Latest charm results from Belle II

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Outline

- Charm physics
- Introduction to Belle II and SuperKEKB
- Recent charm results
  - $D^{0/+}$ lifetimes
- Future prospects
  - Charmed baryon lifetimes
  - CPV and charm mixing
- Summary and outlook

Charm physics

- It was the absence of flavor changing neutral currents (FCNC) that led GIM to propose a suppression mechanism which required the existence of a fourth quark, Charm, in 1970.

- Charm quark: third-heaviest of the six quarks.

- Charm particles can exist as open charm mesons or baryons and as hidden charm (charmonium as J/Ψ).

- Uniqueness of charm: only decays via weak decays, mediated by a $W^{\pm}$ boson, into a strange or down quark, except the decay of ground state charmonium mesons.

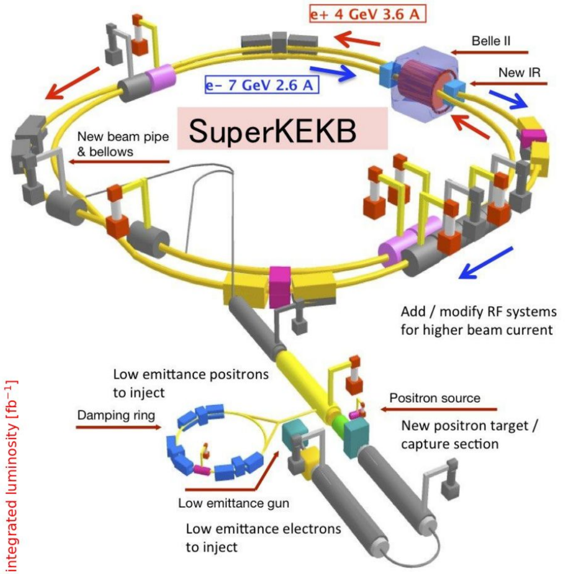
- With the first evidence of mixing of neutral charm mesons reported by BaBar and Belle in 2007, a lot of works has been going to precisely measure the mixing phenomenon and search for CPV in the charm sector.

- Time-integrated CP asymmetry for the decay of charm mesons are also one of the interesting topic in charm sector, that are vigorously being studied at Belle II.

$$A_{CP} = \frac{(B(D \to f) - B(\bar{D} \to \bar{f}))}{(B(D \to f) + B(\bar{D} \to \bar{f}))}$$

SuperKEKB and Belle II

The Belle II experiment at the SuperKEKB asymmetric e^+/e^- collider is designed to make precision measurements in flavor physics at the "intensity frontier"

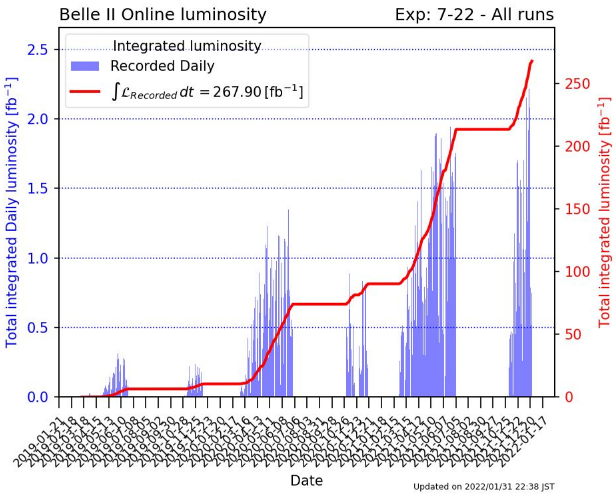


- Low backgrounds with a known collision energy gives Belle II unique opportunities

- Design luminosity of SuperKEKB: 6.5×10^{35} cm^{-2} s^{-1} (~40 times greater than KEKB)

- Target data set: 50 ab^{-1} (~50 times greater than Belle)

- 1,300,000 $c\bar{c}$ events produced per 1 fb^{-1}



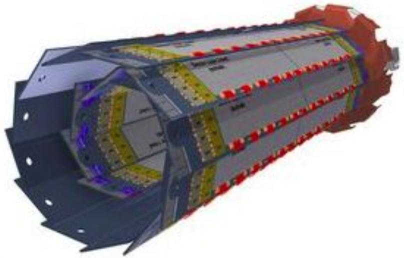
Collected (so far): ~ 268 fb^{-1}

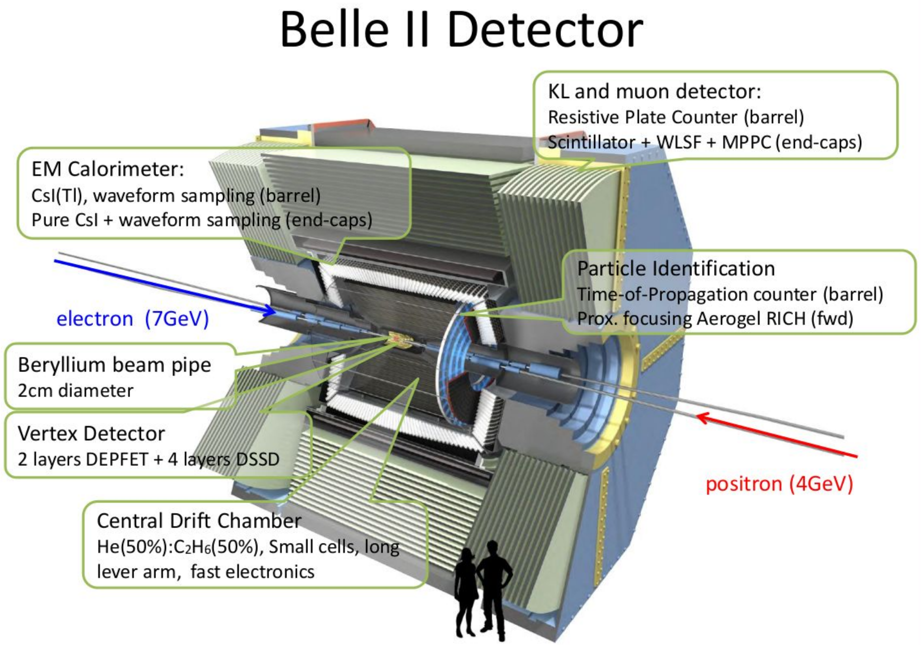
Achieved world record: 3.8×10^{34} cm^{-2} s^{-1}

Belle II detector

- Layers of detectors to enable precision charged particle tracking and particle identification.

- Just outside the interaction point (IP), upgraded vertex detectors:
  - 1 layer of pixel
  - 4 layers of double-sided silicon strips





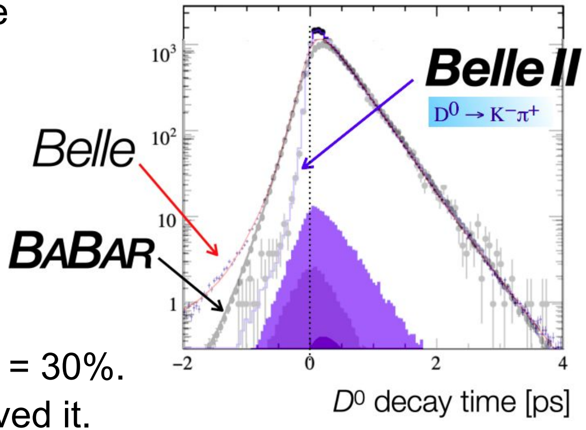
- Precise silicon vertex detectors help to pin point the decay vertex of the particles like the D^0 and D^+

$D^{0/+}$ lifetimes

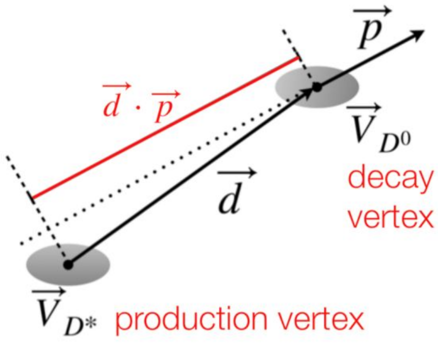
- Measurements of lifetimes are an essential test of non-perturbative QCD

- For charm hadrons, the expansion parameter in Heavy Quark Expansion (HQE) increases by a factor of 3, yielding much larger uncertainties

- In Belle II, precise lifetime measurements are possible because of:
  - Precise calibration of final state particle momenta
  - Excellent vertex detector alignment
  - 1st layer of silicon ensuring a narrow decay time resolution.



- Most precise ratio to date: $\tau(D^+)/\tau(D^0)$ = 30%. Belle II measurement has now improved it.



$$\langle d_{D^0}\rangle \sim 200\,\mu m$$
$$\langle d_{D^+}\rangle \sim 500\,\mu m$$

Once the momentum of the $D^{0/+}$ is determined, the production and decay vertex are used to calculate the decay time:

$$t = \frac{m_D}{p}\left(\vec{d}\,.\,\hat{p}\right)$$

Sample for analysis

D⁰

- Reconstructed from K⁻ and π⁺ with D* tagged ($D^0 \to K^- \pi^+$)
- Binned least square fit:
  - Signal yield: 171K
  - Purity: 99.8%
  - Background: 0.2%
- Background for D⁰: neglected in the life-time fit and systematic assigned

D⁺

- Reconstructed from K⁻, π⁺ and π⁺ with D* tagged ($D^+ \to K^- \pi^+ \pi^+$)
- Binned least square fit:
  - signal yield: 59K
  - Purity: 90%
  - Background: 9%
- Background for D⁺: included in the life-time fit, modeled using data sidebands

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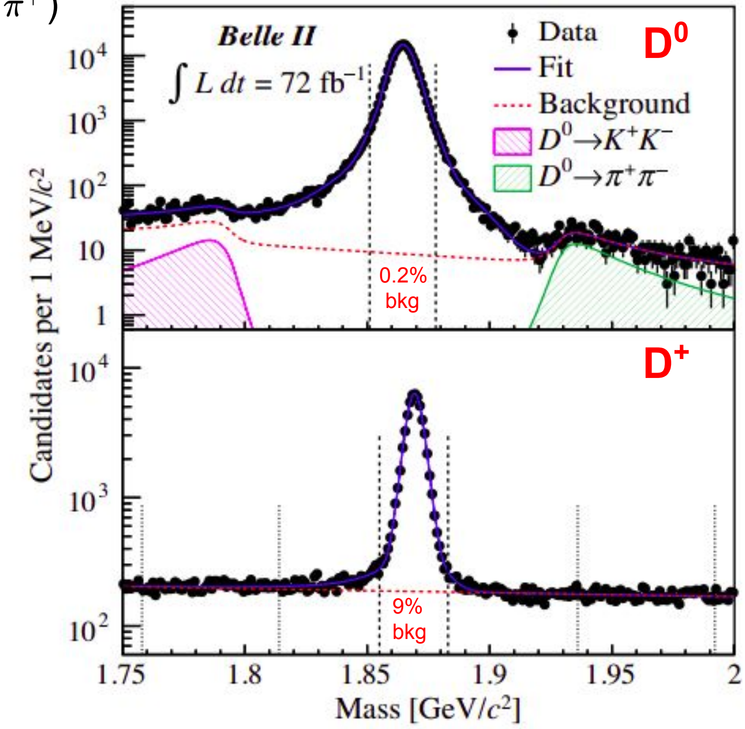
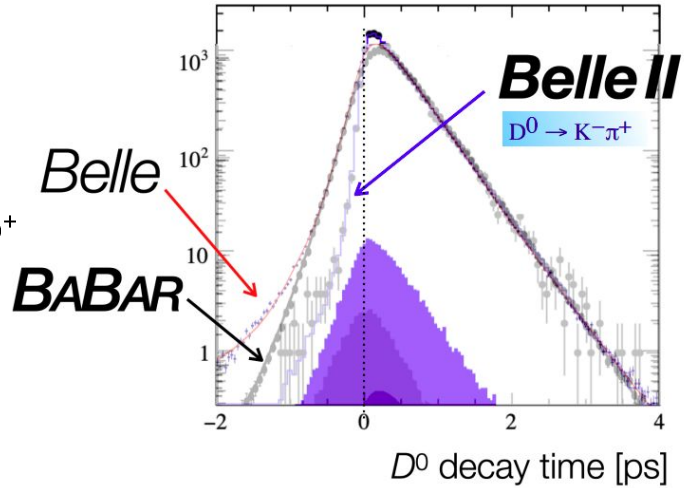
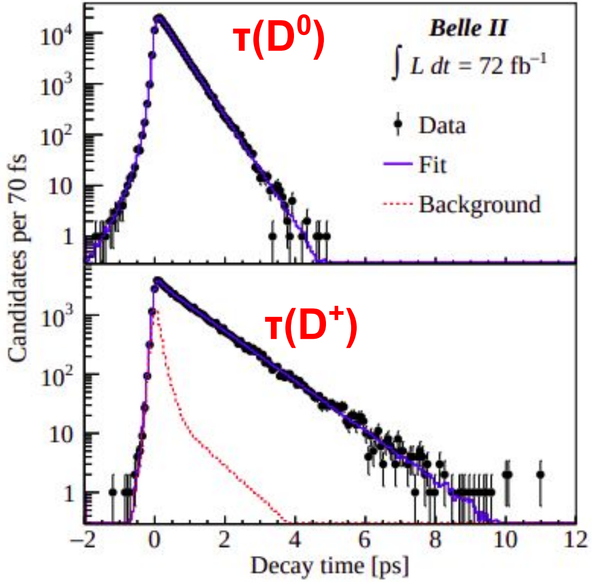


Fit strategy

- Lifetimes are determined with unbinned ML fits to decay time and decay time uncertainty (t, σ_t) of the candidates in the signal region

- Absolute measurement of lifetime: World's most precise D^0 and D^+ lifetimes to date





- PDF: Exponential, convolved with a resolution function:

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

- Resolution function(R) for D^+ is single Gaussian and sum of two Gaussian for D^0.

Results

$\tau(D^0) = 410 \pm 1.1\ (\text{stat}) \pm 0.8\ (\text{syst})$ fs
$\tau(D^+) = 1030.4 \pm 4.7\ (\text{stat}) \pm 3.1\ (\text{syst})$ fs

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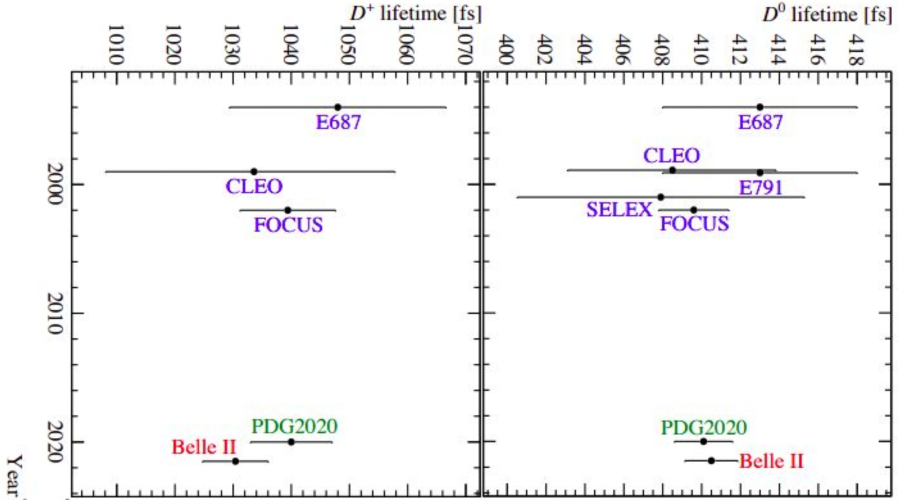
- Correlation coefficient: $\tau(D^+)/\tau(D^0)$ = 18%
- Most precise results, consistent with previous measurements
- Proves excellent vertexing capability of Belle II



- These precise measurements have now paved the road to other lifetime measurements and time dependent measurements.
- Main systematic uncertainty is due to detector alignment, which will improve as we learn more about the detector.

Charmed-baryon lifetime puzzle

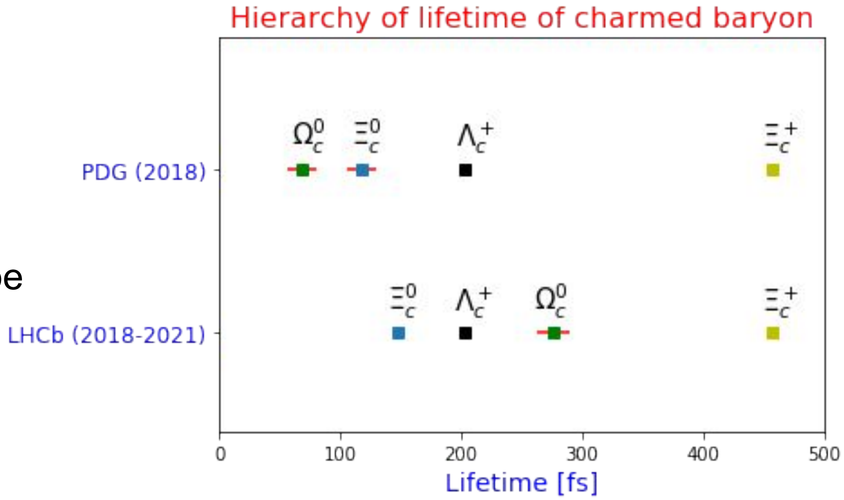
- The charmed-baryon lifetime hierarchy was long believed to be:

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

- In 2018 and 2021, LHCb measured the Ω_c lifetime to be nearly four times larger than previously measured

- This changed the hierarchy to be:

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



- Recent measurements by LHCb were made relative to the lifetime distribution of D^0 via $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ and D^+ via $D^+ \rightarrow K^- \pi^+ \pi^+$ in order to control systematic uncertainties.

- Belle II will measure these lifetimes with high precision and hopefully resolve this discrepancy.

Time-integrated CPV

- As in Belle, Belle II can contribute in measuring more precisely the CPV in the channels with neutral particles as final particles

- A_{CP} expected to reach the $O(10^{-4})$ for neutral channels

- Time-integrated CP asymmetries measured by Belle, and the precisions expected for Belle II in $50ab^{-1}$ of data

- Ongoing analyses on time-integrated CPV:

  1. $D^0 \to K_s\ K_s$
  2. $D^0 \to K_s\ \pi^0$
  3. $D^0 \to \pi^+\ \pi^-\ \pi^0$
  4. $D^0 \to \pi^0\ \pi^0$
  5. $D^+ \to \pi^+\ \pi^0$
  6. $\Xi_c^+ \to \Sigma^+\ \pi^+\ \pi^-$

Mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K_S^0\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.02
$D^0 \to K_S^0 K_S^0$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.23
$D^0 \to K_S^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K_S^0\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	± 0.17
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K_S^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.02
$D^+ \to K_S^0 K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.04
$D_s^+ \to K_S^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \to K_S^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

Belle II Physics Book

Summary

- SuperKEKB and Belle II are breaking records and producing precision measurements already
- Achieved world record in instantaneous luminosity: 3.8x 10^{34} cm^{-2} s^{-1}
- Proven excellent vertexing capabilities
- World's most precise D^0 and D^+ lifetimes measured to date
- Data ~ 268 fb^{-1} has been collected so far (more to come!)
- Excellent platform for charm measurements, more exciting results coming soon with greater luminosities

Thank you !

Backup slides

Charmed-baryon lifetimes

- Another example to test the capability of Belle II for precision measurements

- Helps to strengthen tests of tools like HQE
  - Contributions from spectator effects not present in mesons

- Precise charmed baryon lifetime measurements are necessary to clarify the lifetime hierarchy and better constrain model dependencies

- Most recent (relative) measurement of the Λ_c lifetime by LHCb
  - Because of the new lifetime of D^+ measured precisely by Belle II, lifetime of Λ_c will change
  - Last measurement at an e^+e^- machine by CLEO almost 20 years ago in mild tension with other measurements

- Analysis to directly measure Λ_c lifetime is ongoing

LHCB, $\tau = 203.5 \pm 1.0 \pm 1.3 \pm 1.4$ *fs*

FOCUS, $\tau = 204.6 \pm 3.4 \pm 2.5$ *fs*

CLEO, $\tau = 179.6 \pm 6.9 \pm 4.4$ *fs*