Charm lifetimes at Belle II: recent results

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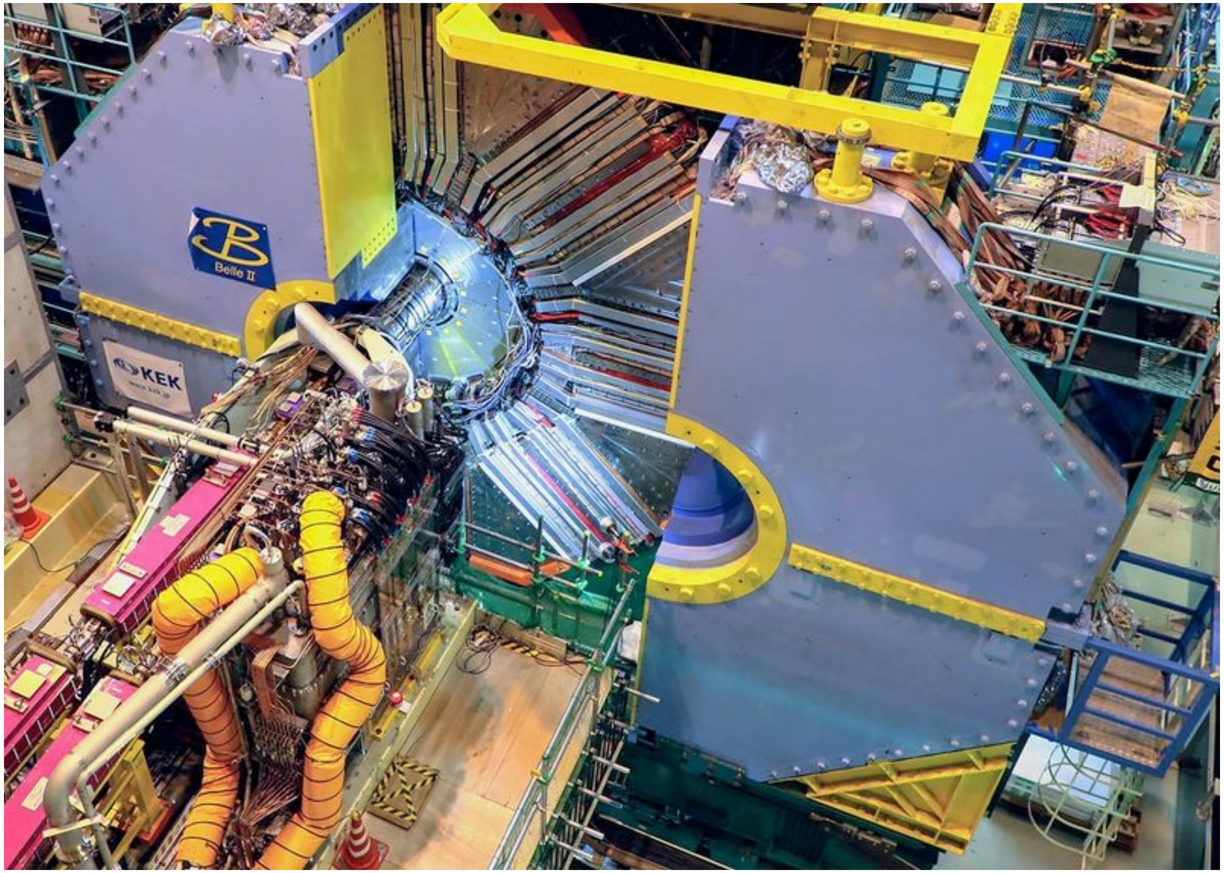
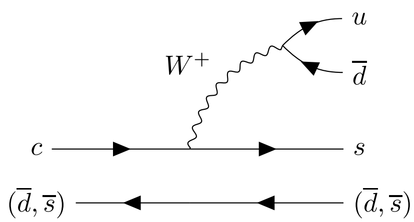


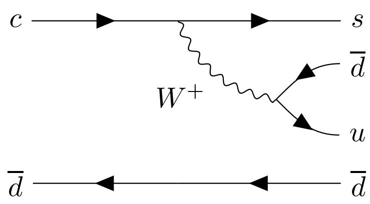
- Overview of Belle II
- Recent measurements:
  - Mesons: D^0, D^+, D_s^+
  - Baryons: Λ_c, Ω_c
- Comparison with theory

Charm lifetimes: theory

Charm particle lifetimes:

- ***qualitatively*** *understood in terms of simple diagrams, e.g., $c \to s\, u$ anti-d gives ubiquitous $G_F^2 m_c^5\, |V_{cs}|^2/(192\pi^3)$ dependence. Long D^+ lifetime can be understood as arising from destructive interference between spectator and color-suppressed amplitudes.*





- ***quantitatively*** *calculated using the Heavy Quark Expansion:*

$$\Gamma(D) = \frac{1}{2m_D}\sum_X \int_{PS} (2\pi)^4 \delta^{(4)}(p_D - p_X)\ |\langle X(p_X)|\mathcal{H}_{\rm eff}|D(p_D)\rangle|^2,$$

ΣX is sum over final states

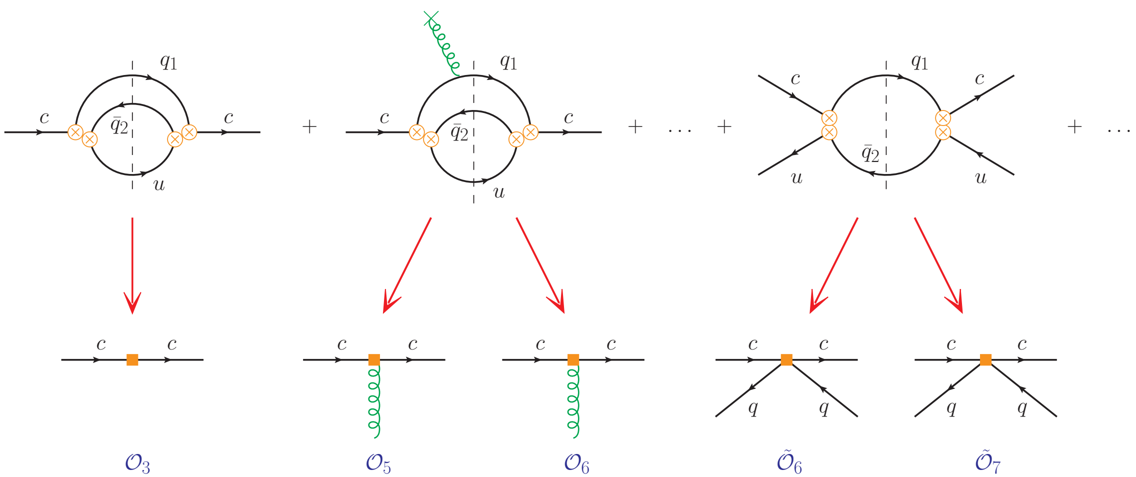
$$\to \frac{1}{2m_D}{\rm Im}\langle D|\mathcal{T}|D\rangle \quad \text{where} \quad \mathcal{T} = i\int d^4x\, T\left\{\mathcal{H}_{\rm eff}(x)\,,\mathcal{H}_{\rm eff}(0)\right\}$$

via optical theorem

$$\to \Gamma_3 + \Gamma_5\frac{\langle\mathcal{O}_5\rangle}{m_c^2} + \Gamma_6\frac{\langle\mathcal{O}_6\rangle}{m_c^3} + \ldots + 16\pi^2\left(\tilde{\Gamma}_6\frac{\langle\tilde{\mathcal{O}}_6\rangle}{m_c^3} + \tilde{\Gamma}_7\frac{\langle\tilde{\mathcal{O}}_7\rangle}{m_c^4} + \ldots\right)$$

via Heavy Quark Expansion

Wilson coefficients Γ_i are expanded in powers of as and calculated perturbatively



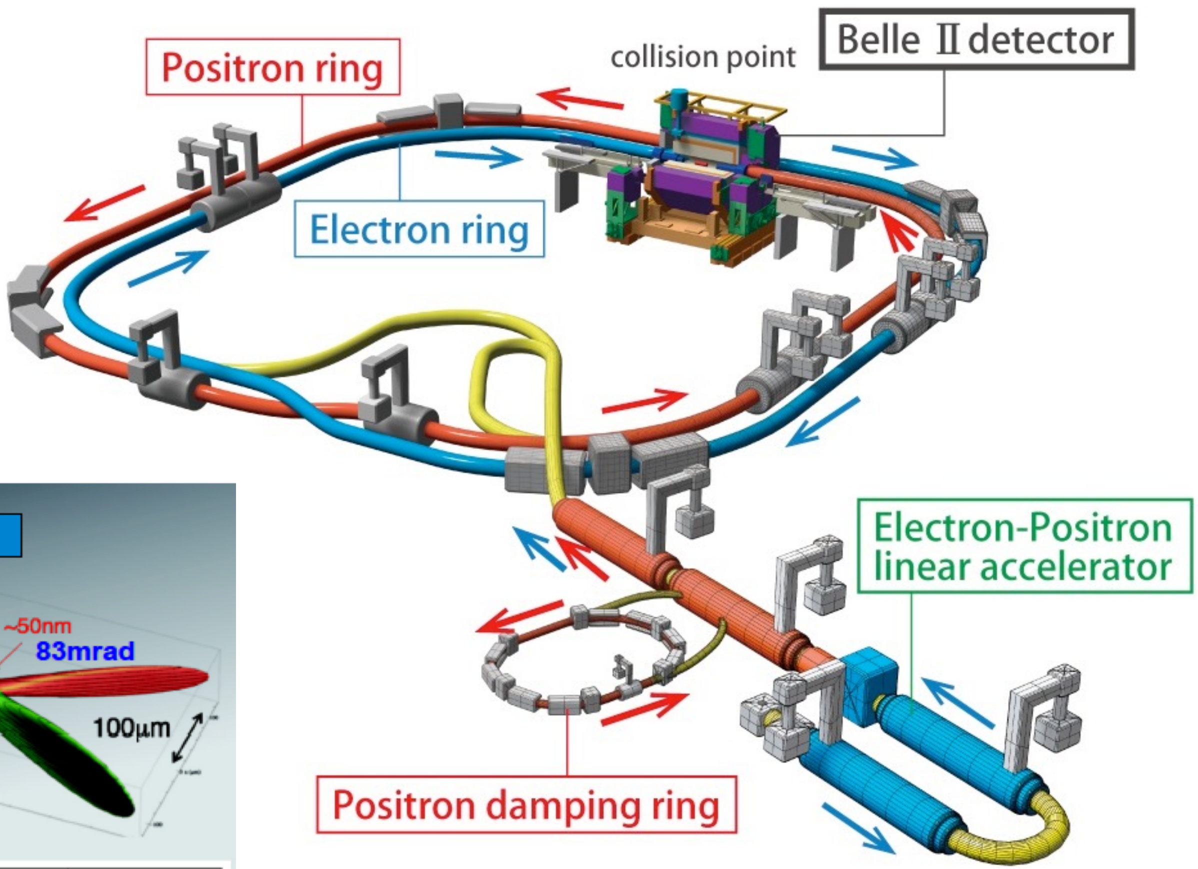
Lenz, IJMP A30 (2015)
Lenz et al., JHEP 12 (2020) 199
King, Lenz et al., JHEP 08 (2022) 241
Gratrex et al., JHEP 07 (2022) 058

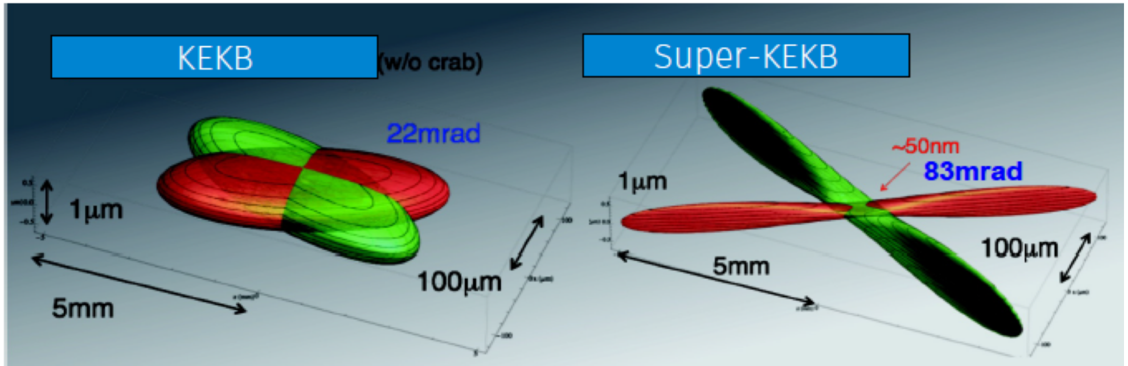
Major accelerator upgrade (KEKB → SuperKEKB)

e^+e^- collider running at the Upsilon(4S) [and Upsilon (5S)] resonances with 7 GeV (e^-) on 4 GeV(e^+) beams.
New e^+ damping ring, new e^+ storage ring, new IR optics, Superconducting FF, new RF

beam size:
100 μm(H) x 2 μm(V)
→ 10 μm(H) x 59 nm(V)

Belle-II Goal:
30 x Belle = ~6 x 10^{35}

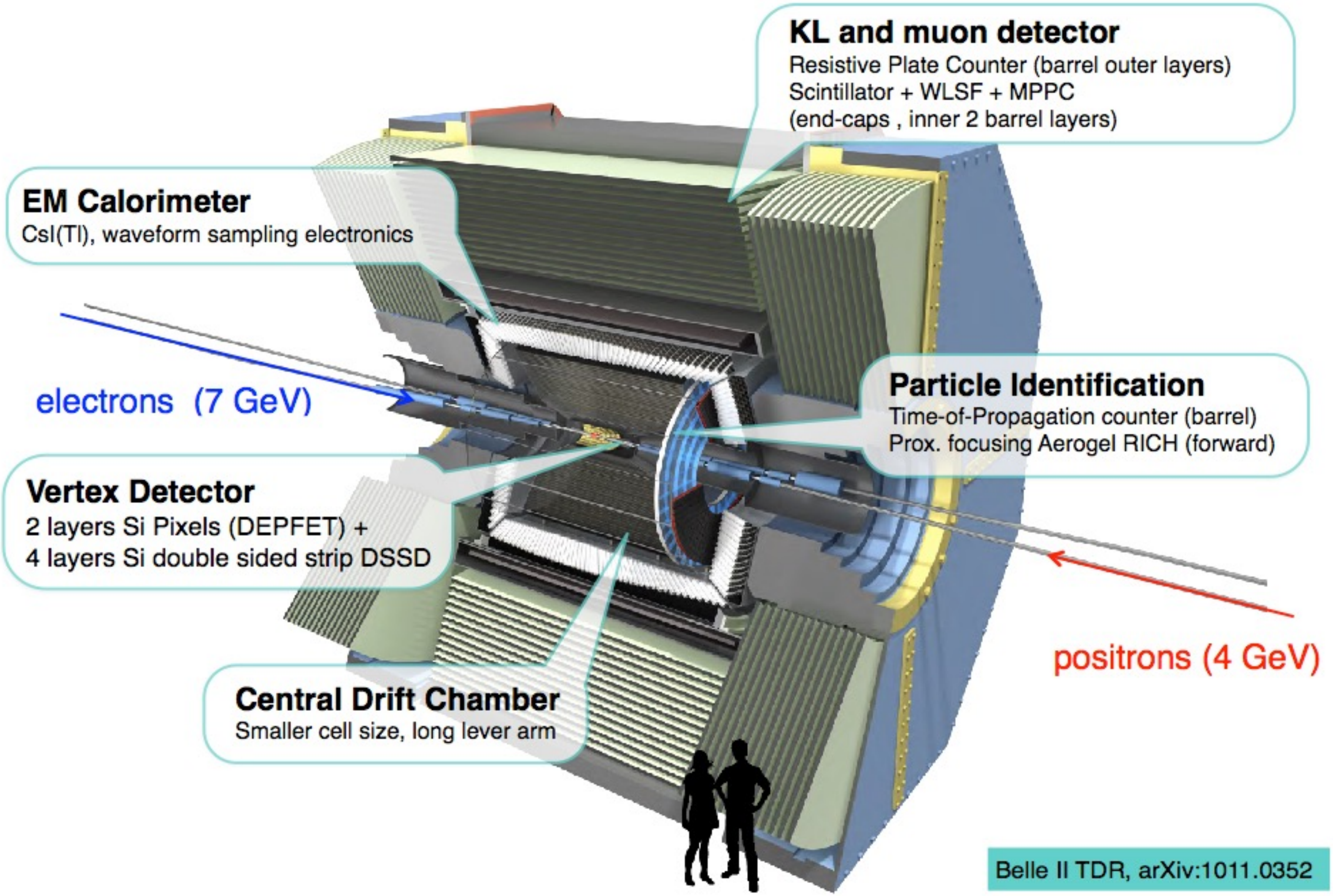




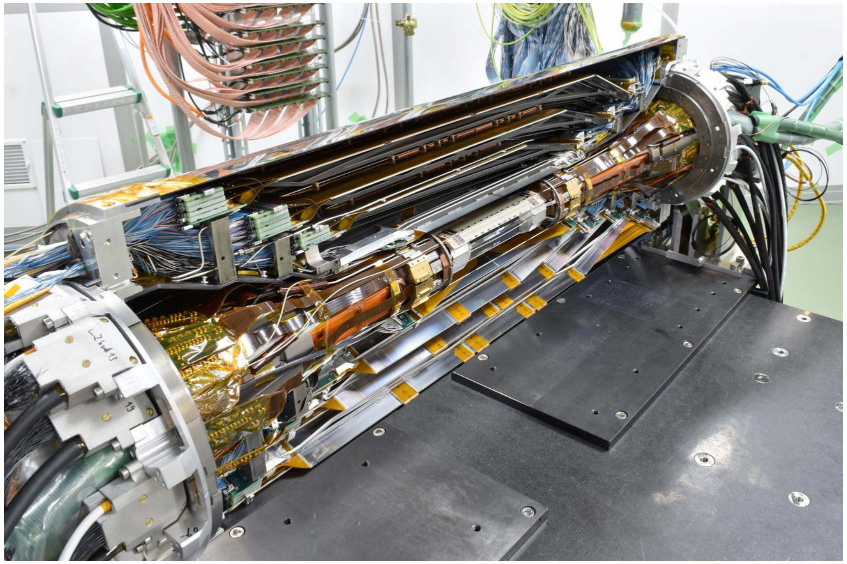
	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm⁻²s⁻¹)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20 factor 2-3

The Belle II Experiment



Charm lifetimes: measurement @ Belle II



Six-layer silicon vertex detector:

(beampipe r = 10 mm)

DEPFET silicon pixels:

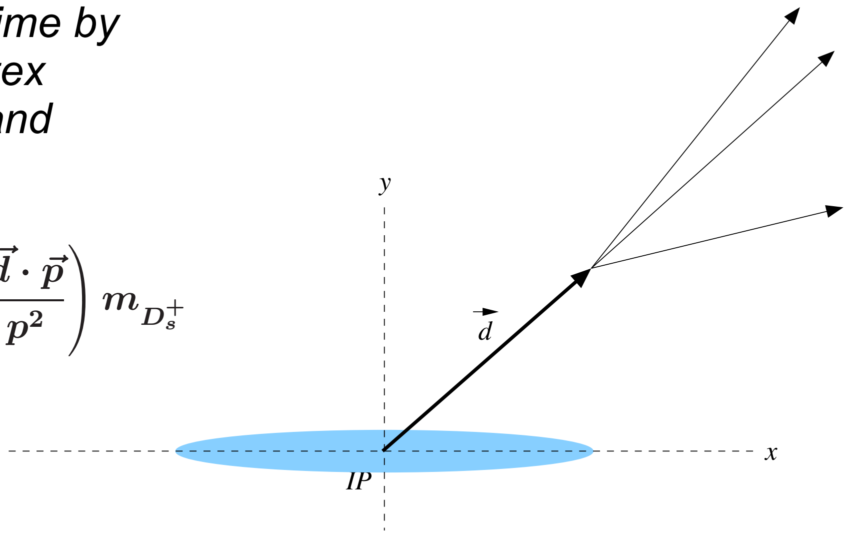
Layer 1 r = 14 mm
Layer 2 r = 22 mm

Double-sided silicon strips:

Layer 3 r = 38 mm
Layer 4 r = 80 mm
Layer 5 r = 115 mm
Layer 6 r = 140 mm

Determine lifetime by measuring vertex displacement and momentum:

$$t = \left(\frac{\vec{d}\cdot\vec{p}}{p^2}\right) m_{D_s^+}$$

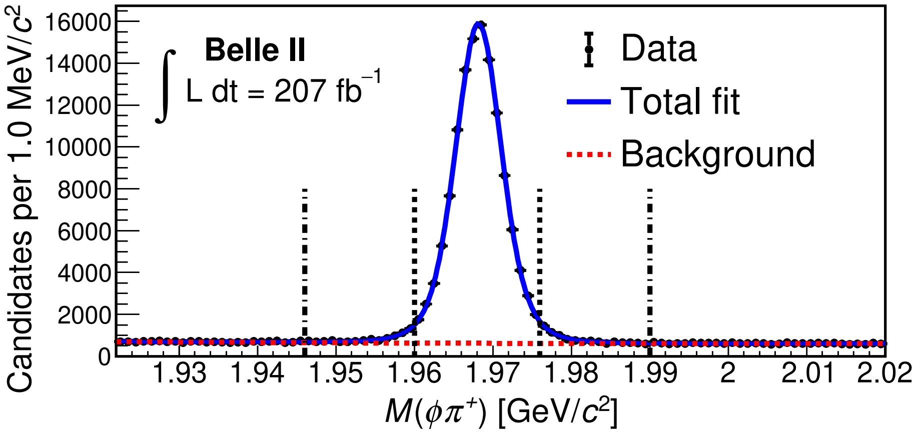


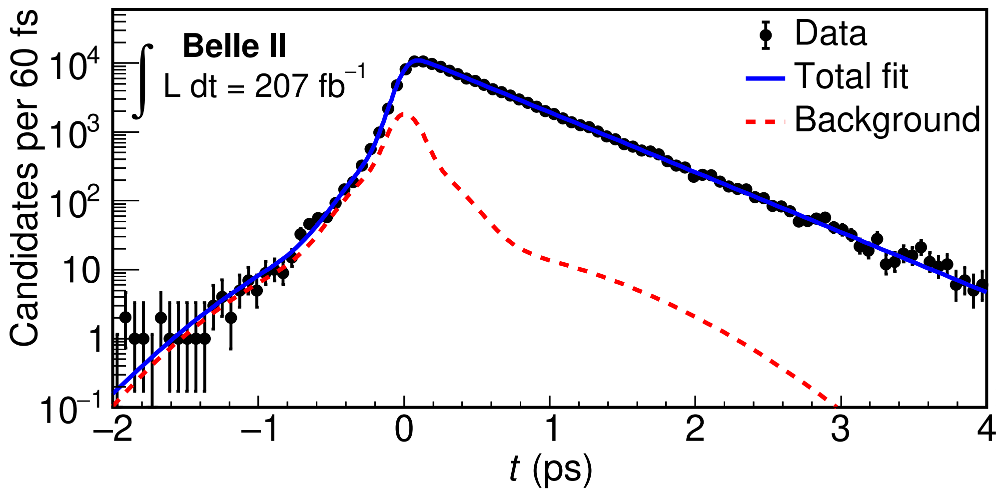
- IP is measured at regular intervals using $e^+e^- \to \mu^+\mu^-$ events
- Uncertainty on t (σ_t) is calculated event-by-event by propagating uncertainties δd_x, δd_y, δd_z, δp_x, δp_y, δp_z and their correlations. The quantity σ_t is used as the width of a Gaussian resolution function for the PDF used to fit the t distribution; this improves the resolution on lifetime.

D_s^+ lifetime (207 fb^{-1})

arXiv:2306.00365, submitted to PRL

- *Select $D_s^+ \to \phi\pi^+$ ($\phi \to K^+K^-$) decays (low background)*
- *$p_{CM}(D_s^+) > 2.5$ GeV/c to eliminate $B \to D_s^+ X$ decays (preserves 2/3 of $e^+e^- \to cc$ events)*
- *small background remaining from random combinations of real ϕ and π^+*
- *require $1.960 < M(\phi\pi^+) < 1.976$ GeV/c^2; unbinned ML fit give 116k signal, 92% purity*
- *lifetime determined from unbinned ML fit to t:*





- *likelihood function for event i:*

$$\mathcal{L}(\tau|t^i,\sigma_t^i) = f_{\rm sig}\, P_{\rm sig}(t^i|\tau,\sigma_t^i)\, P_{\rm sig}(\sigma_t^i) + (1-f_{\rm sig})\, P_{\rm bkg}(t^i|\tau,\sigma_t^i)\, P_{\rm bkg}(\sigma_t^i)$$

(to avoid bias: Punzi, arXiv:physics/0401045)

D_s^+ lifetime (207 fb^{-1})

arXiv:2306.00365, submitted to PRL

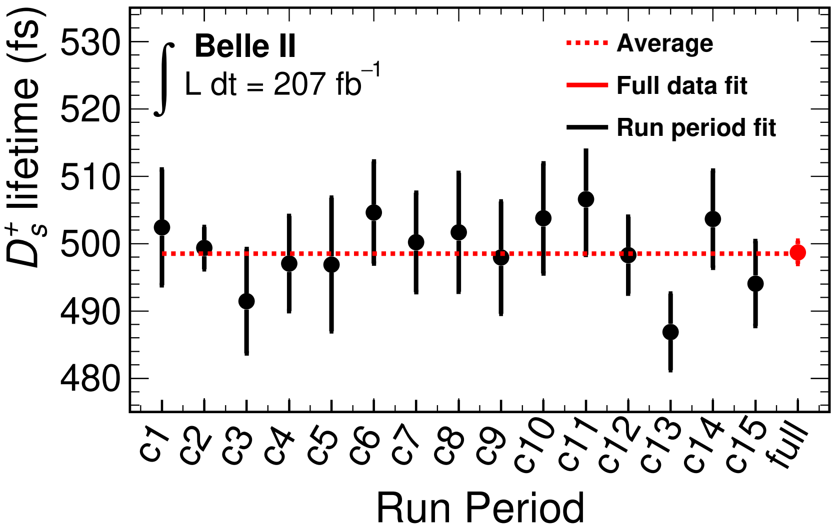
- *PDF for signal D_s^+ decays:*

$$P_{\rm sig}(t^i|\tau,\sigma_t^i) \;=\; \frac{1}{\tau}\int e^{-t'/\tau}\,R(t^i - t';\mu,s,\sigma_t^i)\,dt'$$

- *resolution function R is a single Gaussian with mean μ and per-candidate standard deviation s x σ_t^i ; μ and scaling parameter s are floated*

- *PDF for background is taken from fitting $M(\phi\pi^+)$ upper sideband [1.990, 2.020] GeV/c^2*

- *Result:* $\tau_{D_s^+} \;=\; (498.7 \pm 1.7\,^{+1.1}_{-0.8})$ fs



- *Systematic uncertainties:*

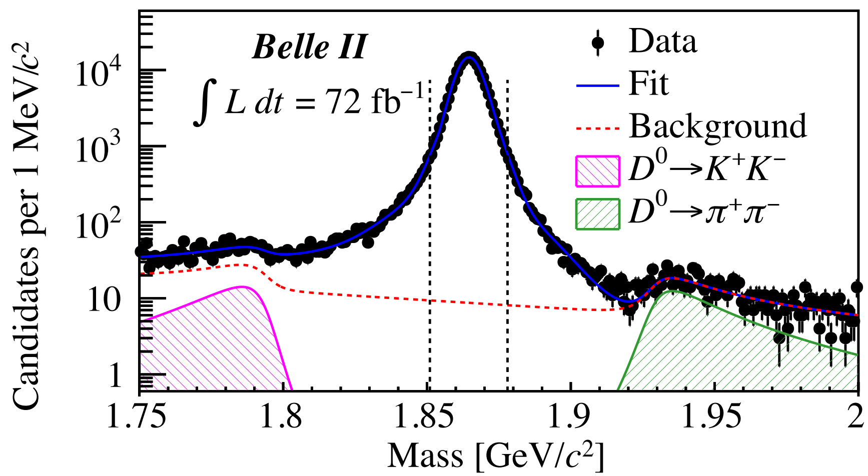
Source	Uncertainty (fs)
Resolution function	+0.85
Background (t,σ_t) distribution	±0.40
Binning of σ_t histogram PDF	±0.10
Imperfect detector alignment	±0.56
Sample purity	±0.09
Momentum scale factor	±0.28
D_s^+ mass	±0.02
Total	$^{+1.14}_{-0.76}$

D^0 and D^+ lifetimes (72 fb^{-1})

Abudinen et al., PRL 127, 211801 (2021) [arXiv:2108.03216]

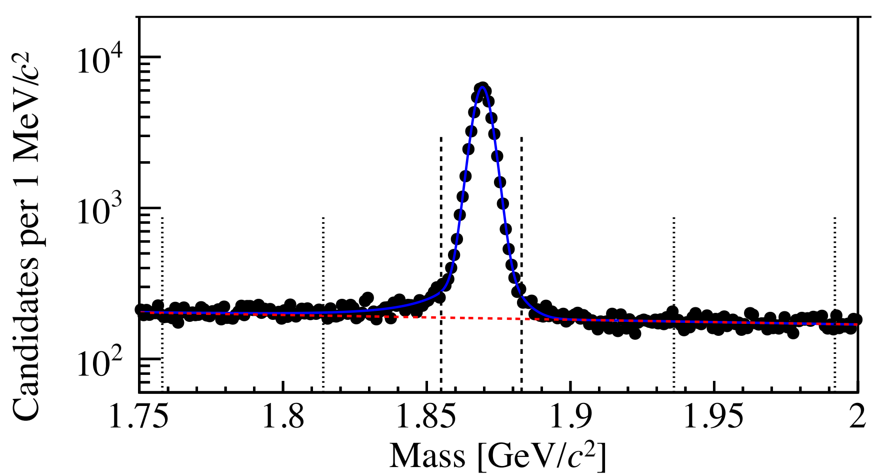
- Select $D^{*+} \to D^0 \pi_s^+$ ($D^0 \to K^- \pi^+$) decays (~no background)
- $p_{CM}(D^{*+})$ > 2.5 GeV/c to eliminate $B \to D^{*+} X$ decays
- require 1.851 < $M(K^-\pi^+)$ < 1.878 GeV/c^2 and 144.94 < $M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$ < 145.90 MeV/c^2; binned χ^2 fit give 171k signal, 99.8% purity

171k $D^0 \to K^-\pi^+$



- Select $D^{*+} \to D^+ \pi^0$ ($D^+ \to K^- \pi^+ \pi^+$) decays (low background), where $\pi^0 \to \gamma\gamma$ and $m(\gamma\gamma) \in$[120,145] MeV/c^2
- $p_{CM}(D^{*+})$ > 2.6 GeV/c to eliminate $B \to D^{*+} X$ decays
- require 1.855 < $M(K^-\pi^+)$ < 1.883 GeV/c^2 and 138 < ΔM < 143 MeV/c^2; binned χ^2 fit give 59k signal, 91% purity

59k $D^+ \to K^-\pi^+\pi^+$



D^0 and D^+ lifetimes (72 fb^{-1})

Abudinen et al., PRL 127, 211801 (2021) [arXiv:2108.03216]

- lifetime determined from unbinned ML fit to (t, σ_t)
- PDF for signal decays:

$$P_{\rm sig}(t^i|\tau,\sigma_t^i) \;=\; \frac{1}{\tau}\int e^{-t'/\tau}\, R(t^i - t'; \mu, s, \sigma_t^i)\, dt'$$

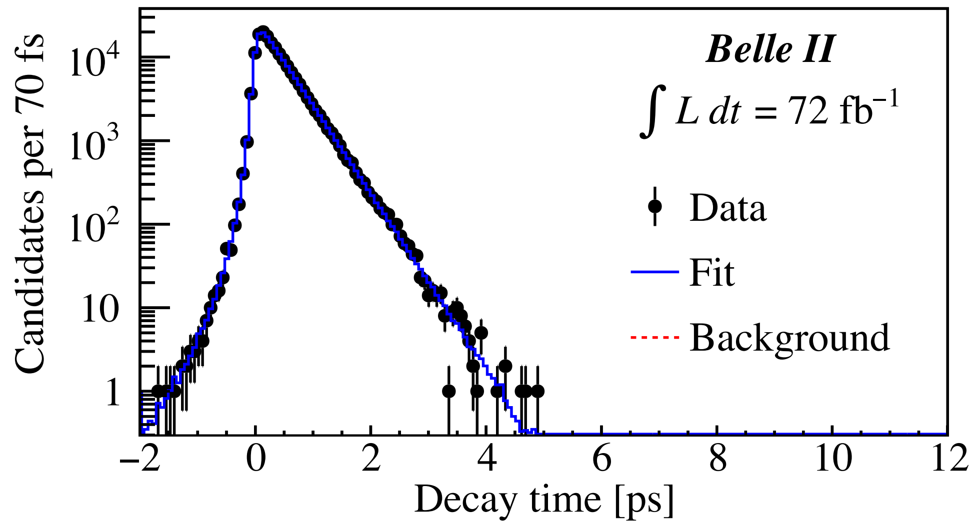
- resolution function R is a double Gaussian for D^0 (single Gaussian for D^+) with mean μ and per-candidate standard deviation s x σ_t^i; μ and scaling parameter s are floated
- PDF for D^+ background is taken from fitting $M(K^-\pi^+\pi^+)$ sidebands [1.758,1.814] and [1.936,1.992] GeV/c^2 . D^0 background is neglected, with a systematic included
- Results:

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

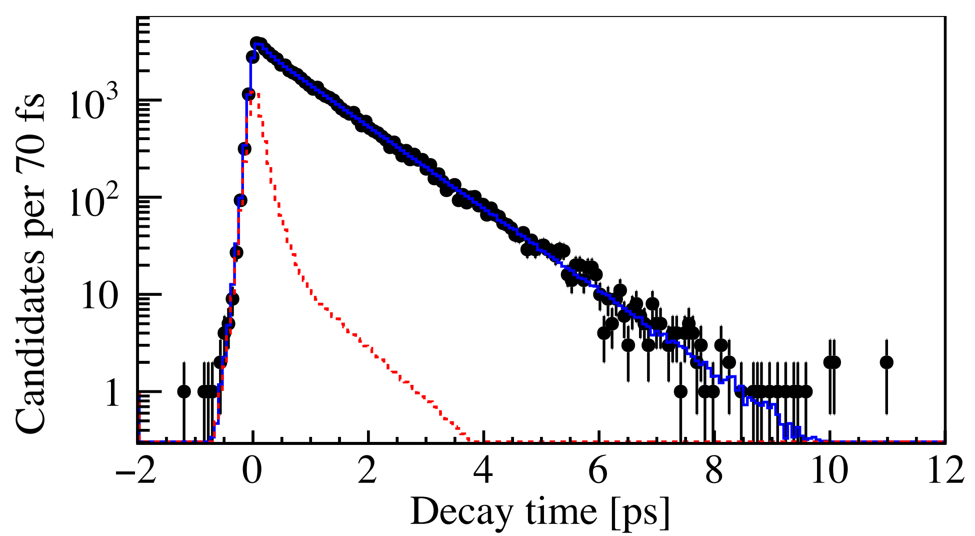
- Systematic uncertainties:

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

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



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

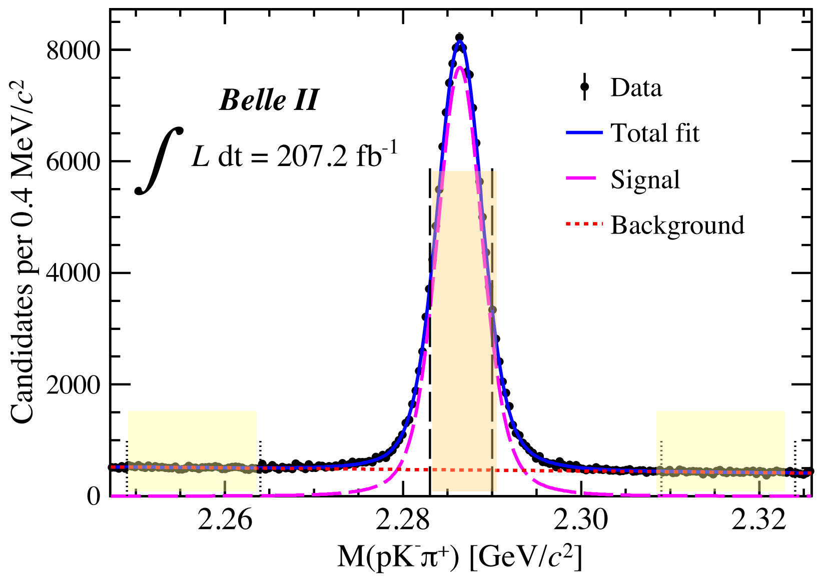


Λ_c^+ lifetime (207 fb^{-1})

Abudinen et al., PRL 130, 071802 (2023) [arXiv:2206.15227]

- Select $\Lambda_c^+ \to pK^-\pi^+$ decays (low background)
- $p_{CM}(\Lambda_c^+) > 2.5$ GeV/c to eliminate $B \to \Lambda_c^+ X$ decays
- require $M(pK^-\pi^+) \in [2.283, 2.290]$ GeV/c^2; binned χ^2 fit gives 116k signal, 93% purity
- lifetime determined from unbinned ML fit to (t, σ_t). Background (t, σ_t) distribution is determined from sidebands $M(pK^-\pi^+) \in [2.249, 2.264]$ GeV/c^2 or $[2.309, 2.324]$ GeV/c^2
- Resolution function $R(t, \sigma_t)$ is a single Gaussian with mean μ and standard deviation s X σ_t , where μ and s are floated
- problematic background from $\Xi_c^0 \to \Lambda_c^+\pi^-$, $\Xi_c^+ \to \Lambda_c^+\pi^0$ decays: $\tau(\Xi_c^0)$ = 153 fs, $\tau(\Xi_c^+)$ = 456 fs.
  - Ξ contamination in Λ_c^+ sample is estimated by fitting distribution of Λ_c^+ vertex displacement in plane transverse to the beam. Result: 374 events (0.003% of Λ_c^+ candidates).
  - To reduce, impose vetos:

    $M(pK^-\pi^+\pi^-) - M(pK^-\pi^+) \notin [183.4, 186.4]$ MeV/c^2
    $M(pK^-\pi^+\pi^0) - M(pK^-\pi^+) \notin [175.3, 187.3]$ MeV/c^2
    This reduces Ξ decays by 40%.
  - Effect of remaining decays is estimated via MC simulation; bias of 0.34 fs is subtracted from fitted $\tau(\Lambda_c^+)$



Λ_c^+ lifetime (207 fb^{-1})

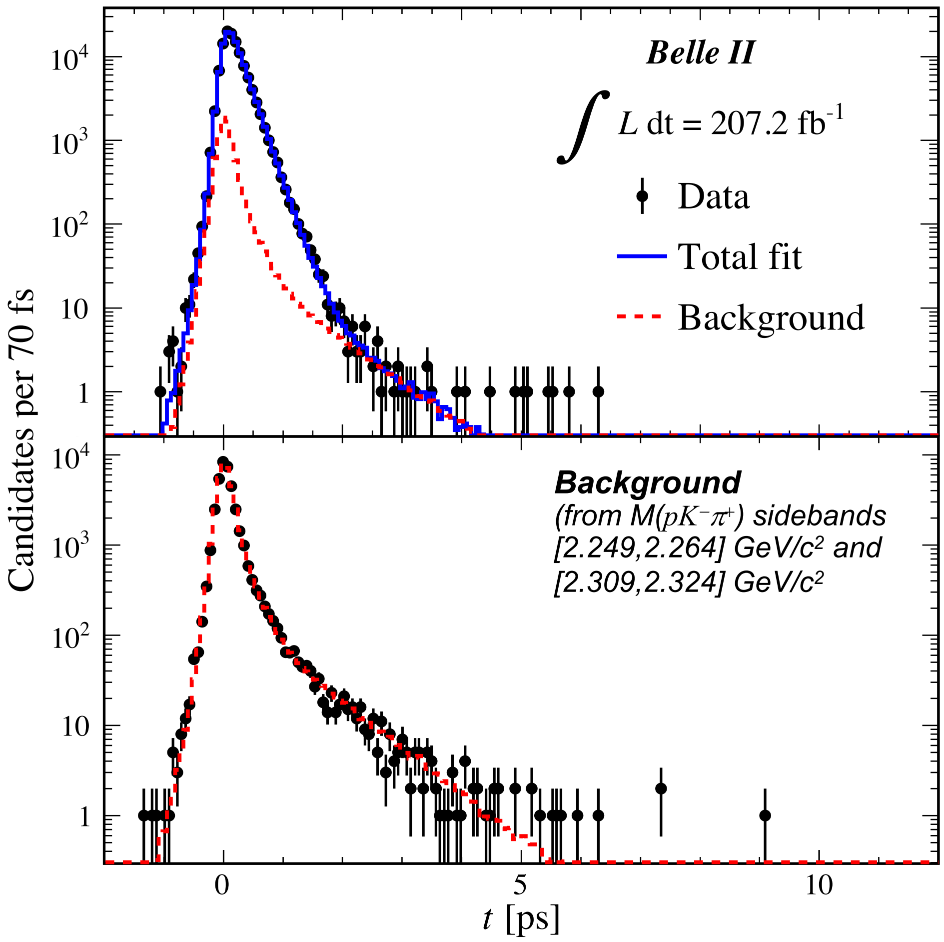
Abudinen et al., PRL 130, 071802 (2023) [arXiv:2206.15227]

- PDF for background is sum of two exponentials and a δ function, all convolved with resolution functions having floated parameters μ_b , s_b
- Result:

$$\tau_{\Lambda_c^+} = (203.20 \pm 0.89 \pm 0.77)\ \text{fs}$$

- Systematic uncertainties:

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

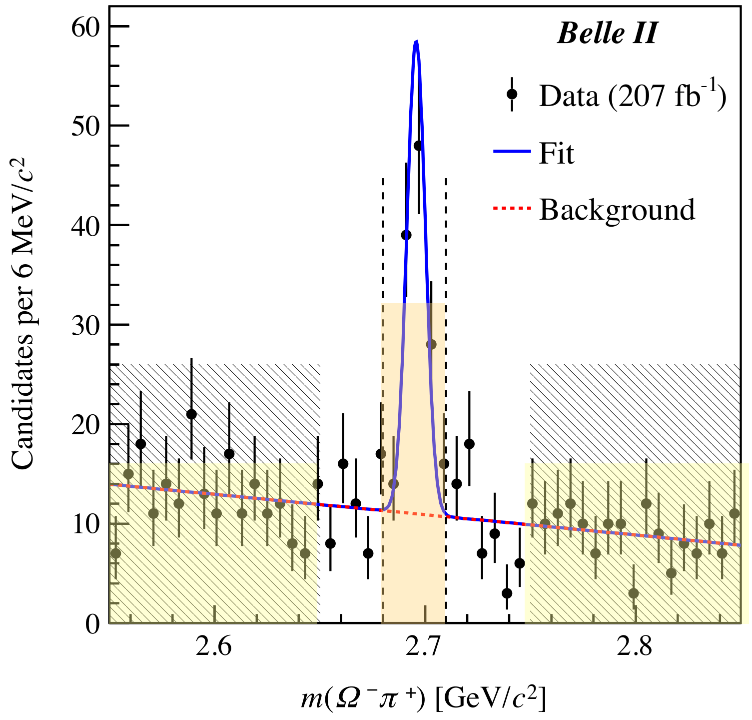


Ω_c^0 lifetime (207 fb^{-1})

Abudinen et al., PRD 107, L031103 (2023) [arXiv:2208.08573]

Theory expectation: (& E687, WA89)	$\tau(\Omega_c) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$	⇒ Belle II can resolve this
LHCb measurement: (2018, 2022)	$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c) < \tau(\Xi_c^+)$	

- Select $\Omega_c \to \Omega^- \pi^+$, $\Omega^- \to \Lambda K^-$, $\Lambda \to p\pi^-$ decays (large CF branching fractions)
- $p_{CM}(\Omega_c)/p_{max} > 0.6$ to eliminate $B \to \Omega_c X$ decays, where $p_{max} = \sqrt{[(E^{CM}_{beam})^2 - m(\Omega\pi)^2]}$
- require $M(\Omega^- \pi^+) \in$ [2.68,2.71] GeV/c^2; unbinned ML fit gives 132 signal decays, 67% purity
- lifetime determined from unbinned ML fit to (t,σ_t). Background (t,σ_t) distribution is determined from sidebands $M(\Omega^- \pi^+) \in$ [2.55,2.65] GeV/c^2 and [2.75,2.85] GeV/c^2
- Resolution function $R(t,\sigma_t)$ is a single Gaussian with mean μ and standard deviation $s \times \sigma_t$, where μ and s are floated



Abudinen et al., PRD 107, L031103 (2023)
[arXiv:2208.08573]

Ω_c^0 lifetime (207 fb^{-1})

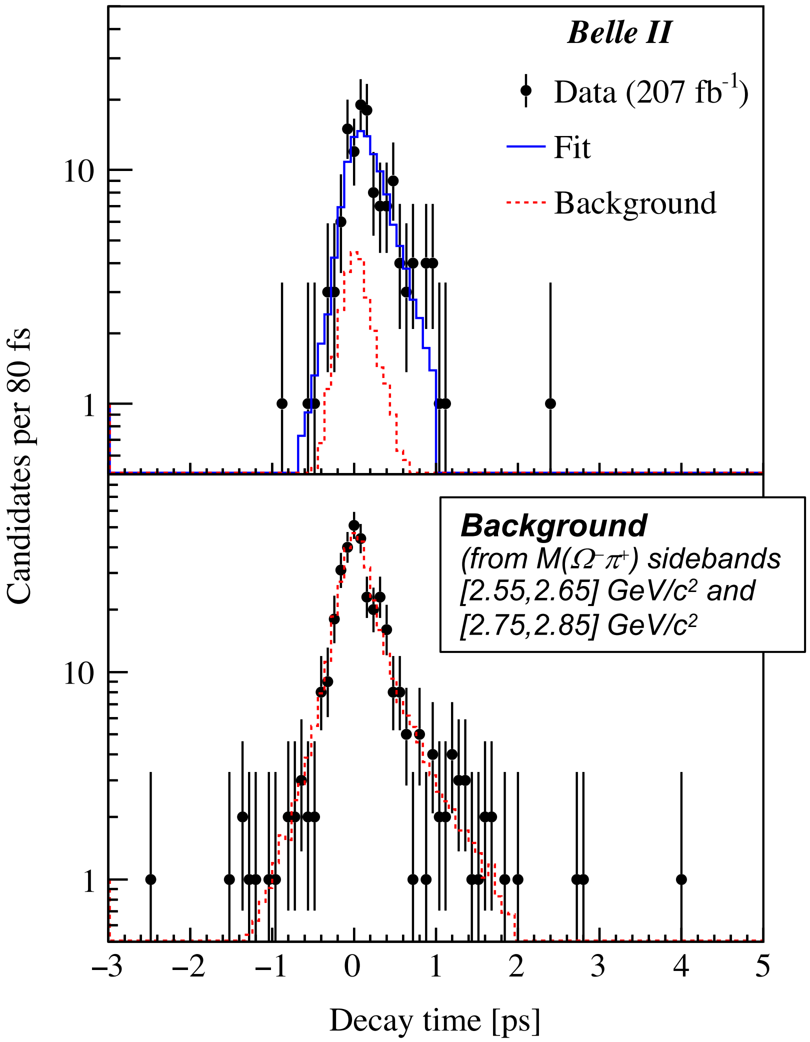
- PDF for background is sum of an exponential and a δ function, both convolved with a Gaussian resolution function having floated parameters μ_b and s_b

- Result:

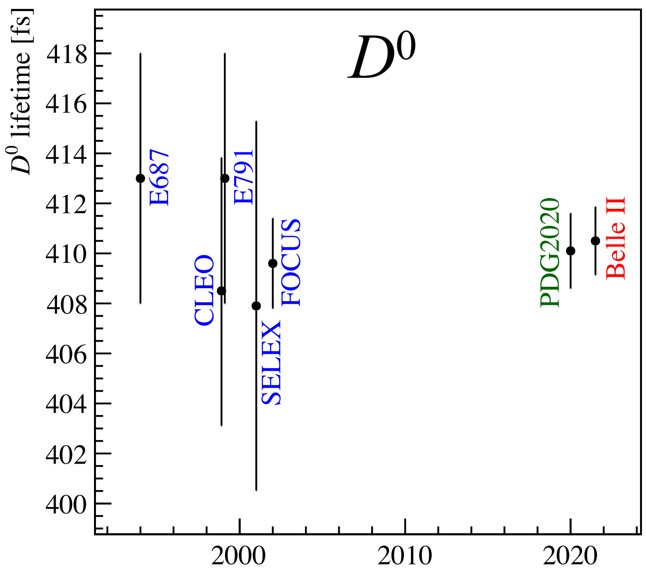
$$\tau_{\Omega_c^0} = (243 \pm 48 \pm 11)\ \text{fs}$$

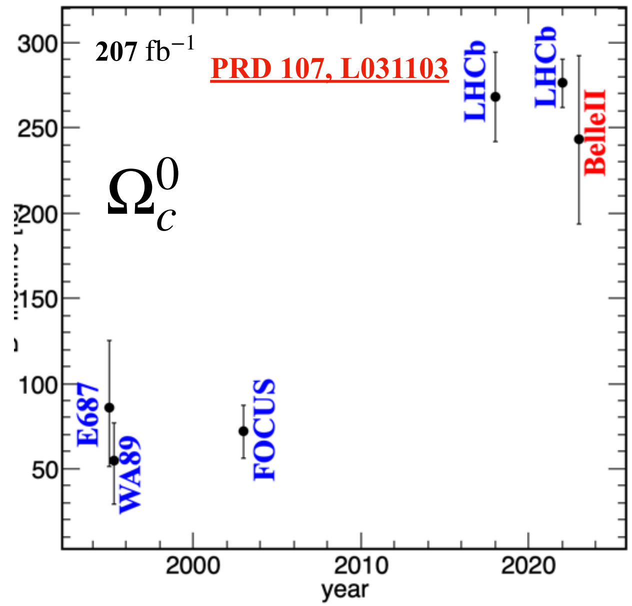
- Systematic uncertainties:

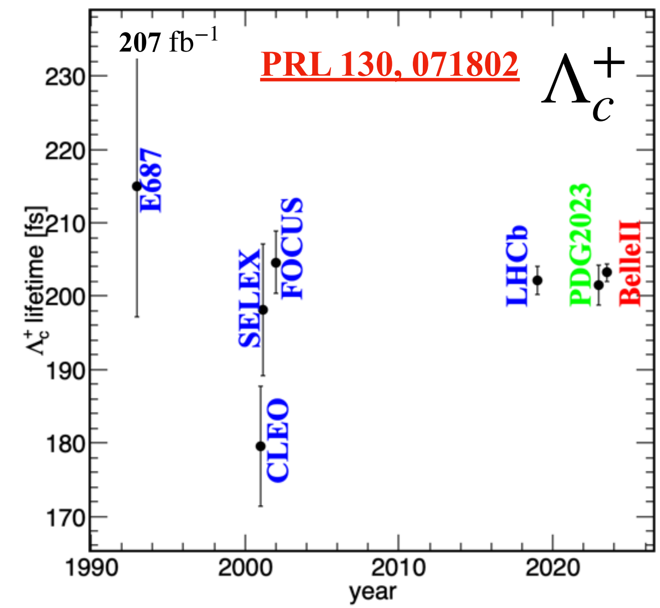
Source	Uncertainty (fs)
Fit bias	**3.4**
Resolution model	**6.2**
Background model	**8.3**
Detector alignment	**1.6**
Momentum scale	**0.2**
Input Ω_c^0 mass	**0.2**
Total	11.0

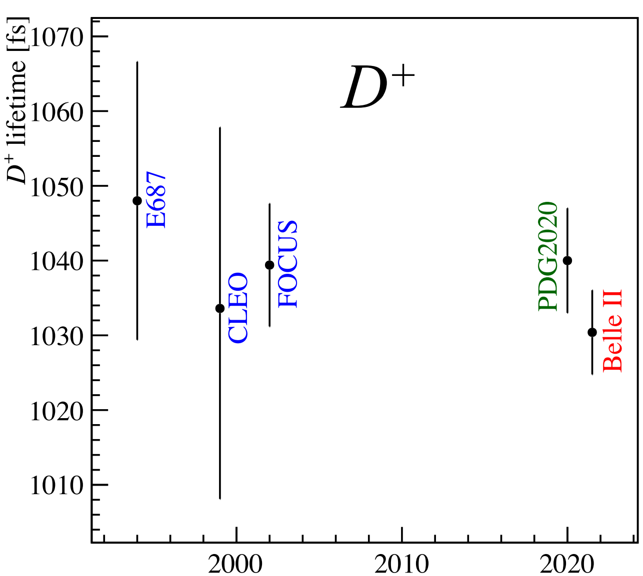


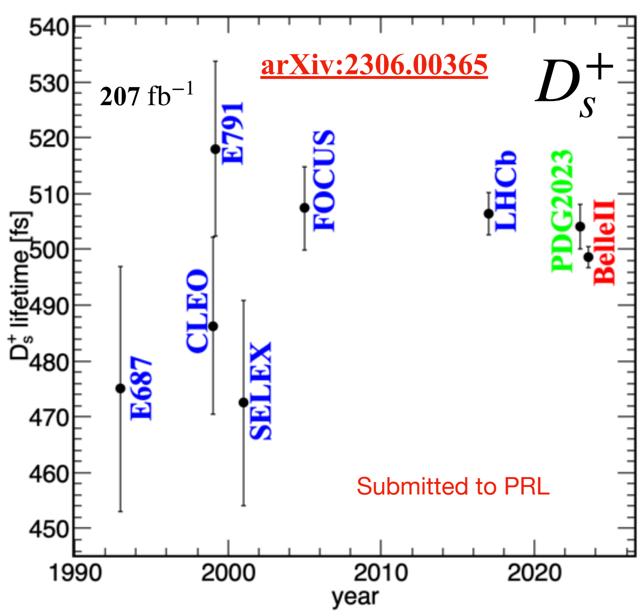
Summary I











- *In all cases except for Ω_c^0, Belle II has made the world's highest precision measurement (in some cases after 20 years)*
- *For Ω_c^0, the Belle II measurement resolves the discrepancy between LHCb and all previous measurements (LHCb's long lifetime looks correct)*

Summary II

King, Lenz et al., JHEP 08 (2022) 241; arXiv:2109.13219
Gratrex et al., JHEP 07 (2022) 058; arXiv:2204.11935

Some comparisons with theory:

Quantity	Belle II	King et al. JHEP 08 (2022) 241	Gratrex et al. JHEP 07 (2022) 058
$\tau(D^0)$	410.5 ± 1.1 ± 0.8		
$\tau(D^+)$	1030.4 ± 4.7 ± 3.1		
$\tau(D^+_s)$	$498.7 \pm 1.7\ ^{+1.1}_{-0.8}$		
$\tau(D^+)/\tau(D^0)$	2.510		
$\tau(D^+_s)/\tau(D^0)$	1.215		
$\tau(\Lambda_c^+)$	203.20 ± 0.89 ± 0.77		
$\tau(\Omega_c^0)$	243 ± 48 ± 11		
$\tau(\Omega_c^0)/\tau(\Lambda_c^+)$	1.20		

All measurements and predictions in reasonable agreement, some tension...

Future running