Quarkonium at Belle II

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@A Virtual Tribute to Quark Confinement and the Hadron Spectrum 2021

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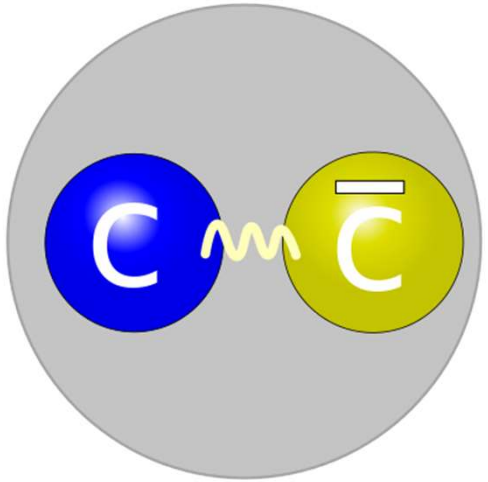
Quarkonium

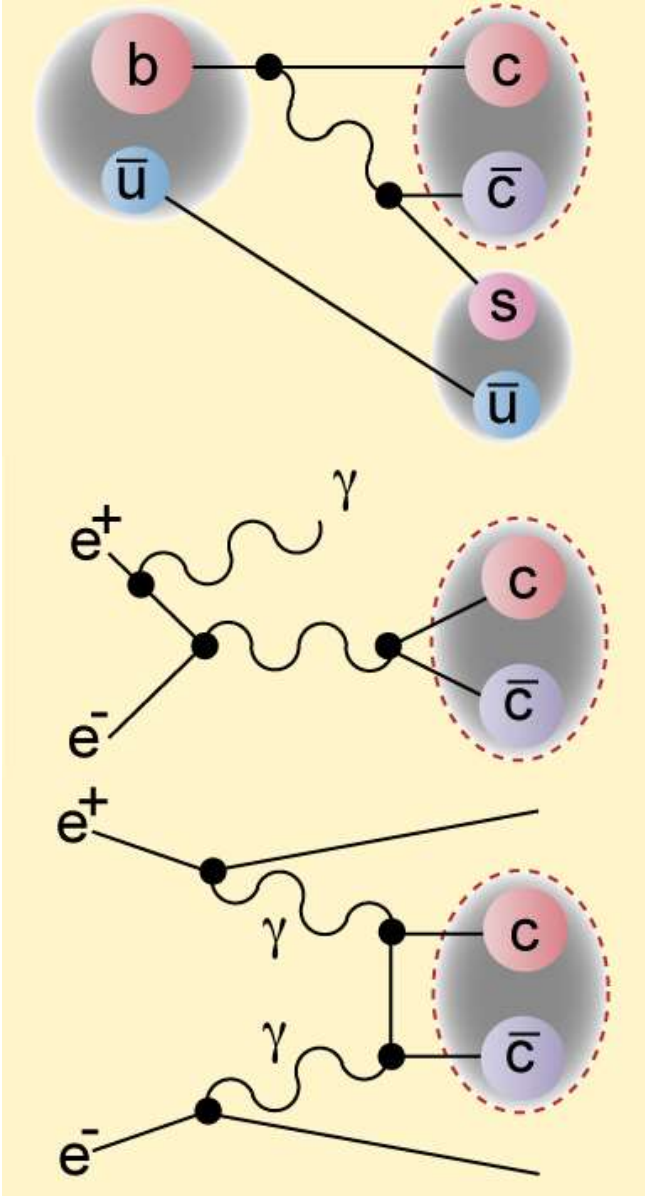
- $Q\bar{Q}$ meson with a heavy quark (i.e., Q=c or b)
- Is a best playground for constituent quark model
  - Simple two body system
  - Large mass
    → Non-relativistic, perturbative



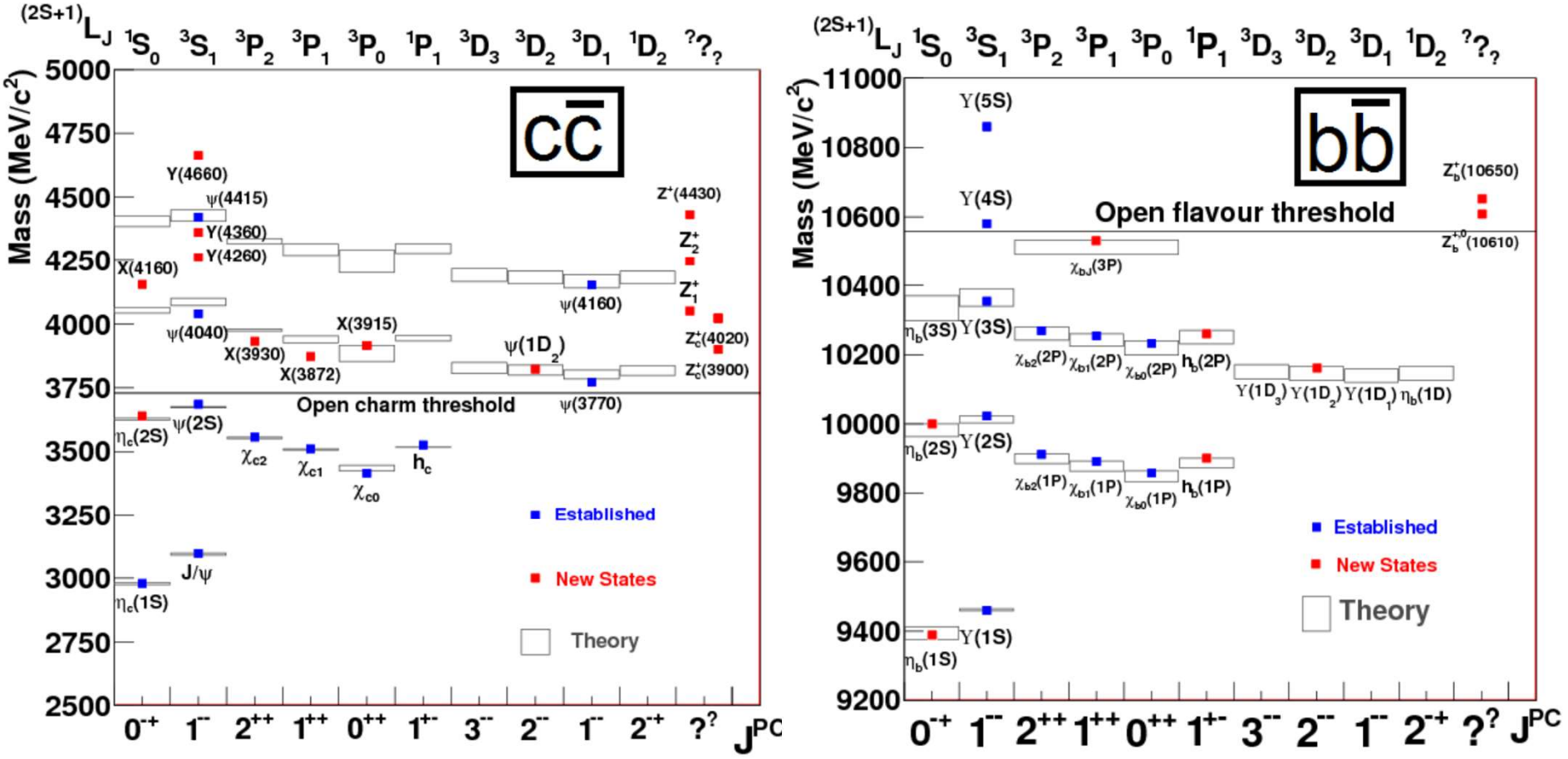
- Also a good playground for exotics
  - QM predictions are robust
    → Exotics (Tetraquarks, hybrids, molecular states, glueballs, …) are distinguishable

Production mechanisms in e^+e^-

- B decays – charmonia
- Direct production/Initial State Radiation (ISR)
  - $J^{PC}=1^{--}$
- Two photon collision
  - $J^{PC}=0^{++}, 2^{++}, \ldots$
- Quarkonium transitions
  - Feed-down from higher states



Quarkonia summary



- Good agreement below open flavor threshold
- Exotic candidates, so called XYZ states, discovered

Remaining questions

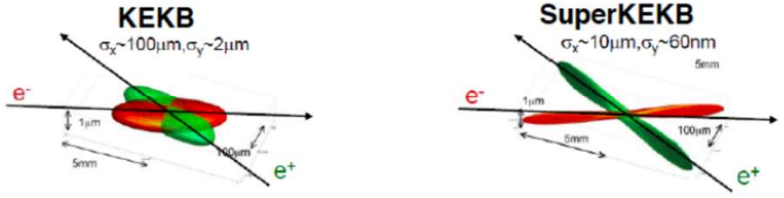
- Many XYZ states were found, but
  - Which ones are exotic?
  - If exotic, what kind?
    Molecule? Tetraquark? Hybrid? Something else?
  - Goal: classification of these states
- J^P is not determined yet for some XZ states
  - Most important measurement in the coming days
- More states?
  - Several more should be discovered especially in b sector
  - Interesting to compare XYZ_c and XYZ_b
  - Discovery of unexpected?

SuperKEKB and Belle II

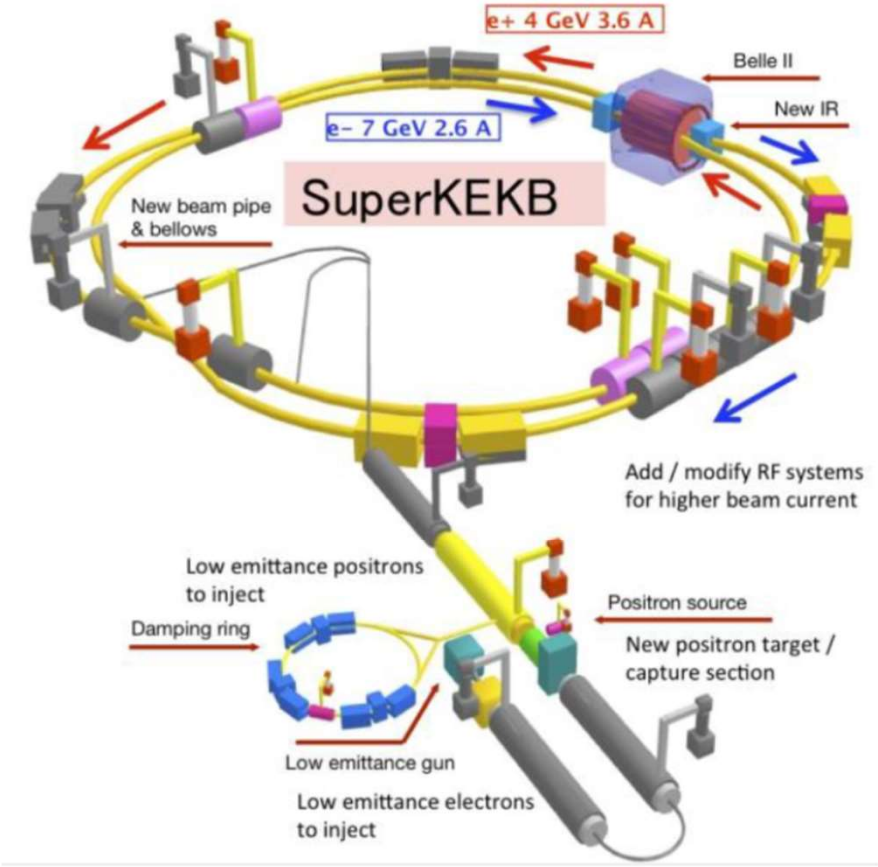
Upgrade for SuperKEKB and Belle II to achieve 30x peak $\mathcal{L}$

- Reduction in the beam size by 1/20 at the IP.
- Doubling the beam currents.

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

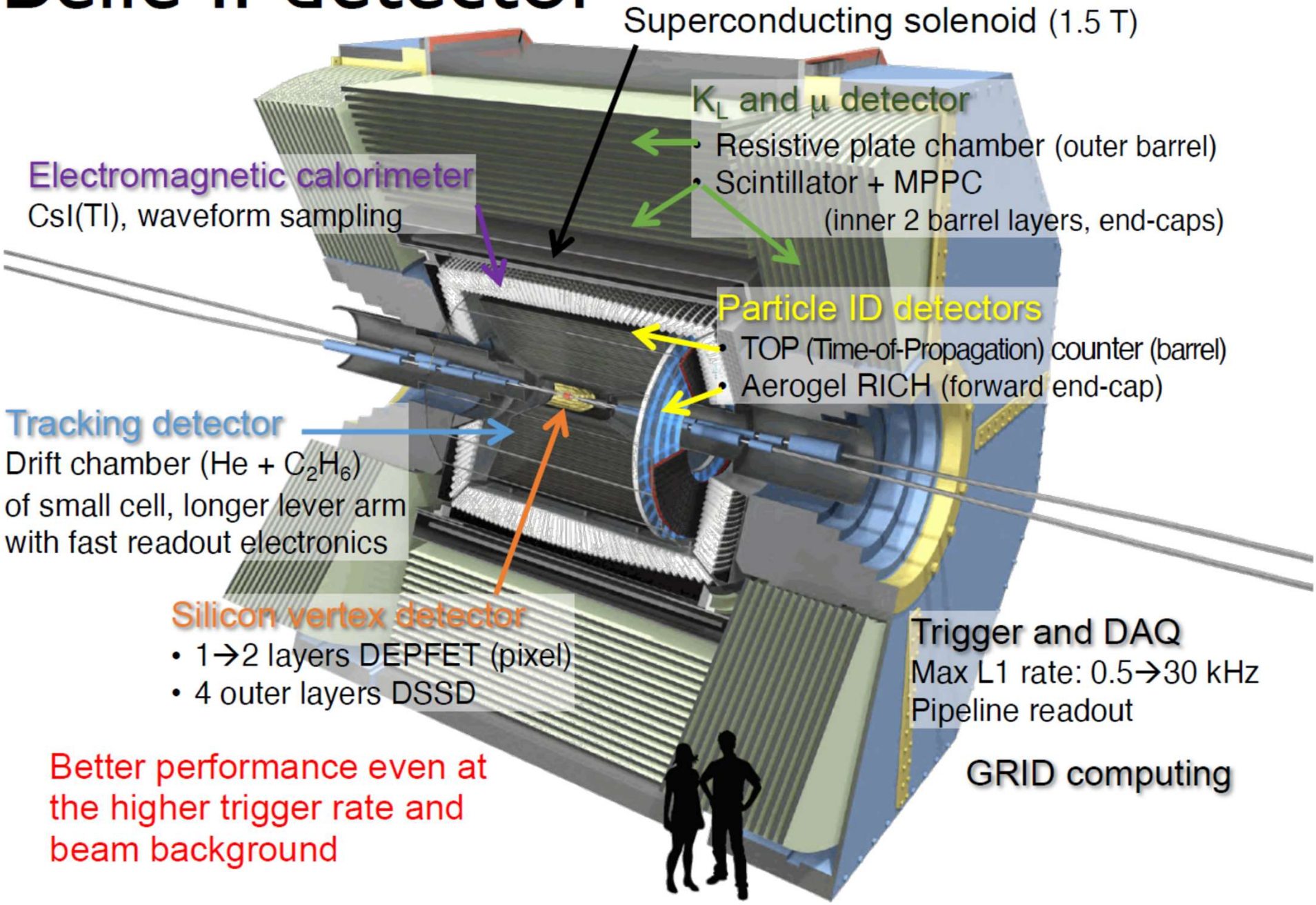


- *First turns achieved Feb. 2016*
- *Beam-background studies ongoing*



Goal: x50 more statistics than Belle

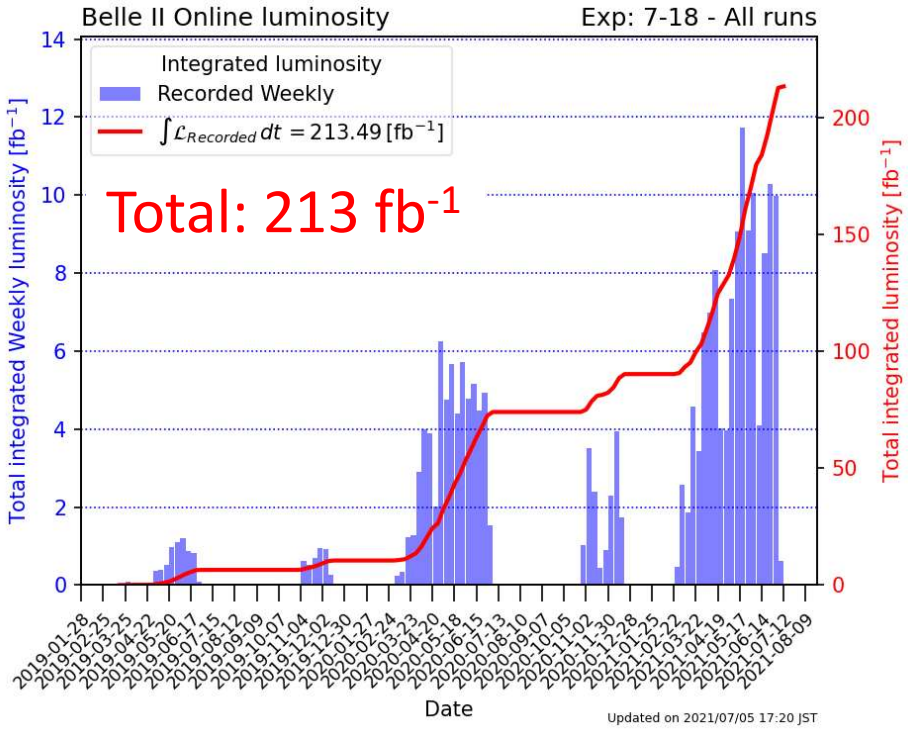
Belle II detector



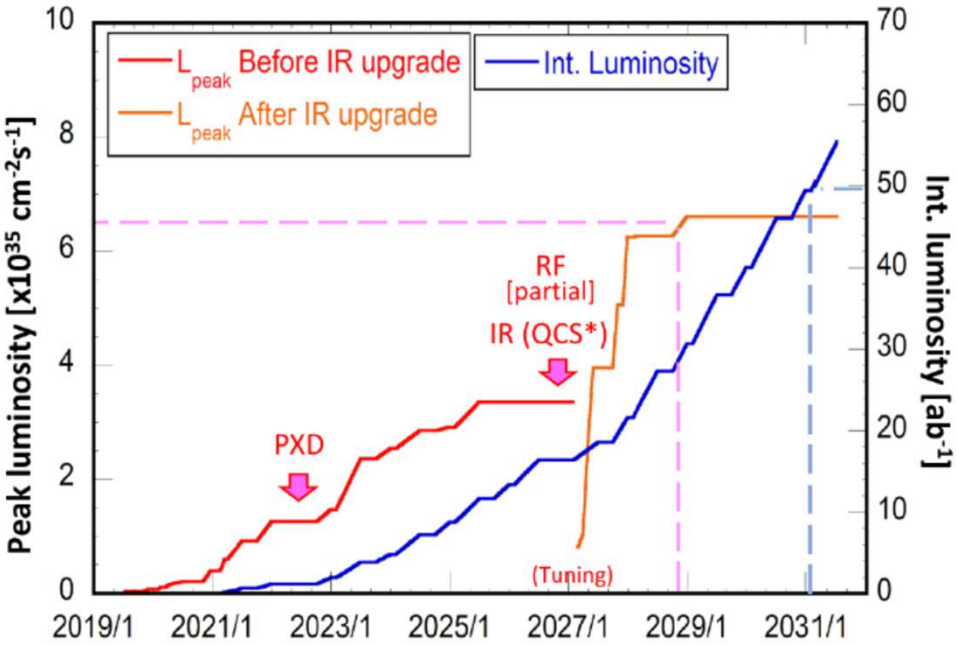
Better performance even at the higher trigger rate and beam background

Belle II integrated luminosity

Achieved



Prospect



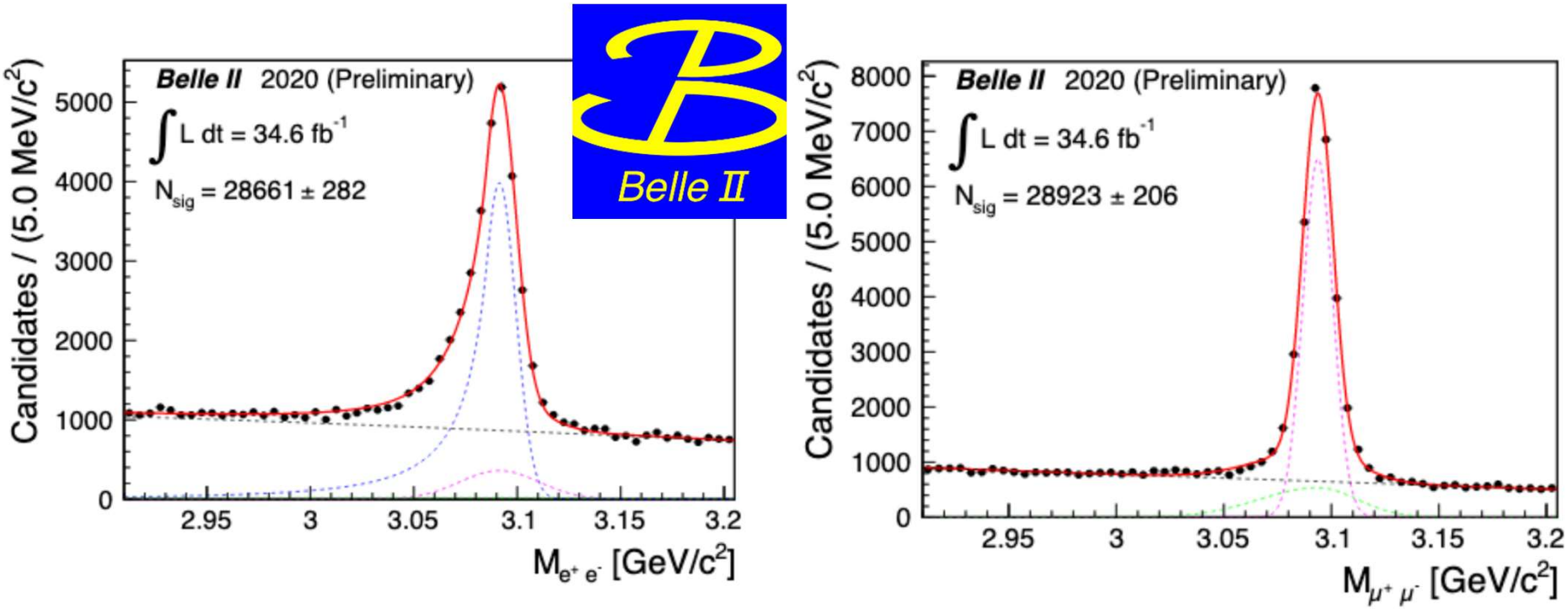
- Instantaneous luminosity already exceeded Belle
- Integrated luminosity will exceed Belle within a few years
- Goal: 50 ab^{-1} around 2031.

Charmonia

Charmonia by B-decay

- Rich source for charmonium-like mesons
  - Not only discovery, but to identify nature of the states
- In decay modes B→KX
  - J^{PC}-determination: B and K are spinless, so $J_Z(X)=0$
  - Determination of absolute branching fraction:
    X can be identified in recoil (missing) mass
- Good signals in Belle II with the present luminosity
  - Clear J/ψ signals both in ee and μμ modes
  - B → ψ(2S)K, ψ(2S) → J/ψ$\pi^+\pi^-$

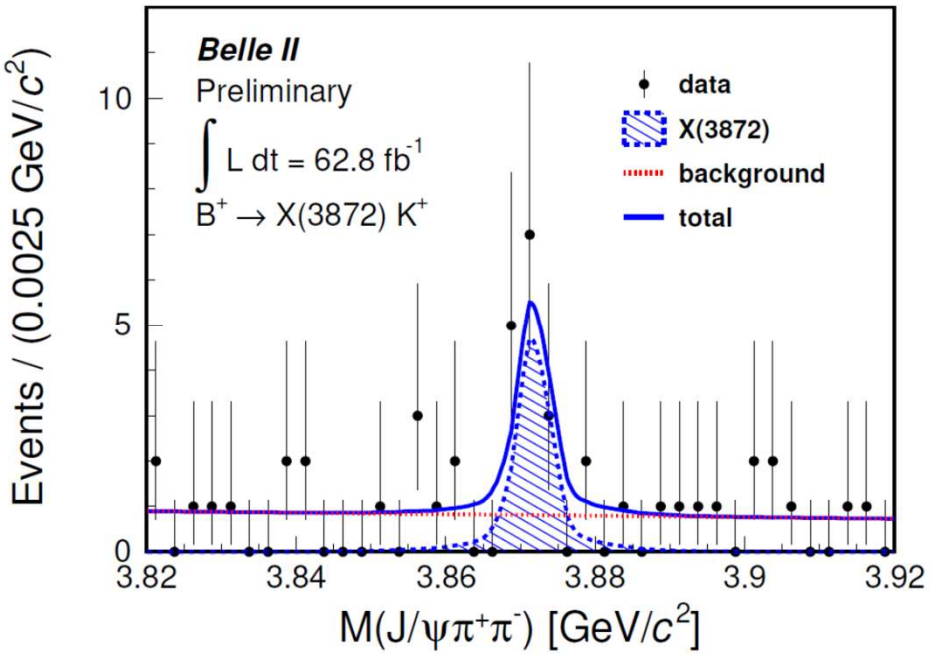
J/ψ in B decay

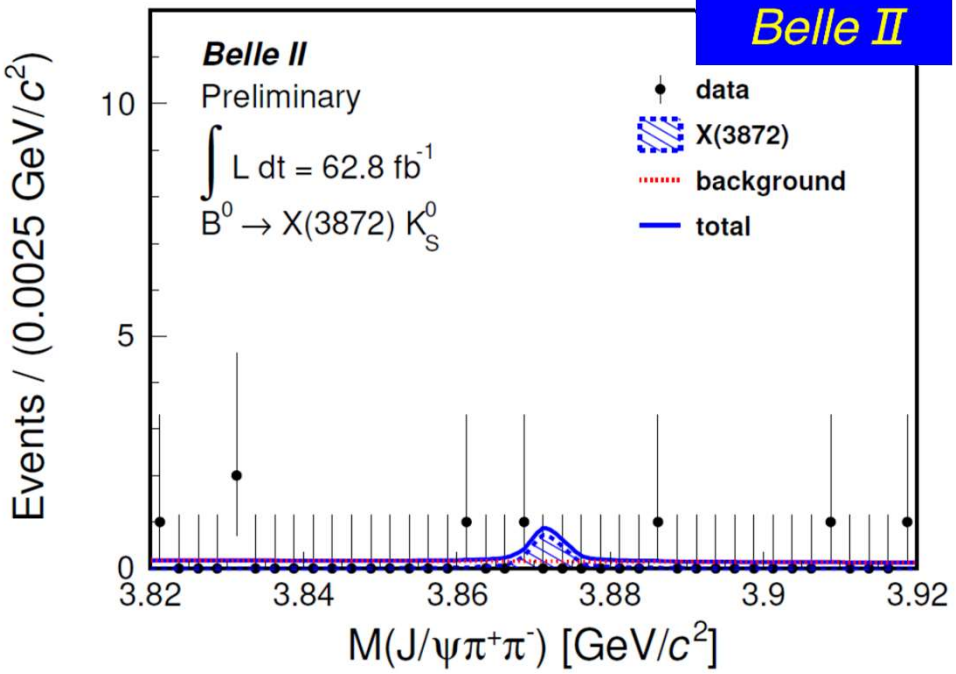


- PDF: CrystalBall+Gaussian for ee ,
  double gaussian for μμ

X(3872)

- Rediscovery of X(3872) in B → X(3872)K → J/ψππK with 63 fb^{-1} (4.6σ significance)
  - ~20% higher efficiency than Belle

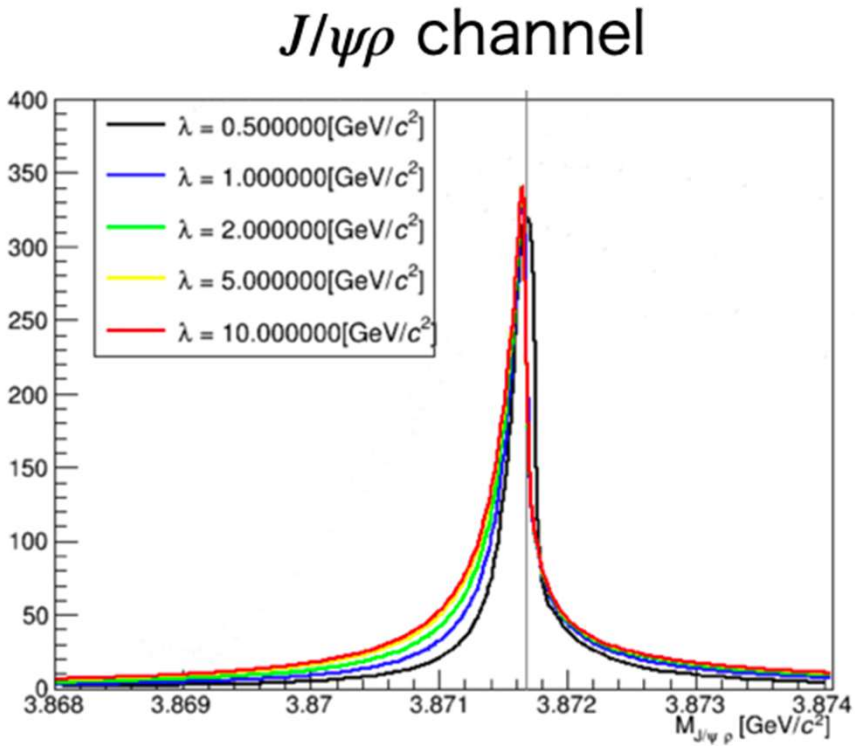


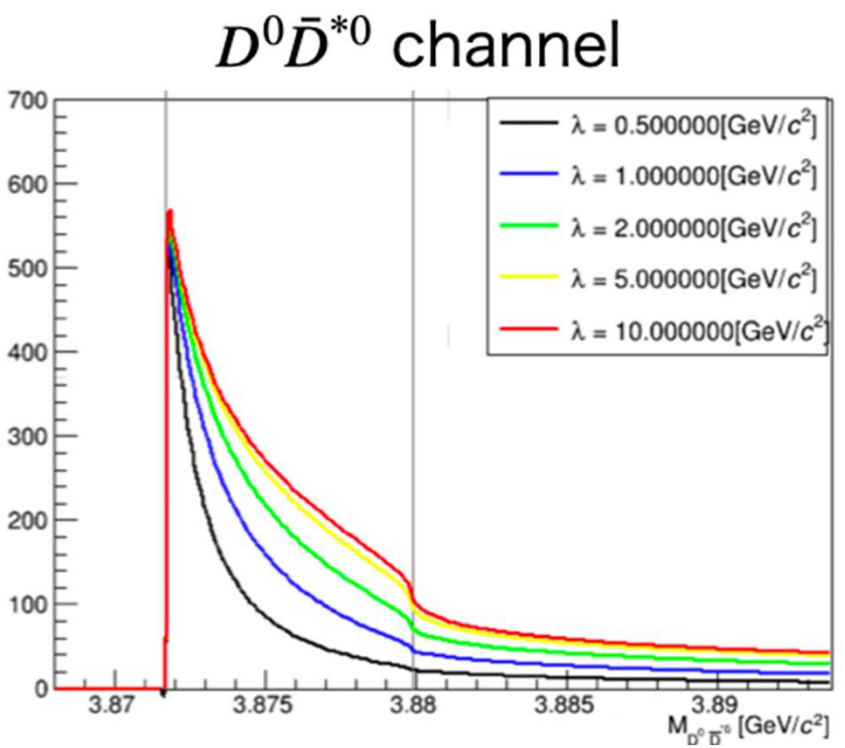


- Near future: Measurement of absolute BR with 1-5 ab^{-1} using missing mass in B → XK.

Pole position search

- Flatte fitting with X(3872) → J/ψππ alone cannot pin-down parameters [LHCb, PRD102.092005(2020)]
  - Scaling behavior of Flatte distribution.
- Simultaneous fit with X(3872) → $D^0\overline{D}^{*0}$

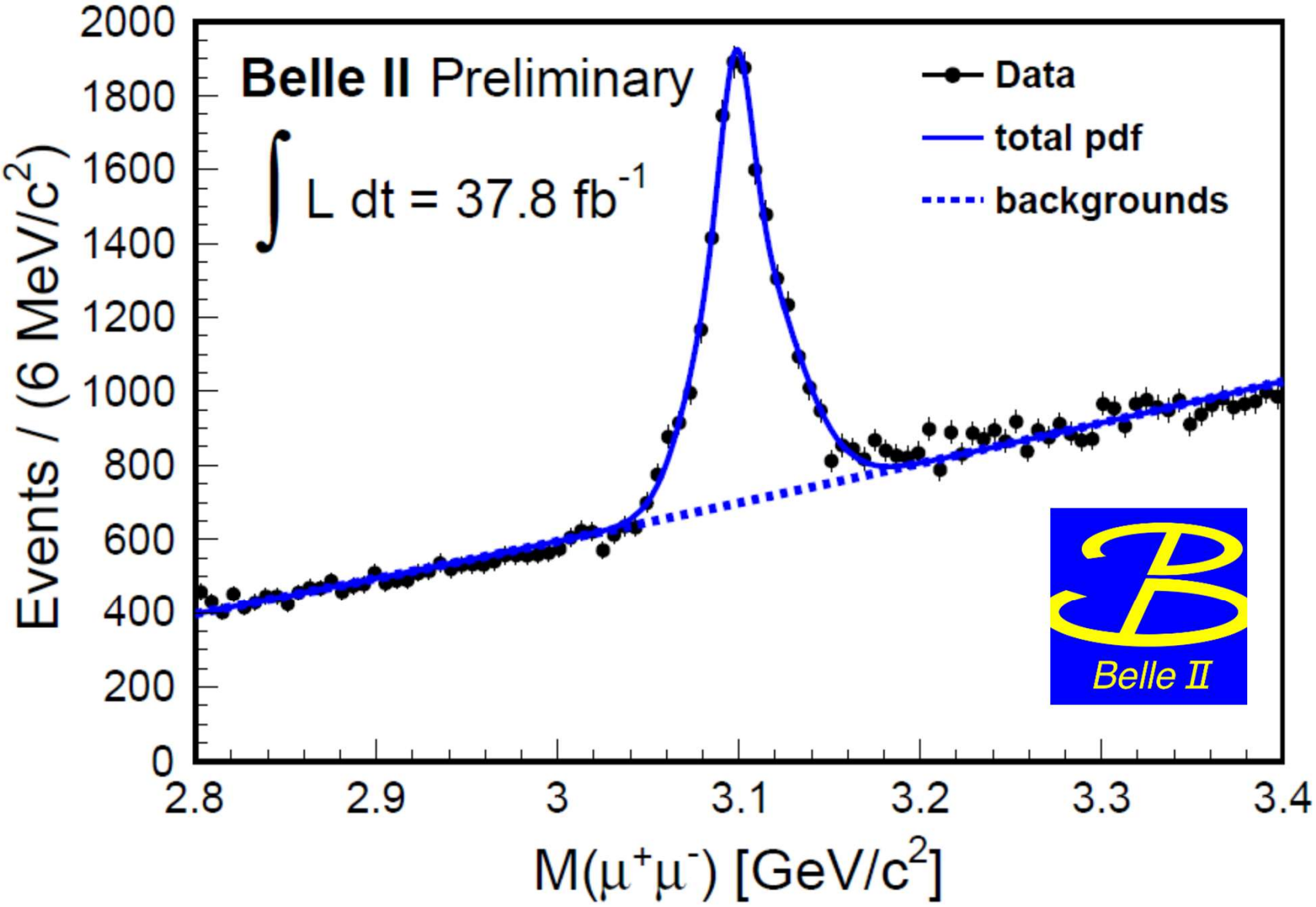




Charmonia by ISR

- Can use data from all higher energies.
  - Line shape study possible with single datasets
  - Decomposition of many nearby states
- Channels of interest
  - $\pi^+\pi^- J/\psi(\psi(2S), h_c, \dots)$: Y(4260), Z(3900), …
  - $K^+K^- J/\psi(\psi(2S))$: Strange partners of Z?
  - $\omega\chi_{c0}$: Y(4220)?
- Competition with BESIII energy scan
  - Similar effective luminosity
  - Wider mass range accessible

Belle II progress: J/ψ → μμ via ISR



Bottomonia

Bottomonia

- New things @Belle II
  - Measurement at $\Upsilon(6S)$ becomes possible
    → Expect more Z_b states
  - Radiative transitions between bottomonia
- Most missing conventional bottomonia below the open bottom threshold should be found; e.g.,
  - $\chi_b(3P)$ triplet
  - $\Upsilon(2D_3)$ triplet
  - $\eta_b(3S)$, $\eta_b(1D)$, $\Upsilon(1D_{1,3})$
  - F-wave states
  - Several others

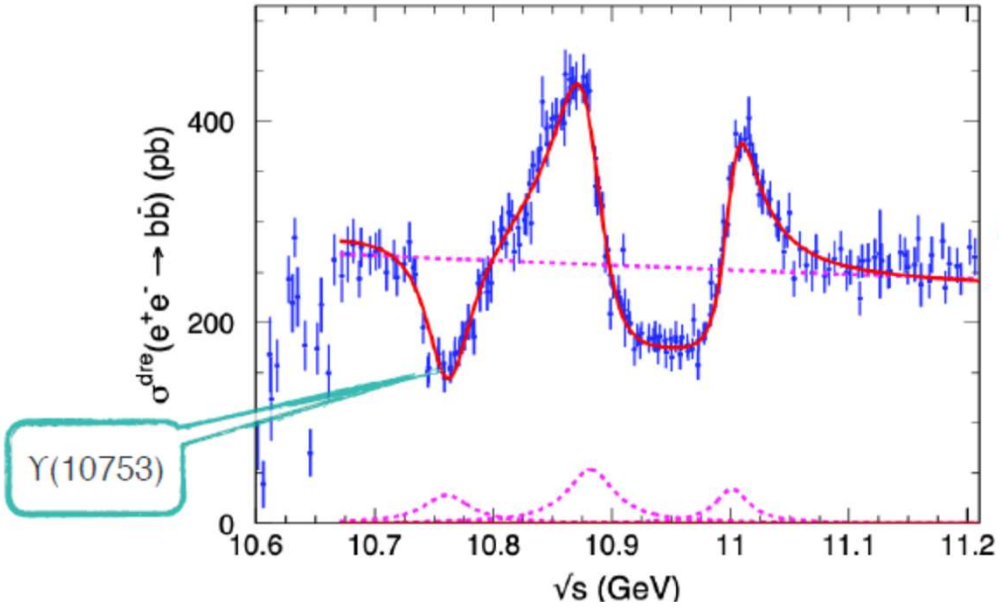
New states?

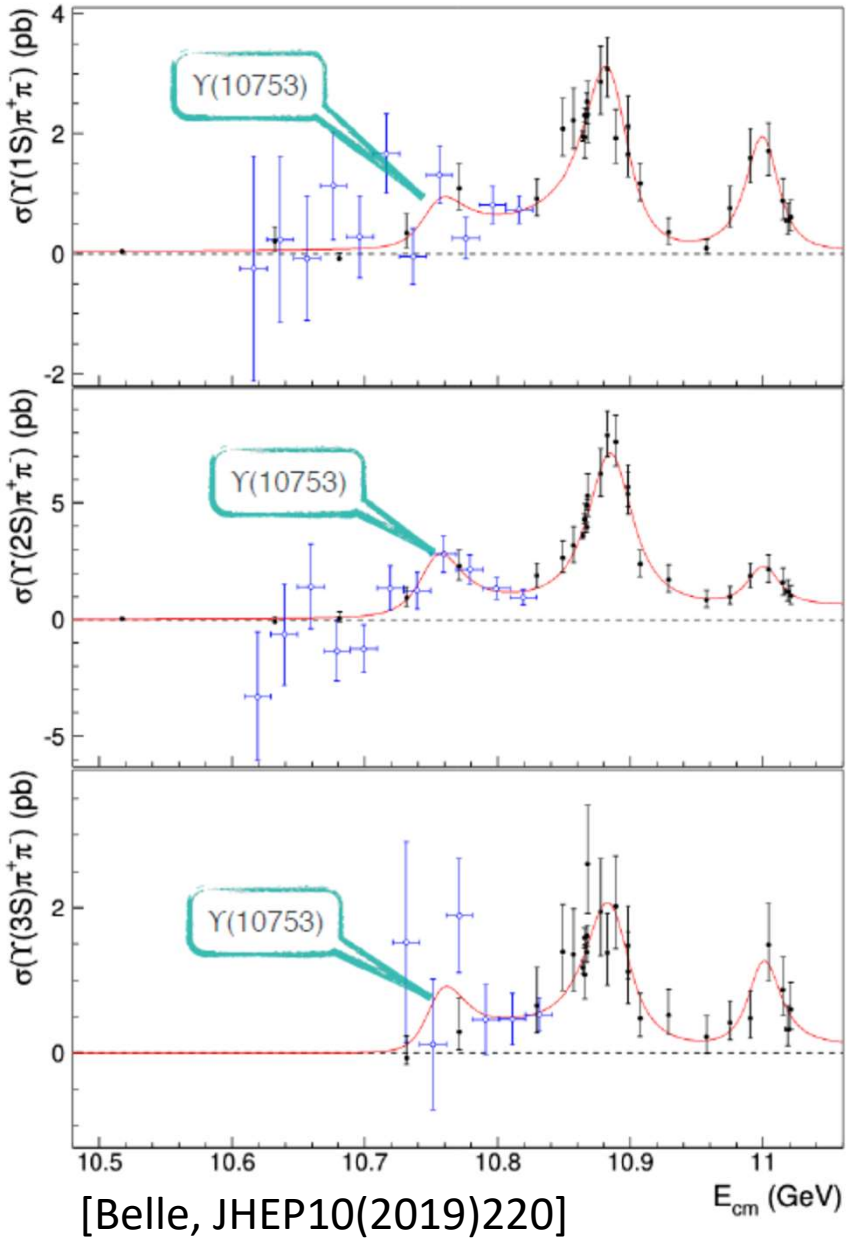
- Some XYZ_c states should have analogs in b sector
  - Y_b states will be searched for in energy scan. (see next slide for $\Upsilon(10753)$)
  - Help to identify the nature of these states
- Expected new states?
  - Yes, there are some: especially for partner states of Z_b
- Possibility for unexpected?
  - Yes, it's always there. Who knows?

Energy scan ~10.751 GeV

- $\Upsilon(10753)$?
  - Hints in $\Upsilon(nS)\pi\pi$ & inclusive $b\bar{b}$ data
  - Significance 5.2σ
  - Exotic? Conventional?

[Chin. Phys. C 44 8, 083001 (2020)]

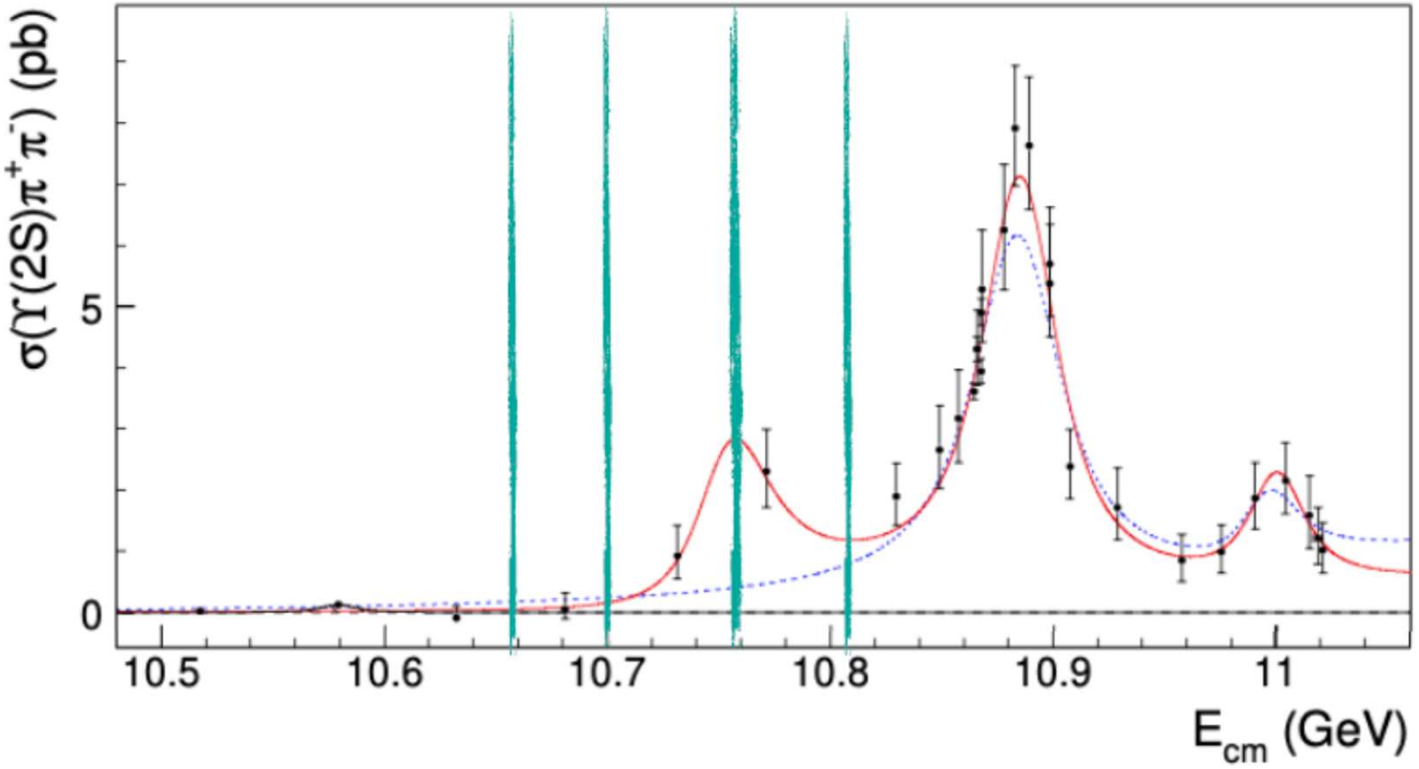




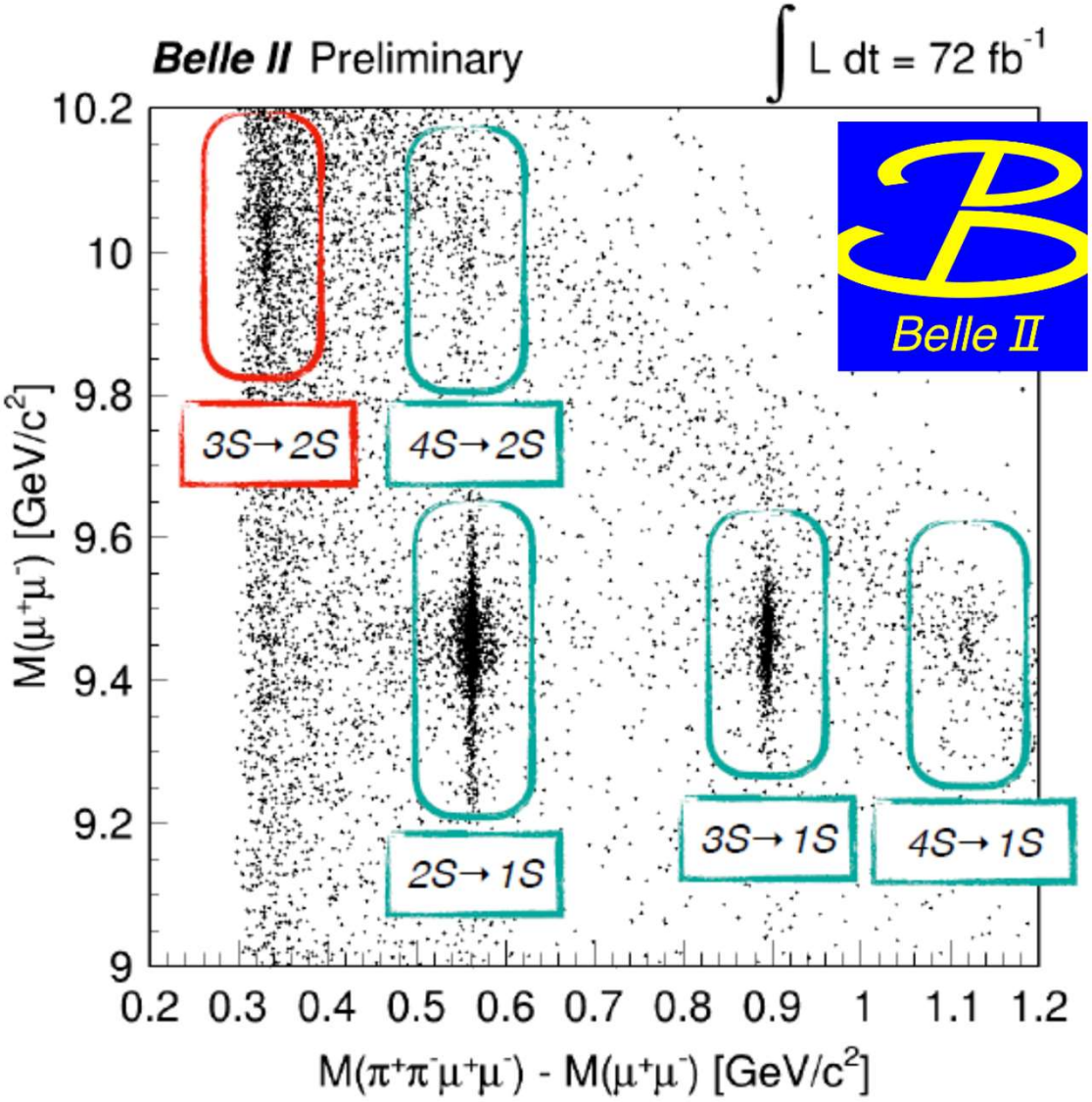
[Belle, JHEP10(2019)220]

Belle II plan

- Near the end of 2021, we will take data at 4 points
  - 10.751 GeV (9.5 fb^{-1}), 10.657 GeV (1.5 fb^{-1}), 10.706 GeV (3.5 fb^{-1}), and 10.810 GeV (2 fb^{-1})
  - To establish the existence



Belle II progress: Υ(nS) → Υ(1,2S)$\pi\pi$



- ISR production
- Better than previous Belle result [PRD96 (2017)052005]
  - 3S→2S transition seen thanks to improved low momentum tracking
- Dalitz analysis of Υ(4S)→ Υ(nS)$\pi\pi$ is ongoing

Summary

- Belle II will acquire x50 more statistics than Belle
  - Instantaneous luminosity already surpassed
  - Identify the nature of known candidates
  - Expecting a lot of further discoveries
- Charmonia -- Rediscovery of X(3872)
  - With better efficiency than Belle
  - Other XYZ states will be rediscovered soon
- Bottomonia
  - Good performance demonstrated in Υ(nS) → Υ(1,2S)$\pi\pi$
  - Plan to take data around 10.75 GeV for Υ(10753) in 2021
  - Higher energy run in future for Υ(6S)