Charm lifetimes at Belle II: recent results

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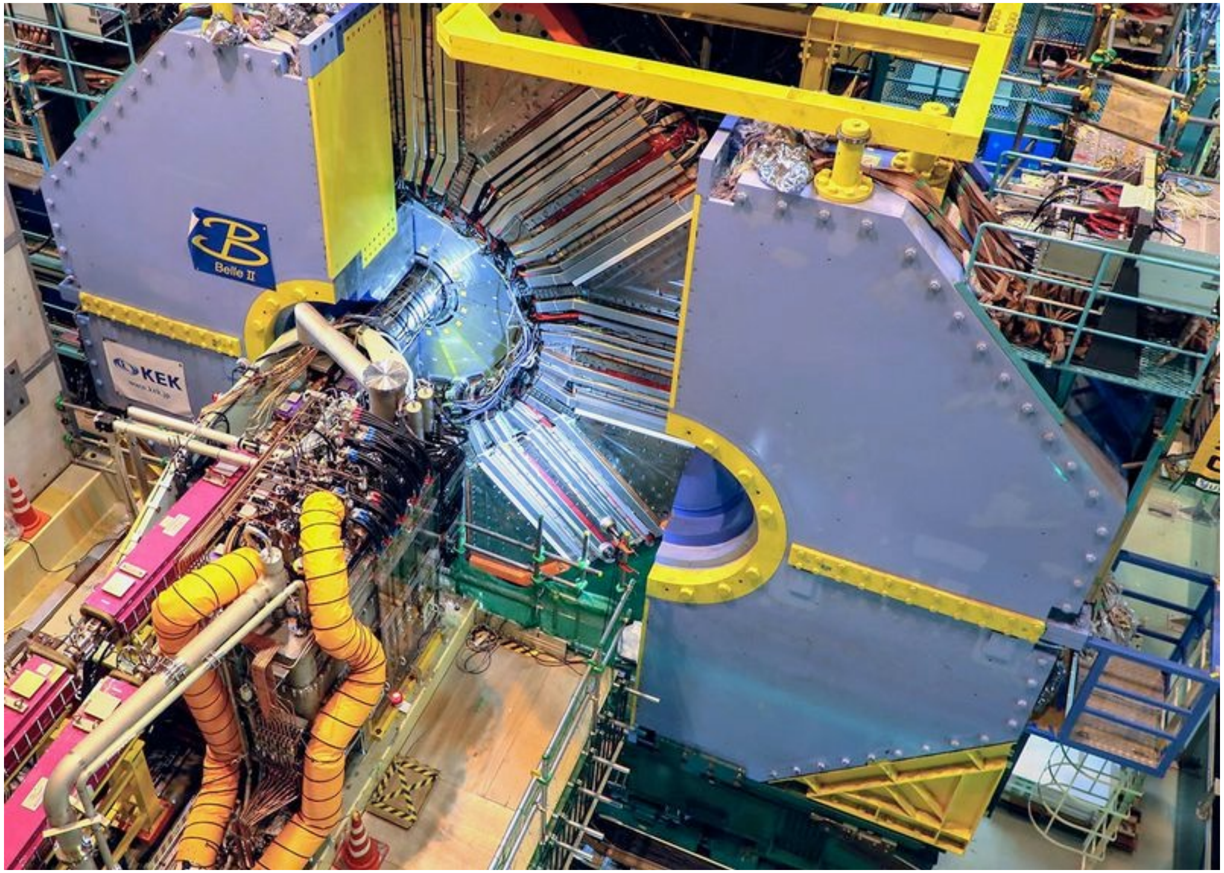
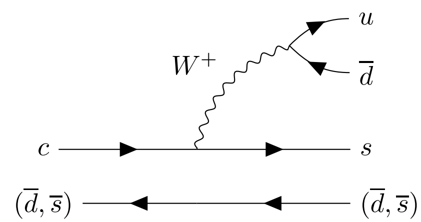


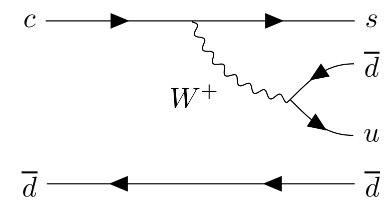
- motivation
- overview of Belle II
- measurements
  - mesons: D^0, D^+, D_s^+
  - baryons: Λ_c^+, Ω_c^0
- comparison with theory
- future

Why measure charm lifetimes?

Theory:

- **qualitatively** understood in terms of simple diagrams, e.g., $c \to s\, e^{+} \nu$ partial width gives $G_F^2 m_c^5\, |V_{cs}|^2/(192\pi^3)$ dependence. Long D^{+} lifetime can be understood as arising from destructive interference between spectator and color-suppressed amplitudes. But this doesn't include QCD...





- **to include QCD:** calculate using the Heavy Quark Expansion

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

ΣX is sum over final states

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

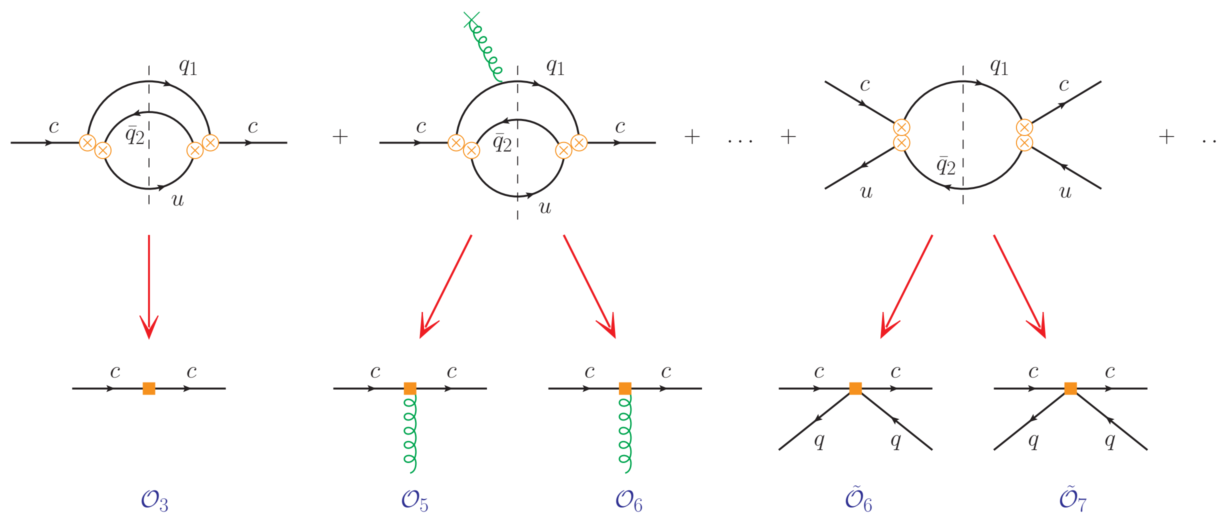
via optical theorem

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

via Heavy Quark Expansion

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

⇒ comparing lifetime calculations with measurements tests/improves our understanding of QCD

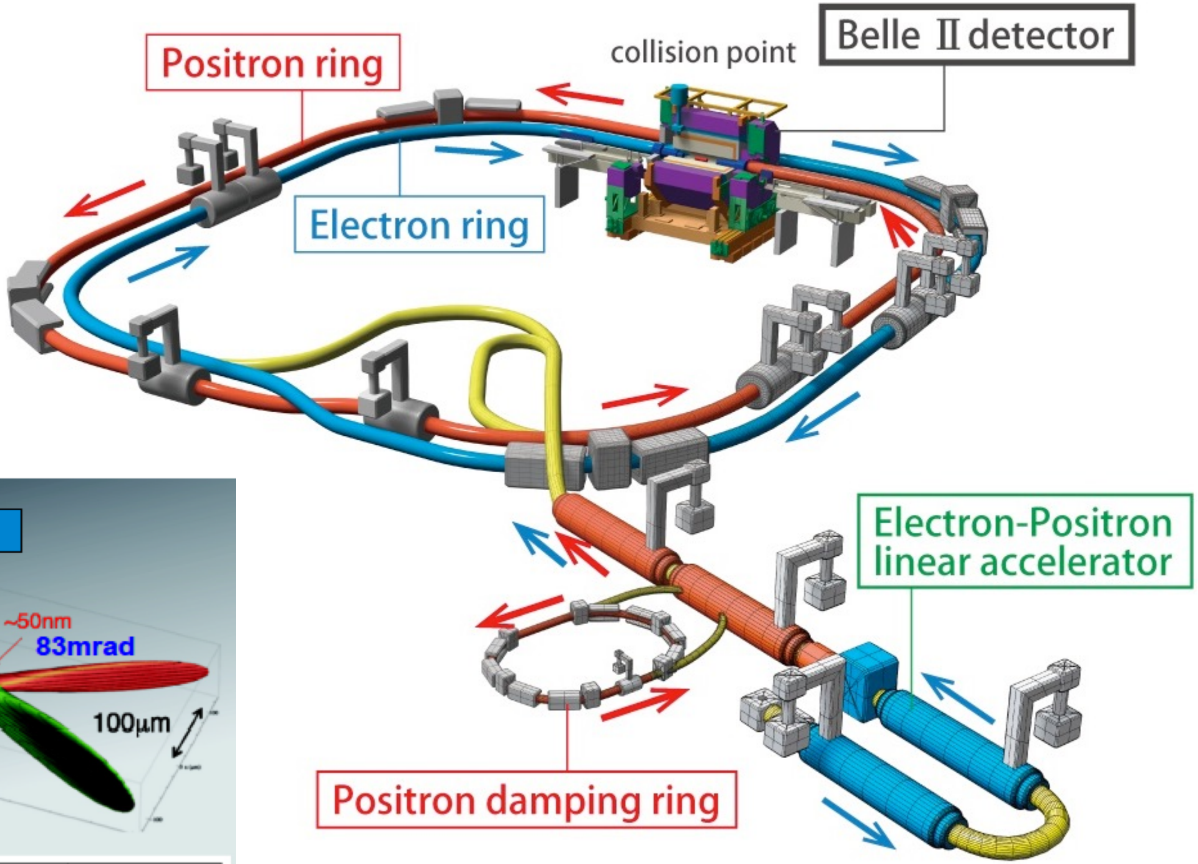


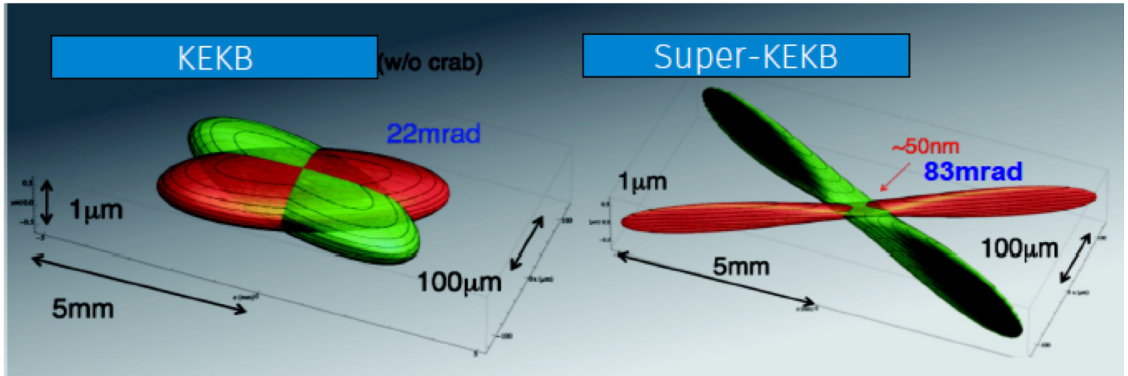
Major accelerator upgrade (KEKB → SuperKEKB)

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}

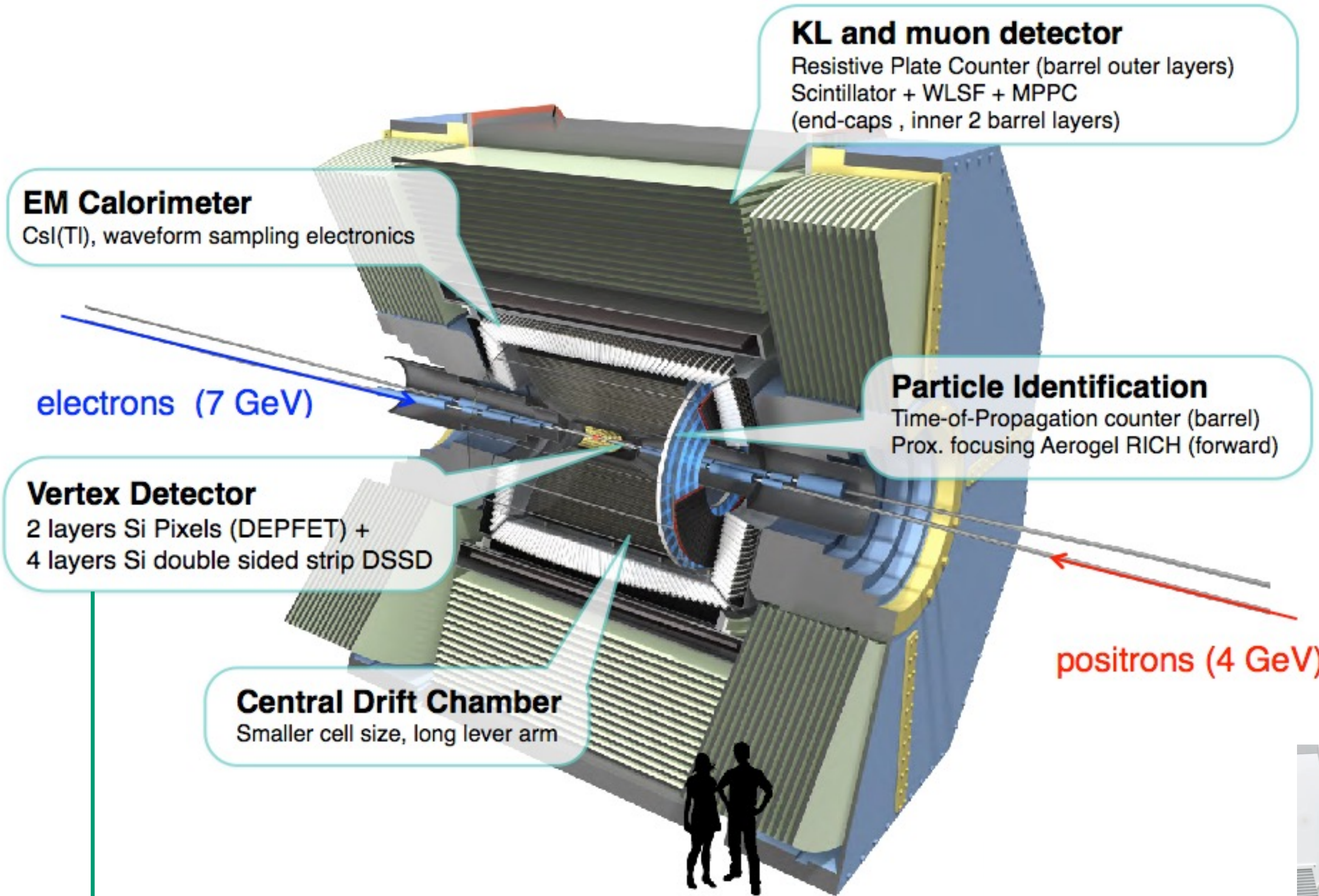




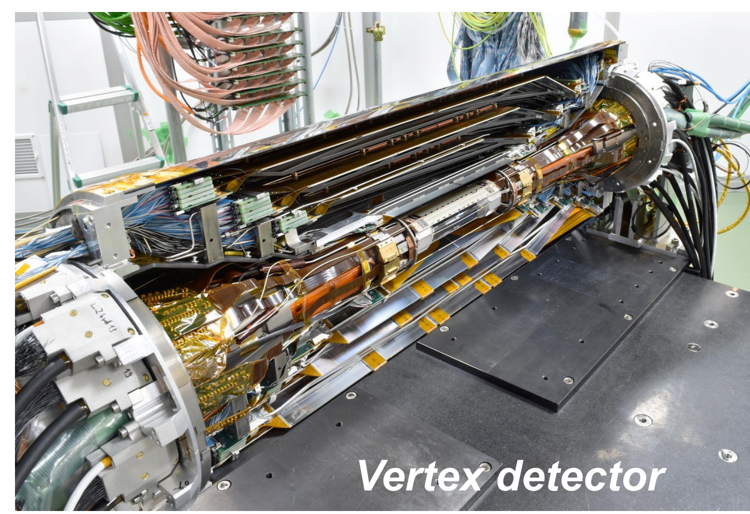
	E (GeV) LER/HER	β*$_y$ (mm) LER/HER	β*$_x$ (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20 factor 2-3

The Belle II Experiment



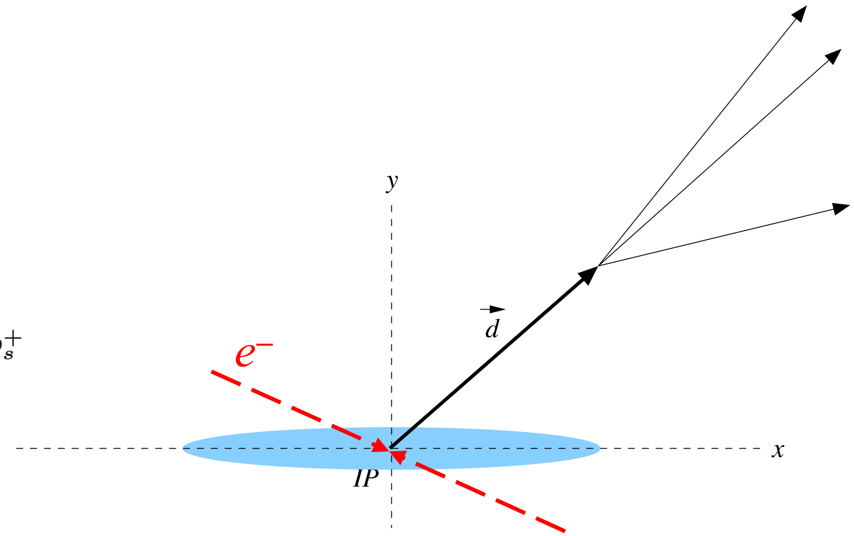
DEPFET pixels:	*Layer 1*	*r = 14 mm*
	Layer 2	*r = 22 mm (1/8 installed)*
double-sided strips:	*Layer 3*	*r = 39 mm*
	Layer 4	*r = 80 mm*
	Layer 5	*r = 104 mm*
	Layer 6	*r = 135 mm*

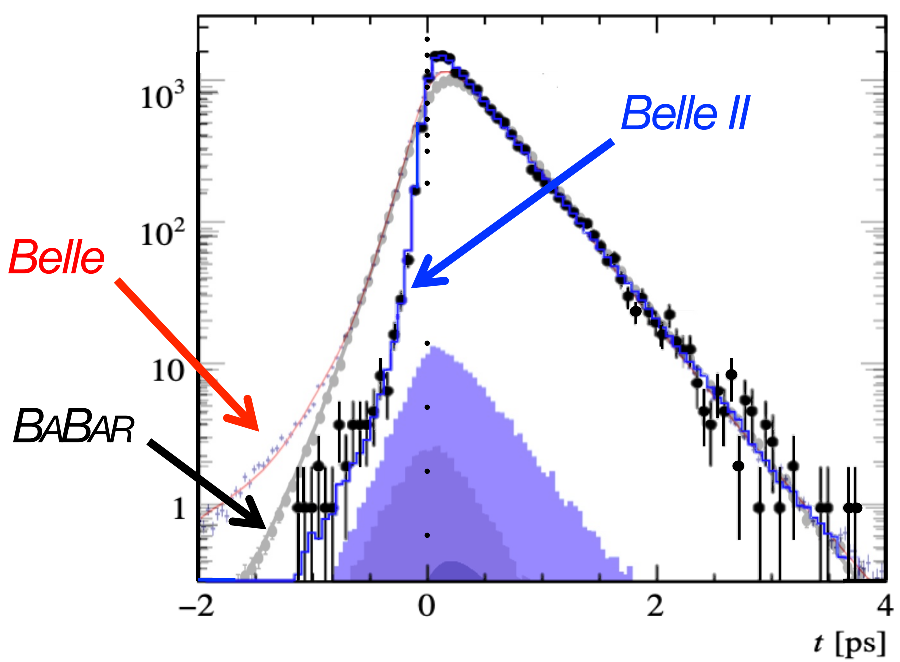


Charm lifetimes: measurement @ Belle II

Determine lifetime by measuring vertex displacement and momentum:

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



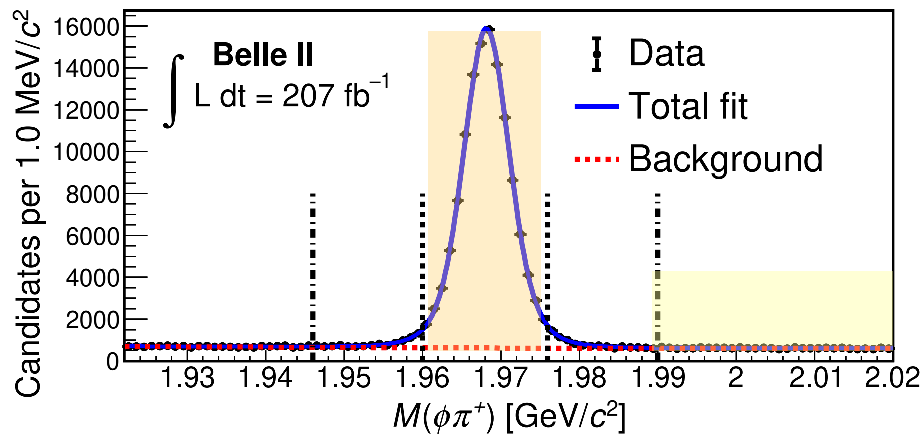


- IP is measured every 30 minutes using $e^+e^- \to \mu^+\mu^-$ events
- Uncertainty on t (σ_t) is calculated event-by-event by propagating uncertainties δd_x, δd_y, δd_z, δp_x, δp_y, δp_z and their correlations.
- The uncertainty σ_t is used as the width of a Gaussian resolution function used to fit the t distribution
- decay time resolution is > 2 times better than Belle/Babar: 80-90 fs vs. 200 fs

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

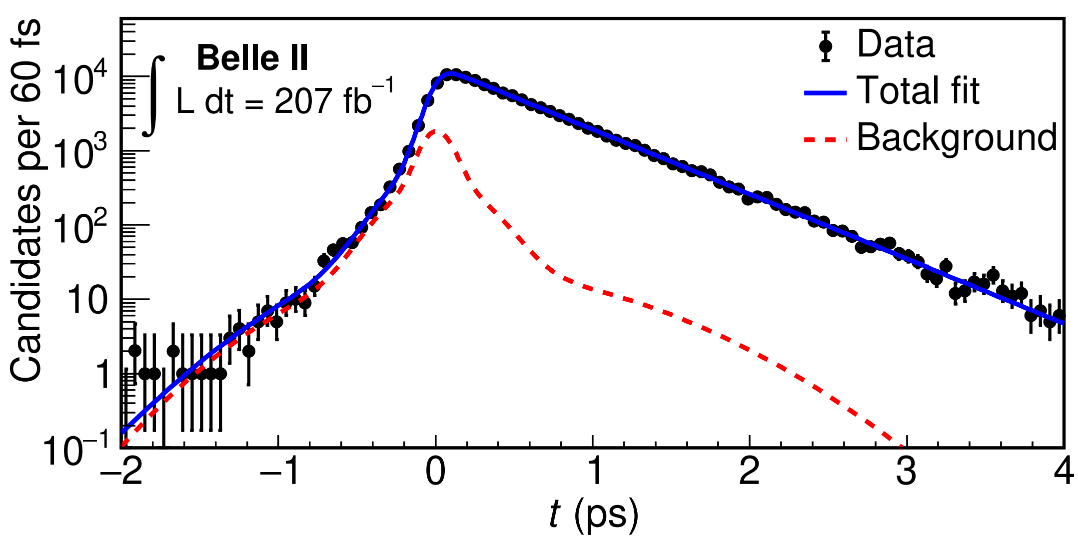
arXiv:2306.00365, submitted to PRL

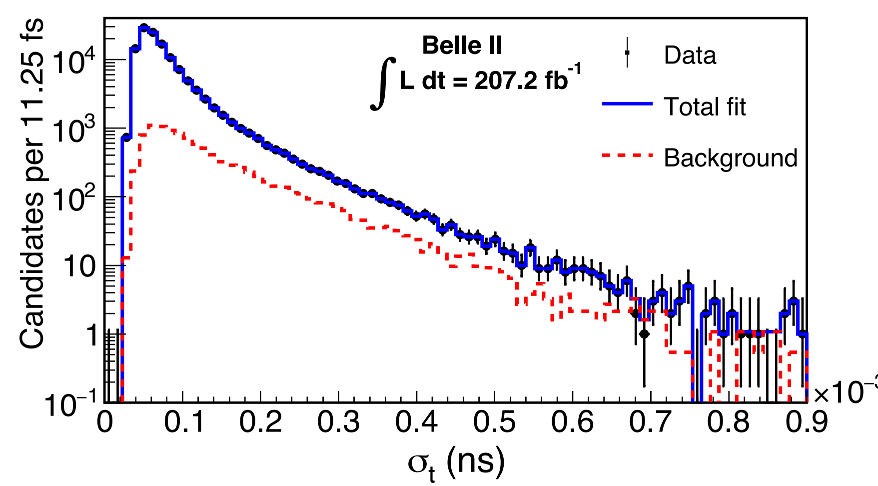
- Select $D_s^+ \to \phi\pi^+$ ($\phi \to K^+K^-$) (low background)
- $p_{CM}(D_s^+) > 2.5$ GeV/c to eliminate $B \to D_s^+ X$ decays (preserves 2/3 of $e^+e^- \to c\bar{c}$ events)
- require $M(\phi\pi^+) \in [1.960, 1.976]$ GeV/c^2; unbinned ML fit give 116k signal, 92% purity. Background from random combinations of ϕ and π^+
- 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

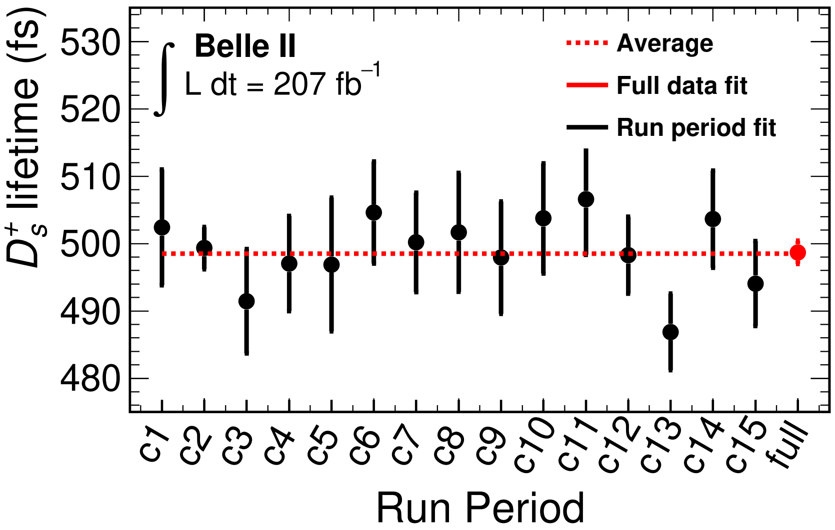
- *PDF for signal D_s^+ decays:*

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

- *resolution function R is a single Gaussian with mean μ and per-candidate standard deviation $s \times \sigma_t^i$; 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:*

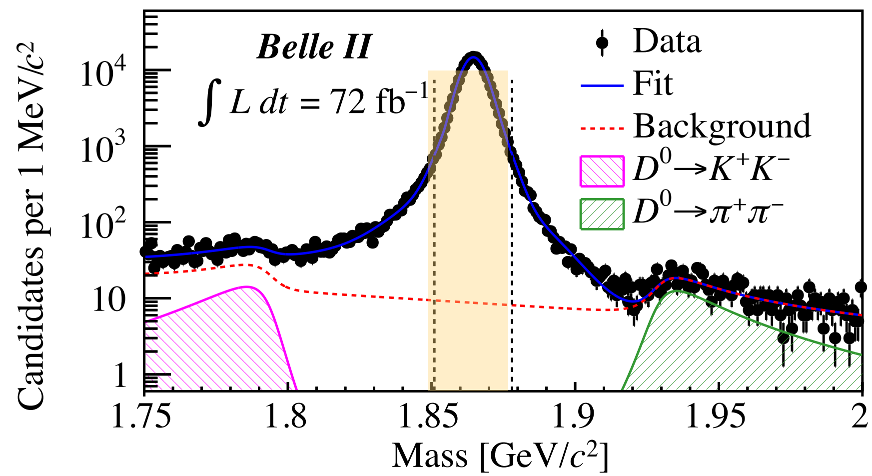
Source	Uncertainty (fs)
Resolution function	$+0.85$
Background (t, σ_t) distribution	± 0.40
Binning of σ_t histogram PDF	± 0.10
Imperfect detector alignment	± 0.56
Sample purity	± 0.09
Momentum scale factor	± 0.28
D_s^+ mass	± 0.02
Total	$^{+1.14}_{-0.76}$

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

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

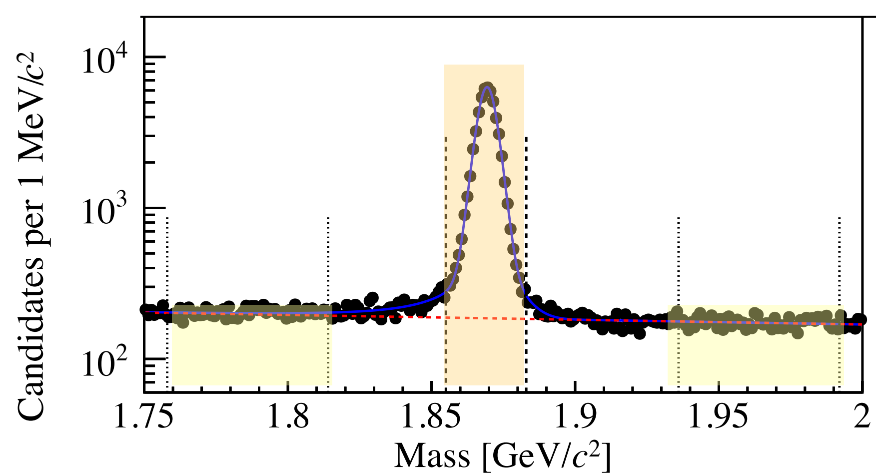
- Select $D^{*+} \to D^0 \pi_s^+$ ($D^0 \to K^- \pi^+$) decays (~no background)
- $p_{CM}(D^{*+})$ > 2.5 GeV/c to eliminate $B \to D^{*+} X$ decays
- require $M(K^- \pi^+) \in [1.851, 1.878]$ GeV/c^2 and $M(K^- \pi^+ \pi_s^+) - M(K^- \pi^+) \in [144.94, 145.90]$ MeV/c^2; binned χ^2 fit give 171k signal, 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 $M(K^- \pi^+) \in [1.855, 1.883]$ GeV/c^2 and $\Delta M \in [138, 143]$ 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]

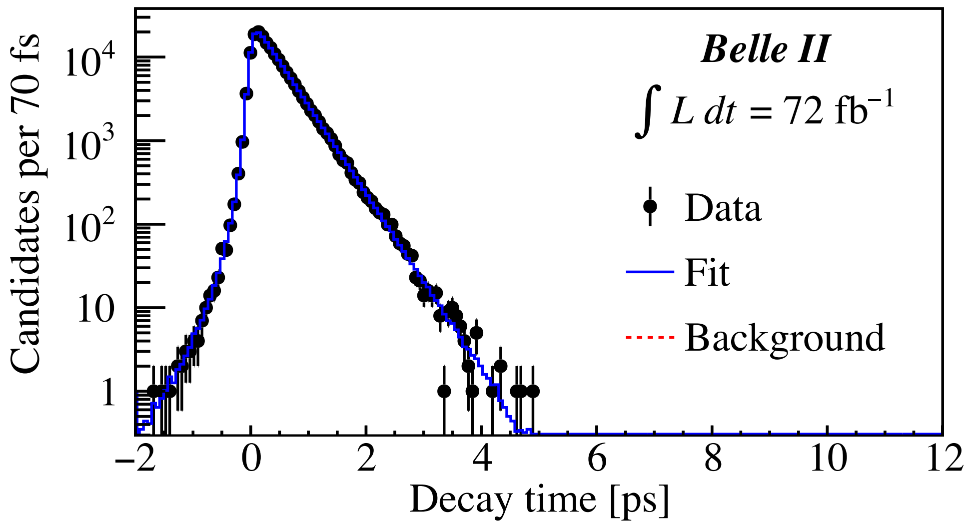
- lifetime determined from unbinned ML fit to (t, σ_t)
- resolution function R is a double Gaussian for D^0 (single Gaussian for D^+) with mean μ and per-candidate standard deviation s x σ_t^i ; μ and scaling parameter s are floated
- PDF for D^+ background is taken from fitting $M(K^-\pi^+\pi^+)$ sidebands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

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

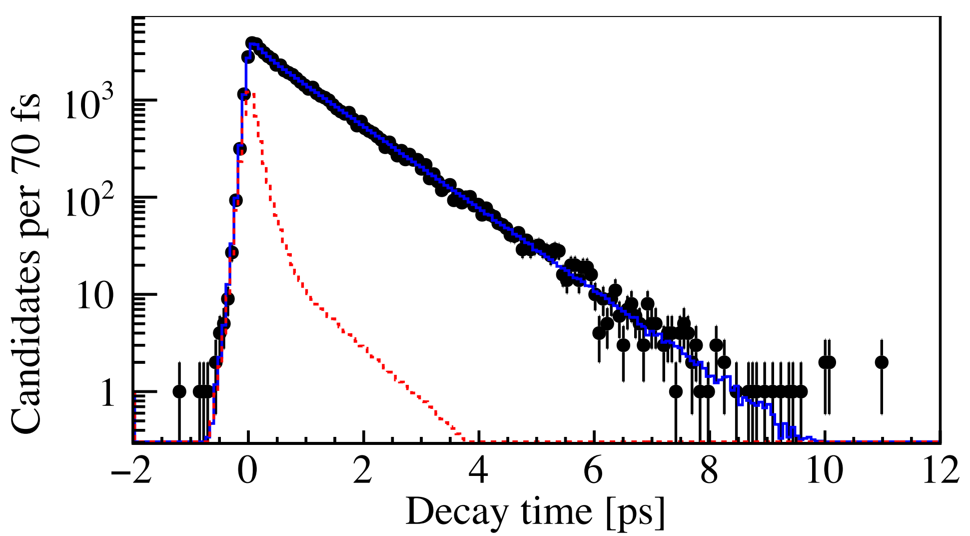
- Systematic uncertainties:

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

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



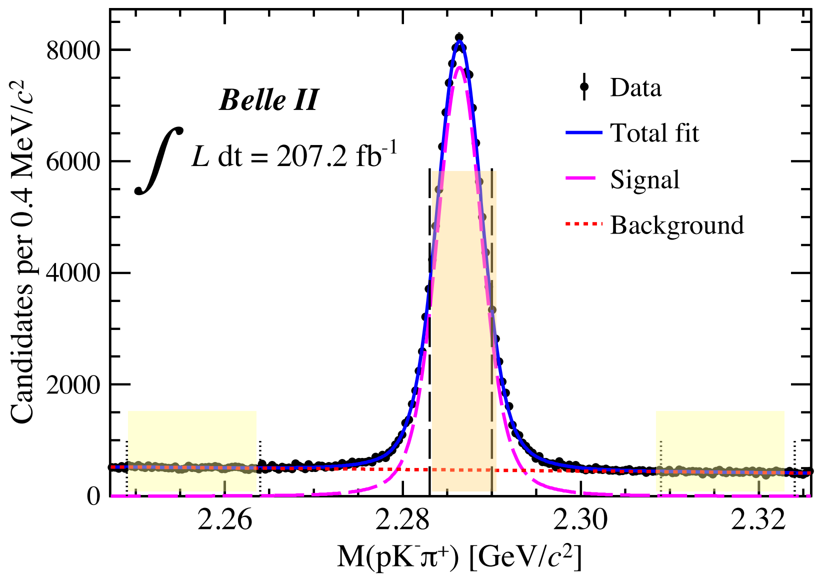
$D^+ \to K^-\pi^+\pi^+$



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 and [2.309,2.324] GeV/c^2
- Resolution function $R(t,\sigma_t)$ is a single Gaussian with mean μ and standard deviation $s \times \sigma_t$; 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})

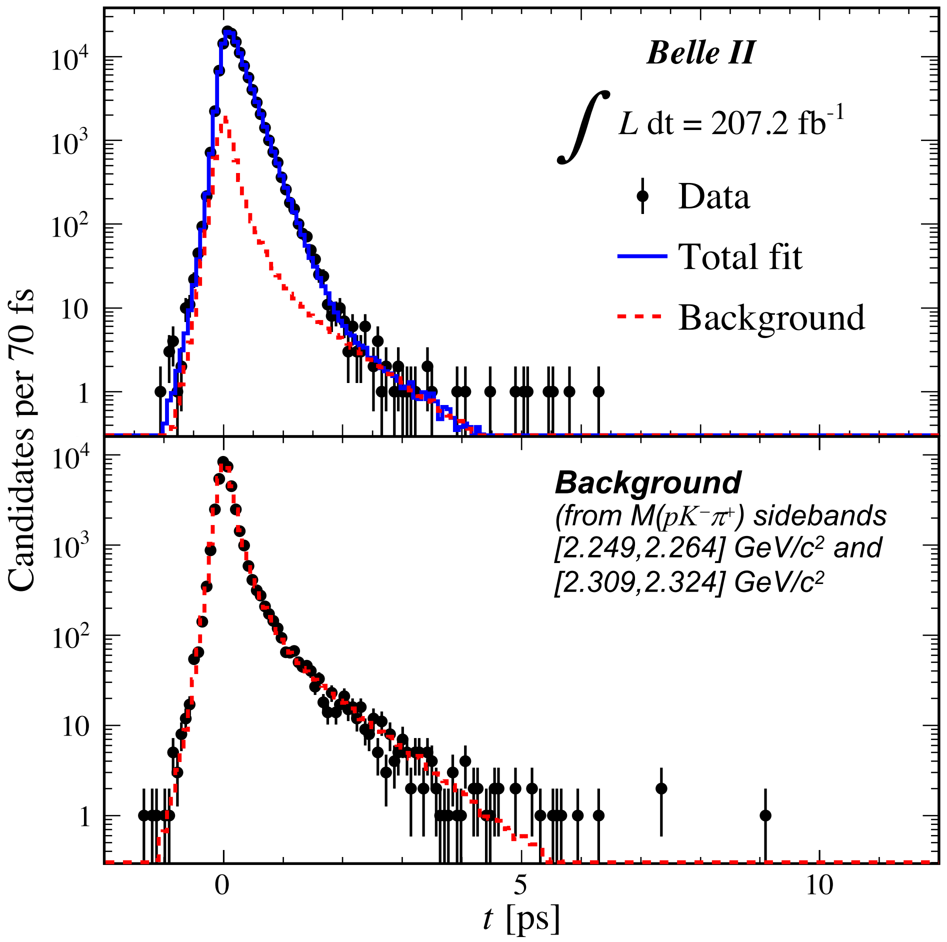
Abudinen et al., PRL 130, 071802 (2023) [arXiv:2206.15227]

- *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

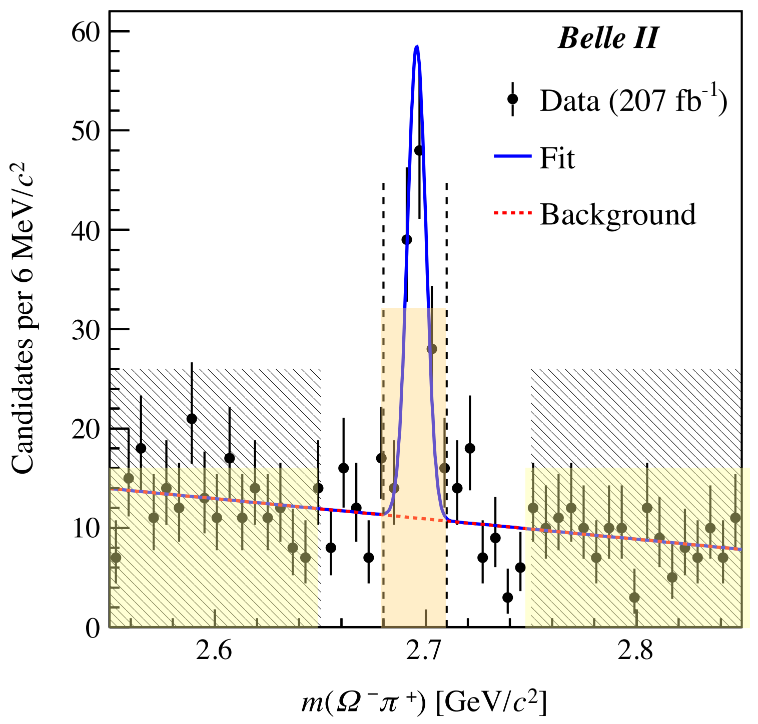


Ω_c^0 lifetime (207 fb^{-1})

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 confirm this (useful to have another experiment confirm)
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 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 $s \times \sigma_t$; μ and s are floated



Ω_c^0 lifetime (207 fb^{-1})

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

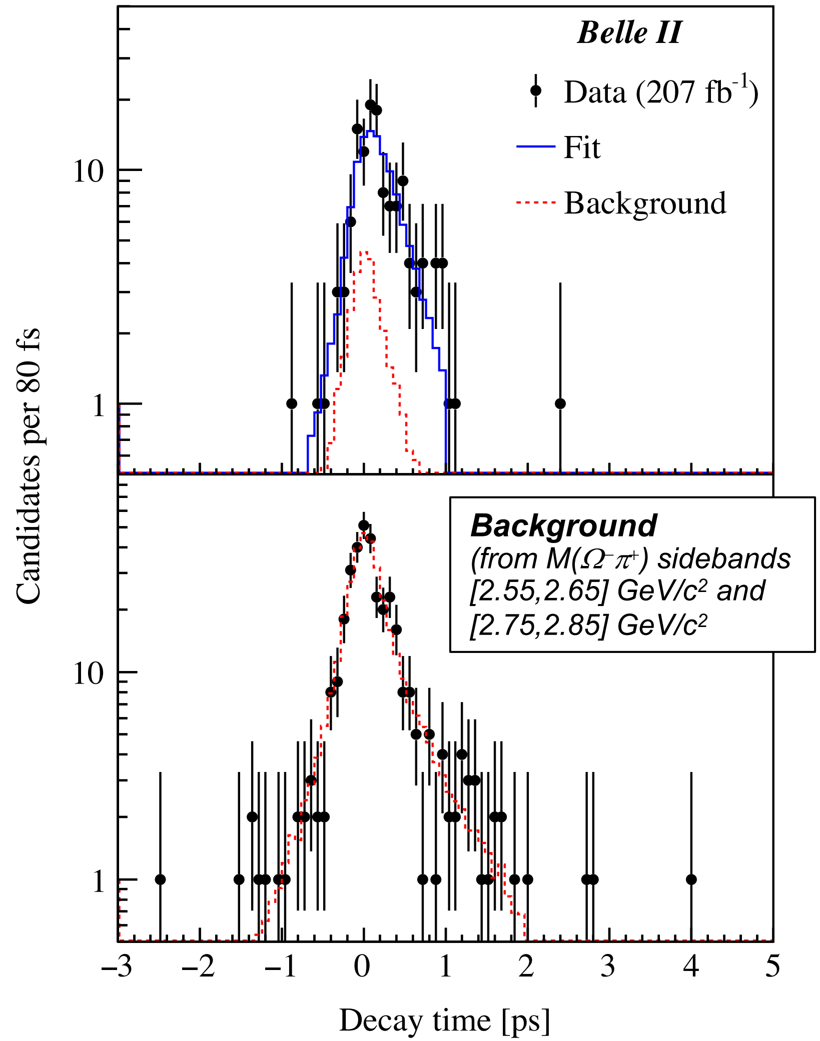
- PDF for background is sum of an exponential and a δ function, both convolved with a Gaussian resolution function having floated parameters μ_b and s_b

- Result:

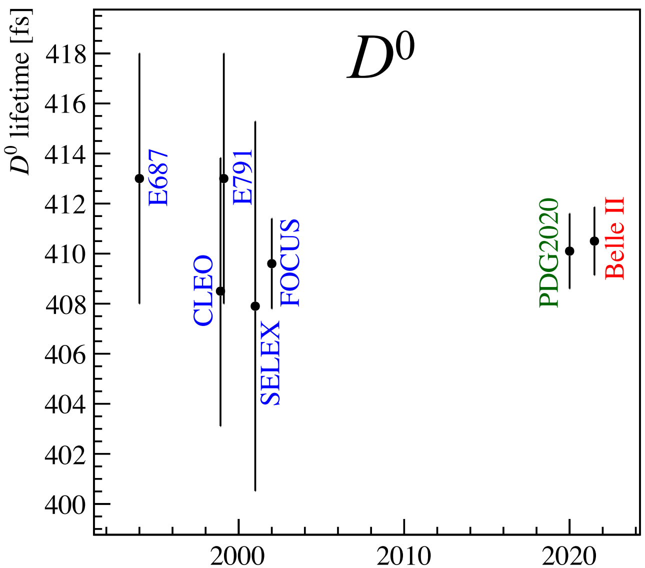
$$\tau_{\Omega_c^0} = (243 \pm 48 \pm 11)\ \text{fs}$$

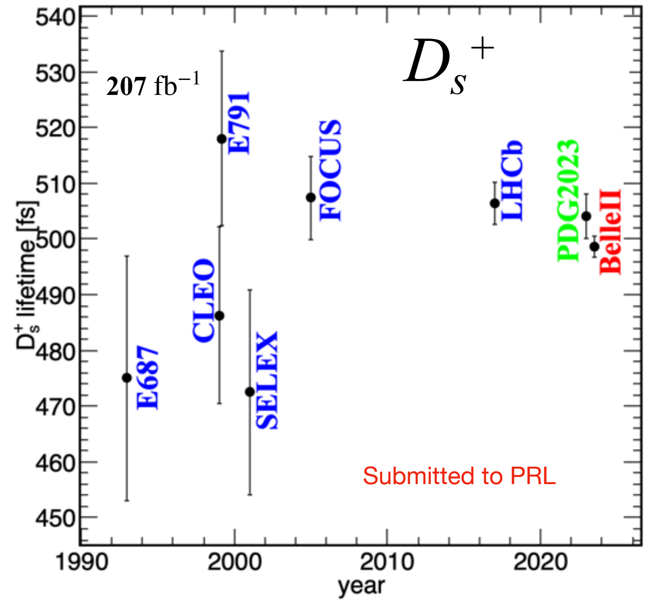
- Systematic uncertainties:

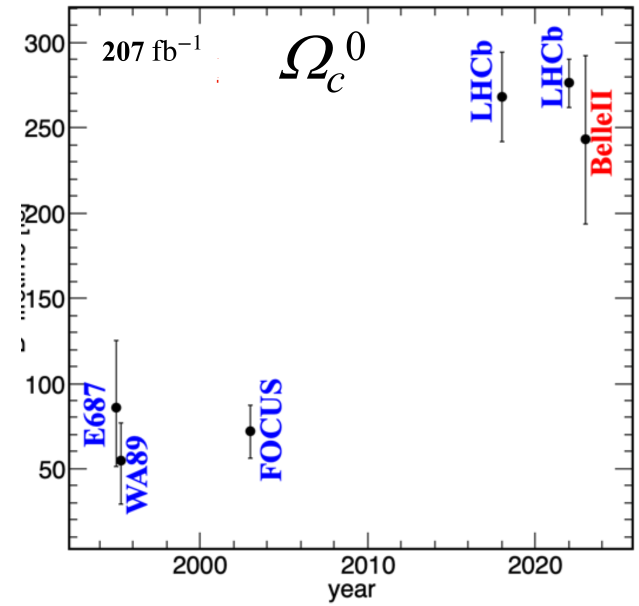
Source	Uncertainty (fs)
Fit bias	**3.4**
Resolution model	**6.2**
Background model	**8.3**
Detector alignment	**1.6**
Momentum scale	**0.2**
Input Ω_c^0 mass	**0.2**
Total	11.0

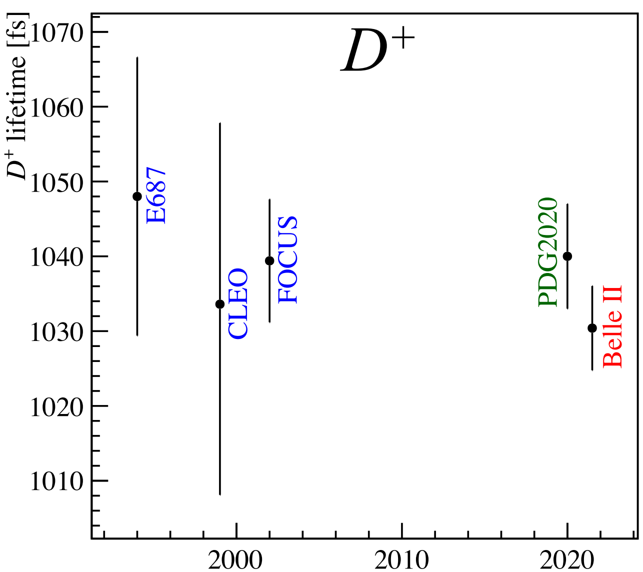


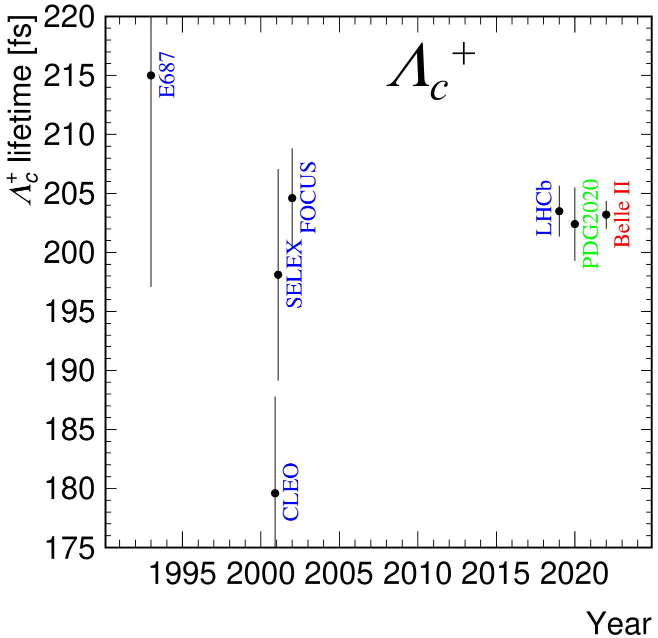
Summary I











- *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 confirms the longer lifetime observed by LHCb (in contrast to older experiments and theory expectations)*

Summary II

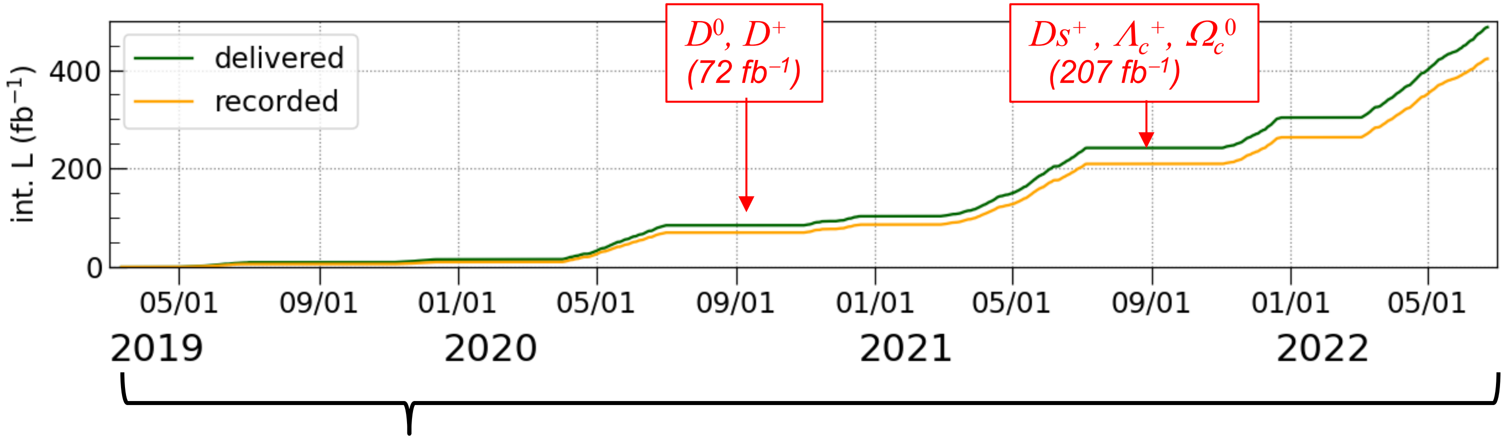
Comparisons with theory:

Quantity	Belle II	King et al. JHEP 08 (2022) 241 (Table 15)	Gratrex et al. JHEP 07 (2022) 058 (Tables 10, 14, MSR)
$\tau(D^0)$	410.5 ± 1.1 ± 0.8	629^{+296}_{-167}	595^{+344}_{-166}
$\tau(D^+)$	1030.4 ± 4.7 ± 3.1	> 897 (90% CL)	> 1260 (90% CL)
$\tau(D^+_s)$	$498.7 \pm 1.7^{+1.1}_{-0.8}$	637^{+381}_{-190}	599^{+459}_{-180}
$\tau(D^+)/\tau(D^0)$	2.510	2.80 ± 0.90	2.89 ± 0.82
$\tau(D^+_s)^*/\tau(D^0)$	1.215	1.01 ± 0.15	1.00 ± 0.22
$\tau(\Lambda_c^+)$	203.20 ± 0.89 ± 0.77		312^{+128}_{-96}
$\tau(\Omega_c^0)$	243 ± 48 ± 11		237^{+111}_{-75}
$\tau(\Omega_c^0)/\tau(\Lambda_c^+)$	1.20 ± 0.24		$0.83^{+0.30}_{-0.18}$

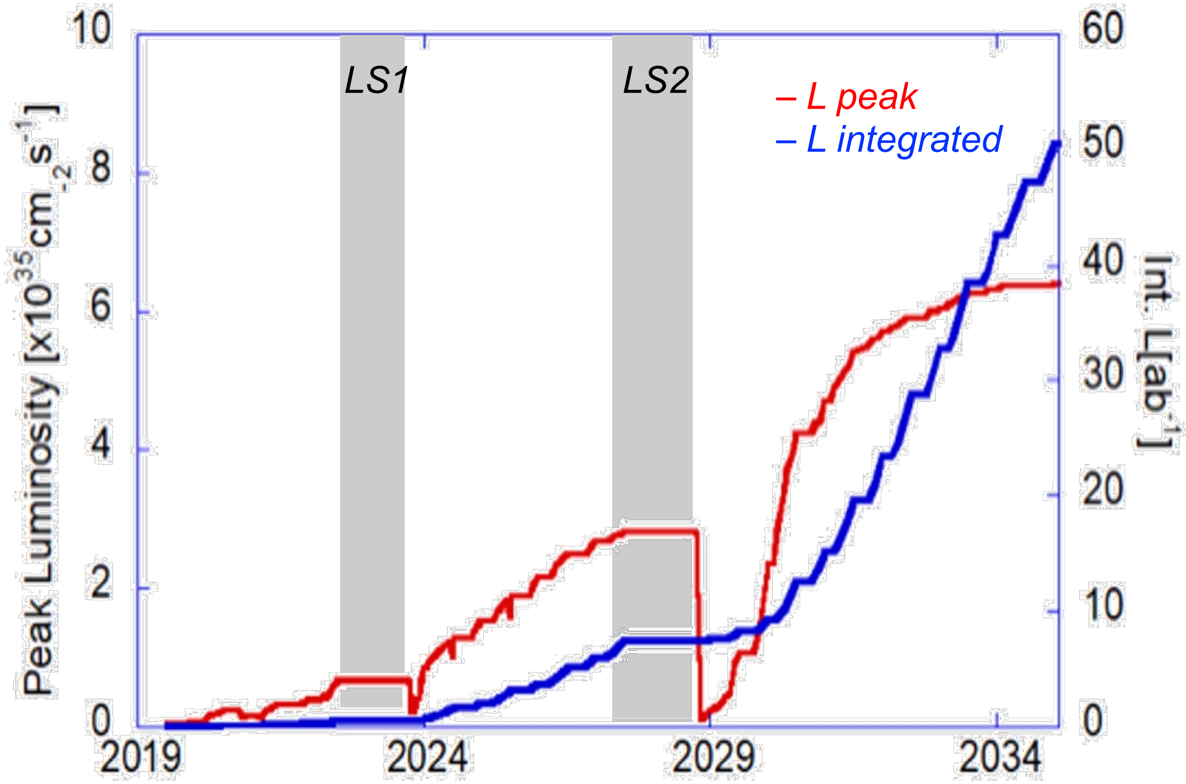
(*subtracting $B(D_s^+ \to \tau^+ \nu)$ = 5.32%)

- Experimental precision is much greater than theory precision (large theory uncertainties)
- Even with large theory uncertainties, a few predictions differ from experiment by > 1σ (but less than 2σ). In the future when theory errors are reduced, such differences could become interesting – stay tuned.

The future



now: 428 fb⁻¹



- Goal is to ultimately accumulate 50 ab⁻¹
- However: a huge amount of physics will be done with ~5-10 ab⁻¹, possibly uncovering new physics (the amount of physics done with < 0.5 ab⁻¹ is surprising)