Recent Belle II results in charm physics

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(on behalf of the Belle II collaboration)

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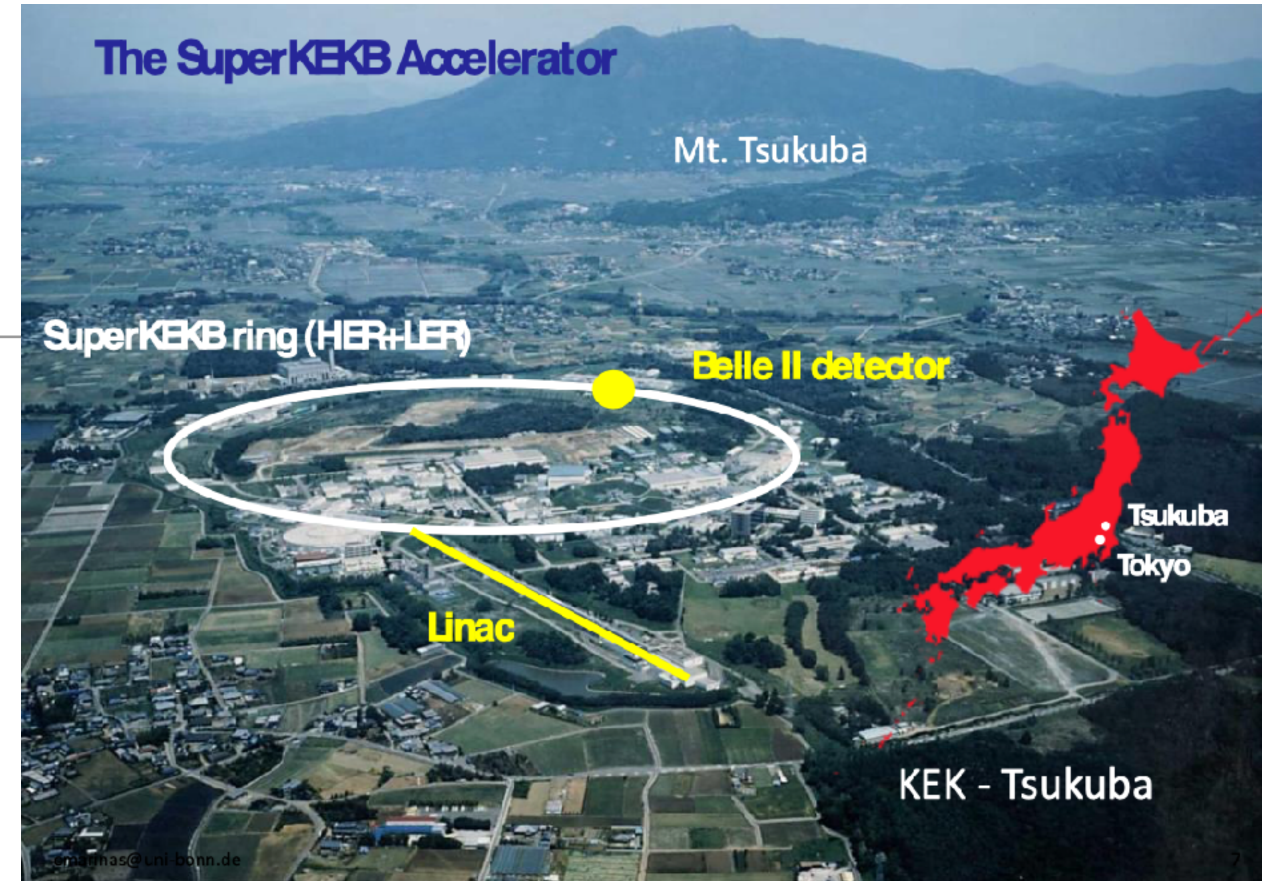
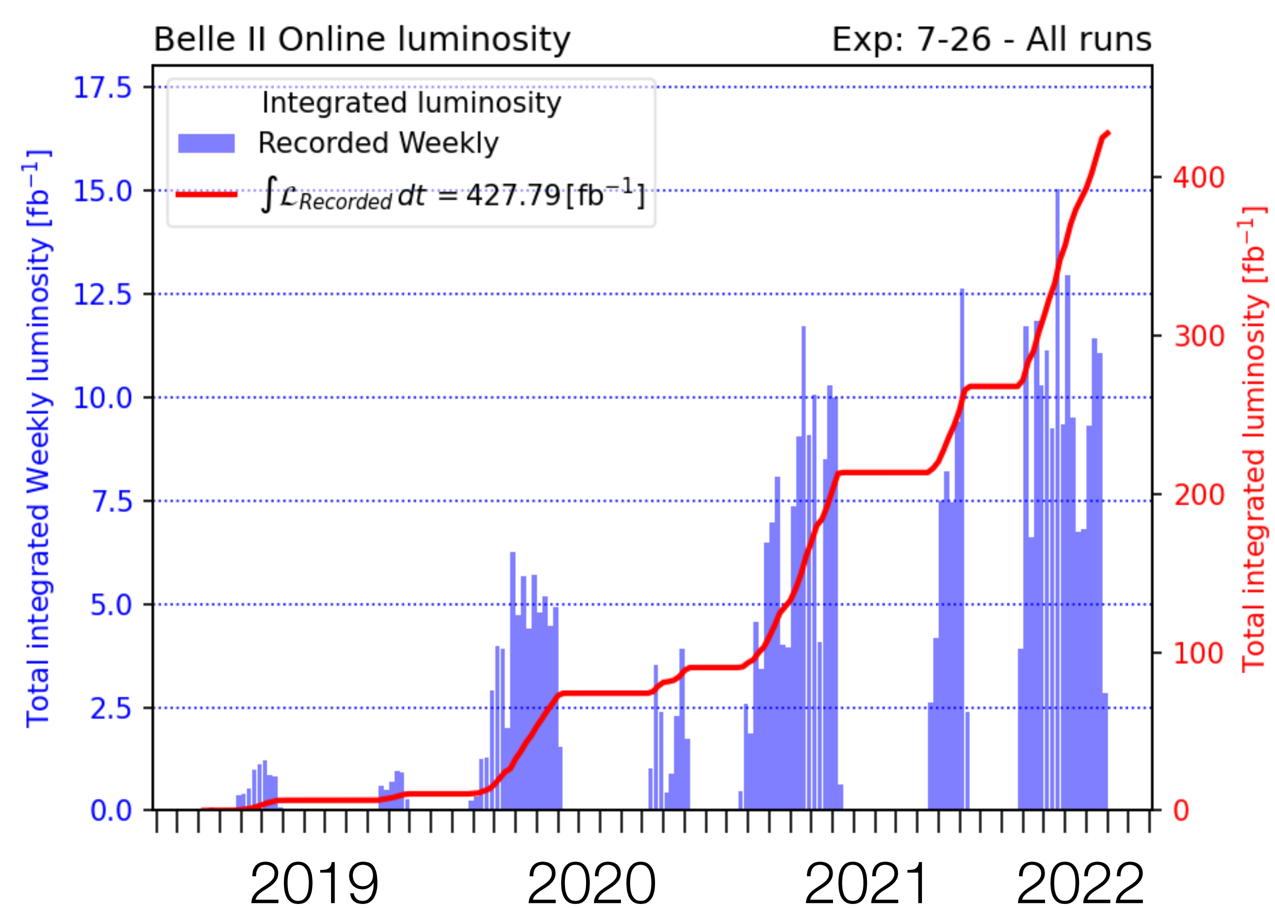
Belle II and SuperKEKB

- Belle II is a multipurpose detector at the SuperKEKB e^+e^- collider, located at KEK in Tsukuba, Japan

- Latest in a series of experiments operating near the $\Upsilon(4S)$ resonance

ARGUS	$0.2\ fb^{-1}$	
CLEO	$9\ fb^{-1}$	
BaBar	$500\ fb^{-1}$	
Belle	$1'000\ fb^{-1}$	
Belle II	$50'000\ fb^{-1}$	(expected)
	$430\ fb^{-1}$	(recorded)





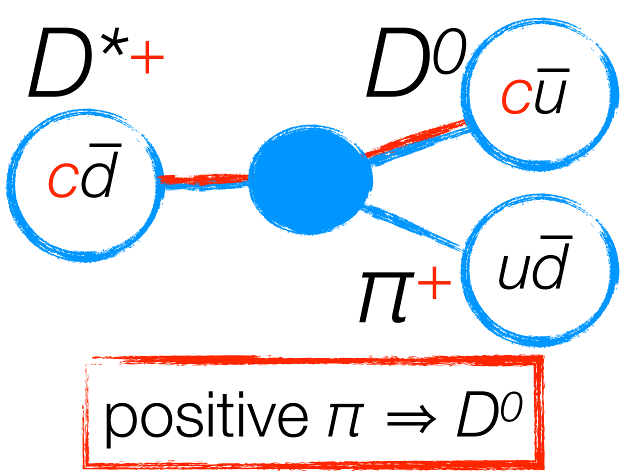
Charm physics program at Belle II

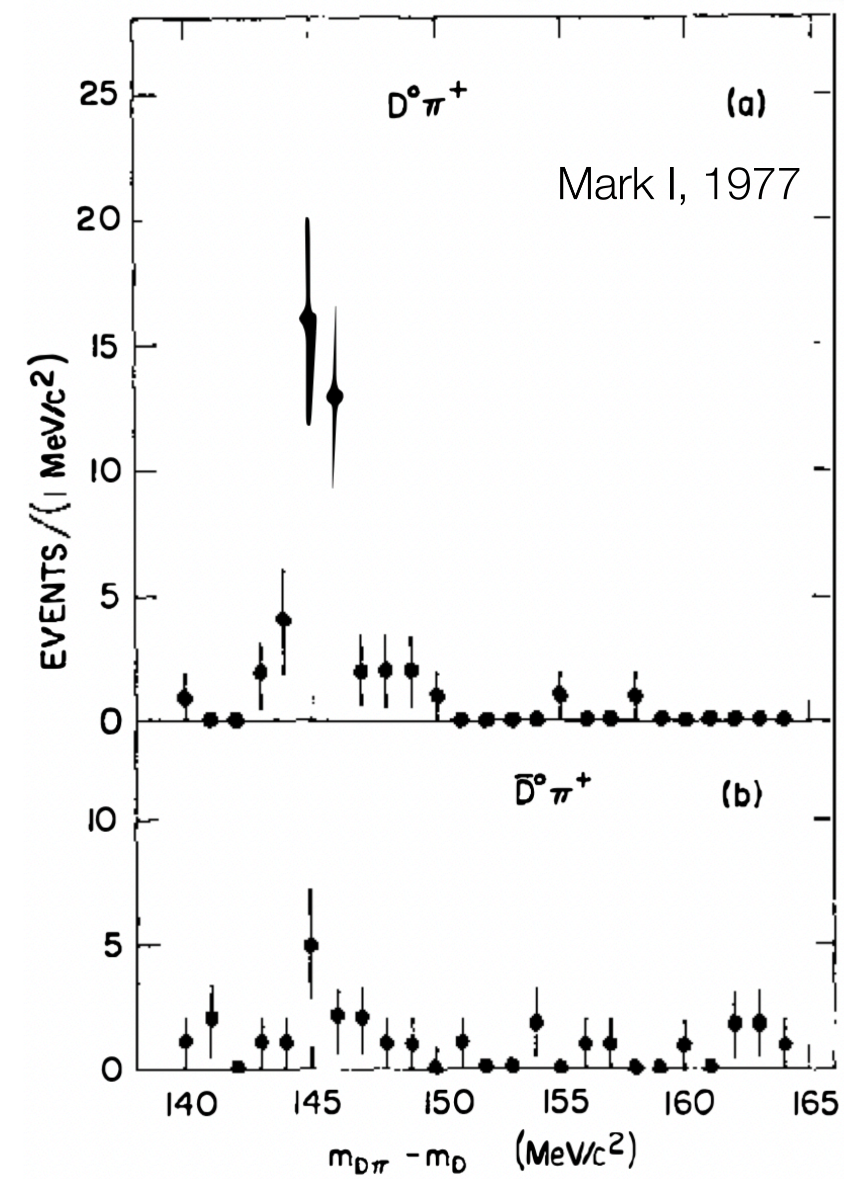
- Large $e^+e^-\to c\bar{c}$ cross-section provides low-background event samples
  - 1.3M $c\bar{c}$ events per 1 fb^{-1}, all recorded to tape (~100% trigger efficiency uniform across decay time and kinematics)
- Rich program of charm physics
  - Excellent reconstruction of final states with neutrals: *e.g.*, $D^0\to\pi^0\pi^0$, $D^+\to\pi^+\pi^0$, $D^0\to\rho^0\gamma$,… to complement LHCb observation of CP violation in $D^0\to\pi^+\pi^-$
  - Unique access to final states with invisible particles: *e.g.*, dineutrino final states

Preparing the tools: charm flavor tagging

- Tagging the production flavor is needed to measure *CP* violation (and mixing) in neutral *D* decays

- Since 1977 this is achieved by restricting to the strong-interaction decays





- Added bonus: sample is much cleaner

- Disadvantage: sample is reduced by factor 5-20

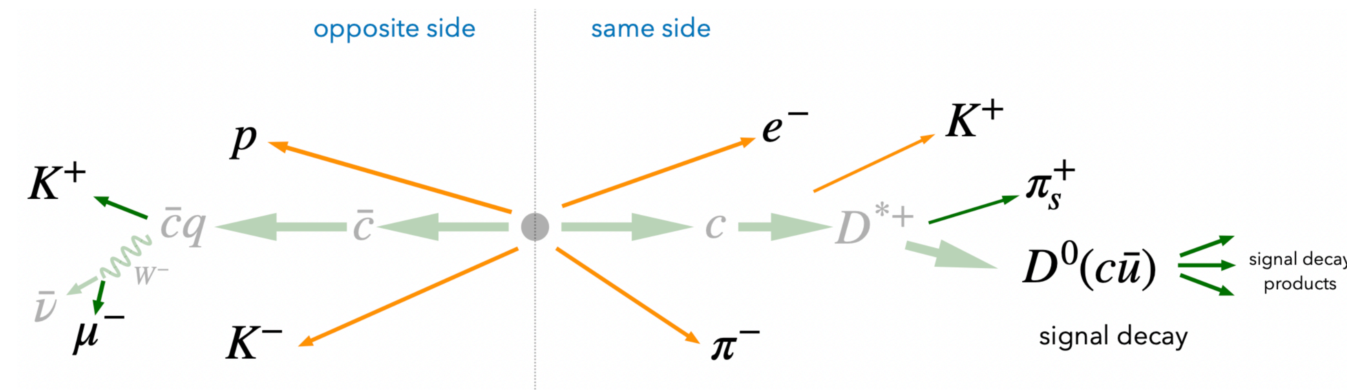
Novel charm flavor tagging (CFT)

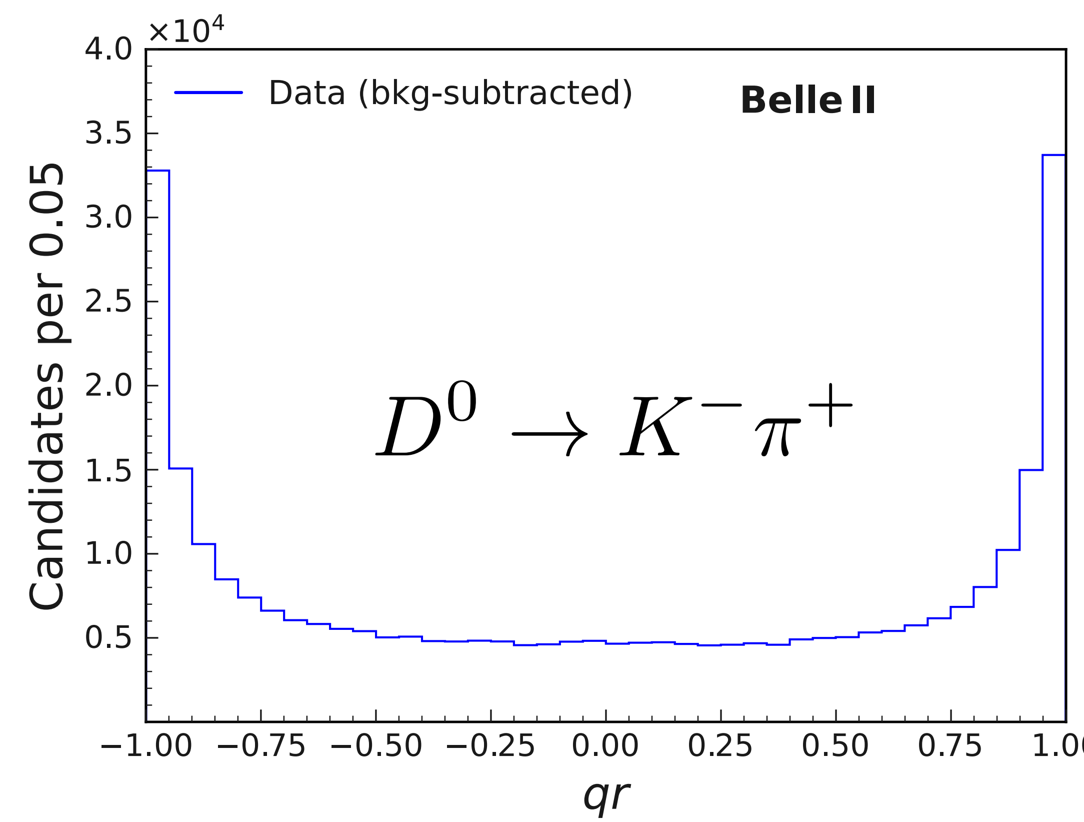
[PRD 107 (2023) 112010]

- Inspired by opposite-side b-flavor tagging
  - Reconstruct particles most collinear with signal meson, use machine learning with kinematic features (ΔR, recoiling mass) and PID as input to predict tagging decision q and dilution r
- Trained using simulation. Performance measured/calibrated with data

$$\varepsilon_{\rm tag}^{\rm eff} = (47.91 \pm 0.07({\rm stat}) \pm 0.51({\rm syst}))\%$$

best performance across any flavor tagger



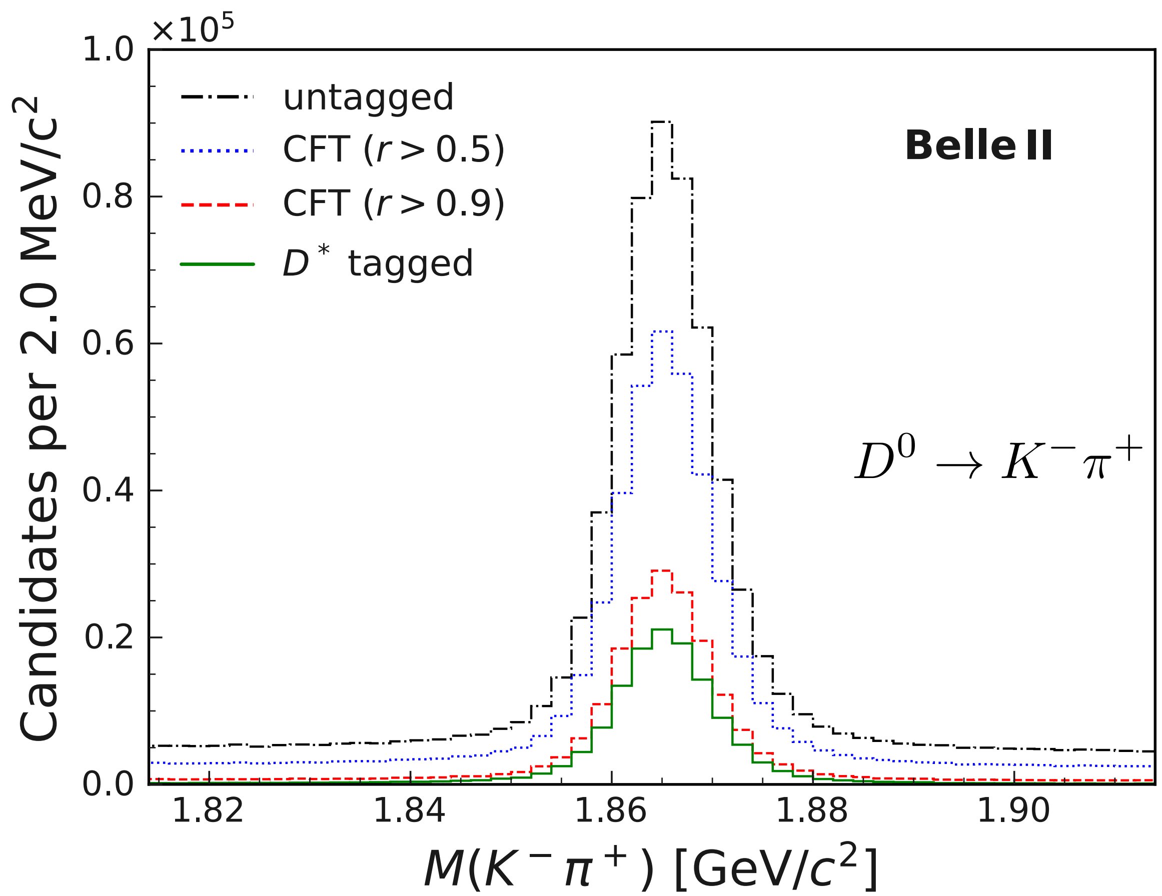


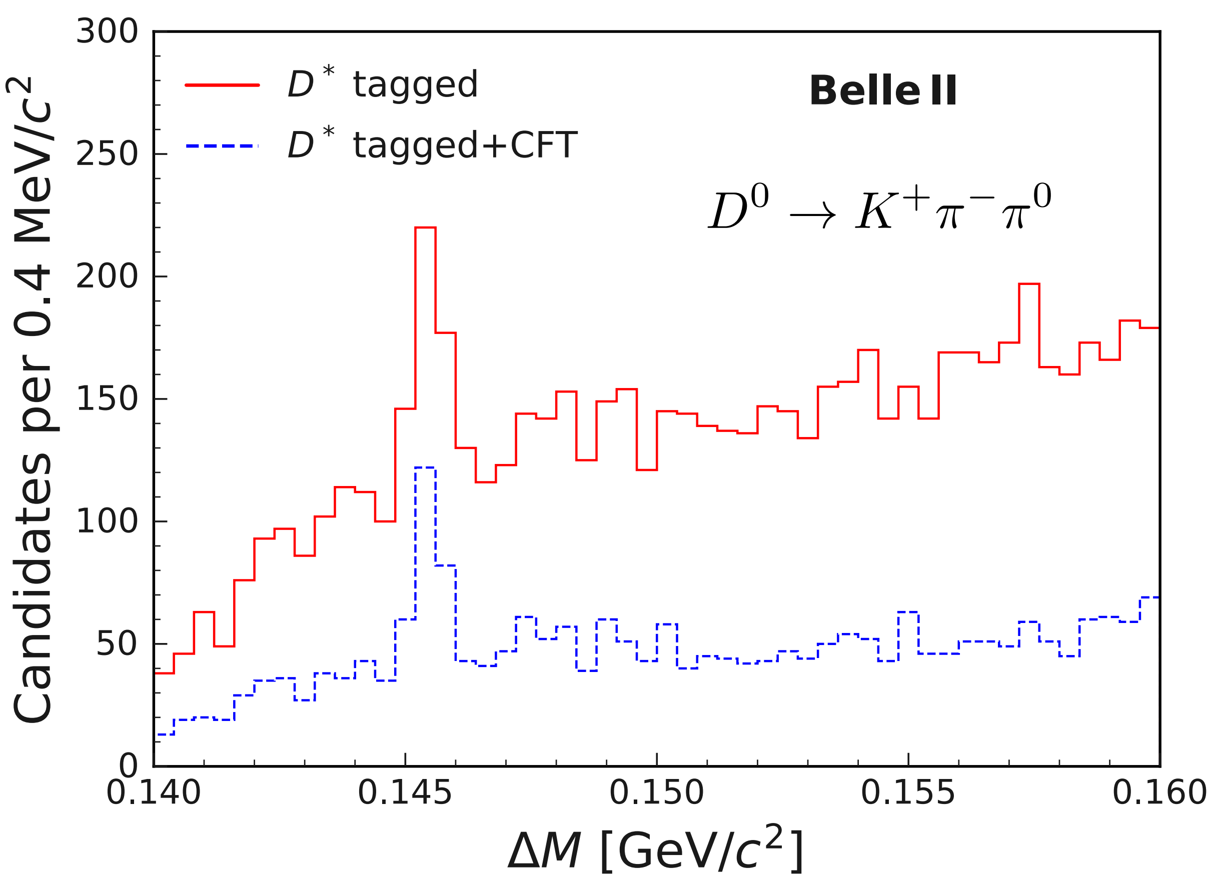
q=+1 for D^0 and −1 for $\bar{D}^0$
r=1 perfect prediction, r=0 random guessing

Novel charm flavor tagging (CFT)

[PRD 107 (2023) 112010]

- Doubles the sample size w.r.t. D^{*+}-tagged decays
- Provides discrimination between signal and background
- Will increase sensitivity for many *CP*-violation and mixing measurements

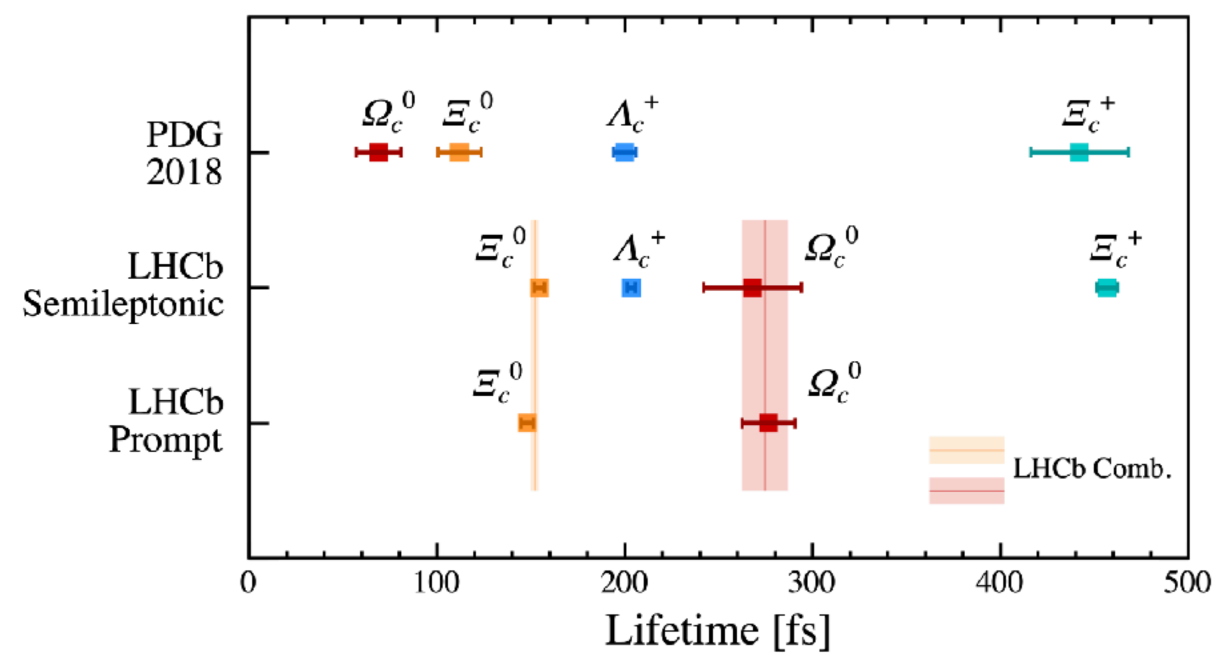




Charm lifetimes

- 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 broke the hierarchy predicted by HQE, requiring revised calculations
- 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
  - Serve also as references for LHCb, where typically ratios of lifetimes are measured

Sci. Bull. 67 (2022) 479



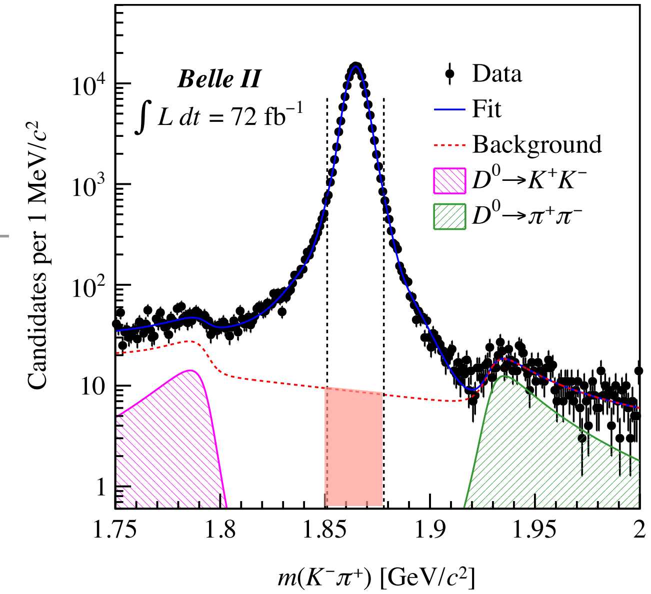
$$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$$

Signal samples

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

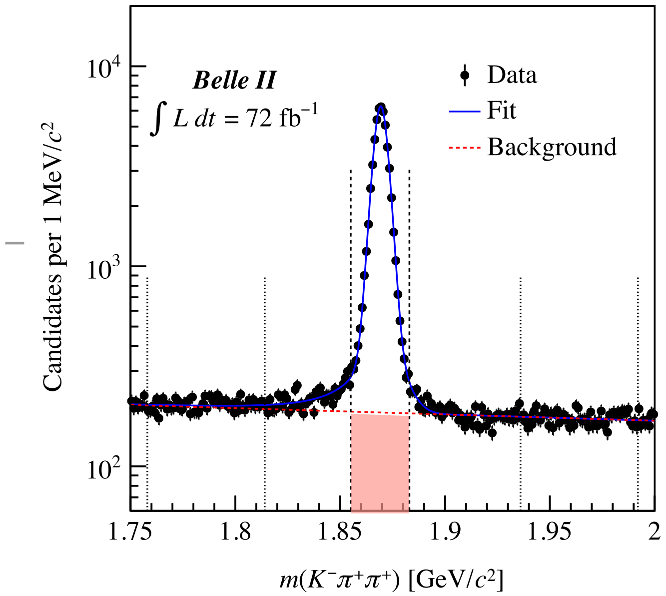
~171k $D^{*+} \to D^0(\to K^- \pi^+)\pi^+$

99.8% purity



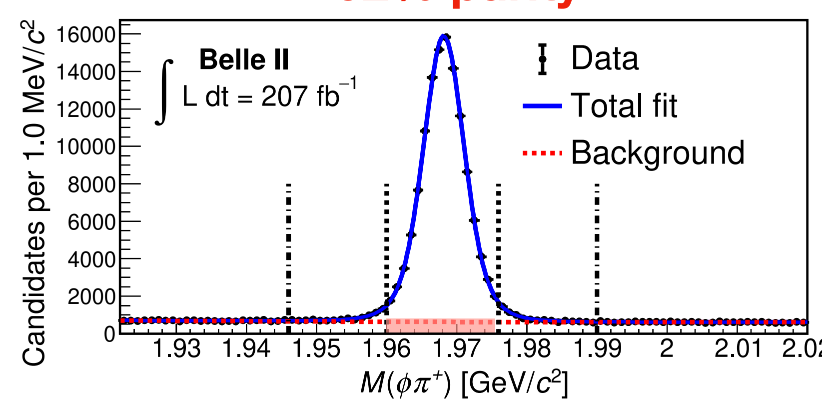
~59k $D^{*+} \to D^+(\to K^- \pi^+ \pi^+)\pi^0$

91% purity



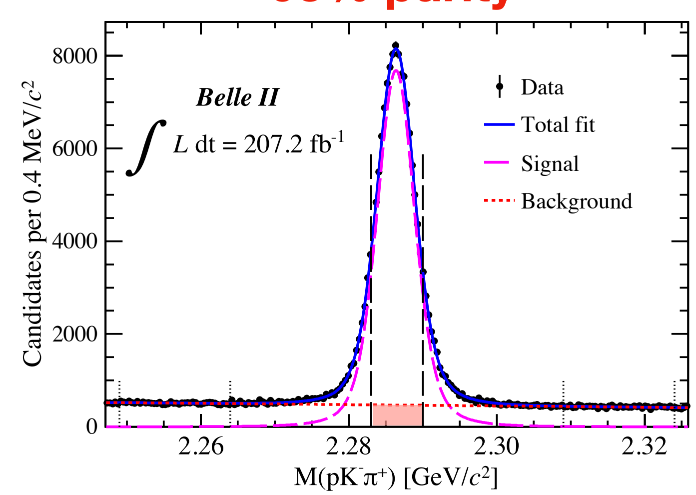
~116k $D_s^+ \to \phi(\to K^- K^-)\pi^+$

92% purity



~116k $\Lambda_c^+ \to p K^- \pi^+$

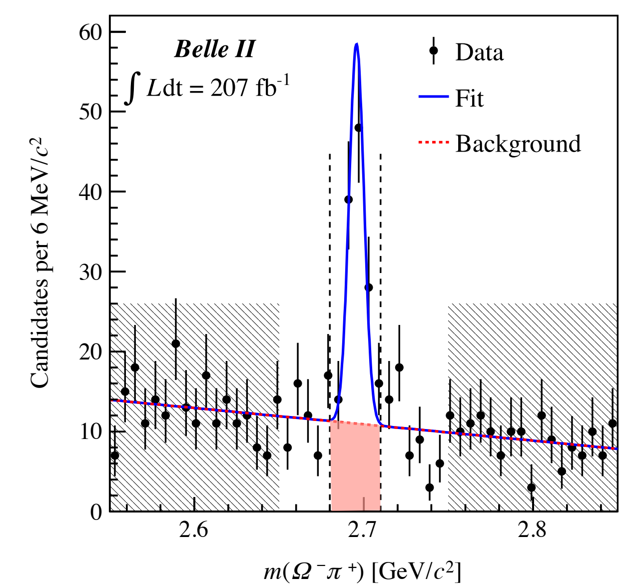
93% purity



~90 $\Omega_c^0 \to \Omega^- \pi^+$

$\Omega^- \to \Lambda^0(\to p\pi^-)K^-$

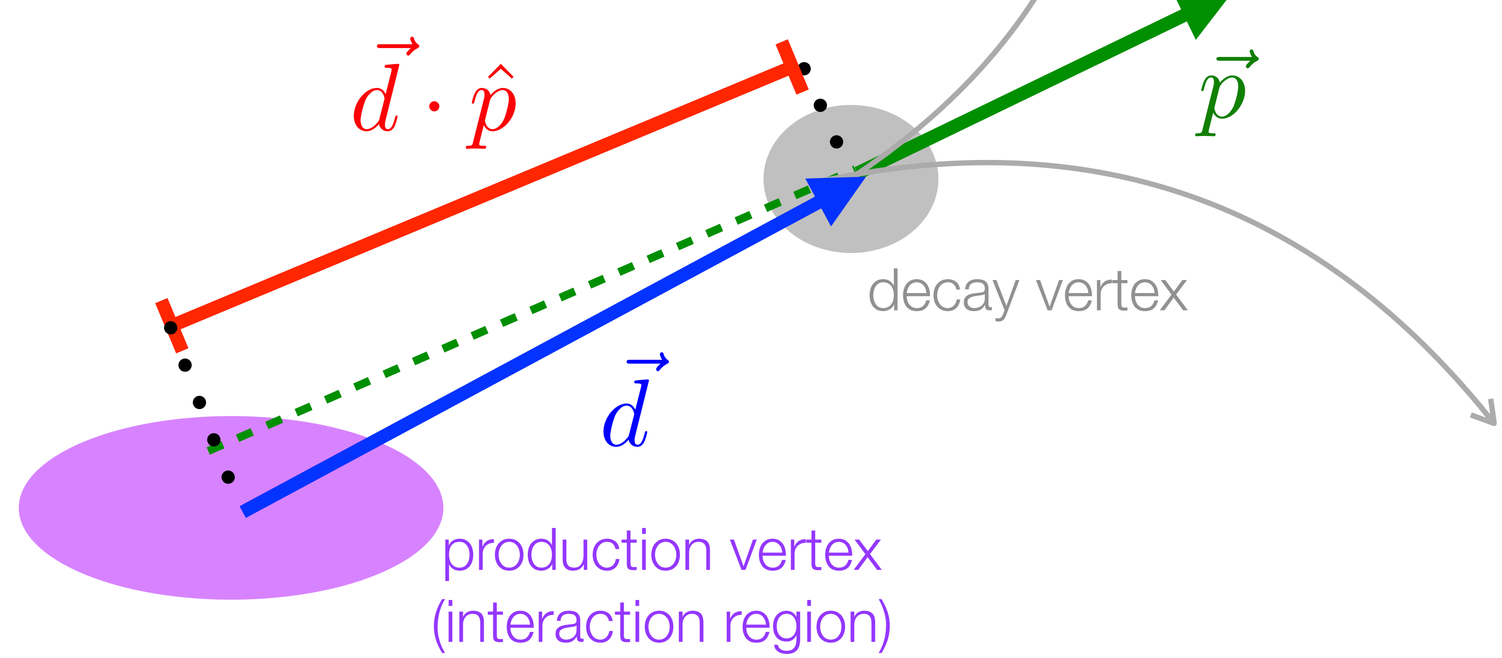
67% purity



Determination of the decay time

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

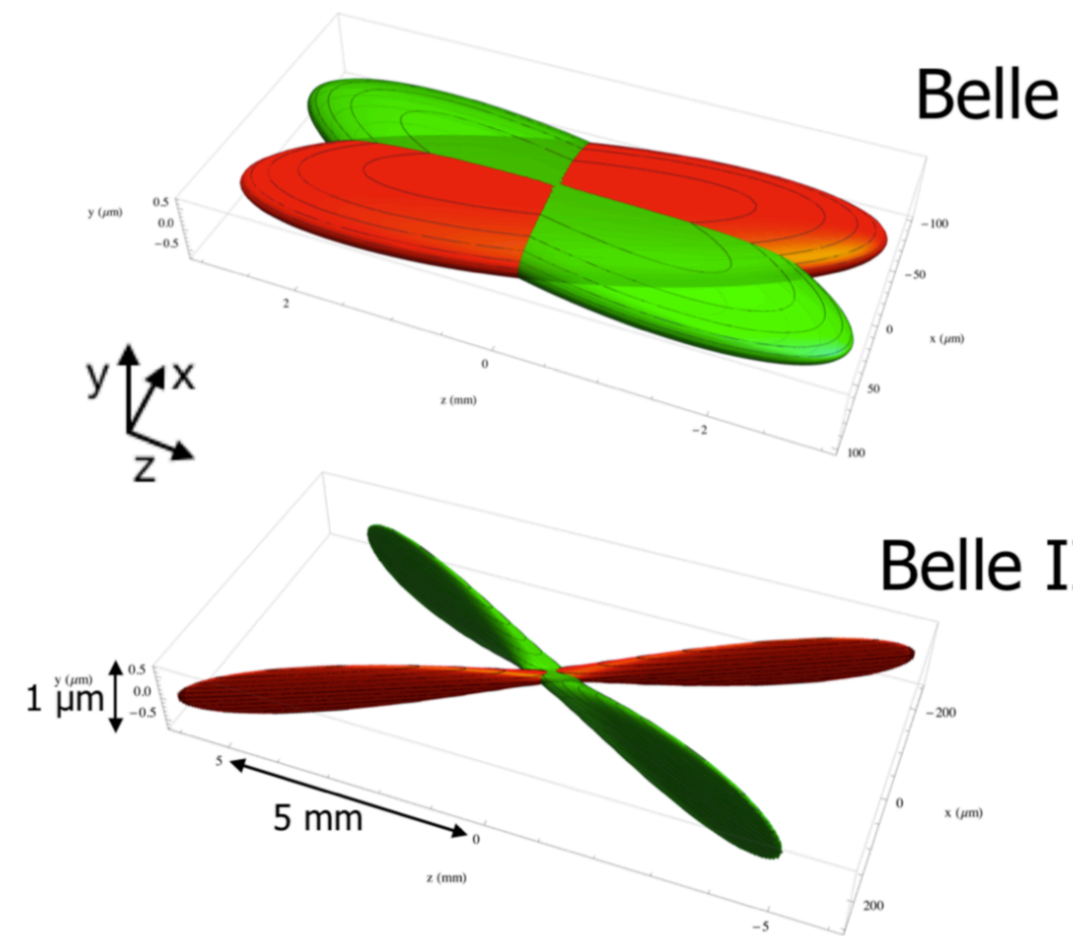
$$t = \frac{m}{p}(\vec{d} \cdot \hat{p})$$



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

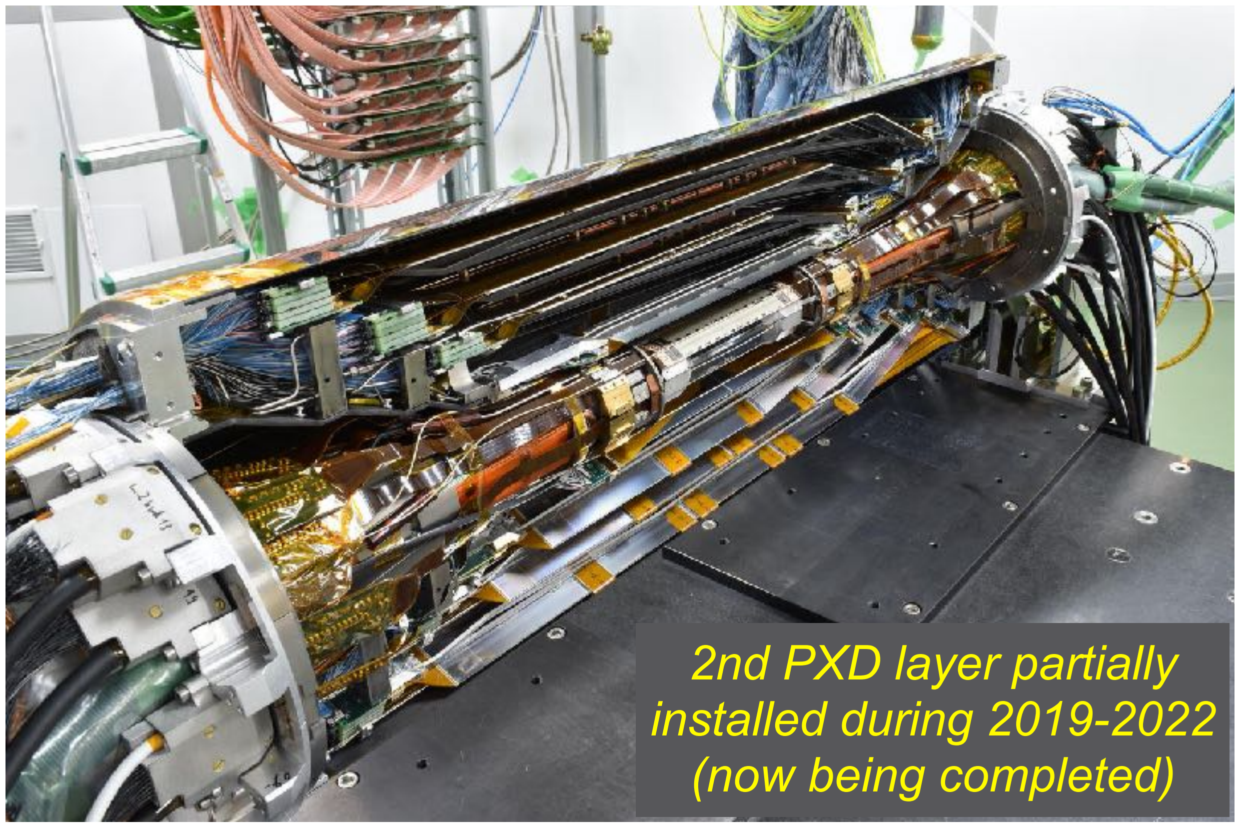
SuperKEKB “nano beams”

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

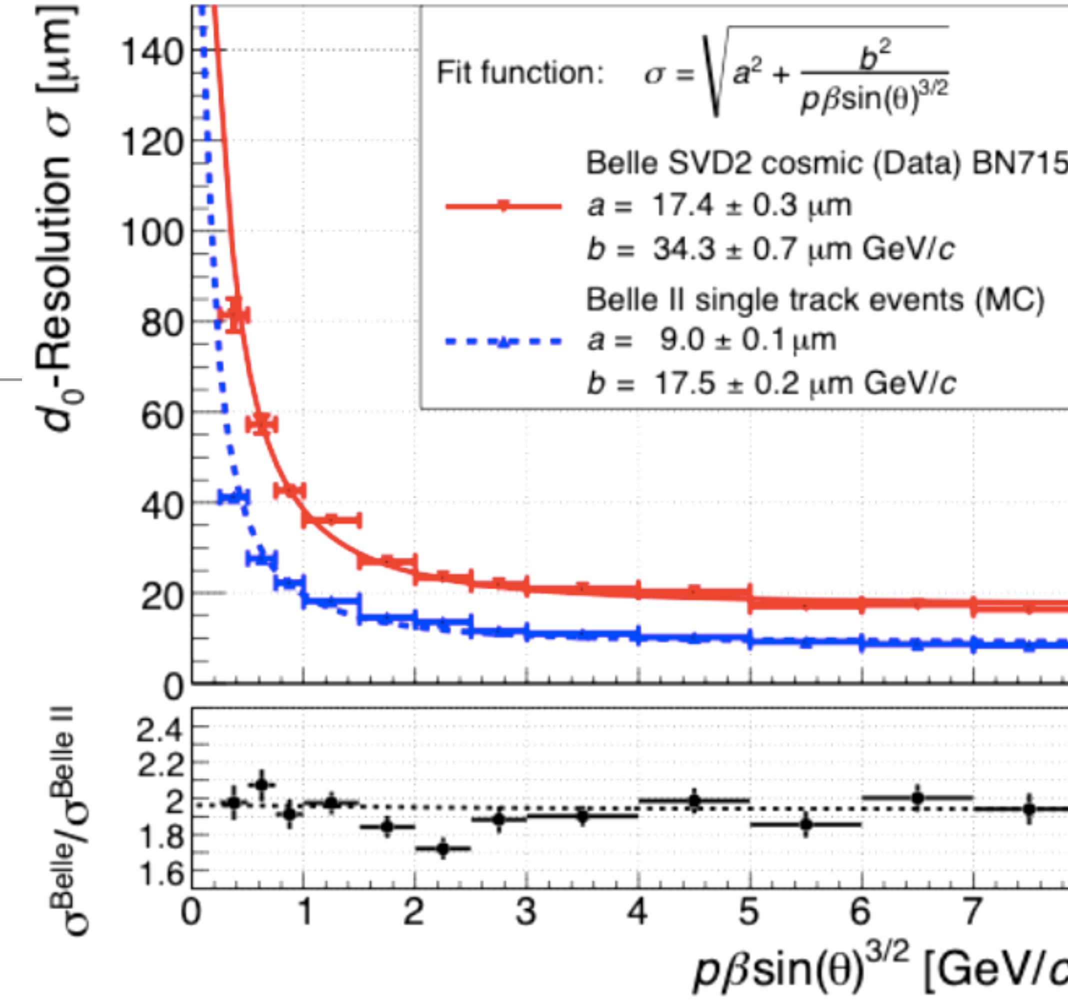


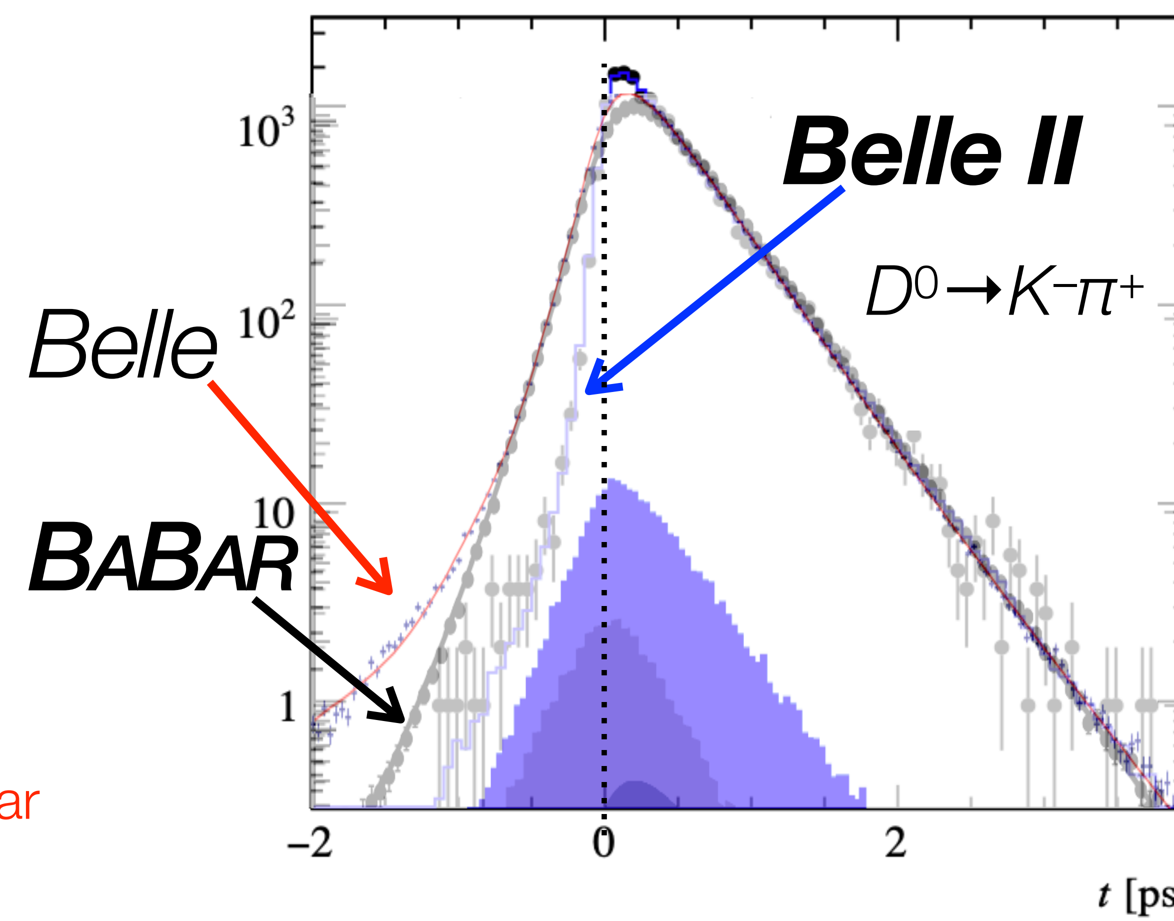
Dimensions of luminous region at Belle II are 10/0.2/250 μm (x/y/z) compared to 100/1/6’000 μm at Belle. Ultimately, *y* size expected to be decreased to ~60 nm

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 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)

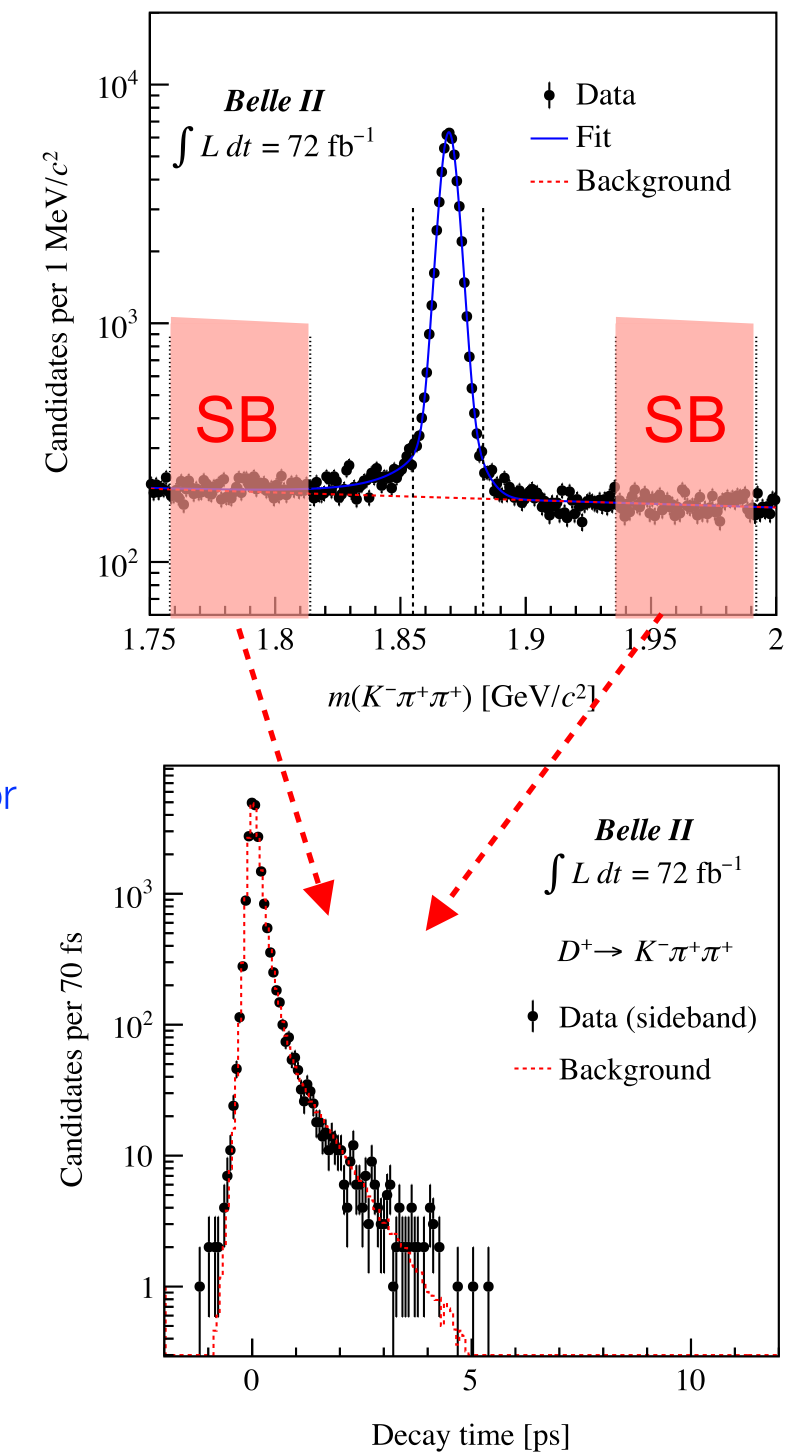
$$\mathrm{pdf}_{\mathrm{sgn}}(t,\sigma_t|\tau,b,s) = \mathrm{pdf}_{\mathrm{sgn}}(t|\sigma_t,\tau,b,s)\,\mathrm{pdf}_{\mathrm{sgn}}(\sigma_t)$$
$$\propto \int_0^\infty e^{-t_{\mathrm{true}}/\tau} R(t - t_{\mathrm{true}}|b, s\sigma_t)\,dt_{\mathrm{true}}\,\mathrm{pdf}_{\mathrm{sgn}}(\sigma_t)$$

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)

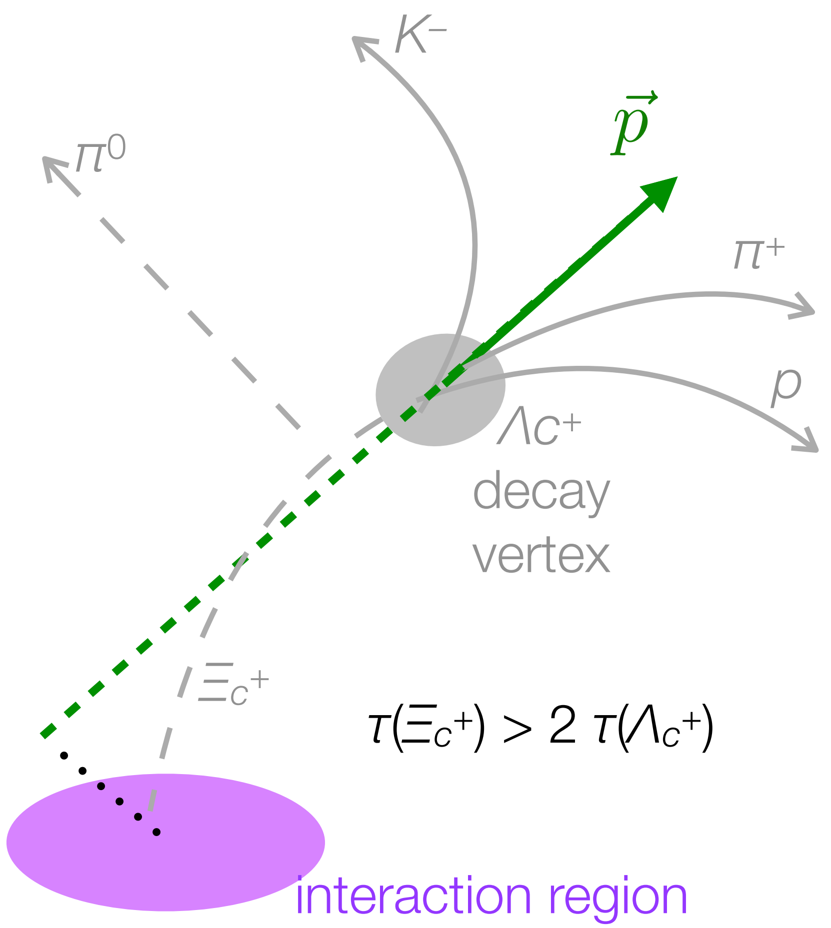
- Background contamination (ignored for D^0 decays) modeled using sideband data (SB)

- 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 $\Xi_c \rightarrow \Lambda_c^+ \pi$ decays

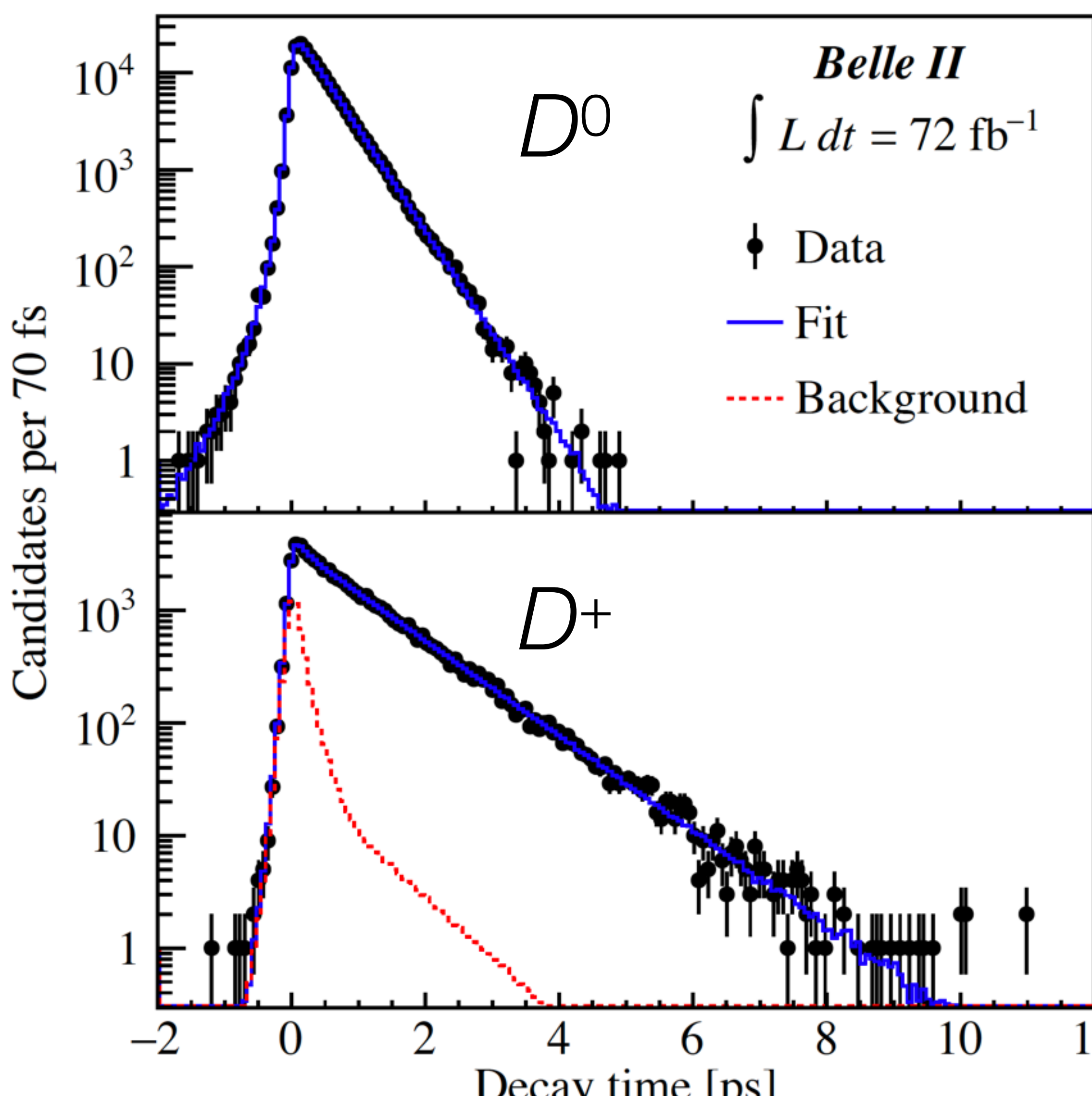
- Contribution from $\Xi_c \rightarrow \Lambda_c^+ \pi$ decays could bias Λ_c^+ lifetime
  - Production rate of Ξ_c not known, Ξ_c^0 branching fraction measured to be ~0.55%, Ξ_c^+ branching fraction expected to be ~1.11%
- Reduce possible contamination with veto and correct for remaining
  - Attach 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^+ flight distance in transverse plane
  - Introduce estimated contamination in simulation to evaluate lifetime bias
  - Take half the shift as correction and as systematic uncertainty



Results

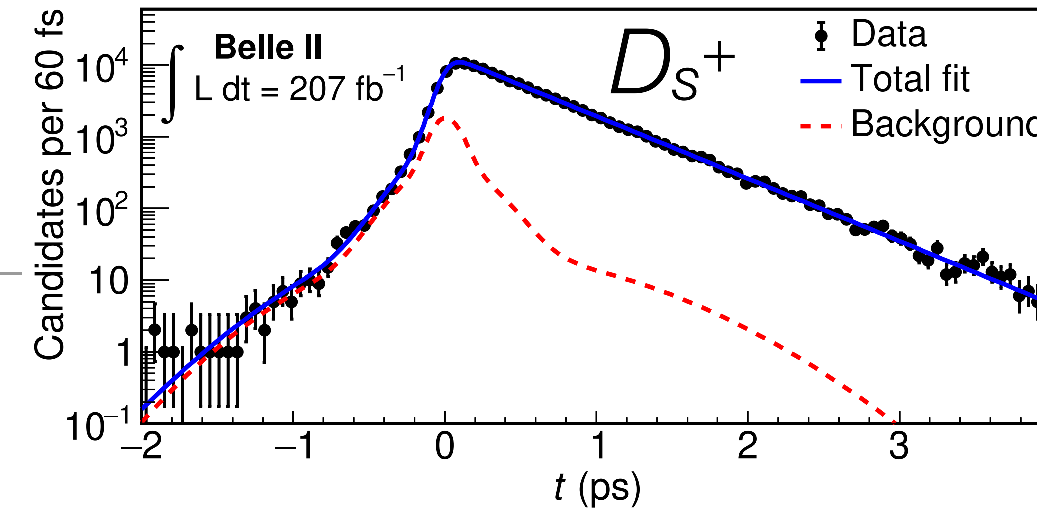
$\tau(D^0) = 410.5 \pm 1.1(\text{stat.}) \pm 0.8(\text{syst.})$ fs

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



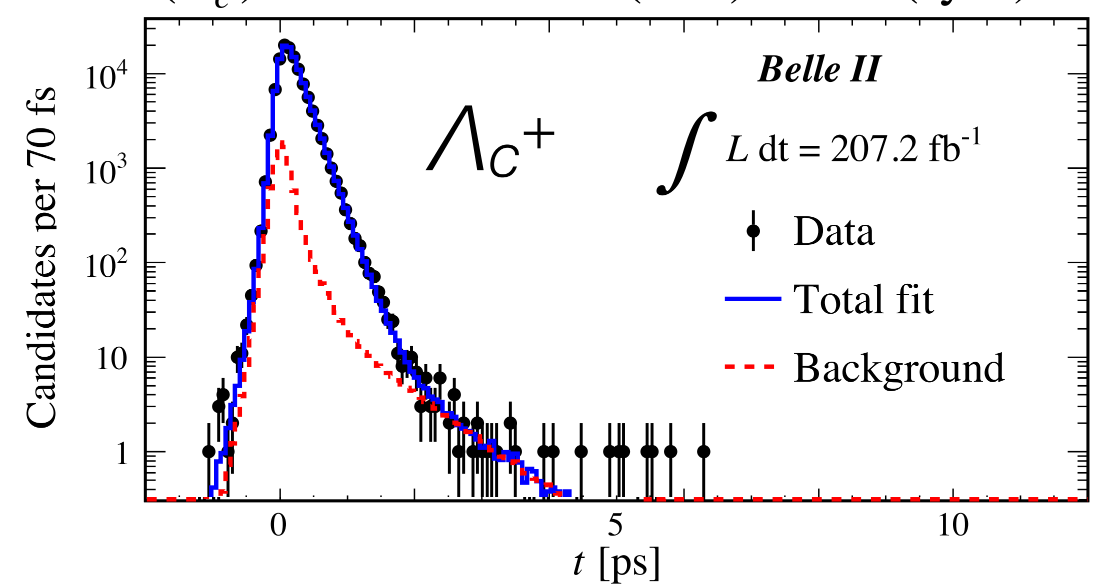
PRL 127 (2021) 21801

$\tau(D_s^+) = 498.7 \pm 1.7(\text{stat.}) {}^{+1.1}_{-0.8}(\text{syst.})$ fs



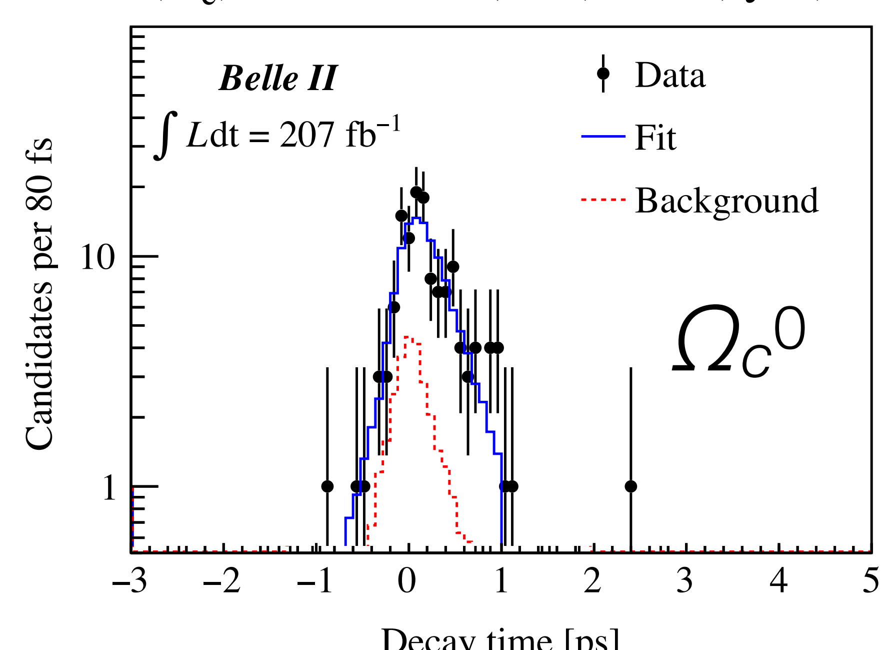
arXiv:2306.00365

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



PRL 130 (2023) 071802

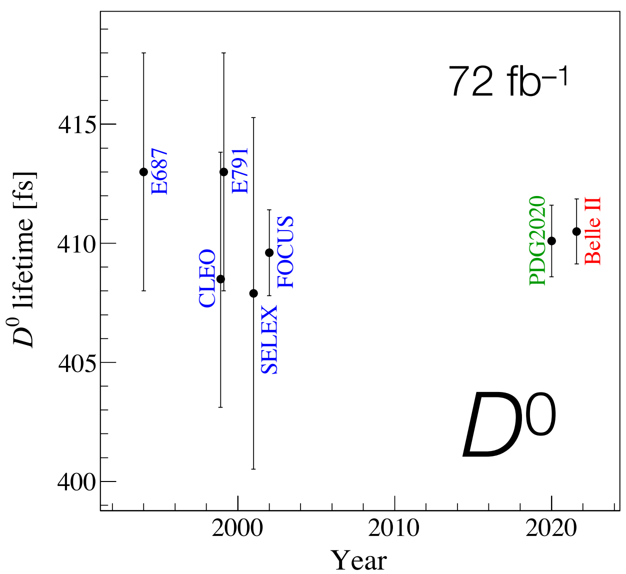
$\tau(\Omega_c^0) = 243 \pm 48(\text{stat.}) \pm 11(\text{syst.})$ fs



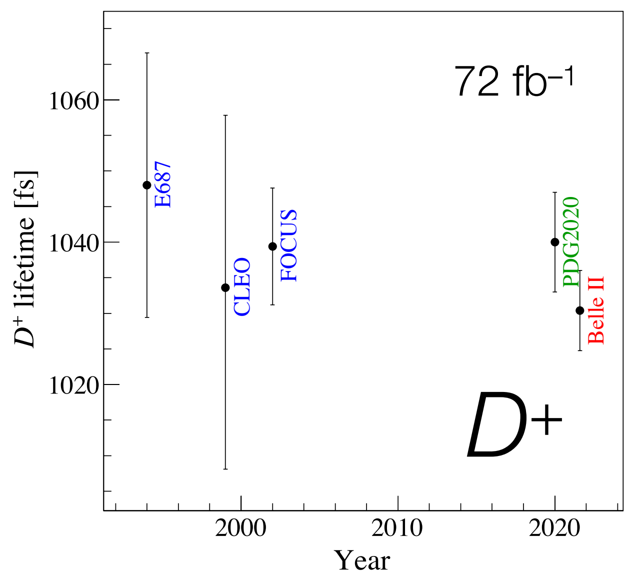
PRD 107 (2023) L031103

Results

PRL 127 (2021) 21801



PRL 127 (2021) 21801



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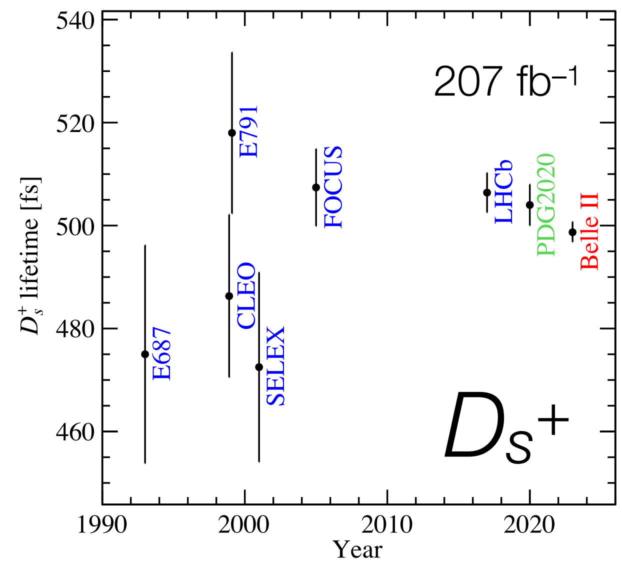
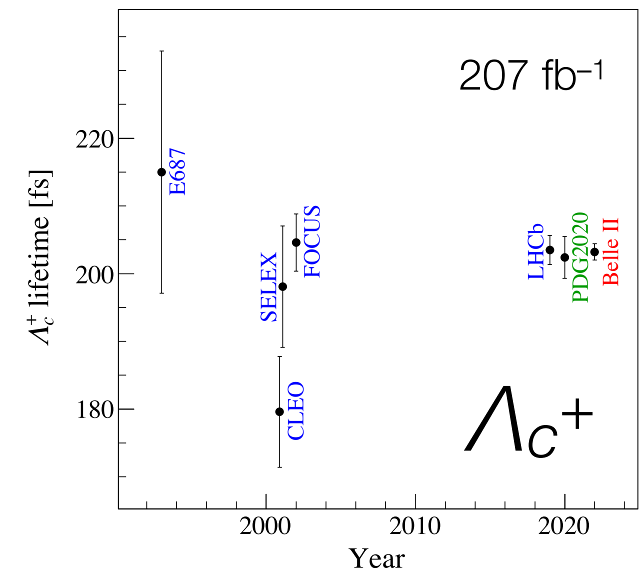
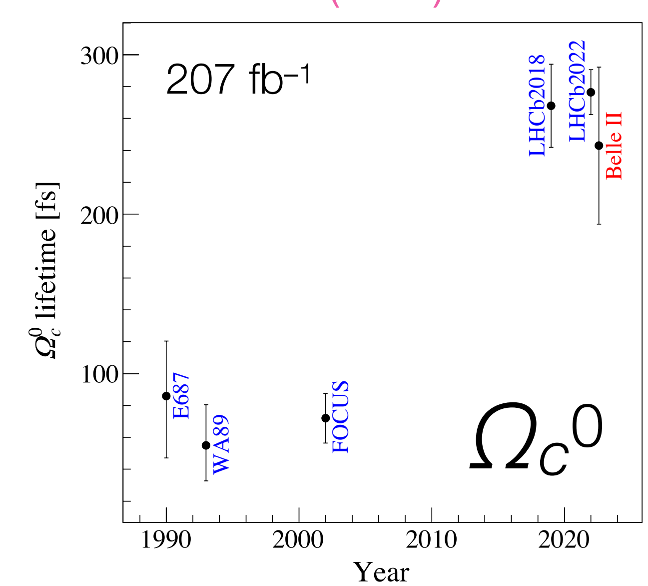


PRL 130 (2023) 071802



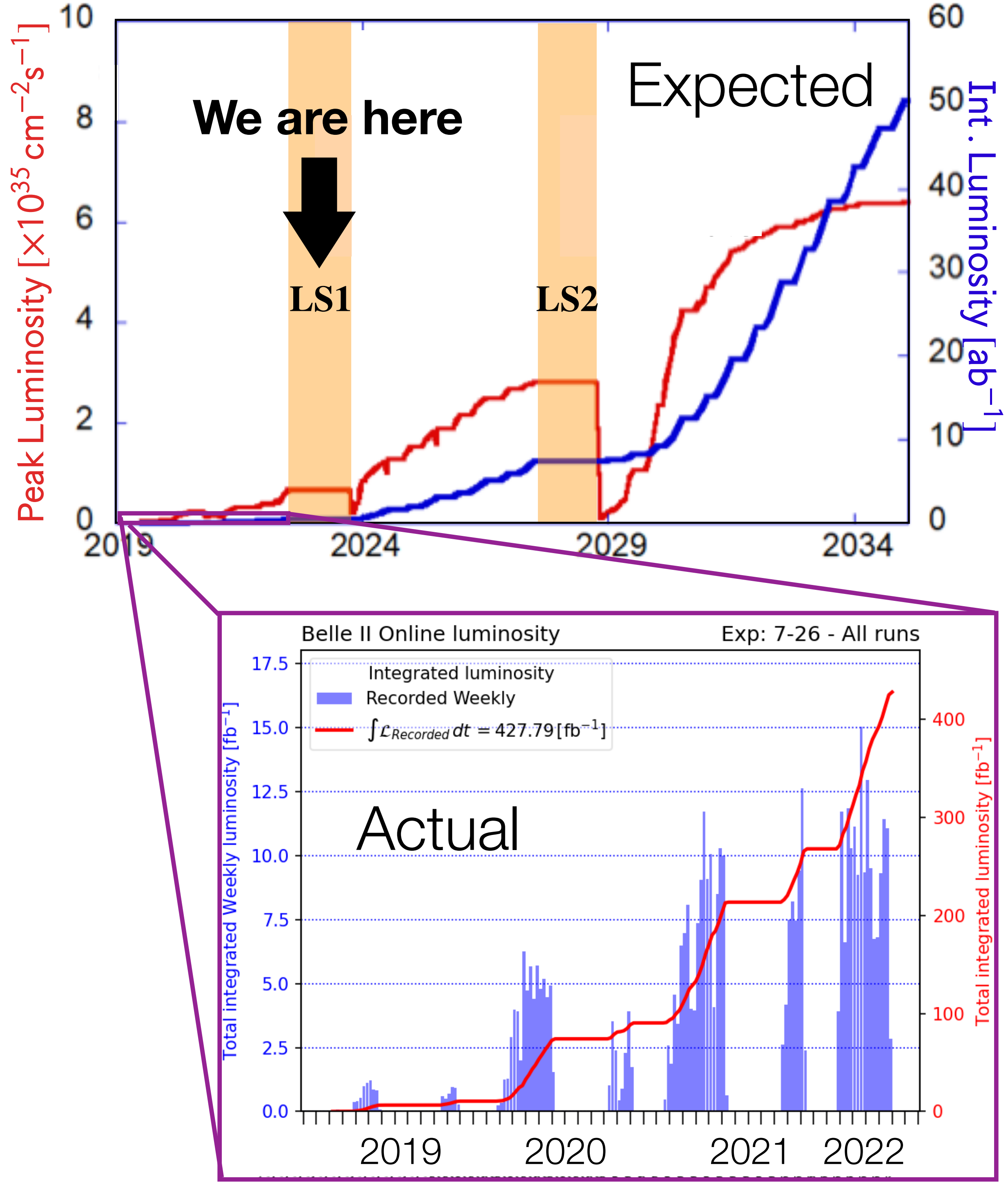
- World-best D^0, D^+, D_s^+ and Λ_c^+ lifetimes
- Confirmation of LHCb result indicating that the Ω_c^0 is not the shortest-lived weakly decaying charmed baryon
- Benchmark for decay-time-dependent measurements in bottom and charm
    - Tiny systematic uncertainties (*e.g.*, 0.2% for D^0) demonstrate excellent performance and understanding of the Belle II detector (*e.g.*, alignment). Never achieved at previous *B* factories

PRD 107 (2023) L031103



Conclusions and outlook

- Belle II has on tape a sample equivalent to that of BaBar, half of Belle
    - Better (and better understood) detector, refined analyses: already achieved competitive or world best results
    - More on the way: some are unique to us
- Will resume data-taking next Winter. Meanwhile we keep refining our tools to further boost the reach

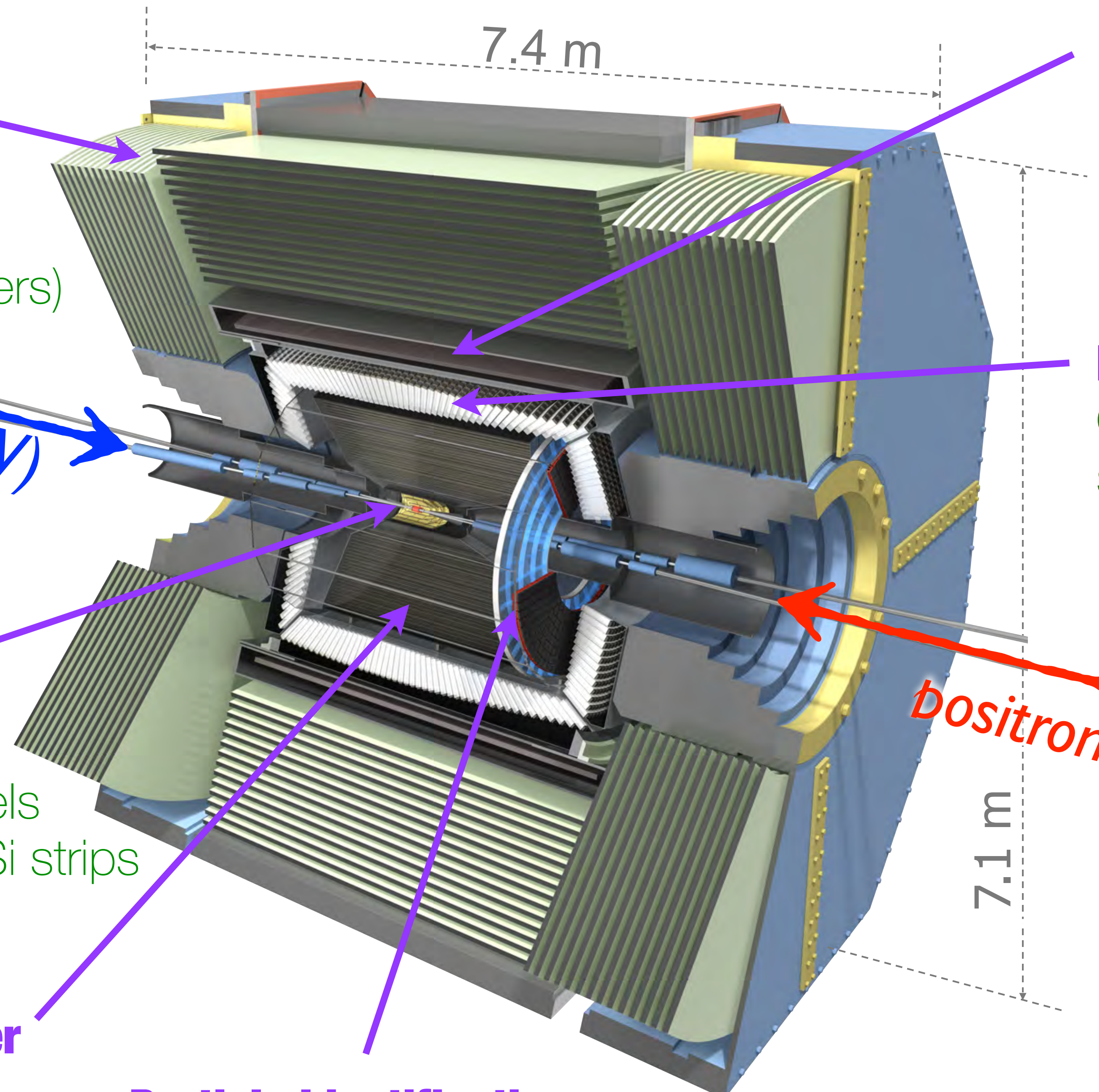


Backup slides

The Belle II detector

K_L & μ Detector
Resistive Plate Counter
(barrel outer layers),
Scintillator + WLSF + MPPC
(end-caps, inner 2 barrel layers)

SC solenoid
1.5 T B field



EM calorimeter
CsI(Tl), waveform
sampling electronics
(barrel+endcaps) and
precise timing

Vertex Detector
PXD: 2 layers DEPFET Si pixels
SVD: 4 layers double-sided Si strips

Central Drift Chamber
He(50%):C_2H_6(50%),
small cells, long lever
arm, fast electronics

Particle Identification
Time-of-Propagation counter (barrel),
Proximity focusing Aerogel Cherenkov Ring Imaging detector (forward)