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Measurements of charm lifetimes at Belle II

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Belle II

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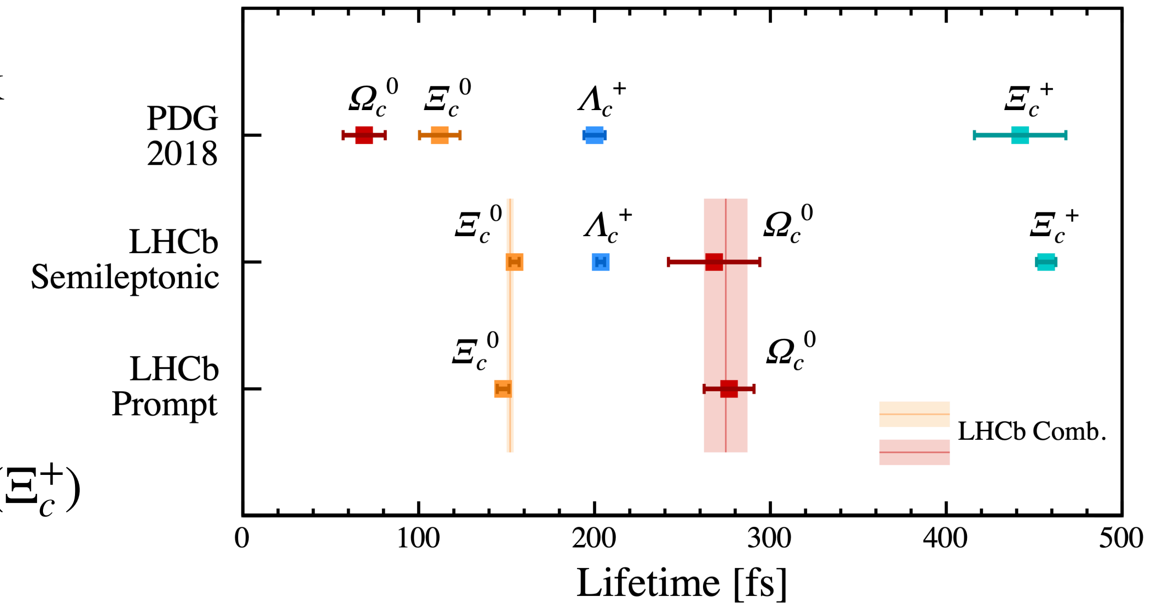
Motivation and status

- Heavy Quark Expansion (HQE) predict beauty and charm hadron lifetimes
  - Charm hadron lifetime prediction is challenging: significant higher order correction+QCD contributions
  - Charm lifetime measurements allow for HQE validation and refinement increasing reliability and precision of SM predictions in flavor dynamics

- The best measurements of charm-meson lifetimes date back to FOCUS; LHCb recently reported precise relative measurements of charm-baryon lifetimes

- The LHCb measurements changed the lifetime hierarchy of singly charmed baryons:

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



LHCb Semileptonic: Phys. Rev. Lett. **121**, 092003 (2018)

LHCb Prompt: Science Bulletin 67 (2022) 479-487

- Possible reasons why HQE has initially failed are being debated (Science Bulletin 67 (2022) 445-447, arXiv:2204.11935)

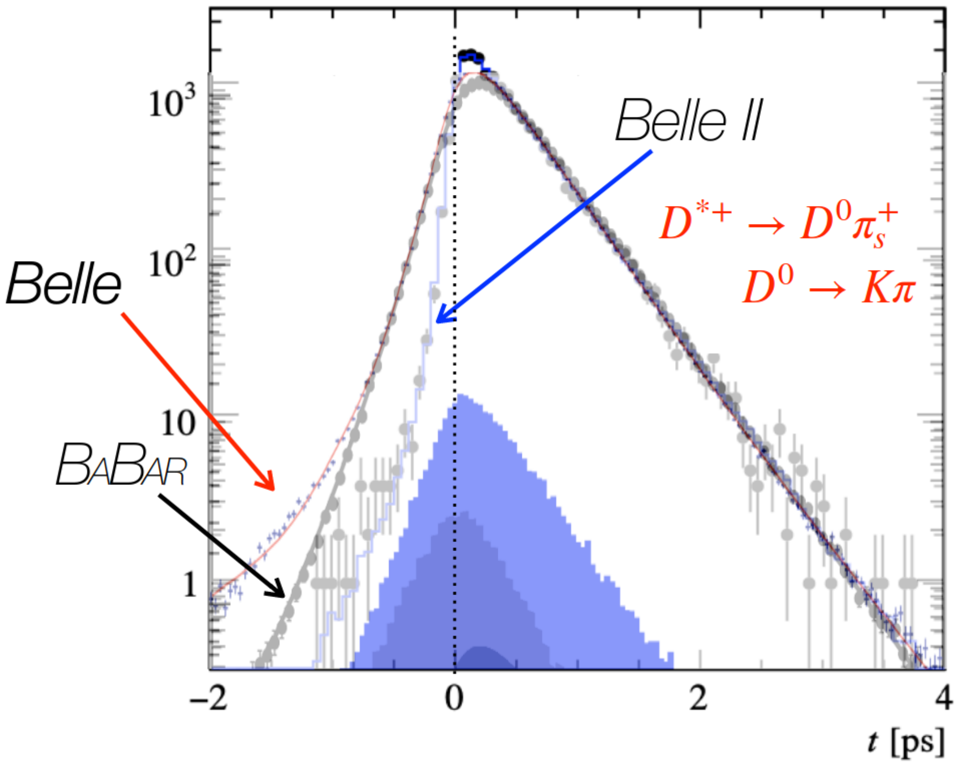
- No other experimental confirmation of the LHCb results

SuperKEKB and Belle II

- SuperKEKB: asymmetric energy e^+e^- collider
  - Squeeze the beam at collision point: (x=10, y=0.2, z=250) µm compared to (100, 1, 6000) µm at Belle.
  - Charm hadrons produced in $e^+e^- \to c\bar{c}$ with large boost; large center-of-mass momentum ($\gtrsim 2.5$ GeV/c) required to select promptly produced charm hadrons
- Belle II detector capabilities:
  - Good vertex resolution (~15 µm): 2x better than Belle
  - Precise alignment of vertex detector
  - Precise calibration of final state particle momenta
- Belle II can measure absolute lifetimes

424 fb^{-1} data collected so far

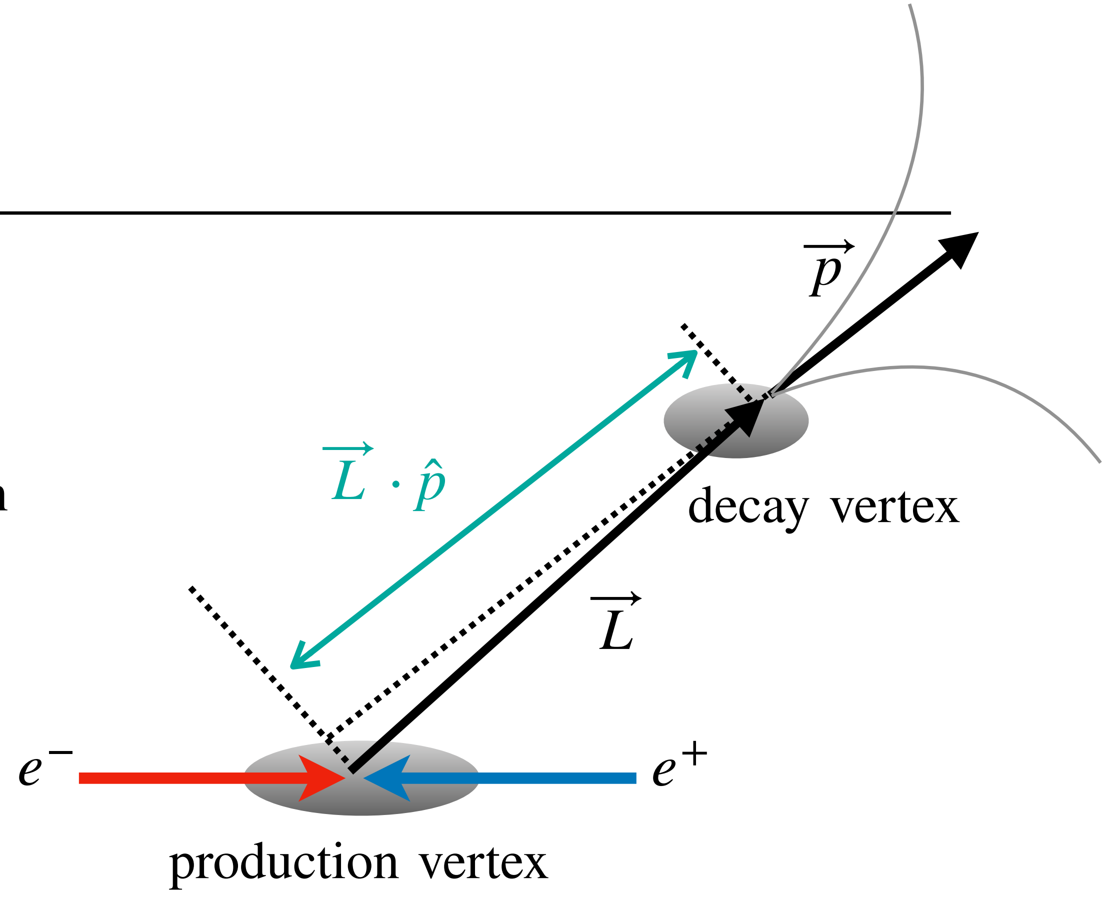
World record instantaneous luminosity:
$4.7 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ (June 2022)



Lifetime fit

- Proper decay time calculated from flight length between production and decay vertices and momentum as:

$$t = \frac{m}{p}(\vec{L}\,.\hat{p}) \quad m - \text{known mass of the charm hadron}$$



- Lifetime (τ): unbinned maximum-likelihood fit to (t, σ_t)
  - simultaneous fit to signal and sideband regions to constrain background
  - background fraction ($\mathrm{f_b}$) is constrained from mass fit

$$\mathrm{PDF}(t,\sigma_t) = (1-\mathrm{f_b})\int_0^\infty e^{-t_{\mathrm{true}}/\tau} R(t - t_{\mathrm{true}}\,|\,b, s\sigma_t)\,dt_{\mathrm{true}}\mathrm{PDF_{sig}}(\sigma_t) + \mathrm{f_b}\mathrm{PDF_{bkg}}(t,\sigma_t)$$

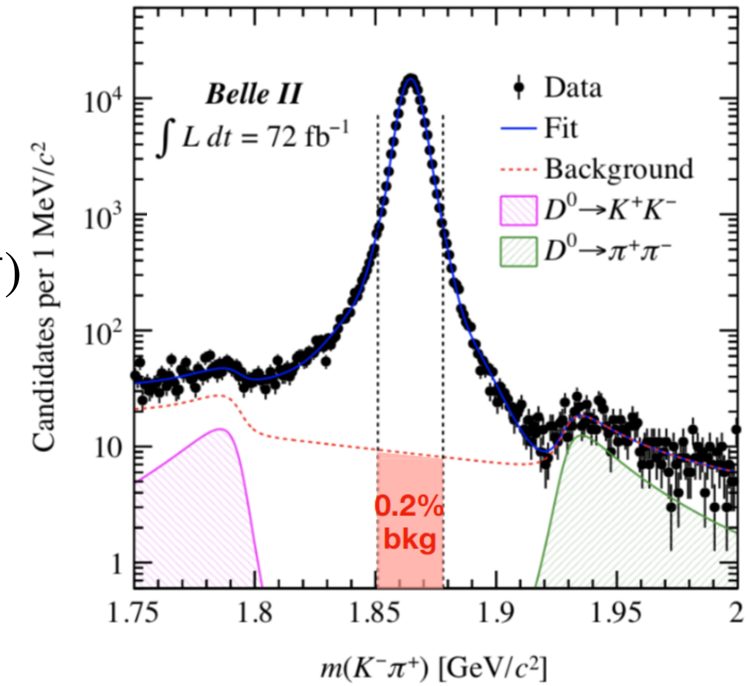
- All measurements are done in blind fashion, receive no input from simulation, and are absolute

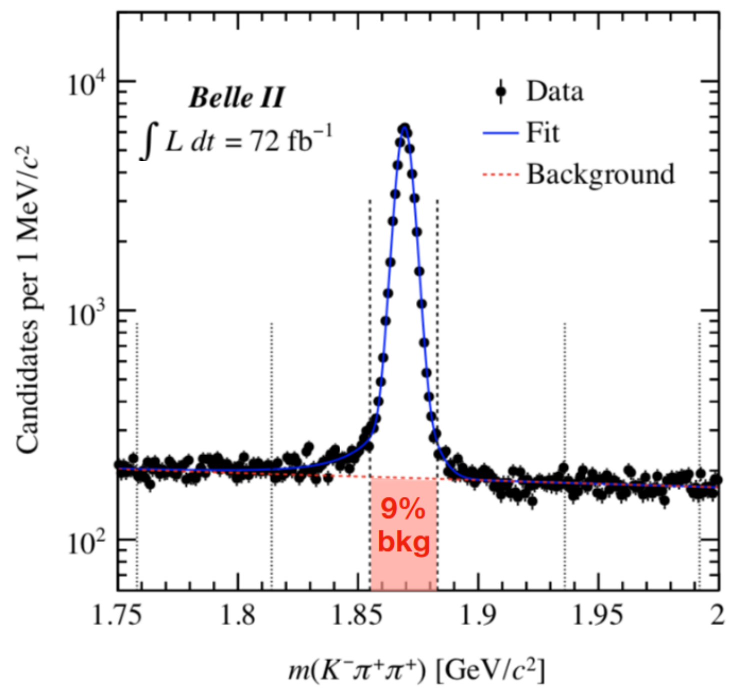
- b-bias
- s-scale
- R - resolution function
  - Gaussian: for D^+, Λ_c^+ and Ω_c^0
  - Double Gaussian: for D^0

D lifetime

- 171k and 59k signal candidates are reconstructed for $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ and $D^{*+} \to (D^+ \to K^-\pi^+\pi^+)\pi^0$ decays
- Remove D from B decays with $p^{\text{CMS}}(D^{*+}) > 2.5(2.6)$ GeV/c for $D^0(D^+)$
  - Avoid possible bias in the lifetime measurement
- Neglected 0.2% background in D^0 signal region (systematics assigned)
- 9% background in D^+ signal regions is included in the fit
  - Background: zero-lifetime + two non-zero lifetime components
- Dominant systematics: vertex detector alignment and background modeling

Source	$\tau(D^0)$ [fs]	$\tau(D^+)$ [fs]
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Total	0.80	3.10





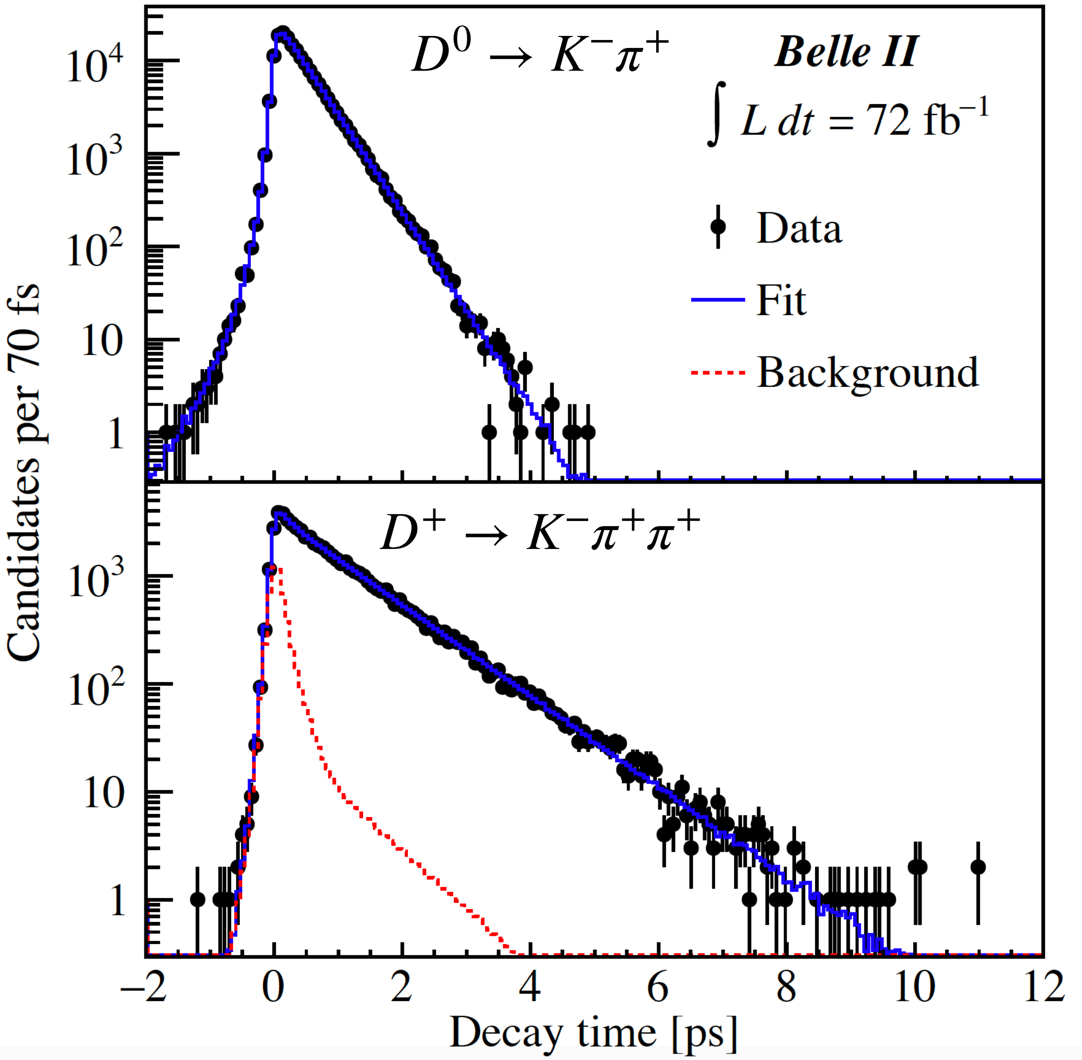
D lifetime

$$\tau(D^0) = 410.5 \pm 1.1(\text{stat.}) \pm 0.8(\text{syst.})\ \text{fs}$$

$$\tau(D^+) = 1030.4 \pm 4.7(\text{stat.}) \pm 3.1(\text{syst.})\ \text{fs}$$

Phys. Rev. Lett. **127** 21801(2021)

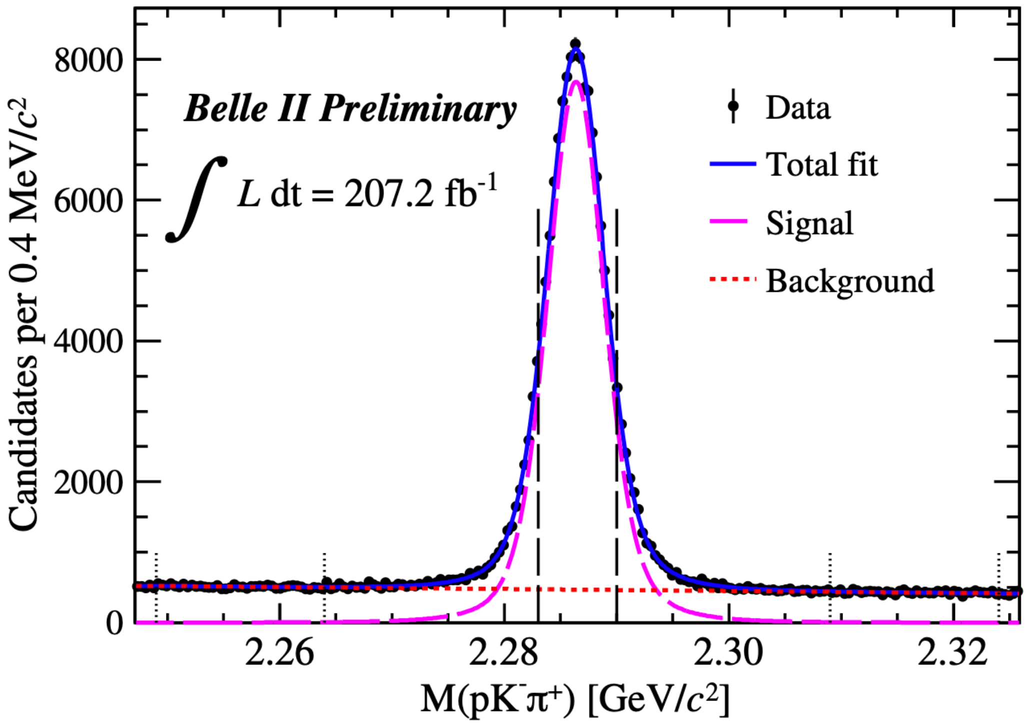
- More precise than and consistent with previous measurements
- Sub-1% accuracy establishes excellent detector performance
- Paves the way for additional lifetime measurements



Λ_c^+ lifetime

- Low-background sample of $\Lambda_c^+ \to pK^-\pi^+$
  - 116k signal with 7.5% background in the signal region
- Potential bias due to $\Xi_c^{0/+} \to \Lambda_c^+\pi^{-/0}$
  - veto applied and corrected for remaining contamination
- Resolution modeling and vertex detector alignment are dominant source of systematics

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



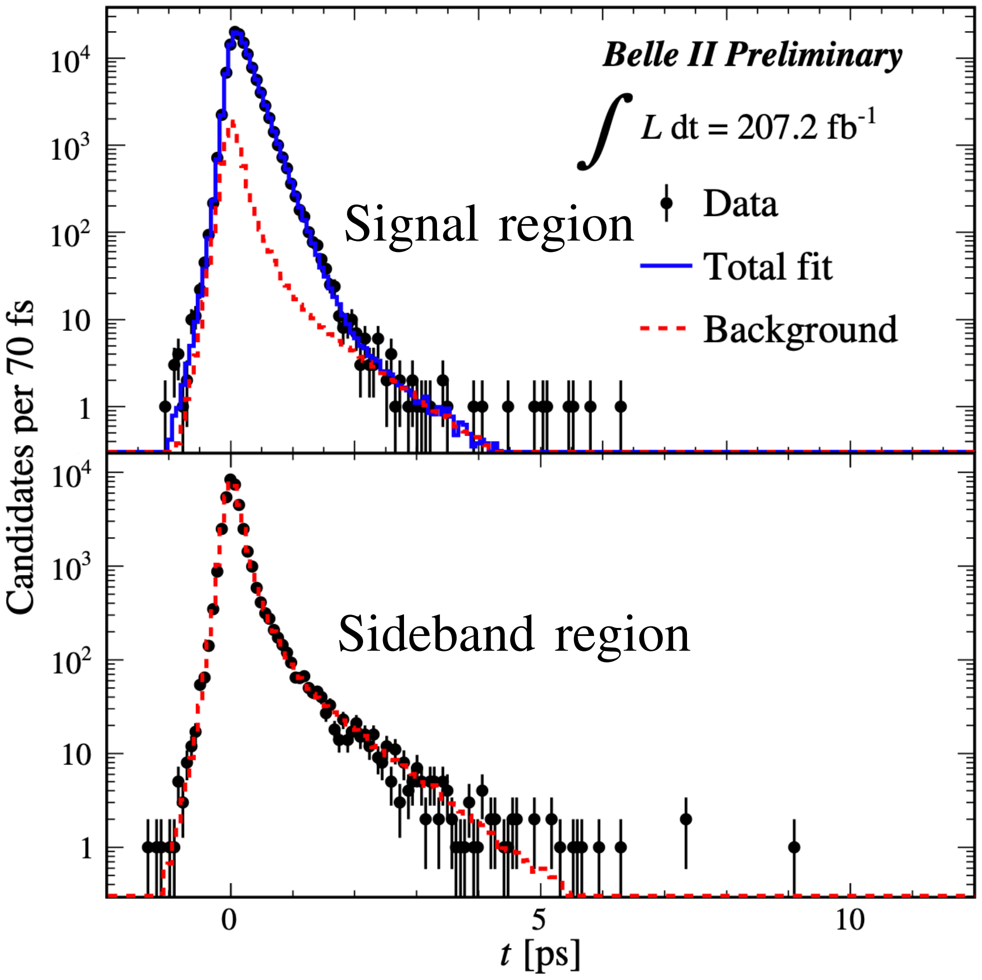
Λ_c^+ lifetime

Belle II preliminary result

$$\tau(\Lambda_c^+) = 203.2 \pm 0.9(\text{stat.}) \pm 0.8(\text{syst.})\ \text{fs}$$

arXiv: 2206.15227[hep-ex]

- World's best measurement of the Λ_c^+ lifetime
  - Consistent with current world averages
  - Slight tension with CLEO measurement remains
  - Benchmark for future baryon lifetime measurements



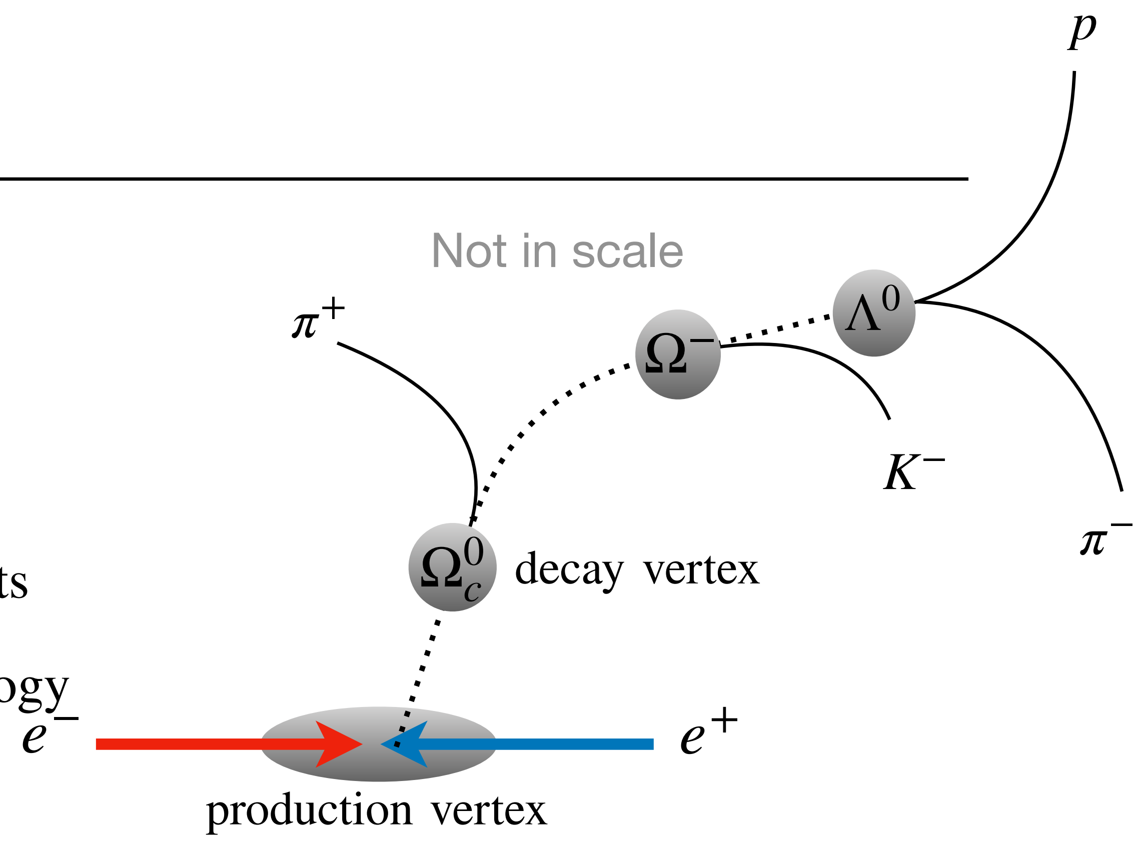
Ω_c^0 lifetime

New for ICHEP!

- ~90 signal candidates are reconstructed in the decay:

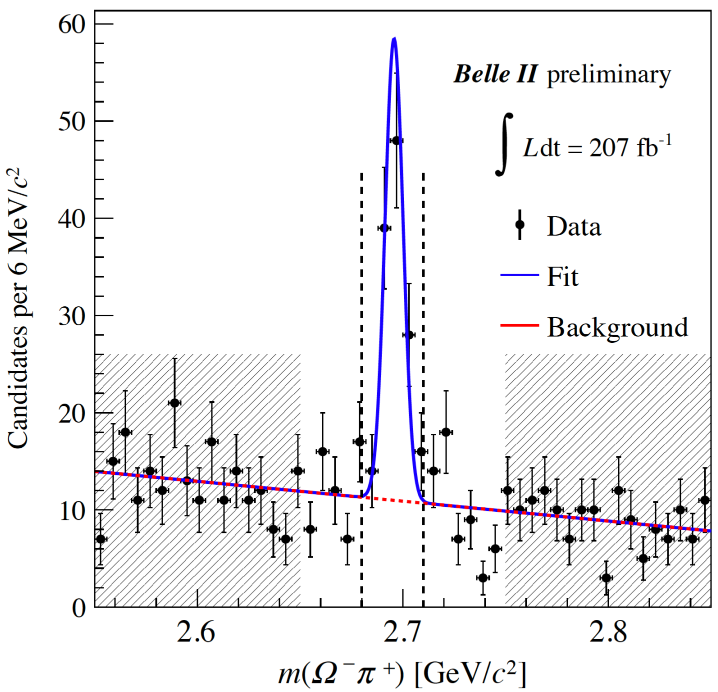
$$\Omega_c^0 \to \Omega^- \pi^+;\ \Omega^- \to \Lambda^0 K^-;\ \Lambda^0 \to p\pi^-$$

  - Background contamination in signal region: 33%
  - Background: zero-lifetime + non-zero lifetime components
- First Belle II lifetime measurement with complex decay topology
  - Two secondary decay vertices



- Dominant systematics: Modeling of background and resolution

Source	Uncertainty (fs)
Fit bias	3.4
Resolution model	6.2
Background model	8.3
Detector alignment	1.6
Momentum scale	0.2
Input charm masses	0.2
Total	11.0

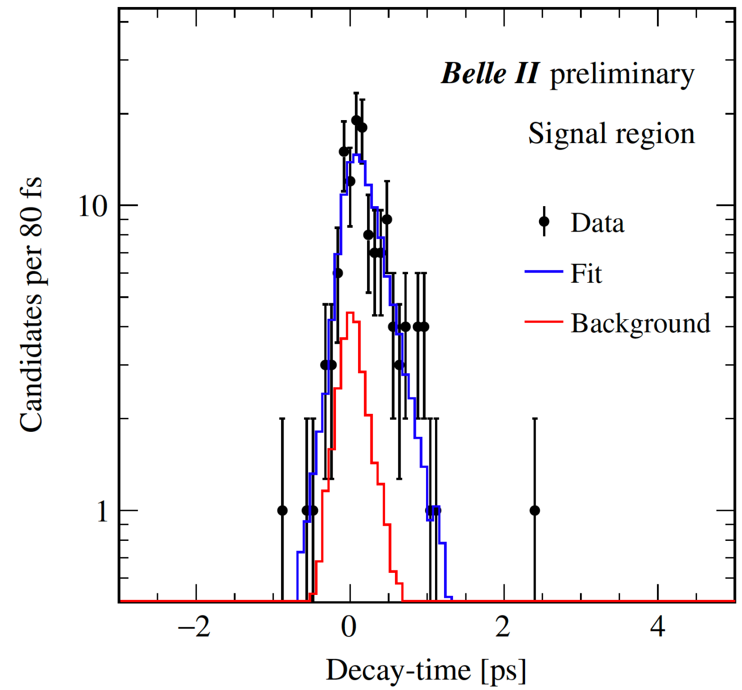


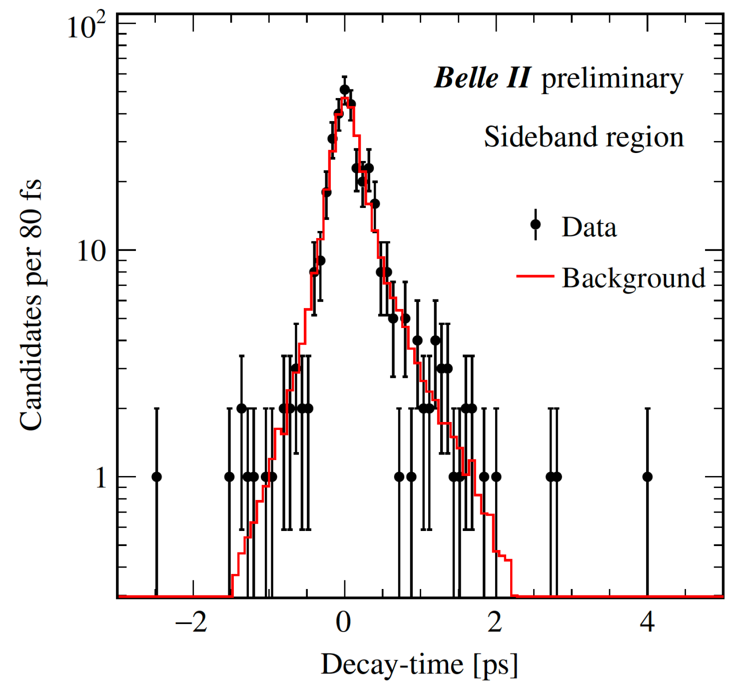
Ω_c^0 lifetime

Belle II preliminary result, new at ICHEP2022

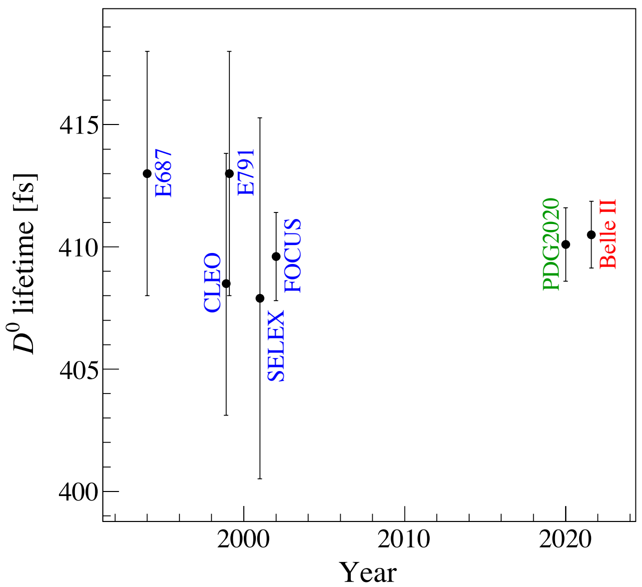
$$\tau(\Omega_c^0) = 243 \pm 48(\text{stat.}) \pm 11(\text{syst.})\ \text{fs}$$

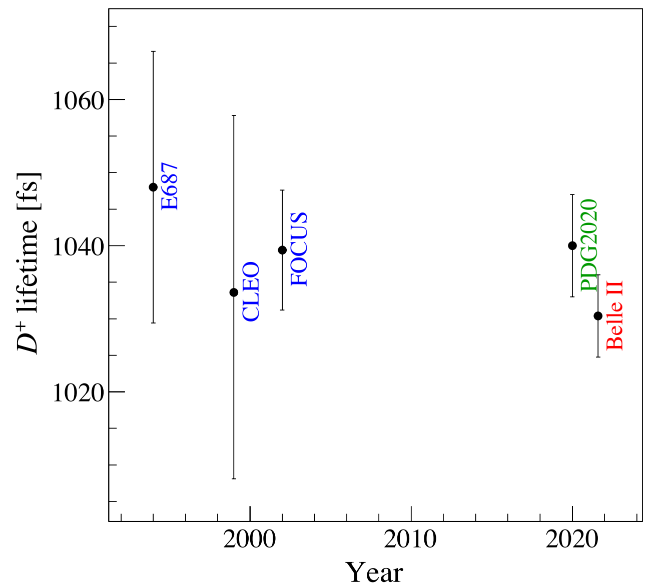
- Ω_c^0 is not the shortest lived singly charmed baryon
  - consistent with LHCb average
  - inconsistent with with pre-LHCb world average at 3.4σ
- Demonstrate the capabilities of the Belle II detector for vertexing complex decay topologies
  - Benchmark for future measurements with complex decay topology
- Limited by statistics and can improve with larger samples and additional decay modes

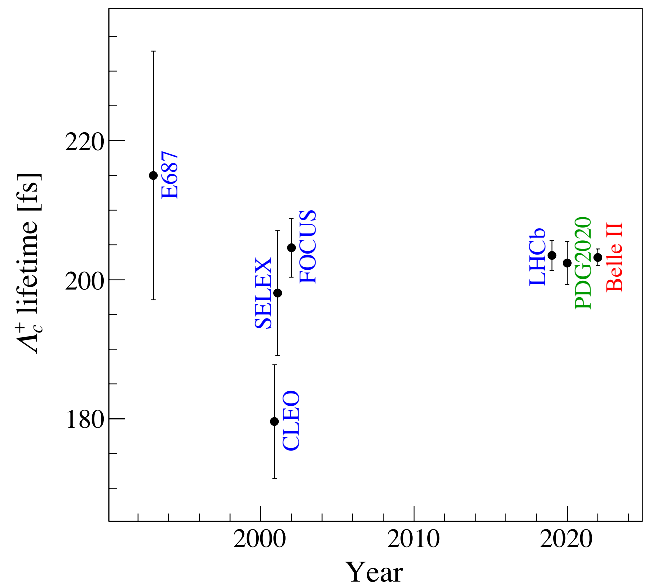


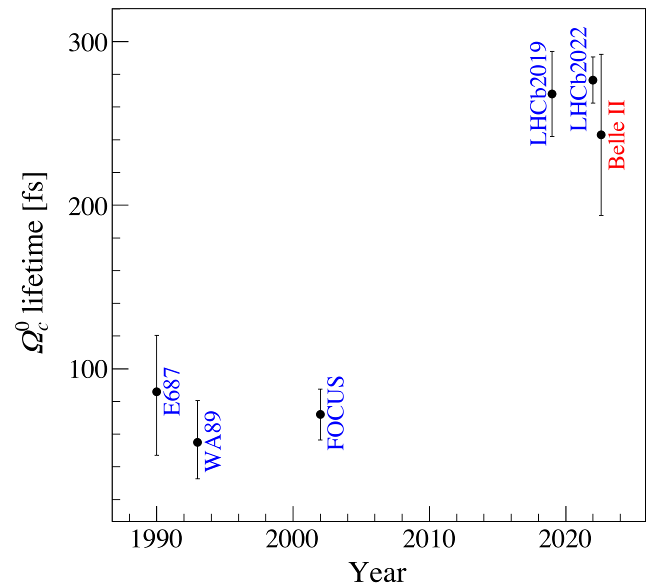


Conclusion









- Absolute lifetime measurements of charm hadrons from Belle II:
  - Improved knowledge of D lifetimes, with world-best measurements, after ~20 years

$$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8 \text{ fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1 \text{ fs}$$

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  - World's best Λ_c^+ lifetime measurement

$$\tau(\Lambda_c^+) = 203.2 \pm 0.9 \pm 0.8 \text{ fs}$$

Belle II preliminary, arXiv: 2206.15227[hep-ex]

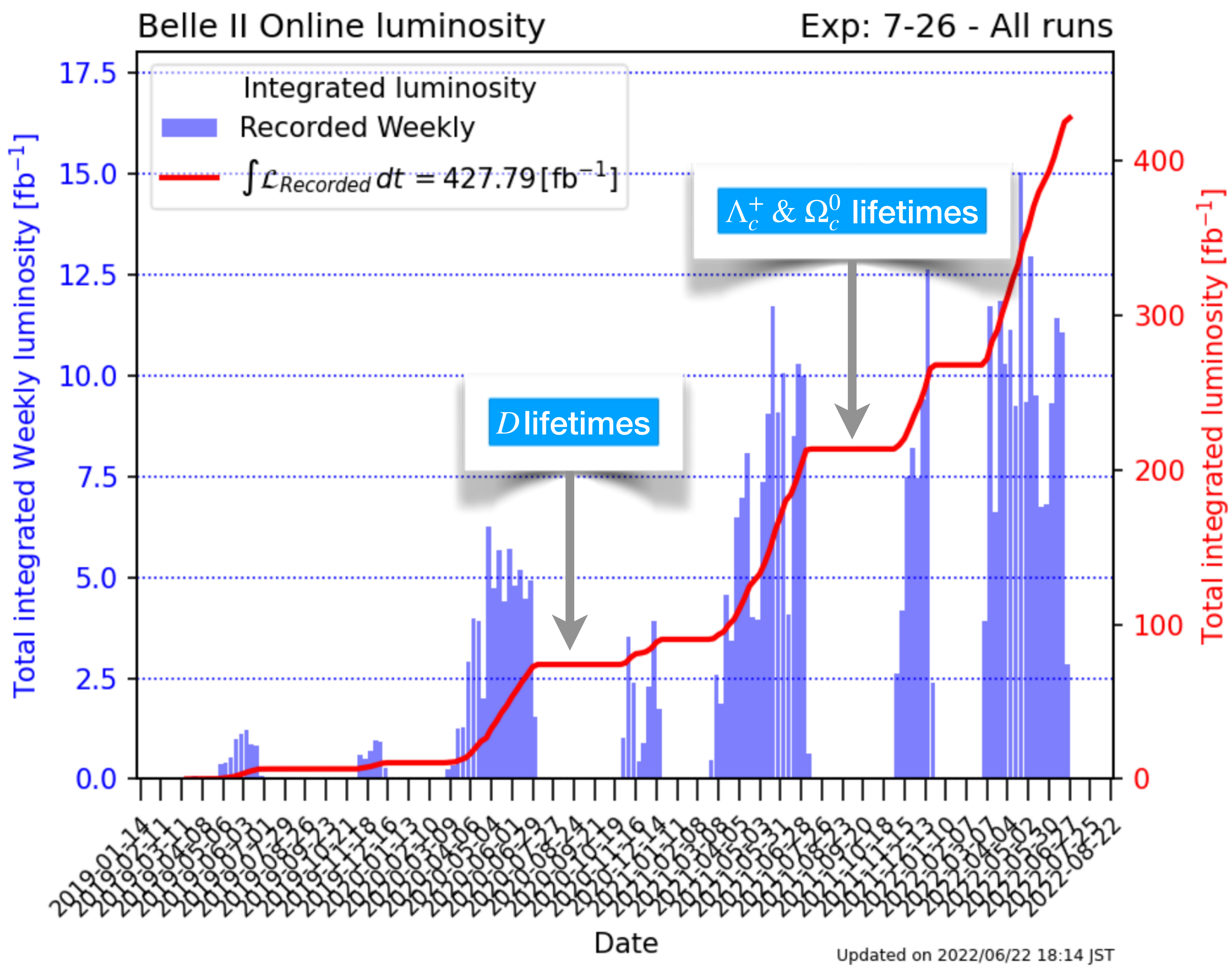
  - Independent confirmation of LHCb's finding that Ω_c^0 is not the shortest-lived weakly decaying charm baryon

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

Belle II preliminary, new at ICHEP2022

Backup

Belle II luminosity



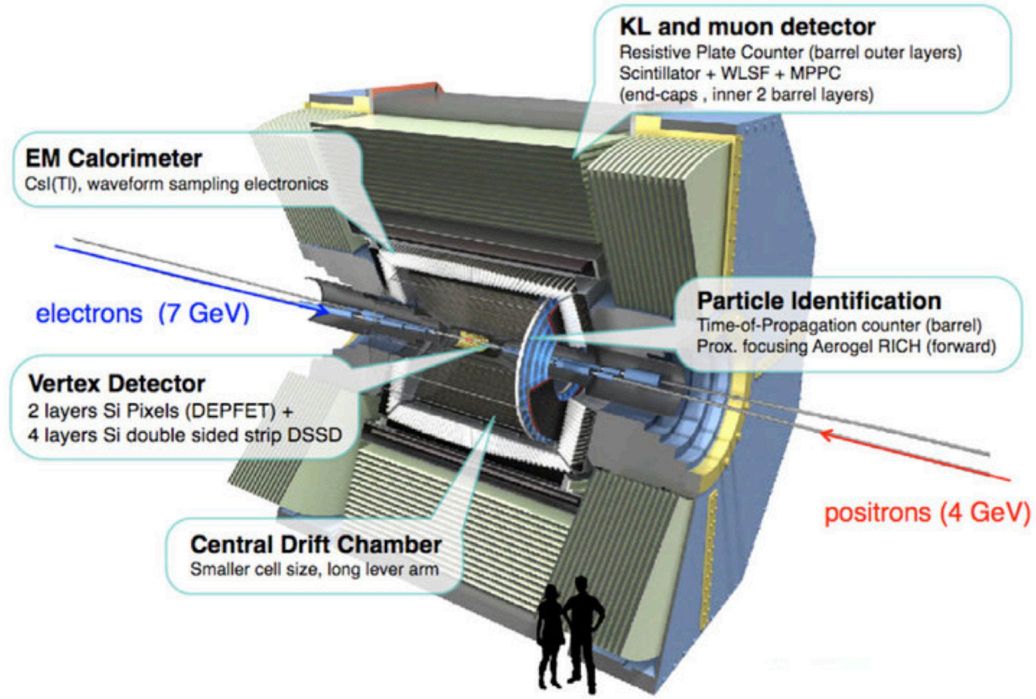
SuperKEKB and Belle II

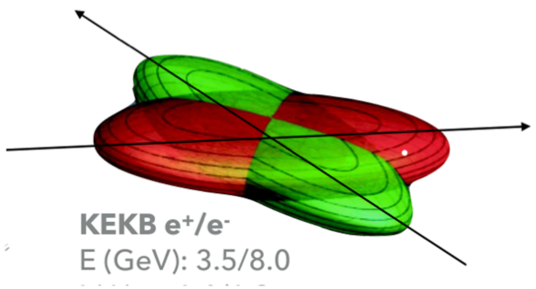
Belle II: general purpose detector situated at the interaction point of SuperKEKB.

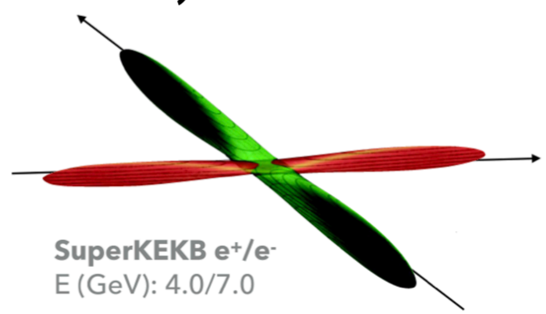
SuperKEKB: asymmetric $e^+ - e^-$ collider operating at $\Upsilon(4S)$ resonance.

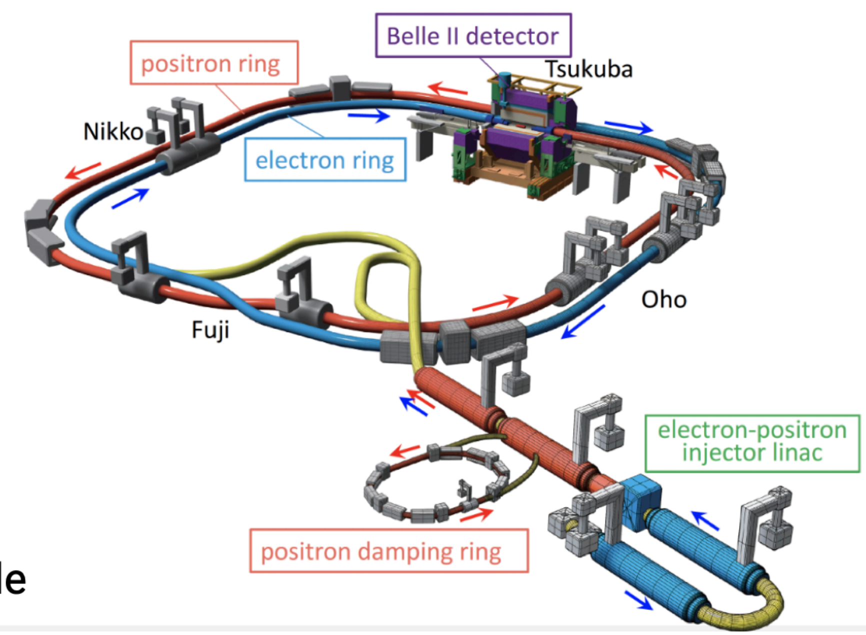
Operation:

- Recorded $\approx$ 430 fb^{-1};
- Achieved world record: $\mathcal{L} = 4.7 \cdot 10^{34} \text{cm}^{-2}/\text{s}$ (more than twice of KEKB/Belle).

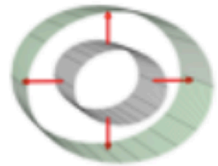
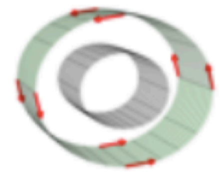
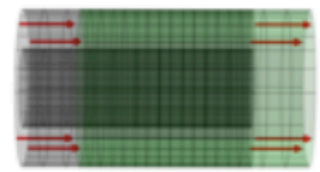
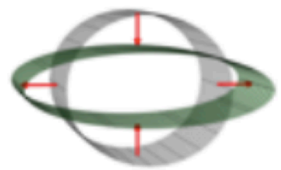
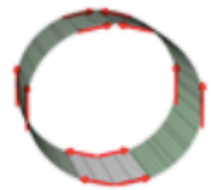
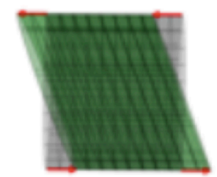
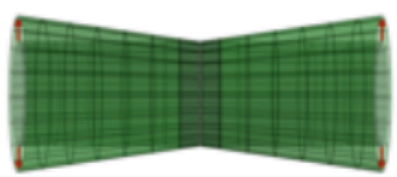
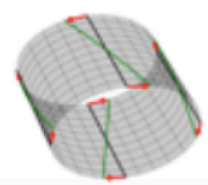








Weak modes of vertex detector misalignment

	Δr	$r\Delta\phi$	Δz
r	**Radial expansion** $\Delta r = c_{scale} \cdot r$ 	**Curl** $r\Delta\phi = c_{scale} \cdot r + c_0$ 	**Telescope** $\Delta z = c_{scale} \cdot r$ 
ϕ	**Elliptical expansion** $\Delta r = c_{scale} \cdot \cos(2\phi) \cdot r$ 	**Clamshell** $\Delta\phi = c_{scale} \cdot \cos(\phi)$ 	**Skew** $\Delta z = c_{scale} \cdot \cos(\phi)$ 
z	**Bowing** $\Delta r = c_{scale} \cdot \lvert z \rvert$ 	**Twist** $r\Delta\phi = c_{scale} \cdot z$ 	**Z expansion** $\Delta z = c_{scale} \cdot z$