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Charm lifetimes at Belle II

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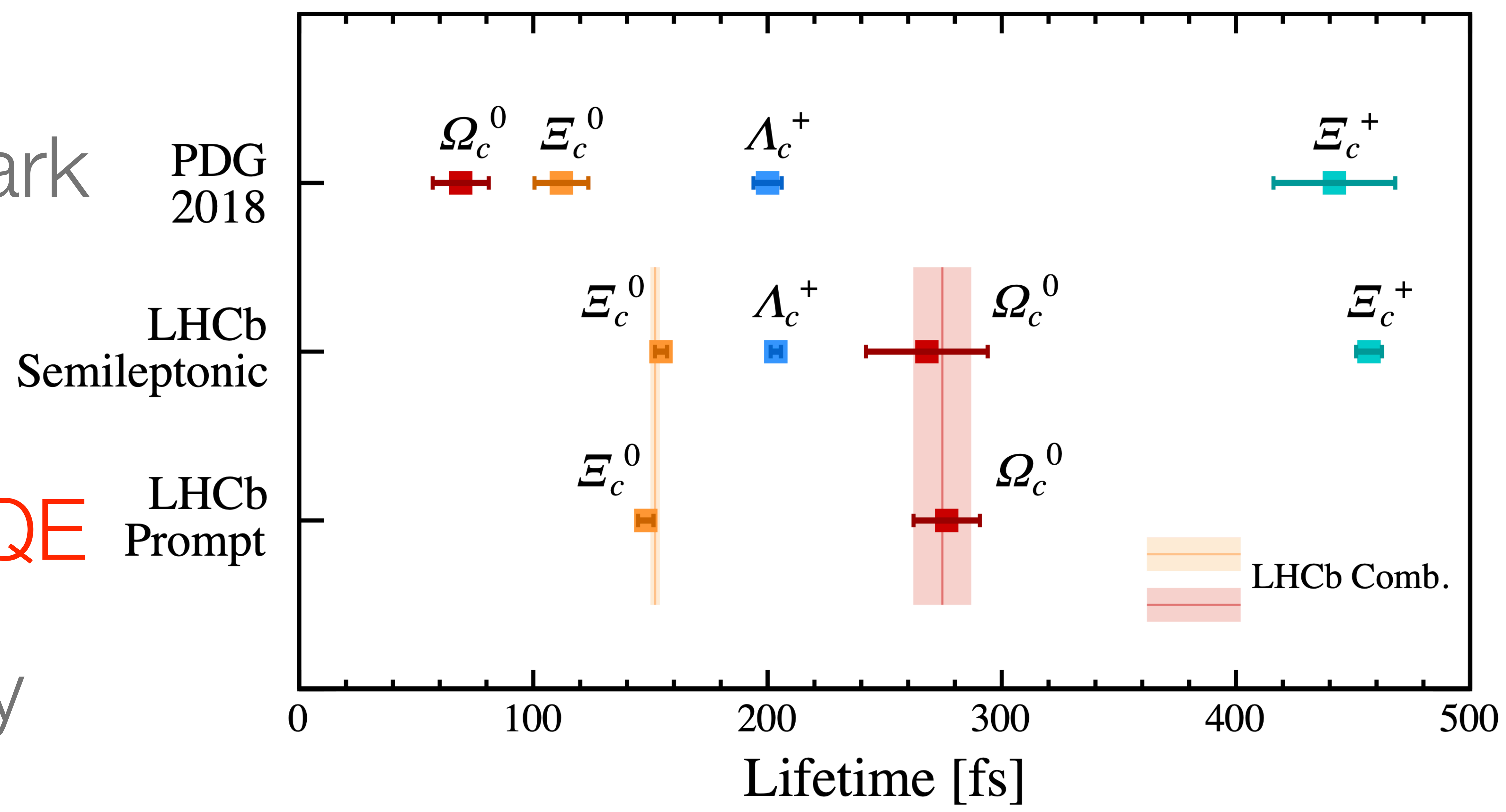
Belle II

Charm lifetimes: why shall we bother?

- Lifetime hierarchy of heavy-flavored hadrons crucial to constrain/validate predictions of mixing and *CP* violation based on heavy quark expansion (HQE)
  - Recent LHCb measurements of lifetime ratios break the hierarchy predicted by HQE
- Early Belle II data provide unique opportunity for precision measurements of absolute lifetimes
  - Never measured at Belle/BaBar/LHCb in past 20 years due to systematic limitations

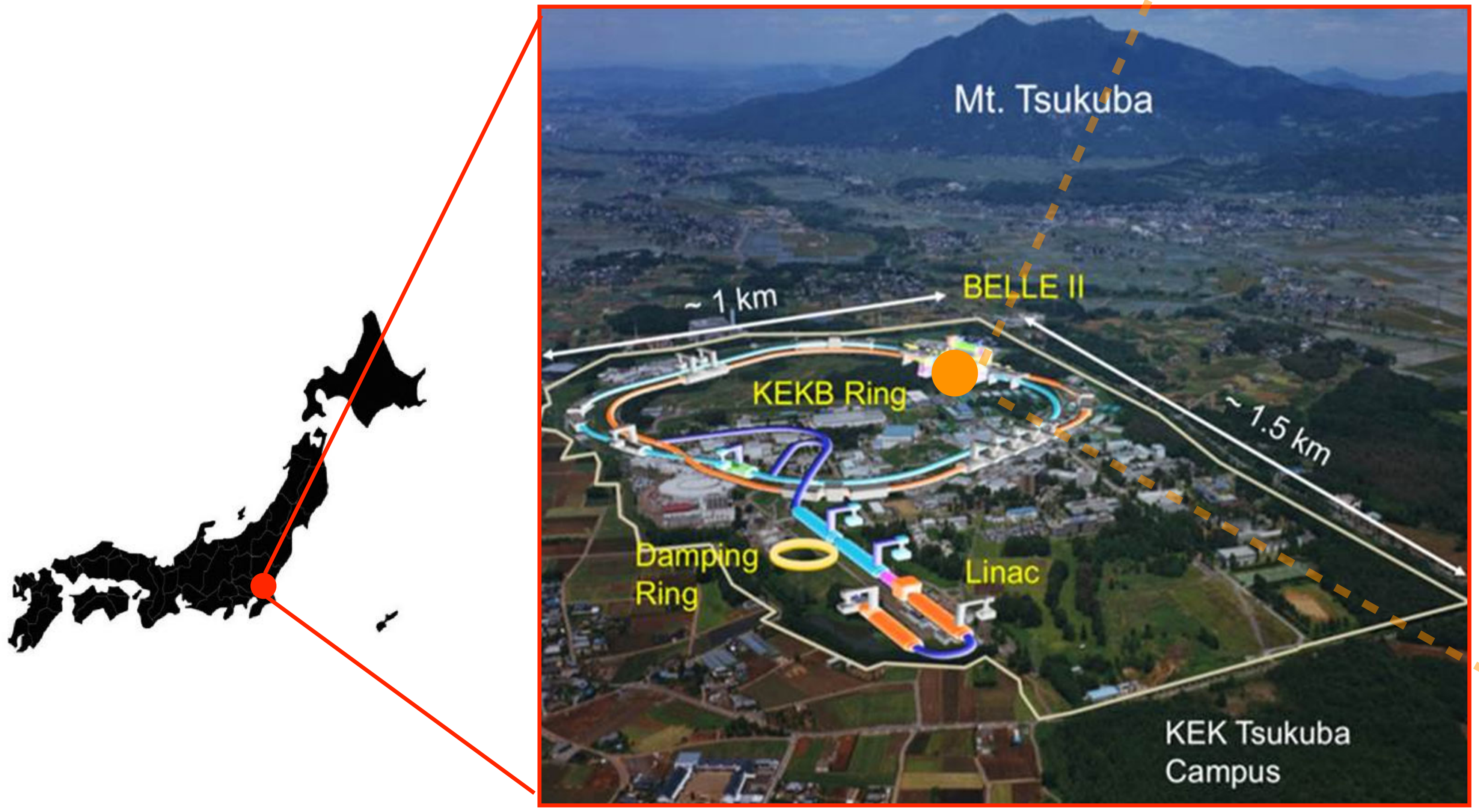
Sci. Bull. 67 (2022) 479

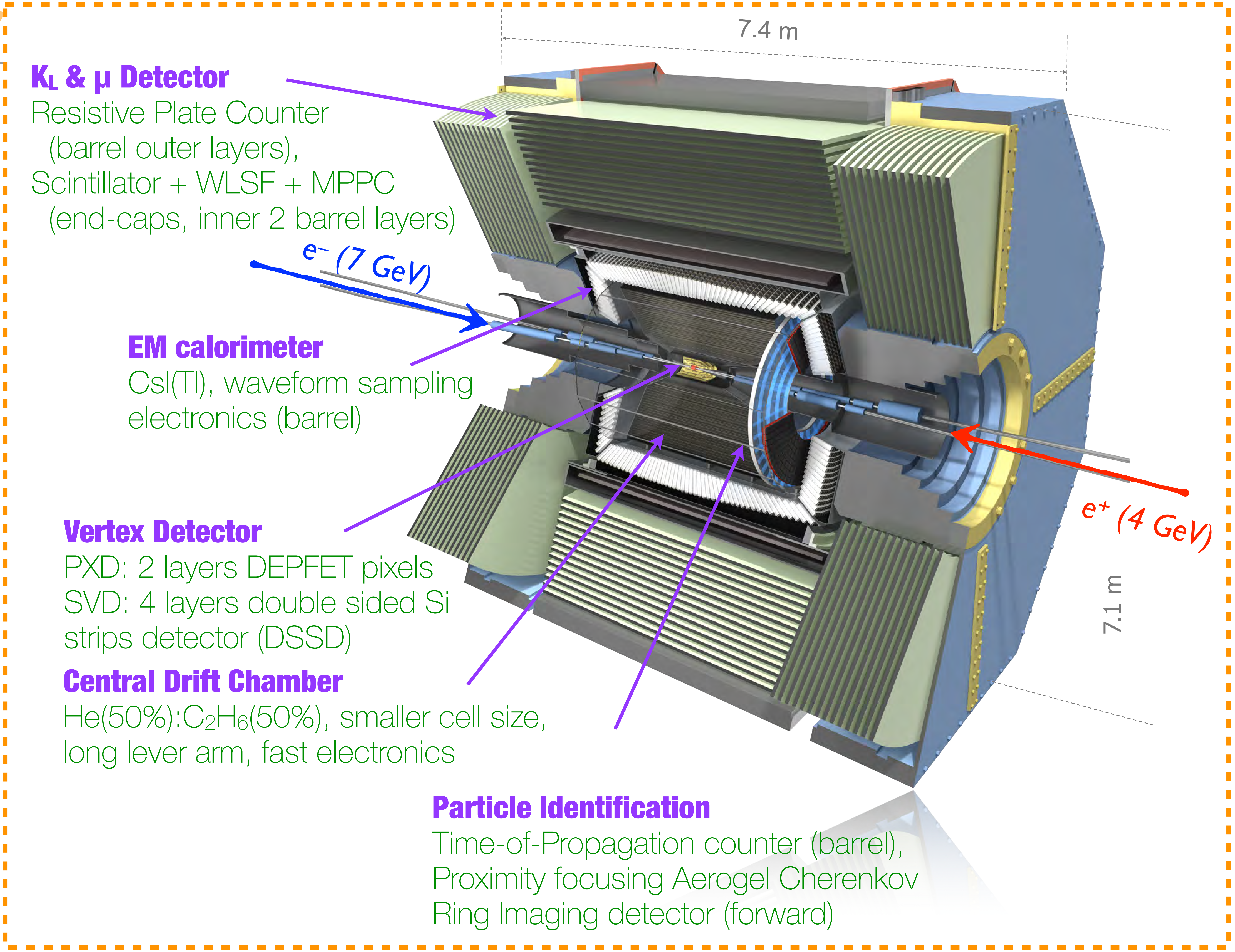


$$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$$

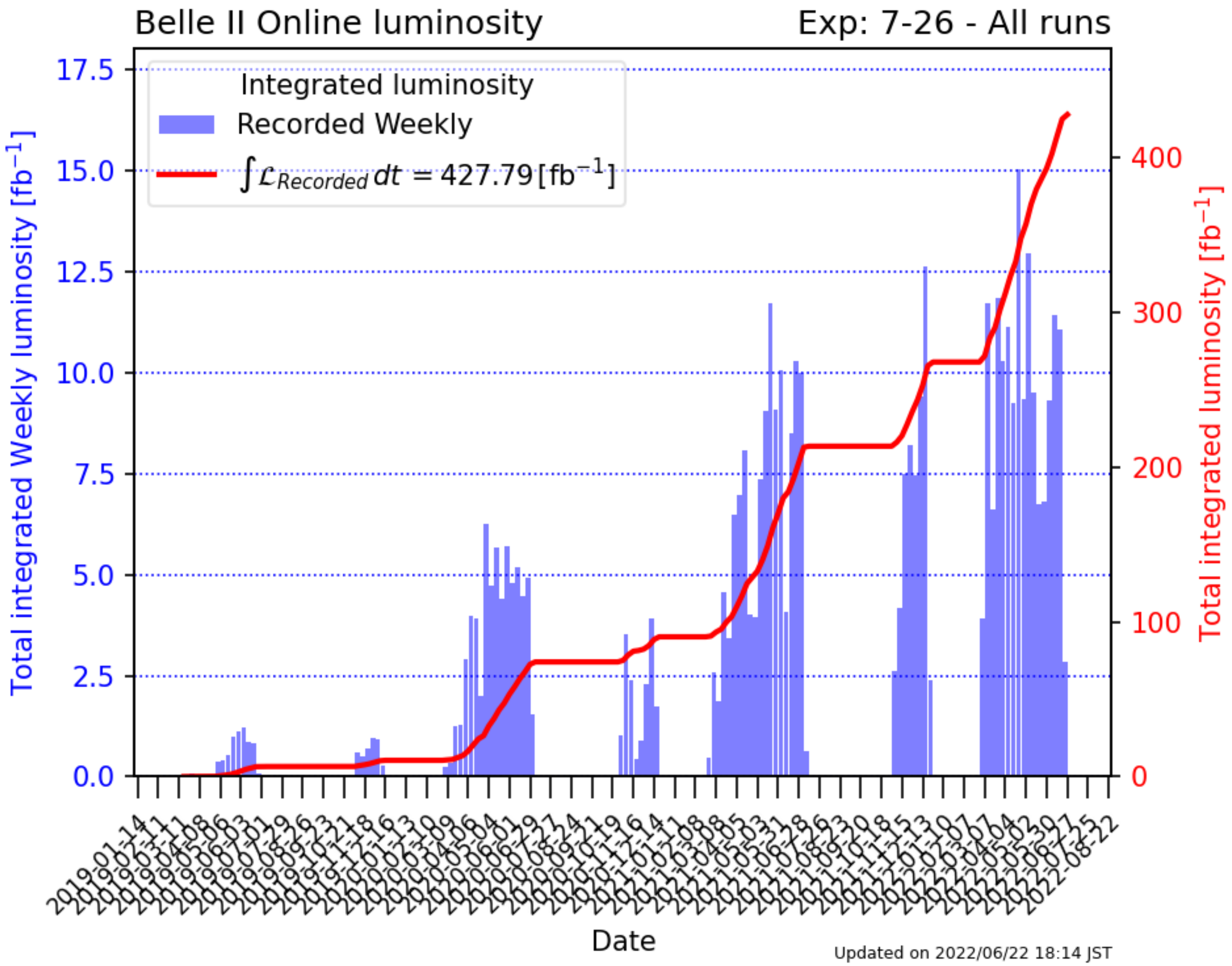
The Belle II experiment

- Multipurpose detector optimized for the study of the heavy flavored hadrons
- Large $e^+e^-\to c\bar{c}$ cross-section provide low-background event samples of charm decays
  - 1.3M $c\bar{c}$ events per 1 fb^{-1}
  - All recorded to tape (~100% trigger efficiency with uniform decay-time acceptance)



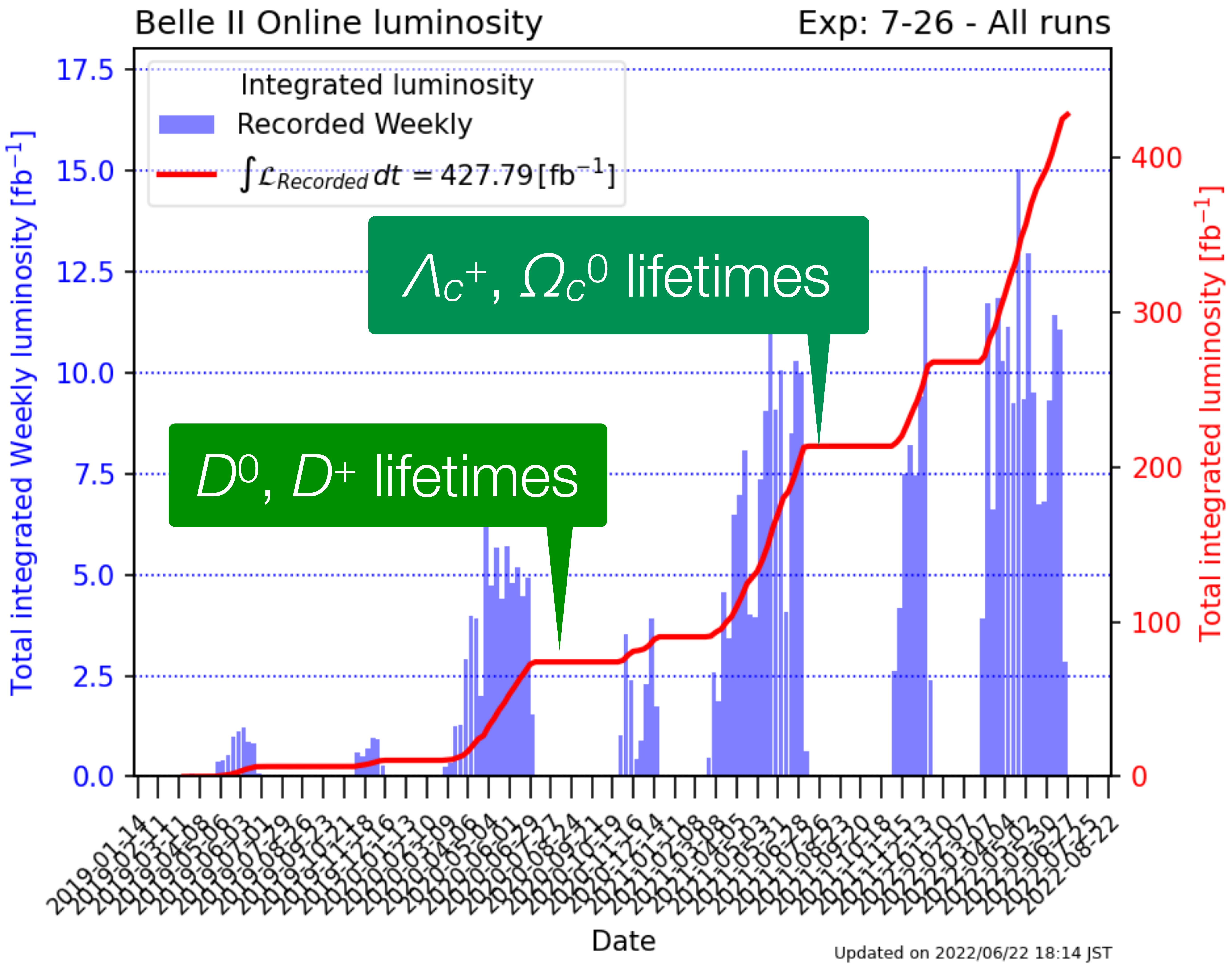


The Belle II experiment



The Belle II experiment

Measurements shown today



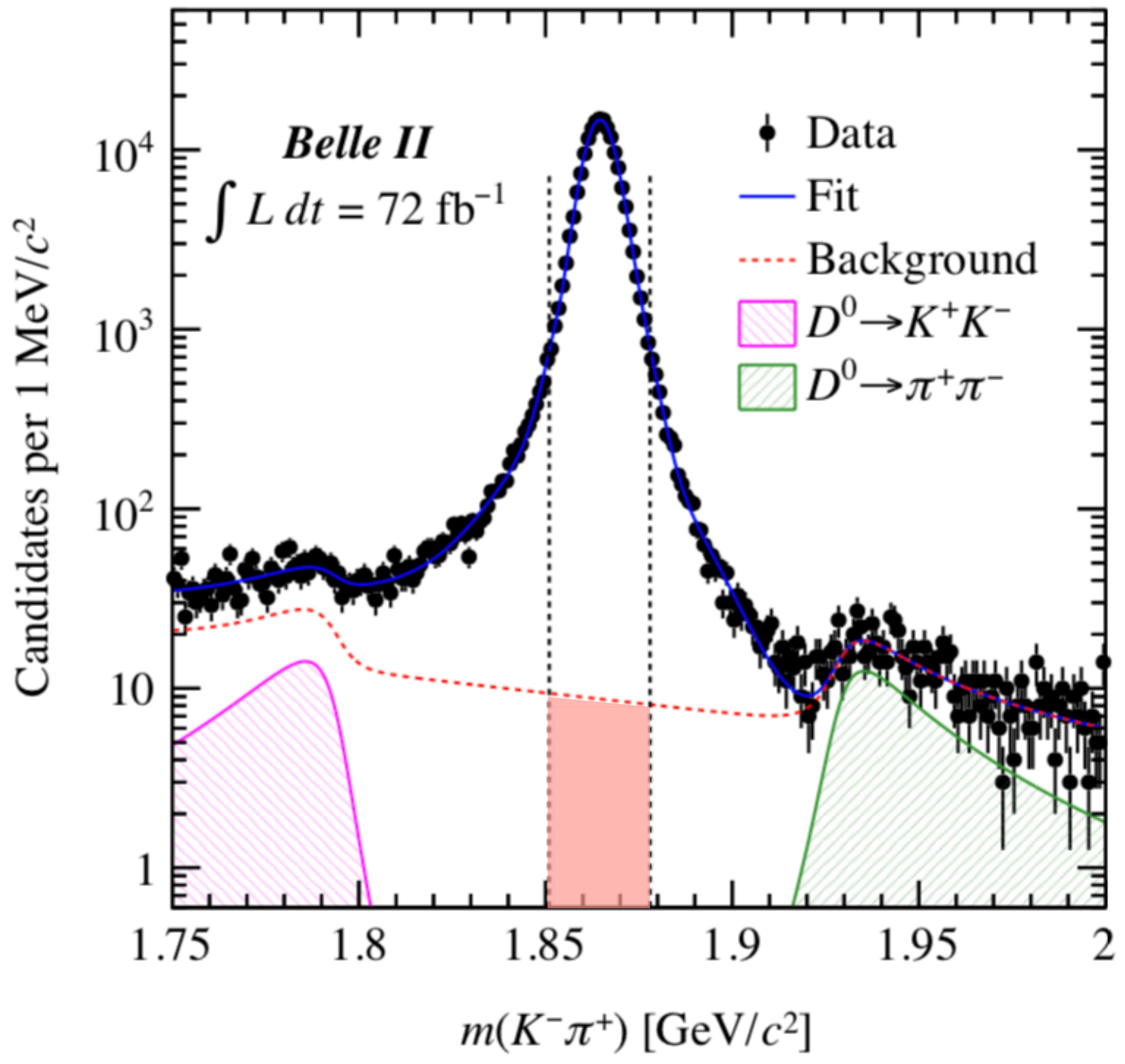
The analysis in a nutshell

- Select high-purity samples of charm decays. Avoid any selection requirement that biases the decay time
- Get the decay-time from the displacement between the decay vertex and the interaction region (and the charm momentum).
- Fit the distribution of the decay time with accurate modeling of the resolution
- Check, check and check… any systematic bias associated to the measurement
- Look at lifetime value only at the end

Signal samples

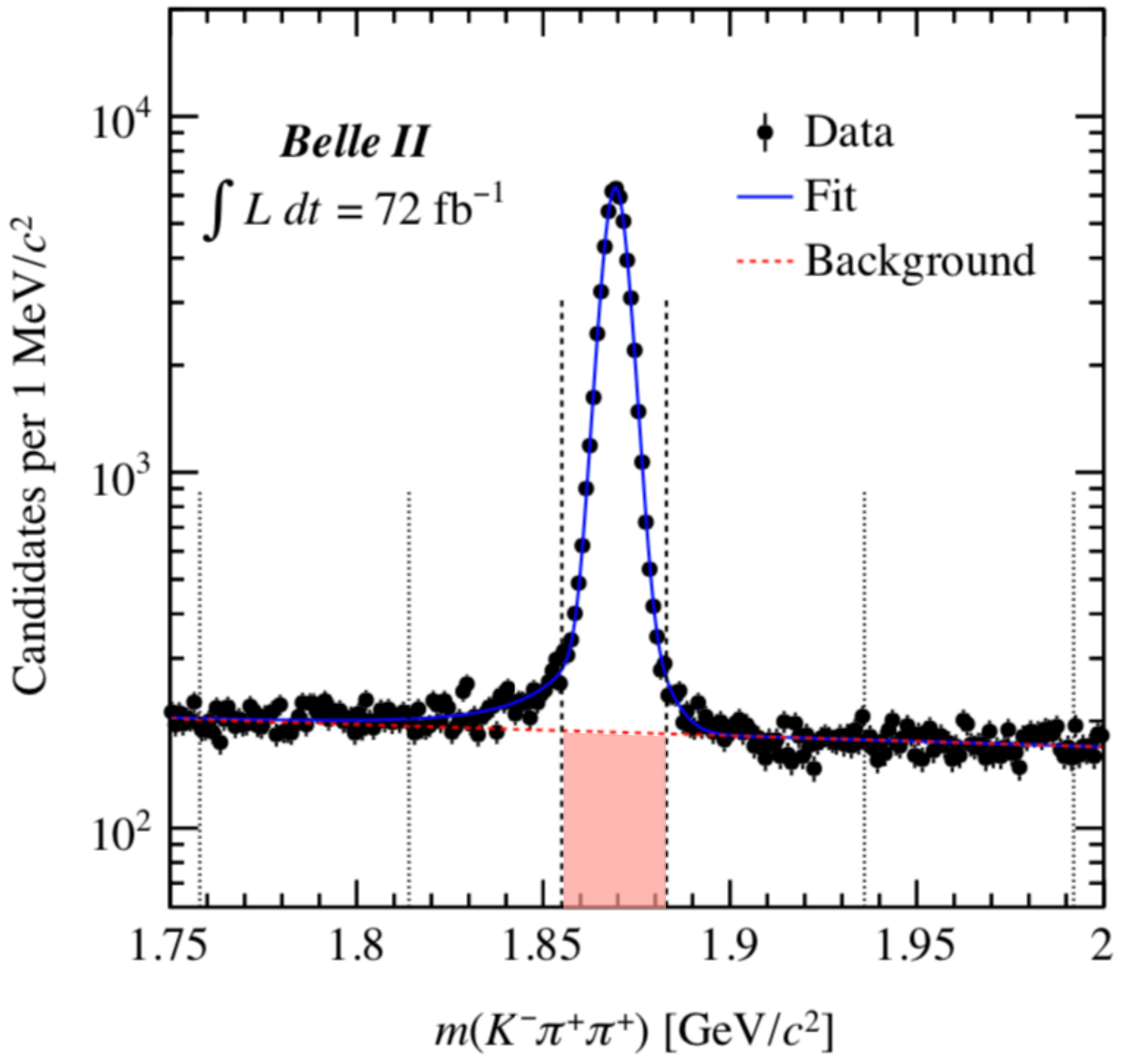
- Large, clean samples limit background-related systematic uncertainties
  - Use only low-track-multiplicity, large-BF decay modes
  - Removing charm from *B* decays (originating from displaced vertex) to avoid bias in charm production-vertex position

~171k $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$



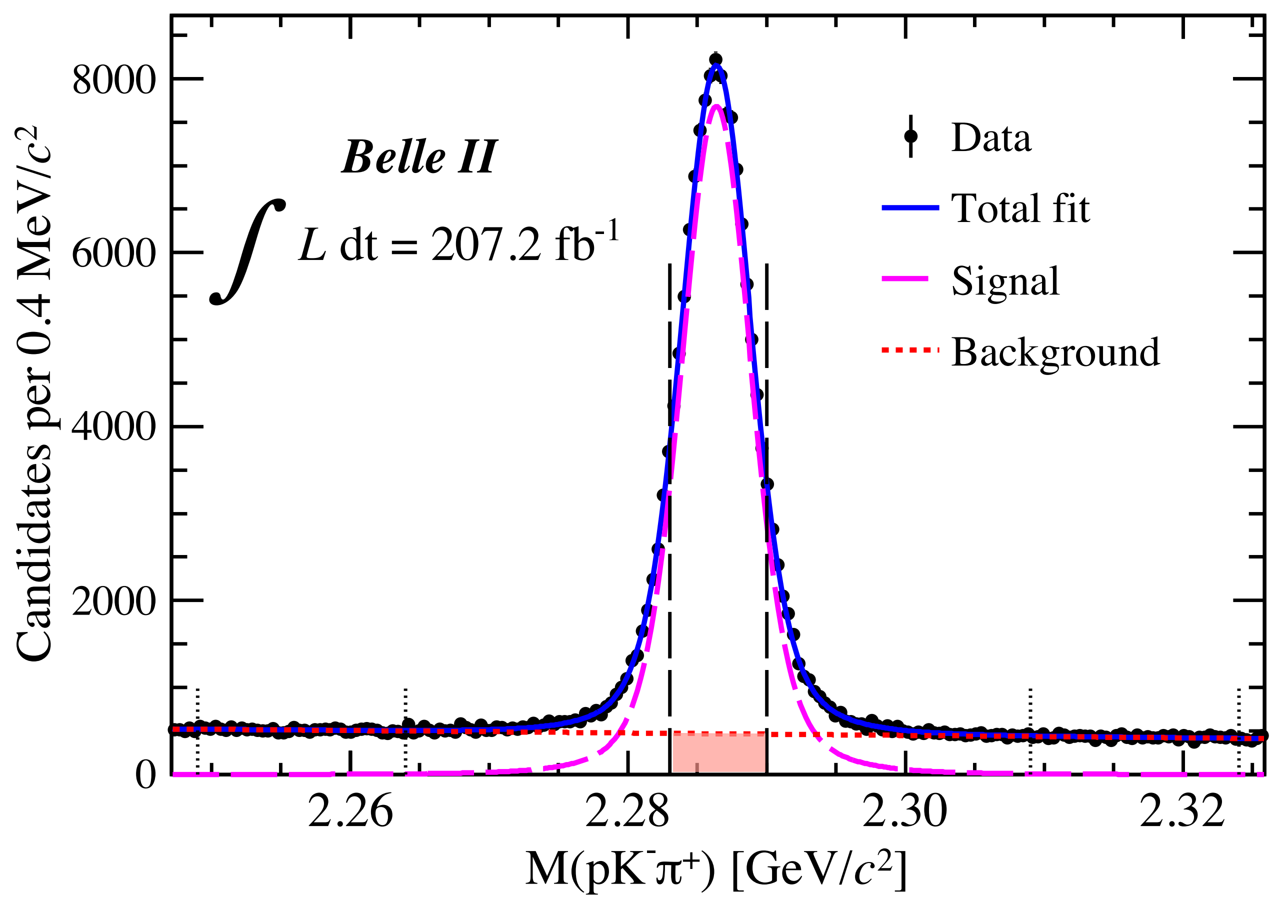
99.8% purity

~59k $D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0$



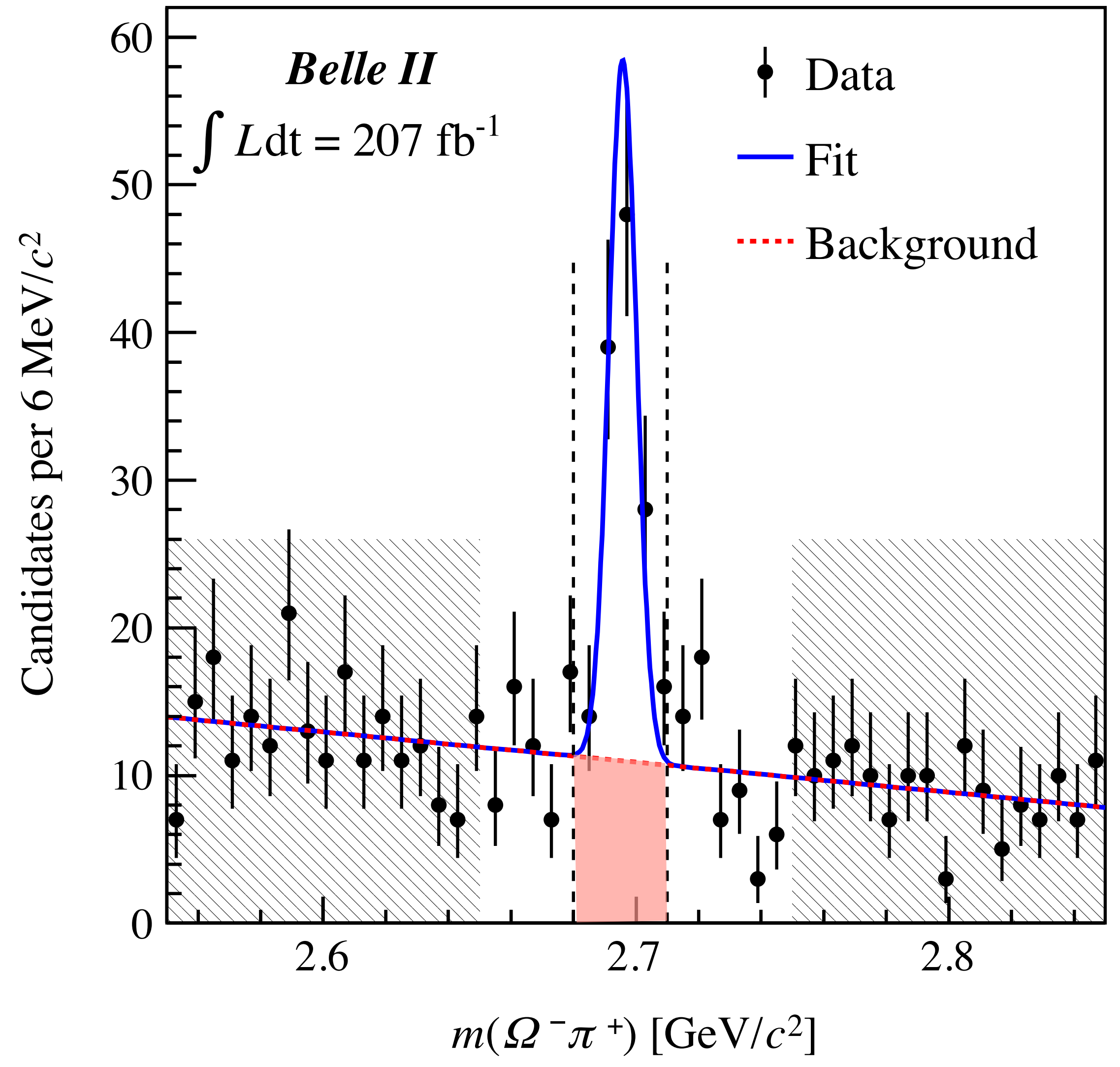
91% purity

~116k $\Lambda_c^+ \to pK^-\pi^+$



92.5% purity

~90 $\Omega_c^0 \to \Omega^-\pi^+$
$\Omega^- \to \Lambda^0(\to p\pi^-)K^-$

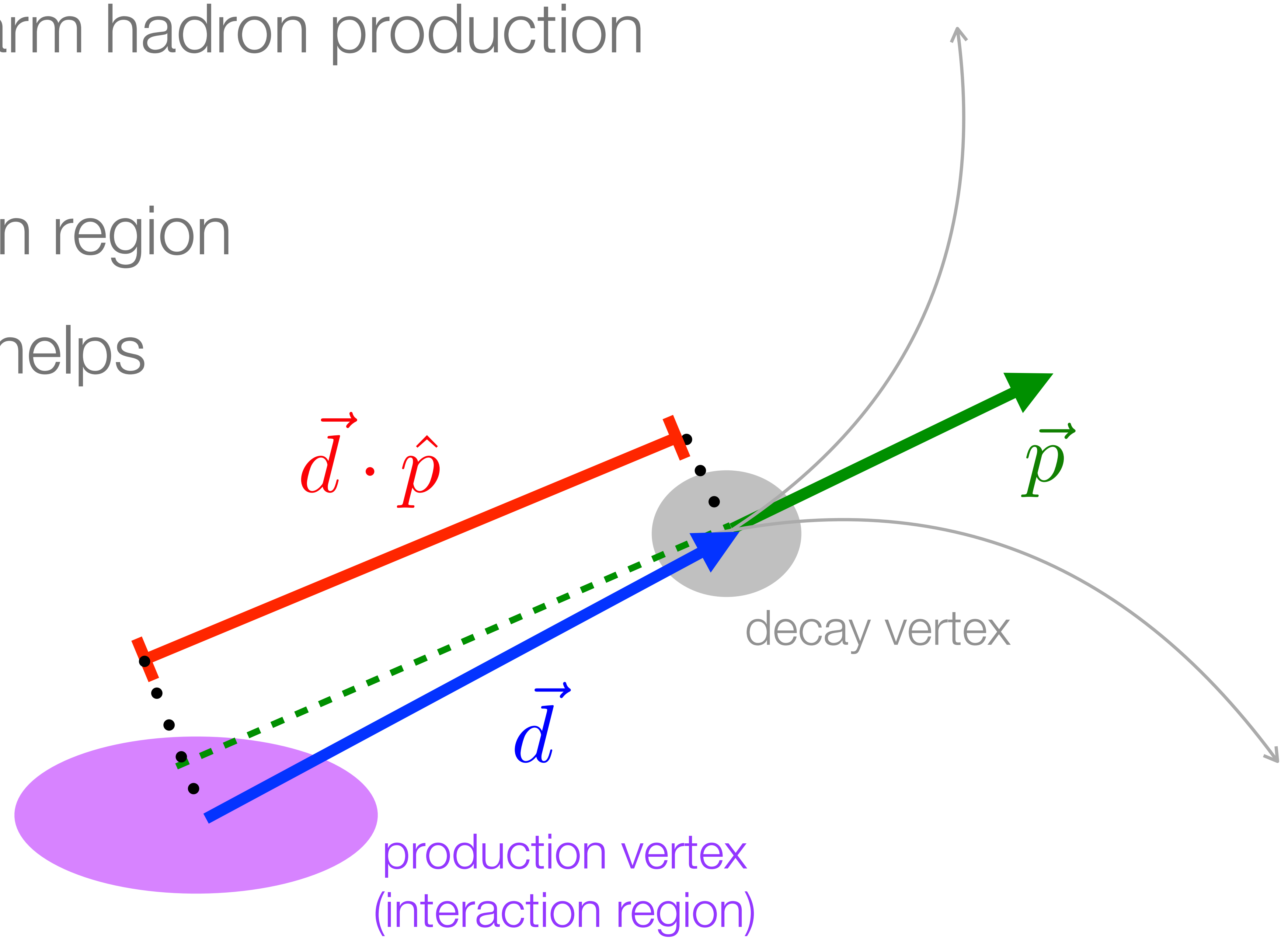


67% purity

Determination of the decay time

- Calculate decay time (and its uncertainty) from charm hadron production and decay vertices, and from momentum
  - Production vertex constrained to e^+e^- interaction region
  - Momentum vector provides flight direction and helps determination of the decay distance

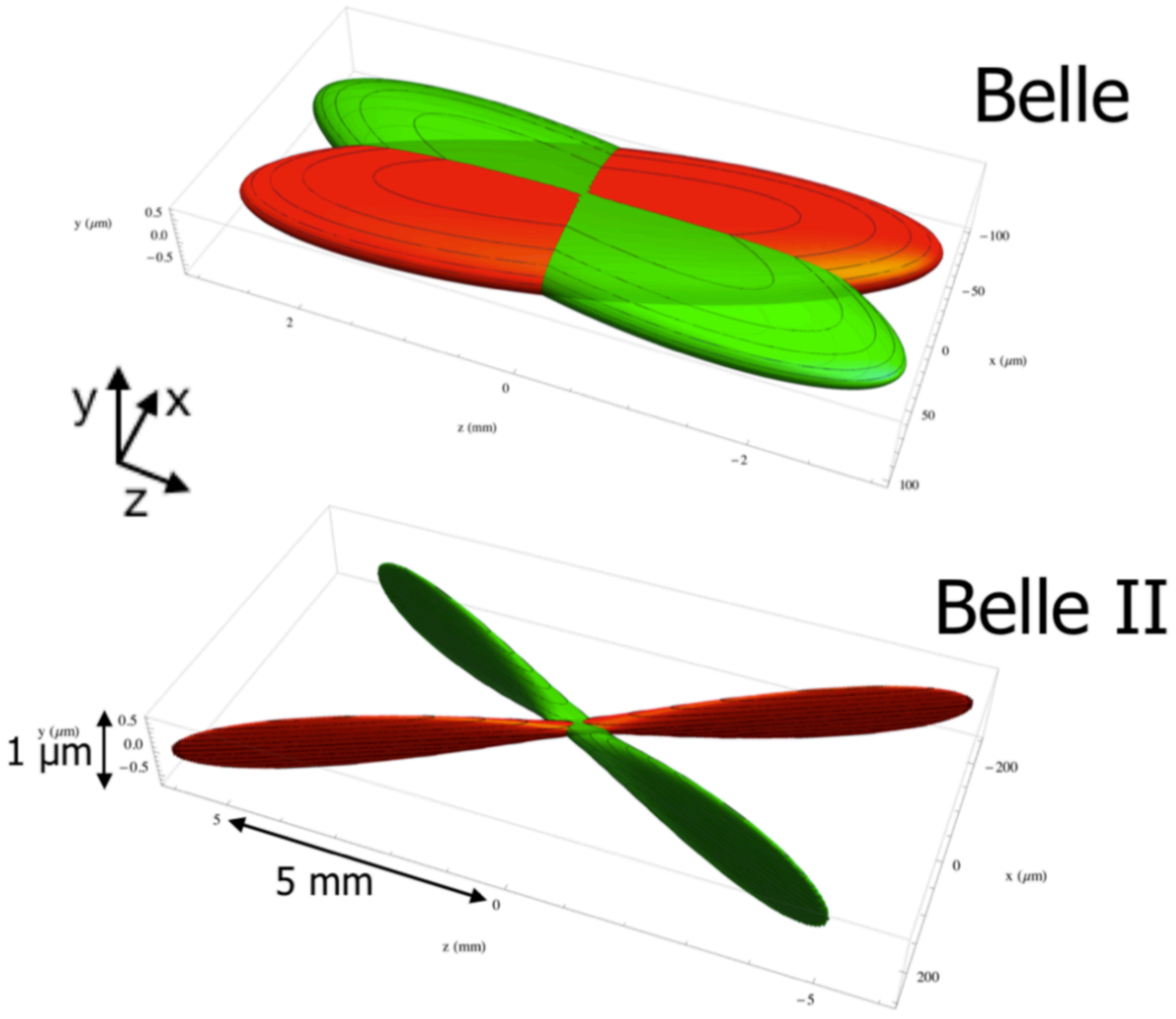
$$t = \frac{m}{p}(\vec{d} \cdot \hat{p})$$



- Average decay distance ranges between 100 and 500 μm for the charm hadrons under study

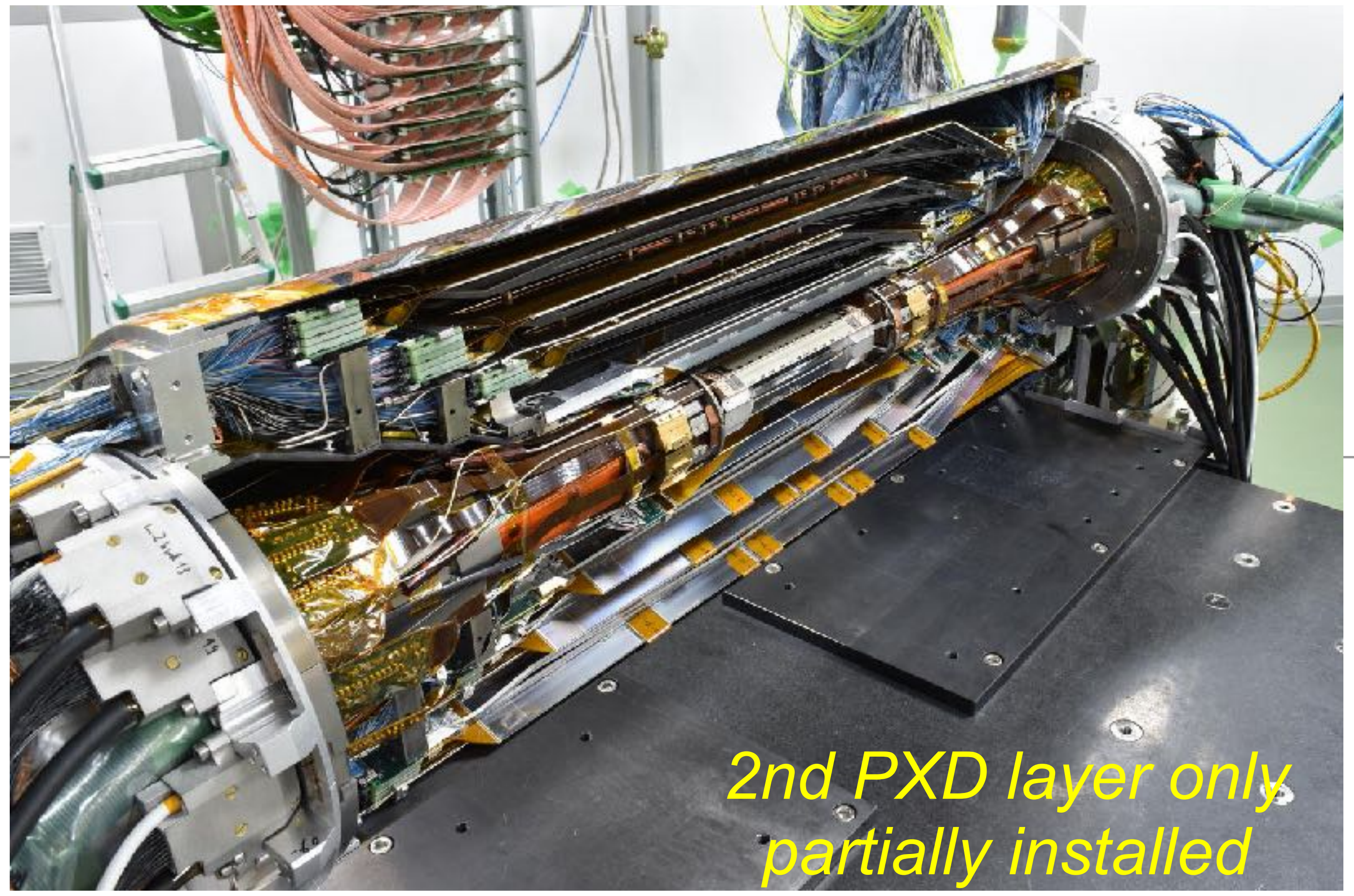
SuperKEKB "nano beams"

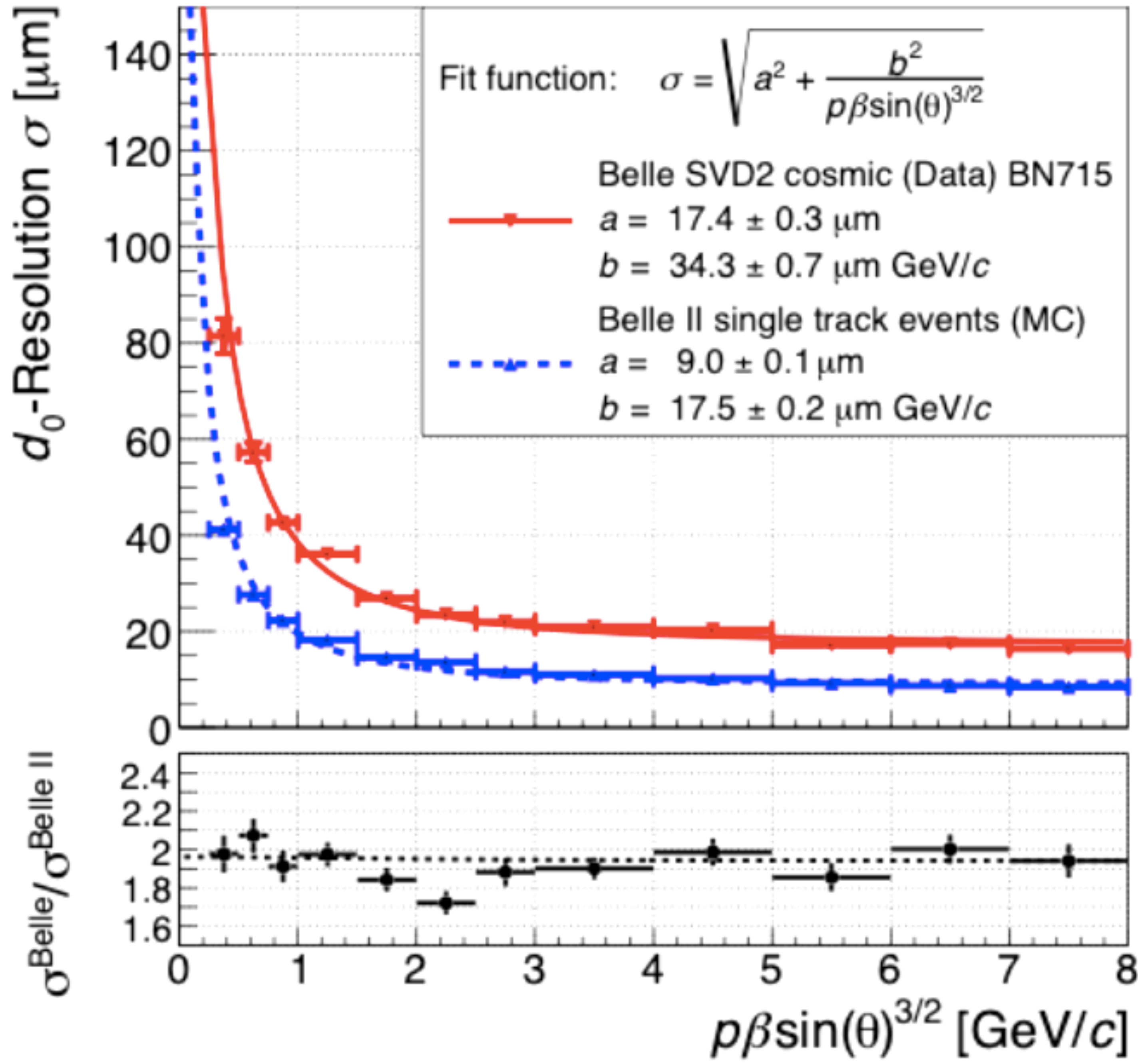
- SuperKEKB requires much smaller interaction region than KEKB in order to reach design luminosity of $6{\times}10^{35}$ cm^{-2}s^{-1}
  - Nano-beams concept (P. Raimondi) realized with super-conducting final focus quadrupoles already achieved luminosity record of $4.7{\times}10^{34}$ cm^{-2}s^{-1}
- Belle II's small luminous region dimensions (in transverse plane) provide effective constraint on the production vertex of charm hadrons
  - Position and size of interaction region measured every ~1-2hrs with $e^+e^-{\rightarrow}\mu^+\mu^-$ events



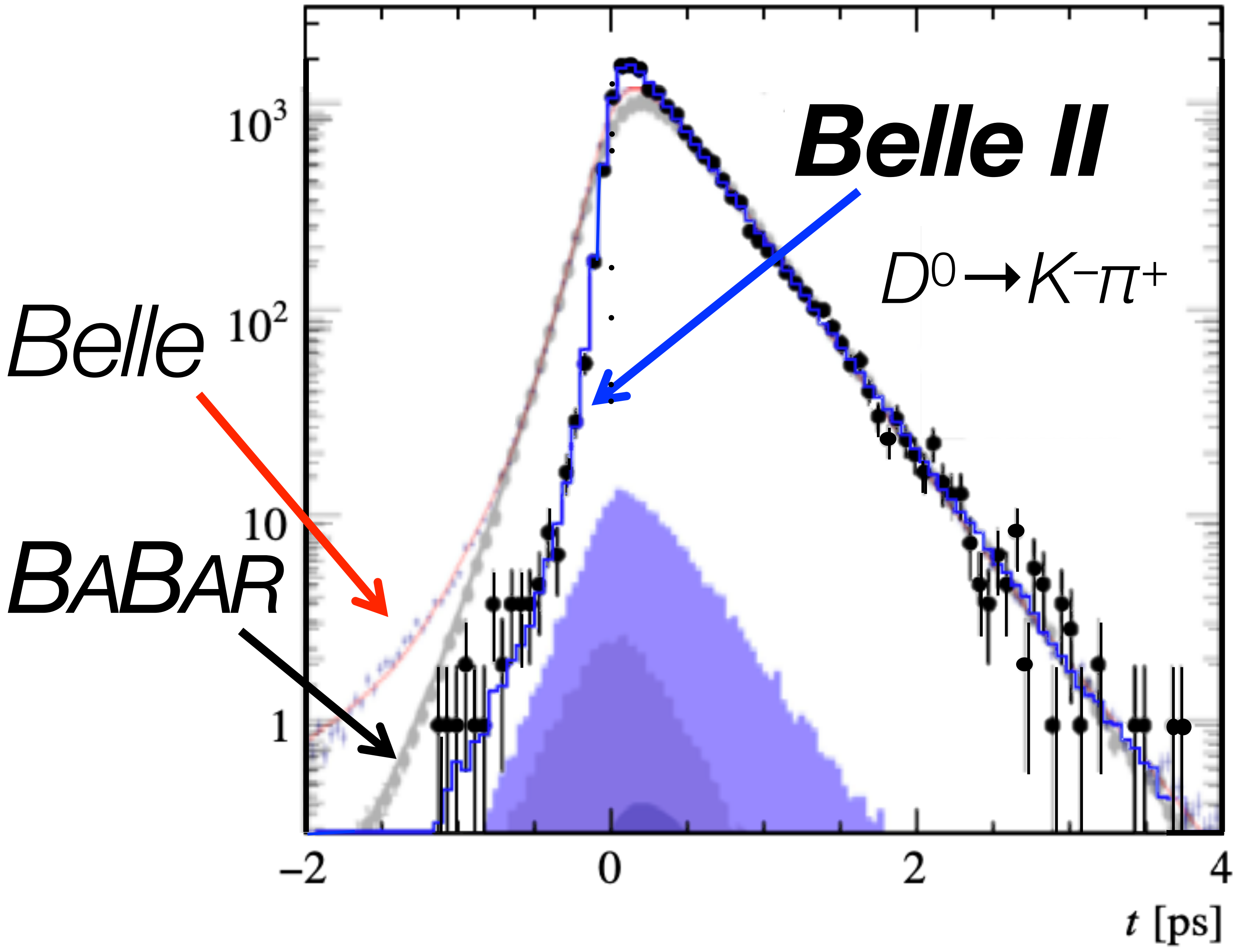
Dimensions of luminous region at Belle II are 10/0.2/250 µm (x/y/z) compared to 100/1/6'000 µm at Belle. Ultimately, *y* size expected to be decreased to ~60 nm

High-precision vertexing





- Silicon vertex detector
  - 2-layer pixel detector (PXD)
  - 4-layer double-sided strip detector (SVD)
- PXD
  - Innermost layer is only 1.4 cm from the interaction region (×2 closer than in Belle)
  - Very low material thickness (0.1% X_0/layer for perpendicular tracks)
  - Excellent hit position resolution
- ×2 better impact parameter resolution than Belle/BaBar shows up in decay-time distribution



Determination of the lifetime

- Unbinned maximum-likelihood fit to the 2D distribution of decay time (t) and decay-time uncertainty (σ_t)
- Signal distribution is convolution of exponential with resolution function

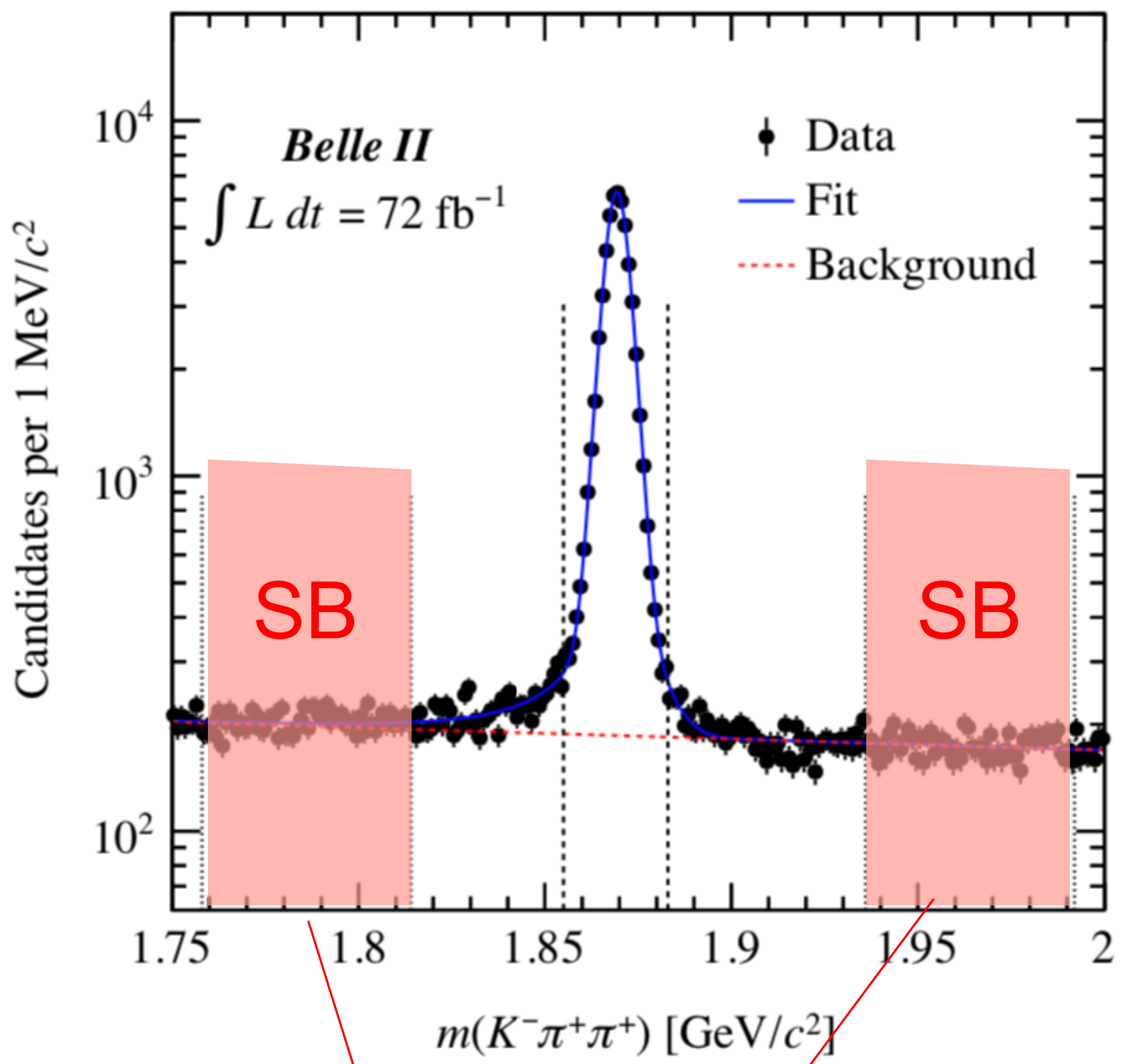
Fixed from data (binned template)

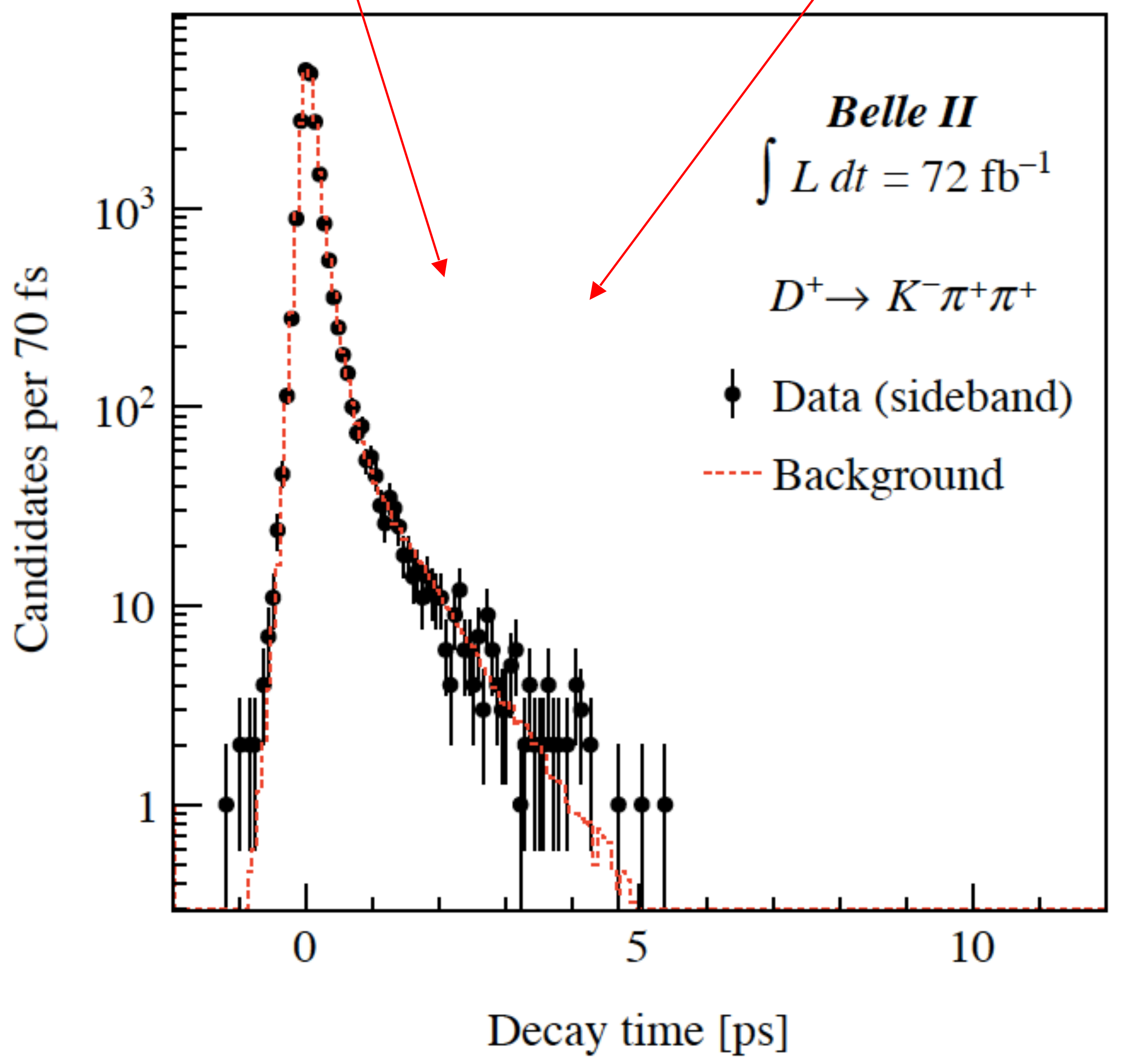
$$\mathrm{pdf}_{\mathrm{sgn}}(t, \sigma_t | \tau, b, s) = \mathrm{pdf}_{\mathrm{sgn}}(t | \sigma_t, \tau, b, s)\, \mathrm{pdf}_{\mathrm{sgn}}(\sigma_t)$$
$$\propto \int_0^\infty e^{-t_{\mathrm{true}}/\tau} R(t - t_{\mathrm{true}} | b, s\sigma_t)\, dt_{\mathrm{true}}\, \mathrm{pdf}_{\mathrm{sgn}}(\sigma_t)$$

True (exponential) distribution

(Single/Double) Gaussian resolution function with mean b (bias) and width $s\sigma_t$ (scaled to account for underestimation of the uncertainty)

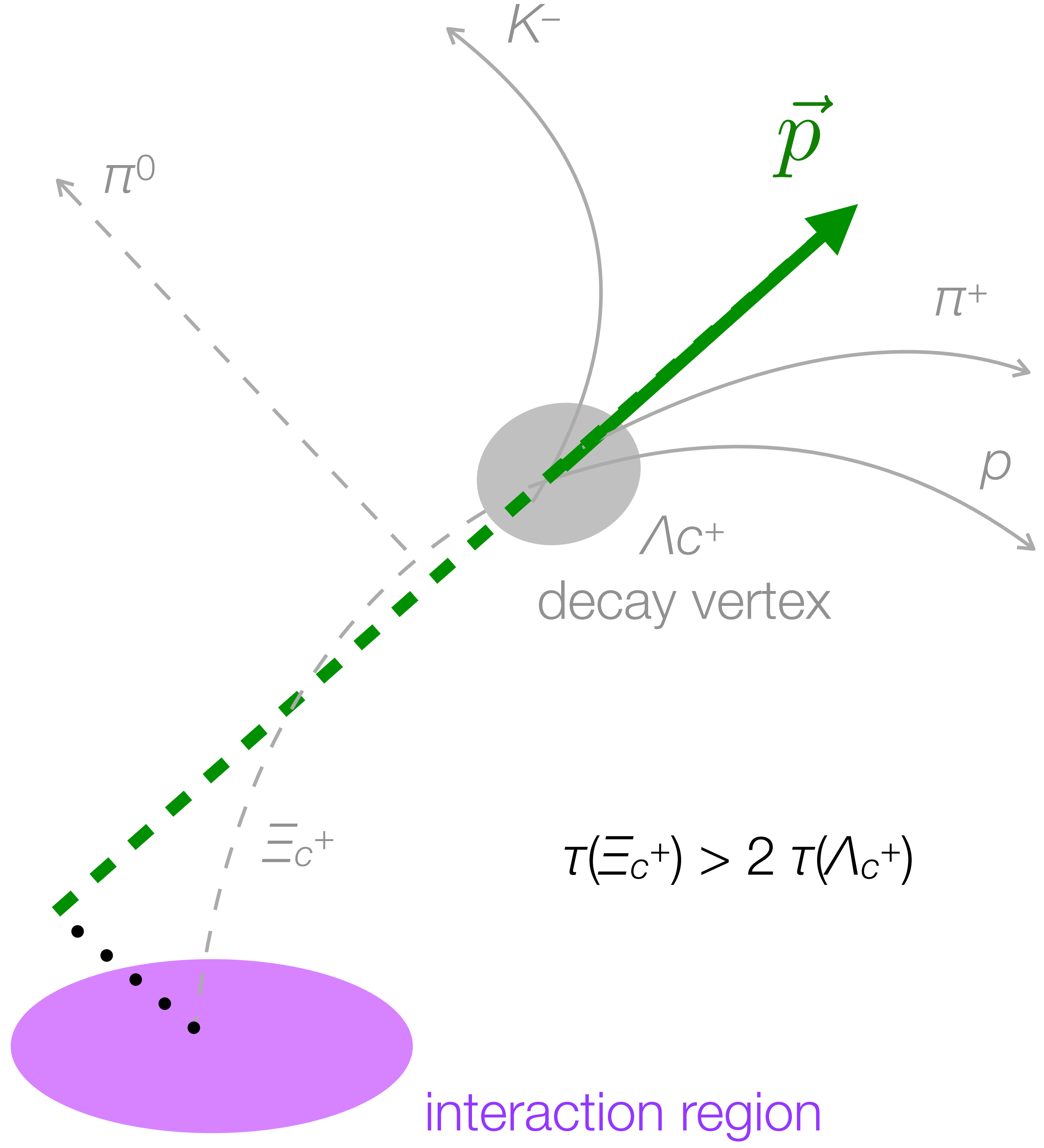
- Background contamination (ignored for D^0 decays) modeled using sideband data (SB)
- Signal region and SB are fit simultaneously with all shape parameters free; the background fraction is constrained to the result of the mass fit; no inputs from simulation





Contamination from $\Xi_c \to \Lambda_c^+ \pi$ decays

- Contribution from $\Xi_c \to \Lambda_c^+ \pi$ decays could bias Λ_c^+ lifetime
  - Production rate of Ξ_c not known, Ξ_c^0 branching fraction measured to be ~0.55%, Ξ_c^+ branching fraction expected to be ~1.11%
- Reduce possible contamination with veto and correct for remaining
  - Attach pions to Λ_c^+ candidates and require $m(\Lambda_c^+\pi) - m(\Lambda_c^+)$ to be 2σ away of expected value
  - Conservative estimate of surviving contamination from fit to Λ_c^+ impact parameter
  - Introduce estimated contamination in simulation to evaluate lifetime bias
  - Take half the shift as correction and as systematic uncertainty



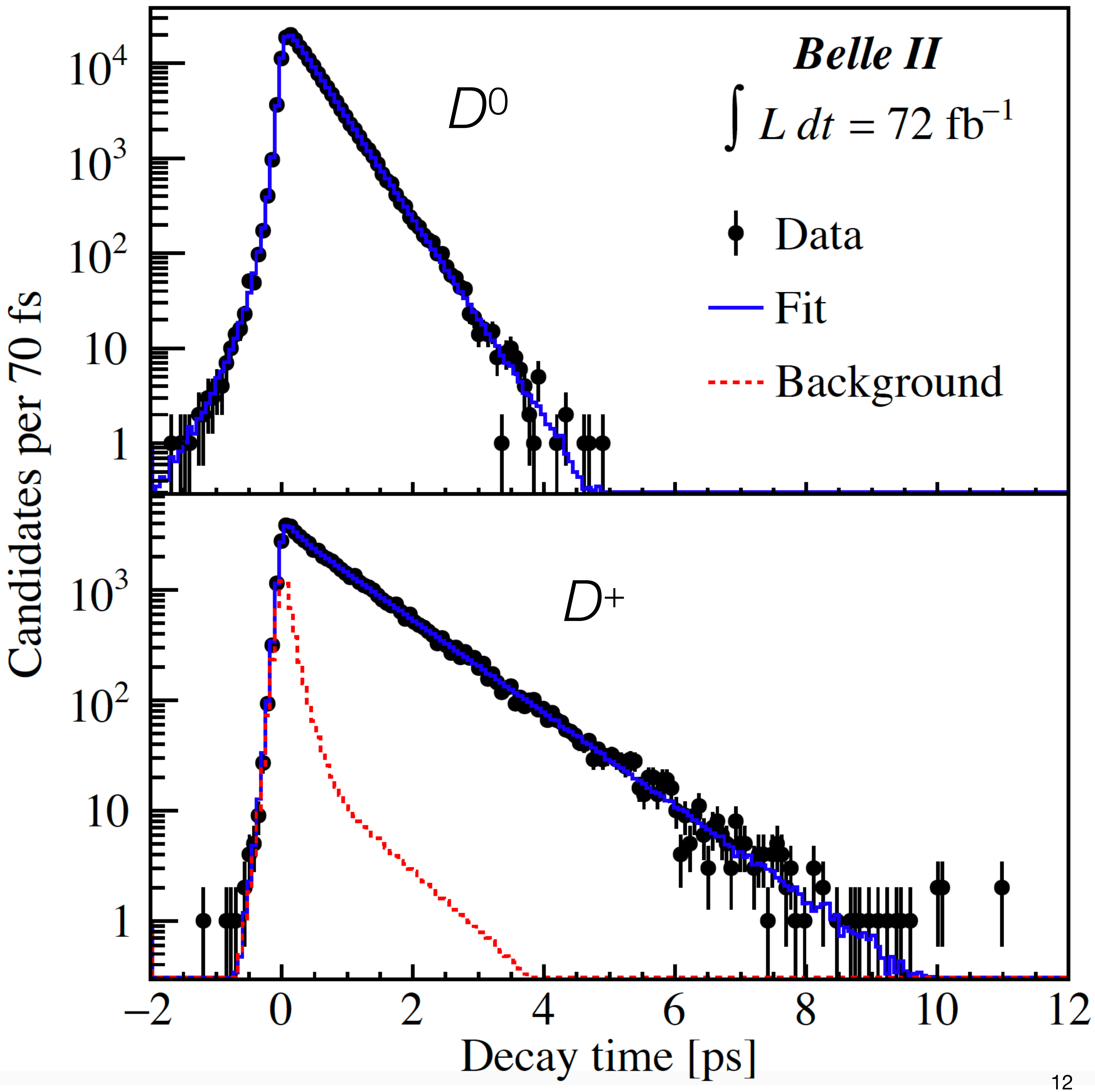
Results

$\tau(D^0) = 410.5 \pm 1.1(\text{stat.}) \pm 0.8(\text{syst.})$ fs

$\tau(D^+) = 1030.4 \pm 4.7(\text{stat.}) \pm 3.1(\text{syst.})$ fs

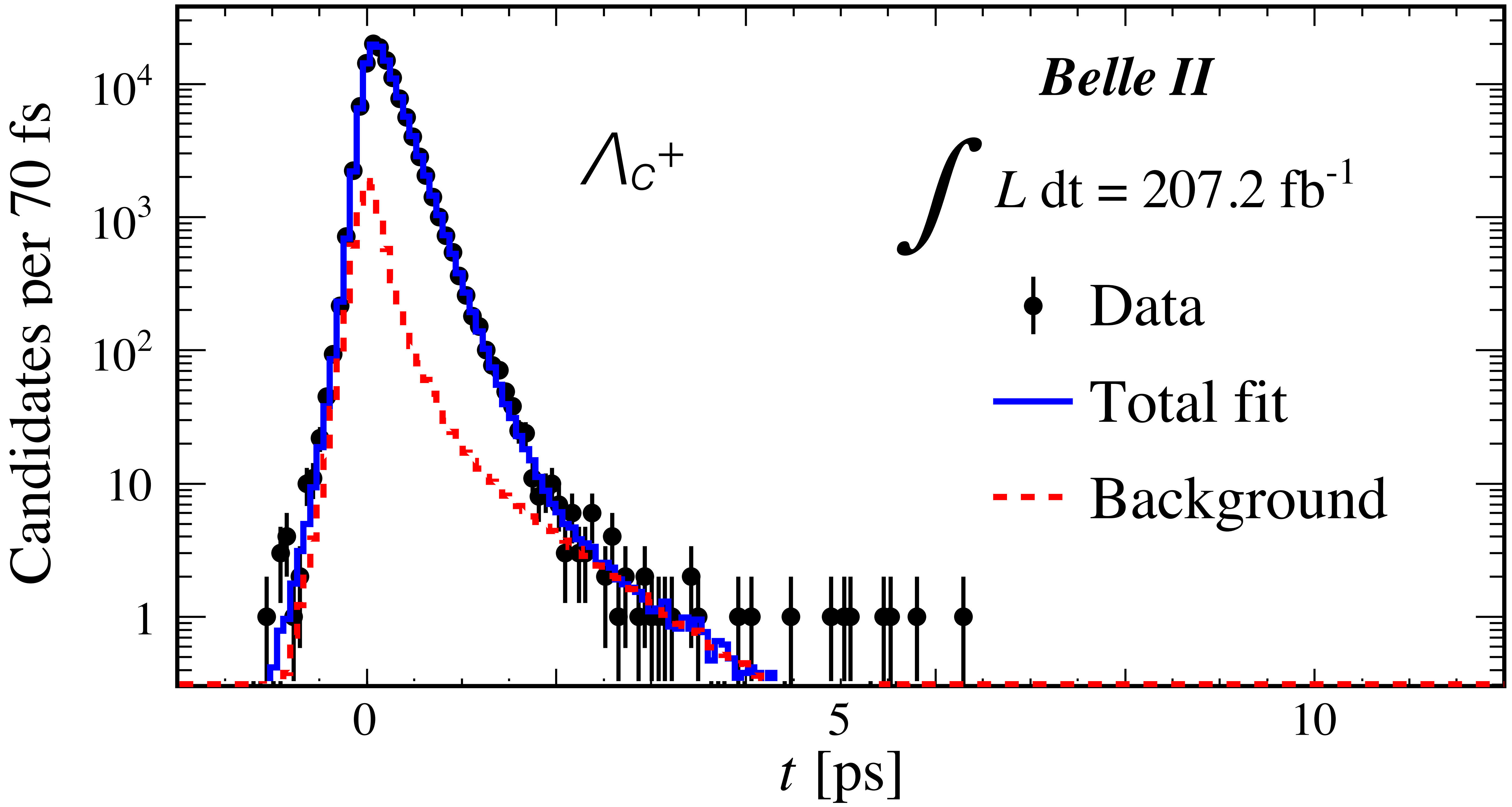
World's best

PRL 127 (2021) 21801



Results

arXiv:2206.15227, to appear in PRL



World's best

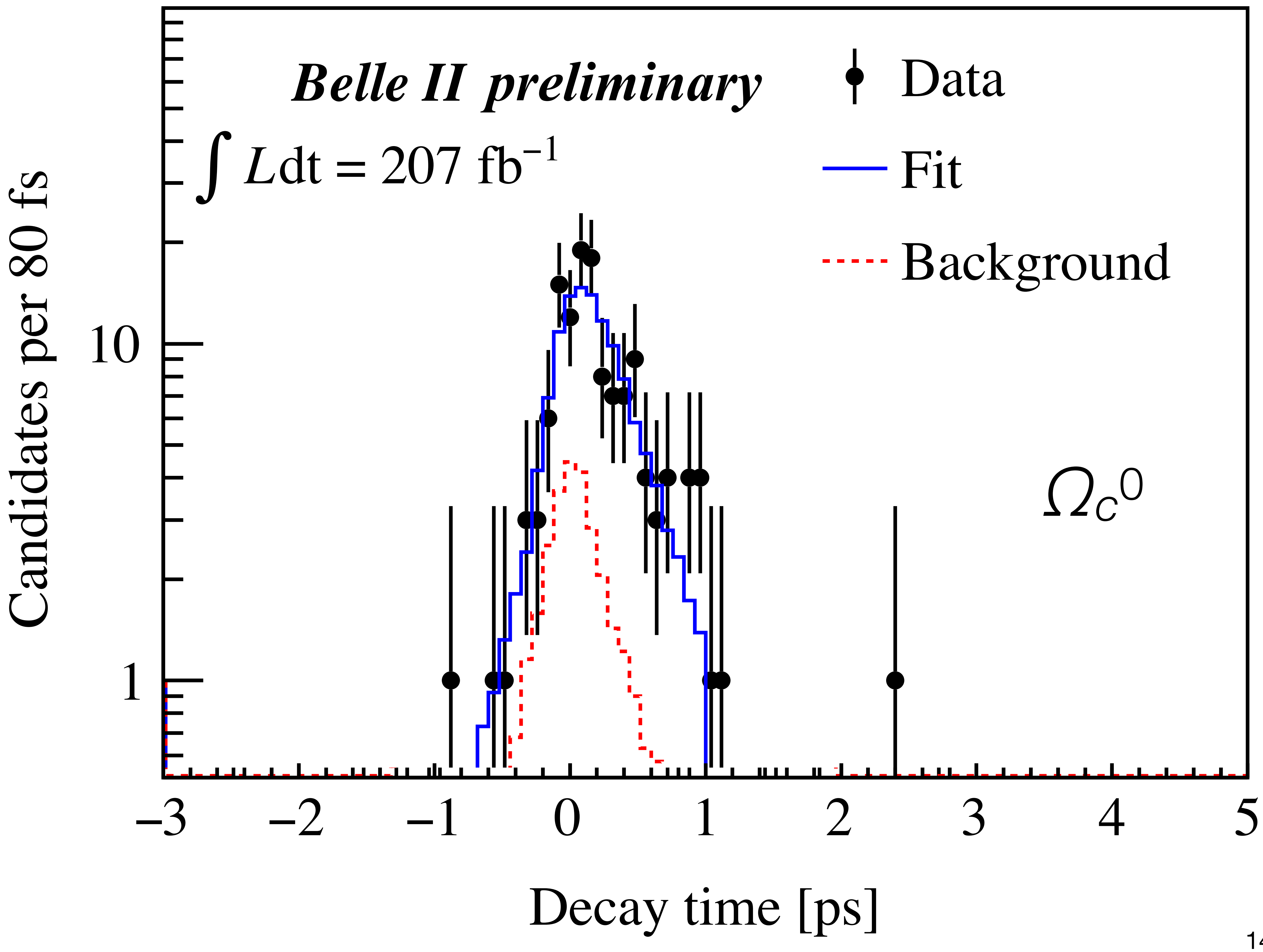
$$\tau(\Lambda_c^+) = 203.20 \pm 0.89(\text{stat.}) \pm 0.77(\text{syst.})\ \text{fs}$$

Results

$$\tau(\Omega_c^0) = 243 \pm 48(\text{stat.}) \pm 11(\text{syst.})\ \text{fs}$$

Consistent with LHCb, inconsistent with pre-LHCb average at 3.4σ: the $\Omega_c{}^0$ is not the shortest-lived weakly decaying charmed baryon

arXiv:2208.08573, submitted to PRD(L)



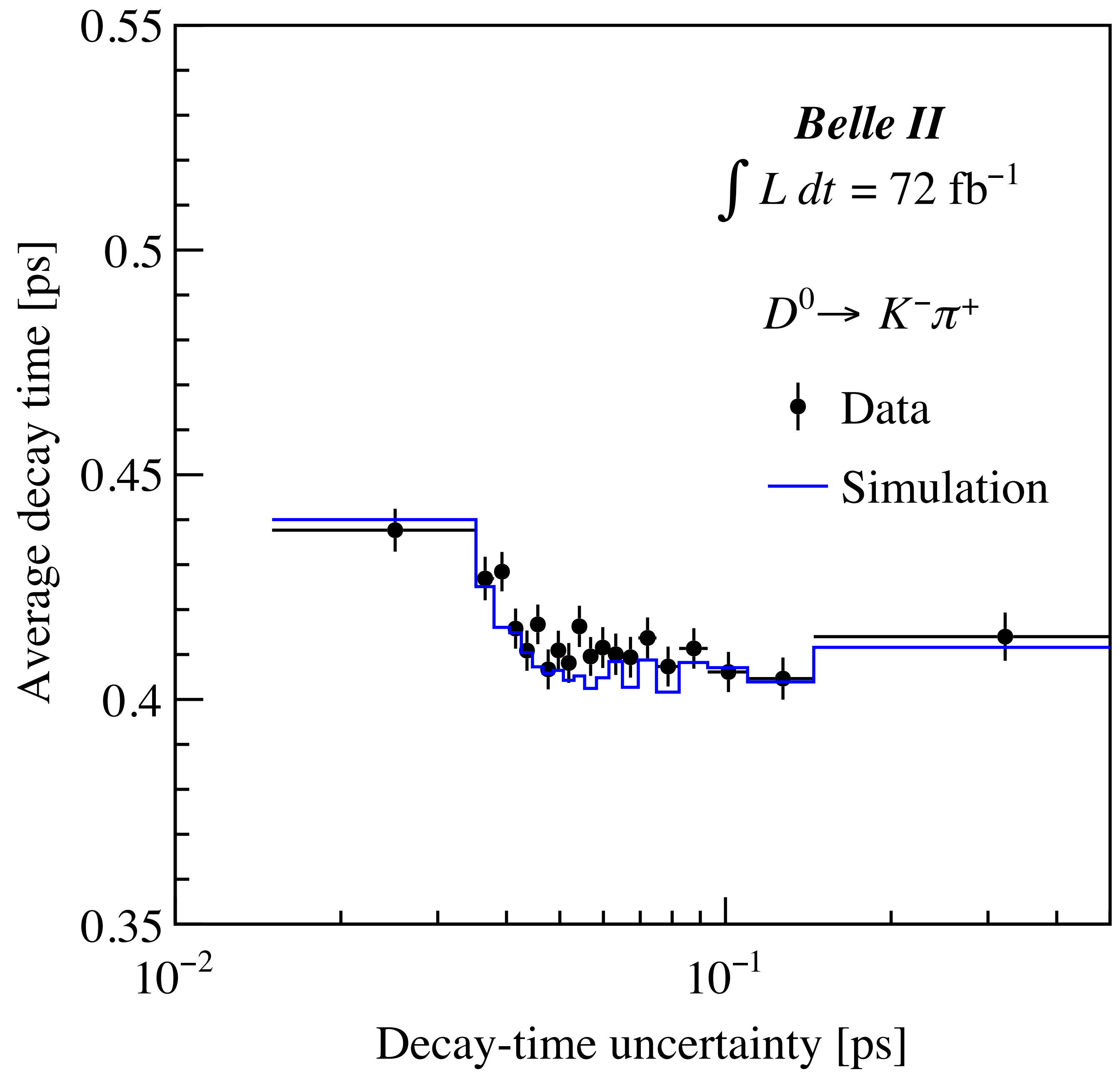
Systematic uncertainties

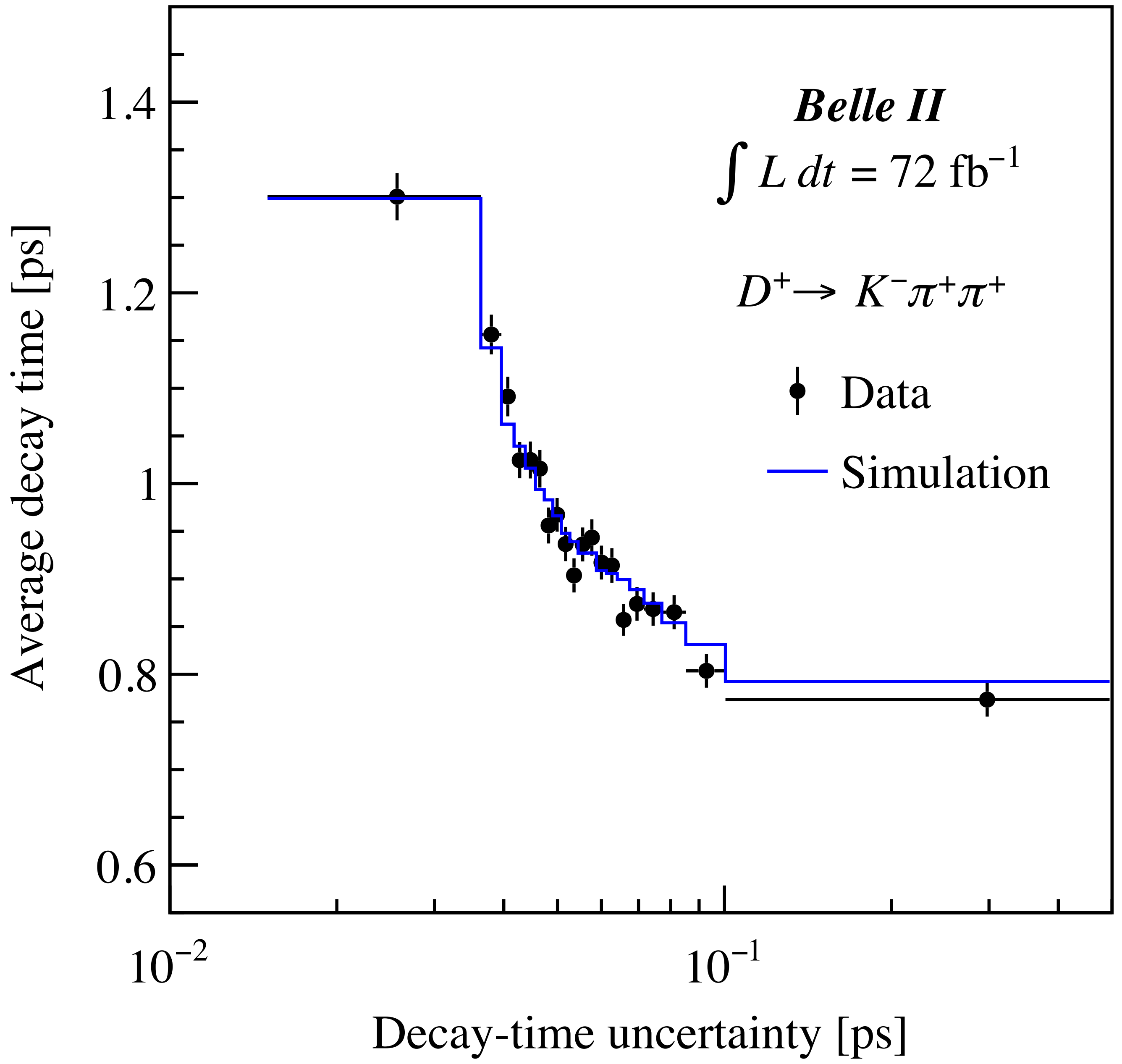
Source	Uncertainty (fs)			
	$\tau(D^0)$	$\tau(D^+)$	$\tau(\Lambda_c^+)$	$\tau(\Omega_c^0)$
Fit bias	–	–	–	3.4
Resolution model	0.16	0.39	0.46	6.2
Background model	0.24	2.52	0.20	8.3
Ξ_c contamination	–	–	0.34	–
Detector alignment	0.72	1.70	0.46	1.6
Momentum scale	0.19	0.48	0.09	0.2
Input charm masses	0.01	0.03	0.01	0.2
Total systematic	0.80	3.10	0.77	11.0
Statistical	1.10	4.70	0.89	48.0

Systematic uncertainties for D^0, D^+ and Λ_c^+ lifetimes ~halved compared to previous best results. Ω_c^0 measurement severely limited by statistical uncertainty

Syst. uncertainties due to resolution model

- The resolution model is somewhat simplified compared to what seen in simulation
  - For example, it ignores correlations between t and σ_t, which are clearly visible also in data
  - This results in discrepancies between the fit model and the data in the 2D (t,σ_t) distribution
- Fits to simulated decays used to assess the impact on the measured lifetimes
- Also tested single Gaussian *vs.* double-Gaussian models

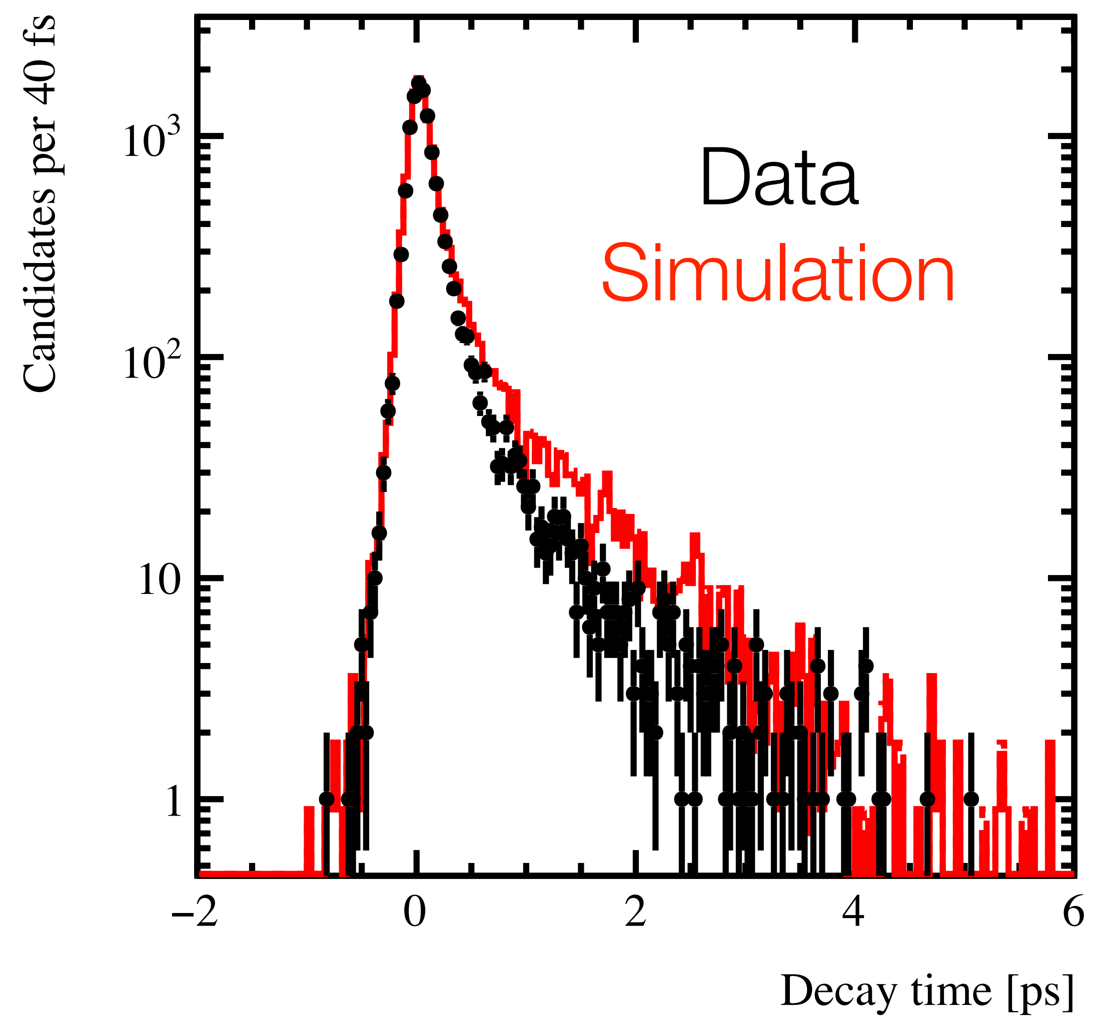




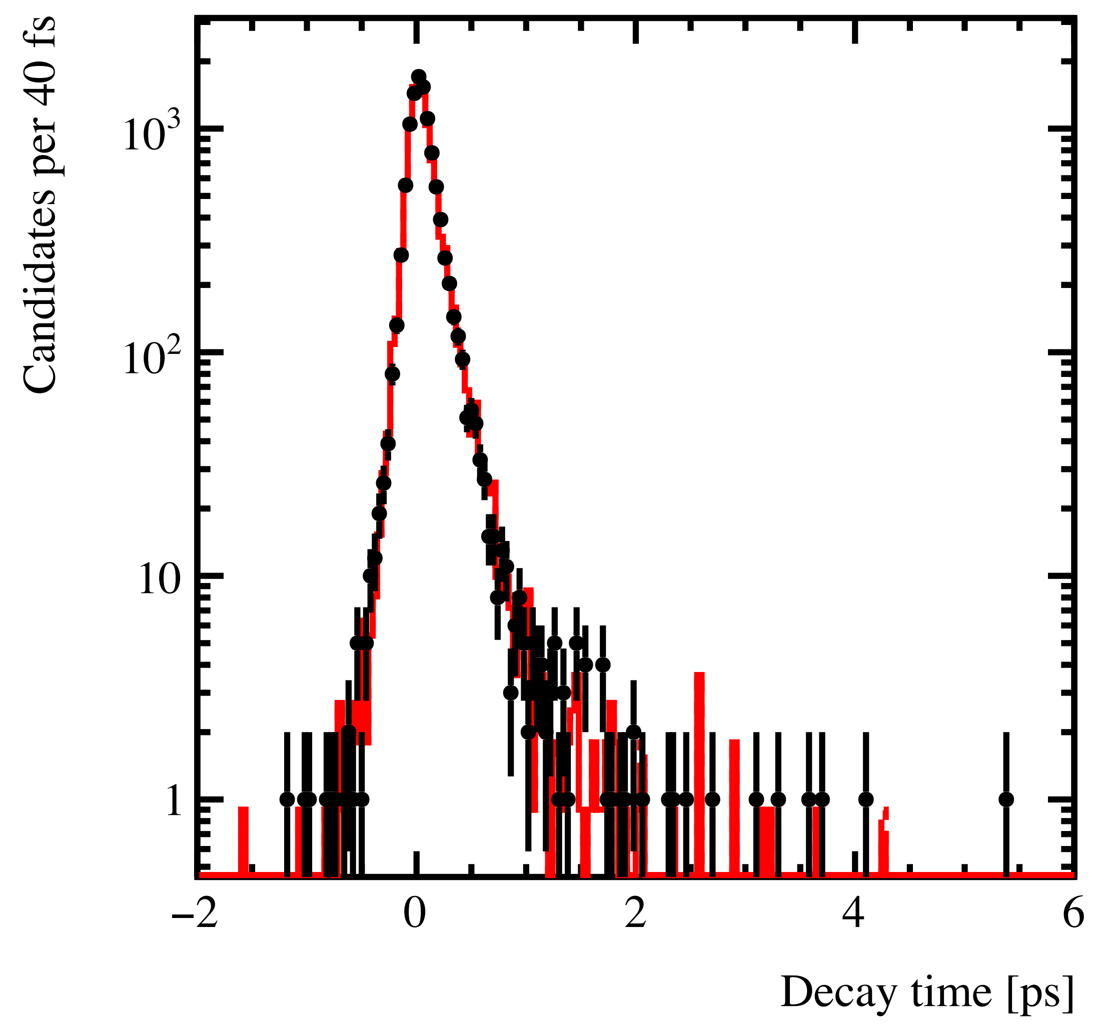
Syst. uncertainties due to background modeling

- Neglected background in D^0
  - Estimate impact on lifetime by fitting simulated samples that reproduce the background of the data
- Background modeling for D^+, Λ_c^+ and Ω_c^0
  - Simulation shows that SB describe the background in the signal region correctly. However, simulation and data show some disagreement in the SB
  - Estimate systematic uncertainty by fitting simulated samples with background shapes that differ between signal region and SB, and by varying the sideband definition

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



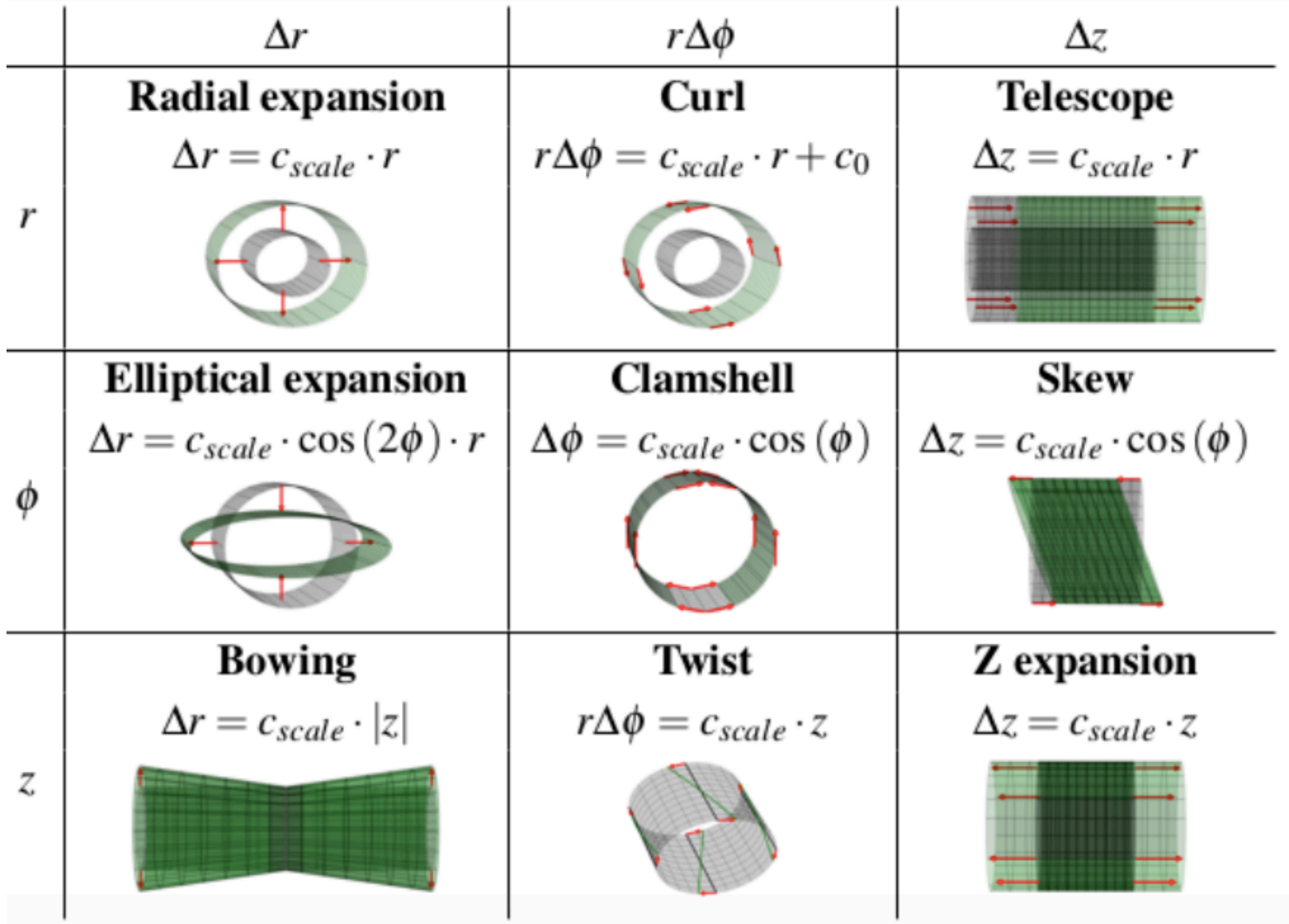
Low-mass sideband



High-mass sideband

Syst. uncertainties due to imperfect alignment

- A misalignment of the tracking detectors may bias the determination of the decay length and hence of the lifetime
- 2 sources of uncertainties due to misalignment
  - Uncertainty in alignment constants from limited alignment sample size; estimated from day-to-day variations between alignments in data
  - Uncertainty from residual misalignments not corrected for by the alignment algorithm; estimated from simulation of a misaligned detector (9 different weak-mode deformations)



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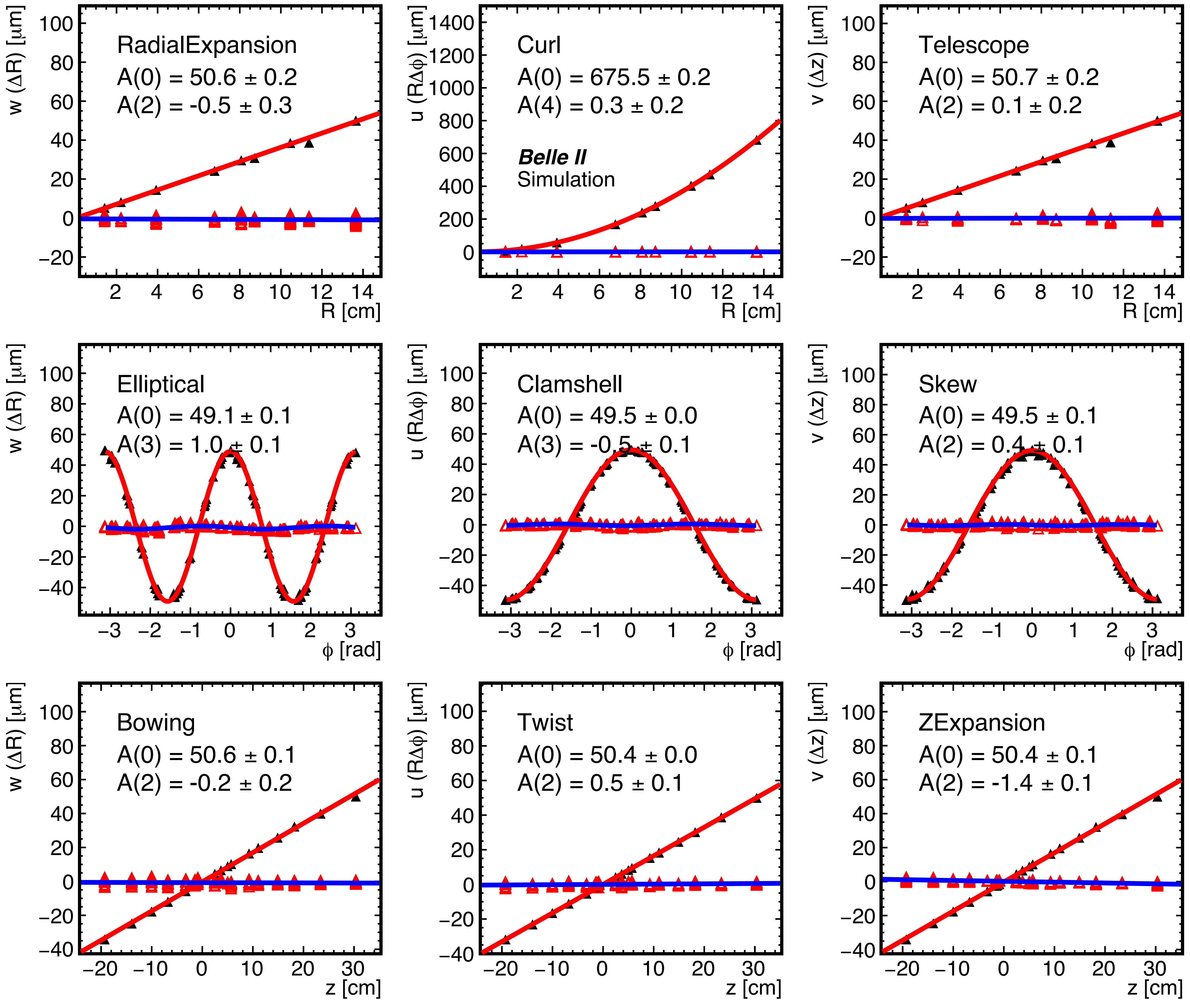
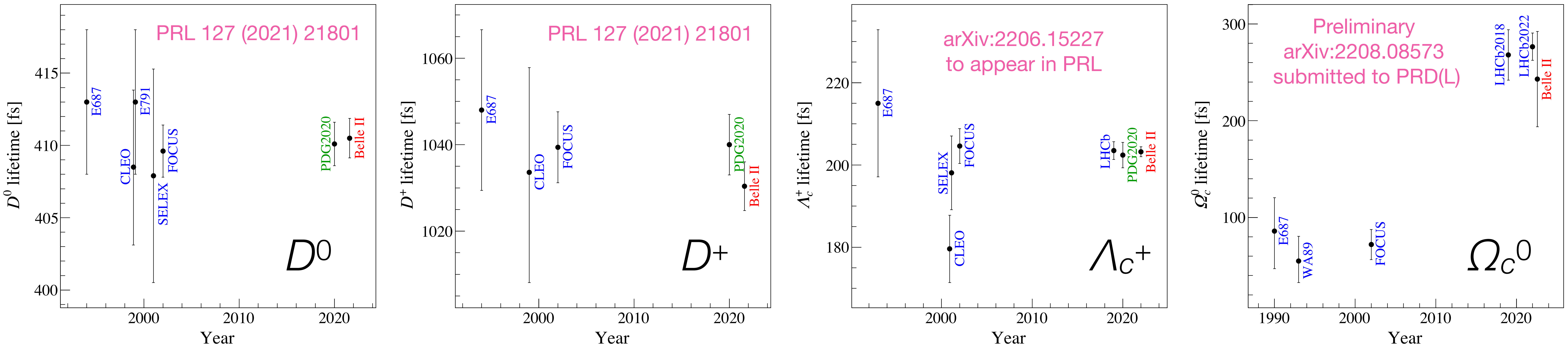


before / after alignment

Summary



- Used early Belle II data to measure lifetimes of charm hadrons
  - World-best D^0, D^+ and Λ_c^+ lifetimes (first Belle II precision measurements)
  - Confirmation of LHCb result indicating that the Ω_c^0 is not the shortest-lived weakly decaying charmed baryon
- Tiny systematic uncertainties (*e.g.*, 2‰ for D^0) demonstrate excellent performance and understanding of the Belle II detector, never achieved at previous *B* factories