Measurements of charm hadron lifetimes at Belle II

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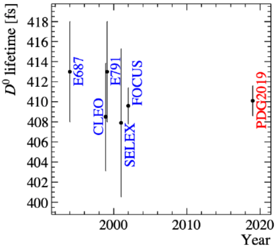
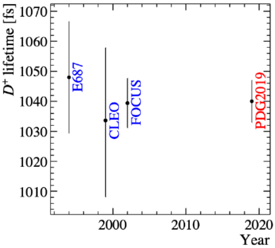
Introduction

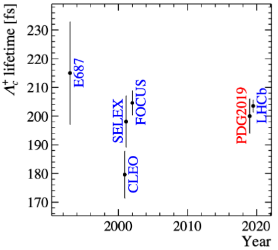
- Searches for BSM physics often rely on accurate theory descriptions of strong interactions at low energy
  - typically achieved using effective models like Heavy Quark Expansion
- Charm hadrons in particular provide excellent tests
  - charm quark mass is much less than that of beauty quark
  - higher order corrections and spectator effects more significant
- Lifetime measurements are an essential test of non-perturbative QCD

Charmed hadron lifetimes: experimental status

- D^0 and D^+ dominated by
  - FOCUS: photon beam experiment
  - SELEX: hyperon beam experiment
  - CLEO: the only e^+e^- measurements
- Charmed baryons dominated by LHCb
  $\rightarrow$ all relative measurements with respect to D^+
  $\tau_{\Lambda_c^+} = 203.5 \pm 1.0(stat) \pm 1.3(syst) \pm 1.4(\tau_{D^+})$ fs PRD 100 (2019) 032001
- Belle II can make absolute measurements







Charmed baryon lifetime hierarchy

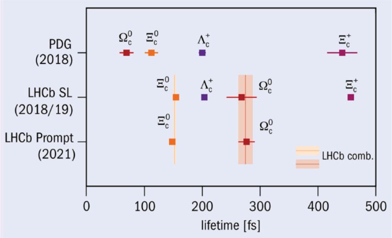
- Hierarchy was long believed to be:

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

- In 2018 and 2021 LHCb measured Ω_c^0 lifetime to be nearly four times larger than previously measured
- This changed the hierarchy to be:

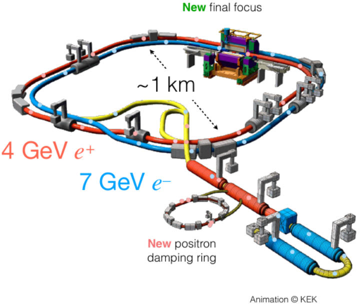
$$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$$

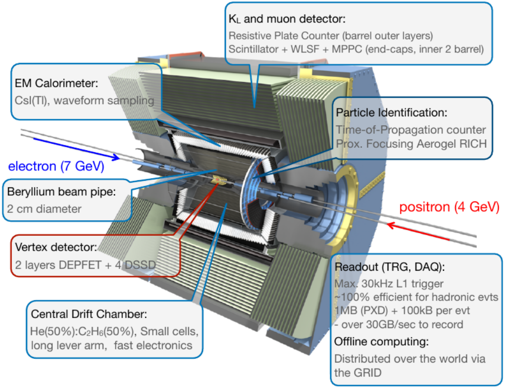
https://cerncourier.com/a/new-charmed-baryon-lifetime-hierarchy-cast-in-stone



- Belle II can measure these lifetimes and hopefully confirm (or disprove) LHCb findings

Belle II experiment: 2nd generation "Super B Factory"





SuperKEKB accelerator

- upgraded KEKB
- target luminosity: 30 × KEKB

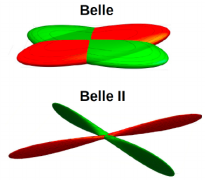
Belle II detector

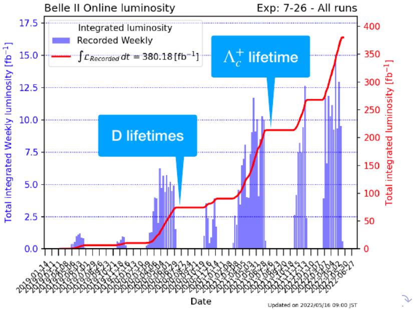
- general purpose spectrometer
- vertexing, tracking, neutral's detection, PID

SuperKEKB accelerator

- Asymmetric e^+e^- collider running at or near $\Upsilon(4S)$
  - $c\bar{c}$ production cross-section similar to $B\bar{B}$ (1 nb vs. 1.2 nb)
  - selection of charmed hadrons from prompt production by a simple kinematic cut: $p^{CMS} > 2.5\ \mathrm{GeV/c}$
- High instantaneous luminosity via the nano-beam optics
  - $20\times$ smaller beam spot compared to KEKB
  - small beam size better constrains event kinematics
  - improves flight time resolution

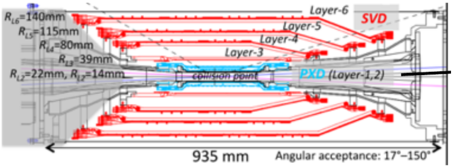
- Beam spot calibrated continuously using $e^+e^- \to \mu^+\mu^-$ events



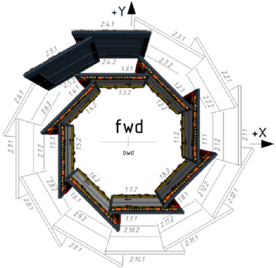


Belle II vertex detector

- Vertex detector
  - 2 DEPFET layers + 4 layers of DSSD
    $\rightarrow$ second DEPFET layer be completely installed in 2023
  - smaller inner radius, larger outer radius compared to Belle
    $\rightarrow$ two-times better vertex resolution
    $\rightarrow$ improved efficiency for slow pions and K_S
    $\rightarrow$ more robust tracking against beam background
- Precise alignment crucial for precision lifetime measurements

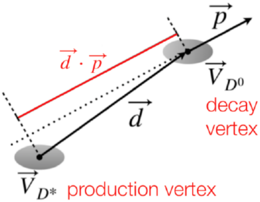


Silicon Vertex Detector (SVD)



Pixel Detector (PXD)

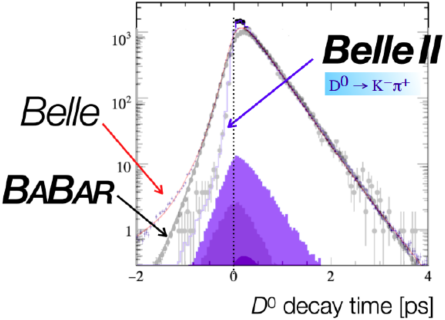
Proper decay time reconstruction



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

Proper decay time calculated from distance between production and decay vertices projected to the momentum vector of reconstructed charmed hadron

D^0 proper decay time distribution
- comparison with Belle and BaBar



→ much improved time resolution at Belle II

(thanks to 2× better vtx resol., 20× smaller BS)

Lifetime fit

- Lifetime measured from unbinned ML fit to the (t, σ_t) distribution
  - simultaneous fit to signal and invariant mass sidebands
  - background fraction constrained from fit to invariant mass distribution
- Probability density function (PDF)

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

  - p is signal fraction
  - $R(t, \sigma_t)$ resolution function, single or double Gaussian
    - b bias parameter (free in the fit)
    - s scaling parameter (free in the fit)
  - $S(\sigma_t)$ PDF of σ_t, histogram template derived from data
  - $B(t, \sigma_t)$ background PDF, shape determined by fitting sidebands
    - zero-lifetime and two exponentials, all convoluted with a Gaussian resolution function with free mean and width corresponding to $s\sigma_t$

D^0 and D^+ lifetime measurements

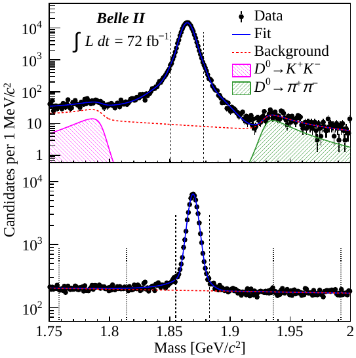
Neutral D meson

- Reconstructed in $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$
- Binned least square fit
  - Signal yield: 171k
  - Background: 0.2%

Charged D meson

- Reconstructed in $D^{*+} \to D^+\pi^0$, $D^+ \to K^-\pi^+\pi^+$
- Binned least square fit
  - Signal yield: 59k
  - Background: 9%

PRL 127 211801 (2021)



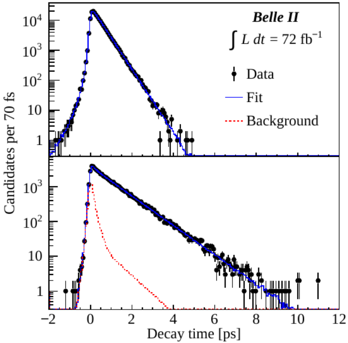
vertical lines indicate signal and sideband regions

D^0 and D^+ lifetime measurements

Lifetime fit

- Neutral D meson
  - Resolution function: double Gaussian
  - Background neglected
    $\rightarrow$ systematics assigned
- Charged D meson
  - Resolution function: Gaussian
  - Background: zero-lifetime + two non-zero lifetime components

PRL 127 211801 (2021)



Systematics

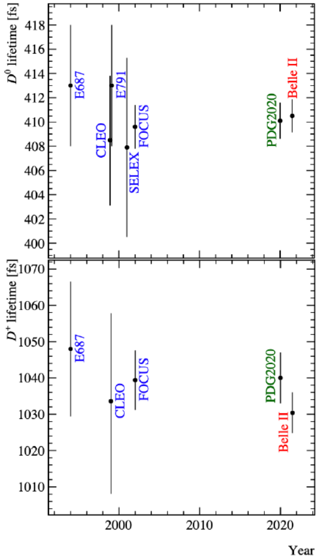
Source	$\tau(D^0)$ [fs]	$\tau(D^+)$ [fs]
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Total	0.80	3.10

D^0 and D^+ lifetime measurements

Results PRL 127 211801 (2021)

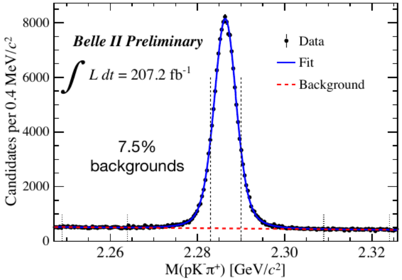
$$\tau(D^0) = 410.5 \pm 1.1_{\text{stat}} \pm 0.8_{\text{syst}}\ \text{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7_{\text{stat}} \pm 3.1_{\text{syst}}\ \text{fs}$$

- World's best measurements
- Consistent with previous measurements

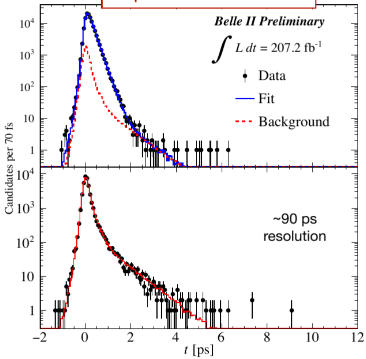


Λ_c^+ lifetime measurement

- Relatively clean sample of $\Lambda_c^+ \to pK^-\pi^+$
  - Signal yield: 116k
  - Background: 7.5%
- Potential bias due to $\Xi_c^{0/+} \to \Lambda_c^+\pi^{-/0}$
  - not accounted in previous Λ_c lifetime measurements (negligible)
  - additional systematics assigned



Updated for FPCP, supersedes Moriond results



Resolution function: Gaussian

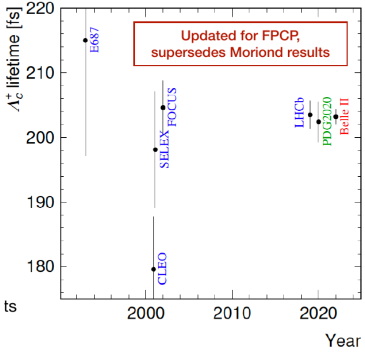
Background: zero-lifetime + two non-zero lifetime components

Λ_c^+ lifetime measurement

Preliminary result

$$\tau(\Lambda_c^+) = 203.20 \pm 0.89_{\rm stat} \pm 0.77_{\rm syst}\ \rm fs$$

- World's best measurement
- consistent with previous measurements



Source	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

→ to be submitted to PRL

Conclusions

- Major upgrade done at KEK for the next generation B-factory
  - Many detector components and electronics replaced, software and analysis tools also improved
  - Rich physics program, complementary to existing experiments
- First high-precision results are here:
  - World's best D meson lifetimes
  - World's best Λ_c lifetime
- Nearly 1% of target integrated luminosity collected so far - much more to come

Backup: Ξ_c contamination

- Potentially problematic backg. from $\Xi_c^0 \to \Lambda_c^+ \pi^-$ and $\Xi_c^+ \to \Lambda_c^+ \pi^0$
  - not accounted in previous Λ_c lifetime measurements

decay	BR	τ
$\Xi_c^0 \to \Lambda_c^+ \pi^-$	0.55 ± 0.20 % (LHCb)	153 ± 6 fs
$\Xi_c^+ \to \Lambda_c^+ \pi^0$	1.11 % (theory pred.)	456 ± 5 fs

- Reduce background with veto and correct for remaining
  - require $M(\Xi_c) - M(\Lambda_c)$ within 2σ of nominal mass difference
  - use conservative upper estimate for production yields determined from fit to impact parameter of Λ_c^+
  - mix signal events with generic MC to test potential remaining bias
  - take half the shift as correction and half as systematic uncertainty

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Total	0.77