Recent Results from Belle II

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HELMHOLTZ

Belle II

DESY.

Outline

SuperKEKB and Belle II

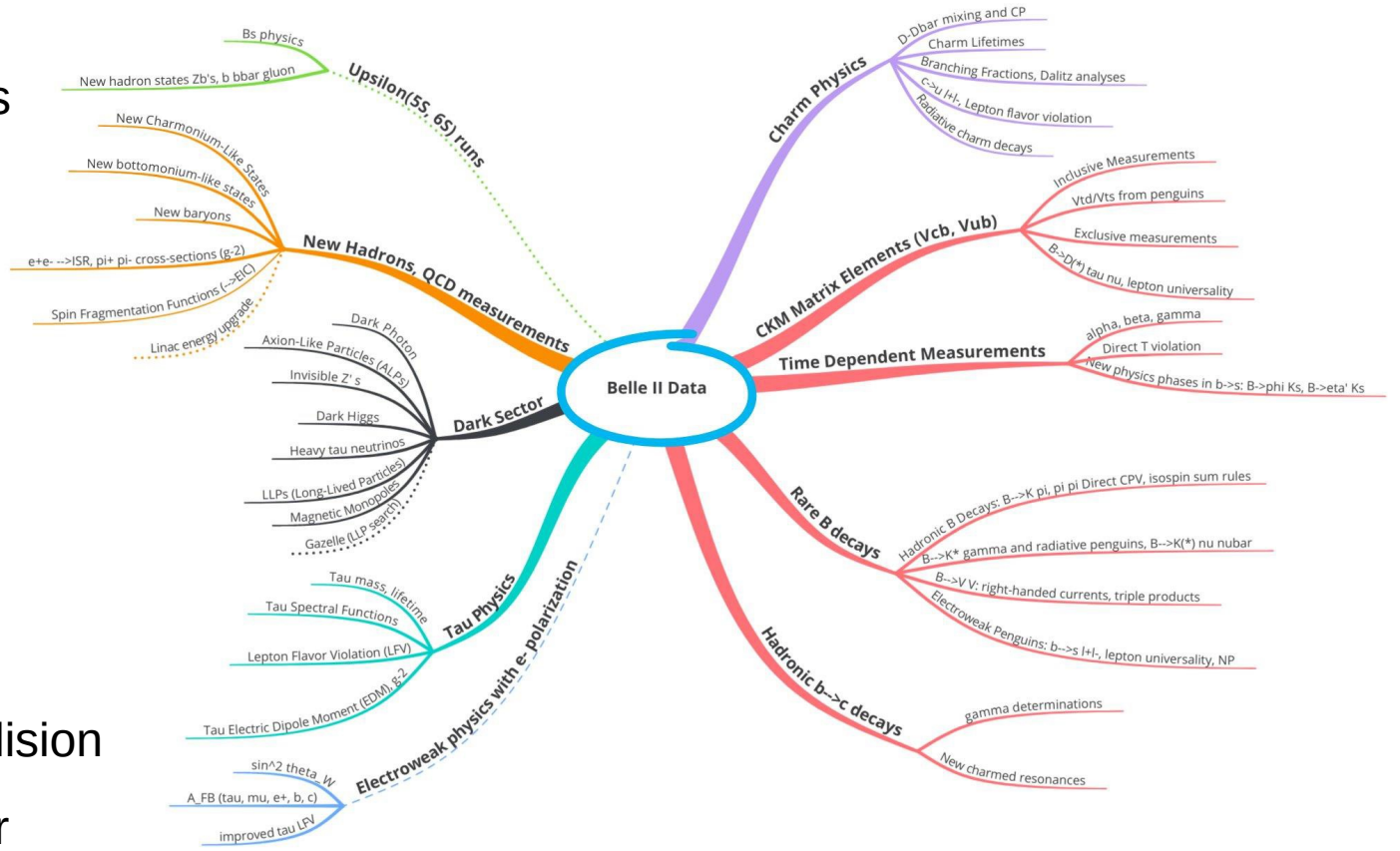
Flavour measurements

Charm baryon lifetimes

Physics at Belle II

Belle II covers a broad spectrum of physics

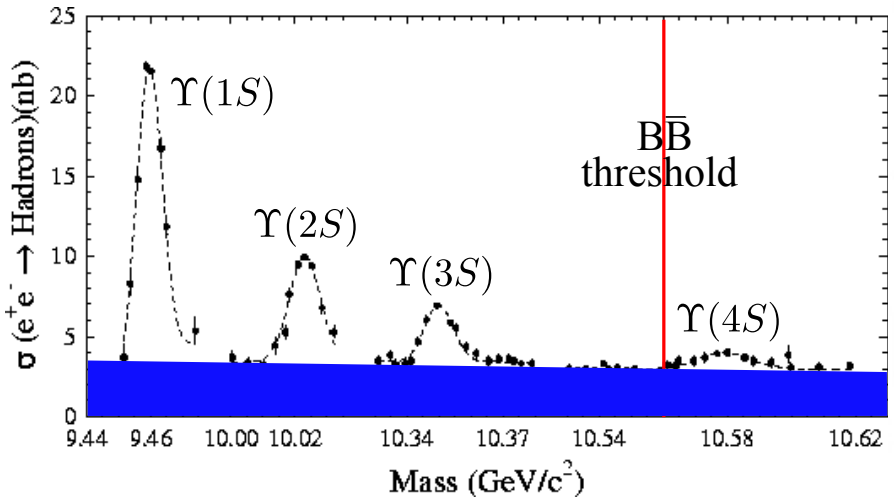
- Intensity frontier experiment: search for physics beyond SM with precise measurements
- Various analyses of B meson decays
- Tau physics
  - Branching fraction for $\tau^+\tau^-$ production similar to $b\bar{b}$ production
    → *B*-factories are also τ factories
- Low multiplicity and dark sector searches
- Clean and well known initial state from e^+e^- collision
  - Advantageous for searches with neutral or missing particles

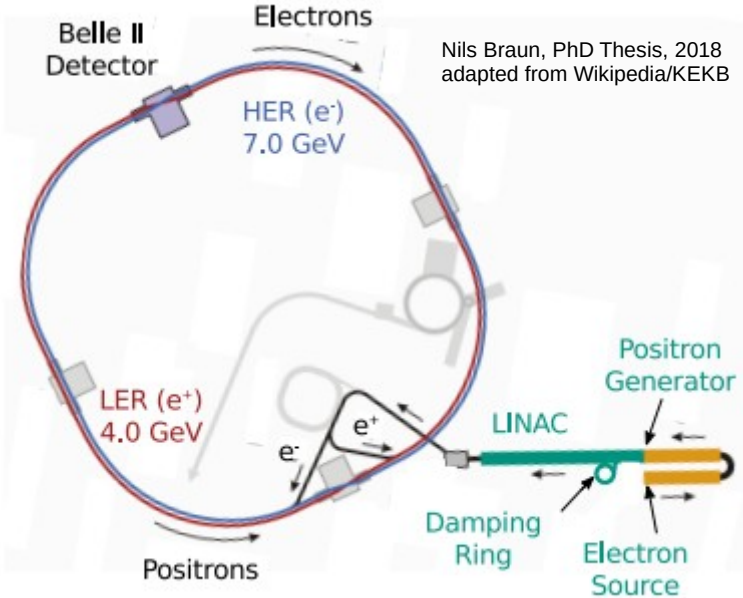


The SuperKEKB collider

SuperKEKB located at KEK in Tsukuba, Japan

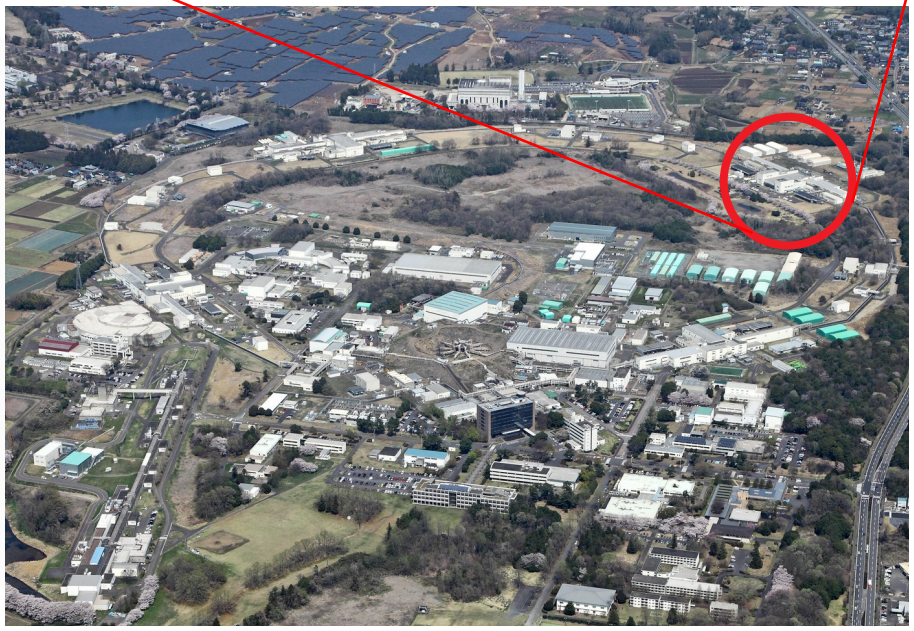
- Asymmetric e^+e^- collider with $\sqrt{s} = m_{\Upsilon(4S)}$ (10.58 GeV)
- e^- @ 7 GeV, e^+ @ 4 GeV
- **Υ(4S)** mostly decays into **two *B*-mesons → *B*-factory**
- Target instantaneous luminosity: $\mathscr{L}$ **= 6•10³⁵ cm⁻²s⁻¹**
  (current WR: 4.7•10³⁴ cm⁻²s⁻¹)
- **Goal:** collect **50 ab⁻¹**





Nils Braun, PhD Thesis, 2018
adapted from Wikipedia/KEKB

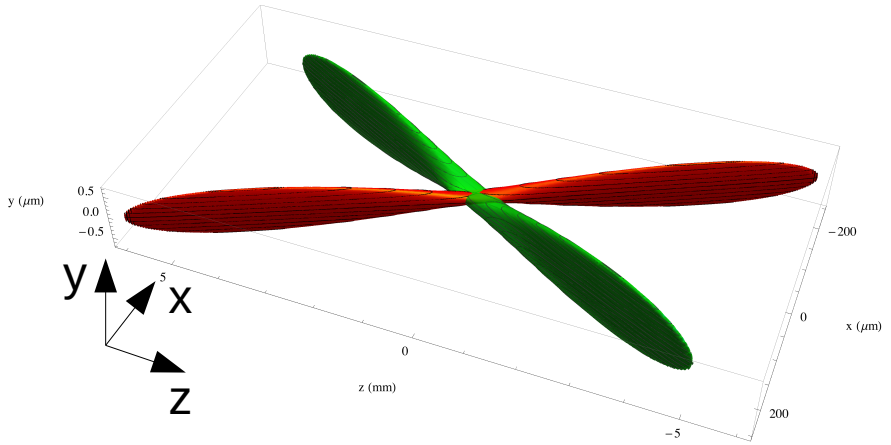
www.kek.jp

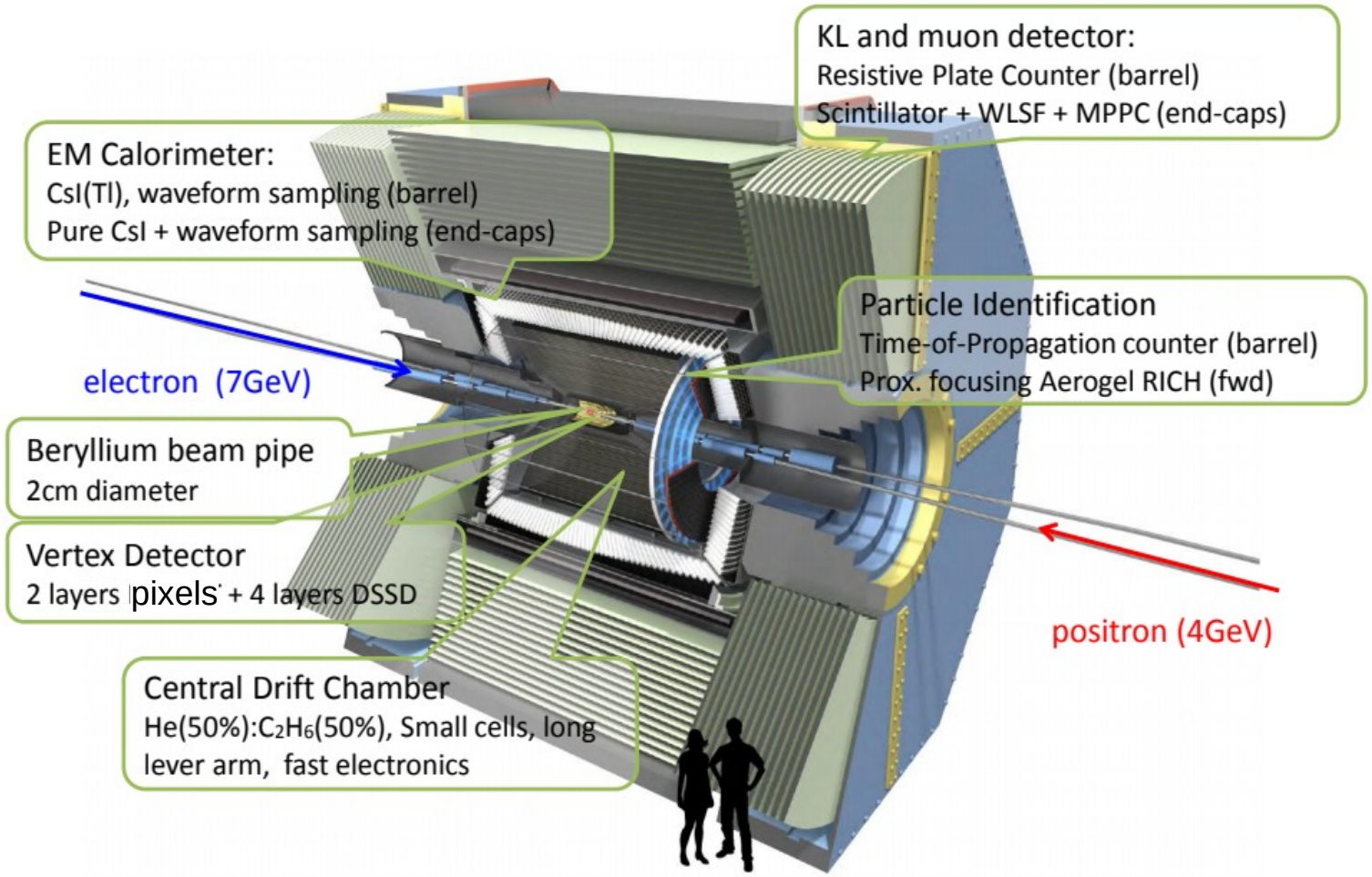


The Belle II experiment

Intensity frontier experiment

- General purpose near-4π detector
- Sub-detectors for
  - Track reconstruction and vertexing
  - Particle identification
  - Energy measurement
  - Superconducting magnet @ 1.5 T





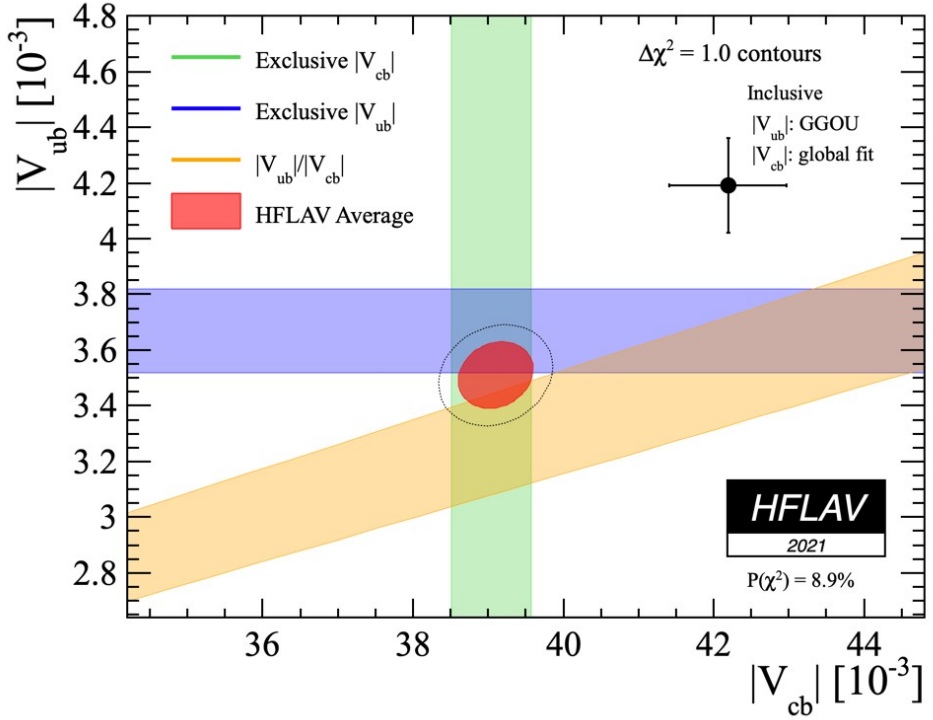
Measurements of $|V_{cb}|$ and $|V_{ub}|$ using semi-leptonic B decays

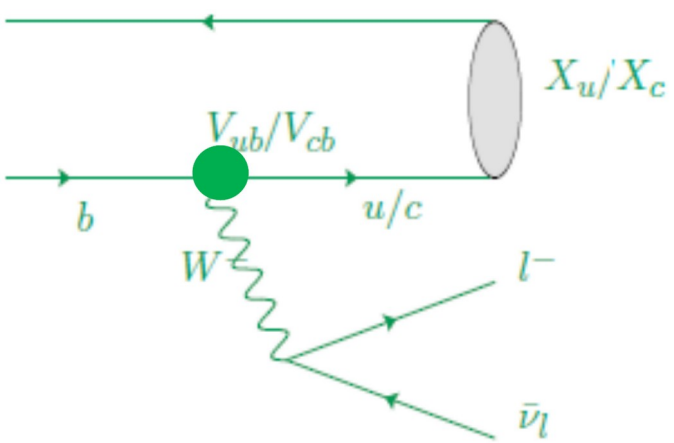
The $|V_{cb}|$-$|V_{ub}|$ puzzle

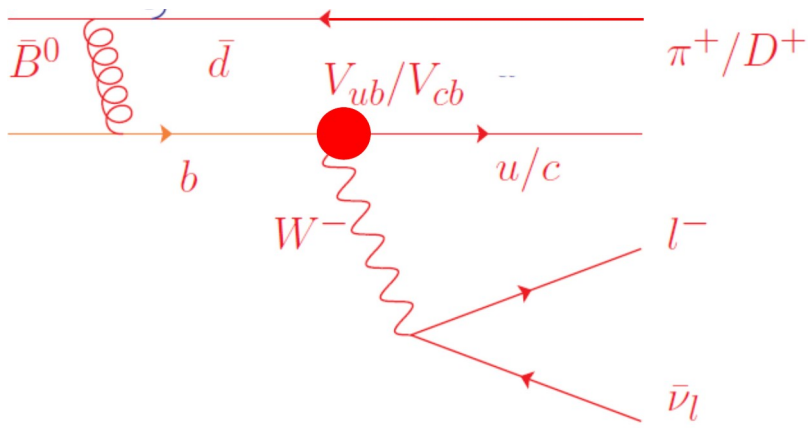
Longstanding discrepancy between exclusive and inclusive measurements

- For $|V_{cb}| \times 10^{-3}$:
  - Inclusive: 42.19 ± 0.78
  - Exclusive 39.10 ± 0.50
- For $|V_{ub}| \times 10^{-3}$:
  - Inclusive: 4.19 ± 0.12
  - Exclusive: 3.51 ± 0.12
- Constrain CKM unitarity triangle

HFLAV, arXiv:2206.07501



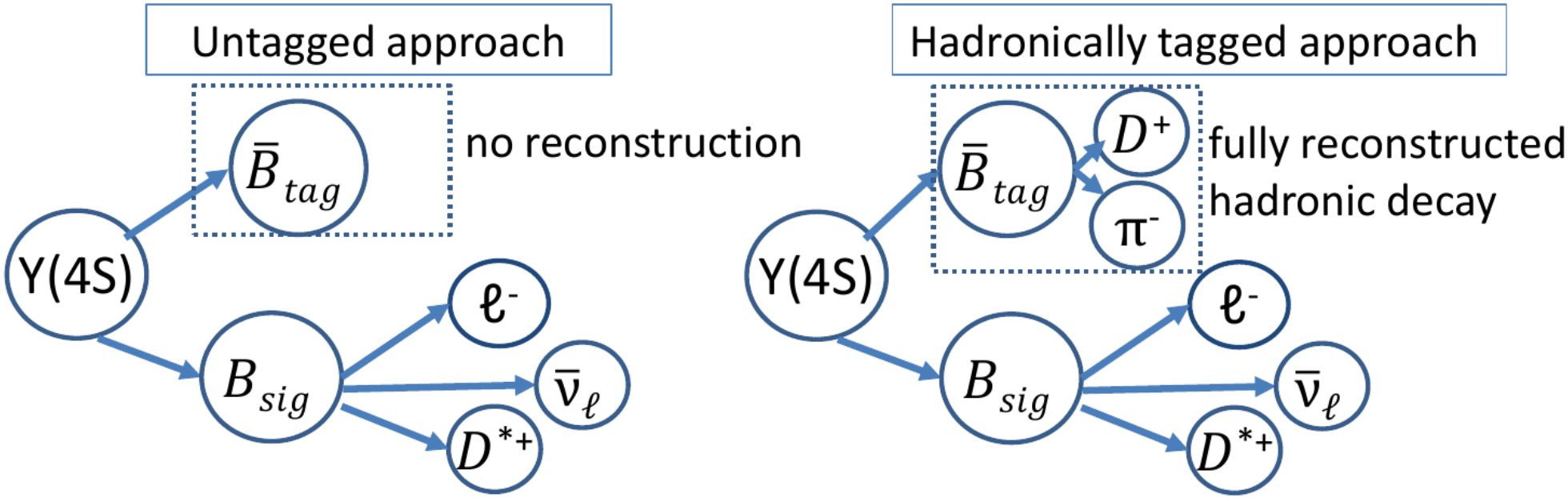




Untagged measurements of $|V_{cb}|$ and $|V_{ub}|$

No or loose reconstruction of tag B-meson in $\Upsilon(4S) \rightarrow B\bar{B}$ decays

- $|V_{cb}|$ via $B_{sig} \rightarrow D\ \ell\ \nu$ (ℓ = e, μ)
- $|V_{ub}|$ via $B^0_{sig} \rightarrow \pi\ \ell\ \nu$ (ℓ = e, μ)
- Challenge: continuum background and b → c decays for $|V_{ub}|$ measurement



Untagged measurement of $|V_{cb}|$

Analysis overview:

- **$B^0 \to D^- \ell^+ \nu_\ell$ with $D^- \to K^+ \pi^- \pi^-$ and**
  $B^+ \to \overline{D}^0 \ell^+ \nu_\ell$ with $\overline{D}^0 \to K^+ \pi^-$ (+ cc. in all cases)

- Reconstruct kinematic variable w

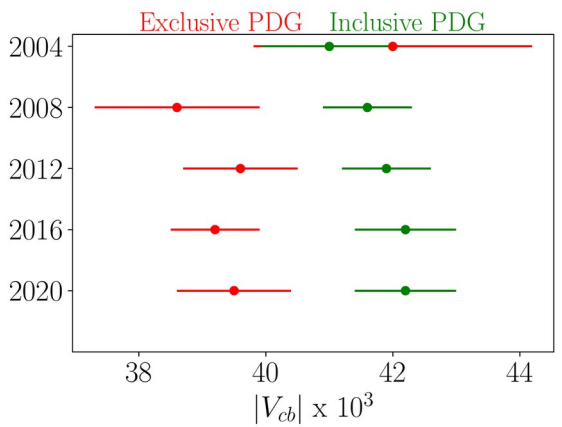
$$w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$

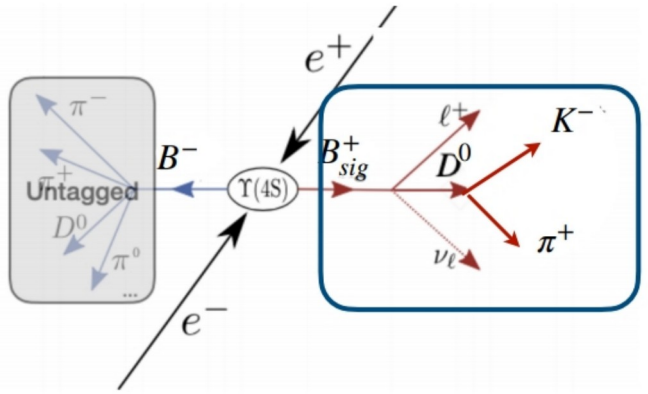
- Fit cos θ_{BY} distributions in 10 bins of w to measure differential decay rates

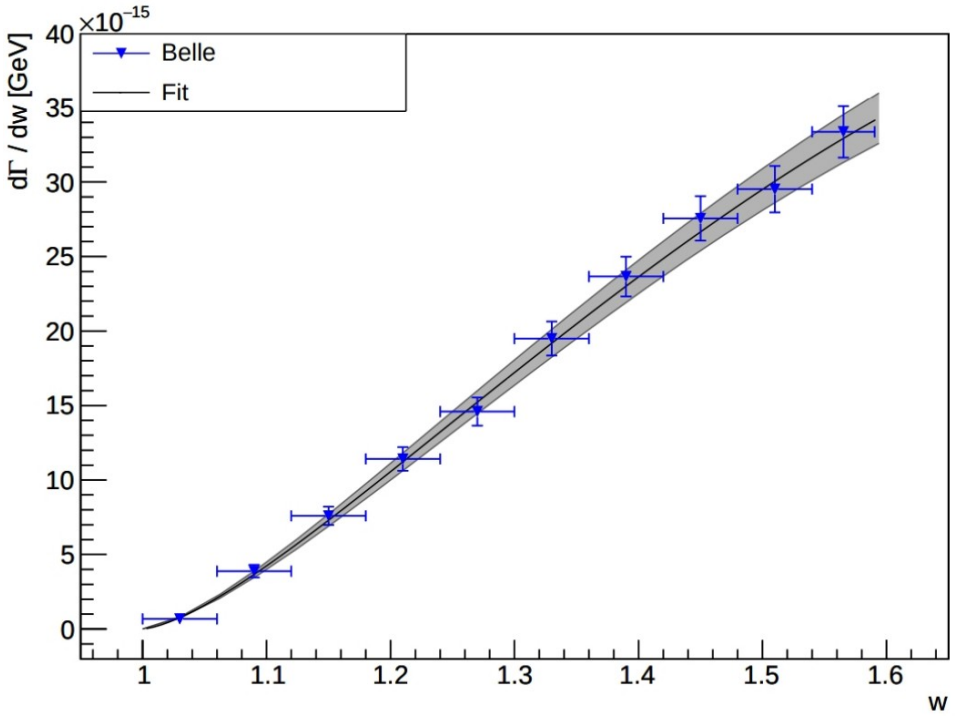
$$\cos\theta_{BY} = \frac{2E_B E_Y - m_B^2 - m_Y^2}{2|\mathbf{p}_B||\mathbf{p}_Y|}$$

- Fit form factor to partial decay rate spectrum to measure $|V_{cb}|$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}w}(B \to Dl\nu_l) = \frac{G_F^2}{48\pi^3}(m_b+m_D)^2 m_D^3 \eta_{EW} |V_{cb}|^2 (w^2-1)^{3/2} \mathcal{G}(w)^2$$

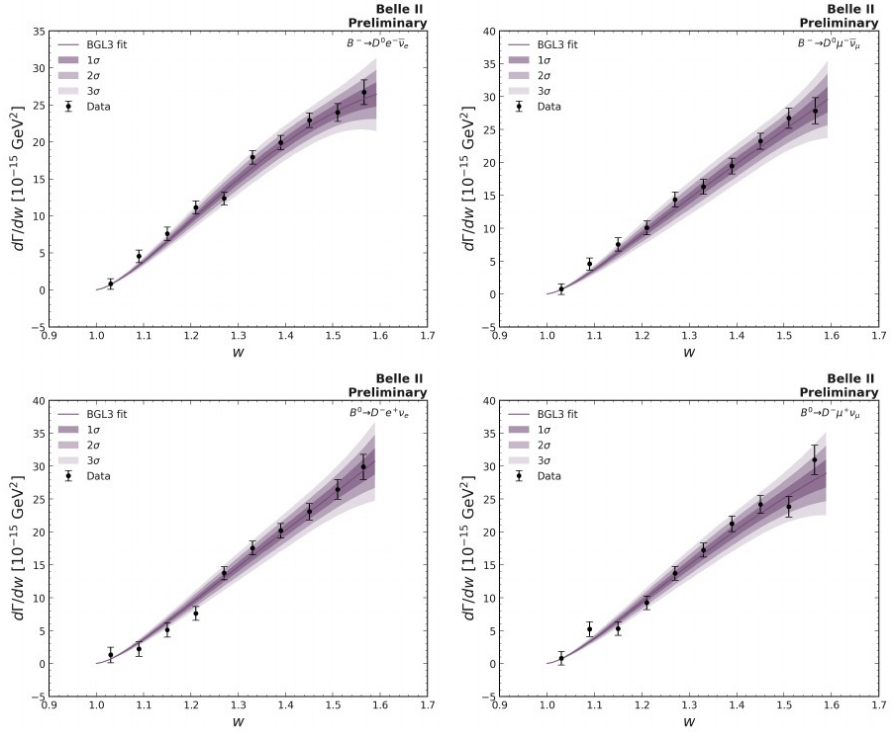


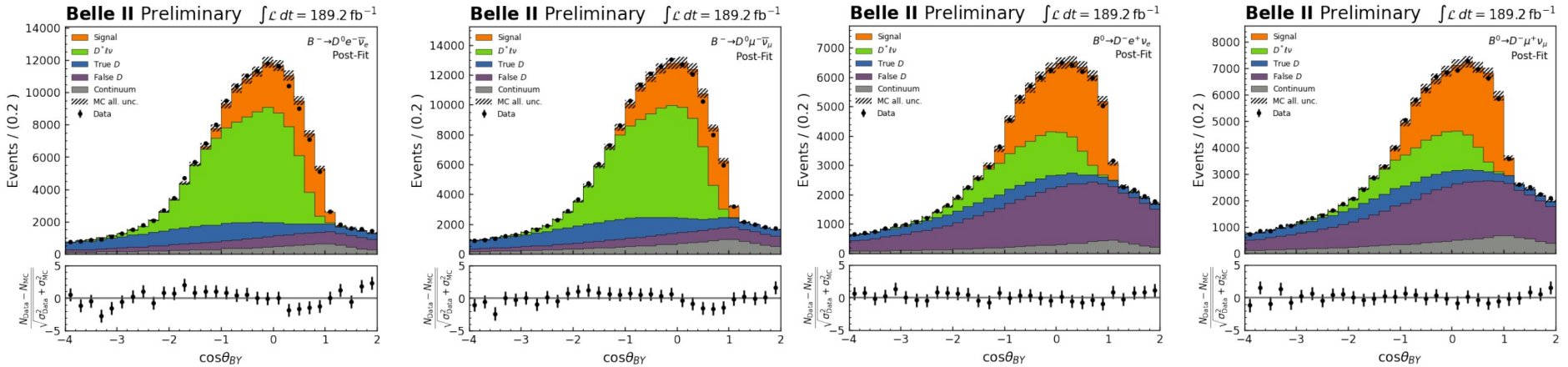




Untagged measurement of $|V_{cb}|$

- **New result: |Vcb| = (38.53 ± 1.15) x 10^{-3}** (stat. + syst. + theo.)
- **Branching ratios:**
  - $B^0 \to D^- e^+ \nu_e$: (1.97 ± 0.04 ± 0.08) %
    $B^0 \to D^- \mu^+ \nu_\mu$: (2.02 ± 0.04 ± 0.09) %
    (PDG: $B^0 \to D^- \ell^+ \nu_\ell$: (2.24 ± 0.09) %)
  - $B^+ \to \overline{D}^0 e^+ \nu_e$: (2.17 ± 0.03 ± 0.10) %
    $B^+ \to \overline{D}^0 \mu^+ \nu_\mu$: (2.19 ± 0.03 ± 0.14) %
    (PDG: $B^+ \to \overline{D}^0 \ell^+ \nu_\ell$: (2.30 ± 0.07) %)
- Main challenge and source of systematic: separation of D and D* and reduction of D* feed-down





Untagged measurement of $|V_{ub}|$

Analysis overview for $B^0 \to \pi^- \ell^+ \nu_\ell$

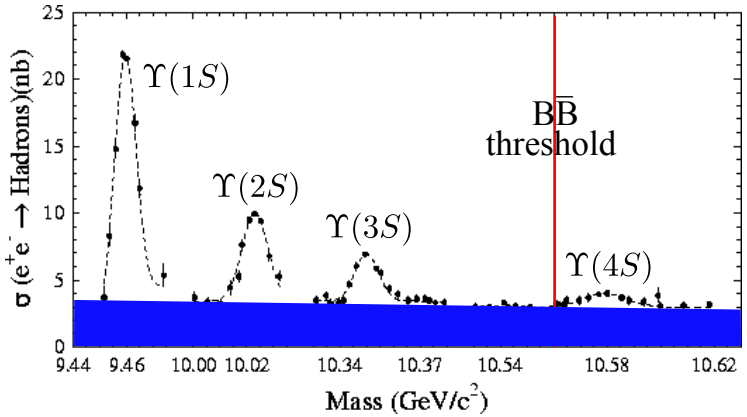
- Determine partial branching fractions in bins of momentum transfer squared (q^2) from 2D fit of ΔE and M_{bc} in each q^2 bin

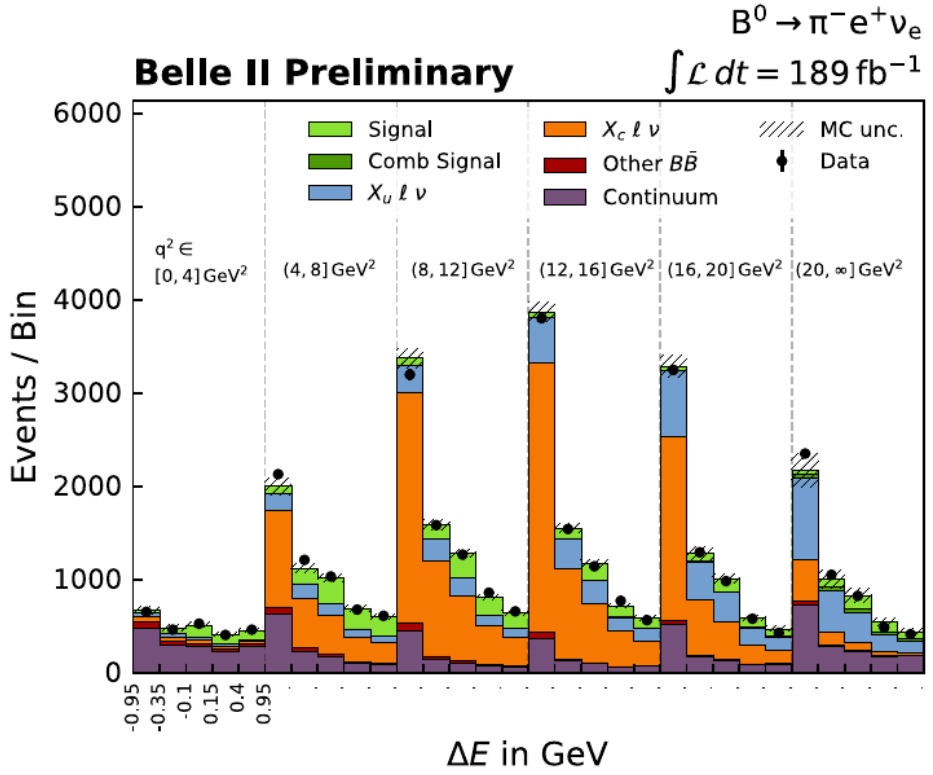
$$\Delta E = E_B^* - E_{beam}^* \qquad M_{bc} = \sqrt{E_{beam}^{*2} - |\mathbf{p}_B^*|^2}$$

- q^2 = momentum transfer squared (eff. mass of the $\ell\ \nu_\ell$ system)
- Extract $|V_{ub}|$ by fitting the measured partial branching fractions as a function of q^2, together with theory constraints

Main challenge

- Large backgrounds: Lead to large number of systematic uncertainties



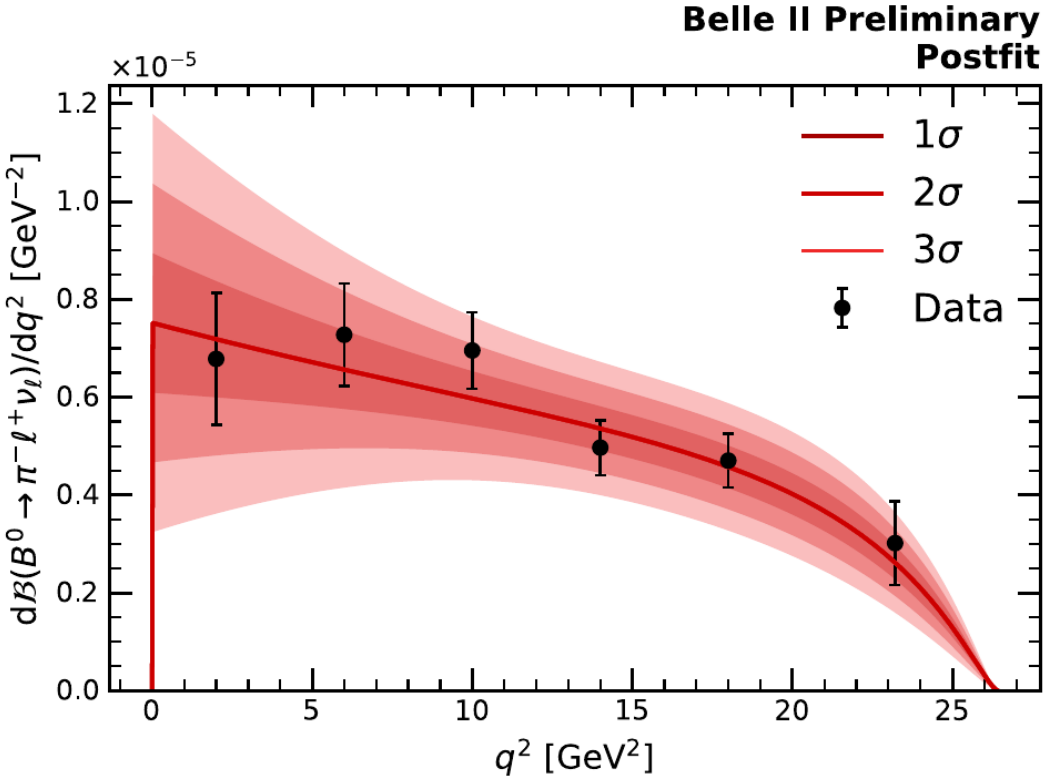


Untagged measurement of $|V_{ub}|$

- Fitted differential decay width to extract $|V_{ub}|$ and form factors

$$\frac{\mathrm{d}\Gamma(B \to \pi l \nu)}{\mathrm{d}q^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^2} |\boldsymbol{p}_\pi|^3 |f_+(q^2)|^2$$

- Using BCL parametrisation (Phys. Rev. D 79, 013008 (2009)) with lattice QCD calculation by FNAL/MILC (Phys. Rev. D 92, 014024 (2015))
- $\mathbf{|V_{ub}|}(B^0 \to \pi^- \ell^+ \nu_\ell) = \mathbf{(3.54 \pm 0.12_{stat} \pm 0.15_{syst} \pm 0.16_{theo}) \times 10^{-3}}$
- Consistent with exclusive world average
- $\mathbf{\mathscr{B}}(B^0 \to \pi^- \ell^+ \nu_\ell) = \mathbf{(1.421 \pm 0.056_{stat} \pm 0.126_{syst}) \times 10^{-4}}$
- Main systematics: description of continuum using off resonance data



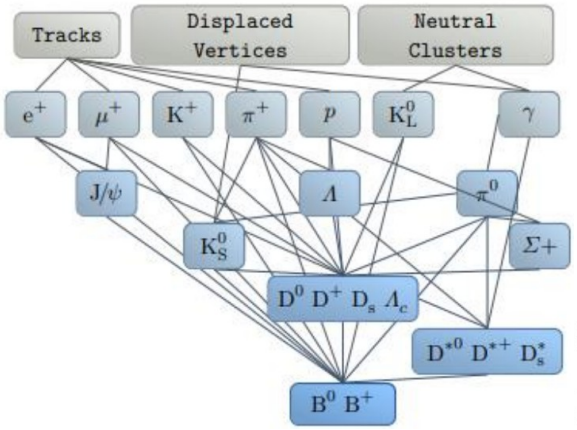
Tagged measurement of $|V_{ub}|$

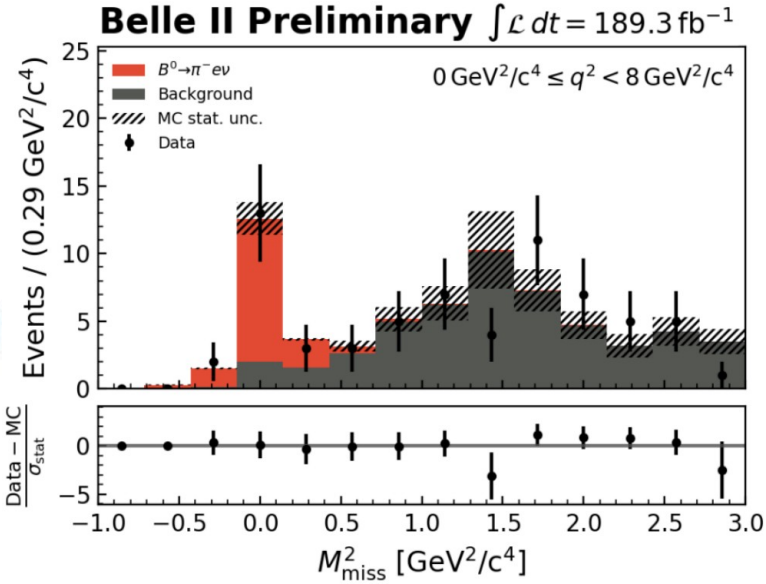
Differential decay width of $B^{0/+} \to \pi^{-/0}\, e^+\, \nu_e$

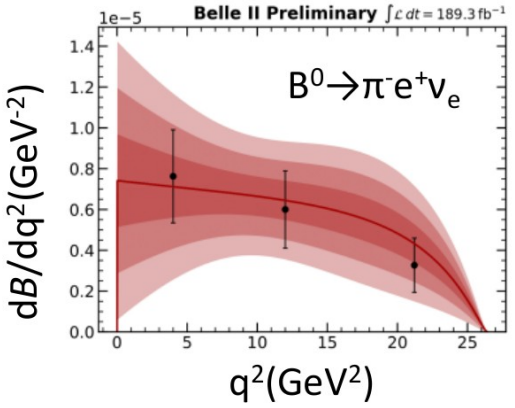
- Using the new and efficient Belle II tagging algorithm: **Full Event Interpretation (FEI)** (arxiv:1807.08680)
- Signal extracted by fitting missing mass squared distribution
- Fitted to extract $|V_{ub}|$ and form factors

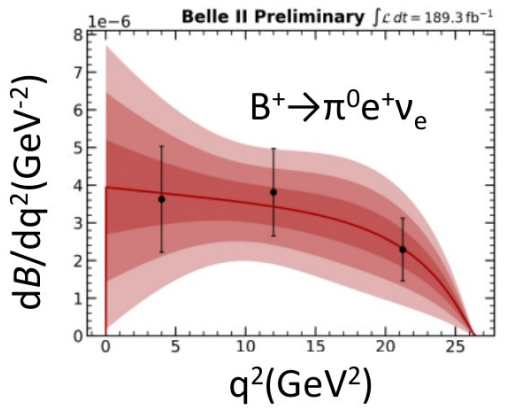
$$\frac{\mathrm{d}\Gamma(B \to \pi l \nu)}{\mathrm{d}q^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^2} |\boldsymbol{p}_\pi|^3 |f_+(q^2)|^2$$

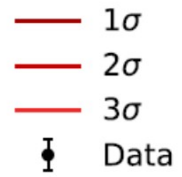
- Using BCL parametrisation (Phys. Rev. D 79, 013008 (2009)) with lattice QCD calculation by FNAL/MILC (Phys. Rev. D 92, 014024 (2015))
- $|V_{ub}|(B^{0/+} \to \pi^{-/0}\, e^+\, \nu_e)$ = **(3.88 ± 0.45) x 10^{-3}** (stat. + syst. + theo.) (arxiv:2206.08102)
- Consistent with exclusive world average











Lepton flavour universality test using semi-leptonic B decays

Lepton flavor universality tests

Several measurements challenge lepton flavour universality showing tension with the SM

- In tree-level decays:

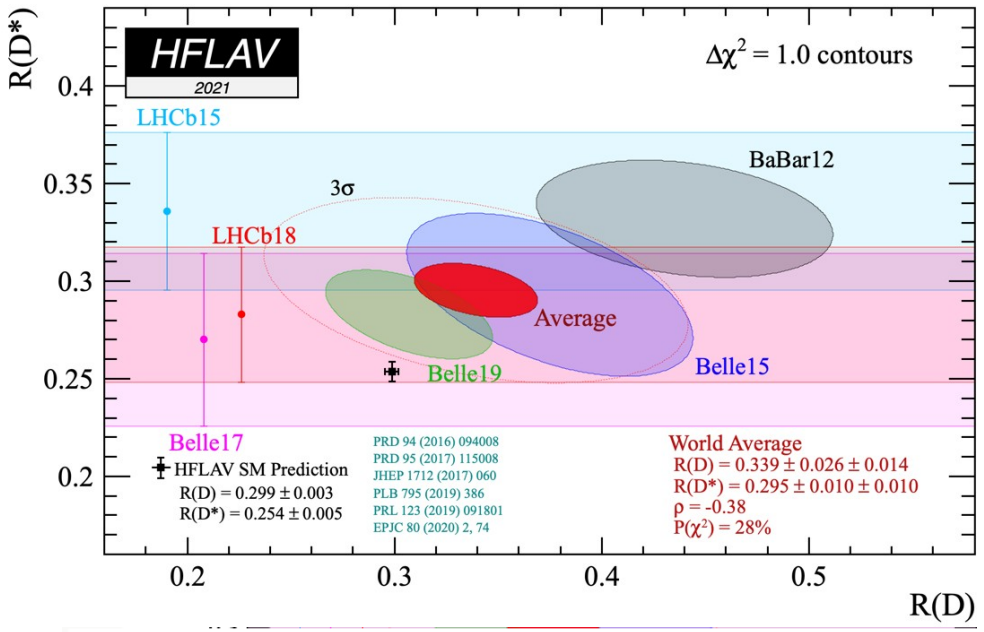
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}l\nu_l)}, \; l = e, \mu$$

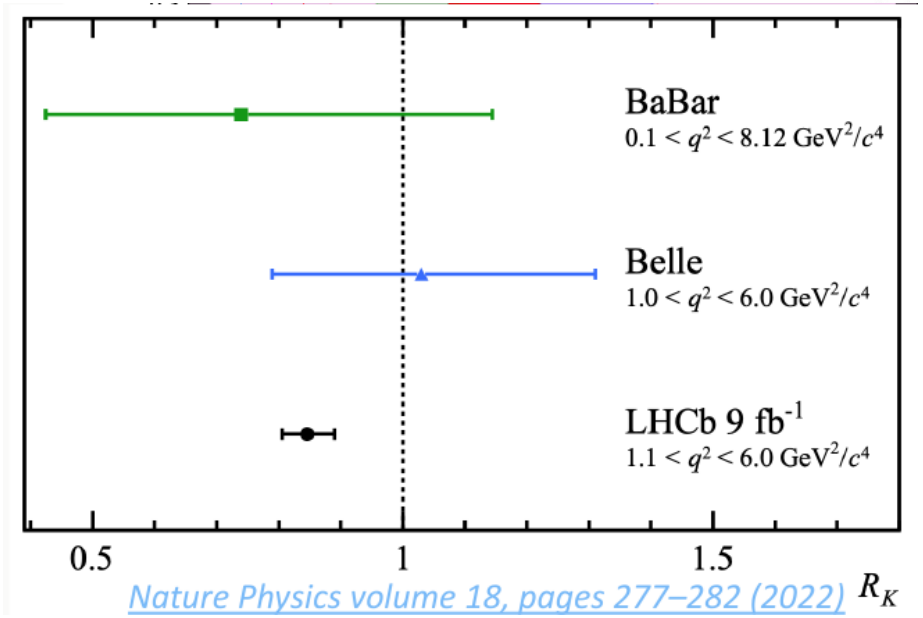
  - Multiple neutrinos on $B \to D^{(*)}\ \tau\ \nu_\tau$ decays → difficult to analyse

- $$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}$$

- And others

- All “anomalies” in direct (not secondary) B decays





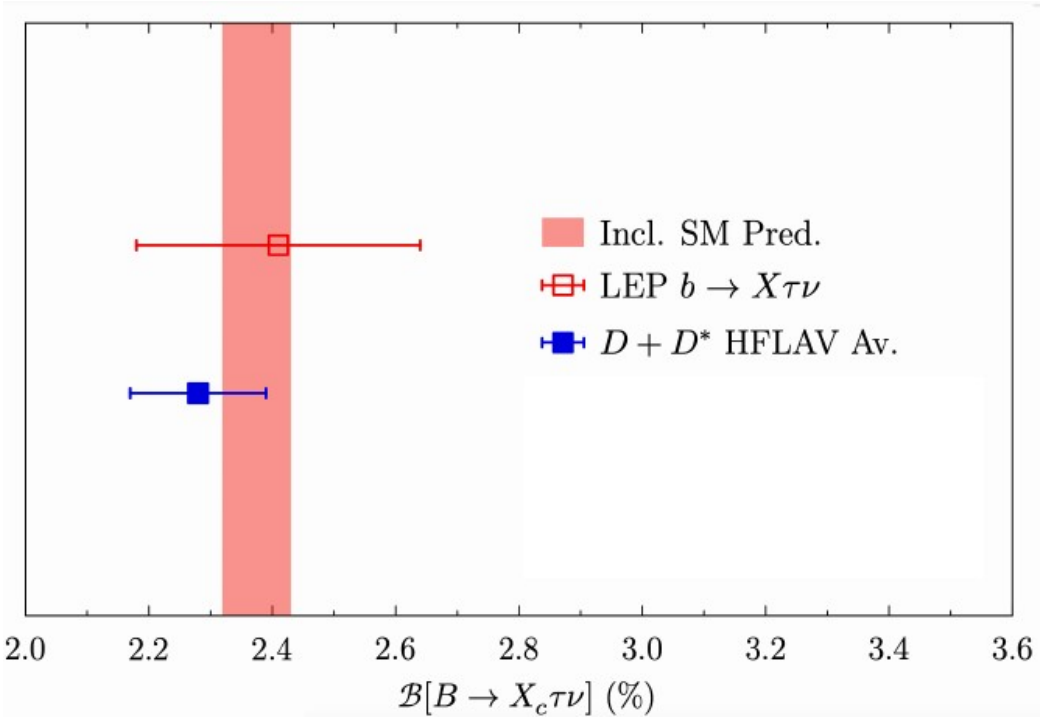
Nature Physics volume 18, pages 277–282 (2022)

Analysis strategy

Complementary tests of LFU via inclusive B decays:

- $R(X_{\tau/l}) = \dfrac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to Xl\nu_l)}$
- One of the unique and high profile goals of Belle II
- Last measurements at LEP (2001)
- **Challenging** due to larger background from **less constrained X system**
- Critically relying on precise modeling of B → X ℓ ν, X → … processes
- Probe inclusive B → X ℓ ν modeling in data driven way
- Test LFU for light leptons as a first step for the R(X) analysis

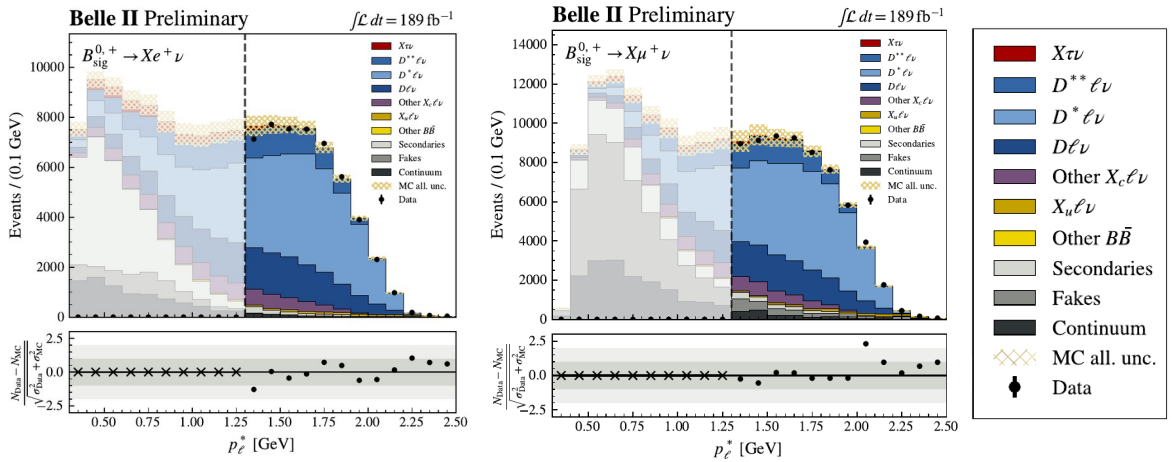
$$R(X_{e/\mu}) = \frac{\mathcal{B}(B \to Xe\nu_e)}{\mathcal{B}(B \to X\mu\nu_\mu)}$$

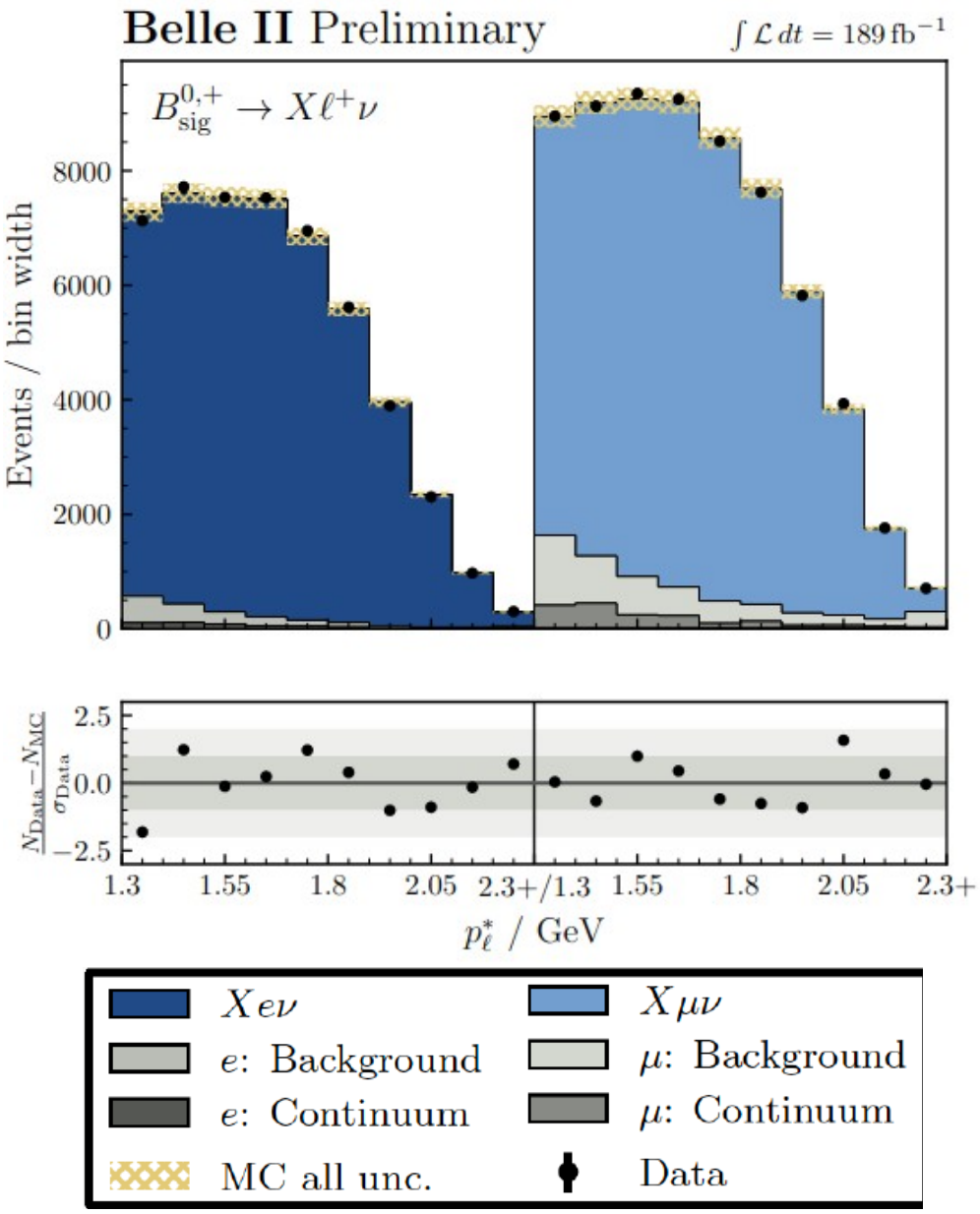


- $R(X_{c,\tau/\ell})_{SM} = 0.223 \pm 0.004$
  Phys. Rev. D 92, 054018 (2015)
- $R(X_{e/\mu})_{SM} = 1.006 \pm 0.001$
  K. Vos, M. Rahimi, in progress
  Published exclusive predictions:
  Eur. Phys. J. C 81, 984 (2021), arXiv:2206.11281,
  arxiv:2207.03432

Analysis strategy

- High momentum leptons with $p^*_\ell > 1.3$ GeV
- Signal extraction in binned log-likelihood fit in p^*_ℓ, backgrounds are constrained in charge sideband
- $$R(X_{e/\mu})_{p^*_l > 1.3GeV} = \frac{\mathcal{B}(B \to X e \nu_e)}{\mathcal{B}(B \to X \mu \nu_\mu)} = 1.033 \pm 0.010^{\text{stat.}} \pm 0.020^{\text{syst.}}$$
- Main systematics: lepton ID with 1.8 %
- Most precise LFU based test in semi-leptonic B decays to date!
- Compatible with SM with value of 1 + O(10^{-3}) within 1.5 σ



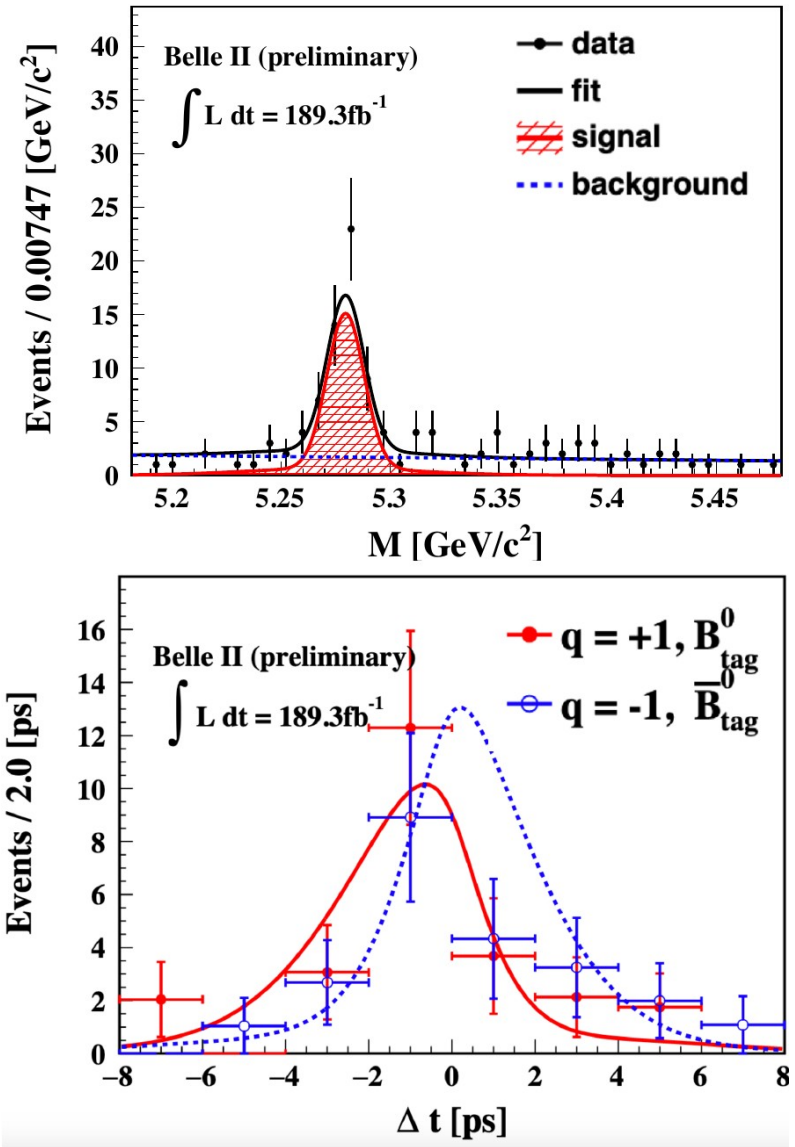


CP violation measurement

Time dependent CP violation in $B^0 \to 3\,K^0_S$ decays

- Unique sensitivity with Belle II
  - Vertexing is critical – flight length difference of O(100 µm)
- Signal extraction fit with 3 variables:
  - M_{bc}, invariant mass M, CS classifier
- $X^0_c\, K_S$ is rejected
- Main background comes from random combinations of tracks from $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ events
  - Suppressed with multivariate method
- Analysis validated with $B^+ \to K^+\, K^0_S\, K^0_S$
- Result:

$$S_{CP} = -1.86^{+0.91}_{-0.46}\,(\text{stat.}) \pm 0.09\,(\text{syst.})$$
$$A_{CP} = -0.22^{+0.30}_{-0.27}\,(\text{stat.}) \pm 0.04\,(\text{syst.})$$

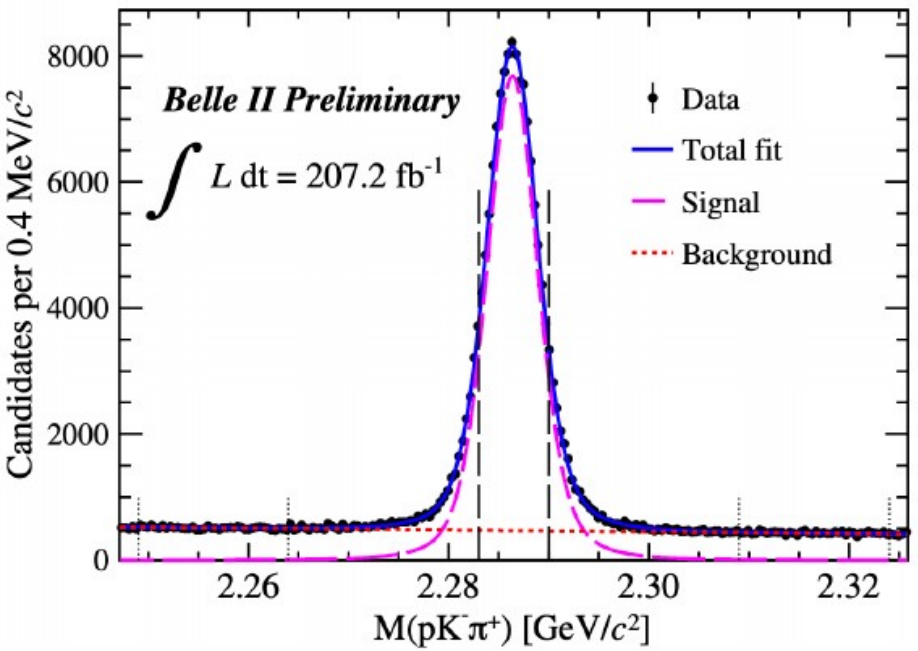


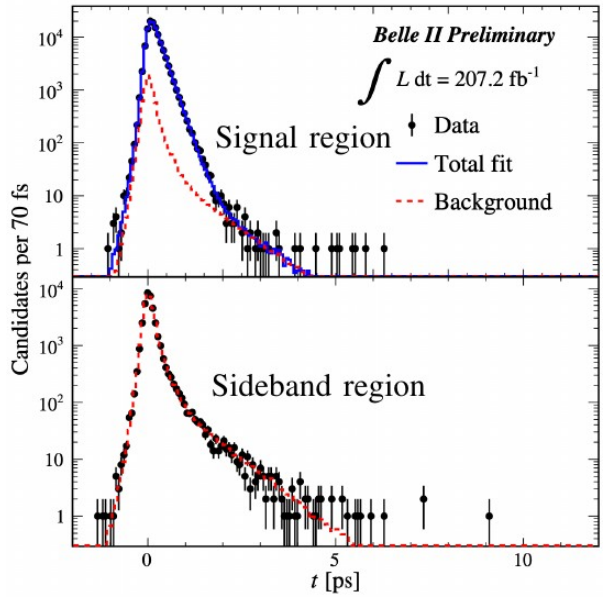
Lifetime measurements of charmed baryons

Λ^+_c lifetime

- Measure Λ^+_c lifetime in $\Lambda^+_c \to p\, K^-\, \pi^+$
  - 116k signal events with 7.5 % background in signal region
- Veto $\Xi_c^{0/+} \to \Lambda^+_c\, \pi^{-/0}$
- Resolution modeling and vertex detector alignment are dominant source of systematics
- Result: **$\tau(\Lambda^+_c)$ = 203.2 ± 0.9 (stat.) ± 0.8 (syst.) fs**
- **World's best measurement of the Λ^+_c** lifetime
  - Consistent with current world average
  - Benchmark for future baryon lifetime measurements

arxiv:2206.15227





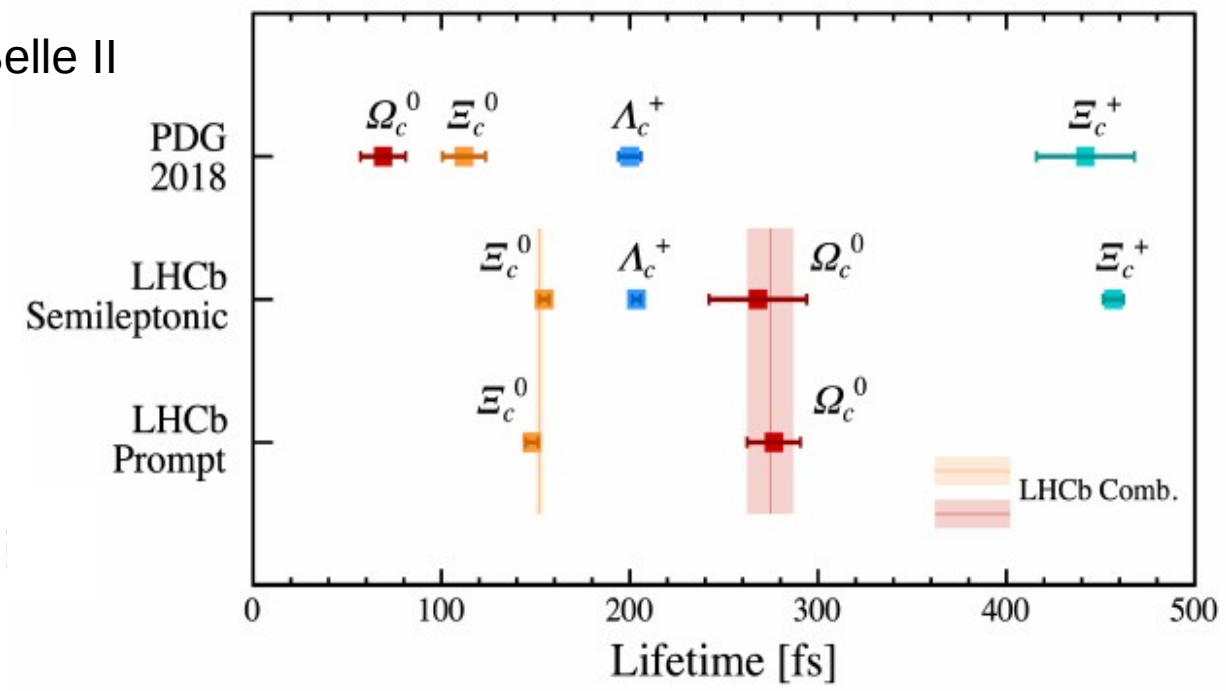
Ω_c lifetime

Ω_c was believed to be the shortest lived singly charmed baryon

- LHCb measurement recently changed the charm baryon lifetime hierarchy (arxiv:2109.01334, arxiv:1807.02024)

$$\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+) \Rightarrow \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$$

- No other experimental confirmation of the LHCb results
  - We provide an independent measurement from Belle II



Results

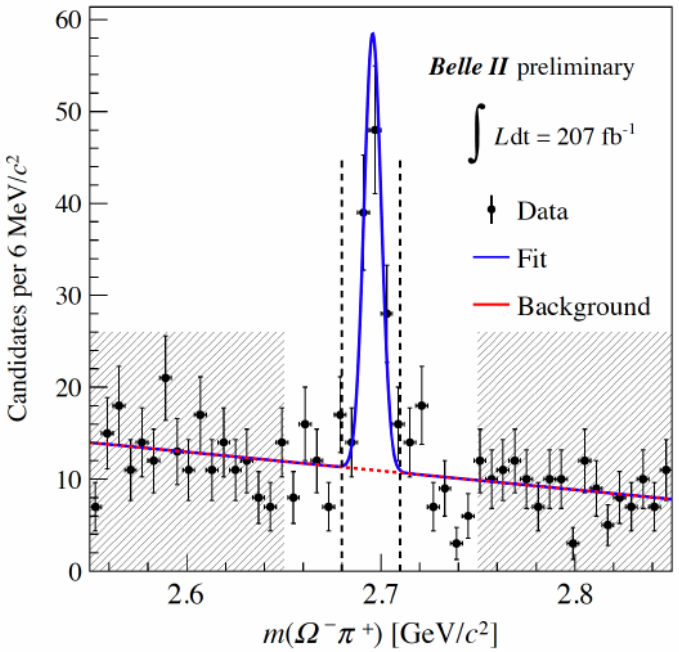
- ~90 signal candidates are reconstructed in the decay

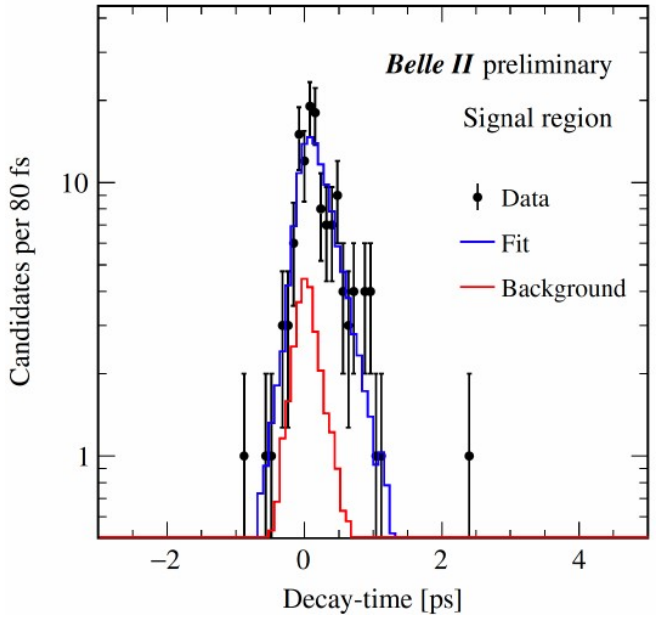
$$\Omega_c^0 \to \Omega^-\pi^+;\ \Omega^- \to \Lambda^0 K^-;\ \Lambda^0 \to p\pi^-$$

  - Background: zero-lifetime + non-zero lifetime components
- First Belle II lifetime measurement with complex decay topology
  - Two secondary decay vertices
- (Preliminary) Belle II result:

$$\tau(\Omega_c^0) = 243 \pm 48^{\text{stat.}} \pm 11^{\text{syst.}}\ \text{fs}$$

- The **Ω_c is not the shortest-lived** singly charmed baryon
  - Consistent with LHCb result, in tension with pre-LHCb result at 3.4 σ
- Demonstrates the capabilities of the Belle II detector!





Summary

Summary

- Belle II physics program has started successfully
- Exclusive $|V_{xb}|$ measurements compatible with current world average
- Measurement of lepton flavour universality using semi-leptonic B decays with world leading precision
- Most precise measurement of the Λ^+_c lifetime to date
- Can confirm the LHCb measurement for the Ω_c lifetime
- More results on dark sector, radiative and hadronic B decays, τ physics, etc.

Summary

- Belle II physics program has started successfully
- Exclusive $|V_{xb}|$ measurements compatible with current world average
- Measurement of lepton flavour universality using semi-leptonic B decays with world leading precision
- Most precise measurement of the Λ^+_c lifetime to date
- Can confirm the LHCb measurement for the Ω_c lifetime
- More results on dark sector, radiative and hadronic B decays, τ physics, etc.

- Belle II is competitive with ~190 fb^{-1} – by now ~420 fb^{-1} recorded
  - Nearly as many data as Babar (434 fb^{-1} on resonance for Babar vs 384 fb^{-1} on resonance for Belle II)

  → Many more measurements with world leading precision about to follow in the next years!

- More recent results shown at ICHEP are linked in the backup

Thank you

Backup

ICHEP presentations

Belle II

- T. Koga: Recent Belle II results on the CKM parameters |Vcb| and |Vub|
- H. Junkerkalefeld: Recent Belle II results on semileptonic decays and tests of lepton-flavor universality
- N. Nellikunnummel: Measurements of charm lifetimes at Belle II
- C. La Licata: Recent Belle II results on decay-time-dependent CP violation
- J. Skorupa: Recent Belle II results on hadronic B decays
- F. Tenchini: Recent tau-lepton results at Belle II
- E. Ganiev: Recent Belle II results on electroweak penguins
- Q. ji: Recent quarkonium results at Belle II
- E. Graziani: Recent dark-sector results at Belle II

ICHEP presentations

Belle

- K. Smith: Branching fractions and CP asymmetries in B decays through b → c processes at Belle
- G. de Marino: Search for baryon-number-violating and lepton-flavor-violating decays at Belle
- M. Prim: New results for semileptonic B decays from Belle
- K. Kang: Radiative and electroweak-penguin B decays at Belle
- A. Sangal: Study of Branching fraction and CP Asymmetry of charm mesons at Belle
- G. Pinna Angioni: Study of charmonia and bottomonia at Belle
- K. Uno: Tau physics at Belle
- J. Chen: Two-Particle Correlations of Hadrons in e+e- Collisions at Belle

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