Charm Lifetime Measurements at Belle II

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on behalf of the Belle II collaboration

August 25, 2022

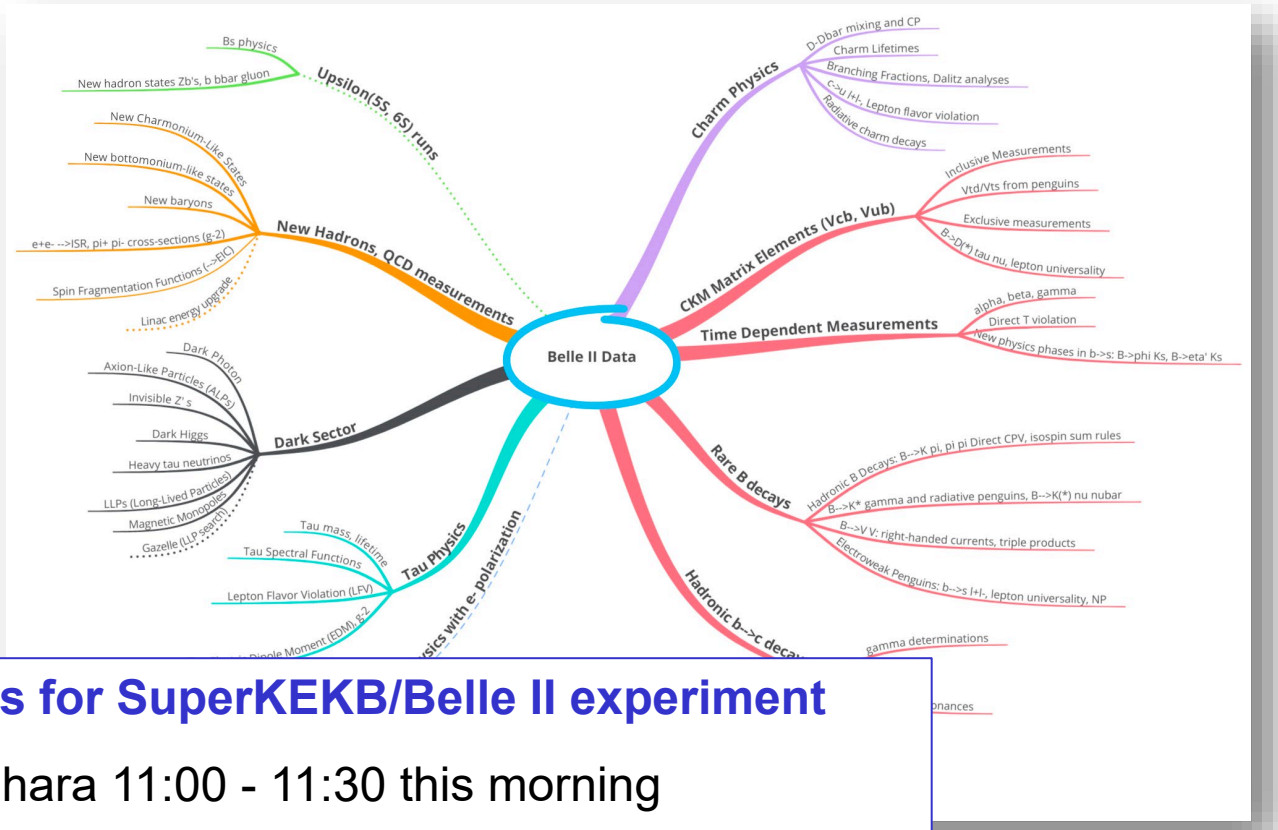
The 15th Asia Pacific Physics Conference (APPC 15)

South Korea and Online

Belle II Physics Prospects

https://confluence.desy.de/display/BI/Snowmass+2021

- **Charm decays**
- Next precision **CKM matrix**
  - Semileptonic B decays (CKM elements)
  - Hadronic B decays (angles and CPV)
  - Time dependent CP violation
- τ physics
- Hadron spectroscopy
- **Rare decays**
- New physics
  - Lepton f
  - Dark sec



Status and prospects for SuperKEKB/Belle II experiment

Keisuke Yoshihara 11:00 - 11:30 this morning

Time-dependent CP violation measurements at Belle II

Ming-Chuan Chang 14:45 – 15:00 after this talk

Introduction and Motivation

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

- At SuperKEKB, $\sigma_{c\bar{c}} \sim \sigma_{b\bar{b}}$, which creates large charm samples from continuum.
  - note: for charm lifetime, b decay products are not used.
- $e^+ e^-$ collision gives clean environment, creating less bias in selection and reconstruction.
- Small interaction region and the new Belle II vertex detector give strong constraints and better resolutions.

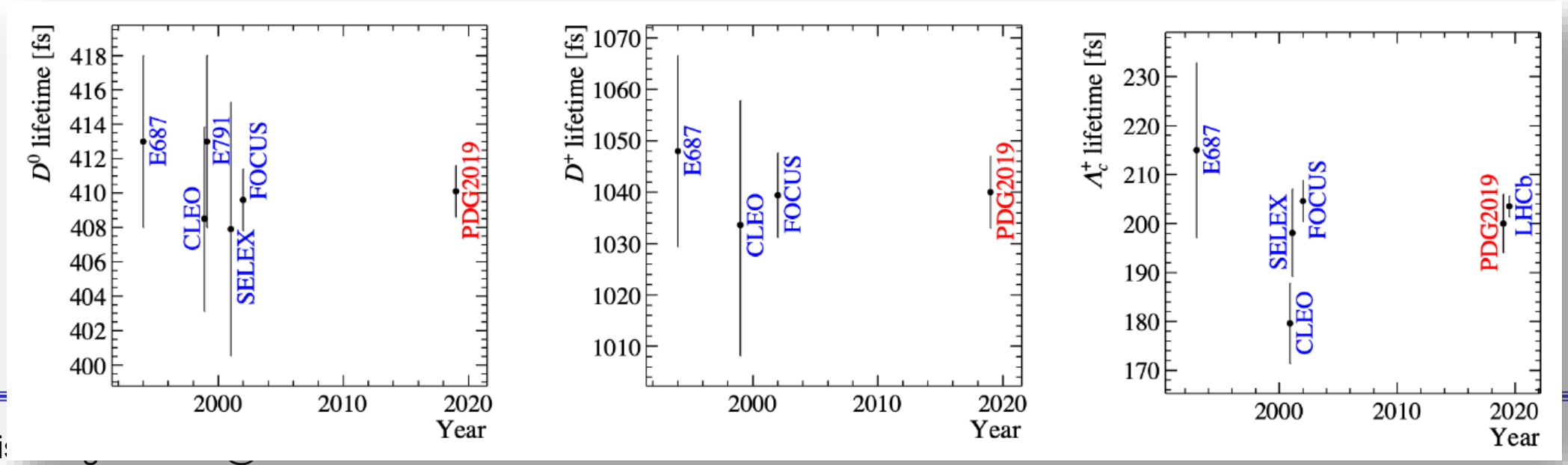
- A great opportunity to measure the world best charm lifetimes.

A Brief History of Charm Lifetime Measurements

Previously, charm particle lifetimes are dominated by

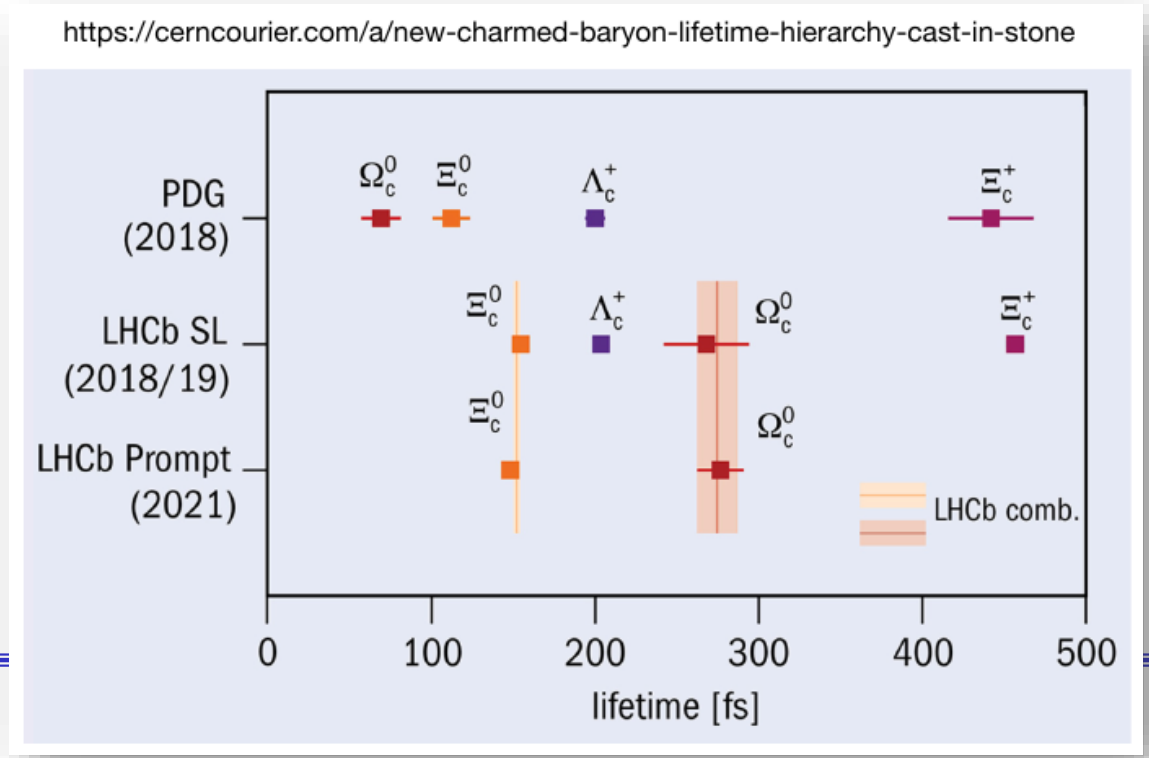
- D0 and D+
  - FOCUS (photon beam), SELEX (hyperon beam), CLEO (e+e-)
- Charm baryons
  - Dominated by LHCb, but its measurements are relative to D+ lifetime.

Belle II can measure lifetimes absolutely.

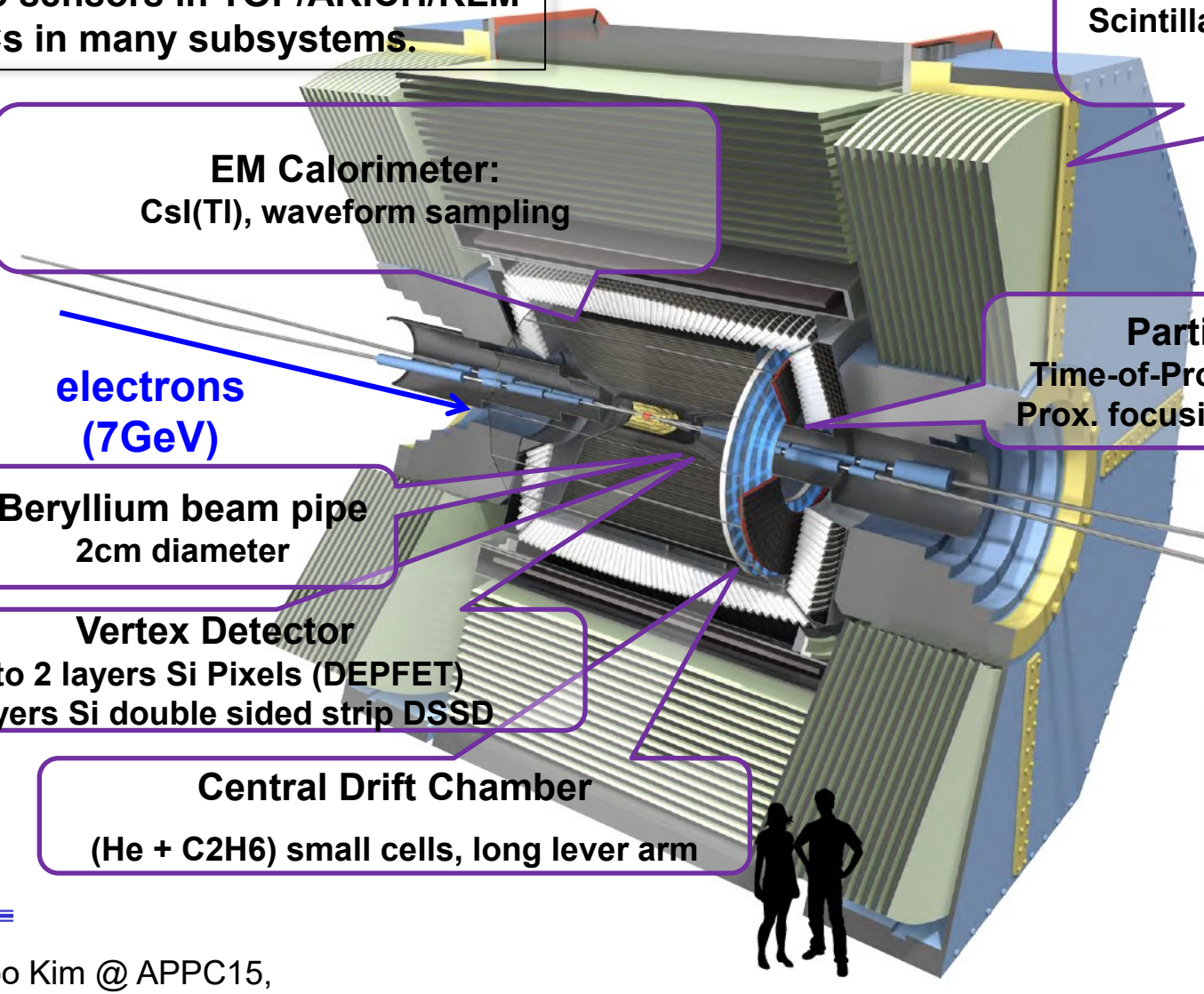


The Puzzle of Ω_c^0 Lifetime

- The effective models predicted the following lifetime order,
  $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$
- However, LHCb (2018 and 2021) measured $\tau(\Omega_c^0)$ four times larger than the previous measurements.
- Belle II can confirm or deny the LHCb findings.



The Belle II Detector



Pixelated photo sensors in TOP/ARICH/KLM
Front-end ASICs in many subsystems.

KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling

electrons (7GeV)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

Beryllium beam pipe
2cm diameter

positrons (4GeV)

Vertex Detector
1 to 2 layers Si Pixels (DEPFET)
4 layers Si double sided strip DSSD

Central Drift Chamber
(He + C2H6) small cells, long lever arm

Vertexing and Tracking Improved
Particle ID improved
Better background insensitivity
Higher event rate

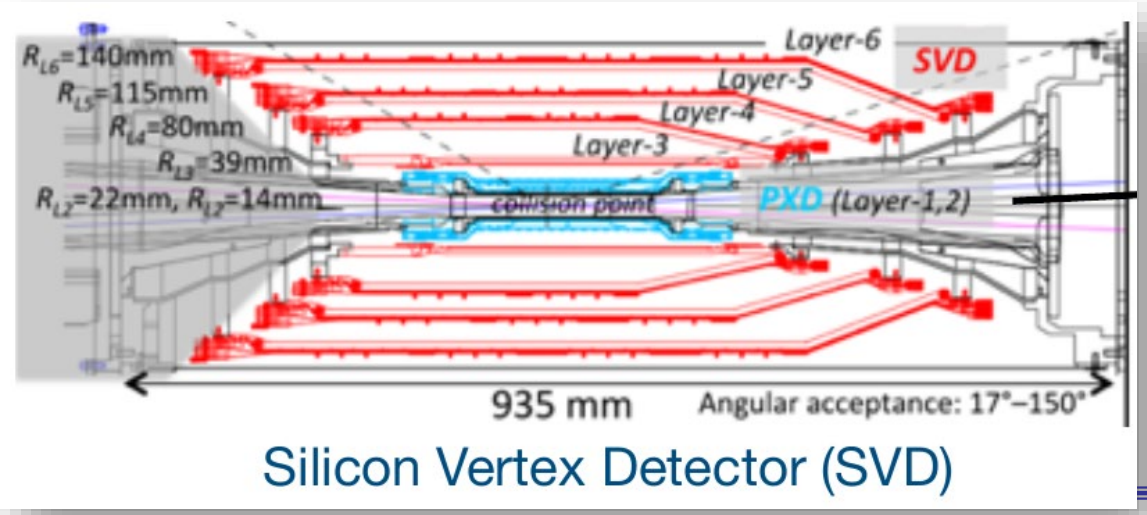
Belle II Vertex Detector

Inner most vertex detector consists of

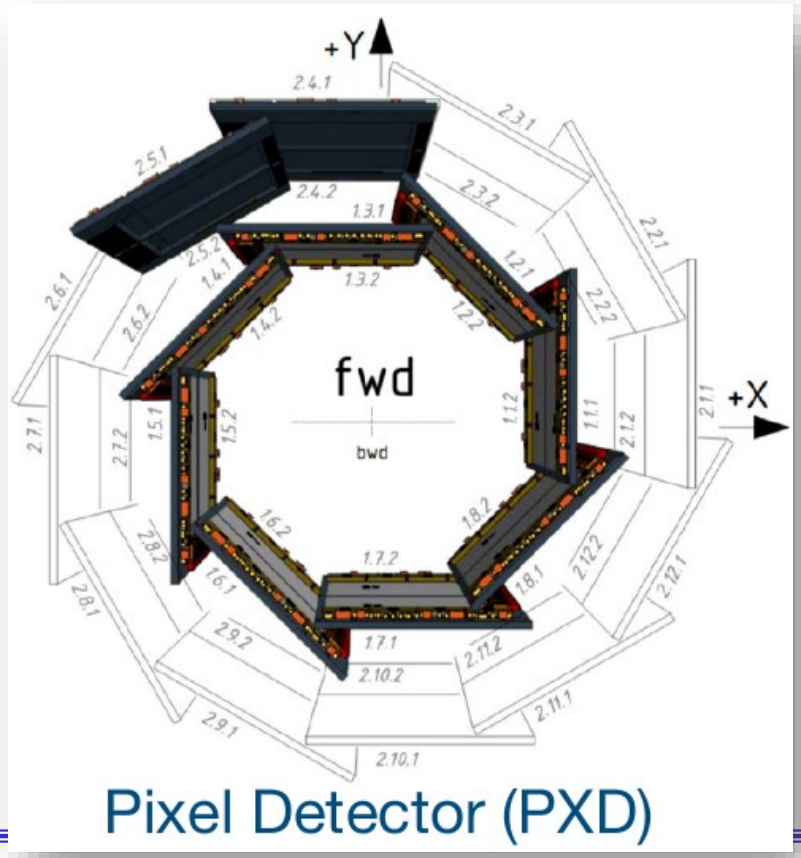
- 1 DEPFET layer (2nd layer will be completed in 2023) and 4 DSSD layers
- Resulting in two times better vertex resolution, improved efficiency for slow pions and Ks's, and better tracking against beam backgrounds w.r.t. Belle.

Alignment is crucial for lifetime measurements.

- Checked thoroughly during analysis.



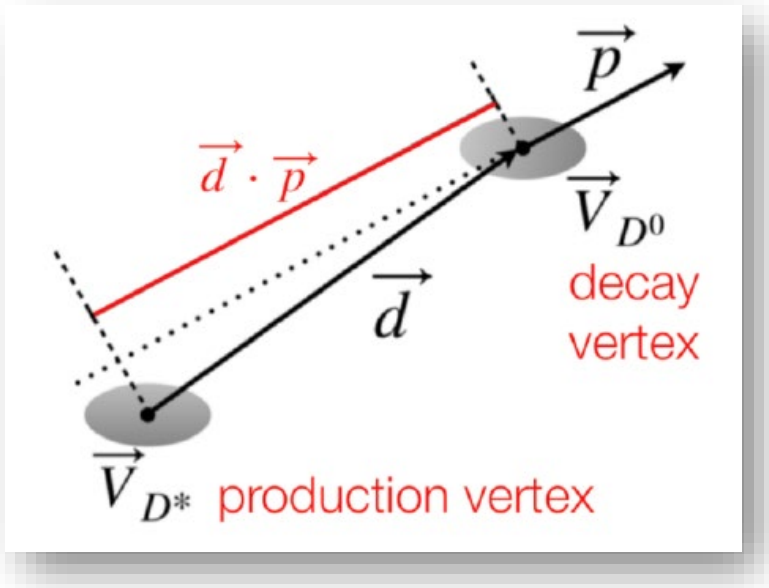
Silicon Vertex Detector (SVD)



Pixel Detector (PXD)

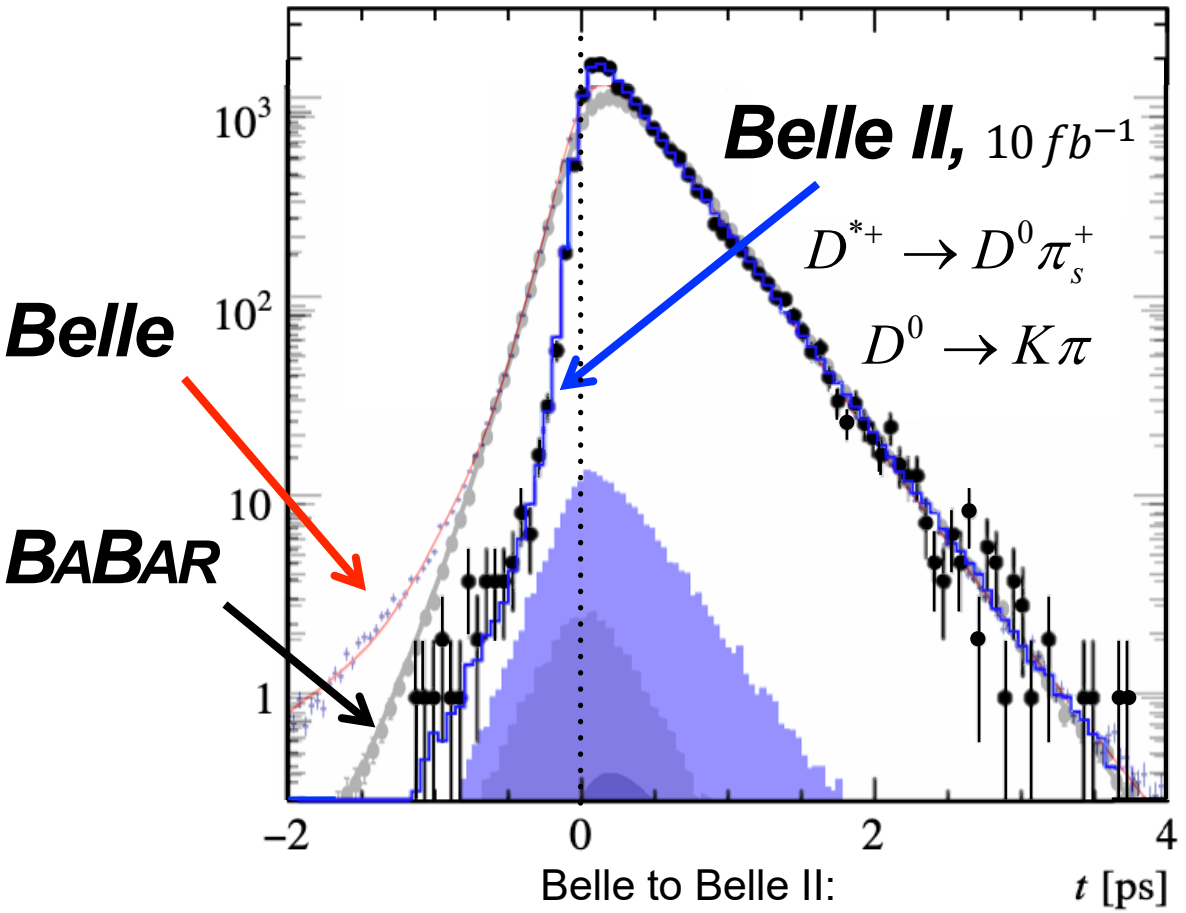
Proper Decay Time Reconstruction

$$t = \frac{m_D}{p}\vec{d}\cdot\hat{p}$$



Proper decay time =
distance between production and decay vertices
projected to the momentum vector
of reconstructed charmed meson/hadron

D^0 lifetime distribution comparison



Belle to Belle II:
2 times better vertex resolution,
20 times smaller beam spot size

Lifetime Fit

- Lifetime fit is applied to the t, σ_t distribution via an un-binned ML method.
  - The signal and sideband regions in invariant mass are fitted at the same time.
  - The background fraction is constrained by a fit to invariant mass distribution.
- The basic probability density function (PDF) used for the fit,

$$f(t,\sigma_t) = f_b \int e^{-t'/\tau} R(t-t'; b, s\,\sigma_t)\, dt'\, S(\sigma_t) + (1-f_b) B(t,\sigma_t)$$

  - f_b: signal fraction
  - $R(t,\sigma_t)$: resolution function, double Gaussian for D^0, single Gaussian for others.
  - b: bias parameter (free in fit), s: scaling parameter (free in fit)
  - $S(\sigma_t)$: PDF of σ_t, derived from data as histogram.
  - $B(t,\sigma_t)$: background PDF, shape determined from the sideband regions. Assumed zero lifetime and non-zero lifetime components, convoluted by a Gaussian resolution function with free mean and σ_t from $s\,\sigma_t$.

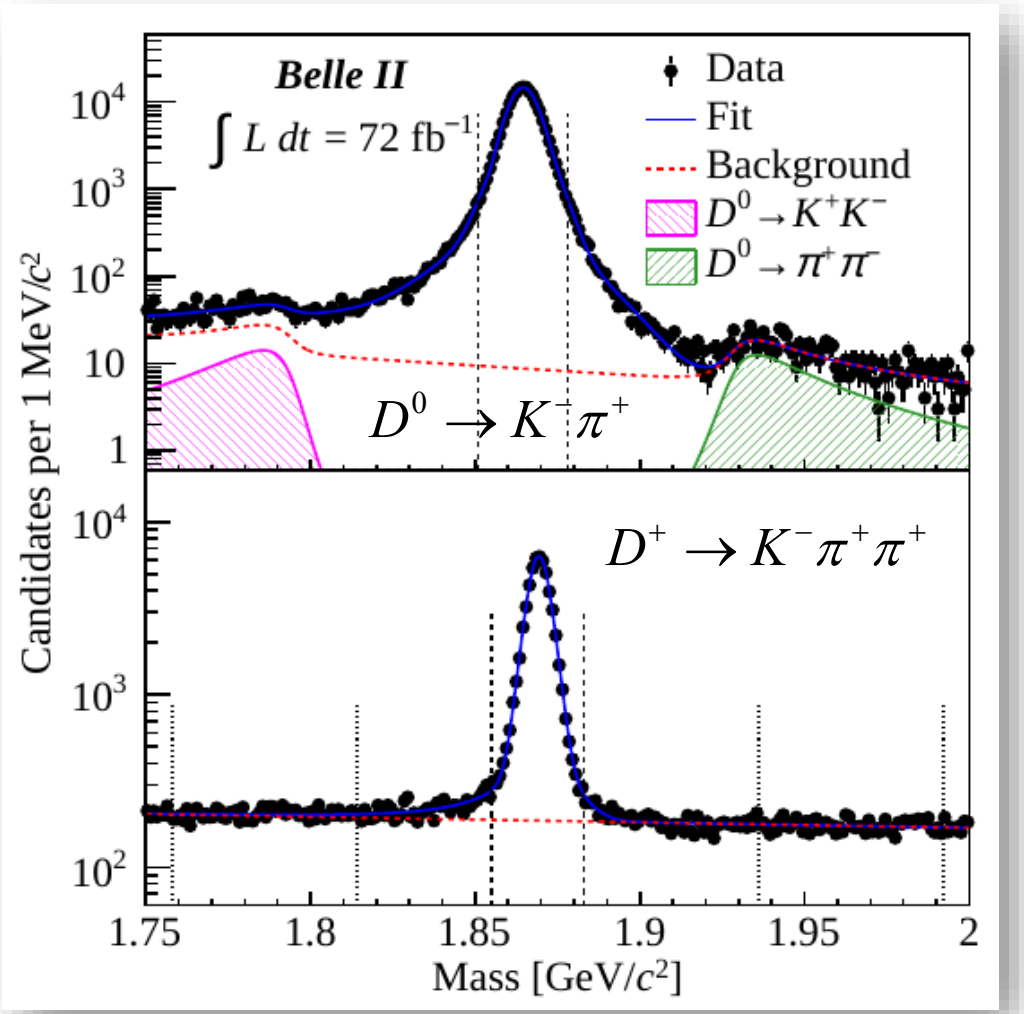
D^0, D^+ Selection for Lifetime

- Neutral D: $D^{*+} \to D^0\pi_s^+,\ D^0 \to K^-\pi^+$
  - 171k signals, 0.2% background from 72 fb^{-1}
  - Assigned systematics to ~0 background
- Charged D: $D^{*+} \to D^+\pi^0,\ D^+ \to K^-\pi^+\pi^+$
  - 59k signals, 9% background from 72 fb^{-1}
  - Background: zero-lifetime + two non-zero lifetime components.
- Removed D from B decays by

$$p^{CMS}(D^{*+}) > 2.5\,/\,2.6 \text{ GeV/c} \quad \text{for} \quad D^0\,/\,D^+$$

-

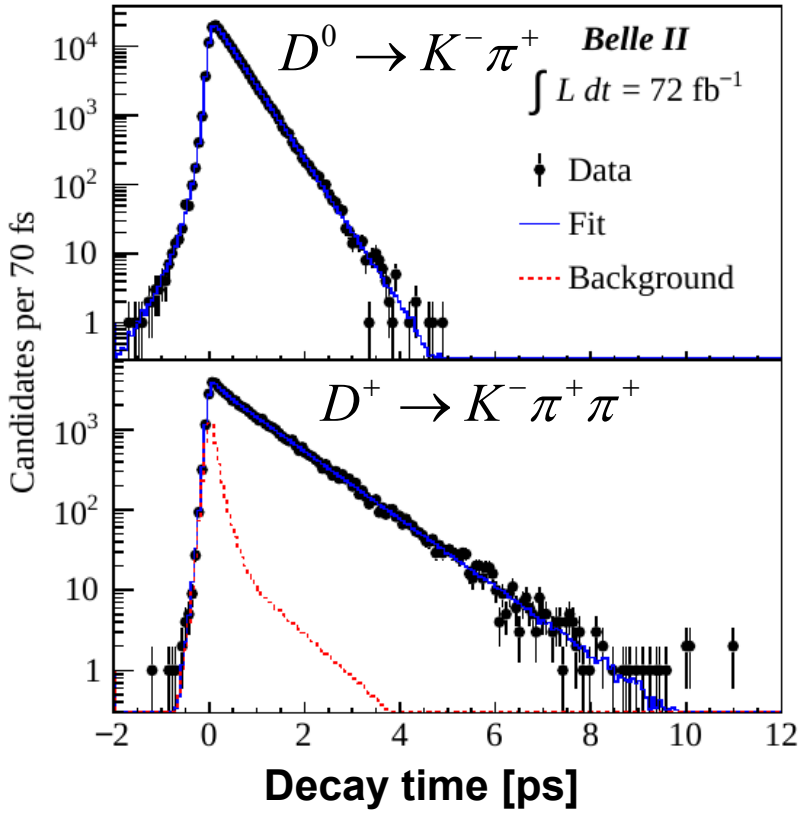
Systematics Sources	$\tau(D^0)$ [fs]	$\tau(D^+)$ [fs]
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Total	0.80	3.10



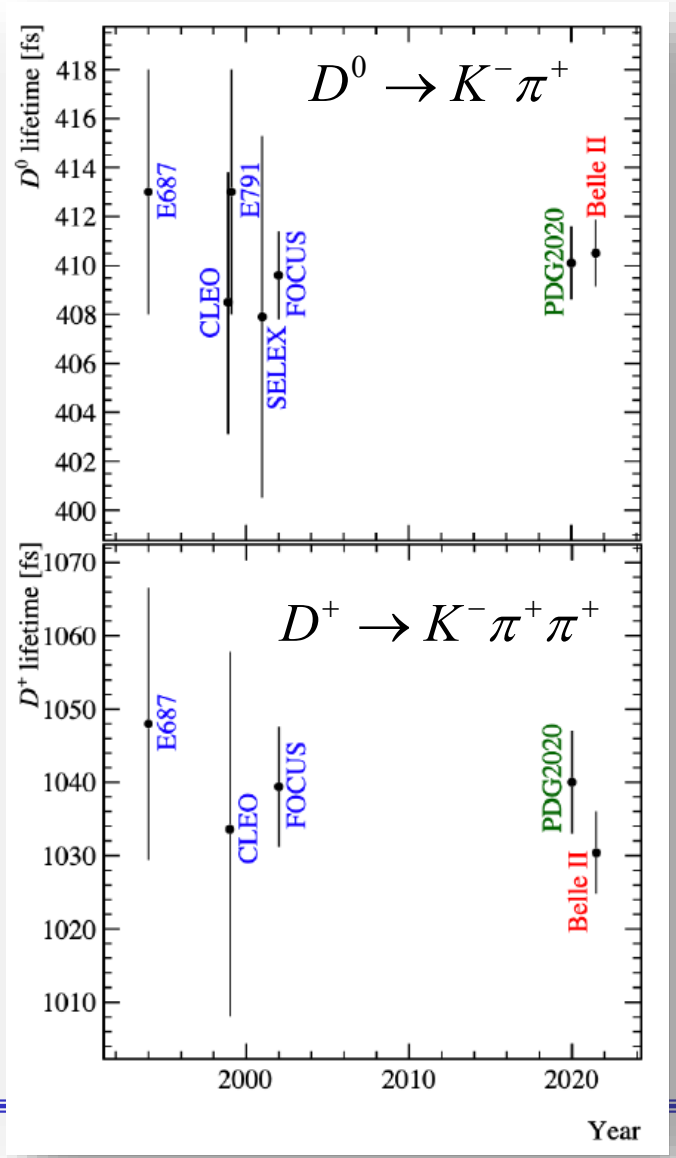
Vertical lines: signal and sideband

Phys. Rev. Lett. 127 (2021), 211801

D^0, D^+ Lifetime Fit Results



Mode	Belle II (fs)	Previous WA (fs)
D^0	$410.5 \pm 1.1 \pm 0.8$	410.1 ± 1.5
D^+	$1030.4 \pm 4.7 \pm 3.1$	1040 ± 7

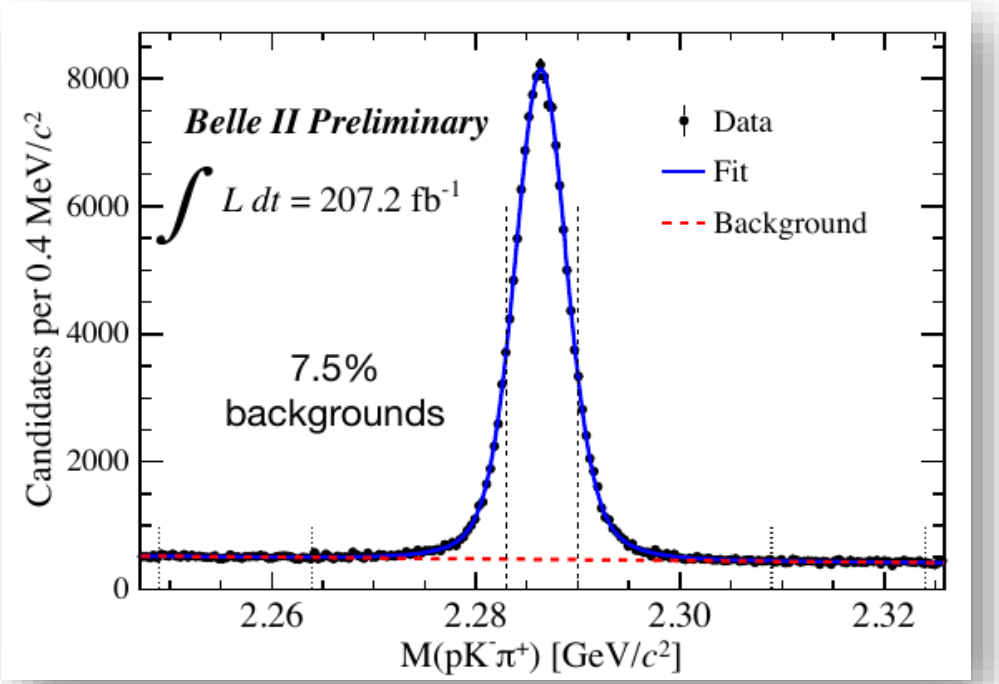


Phys. Rev. Lett. 127 (2021), 211801

Λ_c^+ Selection for Lifetime

- A relatively clean sample of $\Lambda_c^+ \to pK^-\pi^+$
  - 116k signals, 7.5% background from 207.2 fb^{-1}
  - Background: zero-lifetime + two non-zero lifetime components.
- Systematics source
  - Potential bias due to $\Xi_c^{0/+} \to \Lambda_c^+\pi^{-/0}$ accounted. Not accounted in the previous Λ_c^+ lifetime measurements.
  - Veto applied and corrected for remaining contamination

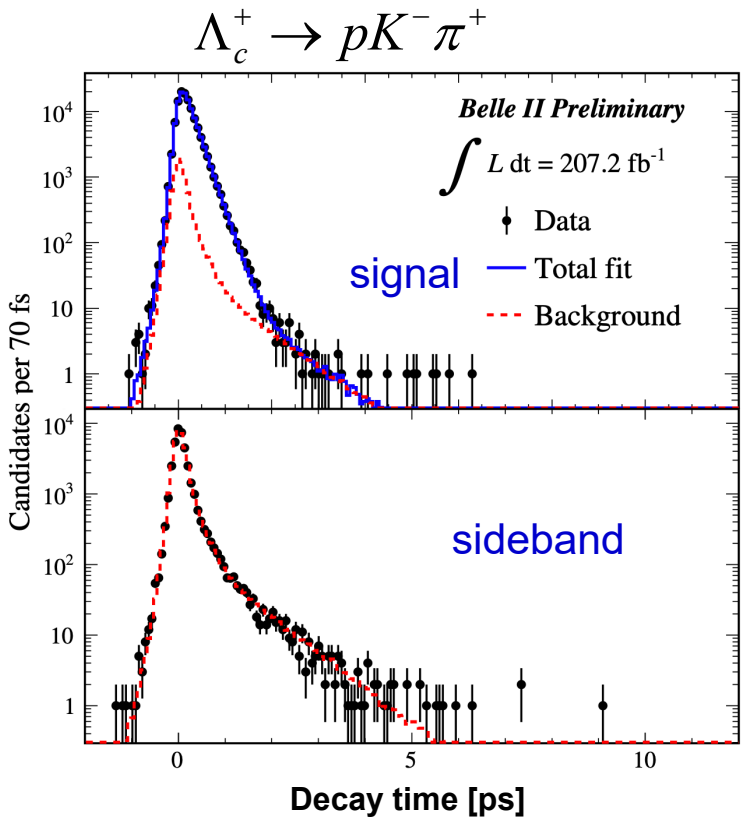
Systematics Sources	Uncertainty [fs]
Ξ_c contamination	0.34
Resolution model	0.46
Backgrounds	0.20
Detector alignment	0.46
Momentum scale	0.09
Total	0.77



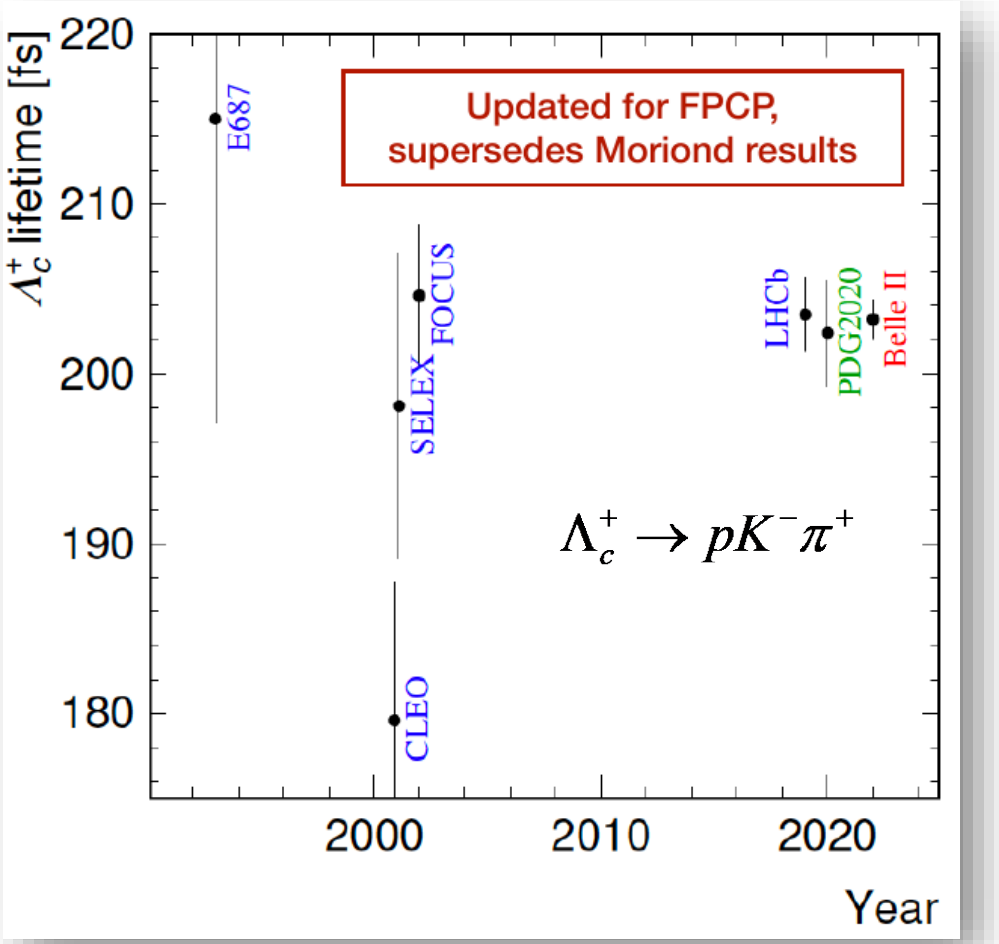
Vertical lines: signal and sideband

arXiv: 2206.15227v1, PRL accepted

Λ_c^+ Lifetime Fit Result



Mode	Belle II (fs)	Previous WA (fs)
Λ_c^+	$203.2 \pm 0.9 \pm 0.8$	202.4 ± 3.1



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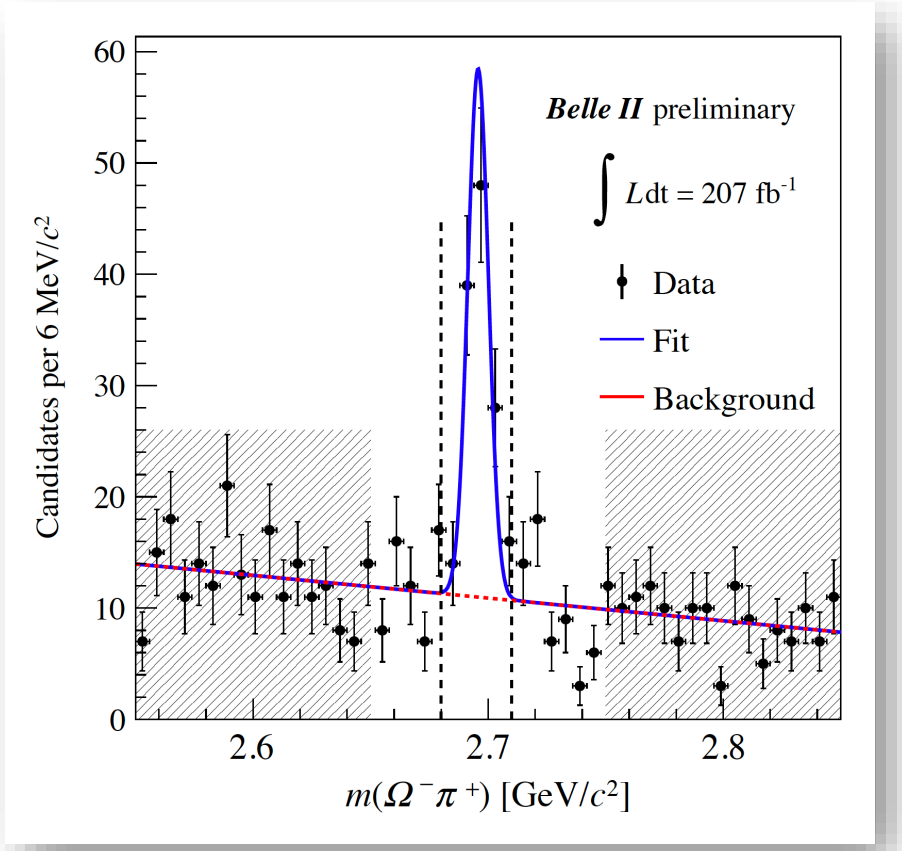
Ω_c^0 Selection for Lifetime

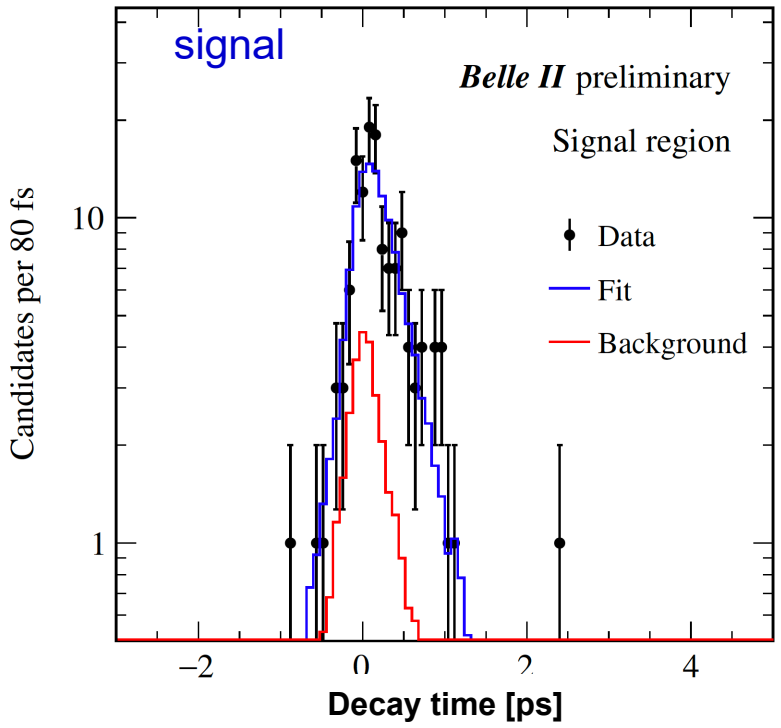
- A sample of $\Omega_c^0 \to \Omega^-\pi^+$, $\Omega^- \to \Lambda^0 K^-$, $\Lambda^0 \to p\pi^-$
  - This channel has two decay vertices reconstructed. First Belle II measurement in such a topology.
  - ~90 signals, 33% background from 207 fb^{-1}
  - Background: zero-lifetime + non-zero lifetime components.
- Systematics source

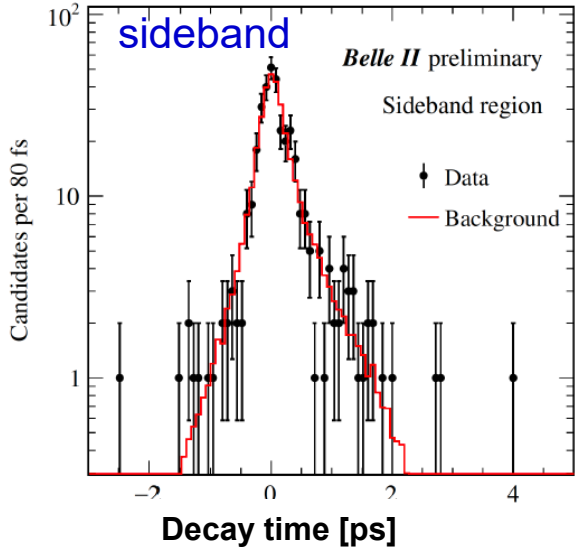
Systematics Sources	Uncertainty [fs]
Fit bias	3.4
Resolution model	6.2
Backgrounds	8.3
Detector alignment	1.6
Momentum scale	0.2
Input charm masses	0.2
Total	11.0

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

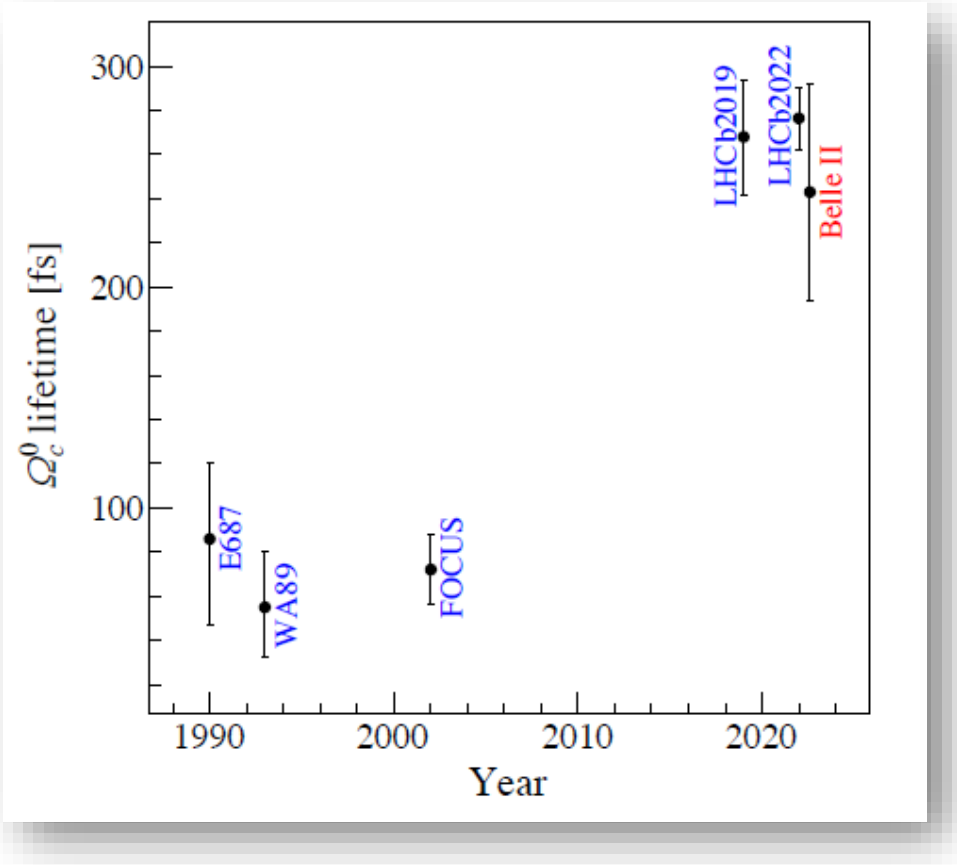


Ω_c^0 Fit Result





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



Mode	Belle II (fs)	Previous WA (fs)
Ω_c^0	$243 \pm 48 \pm 11$	$268 \pm 24 \pm 10$ LHCb 69 ± 12 pre-LHCb

Summary

- SuperKEKB has achieved $L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}$, the world record on June 22nd, 2022.
  - It is a super B factory now, also charm/tau lepton factories.
- First results from the charm sector are presented here.
  - The world best D meson lifetimes.
  - The world best Ω^c lifetime.
  - The Belle II preliminary Ω^c lifetime comparable to the LHCb result.
- This is a very exciting time to do flavor physics, and much more to come.

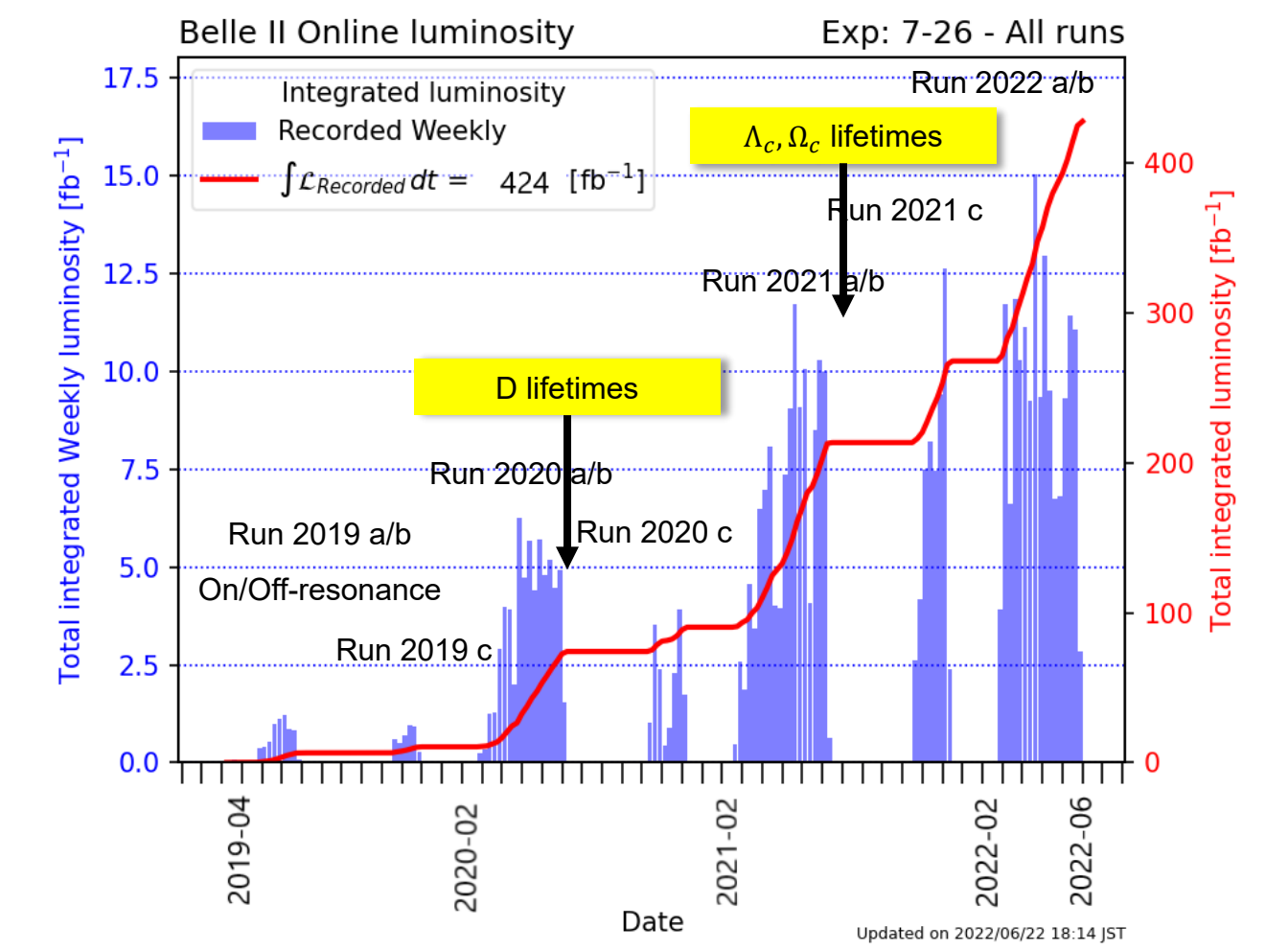
EXTRA

Belle II Experiment in a Nutshell

- HEP experiments have seen huge accomplishments during the last decades.
  - CPV/CKM, discovery of XYZ/tetra/penta particles, discovery of Higgs, etc.
  - Next major theme: New Physics, requiring more precision and larger samples.
- Belle II/SuperKEKB is the upgrade of Belle/KEK.
- Upsilon(4S) decays into $B\ \bar{B}$ meson pairs, coherently with no additional fragments.
  - Full event reconstruction tagging possible
- Direct detection of neutrals such as γ, π^0, K_L.
- A hermetic detector:
  - Detection of neutrinos or invisibles as missing energy/momentum.
- Large continuum charm and τ samples in addition to B samples.
  - Detect both e and μ with similar performance.
  - For example, search for LFV τ decays at $O(10^{-9})$ possible.

SuperKEKB Luminosity: Current Status

- After the commission phases, physics runs started spring 2019.
- Reclaimed the luminosity record June 2020! (Previously held by LHC.)
- Spring/summer 2022 run ended June.
  - Peak luminosity at $\boldsymbol{L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}}$, the current world record on June 22nd.
  - Current integrated luminosity at $\int L_{recorded} dt = 424\ fb^{-1}$. (~ Babar, ~ ½ Belle)
- Long shutdown 1 (LS1) just started for upgrades (beam pipe, pixel, TOP MPT).



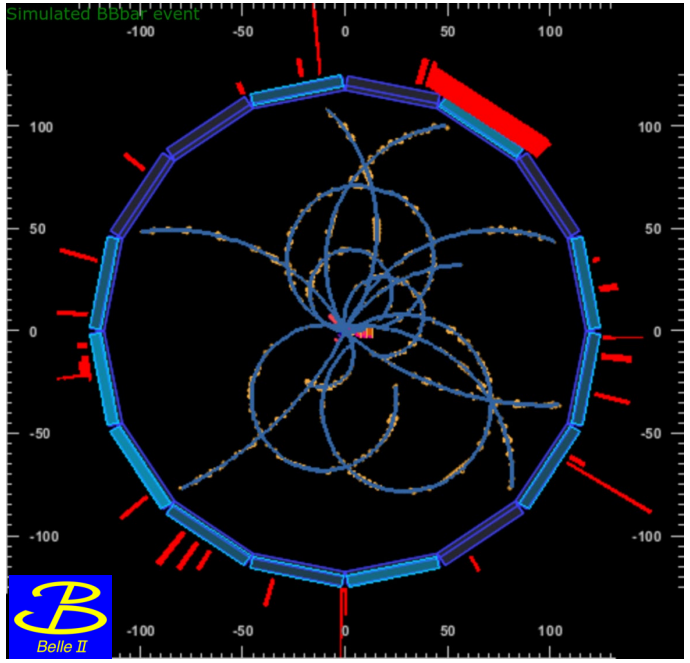
https://confluence.desy.de/display/BI/Belle+II+Luminosity

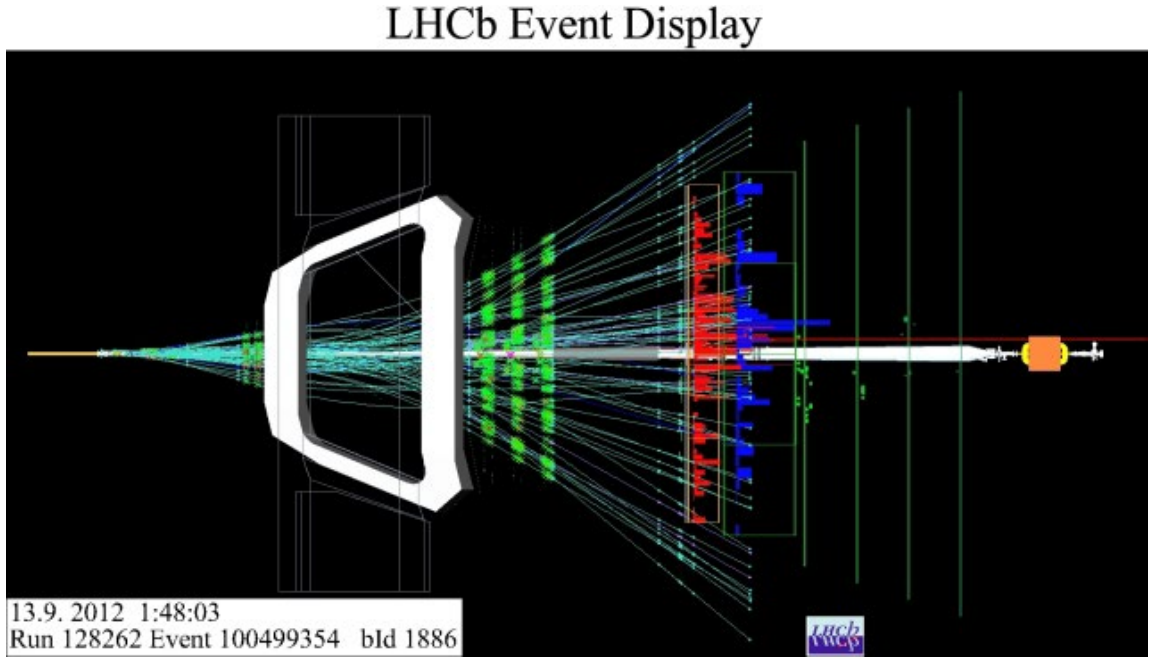
The Belle II Collaboration

- As of July 2022, approximately
- 1,100 members, 120 institutes, 27 countries

Belle II and LHCb

- Belle II and LHCb have different systematics
  - Two experiments are required to establish NP.
  - LHCb: large $b\bar{b}$ cross-section (LHCb 1 fb^{-1} ~ Belle II 1 ab^{-1}). Good sensitivity and S/N with di-muon modes and charged tracks with a vertex.

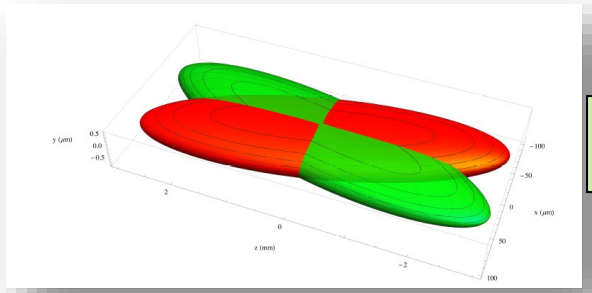




KEKB to SuperKEKB: Accomplished

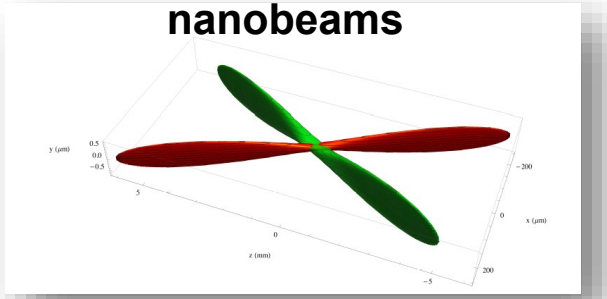
- Nano beam scheme + Crab waist optics
- Target: vertical beta function β_y^* 5.9 mm (KEKB) to 0.3 mm (SuperKEKB)
- Increase beam currents $I_{e\pm}$
- Increase beam-beam interaction ξ_y

KEKB beams



Beam crossing angle 22mrad

SuperKEKB nanobeams



Beam crossing angle 83mrad

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