Belle II: Charmonium, Λ_c, and X(3872) Family

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(Japan Atomic Energy Agency)

@19th International Conference on B-Physics at Frontier Machines (BEAUTY 2020)

23 September 2020

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(+ bottomonium + some Belle results)

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Hadron spectroscopy at e^+e^- collider

- Small background
  - $e^+e^- \to Q\bar{Q}$ production is flavor blind.
    Only (charge)^2 matters.
- Missing mass spectroscopy is possible
  - Absolute branching fraction
  - Study of decays with missing particles (n, ν, …)
- Smaller production rate than hadron machines can be compensated by high luminosity

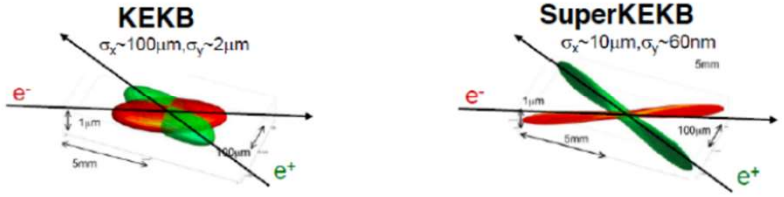
e^+e^- machines are suitable for heavy hadrons!!

SuperKEKB and Belle II

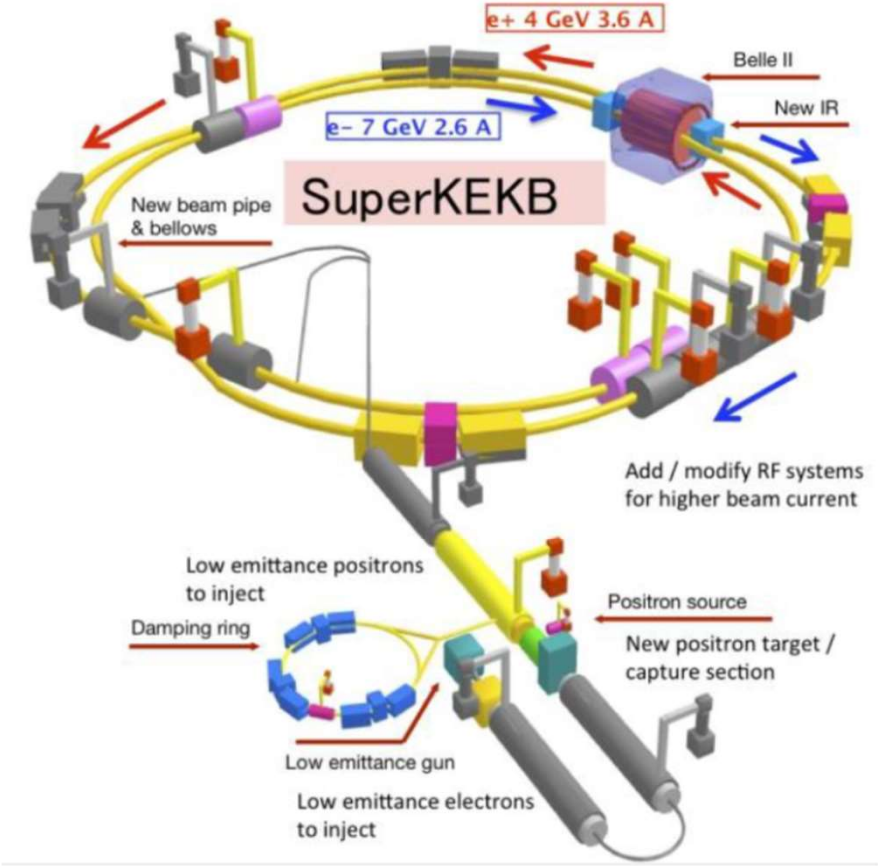
Upgrade for SuperKEKB and Belle II to achieve 40x peak $\mathcal{L}$ under 20x bkgd

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

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

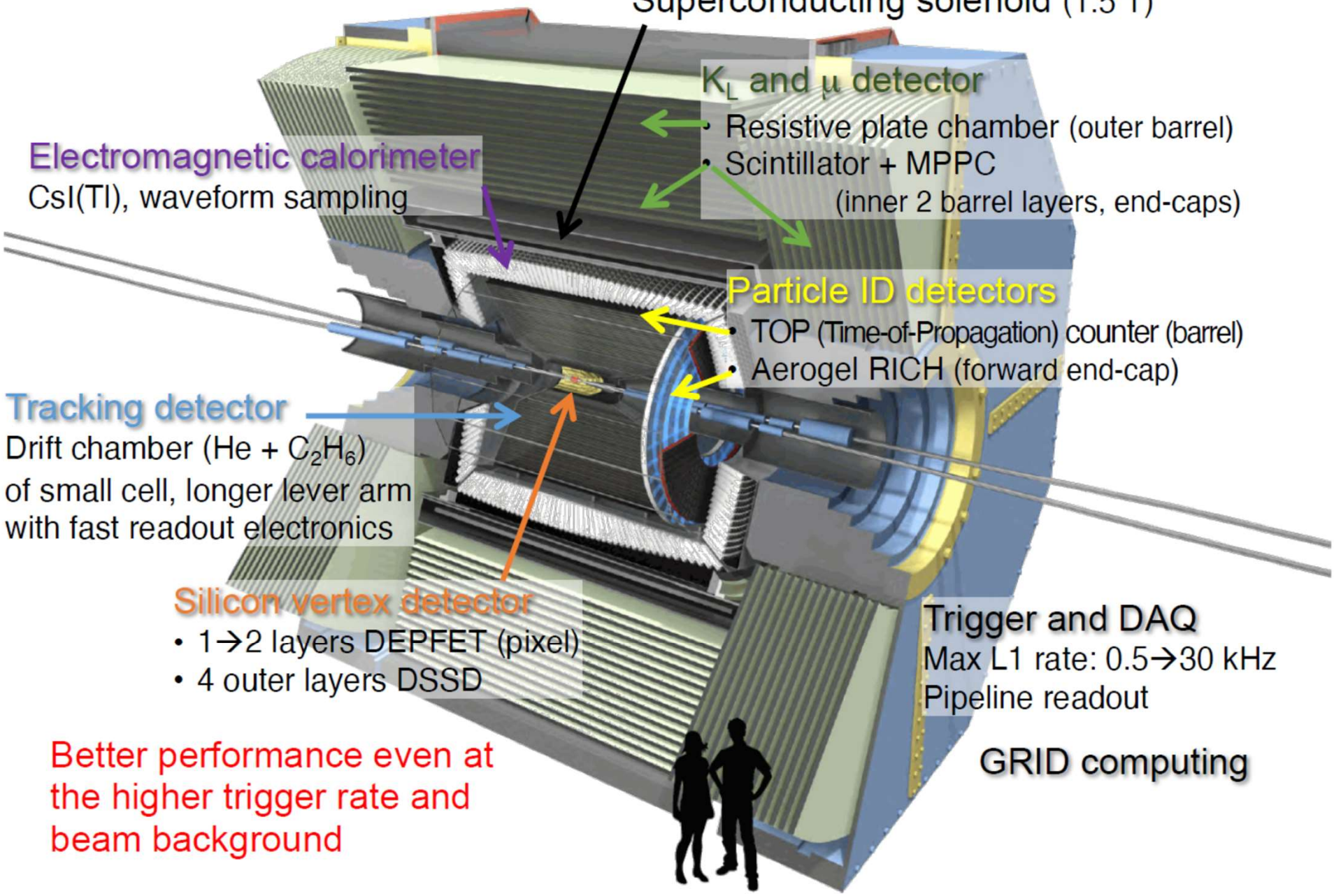


- *First turns achieved Feb. 2016*
- *Beam-background studies ongoing*



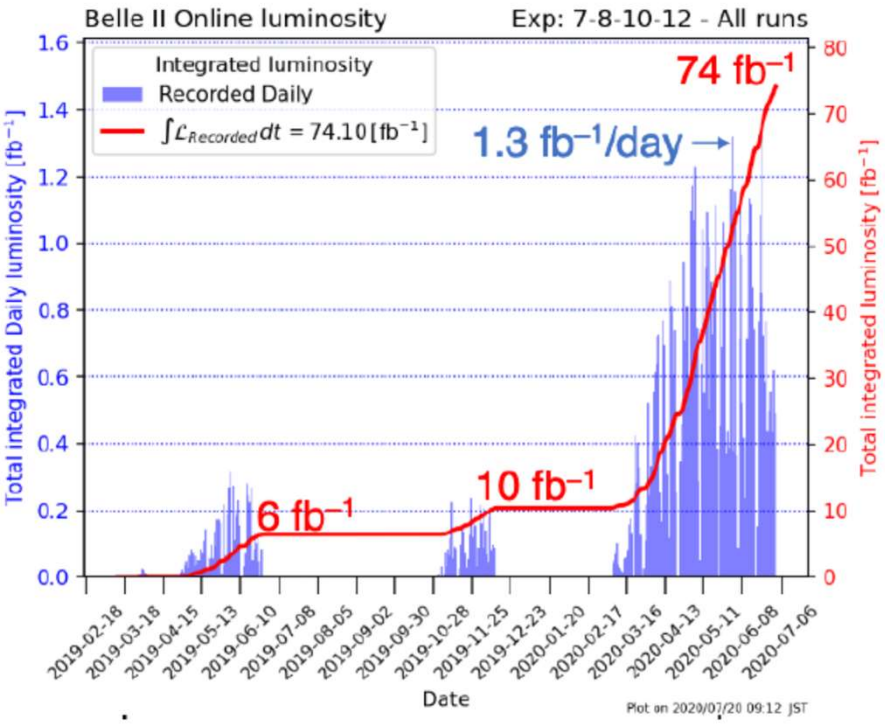
Goal: x50 more statistics than Belle

Belle II detector

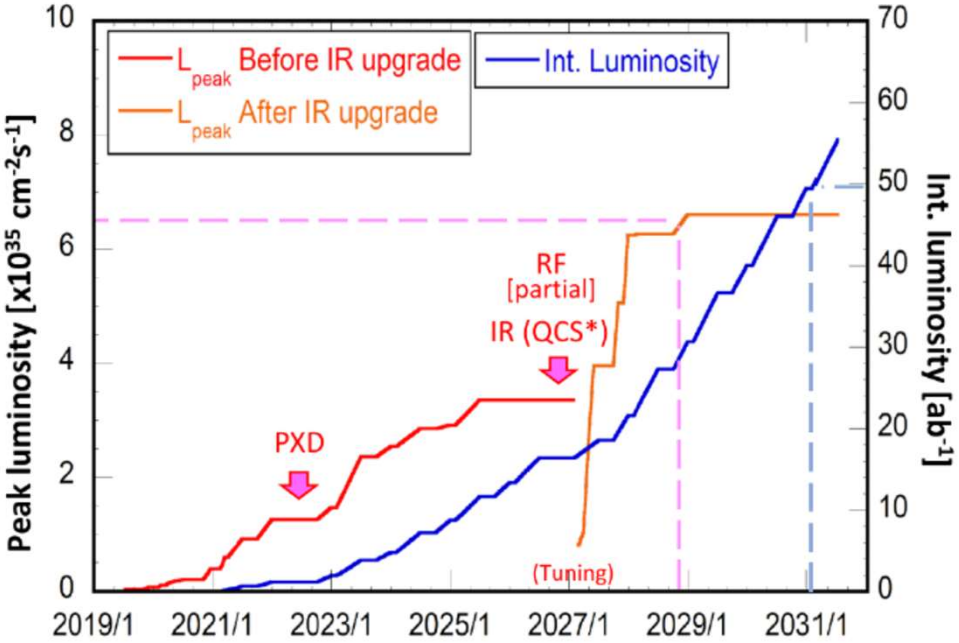


Belle II integrated luminosity

Achieved



Prospect

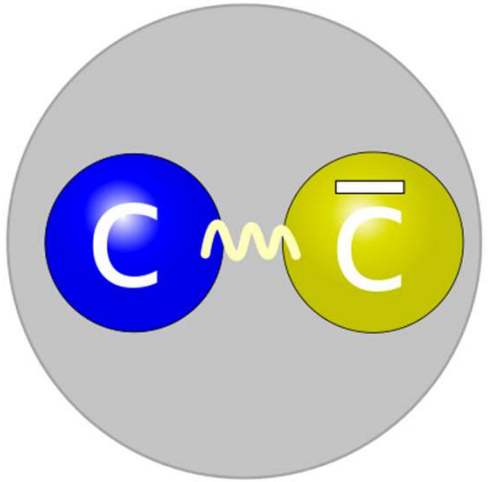


- Instantaneous luminosity already exceeded Belle
- Integrated luminosity will exceed Belle by 2022
- Goal: 50 ab^{-1} around 2031.

Quarkonia, including X(3872)

Quarkonium

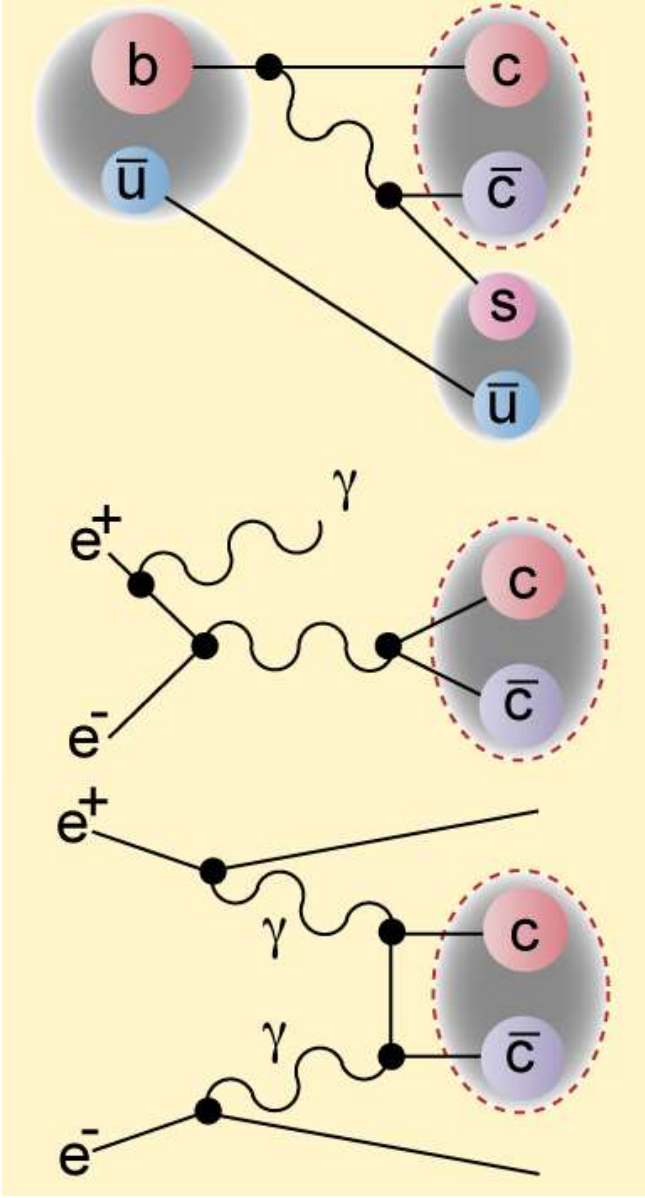
- $Q\bar{Q}$ meson with a heavy quark (i.e., Q=c or b)
- Is a best playground for constituent quark model
  - Simple two body system
  - Large mass
    → Non-relativistic, perturbative



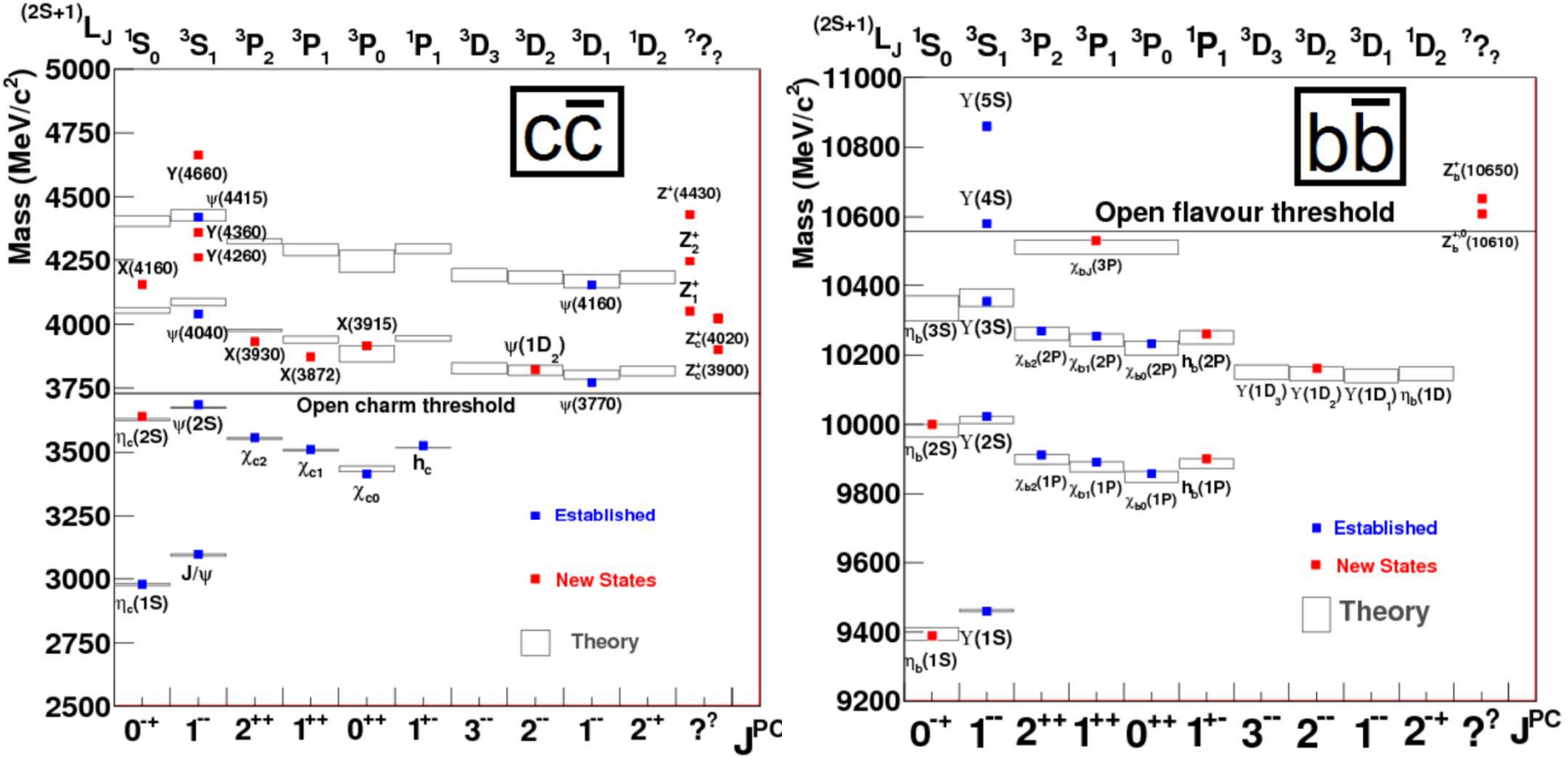
- Also a good playground for exotics
  - QM predictions are robust
    → Exotics (Tetraquarks, hybrids, molecular states, glueballs, …) are distinguishable

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

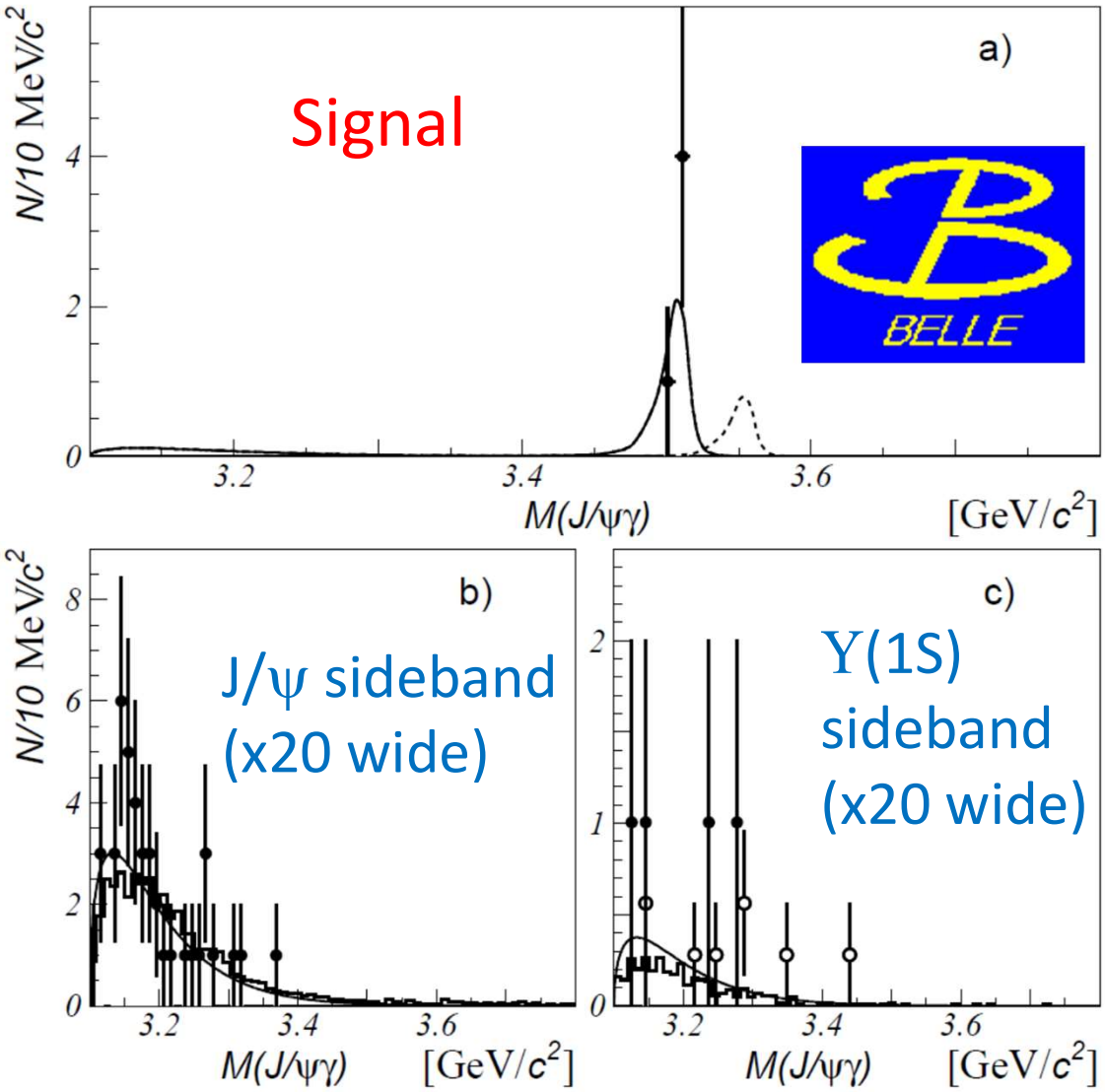
Belle activities

- We have not used the full potential of Belle data yet
  - Belle is still actively producing papers
- Results within ~1 year include
  - Observation of radiative decay, $\Upsilon(1S) \to \chi_{c1}\gamma$ [PRL 124.122001]
  - Search for $\eta_{c2}(1D)$ [JHEP05.634]
  - Vector charmonium-like states in e^+e^- → $D_s^+ D_{S1}(2536)^-$, $D_s^+ D_{S2}(2573)^-$ [PRD100.111103, PRD101.091101]
  - (Search for DDK bound state [arXiv:2008.13341])
- More results are still coming!

$\Upsilon(1S) \to \chi_{c1}\gamma$ in Belle

[PRL 124.122001]

from $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$



- $B = \left(4.7^{+2.4+0.4}_{-1.8-0.5}\right) \times 10^{-5}$
- Higher than theoretical prediction
- Radiative decays to $\chi_{c0,2}, \eta_c(1,2S)$ are not observed

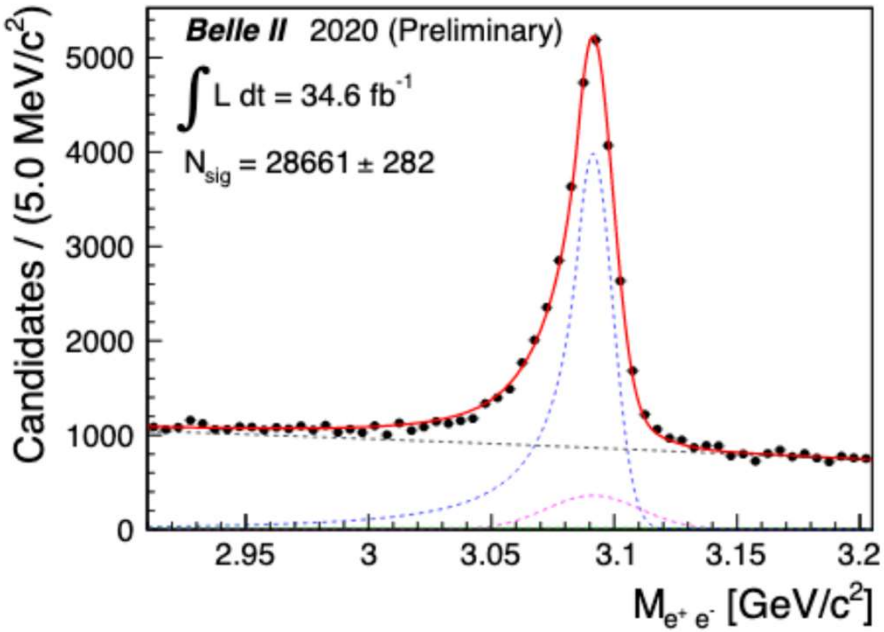
Remaining questions

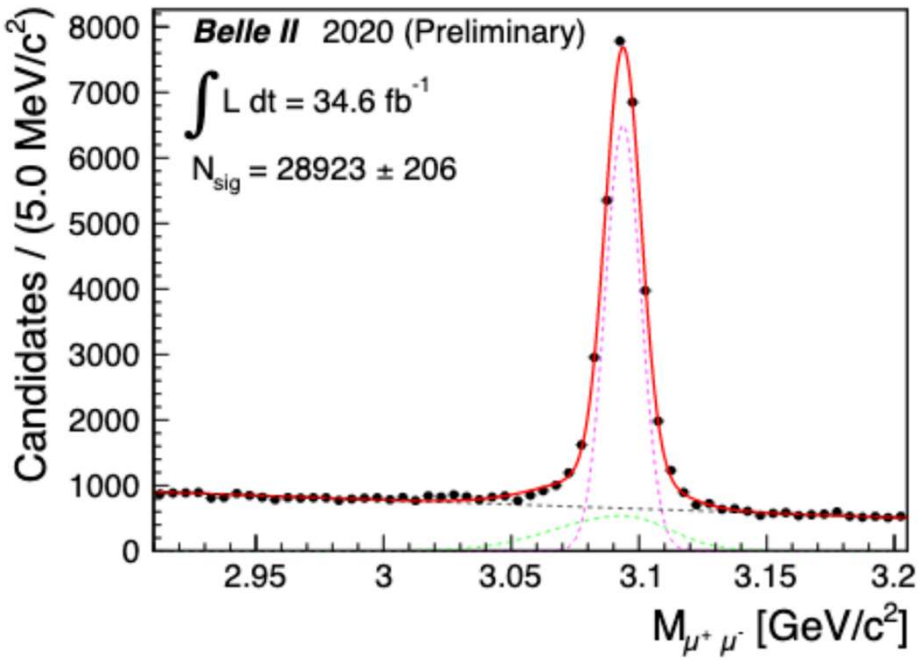
- Many XYZ states were found, but
  - Which ones are exotic?
  - If exotic, what kind?
    Molecule? Tetraquark? Hybrid? Something else?
  - Goal: classification of these states
- J^P is not determined yet for some XZ states
  - Most important measurement in the coming days
- More states?
  - Several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

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$\pi^+\pi^-$

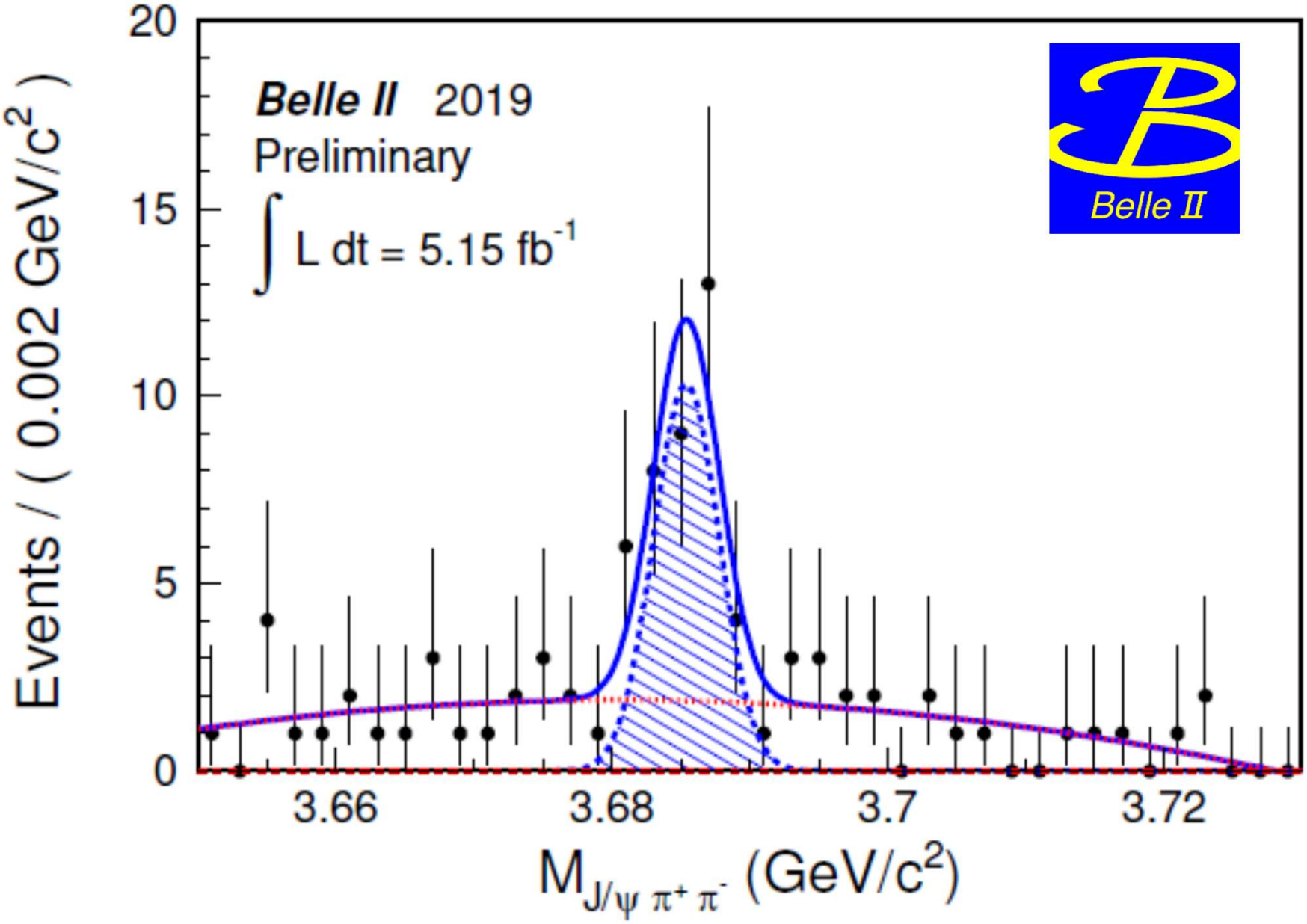
J/ψ in B decay





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

$B \rightarrow \psi(2S)K$, $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$

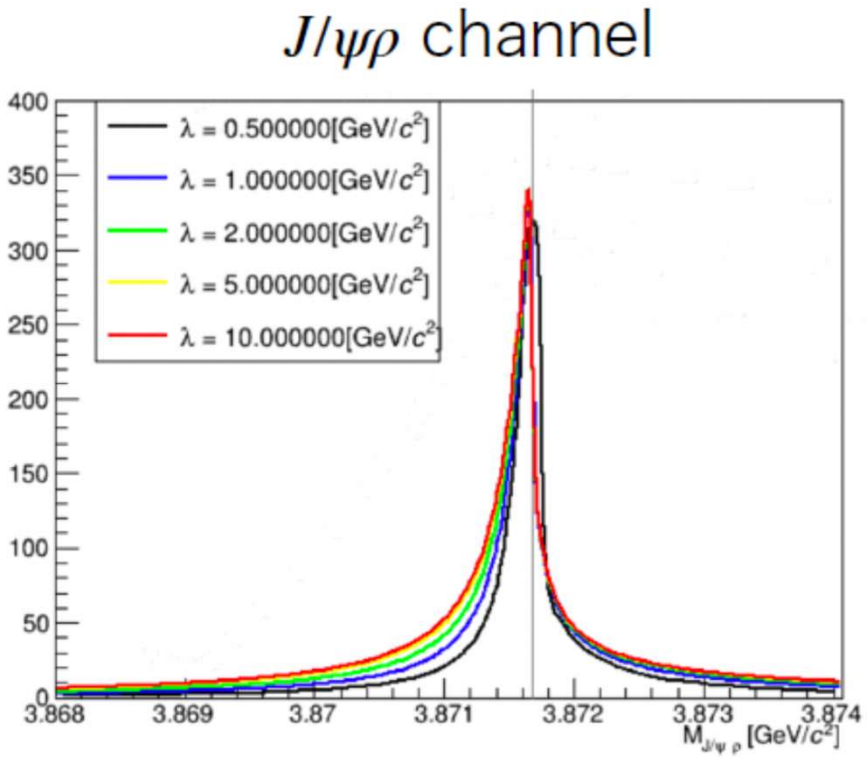


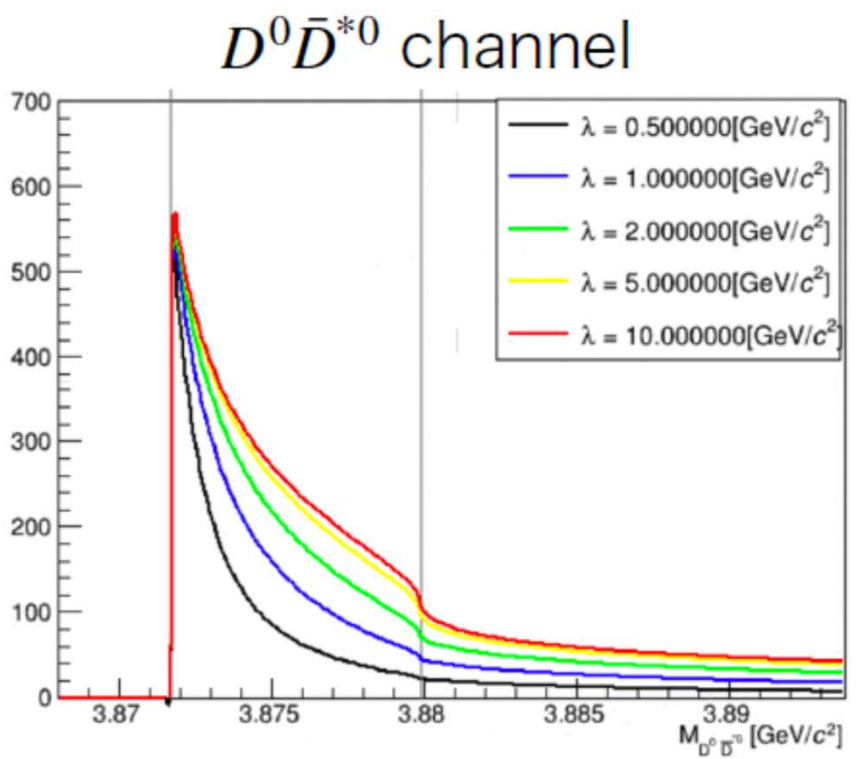
X(3872)

- Rediscovery of X(3872) in B → X(3872)K → J/ψππK will be achieved within late 2020 or early 2021
  - Belle discovery at 140 fb^{-1}
- 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, arXiv:2005.13419] ← scaling behavior of Flatte distribution.
  - Simultaneous fit with X(3872) → $D^0\overline{D}^{*0}$

X(3872)

- Rediscovery of X(3872) in B → X(3872)K → J/ψππK needs > 250 fb^{-1},
  - Will be achieved within late 2020 or early 2021
- Measurement of absolute BR





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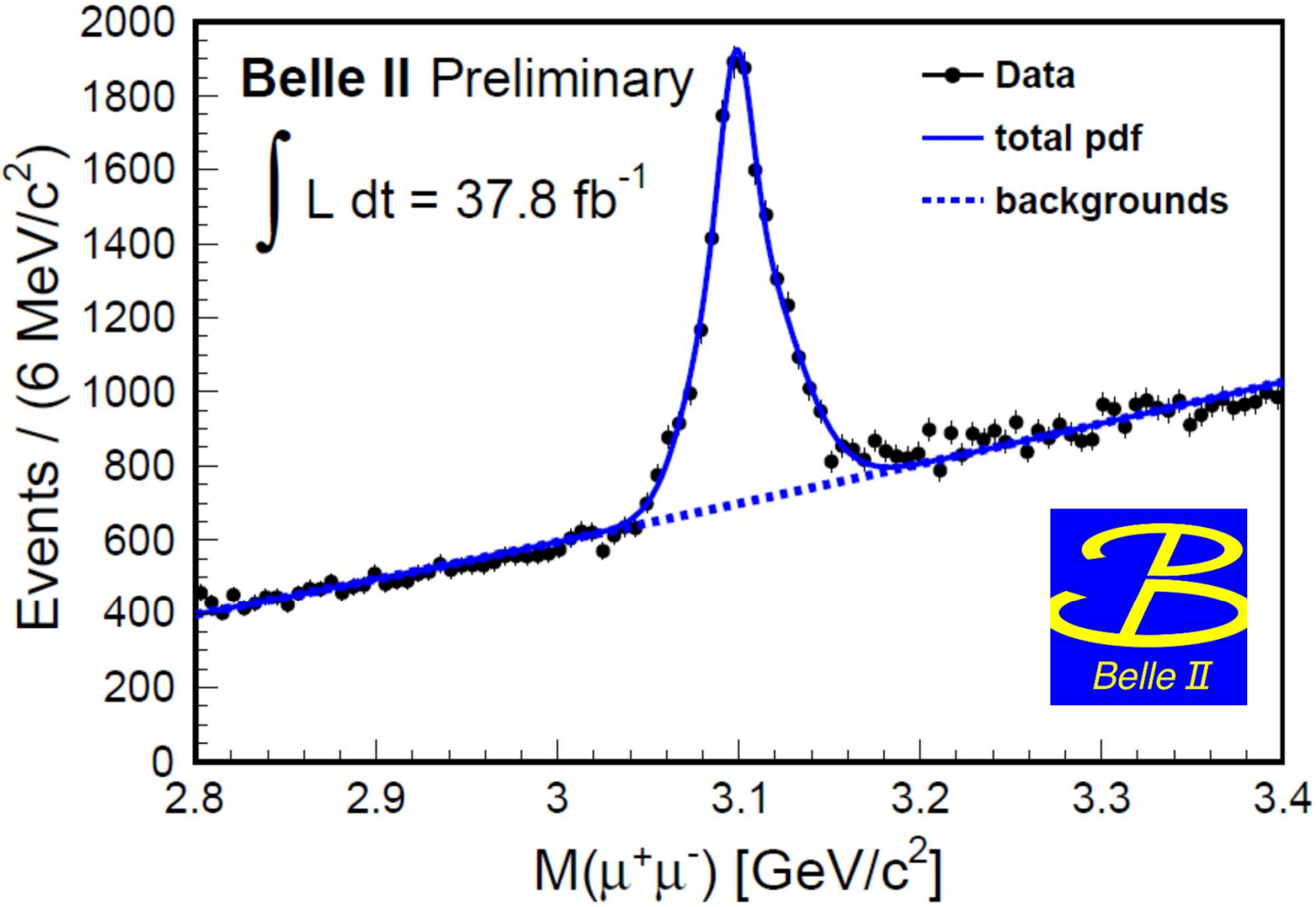
Charmonia by ISR

- 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

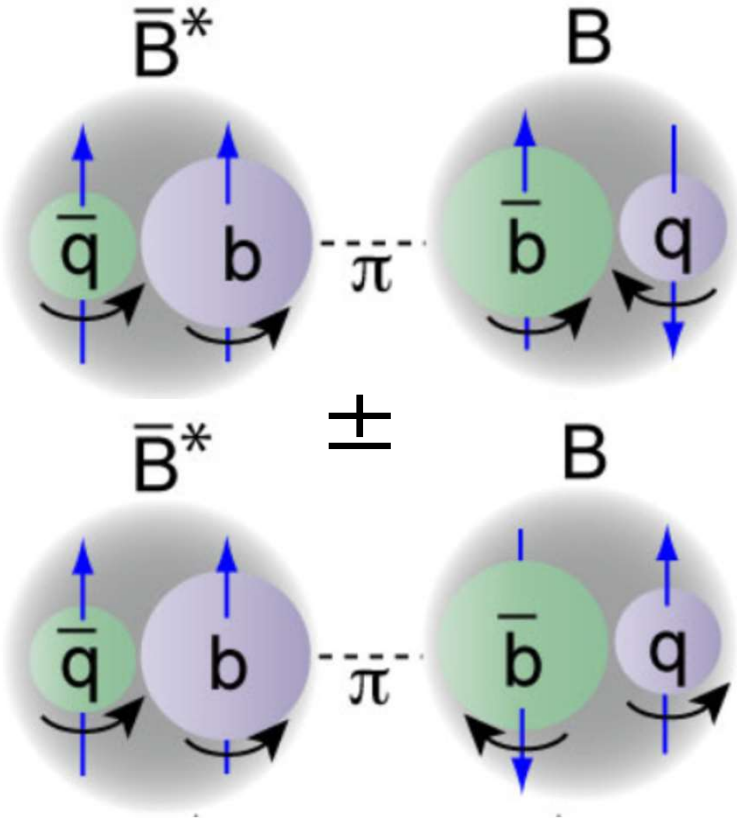
- New things @Belle II
  - Measurement at $\Upsilon(6S)$ becomes possible (~100 fb^{-1})
    → Expect more Z_b states
  - Radiative transitions between bottomonia
- Most missing conventional bottomonia below the open bottom threshold should be found; e.g.,
  - $\chi_b(3P)$ triplet
  - $\Upsilon(2D_3)$ 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.
  - Help to identify the nature of these states
- Expected new states?
  - Yes, there are some: especially for partner states of Z_b (see next slide)
- Possibility for unexpected?
  - Yes, it's always there. Who knows?

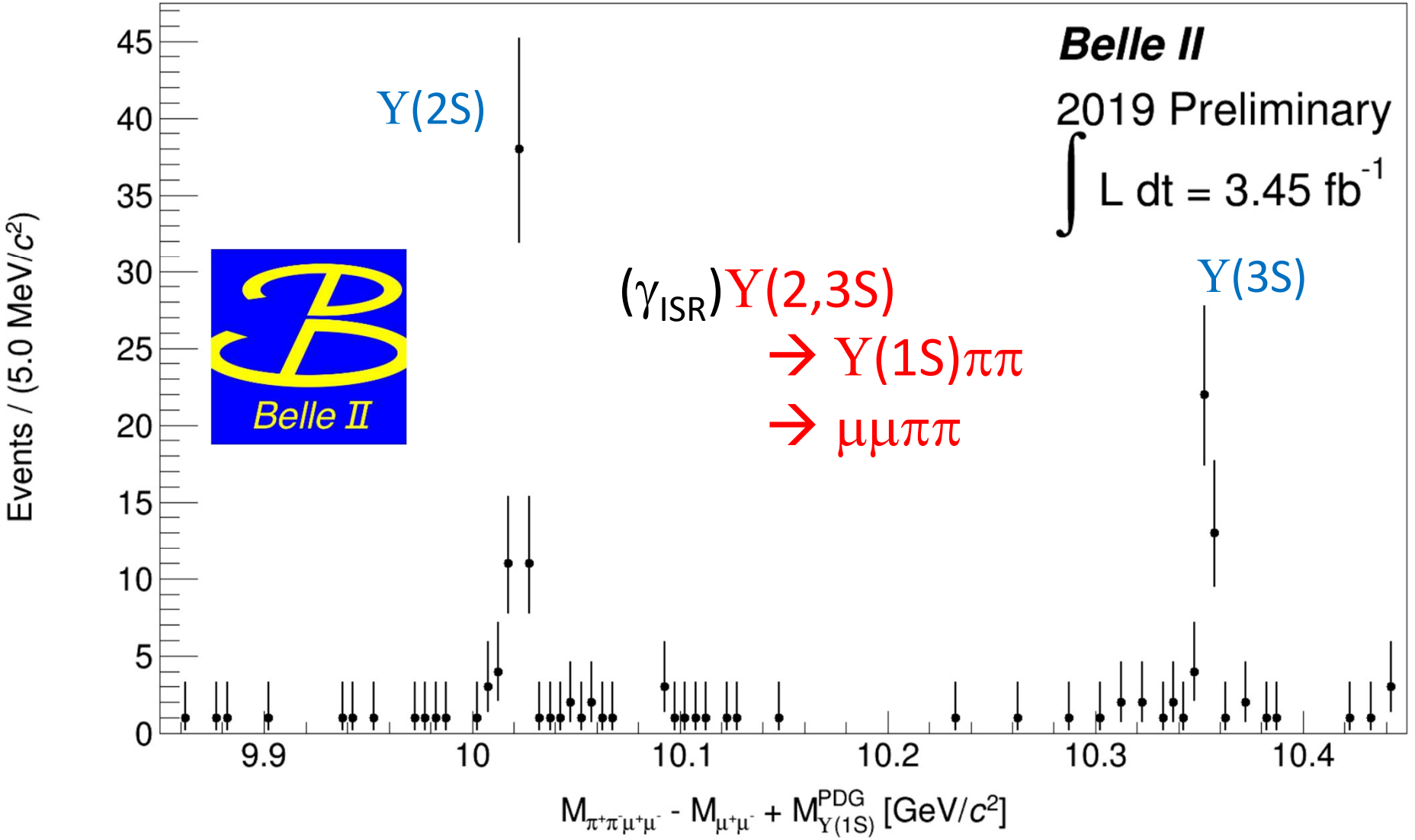
W_b

- $Z_b(10610)$ & $Z_b(10650)$ are molecular states?
  - Explains the fact they can decay both spin triplet states and singlet states
- If so, there should be Heavy-quark-spin-symmetry partner states nearby: W_b
  - Simplest one: $J^P=2^+$ state (B^*B^*)



- Can be searched in radiative transitions & $\pi\pi$ decay from $\Upsilon(5S)$ and $\Upsilon(6S)$

Belle II progress: Υ(2,3S) → Υ(1S)ππ



Λ_c and other baryons

Baryons

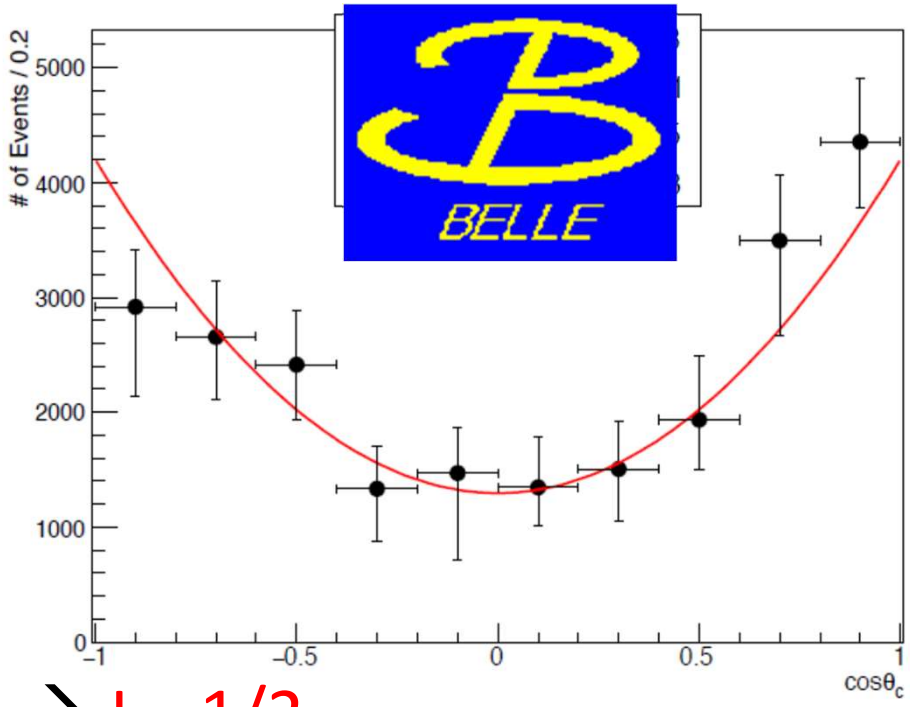
- Much more complicated than quarkonia
  - 3 particles even in QM
- Ground states can be well understood by QM, but exotic candidates even in 1st excited states
  - Notorious examples: $\Lambda(1405)$, N(1440)
- Higher excited states are complete mess
  - Missing resonances
  - Multiple candidates in QM for known states
  - What are ordinary? What are exotic?
- J^P is not determined for most c,b-baryons
- We need more data and analysis effort

Belle activities

- Belle is also active with baryons
- Results within ~1 year include
  - Spin-parity determination of $\Xi_c(2970)$ [arXiv:2007.14700]
  - Radiative decays of $\Xi_c(2790)$ and $\Xi_c(2815)$ [arXiv:2009.03951]
  - $\Lambda_c \rightarrow \Lambda\eta\pi^+$ decay BR and $\Lambda(1670)$ [arXiv:2008.11575]
  - Observation of B $\rightarrow \overline{\Lambda_c}\Xi_c^*$'s [PRD100.112010]
- More results are still coming!

Spin-parity determination of $\Xi_c(2970)$

- In the decay
  $\Xi_c(2970)$
  → $\Xi_c^*(2645)\pi_1$
  → $\Xi_c\pi_1\pi_2$
- Angular correlation of the two pions
  - Consistent with $1+3\cos^2\theta$ → J = 1/2

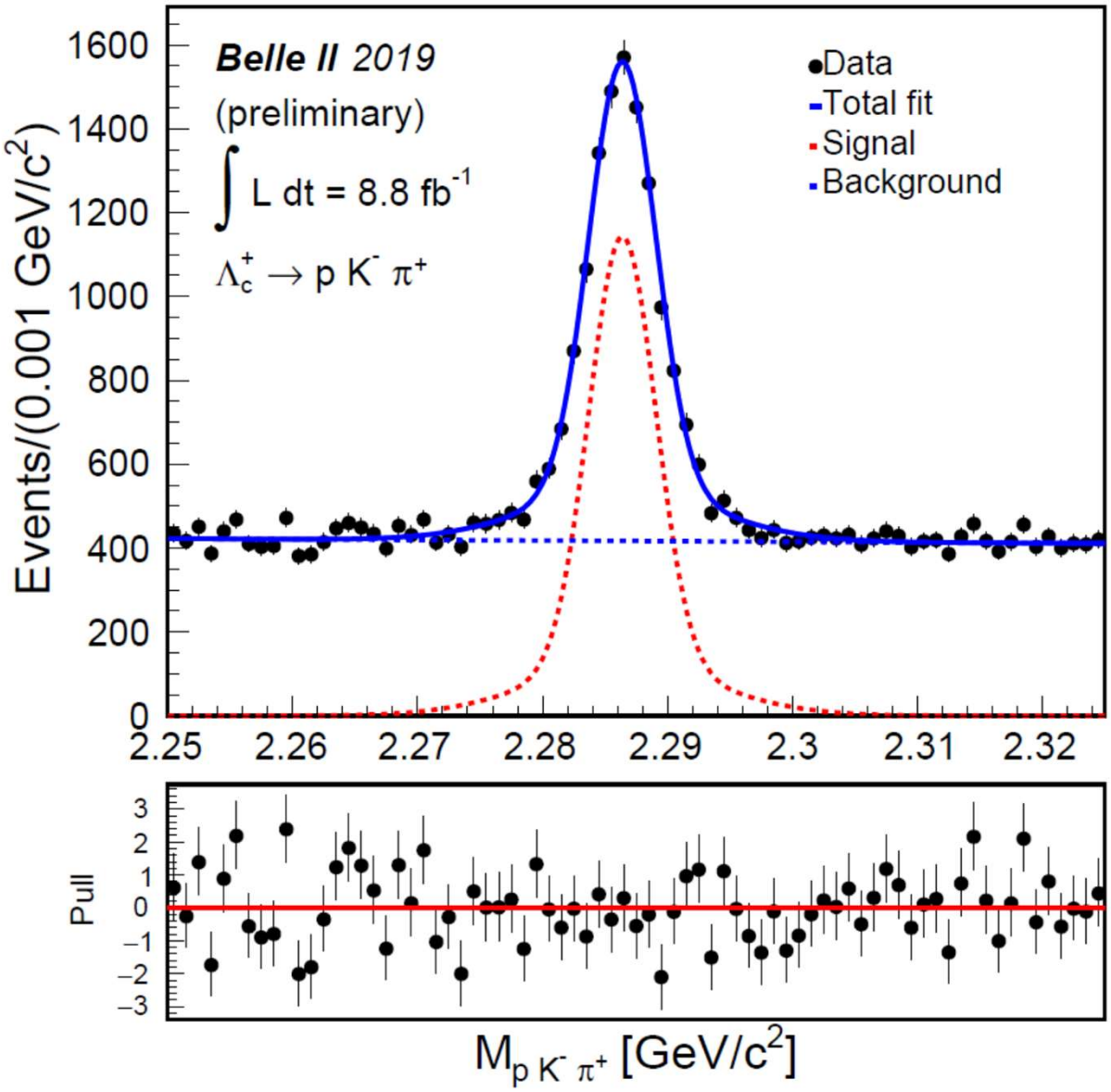


- Parity: +
  - Decay branching fraction + heavy quark symmetry
- $J^P=1/2^+$ is the same as Roper resonance, N(1440)
  - Same E_x (500 MeV). Hint for mysterious Roper resonance

Belle II possibilities

- J^P measurements for Λ_c^*, Ξ_c^*, Ω_c^* …
  → We can determine most presently known states
  → Comprehensive list of charmed baryons
- Search for Ξ^* and Ω^* resonances in the decay of Λ_c, Ξ_c and Ω_c
- Weak decay asymmetry parameters
  → Spin structure, identify exotics, esp. $\Lambda(1405)$
- Exotic search: pentaquarks, dibaryons, charmed hypernuclei, …
  e.g., ND, $N\bar{D}$(or Θ_c), H, H_c, $\Lambda_c N$, …
- And more

Belle II progress: $\Lambda_c \to pK^-\pi^+$ rediscovery



- Mass: consistent with PDG value
- Early Belle II data is promising for baryons, too.

Summary

- A lot of opportunities in Belle II
  - e^+e^- machines are good for hadron spectroscopy, too
  - Belle is also still active and producing many results
- Integrated luminosity is still small, but instantaneous luminosity already surpassed Belle
- Most rediscoveries of the XYZ states are expected after having harvested more than 250 fb^{-1}, i.e. within 2020 or early 2021.
- Not only quarkonia, but also baryons are interesting
  - Spin-parity measurements for charmed baryons
  - Relatively unexplored – more opportunities.