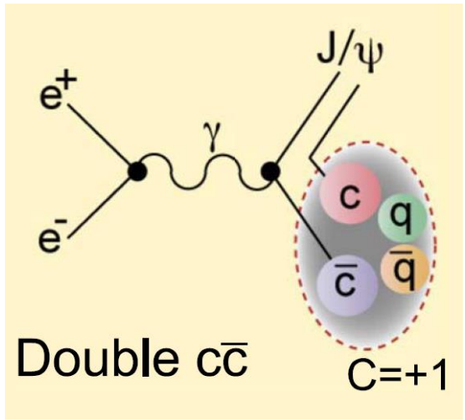

arXiv:1011.0352 (2011)

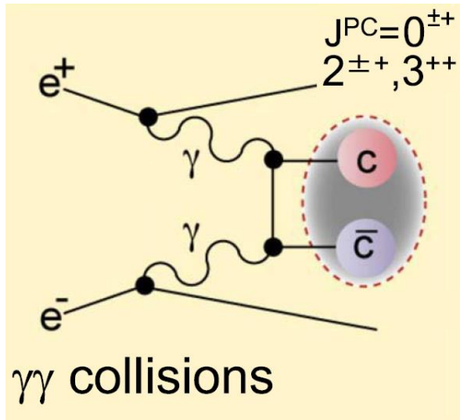


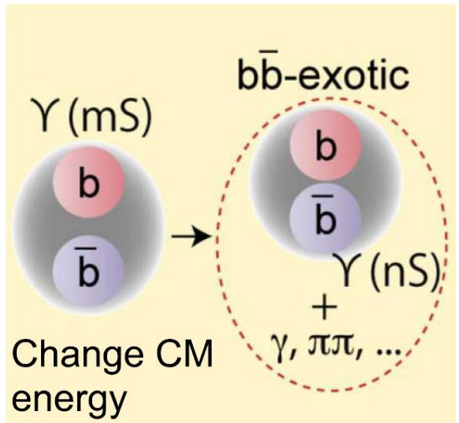

- Belle II is the next generation B-Factory
  - Upgraded detector and accelerator
  - 1107 members, 123 institutions, 26 nations
  - ~10-year program ongoing since 2019
- Advantages
  - ~40x instantaneous and integrated luminosity
  - Full event reconstruction, decays with neutral/soft particles
  - Nominal $\sqrt{s}$ = 10.58 GeV = m($\Upsilon$(4S)), potential to reach ~11 GeV



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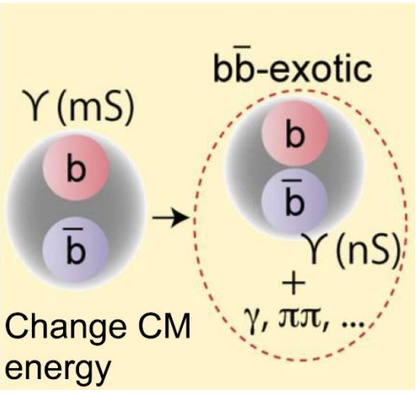
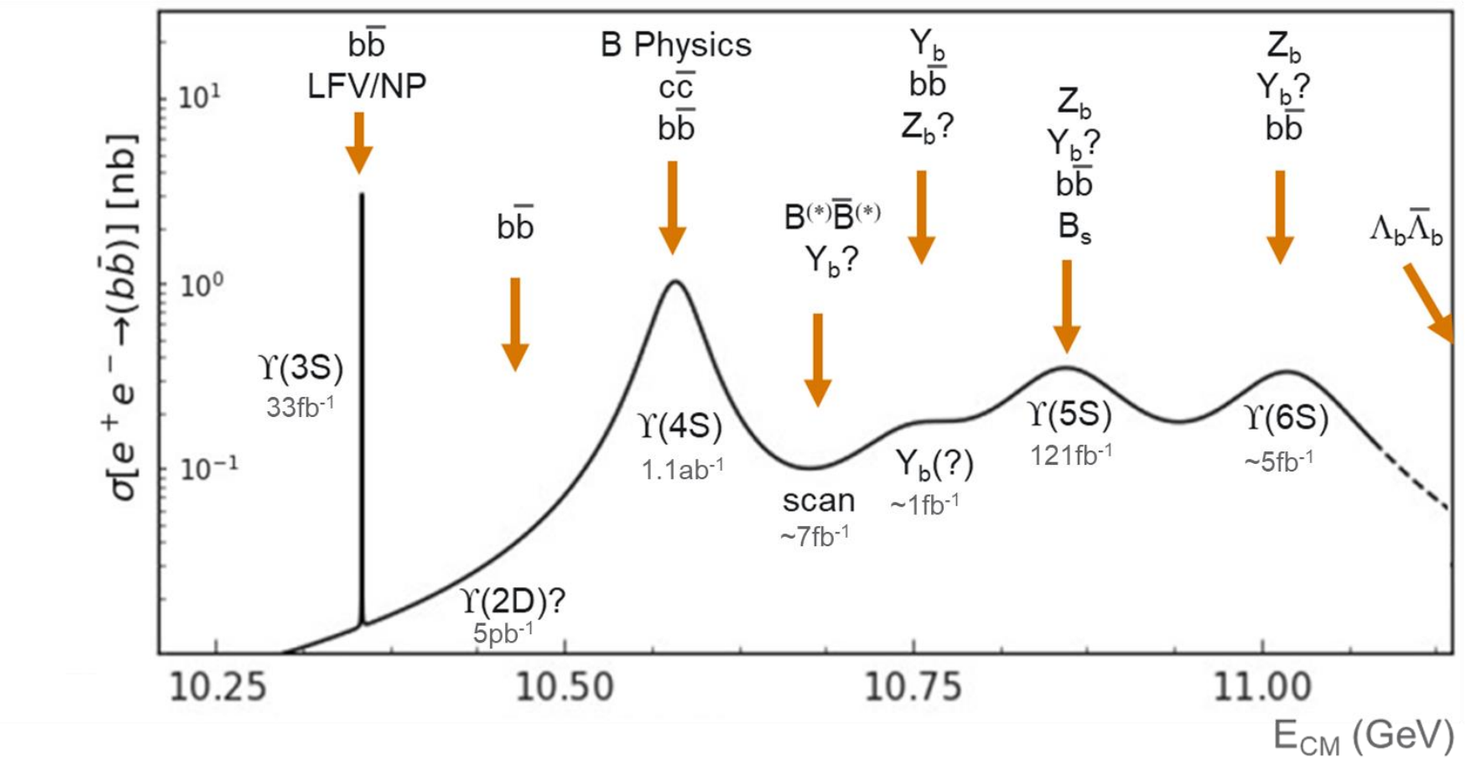
# Belle II Potential

# Belle II Potential at 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: $Y_b(10753)$



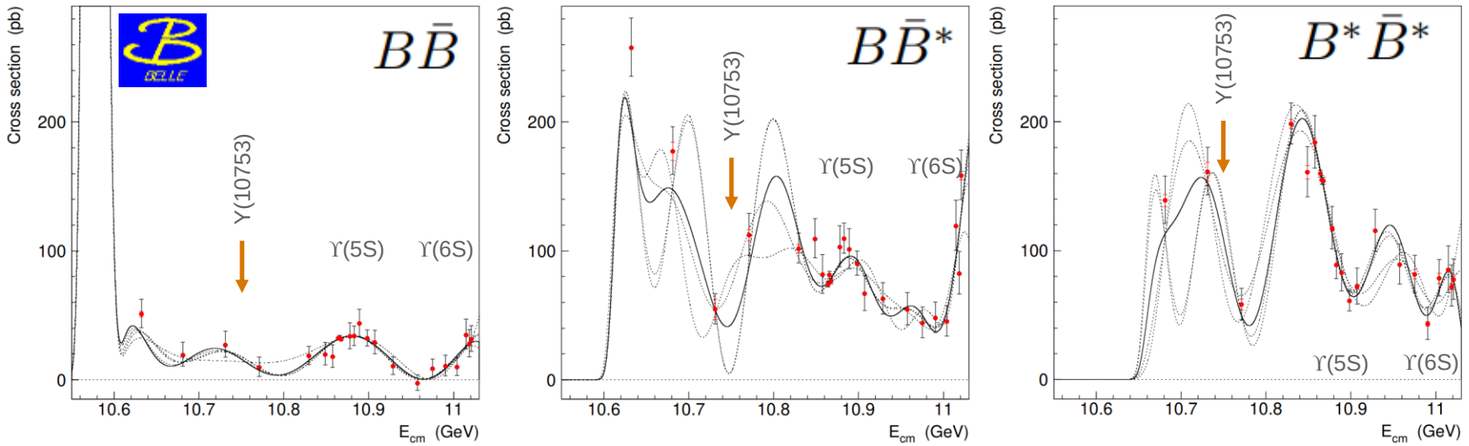
# Belle II Potential – 10.75 GeV

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

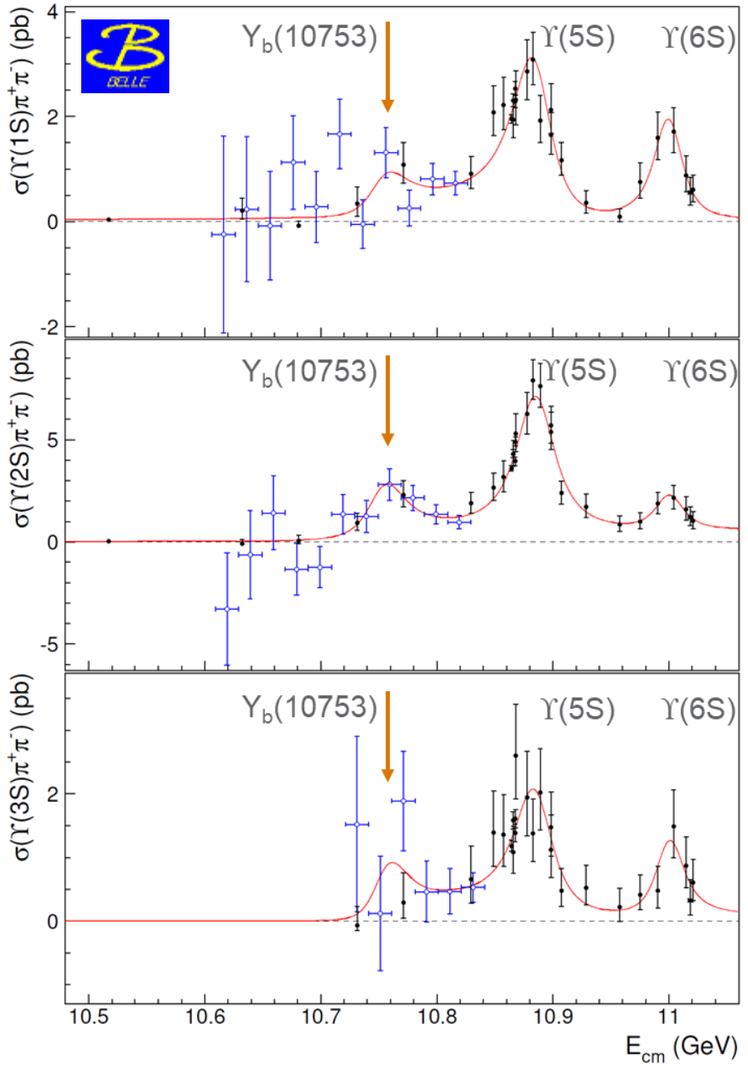
- Varying $B\bar{B}$ cross sections

JHEP 06 (2021) 137




- Revisit this energy region with greater statistics

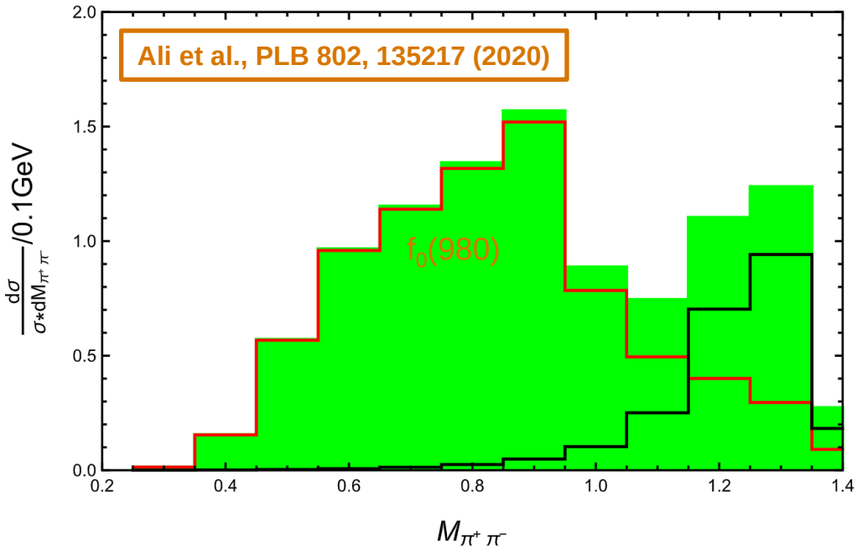
JHEP 10 (2019) 220



# Belle II Potential – 10.75 GeV

- **Belle II plans to conduct a limited higher statistics scan in Nov 2021**
  - **10.751 GeV (10 fb$^{-1}$)**: study $\Upsilon_b(10753)$ on-peak
  - **10.657, 10.706, 10.810 (1+2+3 fb$^{-1}$)**: additional points for $B\bar{B}$ decomposition
- Physics goal: understand the nature of $\Upsilon_b(10753)$ energy region
  - Differing predictions for tetraquarks and bottomonium
  - Invariant mass distributions may hold clues

Tetraquark $m_{\pi\pi}$ prediction




| Mode | $\mathcal{B}(4q)$ (%) | $\mathcal{B}(b\bar{b})$ (%) |
|---|---|---|
| $B\overline{B}$ | $39.3^{+38.7}_{-22.9}$ | 21.3 |
| $B\overline{B}^*$ | $\sim 0.2$ | 14.3 |
| $B^*\overline{B}^*$ | $52.3^{+54.9}_{-31.7}$ | 64.1 |
| $B_s\overline{B}_s$ | - | 0.3 |
| $\omega\eta_b$ | $7.9^{+14.0}_{-5.0}$ | - |
| $\omega\chi_{bJ}$ | - | $\sim 0.3$ |
| $f_0(1370)\Upsilon$ | $0.2^{+0.6}_{-0.2}$ | - |
| $\eta\Upsilon$ | - | $\sim 0.2$ |
| $\eta'\Upsilon$ | - | $\sim 0.06$ |
| $\eta h_b$ | - | $\sim 0.2$ |

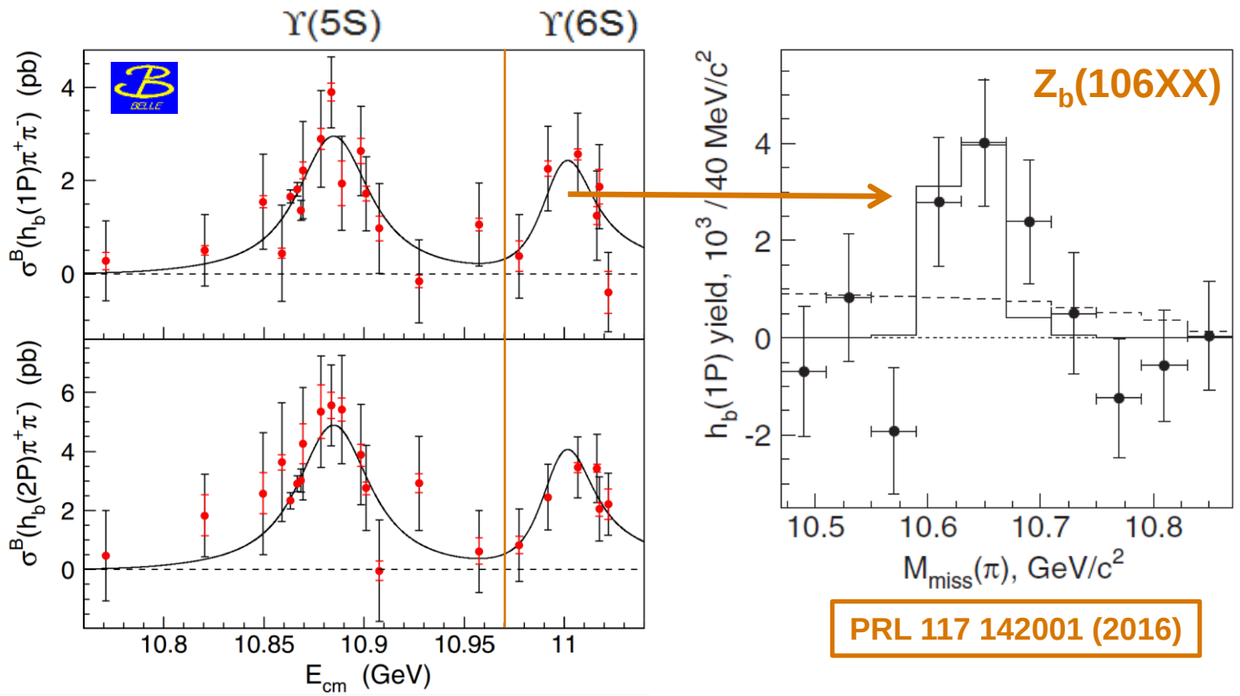
Selected predictions

Wang, CPC 12, 123102 (2019)
Ali et al., PLB 802, 135217 (2020)
Chen et al., PRD 101, 014020 (2020)
Giron & Lebed, PRD 102, 014036 (2020)
Li et al., EPJC 80, 59 (2020)
Liang et al., PLB 803, 135340 (2020)
Bicundo et al., PRD 103, 074507 (2021)
Li et al., arXiv:2106.14123 (2021)

# Belle II Potential – $\Upsilon(6S)$

- Belle limited by statistics
- <1 $fb^{-1}$ per scan point ~4.6 $fb^{-1}$
- Not on $\sigma$ peak, $L_{eff}$=~3 $fb^{-1}$

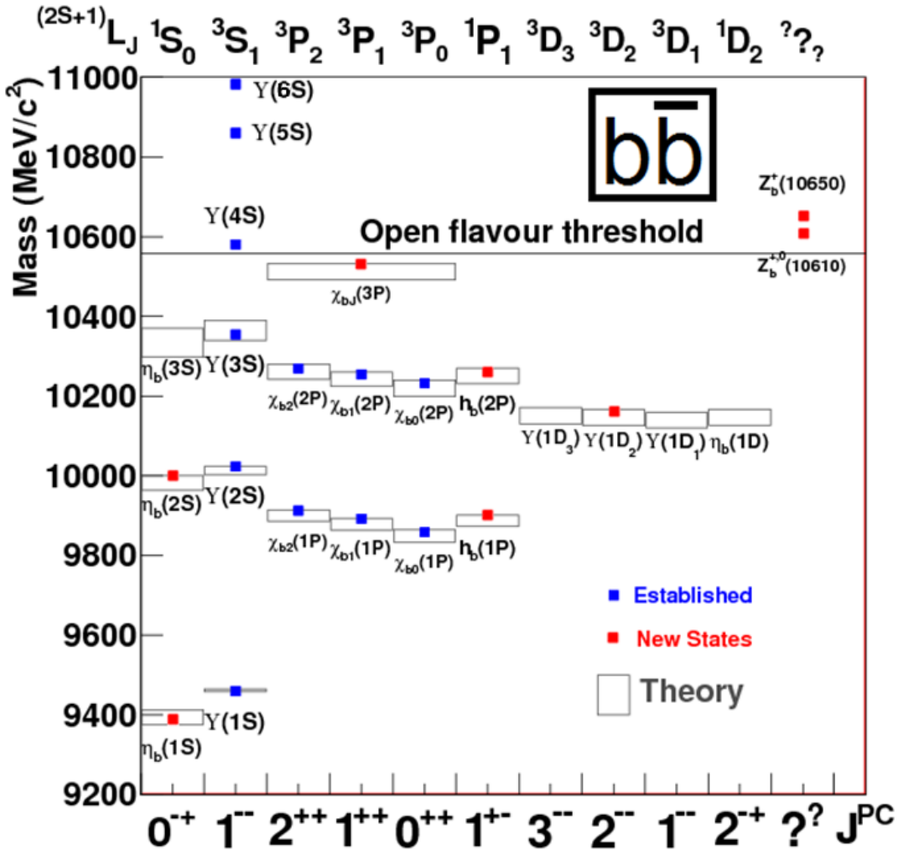
- $\Upsilon(6S) \rightarrow \pi^+\pi^-$ X
  - $h_b$ : evidence for $Z_b$
  - $\Upsilon(123S)$: statistics needed
- Include other decay modes




- 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: $\pi\pi/\eta/\eta'$ (~$4\times10^{-4}$), radiative decays?
  - Inclusive $\Upsilon(1S)$ production: CLEO limit <$40\times10^{-4}$
  - 16k $h_b$ and 5k $\eta_b$ tagged events / 100fb$^{-1}$
- Conventional quarkonium below $\Upsilon(4S)$
  - Rare decays: $\Upsilon(3S) \to \pi^0 h_b(1P)$, $\Upsilon(3S) \to \eta\Upsilon(1S)$, …
  - D-wave: $\Upsilon(3S) \to \gamma\gamma\Upsilon(1D)$, scan for $e^+e^- \to \Upsilon(mD_1)$
  - Inclusive production (D, $\bar{d}$, …) in $b\bar{b}$ decay
- Beyond Standard Model below $\Upsilon(4S)$
  - $\Upsilon(1S) \to$ invisible with dipion tag
  - LFV search $b\bar{b} \to \ell\tau$, LFU $\Upsilon(nS) \to \tau\tau/\mu\mu$
  - $\Upsilon(3S) \to S\Lambda\Lambda(n\pi)$ 'sexaquark' search




See talk by B.Scavino, Exotic hadrons and candidates-5 Jul 28 12:00

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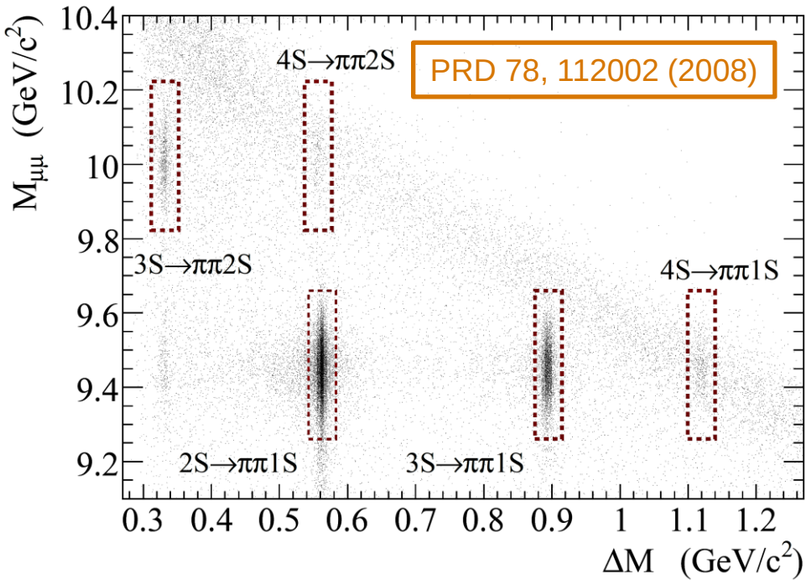
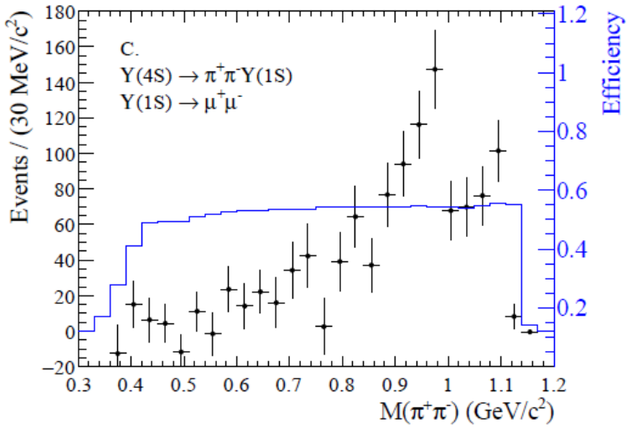
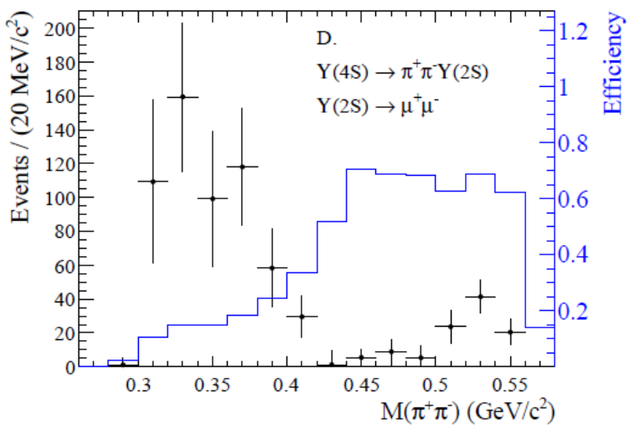
# Results on Early Data

# $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S,2S)$ transitions: B-Factories

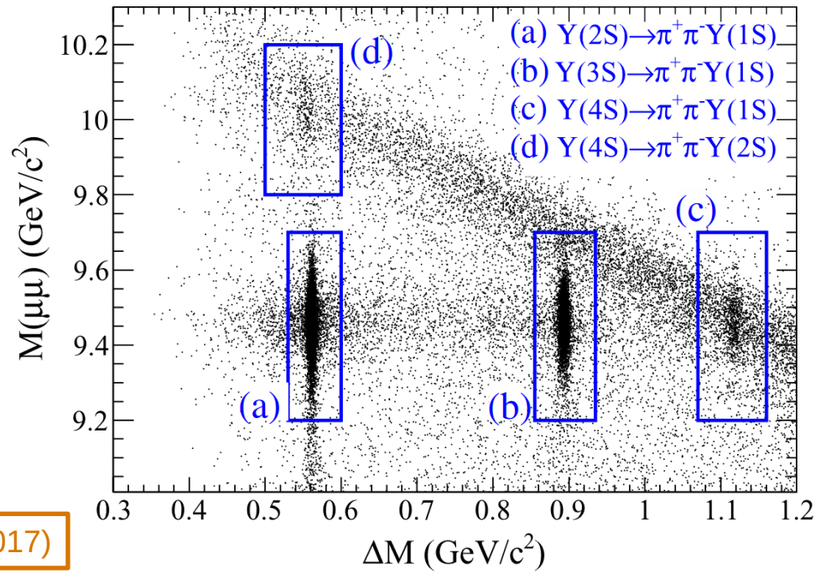
- Measured by BaBar and Belle
- Initial State Radiation production:
  - $\gamma_{ISR}\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)(\ell^+\ell^-)$
  - $\gamma_{ISR}\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S,2S)(\ell^+\ell^-)$
- Direct transitions: $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S,2S)$
- Features in $M(\pi^+\pi^-)$



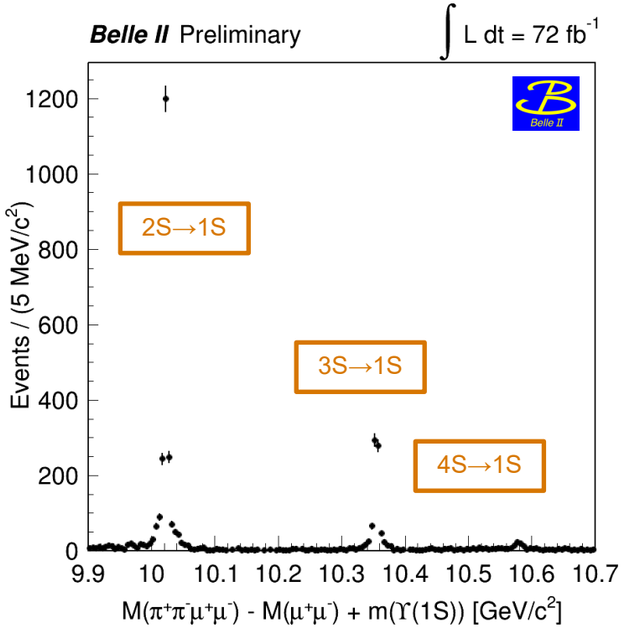

PRD 96, 052005 (2017)

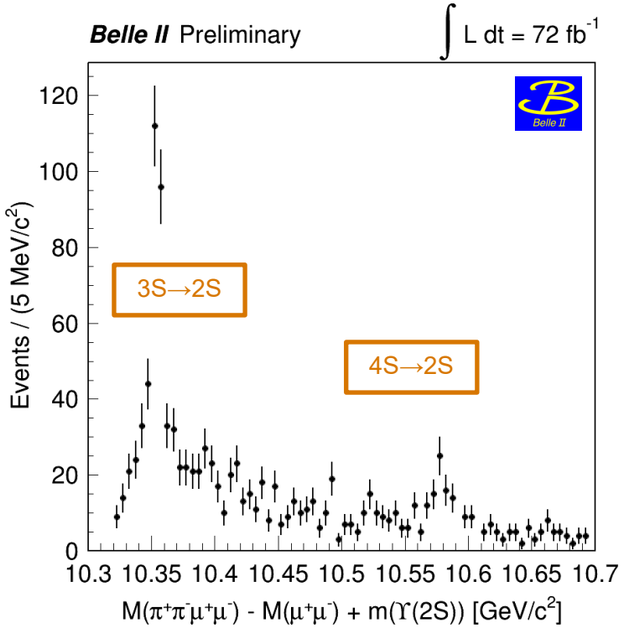


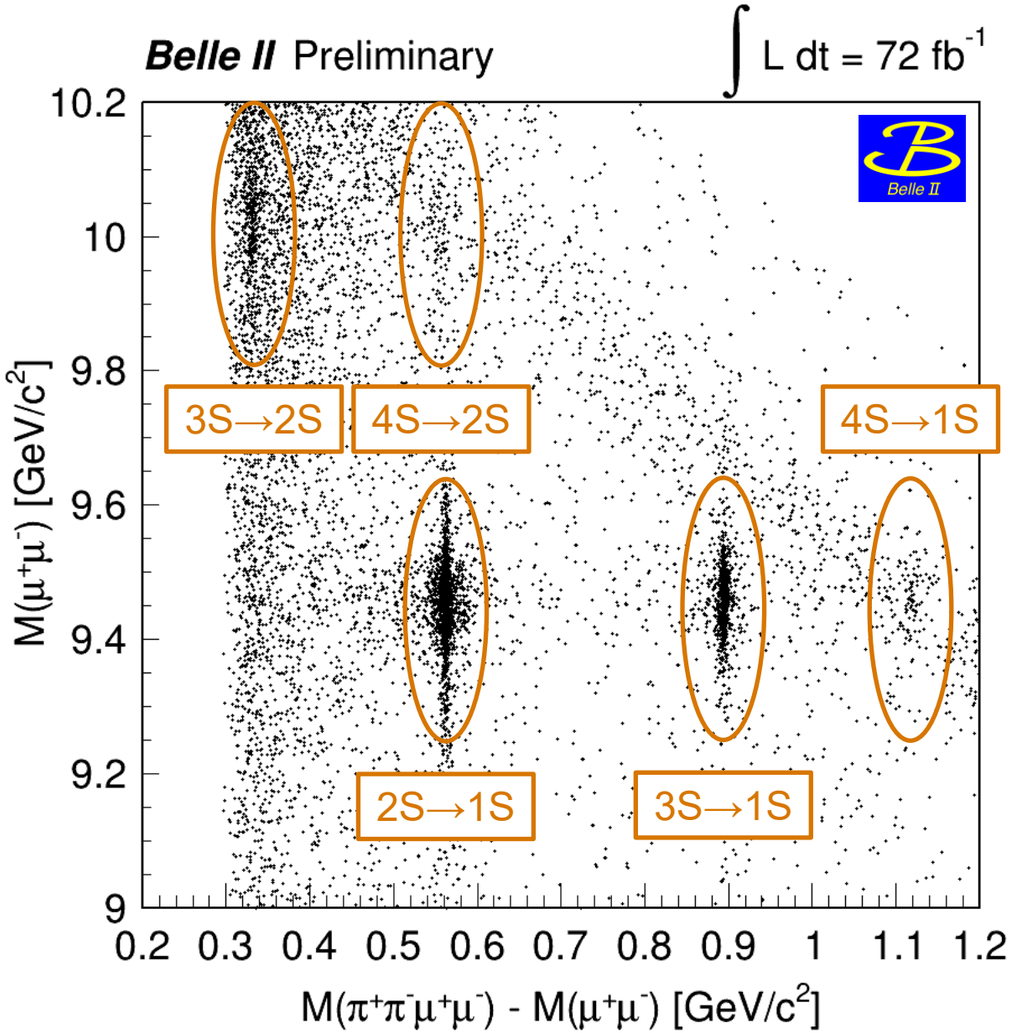

496 fb-1

# Belle II Progress – Dipion transitions

- All signals observed in early Belle II data



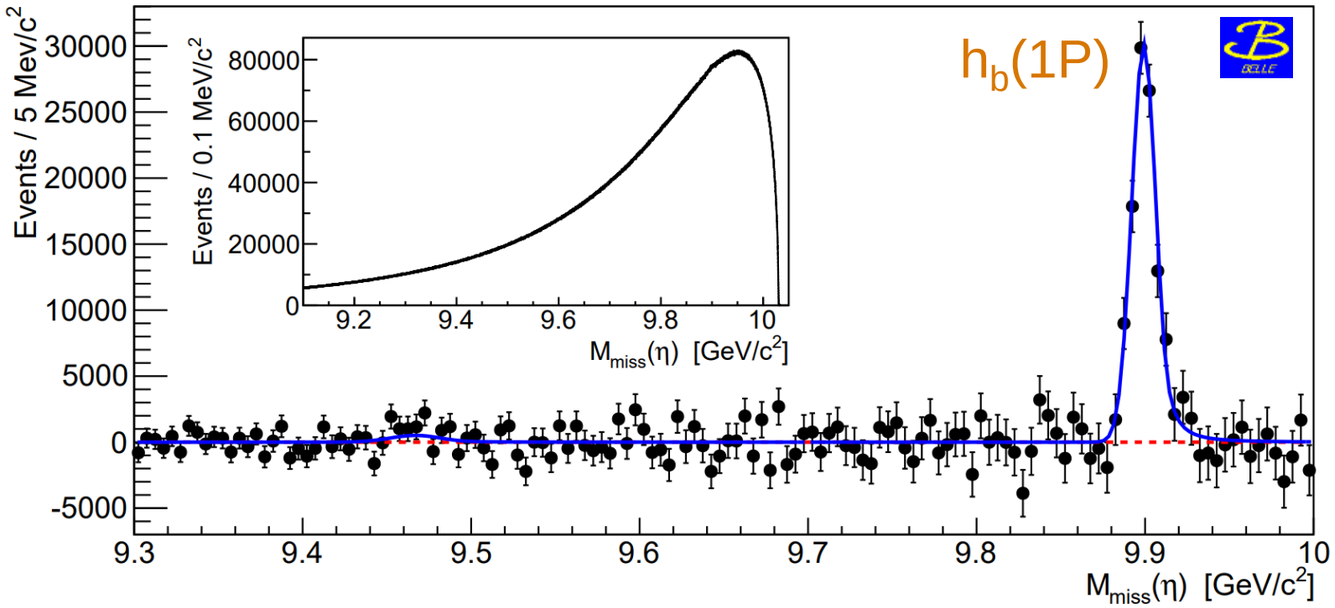



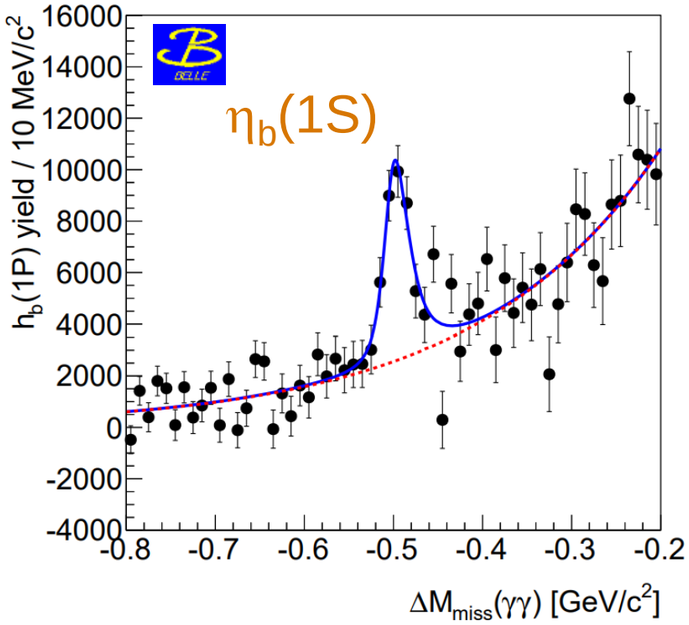




- Verification of analysis chain for $\pi\pi\ell\ell$
- Future studies: $M(\pi^+\pi^-)$ in $\Upsilon(4S)$ transitions

# $\Upsilon(4S) \rightarrow \eta h_b$ transitions: Belle

- Surprisingly enhanced $\eta$ transition rate
- Measurements of $m_{hb}$ and $m_{\eta b}$ (through $h_b(1P) \rightarrow \gamma \eta_b(1S)$)



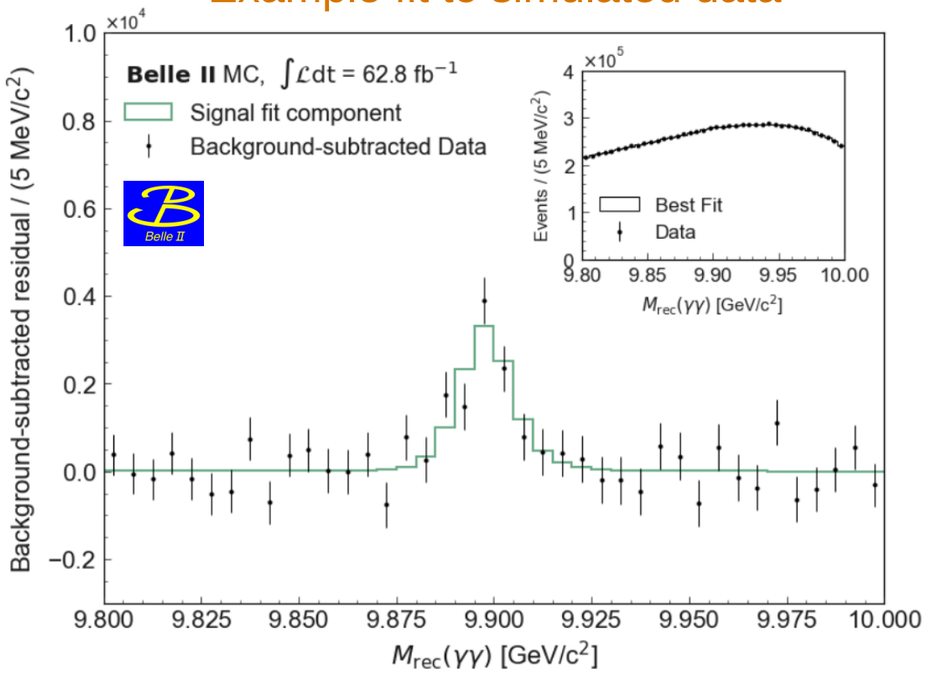

PRL 115, 142001 (2015)

- Revisit in Belle analysis in Belle II

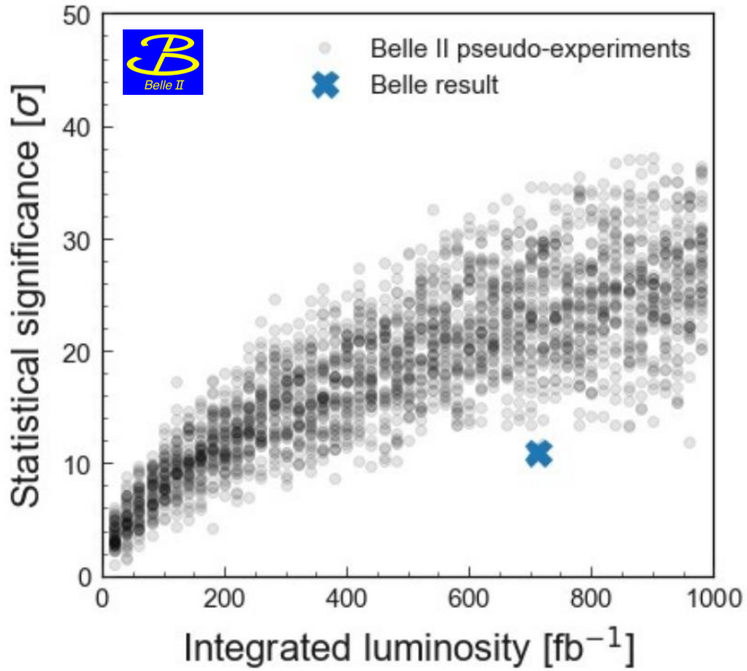
# Belle II Progress – Eta transitions

- Apply advanced selection criteria and improved analysis technique

Example fit to simulated data




Predicted sensitivity vs. luminosity




- Toy experiments indicate better sensitivity expected
- Internal review of analysis underway

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# Conclusions

# Future Plans

Now ~214 $fb^{-1}$ → End 2021 ~400 $fb^{-1}$ → Mid 2022 ~750 $fb^{-1}$ → ~9 month upgrade → 2023~2026 O(10) $ab^{-1}$ → ~2026+ Upgrades To 50 $ab^{-1}$

- Main focus to collect $\Upsilon(4S)$ on-peak data
- Upcoming non-$\Upsilon(4S)$ plans
  - **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 — **Nov 2021**
  - **11 GeV (30+ $fb^{-1}$)**: to study $\Upsilon(6S)$ on-peak — Post-upgrade
- Future proposals: options for larger $\Upsilon(6S)$, perhaps $\Upsilon(3S)$, $\Upsilon(5S)$, datasets…

# Summary

- Belle II: next generation B-Factory
  - Bottomonium / XYZ is a main component of the physics program
  - Advantages with unique production, decay modes related to neutrals
  - Planning for non-$\Upsilon(4S)$ energies

**"The Belle II Physics Book", PTEP 2019, 123C01 (2019)**

- Analysis of early data
  - Rediscoveries of $1^{--}$ $b\bar{b}$ states
  - Statistics soon comparable to BaBar/Belle

- Input welcome from community on 10.75 GeV and other $b\bar{b}$ studies

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# Thank you