Charm Physics at Belle II

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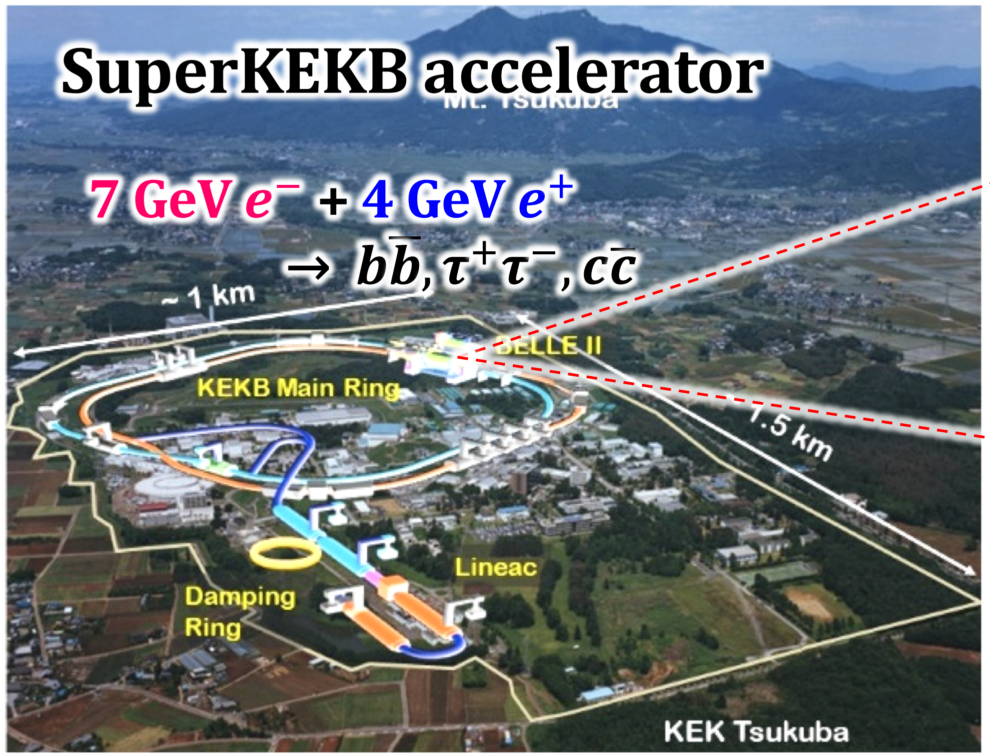
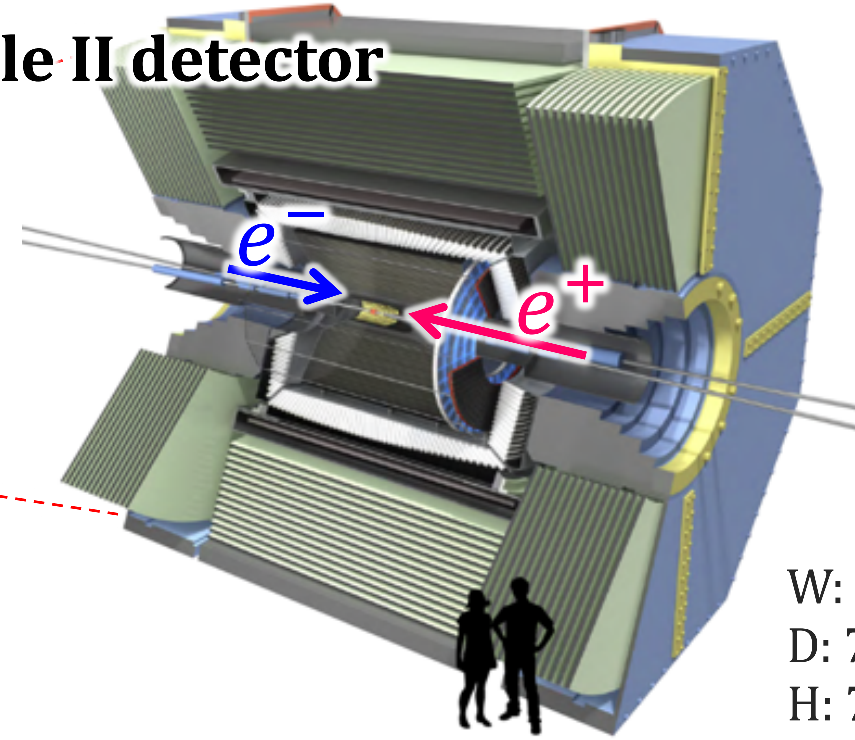
Belle II Experiment

In the quest for the new physics, we started an $e^{+}e^{-}$ collider experiment Belle II in Japan in March 2019.





W: 7.7m
D: 7.2 m
H: 7.9 m

	Current record	Target / design
$\int \mathcal{L} dt$	424 fb^{-1}	50 ab^{-1}
$\mathcal{L}_{\text{peak}}$ [$\text{cm}^{-2}\text{s}^{-1}$]	4.7×10^{34} (WR)	60×10^{34}

- **Silicon detectors** for particle position measurement
- **Drift chamber** for momentum and dE/dx measurement
- **TOP counters** and **ARICH counters** for PID
- **CsI(Tl) crystals** for $e^{\pm}$ and γ calorimetry
- **Iron/RPC sandwiches** for K_L and μ detection

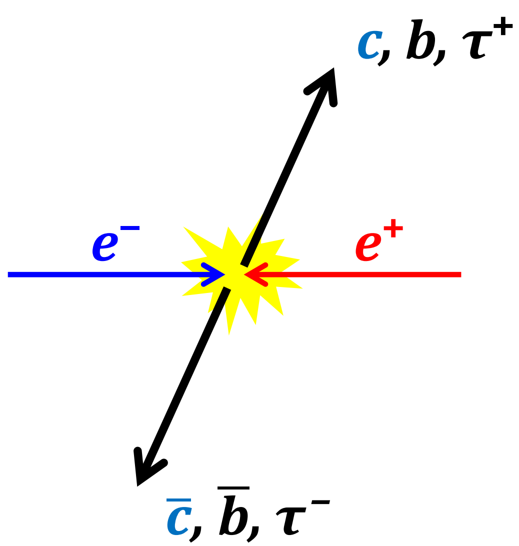
Charm Physics at Belle II

Motivation for charm physics

- Charmed particles require low-energy QCD calculation (non-perturbative and high order corrections) for NP searches. The effective models do have uncertainties.
- Measurements of charm lifetimes can test and improve the model calculations.

Belle II: a *B*-factory, τ-factory, and "charm-factory" experiment

- At SuperKEKB, $\sigma_{c\bar{c}} \sim \sigma_{b\bar{b}} \sim \sigma_{\tau\tau} \sim 1$ nb; large charm samples are created there.
- $e^{+}e^{-}$ collision provides a clean environment, creating less bias in selection and reconstruction.
- The small $e^{+}e^{-}$ interaction region, known as the nano-beam scheme, and the new Belle II vertex detector provide precise *D*-decay vertices.

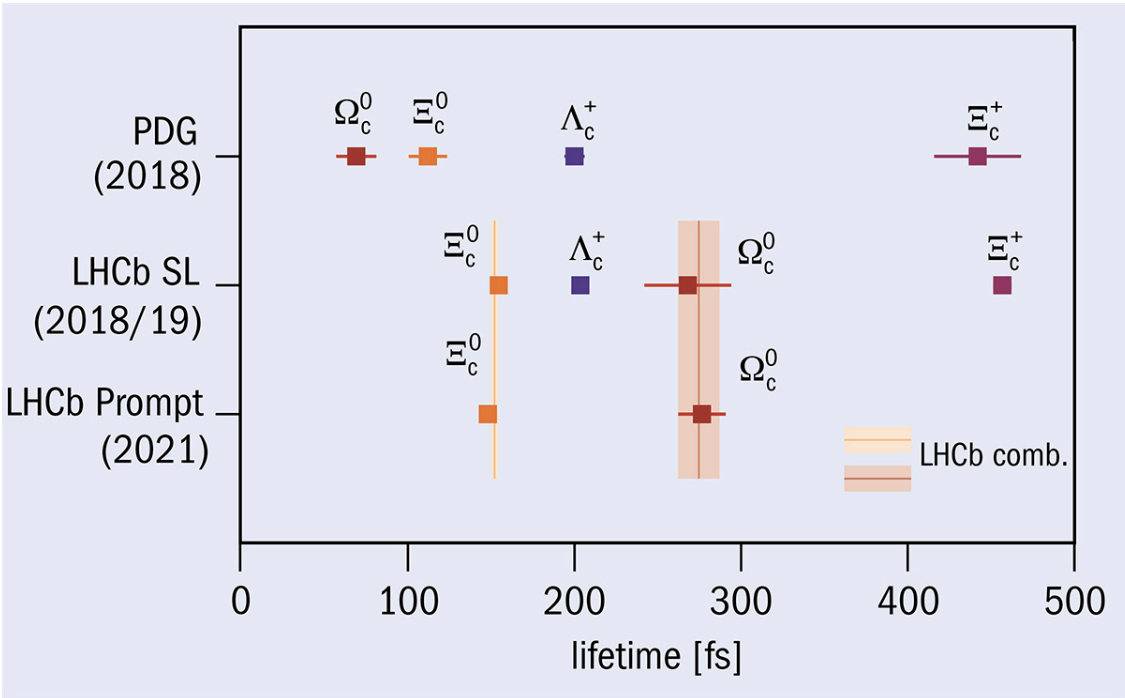


Debate on the Charmed-Baryon Lifetimes

- The hierarchy of the charmed-baryon lifetimes, recently measured by LHCb, is different from old measurements.

Pre LHCb: $\tau_{\Omega_c^0} < \tau_{\Xi_c^0} < \tau_{\Lambda_c^+} < \tau_{\Xi_c^+}$

Meas. by LHCb: $\tau_{\Xi_c^0} < \tau_{\Lambda_c^+} < \tau_{\Omega_c^0} < \tau_{\Xi_c^+}$



https://cerncourier.com/a/new-charmed-baryon-lifetime-hierarchy-cast-in-stone/

- It suggests a revision of the higher order correction of the HQE.

- Belle II joins the debate by measuring the Λ_c^+ and Ω_c^0 lifetimes.

Charm Lifetime Measurement at Belle II

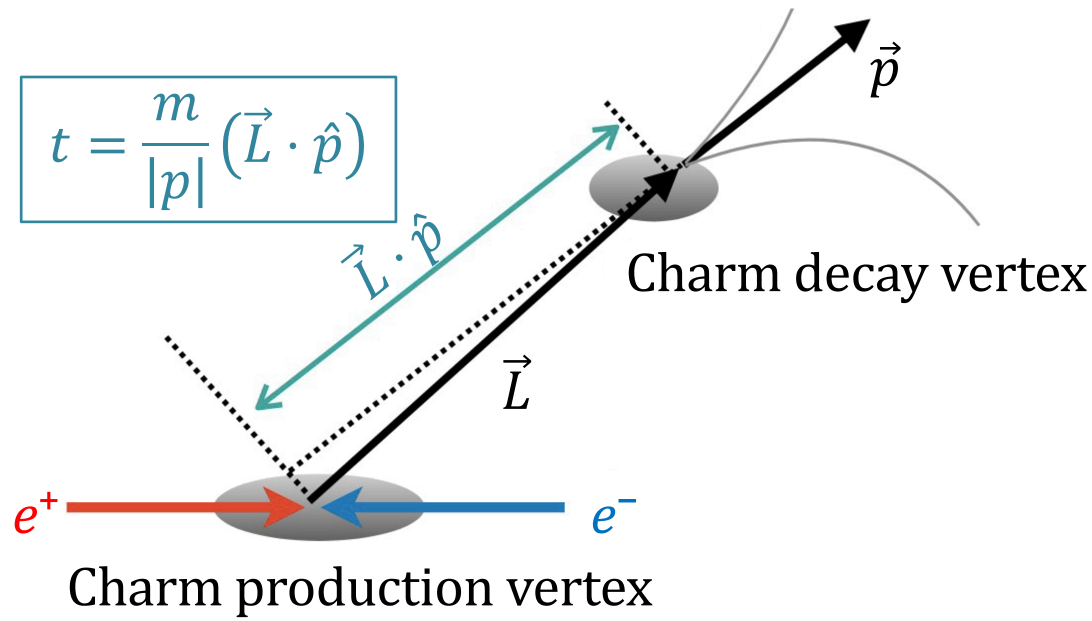
1. Event reconstruction

- Fully reconstruct the charmed particle from the daughter particles.
- Remove lifetime-biasing *B* decays by kinematical selections.

2. Signal and background separation

- Determine the signal probability f_{sig} from a mass distribution fit.

3. Decay time reconstruction

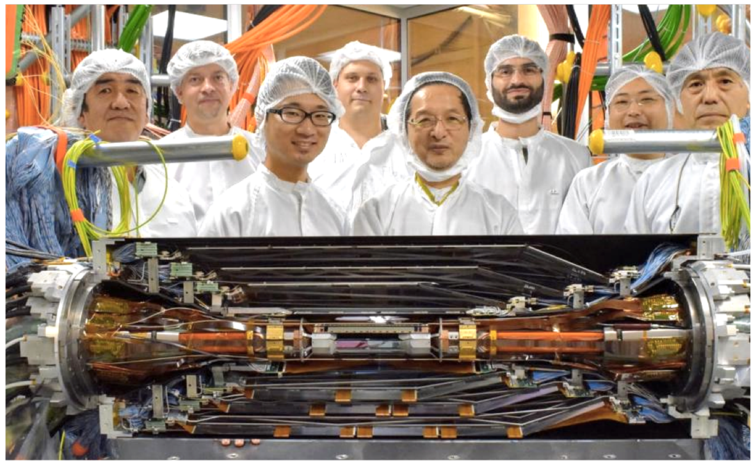


4. Maximum likelihood fit for τ

- $P(t;\tau) = f_{\text{sig}}\, e^{-t/\tau} \otimes R + (1 - f_{\text{sig}})BG(t)$
- Maximize $\ln \mathcal{L}(\tau) = \sum_i \ln P(t_i;\tau)$

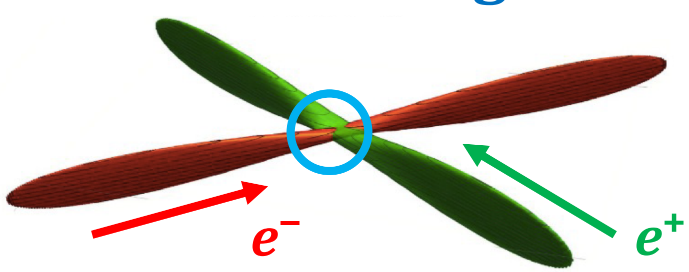
Technology for Precision Lifetime Measurement

Precise vertex detectors



About twice better impact parameter resolution than Belle (10/15 μm for radial/longitudinal direction).

Small IR and good IR calibration



$\sigma_{Y'}$ = 0.2 μm, $\sigma_{X'}$ = 13 μm, $\sigma_{Z'}$ = 320 μm,

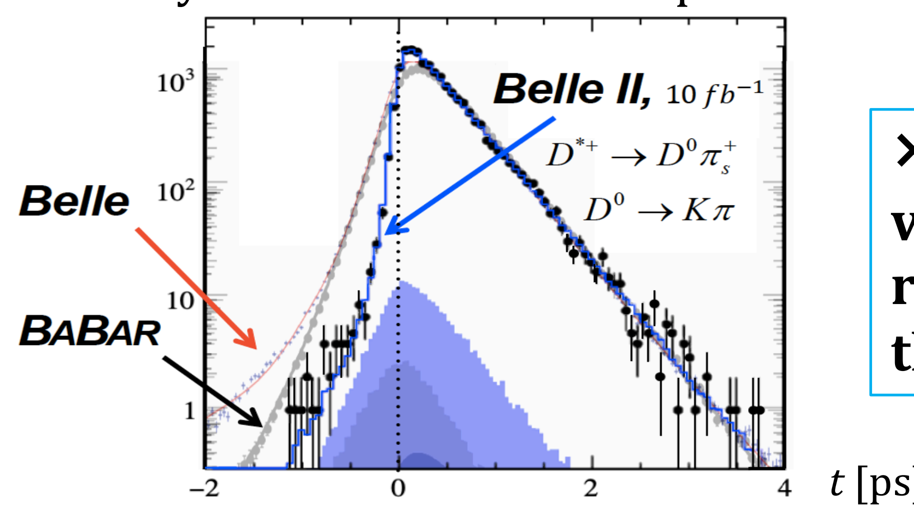
Position and orientation in space calibrated every 30 minutes with $e^+e^- \to \mu^+\mu^-$ events.

Tracker alignment

- Simultaneous global and local vertex detectors and wire chamber alignment including the evaluation of sensor deformations using charged particles.
- Run-dependent alignment.

Decay-time resolution comparison

D^0 decay-time distribution comparison



×2 better vertex resolution than Belle

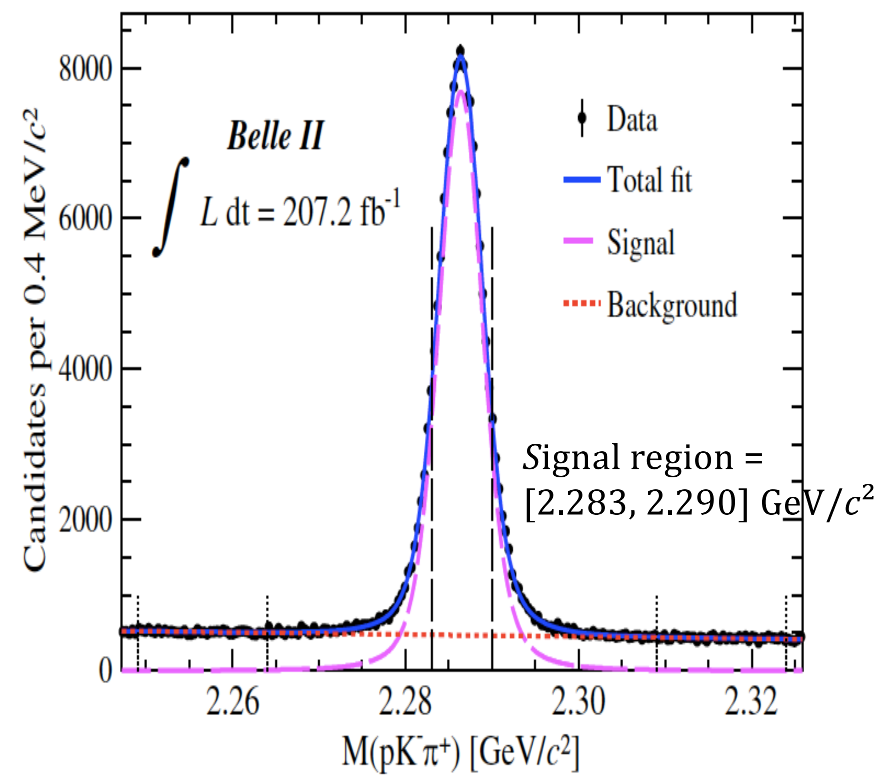
Λ_c^+ Reconstruction

- Decay: $\Lambda_c^+ \rightarrow pK^-\pi^+$

- Λ_c^+ from B decays are eliminated with a selection of $p^*_{\Lambda_c^+} > 2.5$ GeV/c.
- $p \Rightarrow \pi$ mis-identified $D^+ \rightarrow \pi^+ K^- \pi^+$ is suppressed by a veto on $M_{pK^-\pi^+}$.
- Other charm-related backgrounds are suppressed using $p_{\mathrm{t}}(\pi^+) > 0.35$ GeV/c and $p_{\mathrm{t}}(p) > 0.7$ GeV/c.

- Λ_c^+ from $\Xi_c^{+/0} \rightarrow \Lambda_c^+ \pi^{+/0}$ can bias the measured lifetime because its production vertex is shifted away from the IR. Such events are vetoed with $m_{\Xi^{+/0}}$.

- Signal $M_{pK^-\pi^+}$ … Johnson + Gaussian; BG $M_{pK^-\pi^+}$ … line.
- 1.16×10^5 Λ_c^+ candidates in the signal region with a signal purity of 92.5%.



Maximum Likelihood Fit for the Lifetime Extraction

- Lifetime fit is applied to the (t, σ_t) distributions via an unbinned maximum likelihood fit method.

Basic probability density function for (t, σ_t)

$$P(t, \sigma_t; \tau) = f_{\mathrm{sig}} \times S(\sigma_t) \times e^{-t/\tau} \otimes R(b, s\sigma_t) \ + \ \left(1 - f_{\mathrm{sig}}\right) BG(t, \sigma_t)$$

- t … decay time; σ_t … uncertainty of the reconstructed decay time. τ … lifetime.
- f_{sig} … signal fraction constrained by a fit to invariant mass distribution.
- $S(\sigma_t)$ … σ_t PDF derived from data as histogram.
- $R(b, s\sigma_t)$ … resolution function (Gaussian) for the decay time t; the bias parameter b and the scale factor s for σ_t are floated in the ML fit.
- BG(t, σ_t) … background PDF, shape determined from the sideband regions. Modeled with zero lifetime and non-zero lifetime components convoluted with a Gaussian resolution function.

Phys Rev. Lett. **130**, 071802 (2023)

Belle II 207 fb^{-1}

Λ_c^+ Lifetime

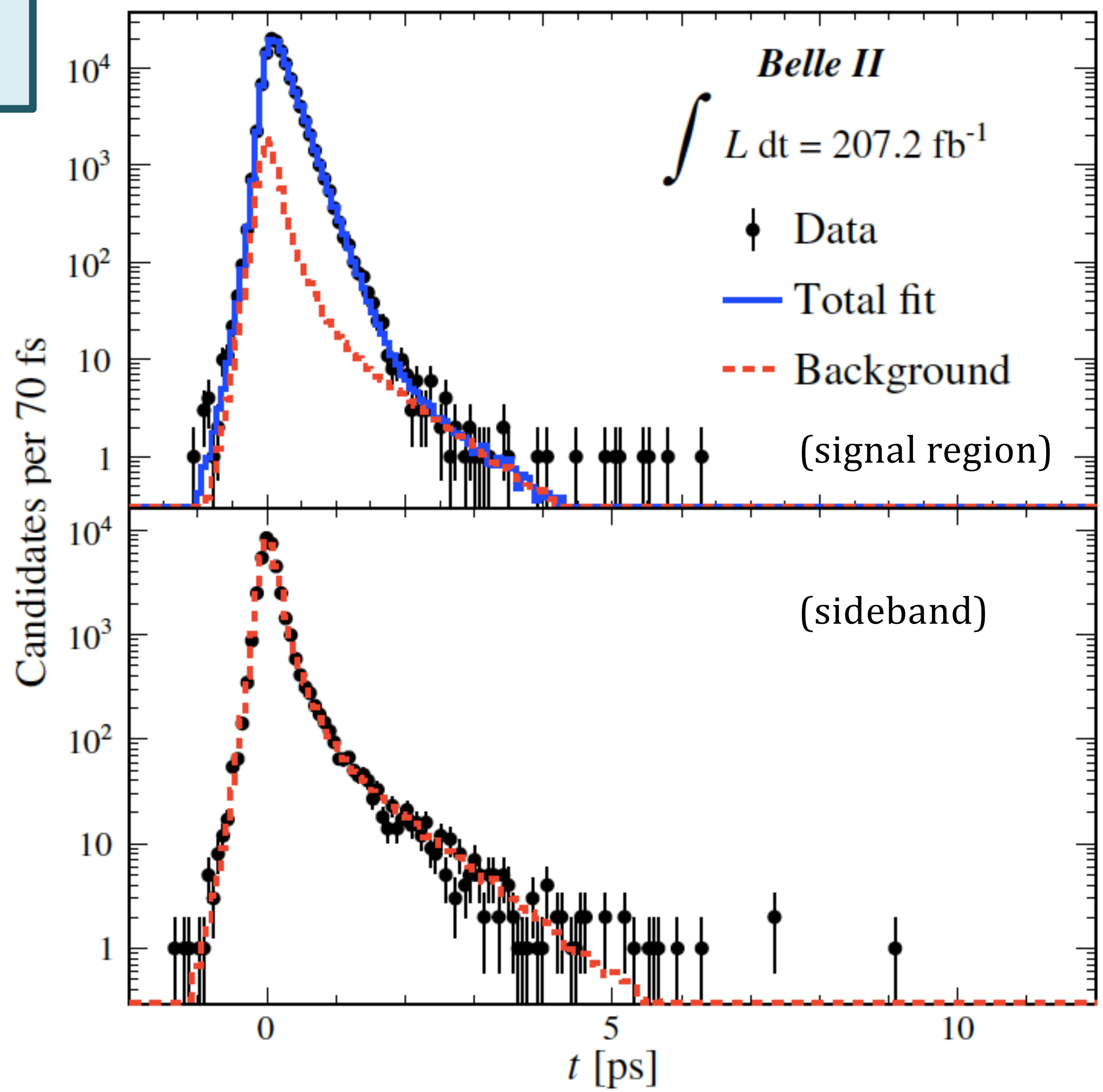
$$\tau(\Lambda_c^+) = 203.20 \pm 0.89 \pm 0.77\ \text{fs}$$

- Consistent with the current world average (201.5±2.7 fs) and the most precise measurement to date.

Systematic uncertainties

Source	Uncertainty (fs)
Ξ_c contamination	0.34
Resolution model	0.46
Non-Ξ_c backgrounds	0.20
Detector alignment	0.46
Momentum scale	0.09
Total	0.77

Decay time distributions

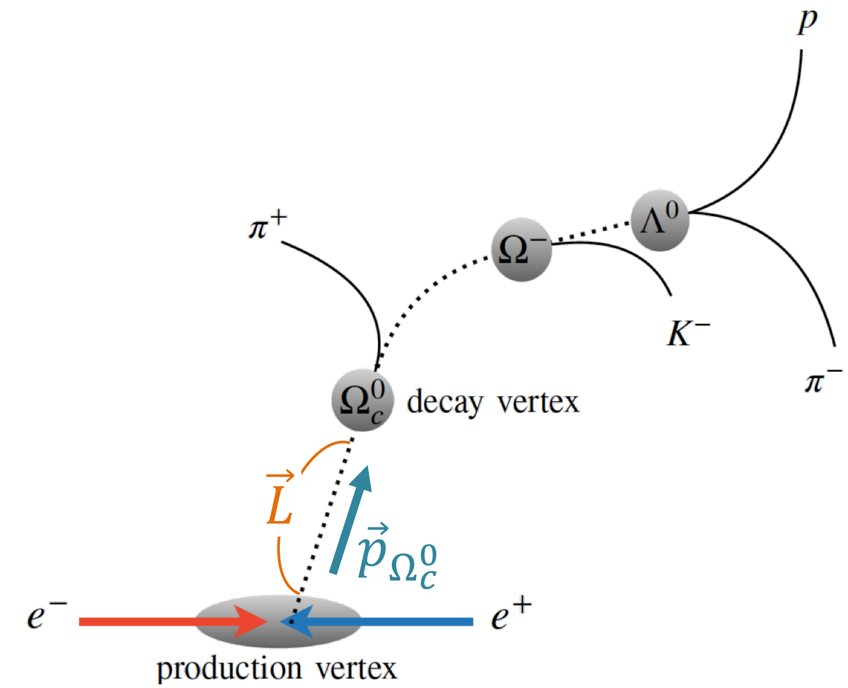


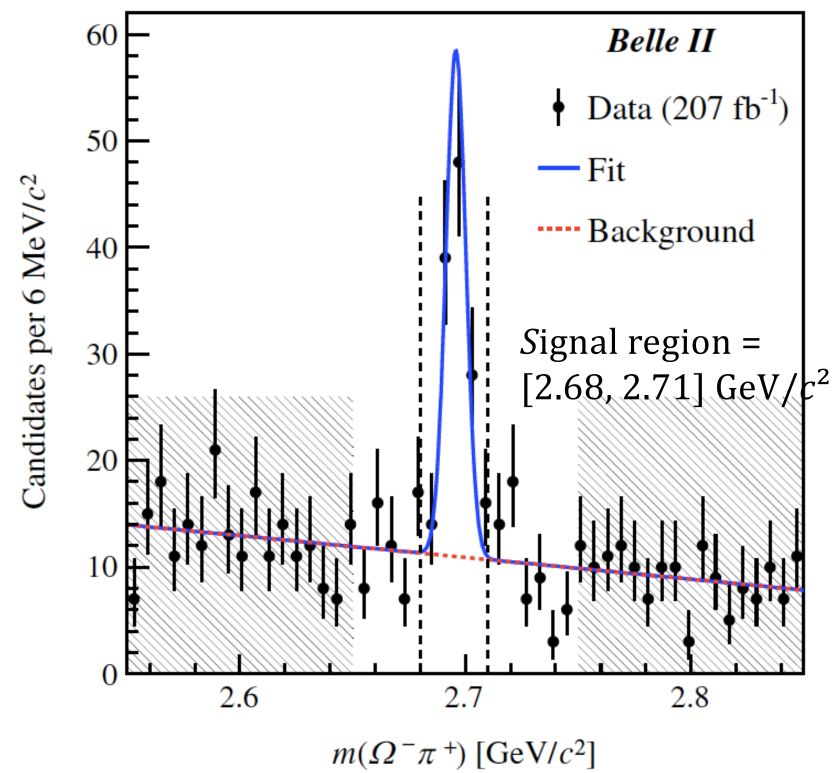
Ω_c^0 Reconstruction

- Decay chain: $\Omega_c^0 \to \Omega^-\pi^+,\ \Omega^- \to \Lambda^0 K^-,\ \Lambda^0 \to p\pi^-$

- Λ^0 is reconstructed by combining oppositely charged tracks one of which must be a proton. The Λ^0 decay vertex must be > 3.5 mm away from the e^+e^- IR.
- Ω^- is reconstructed by combining Λ^0 and K^- with p_t > 0.15 GeV/c. The Ω^- decay vertex lies between Λ^0 and IR and > 0.5 mm away from the IR.
- Ω_c^0 is reconstructed by combining Ω^- and positively charged track with p > 0.5 GeV/c.

- Signal $M_{\Omega^-\pi^+}$ … Gaussian; BG $M_{\Omega^-\pi^+}$ … line.
- 132 Ω_c^0 candidates in the signal region with a signal purity of (66.5±3.3)%.





Phys. Rev. D **107**, L031103 (2023)

Belle II 207 fb^{-1}

Ω_c^0 Lifetime

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

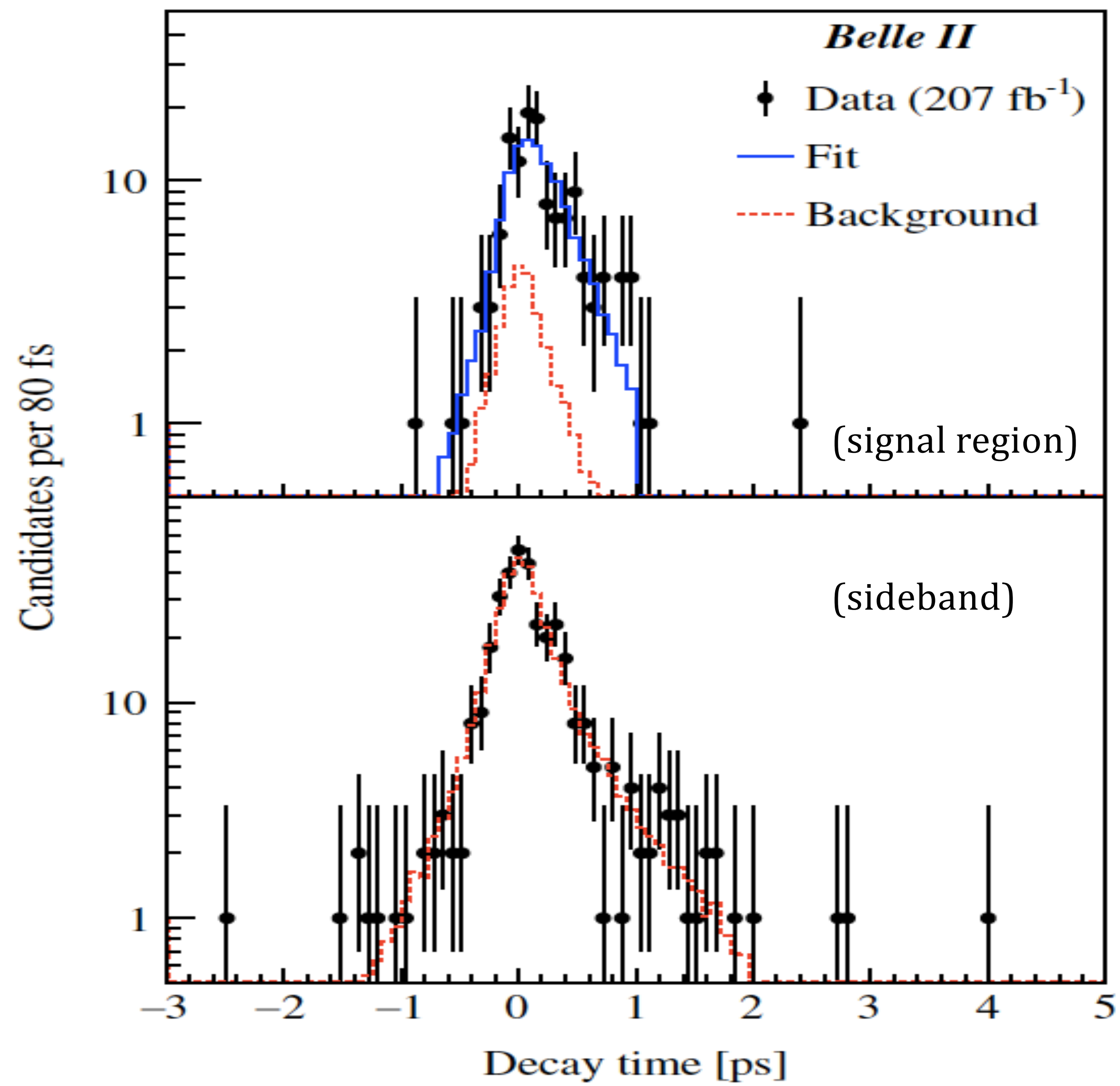
- Consistent with the LHCb average (274.5±12.4 fs) [1] and 3.4σ tension with the pre-LHCb (69±12 fs) [2].

[1] LHCb, Sci. Bull. **67**, 479 (2022).
[2] PDG 2018.

Systematic uncertainties

Source	Uncertainty (fs)
Fit bias	3.4
Resolution model	6.2
Background model	8.3
Detector alignment	1.6
Momentum scale	0.2
Input Ω_c^0 mass	0.2
Total	11.0

Decay time distributions



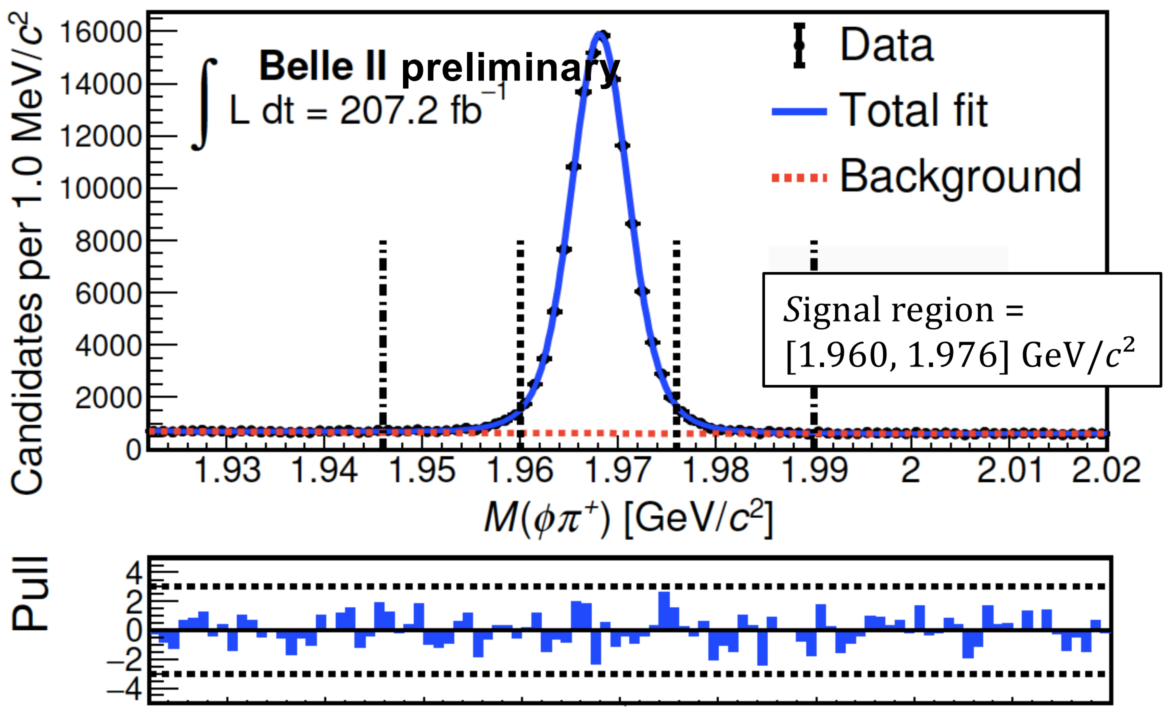
Another World-Leading Lifetime Measurement: $\tau(D_s^+)$

- Decay chain: $D_s^+ \to \phi\pi^+,\ \phi \to K^+K^-$

- ϕ is reconstructed by combining oppositely charged two tracks with a PID likelihood ratio $\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi) > 0.6$ with $1.01 < M_{K^+K^-} < 1.03$ GeV/c^2.
- D_s^+ is reconstructed from ϕ and π^+ with a PID likelihood ratio $\mathcal{L}_\pi/(\mathcal{L}_K + \mathcal{L}_\pi) > 0.45$.

- D_s^+ from B decays are eliminated with a selection of $p^*_{D_s^+} > 2.5$ GeV/c.

- Signal $M_{\phi\pi^+}$ … Gaussians + asymmetric Student's t; BG $M_{\phi\pi^+}$ … 2nd order Chebyshev.
- 115,560 D_s^+ candidates in the signal region with a signal purity of 92%.



arXiv:2306.00365

Belle II 207 fb^{-1}

D_s^+ Lifetime

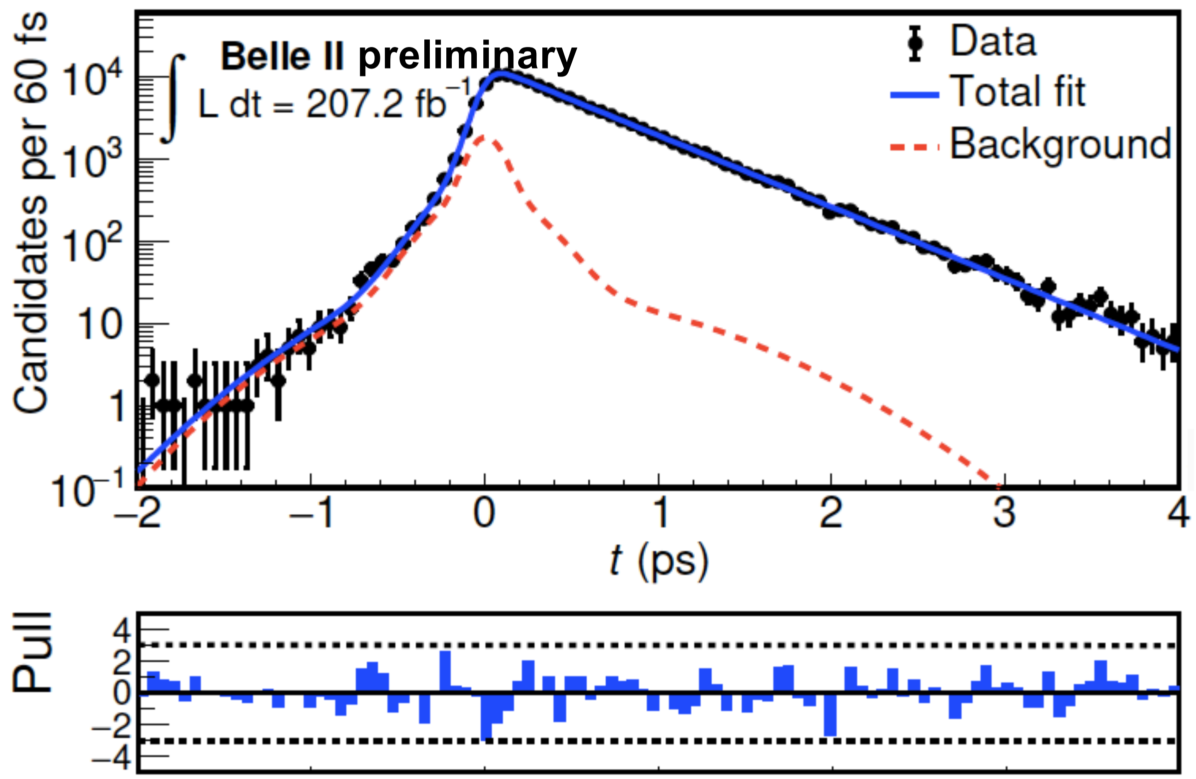
$$\tau(D_s^+) = 498.7 \pm 1.7\,^{+1.1}_{-0.8}\ \text{fs}$$

- Consistent with the world average (504±4 fs) with twice precision.
- Also consistent with theory predictions.

Systematic uncertainties

Source	Uncertainty (fs)
Resolution function	$+0.85$
Background (t, σ_t) distribution	± 0.40
Binning of σ_t histogram PDF	± 0.10
Imperfect detector alignment	± 0.56
Sample purity	± 0.09
Momentum scale factor	± 0.28
D_s^+ mass	± 0.02
Total	$^{+1.14}_{-0.76}$

Decay time distribution



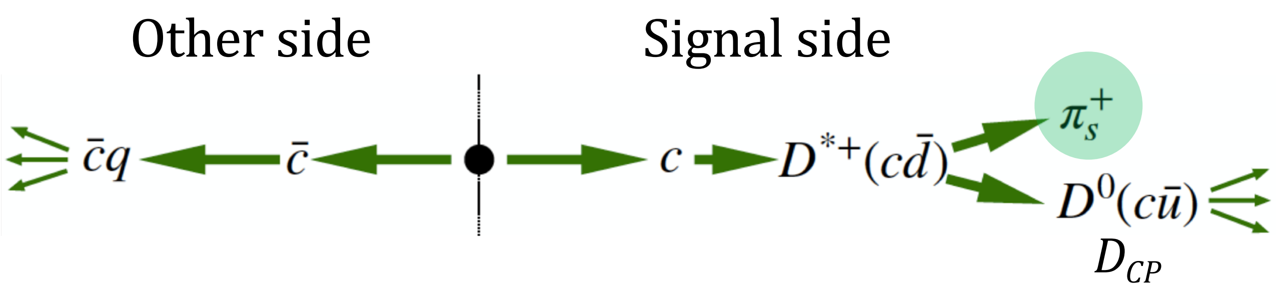
Charm Flavor Tagger

Motivation

- Precise measurements of *CP* asymmetries in charmed-hadron decays are useful to conclude the debate on a NP contribution in the charm-sector *CP* violation.

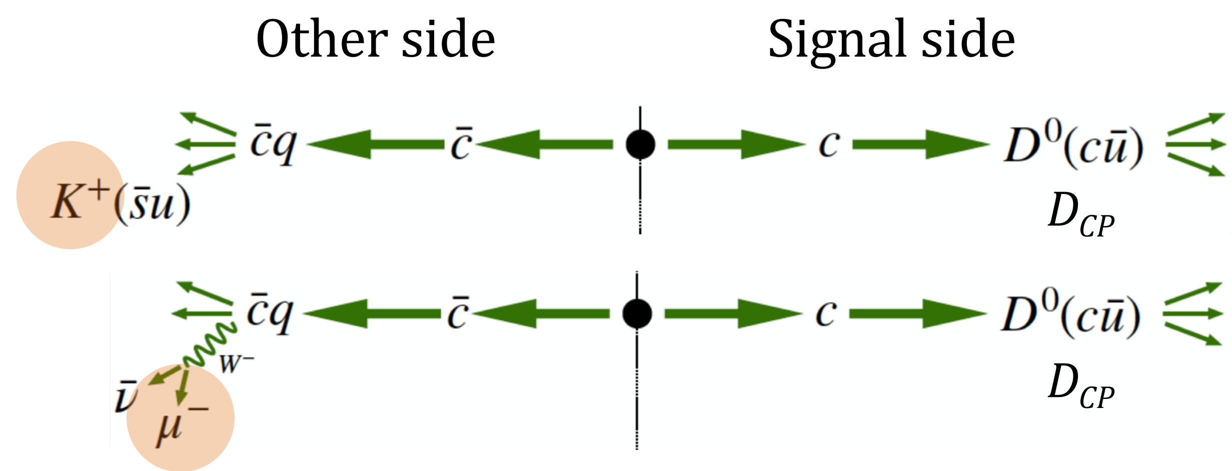
Charm flavor tagger identifies the flavor of a neutral D_{CP} meson to be D^0 or $\overline{D}^0$.

Previous method



- Infer the D_{CP} flavor from the *same-side* π_s info.
- Only 25% of $c\bar{c}$ events have the $D^{*}\to D^0\pi_s$ decay → a new method is desired to make up for the loss of 75% decays.

Novel method introduced here

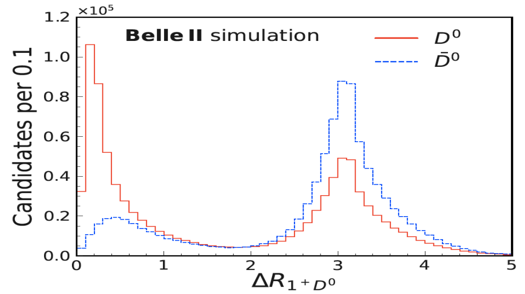
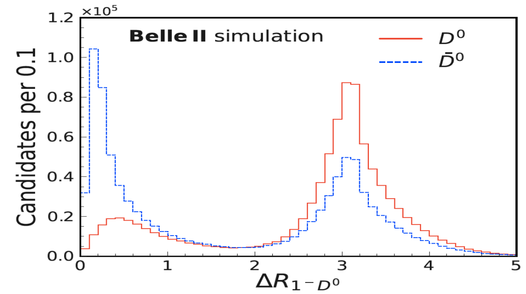
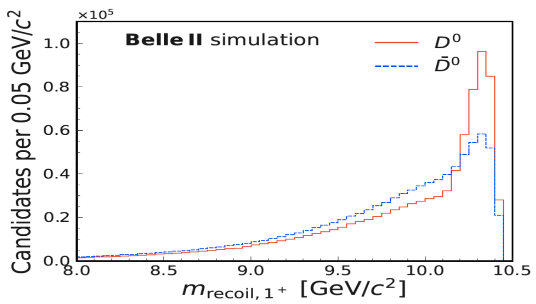
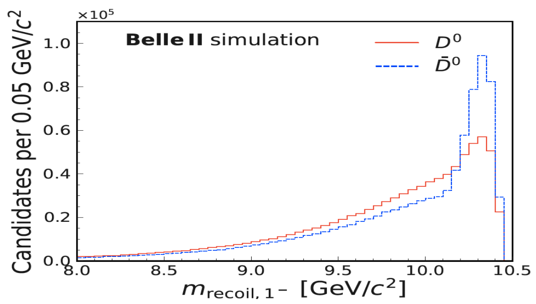
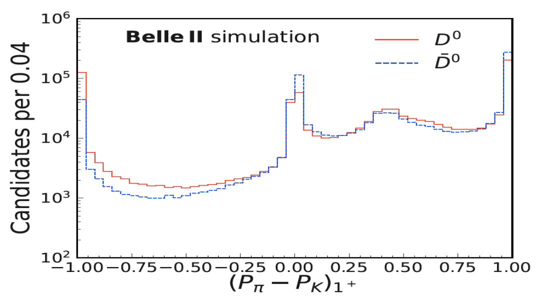
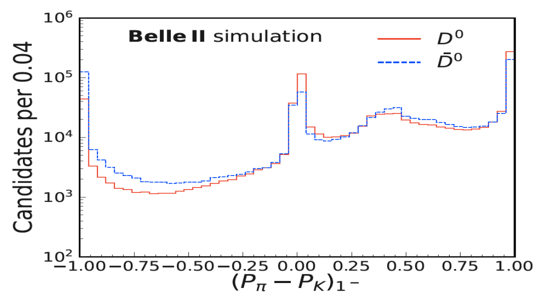


- Infer the D_{CP} flavor also with the *other-side particle* info; no requirement on the signal-side decay.

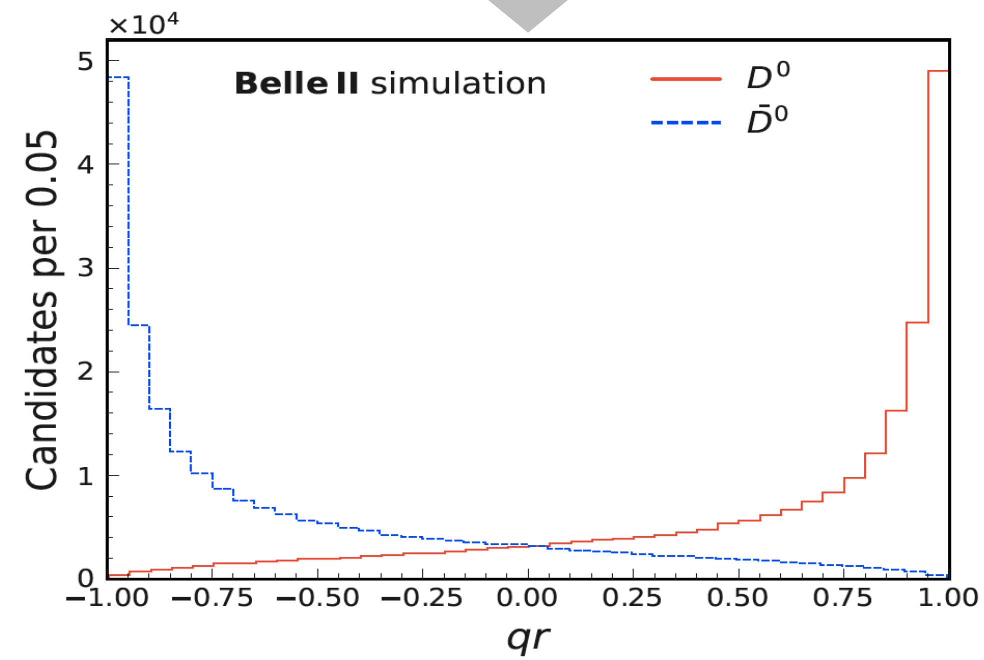
Phys. Rev. D **107**, 112010 (2023)

Belle II 362 fb^{-1}

Charm Flavor Tagger – cont’d

	Positive-charge particle	Negative-charge particle
$\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ w.r.t. D_{sig}		
Recoil mass against the R-O-D_{CP}		
PID difference $P_\pi - P_K$		

Tagging decision q (+1 for D^0, −1 for $\bar{D}^0$) and r (unambiguity ranging 0 … 1) based on a BDT

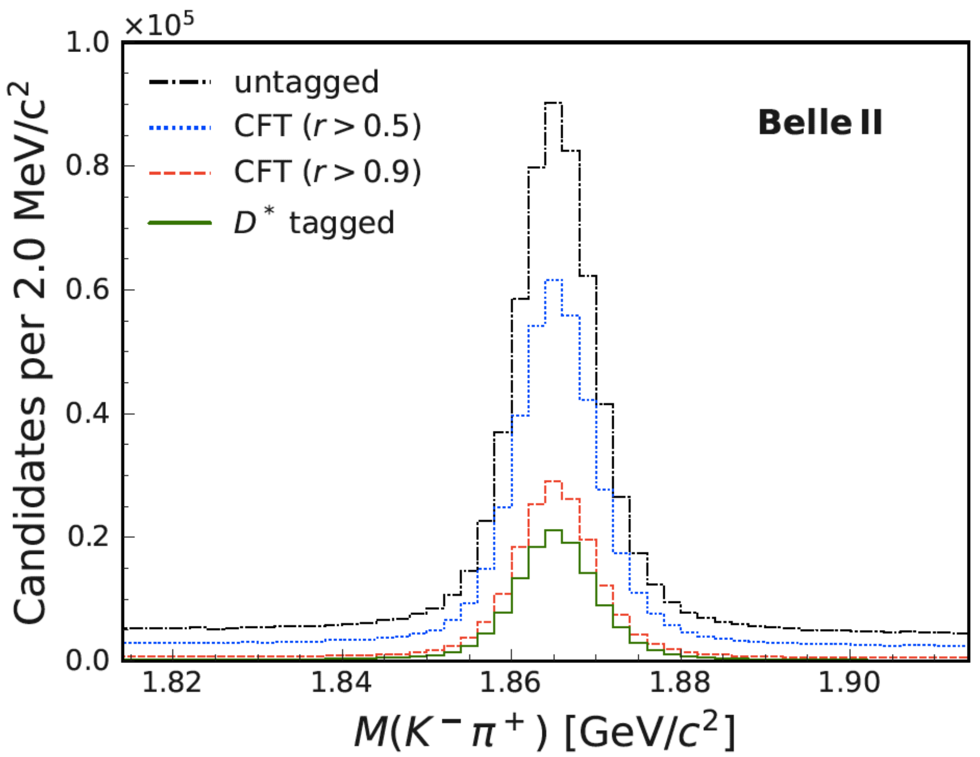


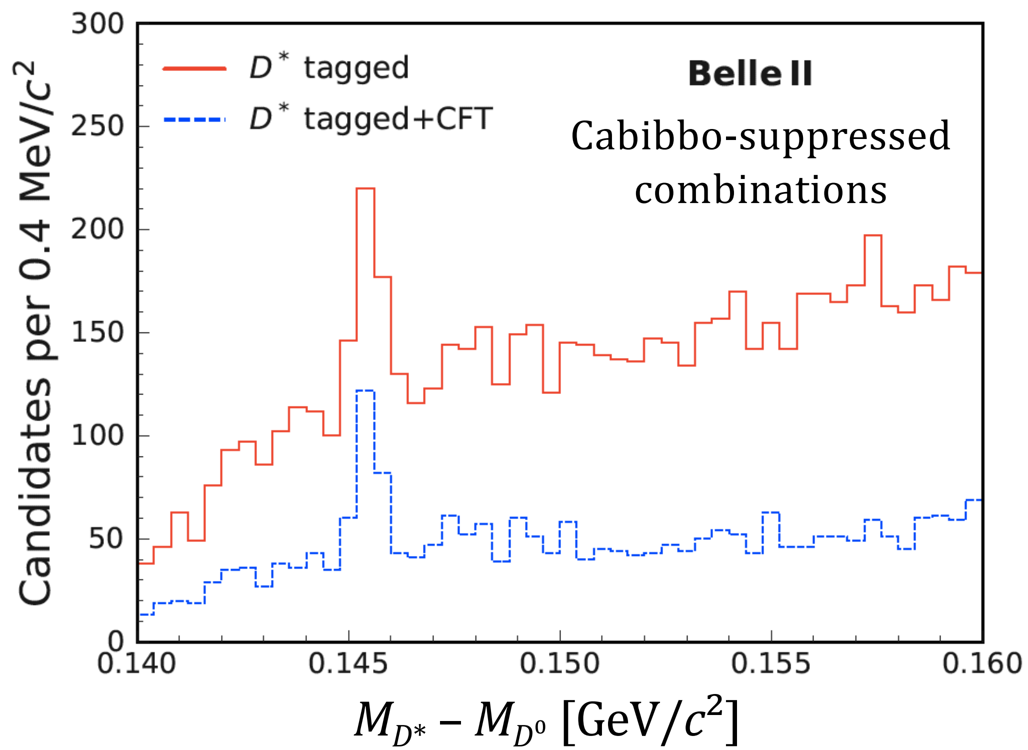
Effective tagging efficiency estimated with 362 fb^{-1} data: $\epsilon_{\text{tag}}^{\text{eff}} = \mathbf{47.91 \pm 0.07 \pm 0.51}$ %

Charm Flavor Tagger – cont'd

Impact on physics

- Doubles the sample size w.r.t D^{*+}-tagged events.
- Increases the sensitivity for many charm decays: $D^0 \to \pi^0\pi^0, K_S^0 K_S^0, K\pi\pi^0, \pi\pi\pi^0$...
- Provide discrimination between signal and backgrounds.





Summary

Belle II strongly advances charm-sector studies as well as B-meson and τ-lepton studies.

Presented the measurement of three charmed-hadron lifetimes:

- $\tau(\Lambda_c^+)$, $\tau(D_s^+)$ ... world-leading measurements.
- $\tau(\Omega_c^0)$ ... consistent with the LHCb average.

New inclusive algorithm for charm flavor tagging, which exploits correlation between the signal flavor and charge of tagging particles, significantly enlarges the available sample size.

Backup Slides