Precise measurements of the *D* meson lifetimes

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Belle II

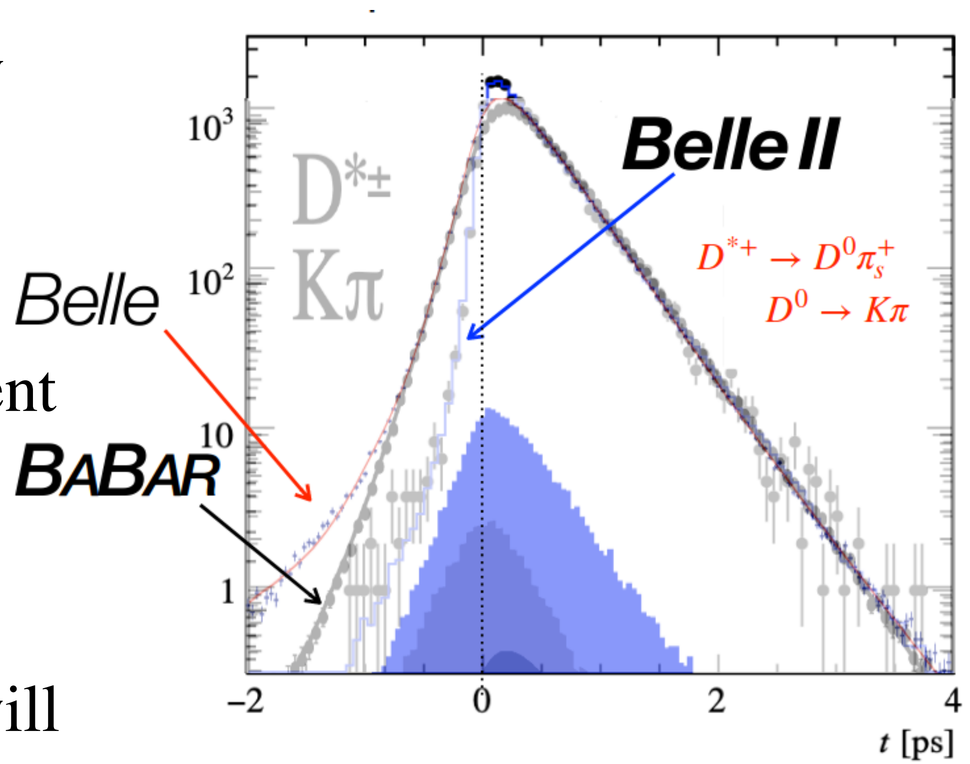
Brookhaven National Laboratory

Introduction

- Accurate prediction of charm meson lifetime is challenging due to QCD contributions to the decay amplitudes and it is an important ingredient to many theoretical calculations as well as experimental measurements.

- The D^0 and D^+ lifetimes rely on a single measurement made by FOCUS collaboration, two decades ago. (Not measured at Belle or BaBar)

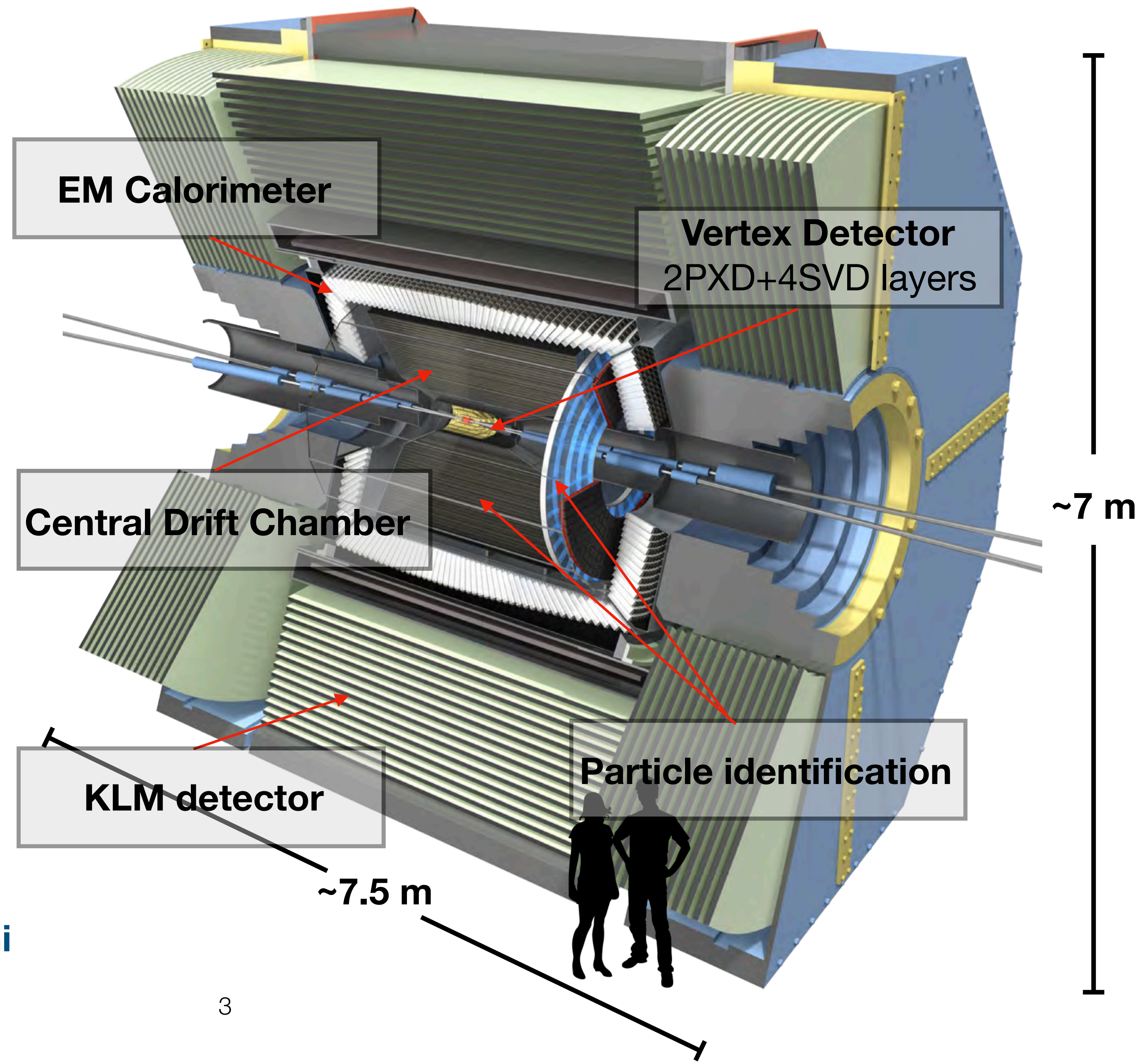
- The lifetime measurement with early Belle II data will demonstrate the excellent vertexing capability of the Belle II detector which is essential for future analyses of decay-time-dependent effects.



G. Casarosa, ICHEP 2020

Belle II detector

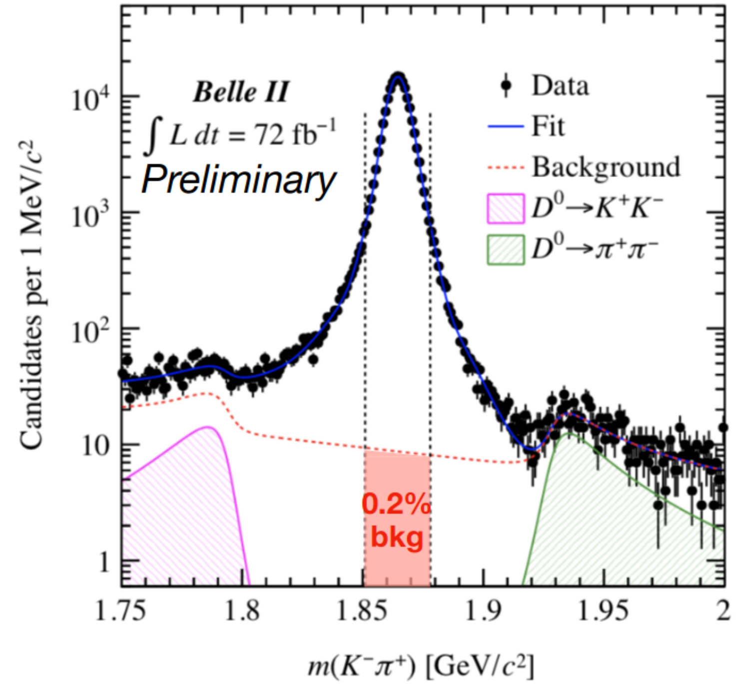
- Second generation *B*-factory detector at SuperKEKB e^+e^- collider, aiming to collect 50 times the Belle data.
- SuperKEKB: nano-beam scheme to achieve larger instantaneous luminosity.
- Improved vertexing w.r.t. Belle. (First layer of silicon pixel is close (1.4 cm) to interaction region, smaller Beam-spot)

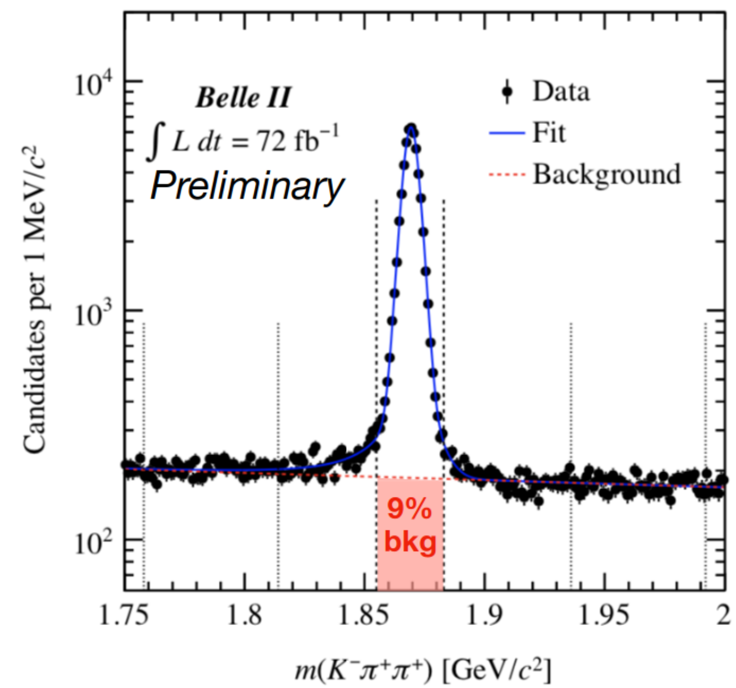


For details:
"Belle II: status and prospects"-T. Higuchi on 7 September 2021

Data sample

- The measurements use 72/fb of data sample collected by the Belle II detector at or near $\Upsilon(4S)$ resonance.
- The D^0 and D^+ lifetimes are measured by reconstructing $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ and $D^{*+} \to (D^+ \to K^-\pi^+\pi^+)\pi^0$ decays.
- To suppress D mesons coming from B mesons, the momentum of D^{*+} in C.M. frame is required to be greater than 2.5 (2.6) GeV/c for D^0 (D^+).
- ~171k D^0 signal decay candidates in signal region with a background contamination ~0.2%.
- ~59k D^+ signal decay candidates in signal region with a background contamination ~9%.

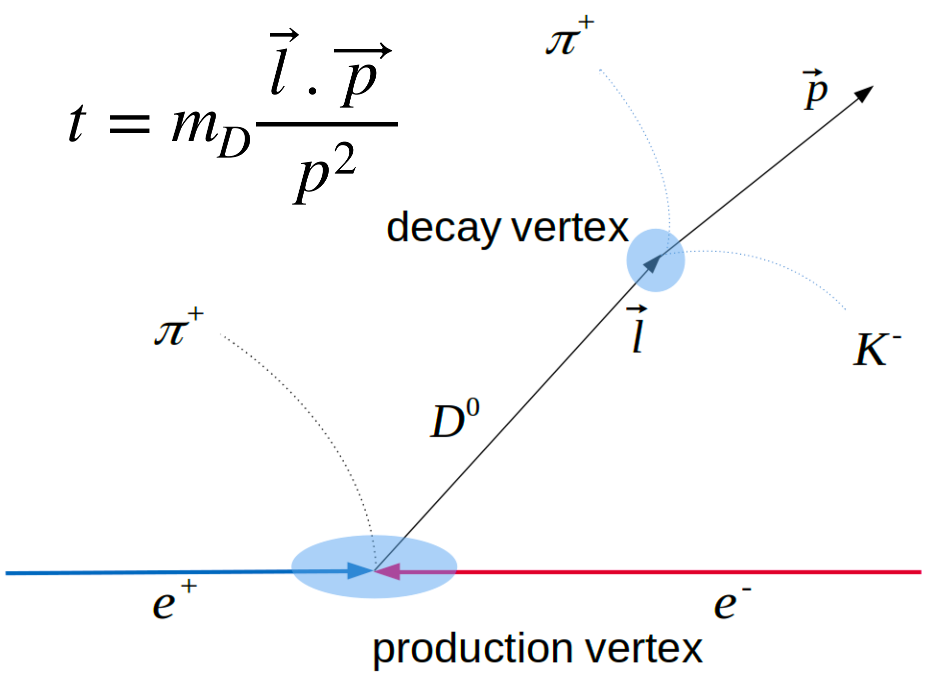




Lifetime fit

- Unbinned maximum-likelihood fit to the 2D distribution of decay time (t) and decay-time uncertainty (σ_t).
- The t and σ_t are obtained from the flight length between decay vertex and the production vertex.
- Signal distribution for t is a convolution of exponential with resolution function ($\mathrm{PDF}_{\mathrm{sig}}(\sigma_t)$ is fixed from data).

$$t = m_D \frac{\vec{l}\,.\,\vec{p}}{p^2}$$



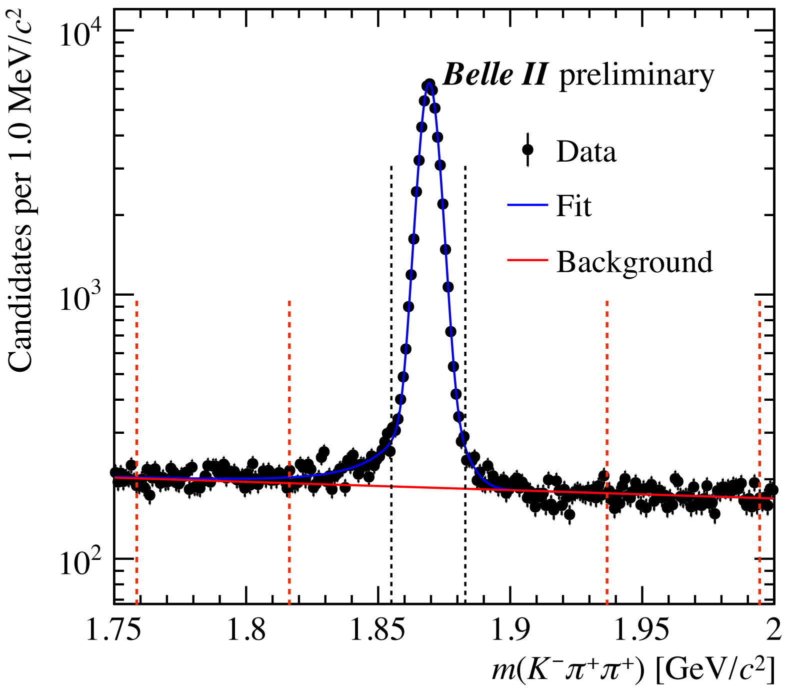
$$\mathrm{PDF}_{\mathrm{sig}}(t, \sigma_t \,|\, \tau, b, s) = \mathrm{PDF}_{\mathrm{sig}}(t \,|\, \sigma_t, \tau, b, s)\mathrm{PDF}_{\mathrm{sig}}(\sigma_t) \propto \int_0^\infty e^{-t_{\mathrm{true}}/\tau} R(t - t_{\mathrm{true}} \,|\, b, s\sigma_t) dt_{\mathrm{true}} \mathrm{PDF}_{\mathrm{sig}}(\sigma_t)$$

- This is the total PDF for D^0 where sub-1% background is ignored (a systematic uncertainty is assigned).
- Resolution model (decided from decay-time pull): a double (single) Gaussian with common mean for D^0 (D^+) .

τ – lifetime
b – bias parameter
s – scaling parameter

Background components

- In D^+ case, sidebands represent a good proxy of the background in signal region and hence the data sidebands are used to model the background in signal region.



$$\text{PDF}(t, \sigma_t) = (1 - f_b)\text{PDF}_{\text{sig}}(t, \sigma_t) + f_b \text{PDF}_{\text{bkg}}(t, \sigma_t)$$

- An empirical model is used for background in t ($\text{PDF}_{\text{bkg}}(\sigma_t)$ is fixed from data sideband):

$$\text{PDF}_{\text{bkg}}(t) = (1 - f_{bl})R(t\,|\,b, s\sigma_t) + f_{bl}[f_{bl1}\text{PDF}_{bl1}(t\,|\,\sigma_t, \tau_{b1}, b, s) + (1 - f_{bl1})\text{PDF}_{bl2}(t\,|\,\sigma_t, \tau_{b2}, b, s)]$$

where τ_{b1} and τ_{b2} are lifetimes of the background.

- Signal and sideband regions are fit simultaneously with all shape parameters but background fraction free. f_b is constrained to the result of the mass fit.

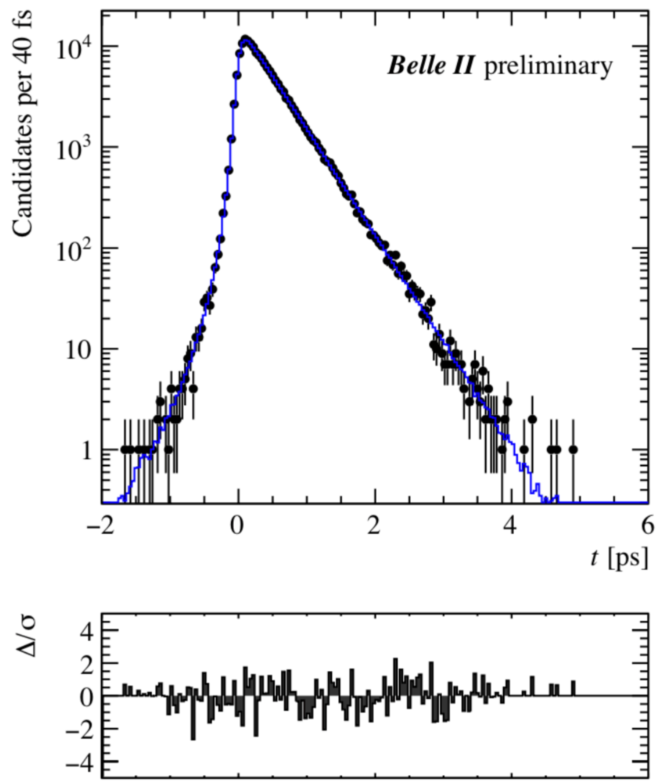
Results

- Lifetime fitter is tested using the simulated samples and the results are consistent with the generated lifetimes.
- Results are more precise than, and consistent with, the respective world-average values of 410.1±1.5 (1040±7) fs for D^0 (D^+).

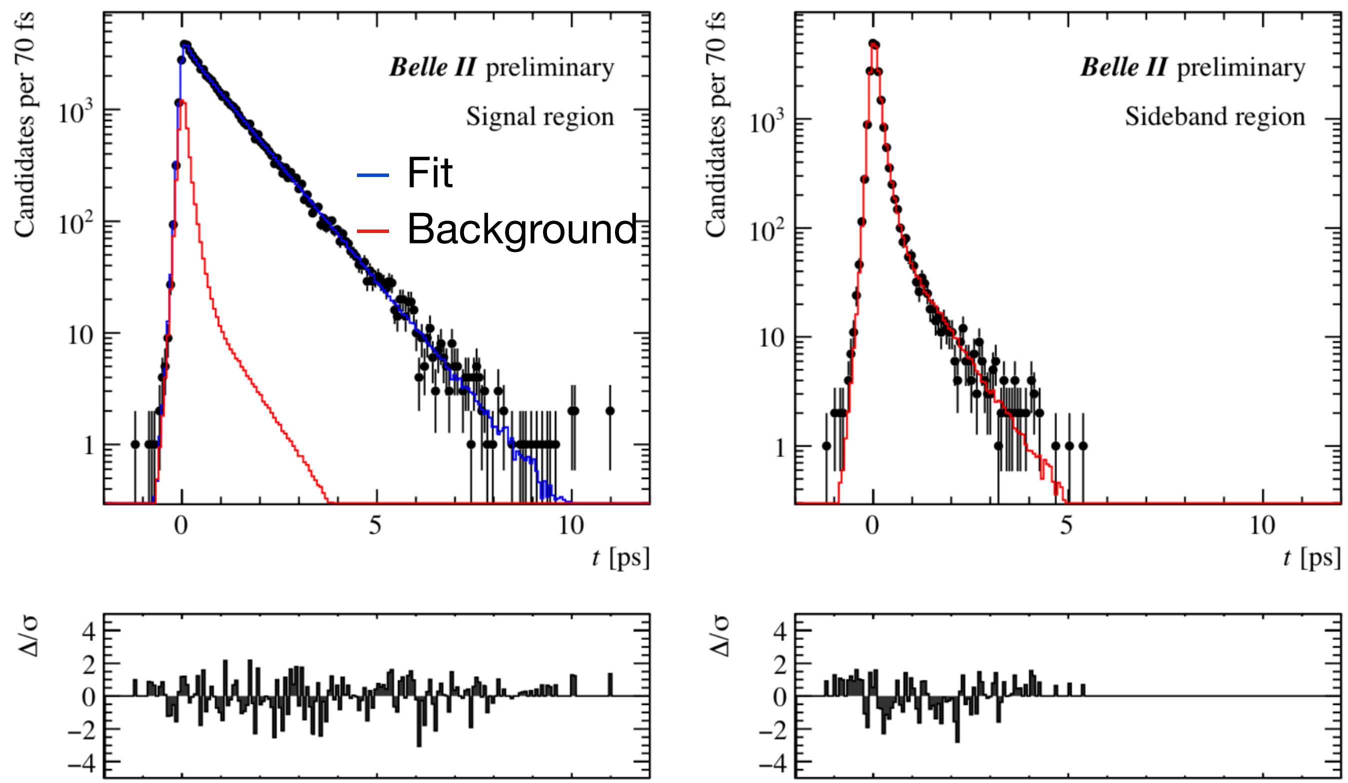
Belle II preliminary

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

$$\tau(D^+) = 1030.5 \pm 4.7 \text{ fs}$$



$D^0 \to K^-\pi^+$



$D^+ \to K^-\pi^+\pi^+$

Systematic uncertainties

Source	Uncertainty (fs)	
	$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$
Momentum scale	0.19	0.48
Input charm masses	0.01	0.03
Resolution Model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Total	0.8	3.1

- Uncertainties in the scaling of momentum and relative error on the D meson masses are assigned as systematic uncertainties.
- Resolution Model: neglect a correlation between t and σ_t in the nominal fit model.
  - The nominal model is fit to 1000 simulated samples of signal-only decays (the same size as data). Average absolute deviations of measured lifetimes from true value are assigned as systematic uncertainty.

Systematic uncertainties

- Backgrounds

  1. $D^0 \to K^-\pi^+$: due to neglecting sub-1% background. 500 simulated samples of generic e^+e^-collision (same statistics and S/B ratio as the data) fit with nominal model and average bias is assigned as systematics.

  2. $D^+ \to K^-\pi^+\pi^+$: due to mismatch between data and simulation in the sidebands. Average bias returned from 1000 pseudo experiments mimic similar disagreement between signal and sidebands is assigned as systematic uncertainty.

- Detector alignment: misalignment of tracking detectors may affect the decay-length determination and hence the lifetime.

  - Samples (same statistics as data) are simulated by introducing realistic misalignment effects. The difference in lifetime residual for a given misalignment configuration and that from a perfectly aligned sample is assigned as systematics.

Conclusion

- We measured the D^0 and D^+ lifetimes based on 72/fb of data collected at Belle II:

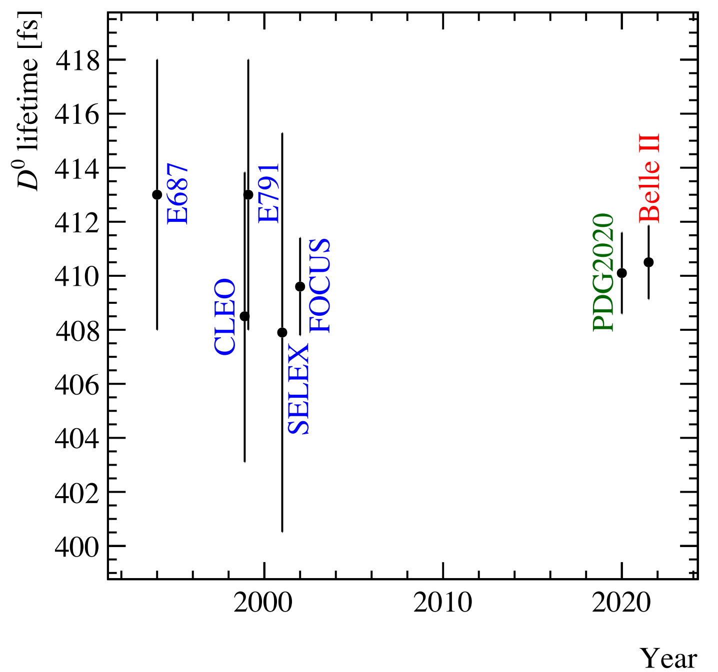
$$\tau(D^0) = 410.5 \pm 1.1(\text{stat}) \pm 0.8(\text{syst})\ \text{fs}$$

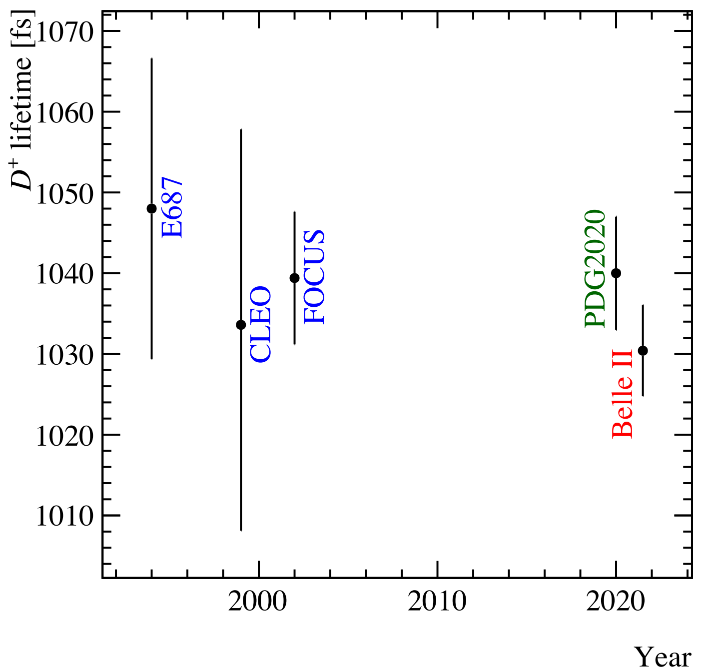
$$\tau(D^+) = 1030.5 \pm 4.7(\text{stat}) \pm 3.1(\text{syst})\ \text{fs}$$

- World's best results of D^0 and D^+ lifetime, consistent with current world averages.
- Sub-1% accuracy establishes excellent performance of Belle II detector.
- Also estimated the lifetime ratio by considering correlations between uncertainties:

$$\tau(D^+)/\tau(D^0) = 2.510 \pm 0.015$$

- The results are submitted to PRL (arXiv:2108.03216).

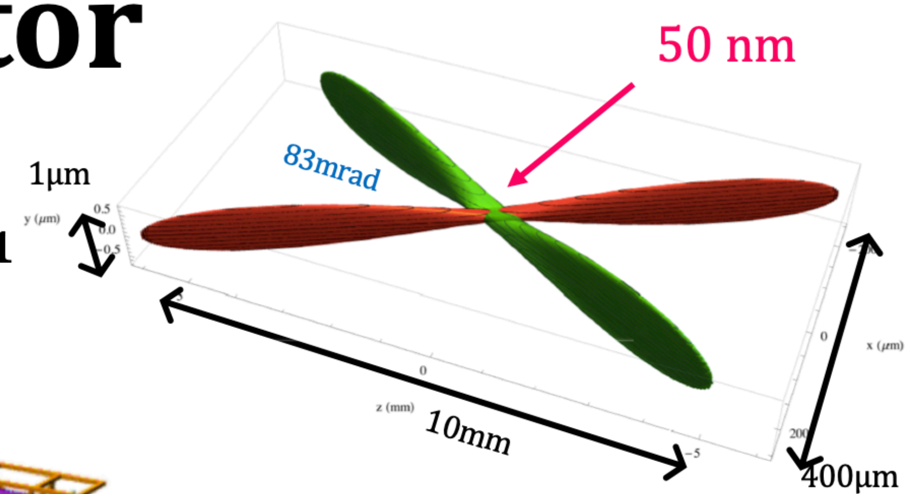




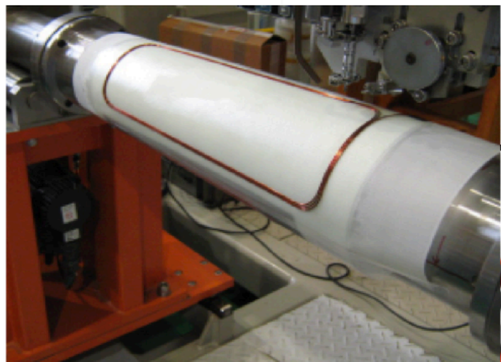
Backup

SuperKEKB Accelerator

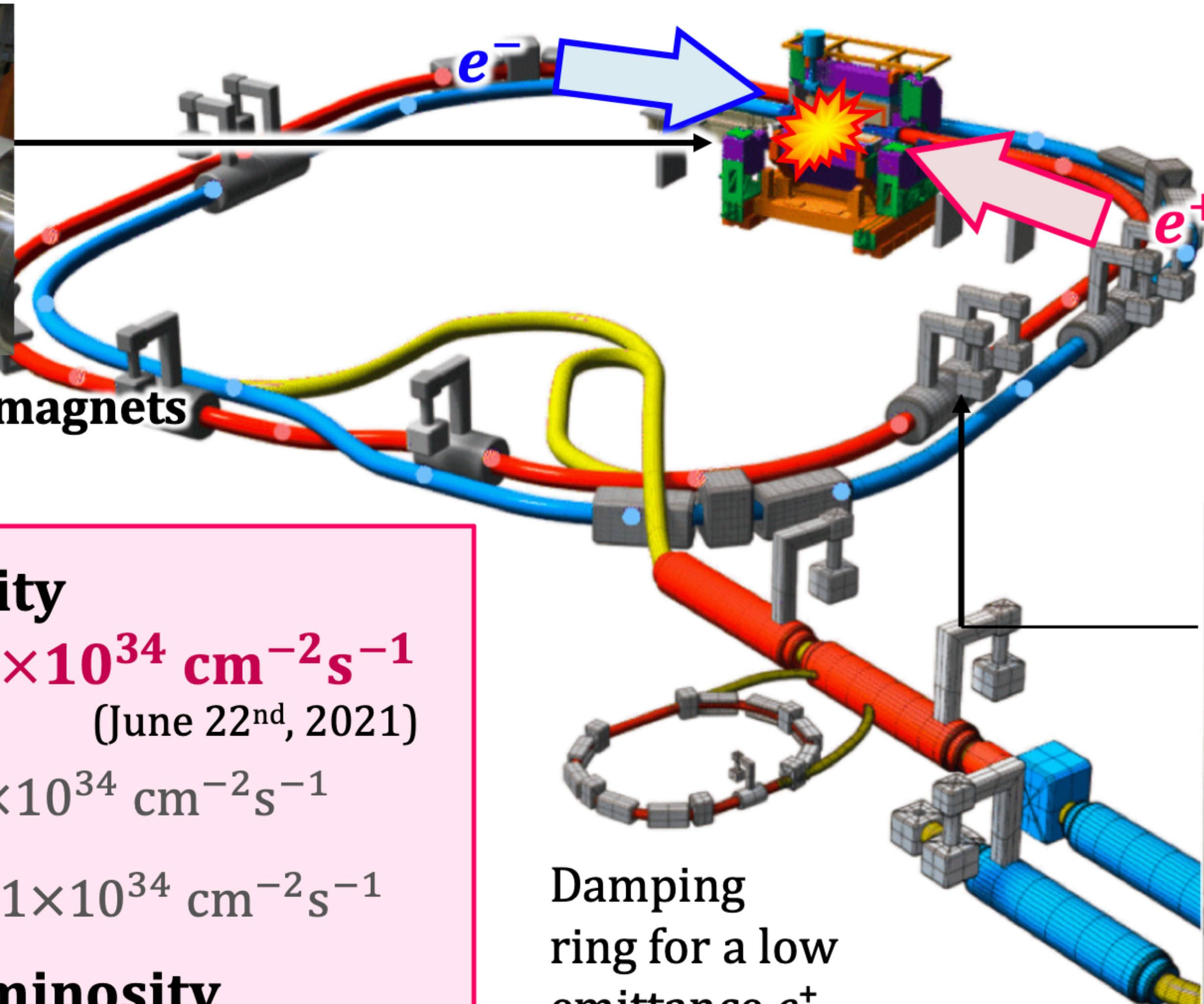
- **7 GeV e^- + 4 GeV e^+ $\rightarrow b\bar{b}, \tau^+\tau^-, c\bar{c}, \ldots$**
- **Ultimate luminosity: $6.5\times10^{35}\ \mathrm{cm^{-2}s^{-1}}$**
- **Target integrated luminosity: $50\ \mathrm{ab^{-1}}$**



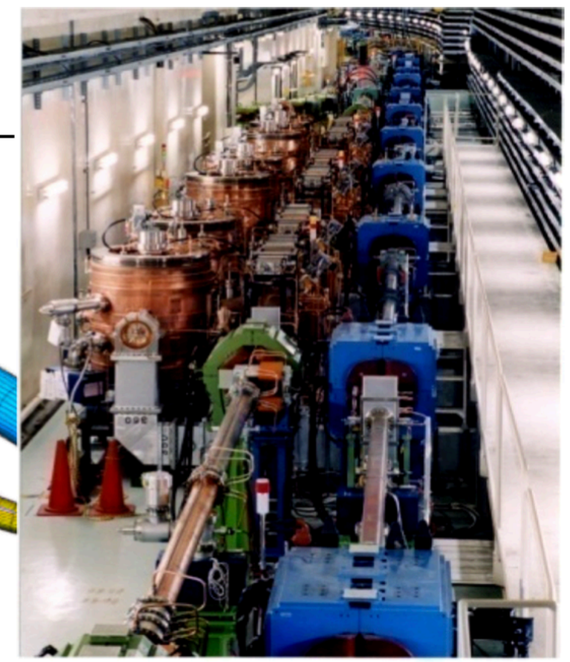
Nano-beam scheme



New final focusing magnets



More RF cavities to increase the beam currents



Damping ring for a low emittance e^+ beam

- **Peak luminosity**

  $\mathcal{L}_{\mathrm{peak}}^{\mathrm{SKEKB}} = 3.1\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (June 22nd, 2021)

  $\mathcal{L}_{\mathrm{peak}}^{\mathrm{KEKB}} = 2.1\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$

  $\mathcal{L}_{\mathrm{peak}}^{\mathrm{PEP-II}} = 1.21\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$

- **Integrated luminosity**

  $213\ \mathrm{fb^{-1}}$

Belle II Detector

K. R. Nakamura, talk at TIPP2021 (2021);
BELLE2-NOTE-PL-2020-014;
BELLE2-NOTE-PL-2020-027.

Strip and pixel vertex detector

- Inner 2 layers: Pixel detector
- Outer 4 layers: Strip detectors

$\sigma_{\text{min}}^{\text{SVD}} \approx$ 10-25μm

Drift chamber (p, PID)

- Longer lever arm than Belle
- Smaller cell size than Belle

eff. × accept. ≥ 0.8 (for $p_T > 1$ GeV/c)

PID detectors (K/π separation)

- Barrel: Time-Of-Propagation counters
- Endcap: Aerogel RICH
- Wrong PID: x0.5 smaller than Belle

$\epsilon_K^{\text{average}} \gtrsim 0.8$ (for all p region)

EM calorimeter (E_e, E_γ)

- CsI(Tl) + wave-form sampler

$\epsilon_{e^\pm} \approx 94\%$, wrong $h^\pm \to e^\pm$ ID $\approx 2\%$

K_L^0/μ detector

- Outer barrel: RPC (streamer mode)
- Endcap, inner barrel: Sci. + WL shifter

$\epsilon_{\mu^\pm} \approx 90\%$, wrong $h^\pm \to \mu^\pm$ ID $\approx 4\%$