Bottomonium results and prospects at Belle II

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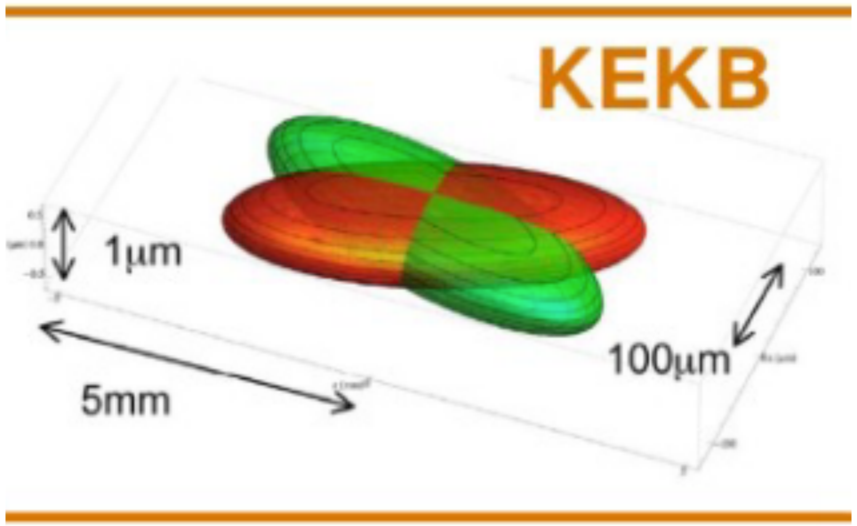
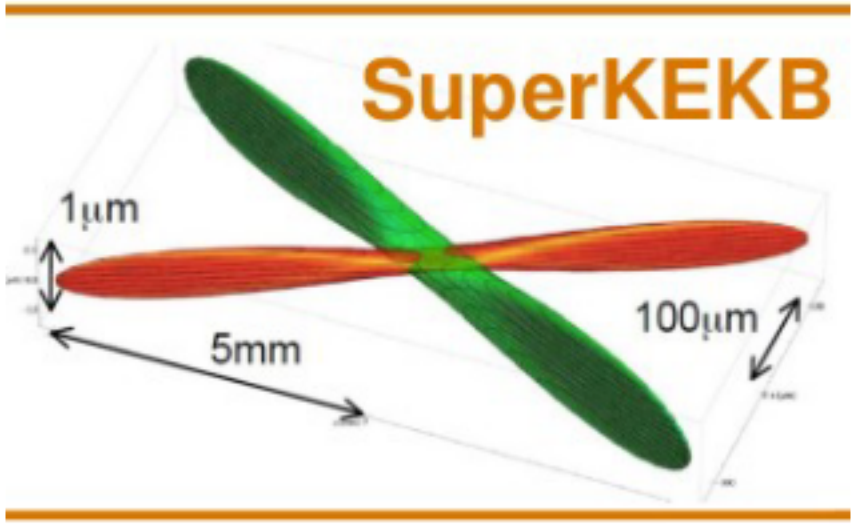
On behalf of the Belle II collaboration

Super-KEKB

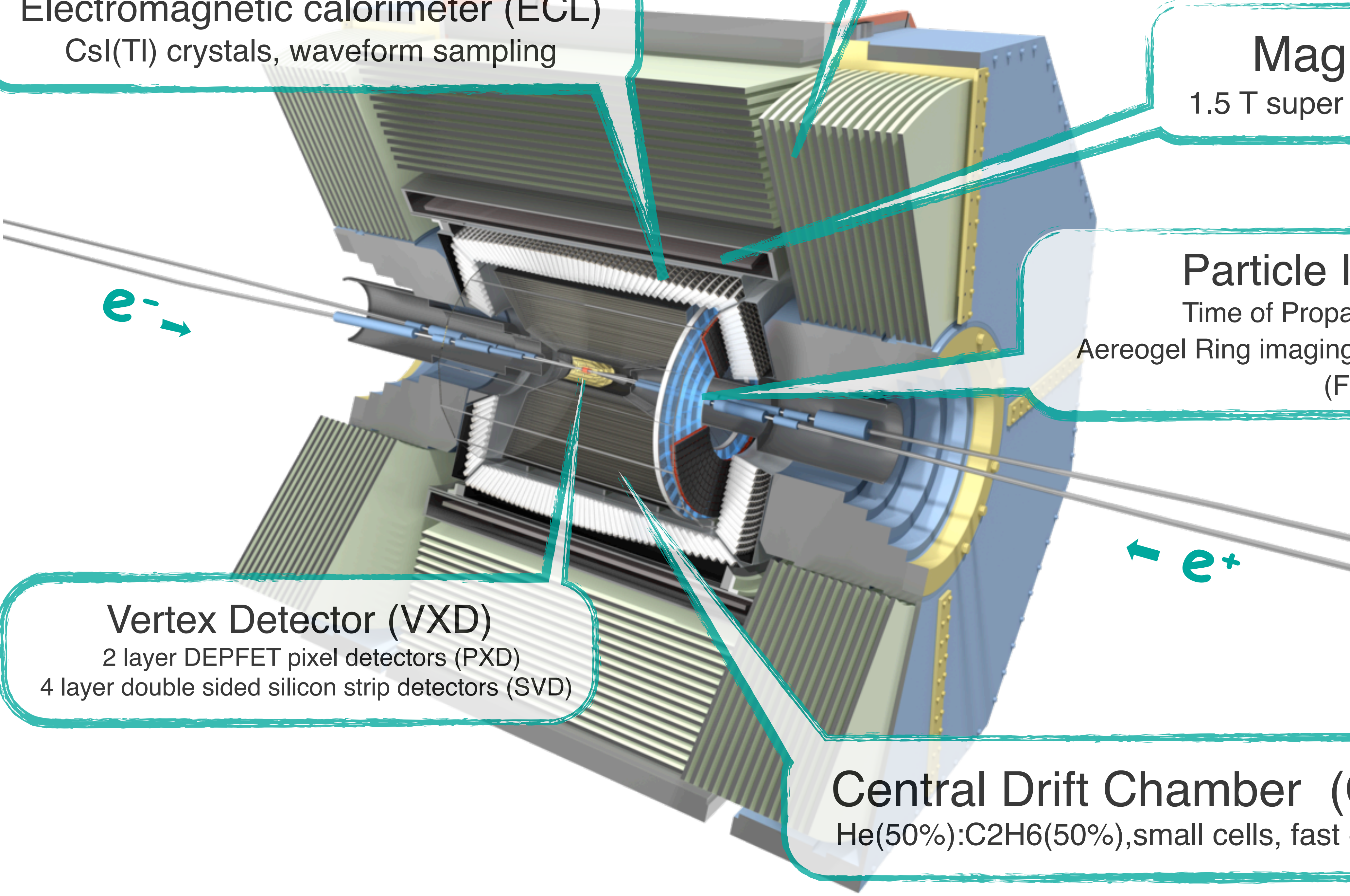
- SuperKEKB is an asymmetric e^+ (4 GeV) e^- (7 GeV) collider at Tsukuba, Japan.
- Energy limit 11.02 GeV
  - 11.24 GeV only with major upgrades.
- Belle II detector is placed around the IP of SuperKEKB
- Super-KEKB goal: > ~40 ⨉ KEKB instantaneous luminosity
  - $\mathscr{L} = 6.5\times10^{35}\ \mathrm{cm^{-2}s^{-1}}$
- Belle II goal: collect 50 ab^{-1} (~50x Belle data)
- How to achieve that?
  - Beam current, 1.64/1.19 A (Belle) → 2.5/1.8 A (Belle II) for e^- / e^+ beam.
  - Beta function at IP ($\beta^{+-*}y$), 5.9/5.9 mm (Belle) → 0.27/0.30 mm (Belle II).





$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y\pm}}\right)$$

Belle II

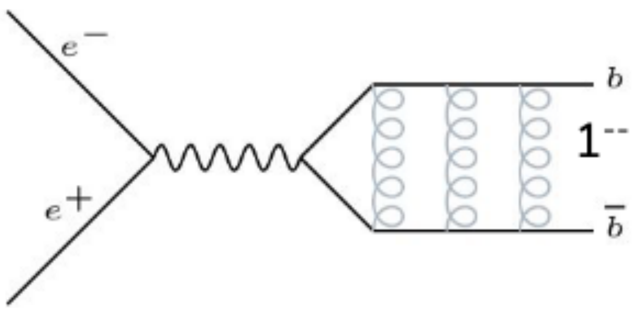


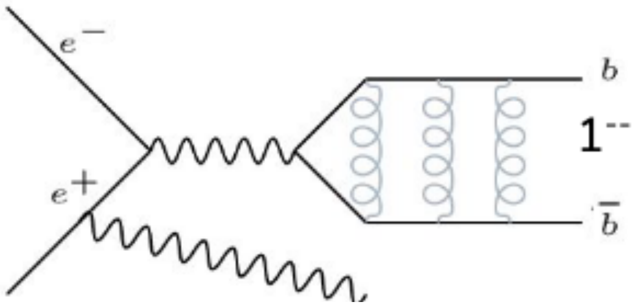
K_L and muon detector KLM
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (Endcaps, Inner barrel)
Electromagnetic calorimeter (ECL)
CsI(Tl) crystals, waveform sampling
Magnet
1.5 T super conductive
Particle Identification
Time of Propagation (TOP) (barrel)
Aereogel Ring imaging Cherenkov Counter (ARICH) (Forward)
e-
e+
Trigger
Hardware < 30 kHz
Software < 10 kHz
Vertex Detector (VXD)
2 layer DEPFET pixel detectors (PXD)
4 layer double sided silicon strip detectors (SVD)
Central Drift Chamber (CDC)
He(50%):C2H6(50%),small cells, fast electronic

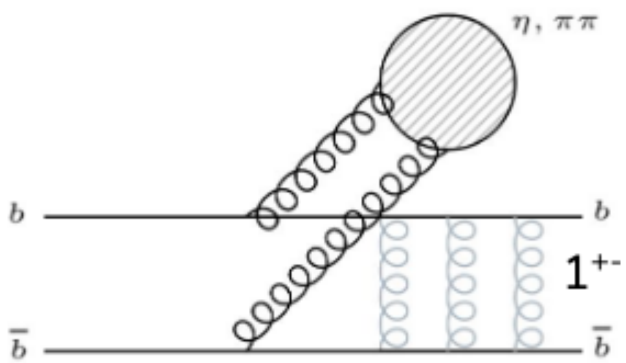
Bottomonia

How to produce them at e^+e^- collider:

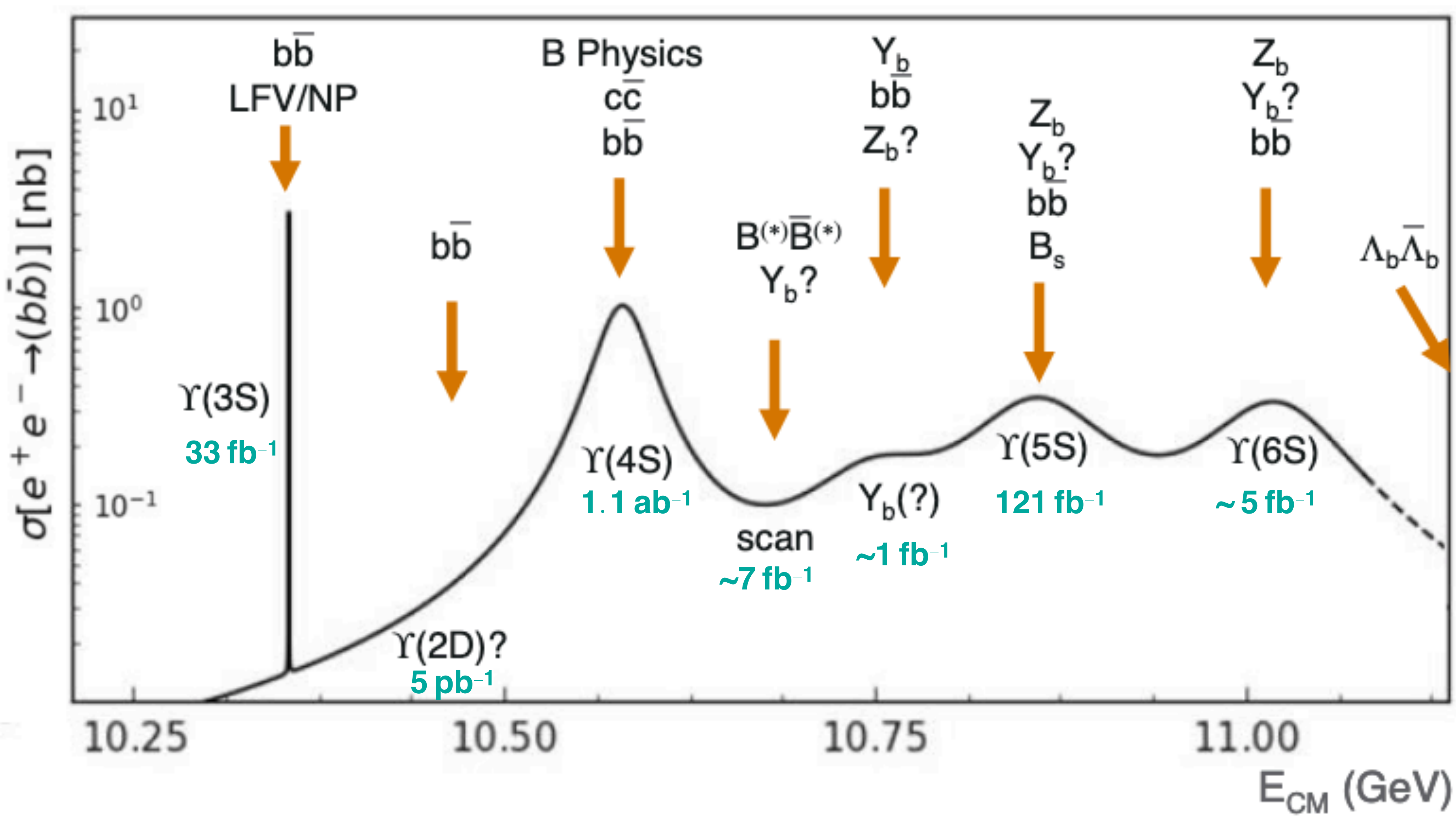
- Directly from e^+e^-
  - Only $J^{PC}=1^{--}$ ($\Upsilon(nS)$)
- ISR production
  - Only $J^{PC}=1^{--}$ ($\Upsilon(nS)$)
- Hadronic transitions from $\Upsilon(nS)$ trough $\eta,\pi\pi$…
  - $J^{PC}=1^{--}, 0^{-+}, 1^{+-}$ … ($\Upsilon(nS)$, $h_b(nS)$, $\eta_b(nS)$,..)
- Radiative transitions from $\Upsilon(nS)$
  - $J^{PC} = 0^{++}, 1^{++}, 2^{++}$ (χ_{bj})
    - Electric dipole transition (E1)
  - $J^{PC} = 0^{--}$ (η_b)
    - Hindered magnetic dipole (M1) transitions







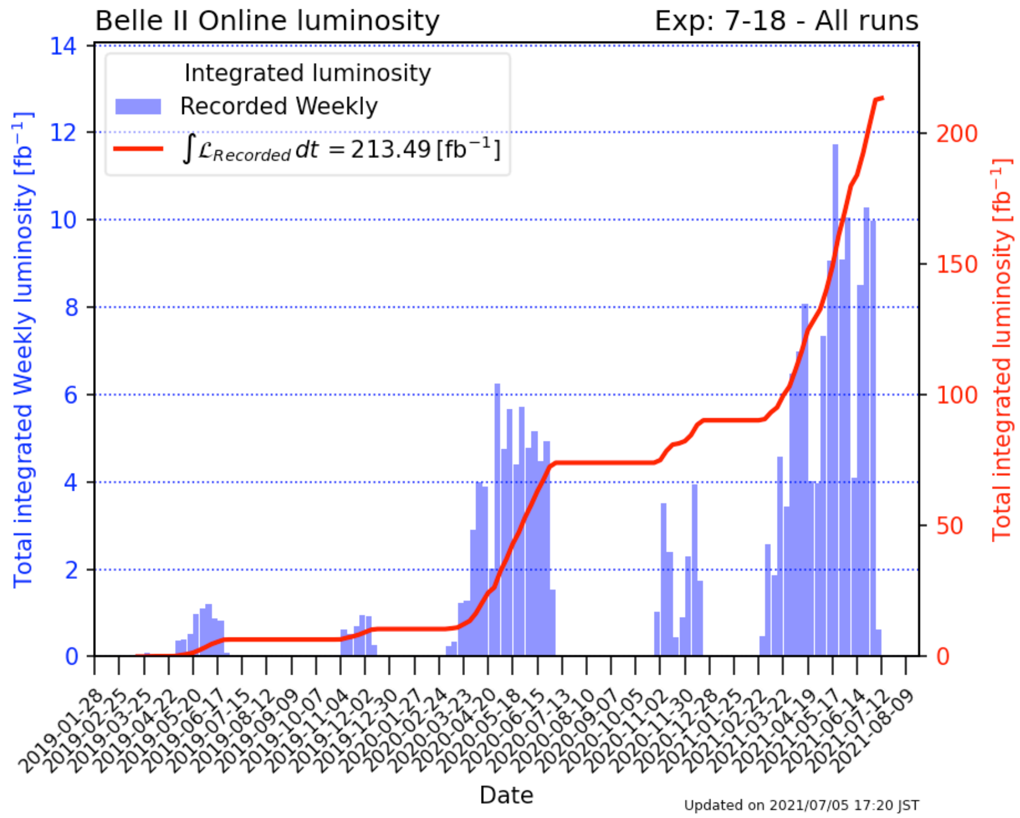
Currently available datasets



- Small dataset outside $\Upsilon(4S)$
- Even a small data set can make the difference

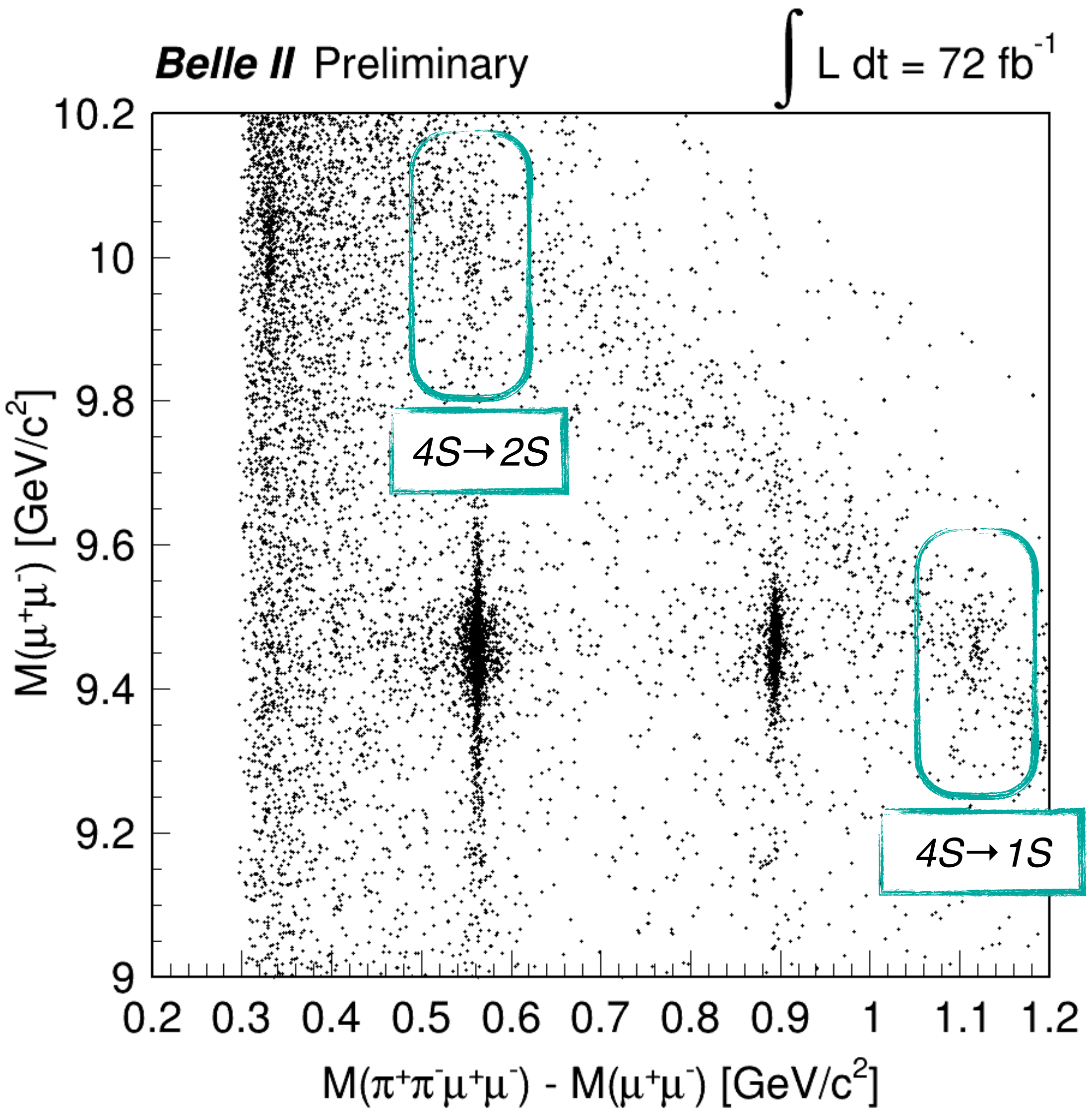
Belle II current status

- Running at $\Upsilon(4S)$
  - Recorded 213.49 fb^{-1}
  - By 2022 Belle II should have as much $\Upsilon(4S)$ as Belle
    - Many analysis already ongoing, just need more data
    - Rediscovery analyses
      - Thanks to improved analysis techniques may need less data to have competitive/better results
    - Many analyses at $\Upsilon(4S)$ are preparatory for analyses at 10.751 GeV
      - See next topic
  - Feasibility studies for future



ϒ(nS) dipion transitions

BELLE2-NOTE-PL-2021-001

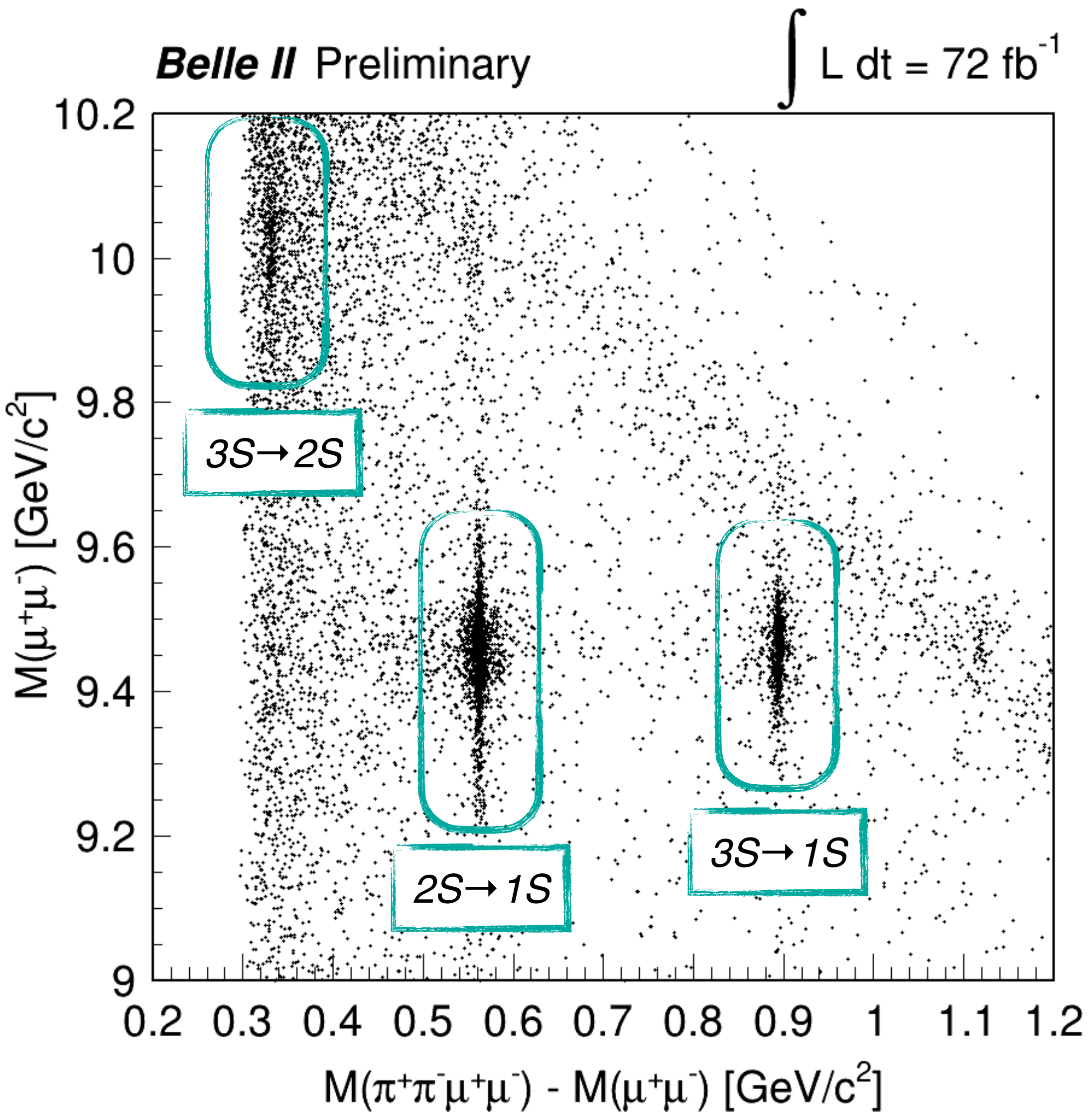


$e^+e^- \to \pi^+\pi^- \mu^+\mu^-$ (+γ undetected)

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

Υ(nS) dipion transitions

BELLE2-NOTE-PL-2021-001

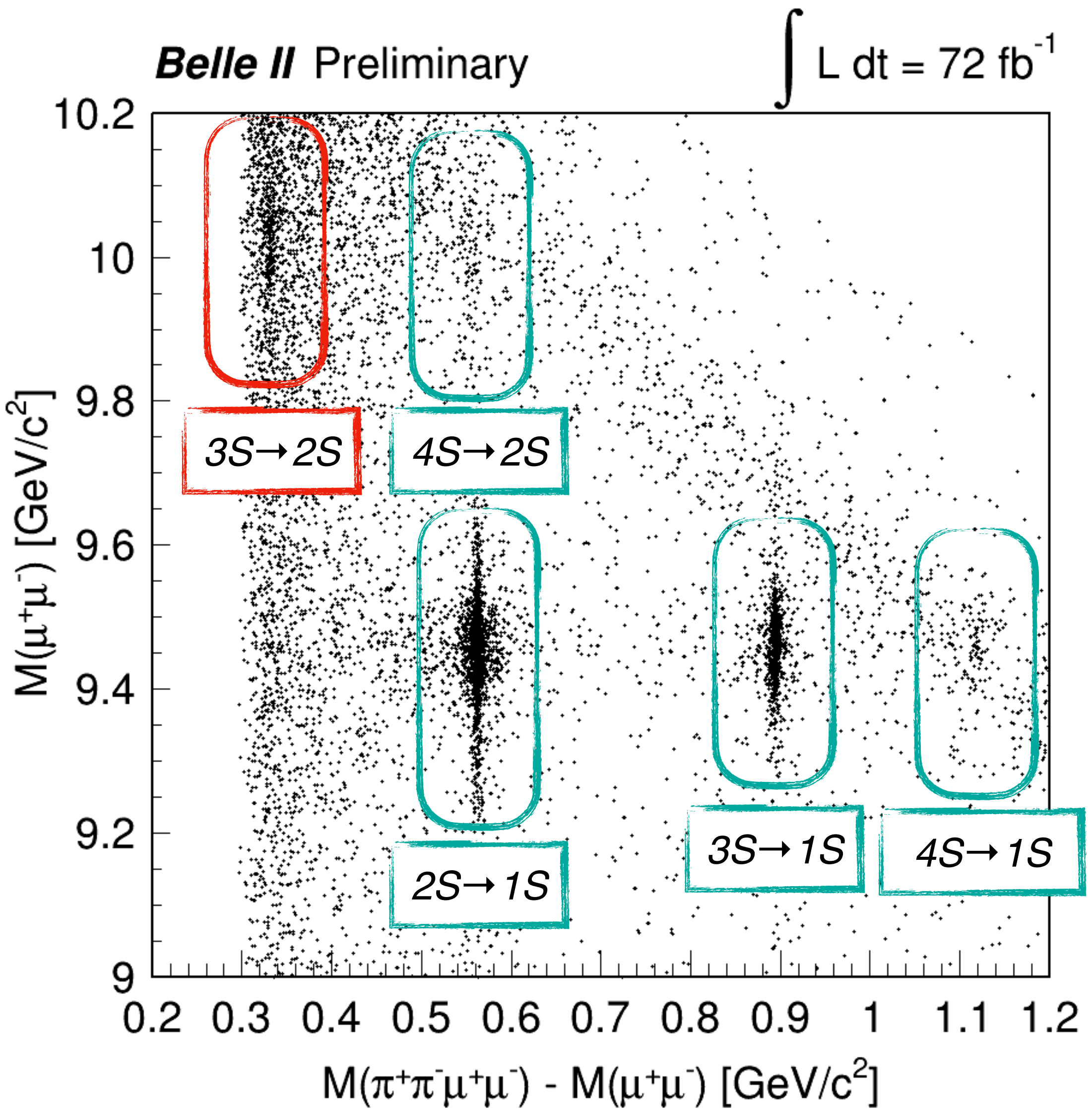


$e^+e^- \to \pi^+\pi^- \mu^+\mu^-$ (+γ undetected)

- e+e- →Υ(nS) γ_{ISR}→$\pi^+\pi^-$ Initial State Radiation (ISR) production:
  - γ_{ISR} Υ(3S)→π+π-Υ(1S,2S)($\ell^+\ell^-$)
  - γ_{ISR} Υ(2S)→π+π-Υ(1S)($\ell^+\ell^-$)

Υ(nS) dipion transitions

BELLE2-NOTE-PL-2021-001



$e^+e^- \to \pi^+\pi^- \mu^+\mu^-$ (+γ undetected)

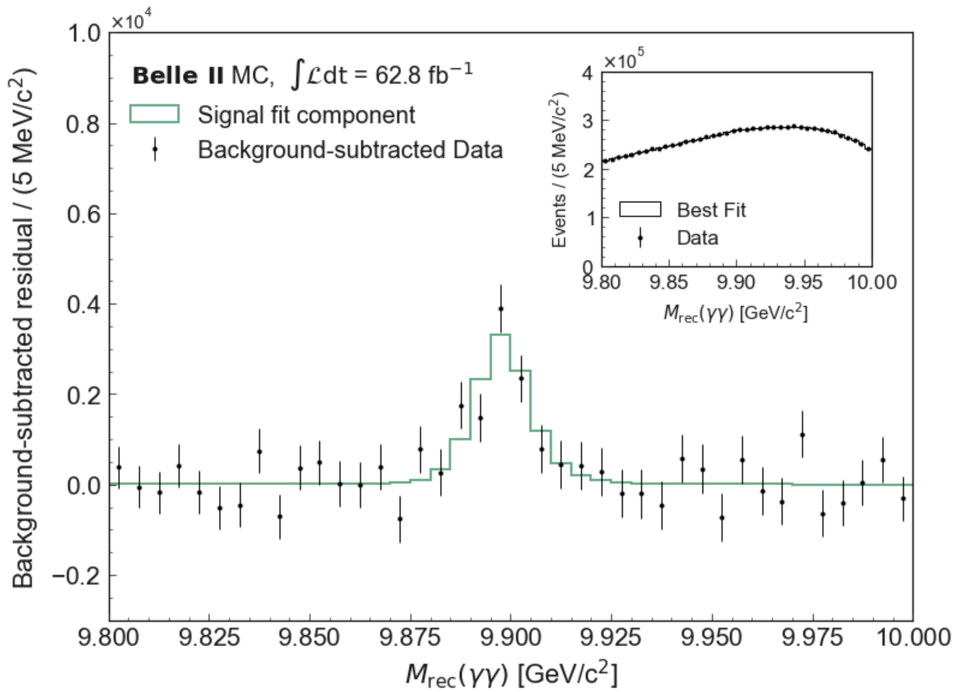
- Done better than Belle analysis
  - 496 fb^{-1} [PRD 96 (2017) 5, 052005]
  - $\Upsilon(3S) \to \pi^+\pi^- \Upsilon(2S)$ was not visible
- Improved low momentum tracking

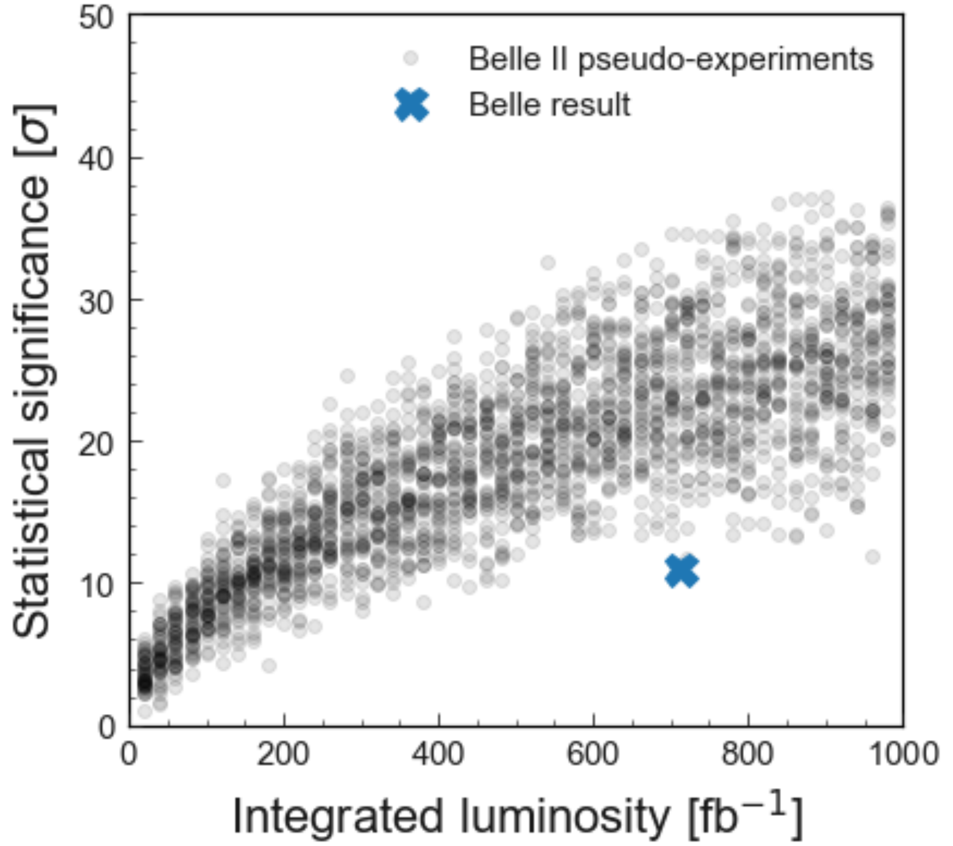
Dalitz analysis of $\Upsilon(4S) \to \pi^+\pi^- \Upsilon(nS)$ ongoing. Possible with the 2022 data set (~1ab^{-1})

MC study on rediscovery of the $\Upsilon(4S)\to\eta\, h_b(1P)$ transition

$$\Upsilon(4S) \to \eta\ [\ h_b(1P) \to \gamma\eta_b(1S)\ ]$$

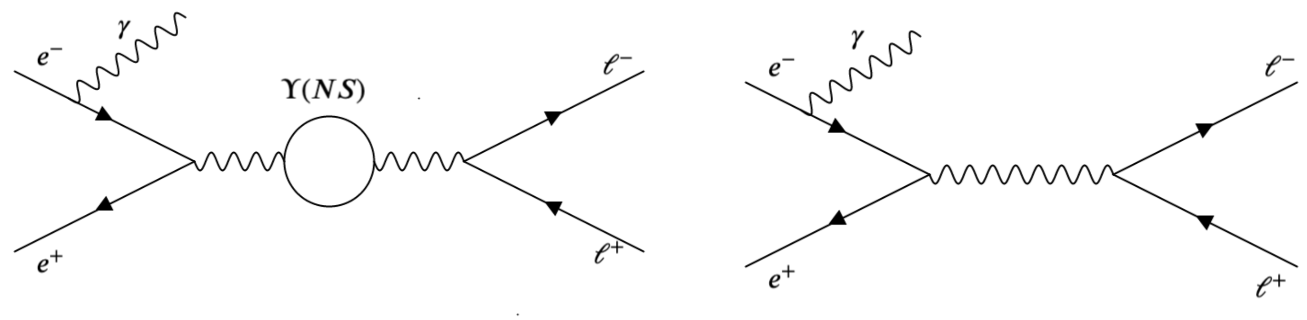
- η reconstructed in **γγ**
- Signal extracted fitting the recoil mass distribution of the $\eta\to\gamma\gamma$ candidates.
- Belle already measured BR[$\Upsilon(4S)\to\eta\, h_b(1P)$] = 2.18×10^{-3}
  - *[Phys. Rev. Lett.115 (2015) 14, 142001]*
- Belle II analysis:
  - Better background reduction
  - 25 % more efficiency
- Belle II should be able to re-observe the process with as little as 50 fb^{-1}

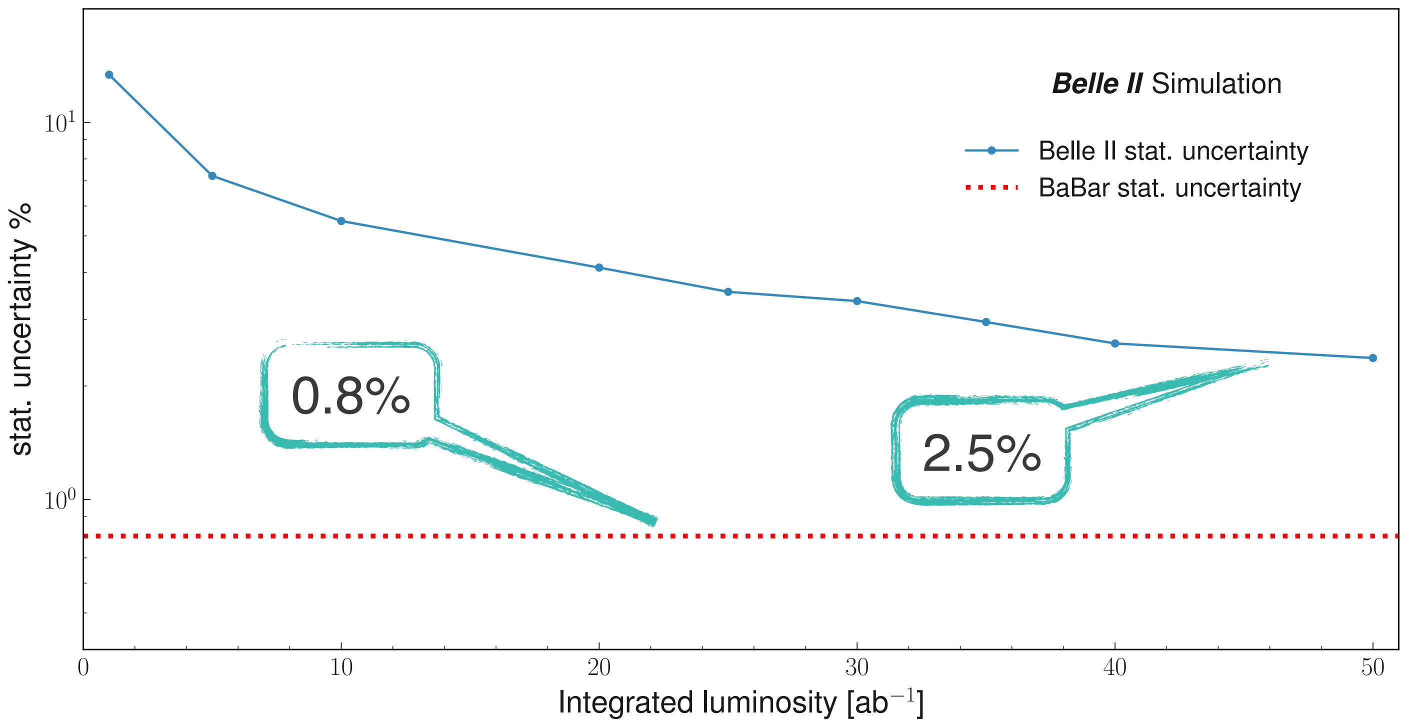




Feasibility study on lepton flavour universality

- MC sensitivity studies on the LFU in the channel $\Upsilon(nS) \rightarrow \ell\ell$ via initial-state radiation from run at $\Upsilon(4S)$
- Potential NP in R(D*) affects also this process *[Aloni et al, JHEP 06 (2017) 019]*
- Measure $\Upsilon(1S) \rightarrow \tau\tau$, $\mu\mu$ and continuum by fitting the ISR peak in the recoil mass distribution
- Measure $\dfrac{\Upsilon(1S) \rightarrow \tau\tau}{\Upsilon(1S) \rightarrow \mu\mu} \Big/ \dfrac{ee \rightarrow \tau\tau}{ee \rightarrow \mu\mu}$
- Check statistical uncertainty as function of integrated luminosity
- More competitive BaBar result with a different technique:
  - $B(\Upsilon(3S) \rightarrow \tau^+\tau^-)/B(\Upsilon(3S) \rightarrow \mu^+\mu^-)$.
  [Phys. Rev. Lett., 125:241801, 2020]



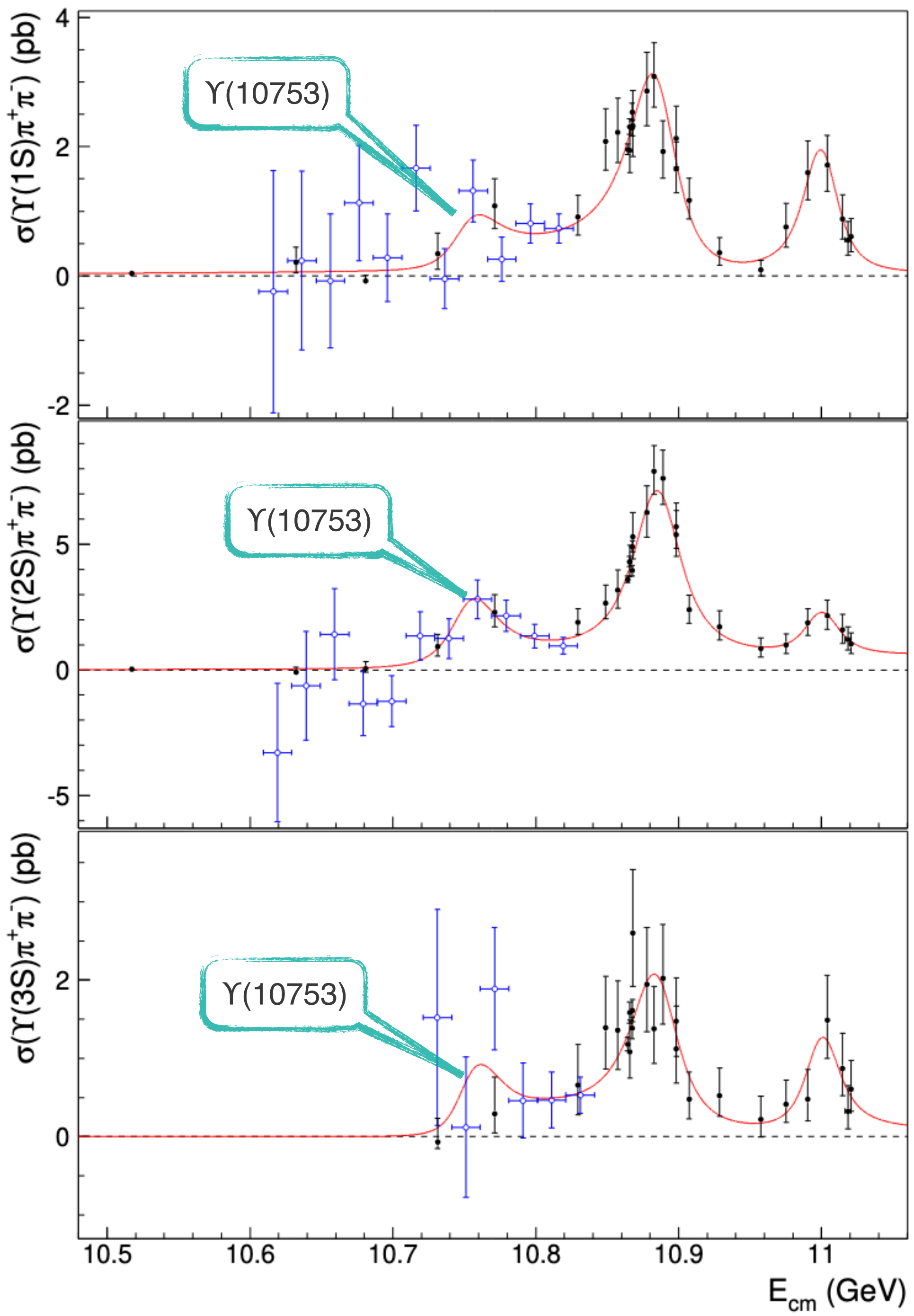


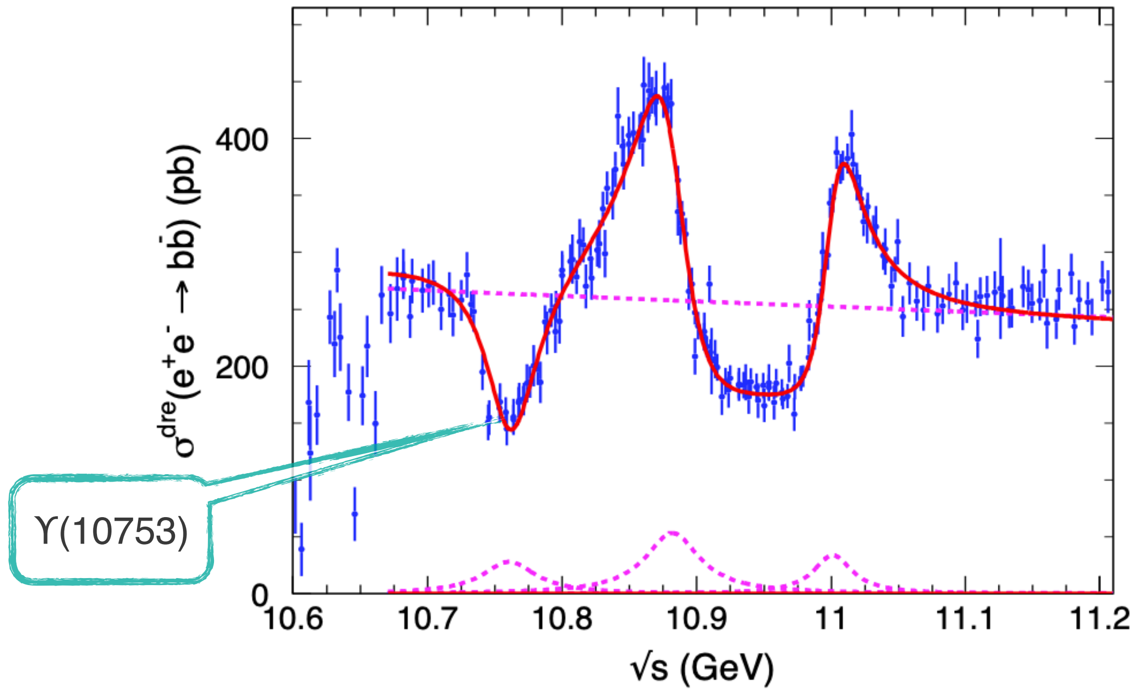
No feasible running at Υ(4S)

Near term plans:
Energy scan around 10.751 GeV to study the new structure

About Υ(10753)

- JHEP10(2019)220 (Belle)
  - $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$
    - $\Upsilon(nS) \to e^+e^-, \mu^+\mu^-$
    - n= 1,2,3
  - High-stat scan points: 1 fb^{-1} each (black)
  - +ISR process at the Υ(10860) [Υ(5S)] (blue)
  - New $J^{PC}=1^{--}$ structure
    - significance of 5.2 σ





- Chin.Phys.C 44 8, 083001 (2020):
  - Refit the Belle + BaBar R_b scan
  - Evidence of Υ(10753) in interference

Possible interpretations

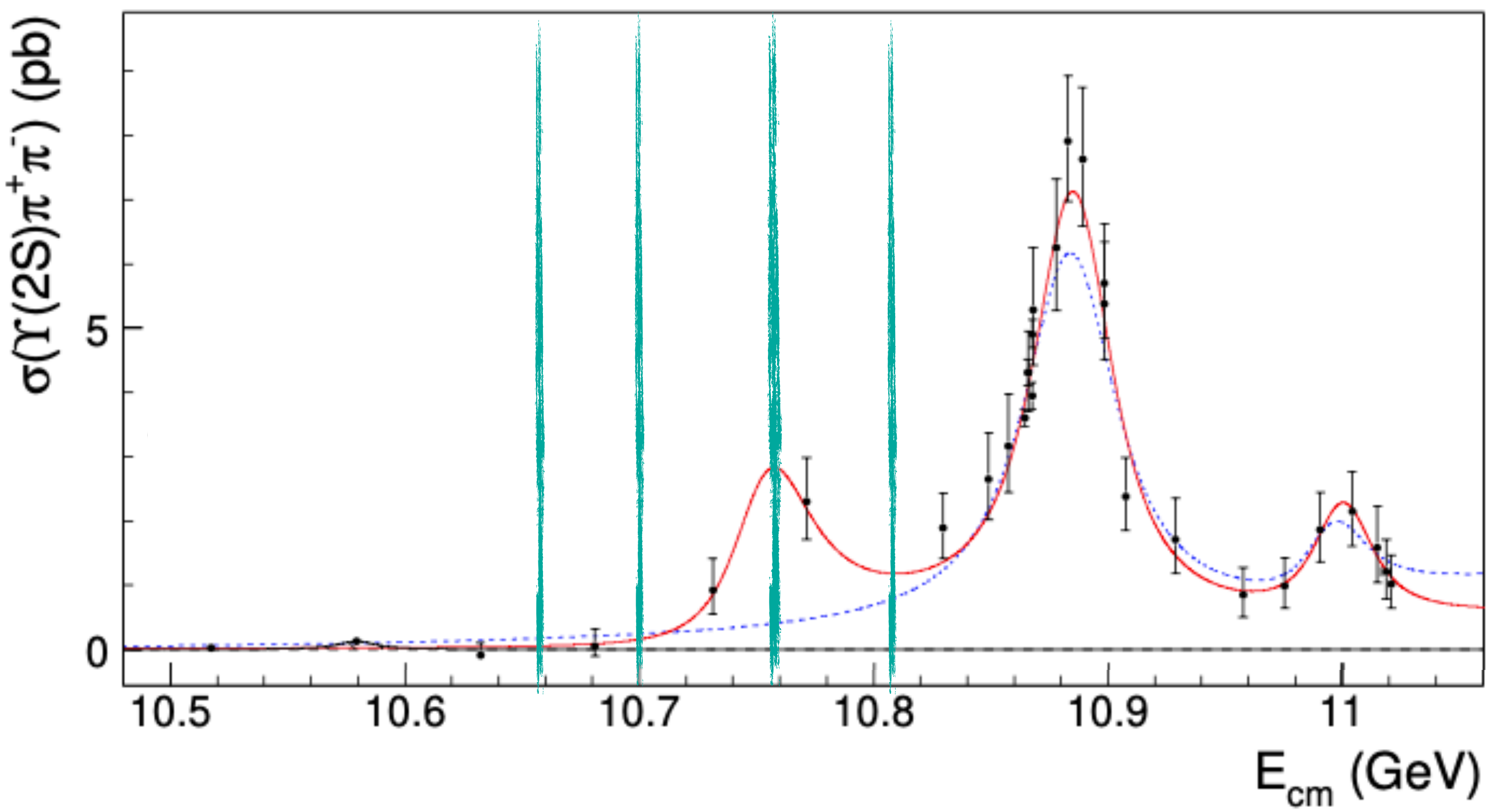
- **Conventional D- or S-D mixed state**
  - Phys.Rev.D 101 (2020) 1, 014020
  - Phys.Lett.B 803 (2020) 135340
  - Eur.Phys.J.C 80 (2020) 1, 59
  - arXiv:2106.14123v1 (2021)

- **Exotic**:
  - Arxiv:2008.05605 (Dynamic resonance)
  - Chin.Phys.C 43 (2019) 12, 123102 (Tetraquark)
  - Phys.Lett.B 802 (2020) 135217 (Tetraquark)
  - Phys.Rev.D 102 (2020) 1, 014036 (Y(5S) is 4q)

Working plans

End of 2021

- **Take data at:**
- 10.751 GeV (9.5 fb^{-1})(on resonance)
- 3 scan point for $B\bar{B}$ decomposition study:
  - 10.657 GeV (1.5 fb^{-1})
  - 10.706 GeV (3.5 fb^{-1})
  - 10.810 GeV (2 fb^{-1})



BELLE II POTENTIAL

- Run at $\Upsilon(6S)$ and $\Upsilon(5S)$ and high energy scan
  - Search for new, predicted, resonances such missing bottomonia, exotic states, ecc..
  - Improve precision of already known process and states.
    - Zb states were only found so far in $\Upsilon(5S)$ decays.
  - Measure the effect of the coupled channel contribution.
  - Study $B^{(*)}\bar{B}^{(**)}$ and $B_s^{(*)}\bar{B}_s^{(**)}$ threshold regions.
    - Maybe challenging for Super-KEKB

Far future

- Run at $\Upsilon(3S)$ and $\Upsilon(2S)$
  - Search for missing ππ/η transitions to constrain further theoretical models.
  - Search for new physics:
    - LFV, LFU, new scalars…

Summary

- Currently taking data at $\Upsilon(4S)$
  - Rediscovery analysis going on
  - Preparatory works for analysis at 10.751 GeV
  - Feasibility studies
- Scan around 10.751 GeV scheduled for the of the year
  - Ready to study new structure
- Possible run at $\Upsilon(6S)$, $\Upsilon(5S)$, $\Upsilon(3S)$ and $\Upsilon(2S)$
  - Not scheduled yet
  - Plans are under discussion

Backup slides

Belle II VS Belle

- Much higher background with respect to Belle but Belle II is designed to perform as well as or better than Belle:

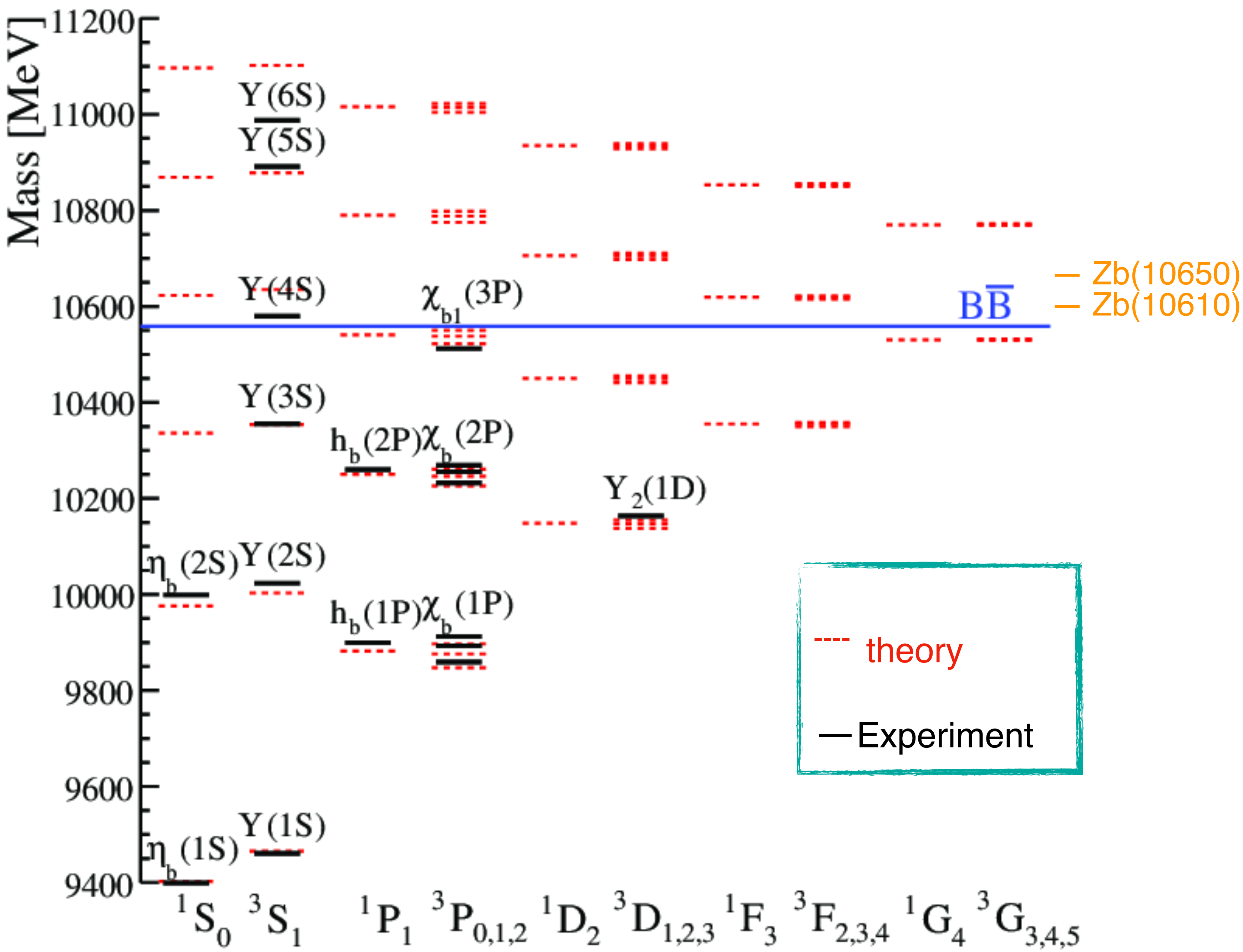
- Tracking [Comp. Phys. Comm. 259 (2021) 107610 (Monte Carlo only), in preparation (data)]
    - Better resolution at both low and high pt
    - Better efficiency at low pt
    - 2x better vertexing and decay time resolution

- Full event reconstruction [Comput. Softw. Big Sci3, 6 (2019)]
    - Better purity and efficiency

- Neutrals [paper in preparation]
    - Better algorithms and electronics
    - (Currently) only enough to compensate the increased backgrounds

- Particle identification [paper in preparation]
    - Better algorithms and new detectors (working on NN-based approaches)
    - (Currently) only enough to compensate the increased background

Bottomonia



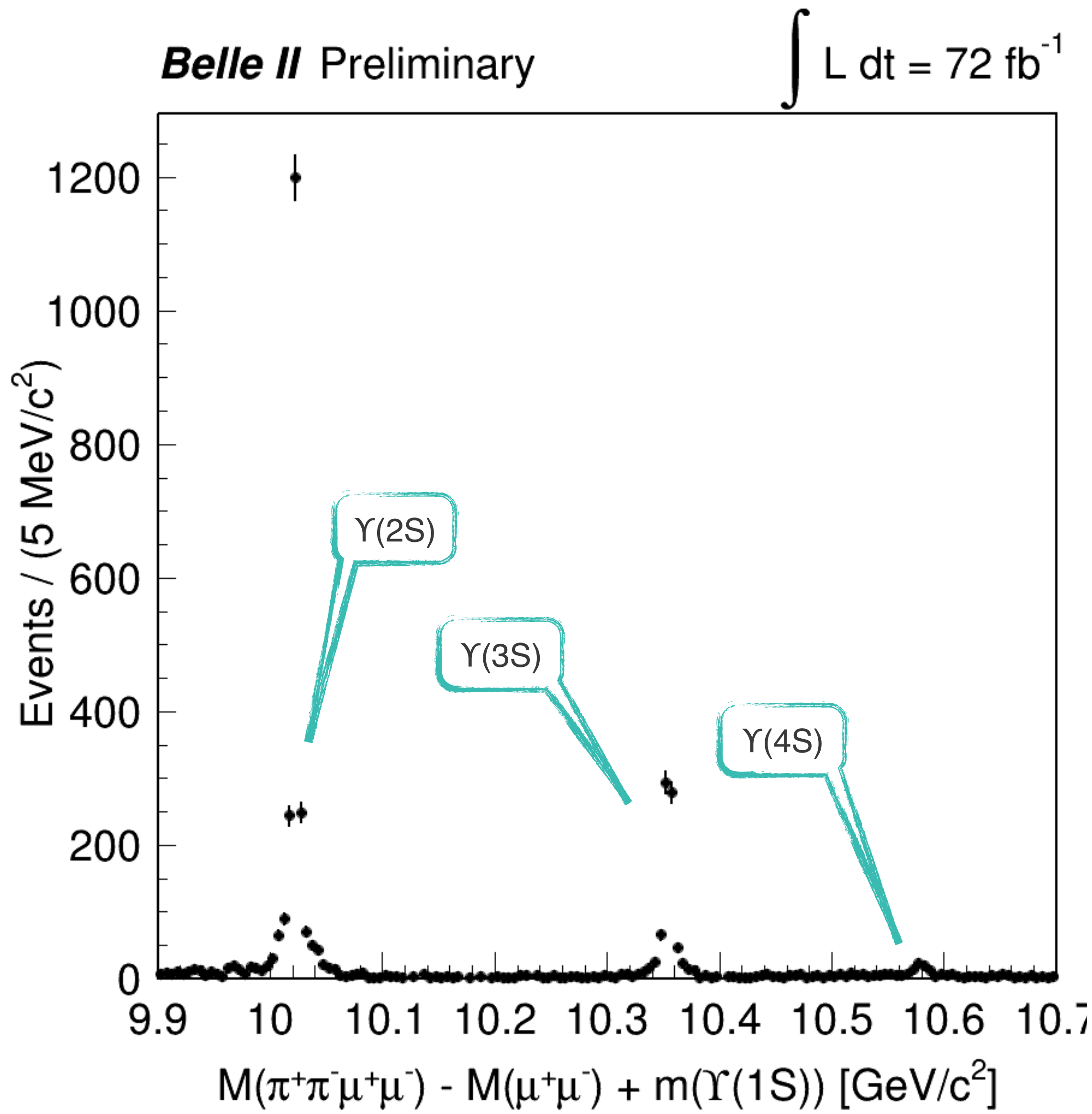
$n^{(2S+1)}L_J$

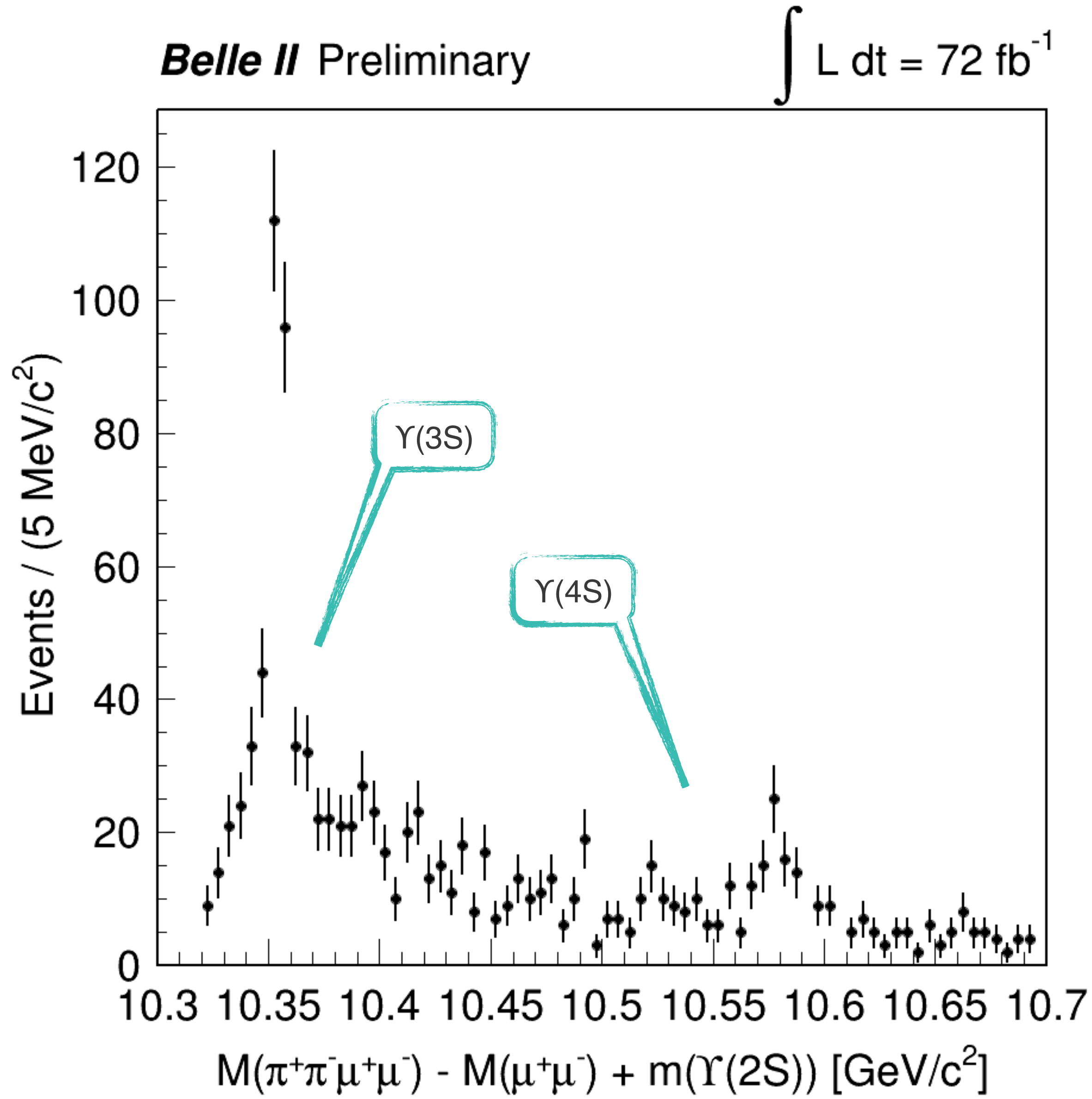
- **n** radial quantum number
- **S** total spin of q$\bar{q}$ system
- **L** relative orbital ang. momentum
- **L**= 0,1,2 .. correspond to S,P,D
- **J**=L+S
- Parity **P** = $(-1)^{L+1}$
- Charge Conj. **C** = $(-1)^{L+S}$

States with masses above corresponding open flavour thresholds have properties unexpected for a pure q$\bar{q}$ state;

Υ(nS) dipion transitions

- Variable of interest: ΔM=M(ππℓℓ)−M(ℓℓ)+M(PDG)
  - M(PDG) = mass of the daughter





$\Upsilon(10753)$ potential analyses

- $\Upsilon(10750) \to \Upsilon(nS)\pi^+\pi^-$
- BBbar decomposition
- Di-pion Dalitz
- $\Upsilon(10750) \to \omega\eta_b(1S)$
- $\Upsilon(10750) \to \pi\pi\, h_b(1P, 2P)$
- $\Upsilon(10750) \to \eta\, h_b(1P)$
- $\Upsilon(10750) \to \Upsilon(1S)$
- $\Upsilon(10750) \to \omega\chi_b(1P)$
- $\Upsilon(10750) \to \eta\Upsilon(1S, 2S)$
- $\Upsilon(10750) \to \gamma X_b$

Exotic states

- Many other possible states beyond Zb states are expected

Re-elaborated from Mod. Phys. Lett. A 32, 1750025 (2017)