Precision measurements of the D^0 and D^+ meson lifetimes with the Belle II detector

Soeren Prell

(Iowa State University)

CKM 2021

Melbourne (virtual)

November 22-26, 2021

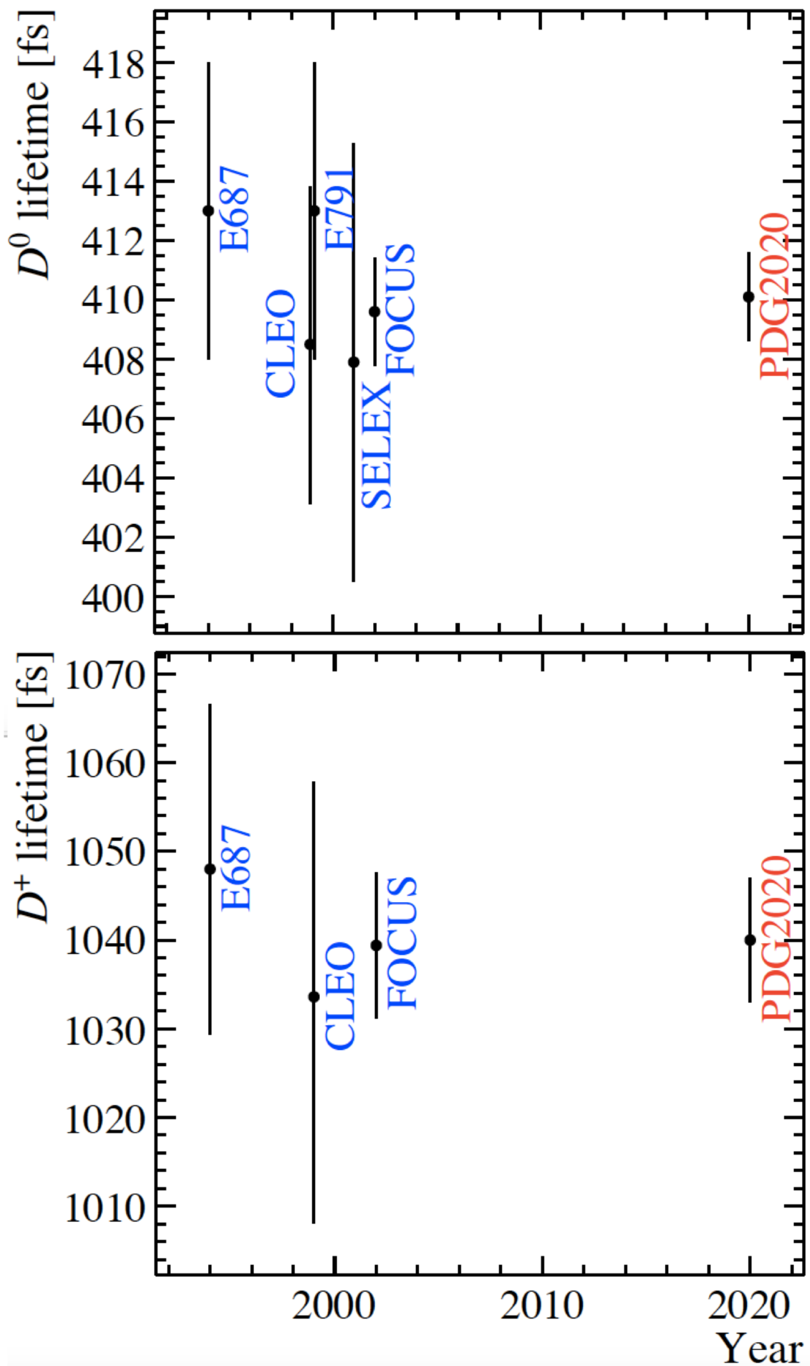
On behalf of the Belle II Collaboration

Outline

- *Introduction*
- *The Belle II experiment and SuperKEKB*
- *Measurement of the D^0 and D^+ meson lifetimes*
- *Summary and conclusions*

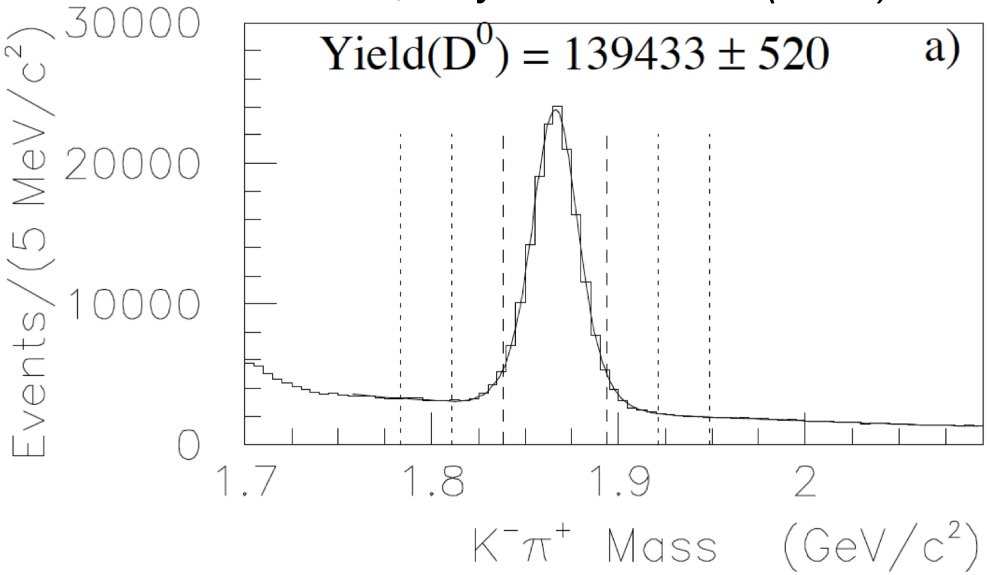
Brief overview of charm lifetimes …

- *World averages of D^0 and D^+ lifetimes are dominated by sub-1% precision measurements from photoproduction experiment FOCUS in 2001*
  - *Very different syst. uncertainties at e^+e^- collider (backgrounds, topology, etc.)*
  - *Only precision e^+e^- measurement from CLEO in 1999; no measurements at LEP, BABAR, or Belle*
- *Other charm hadron lifetimes ($D_s^+, \Lambda_c^+, \Xi_c^0, \Xi_c^+, \Omega_c^0$) are dominated by LHCb measurements … but*
  - *Measurements relative to D^+ lifetime*
- *D lifetimes could in principle be used to determine charm quark lifetime, but strong-interaction effects dominate ($\tau(D^+) \sim 2.5\times\tau(D^0)$)*
  - *Testing ground for non-perturbative QCD calculations*

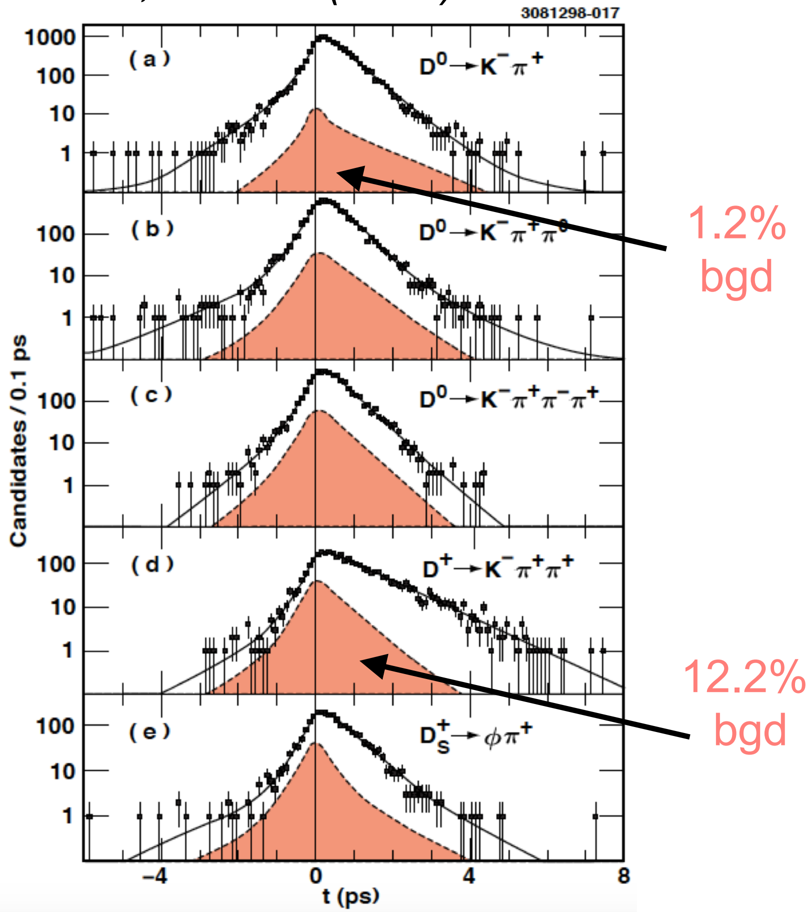


Best D lifetime measurements for last 20 years

FOCUS, Phys. Lett. B537 (2002) 192



CLEO, PRL 82 (1999) 4586

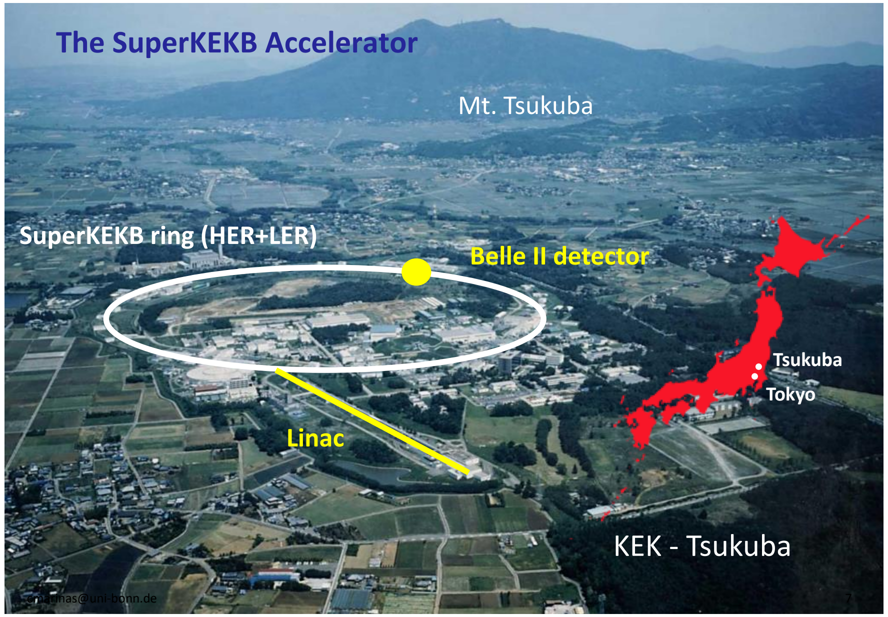


- ***Photoproduction***
  - $D^0 \to K^-\pi^+$ (139k), $K^-\pi^+\pi^-\pi^+$ (68k), $D^+ \to K^-\pi^+\pi^+$ (110k)
- *Dominant syst. uncertainties*
  - *Target absorption correction*
  - *Acceptance correction*

- $\boldsymbol{e^+e^- \to c\bar{c}}$
  - $D^0 \to K^-\pi^+$ (11k), $K^-\pi^+\pi^-\pi^+$ (6k), $K^-\pi^+\pi^0$ (9k), $D^+ \to K^-\pi^+\pi^+$ (4k)
- *Dominant syst. uncertainties*
  - *Alignment and vertexing*
  - *Backgrounds*
  - *MC statistics*

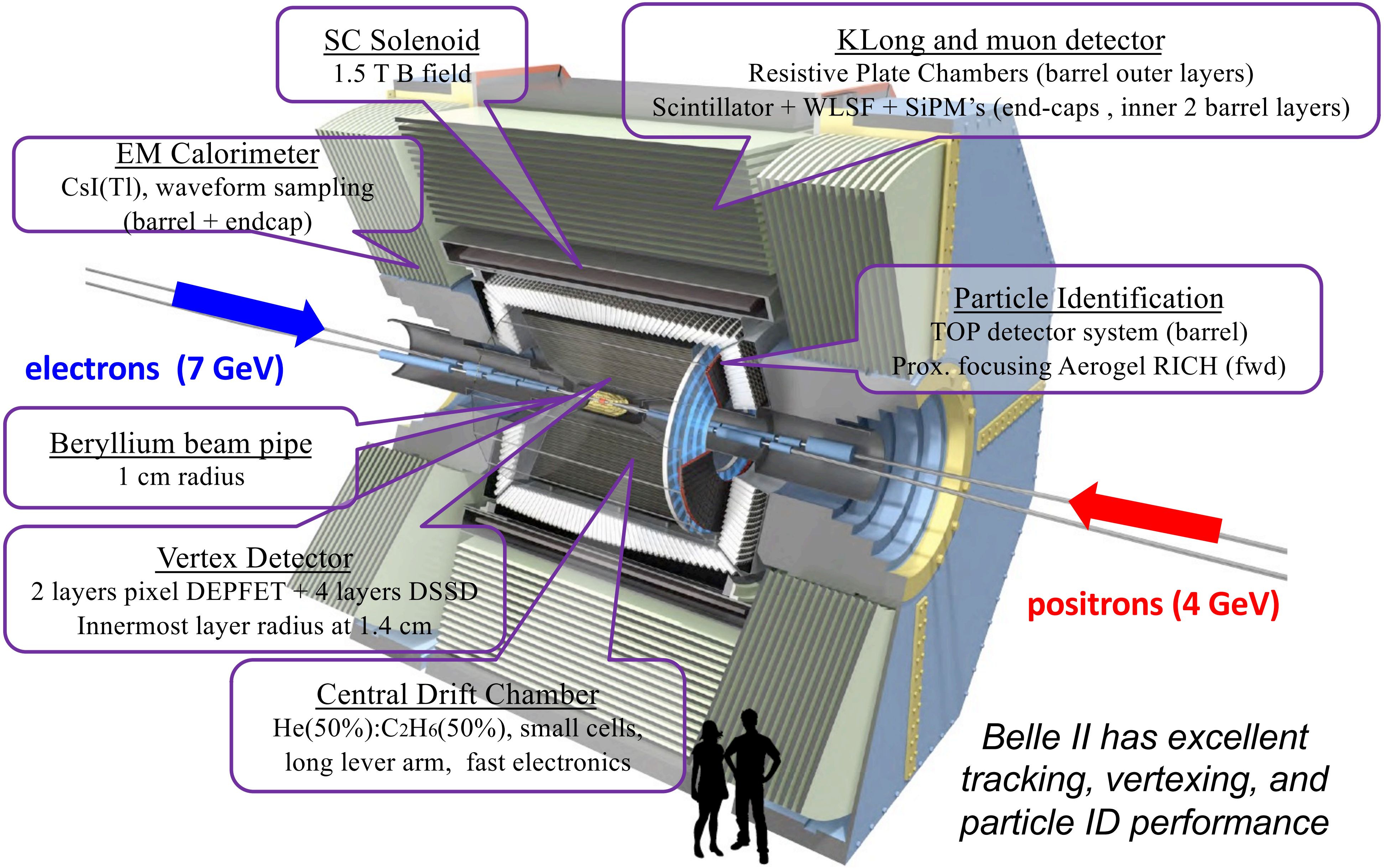
Belle II and SuperKEKB

- *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)*
    230 fb^{-1} (recorded)
- *Large $e^+e^- \to c\bar{c}$ cross-section (~40% of $e^+e^- \to q\bar{q}$ continuum cross-section) provide low-background event samples*
  - *1,300,000 $c\bar{c}$ events per 1 fb^{-1}*
  - *All $c\bar{c}$ bar events are recorded (~100% trigger efficiency)*



- *Need excellent detector performance and control of syst. uncertainties to exploit potential of full Belle II data sample*
  - *Precision D lifetime measurements will demonstrate vertexing performance and provide detailed understanding of syst. effects necessary for other time-dependent measurements (lifetimes/CP violation/mixing)*

Belle II Detector

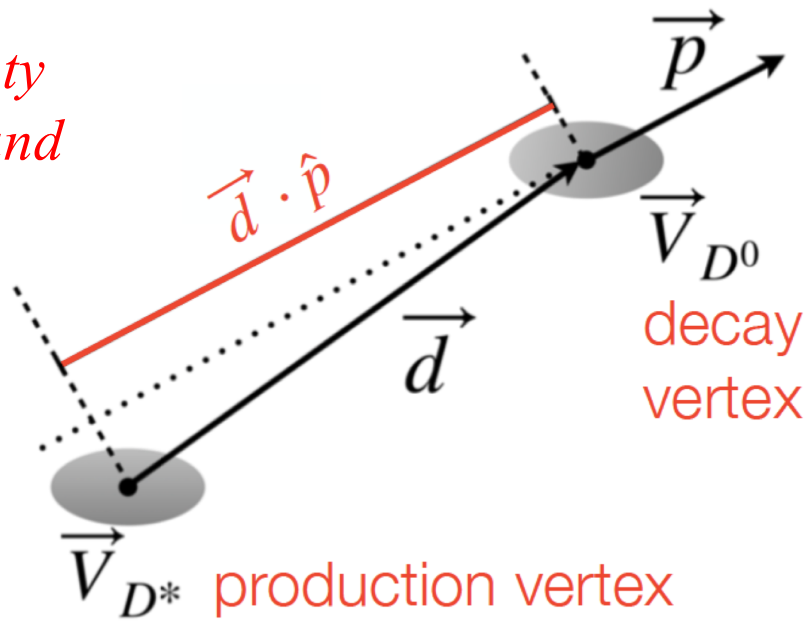


Belle II has excellent tracking, vertexing, and particle ID performance

The D lifetime measurement in a nut shell

- *Select high-purity, prompt D samples*
  - *reconstruct D^{*+}-tagged $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$*
  - *D^{*+} momentum requirement rejects candidates from B decays*
  - *PID suppresses fake kaon background*
- *Calculate D proper time t and uncertainty from D production and decay vertices, and D momentum p*

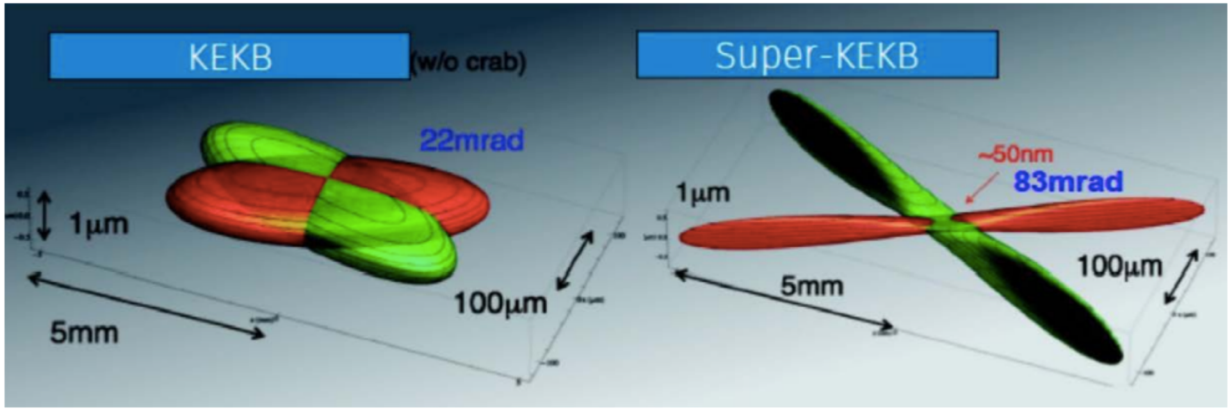
$$t = \frac{m_D}{p}\left(\vec{d} \cdot \hat{p}\right)$$



  - *Production vertex constrained to e^+e^- "nano" beam spot*
  - *Average decay distance is 200(500) μm for $D^0(D^+)$*
- *Extract D lifetime from fit to t and σ_t distributions*
  - *Signal and bgd pdf parameters are determined from data (no input from MC used)*

SuperKEKB's "nano beams"

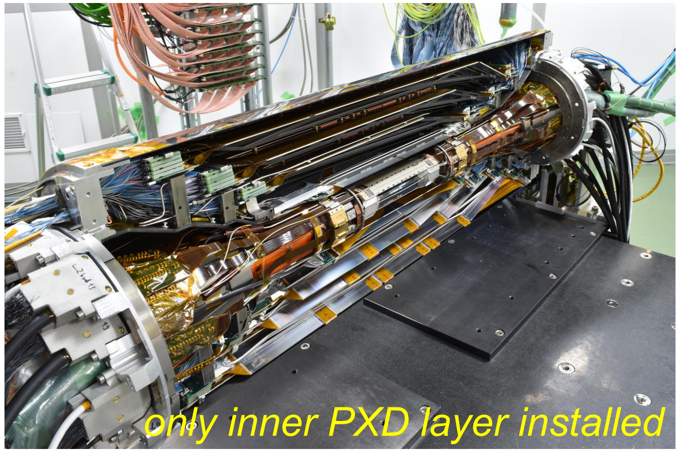
- *SuperKEKB requires much smaller interaction region than KEKB in order to reach design luminosity of $6\times10^{35}cm^{-2}s^{-1}$*
  - *Nano-beam concept (P. Raimondi) realized with super-conducting final focus quadrupoles already achieved world luminosity record at $3.12\times10^{34}cm^{-2}s^{-1}$*



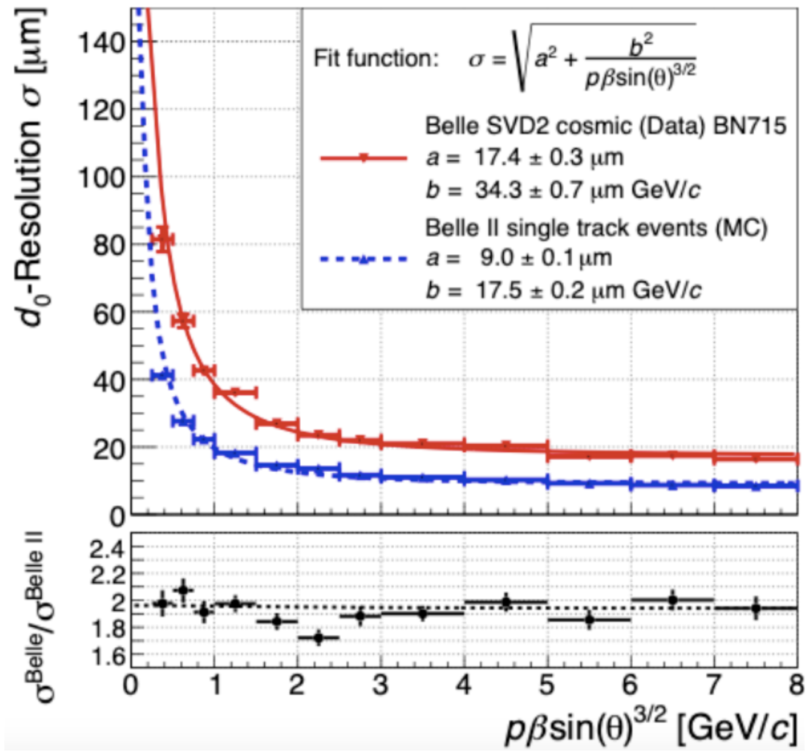
Luminous region dimensions at Belle II are 10/0.2/250 μm (x/y/z) compared to 100/1/6,000 μm at Belle

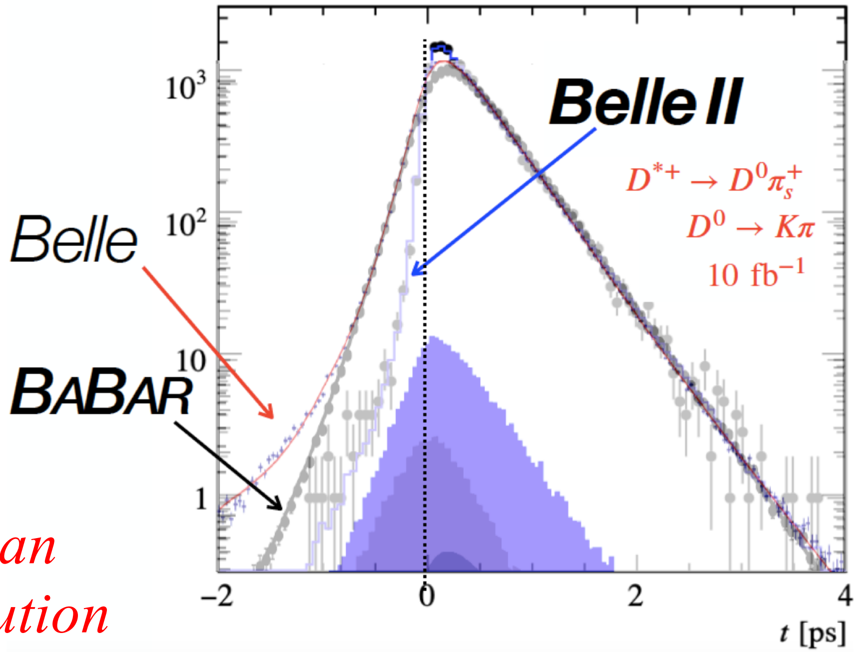
- *Belle II's small luminous region dimensions (in transverse plane)*
  - *Provide effective constraint on the D production vertex*
  - *Dominant uncertainty in the decay length from D decay vertex*
- *Beam spot position and size calibrated every ~1-2 h from di-μ events*
- *Ultimately, beam spot y size is expected to be decreased to ~60 nm*

A high-precision SVD



- 2-component SVD
  - 2-layer pixel detector (PXD)
  - 4-layer double-sided strip detector
- PXD
  - Innermost layer is only 1.4 cm from the IP (×2 closer than in Belle)
  - very low material thickness (0.1% X_0/layer for ⊥ tracks)
  - excellent hit position resolution
- ×2 better impact parameter resolution than Belle/BABAR shows in decay-time distribution

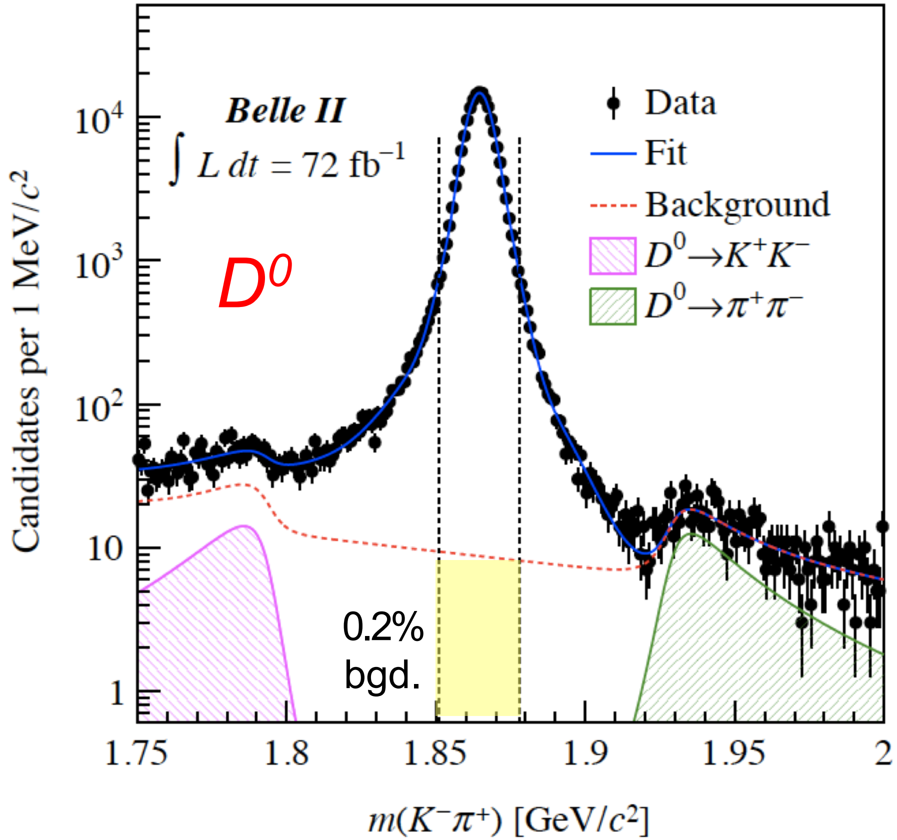




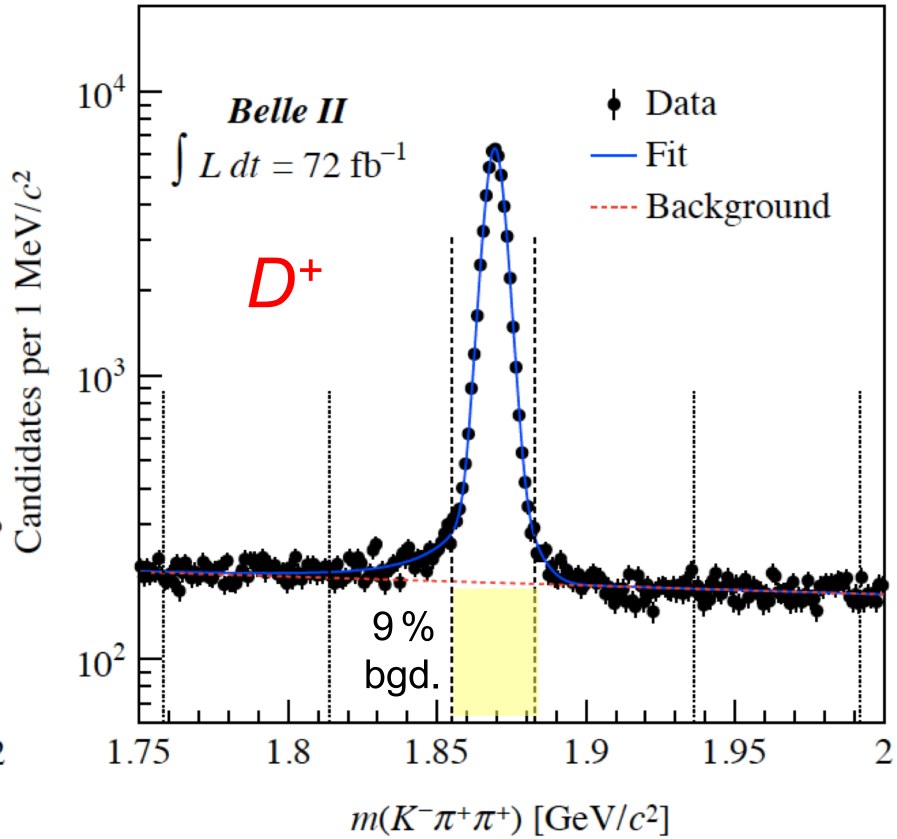
D signal samples

- *Large, clean samples limit background-related systematic uncertainties*
  - *Use only low track multiplicity, large BF decay modes*
  - *Removing D from B decays (originating from a secondary vertex) with $p(D^{*+}) > 2.5(2.6)$ GeV requirement avoids bias in $D^0(D^+)$ production vertex position*

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



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



Lifetime fit signal PDF

- *Lifetime determined with unbinned ML fit to distributions of proper time t and its uncertainty σ_t*

Exponential t distribution convolved with a resolution function R

Exponential true proper-time distribution

Binned template σ_t pdf from data

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

(Single/Double) Gaussian resolution function (for D^0/D^+) with mean b (bias) and width $s\,\sigma_t$ (scaled uncertainty)

- *Functional form validated with MC-simulated events*
  - *Bias b largely decorrelates pdf from potential detector misalignment*
- *This is the complete pdf for D^0 fit, the effect of 0.2% background fraction is accounted for as a systematic uncertainty*
- *In the D^+ fit, background is described by an additional term in the pdf*

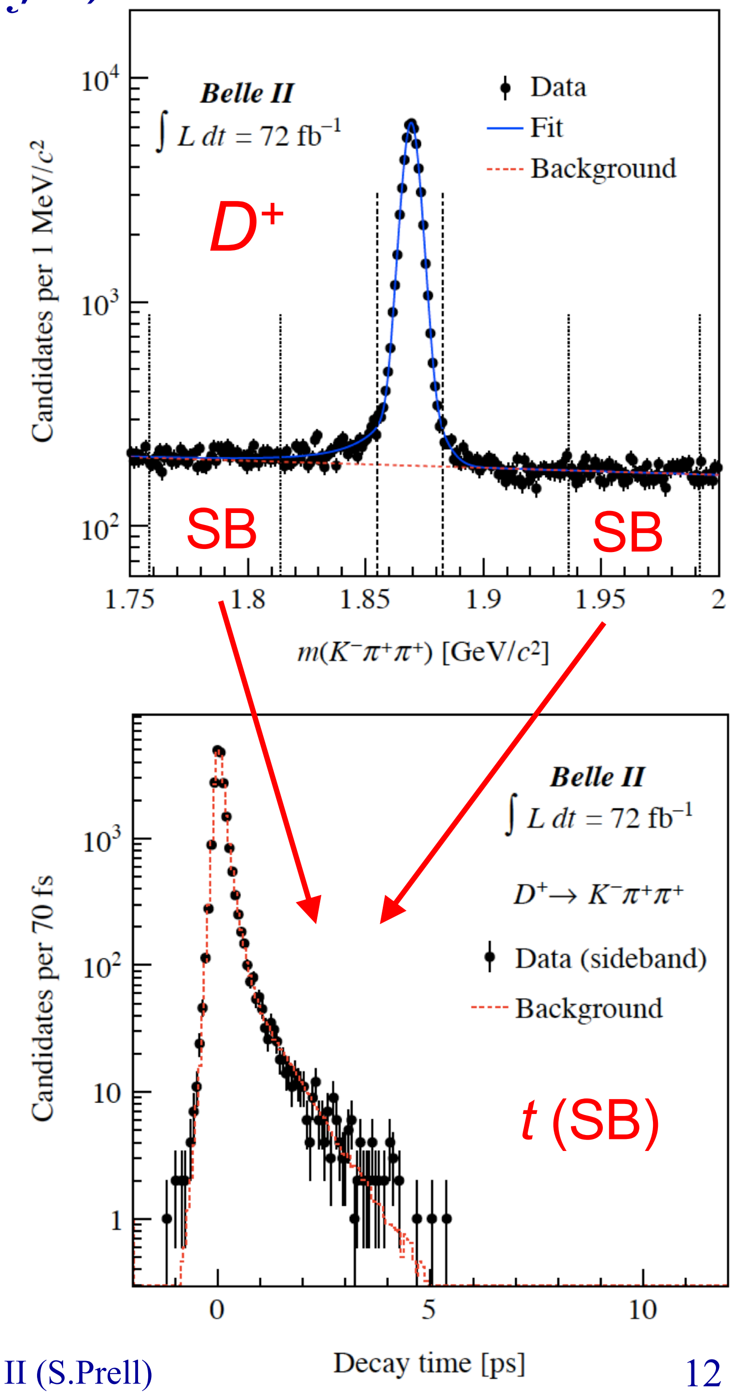
Background PDF (only for D^+ fit)

- *Total pdf is sum of signal and bgd terms*

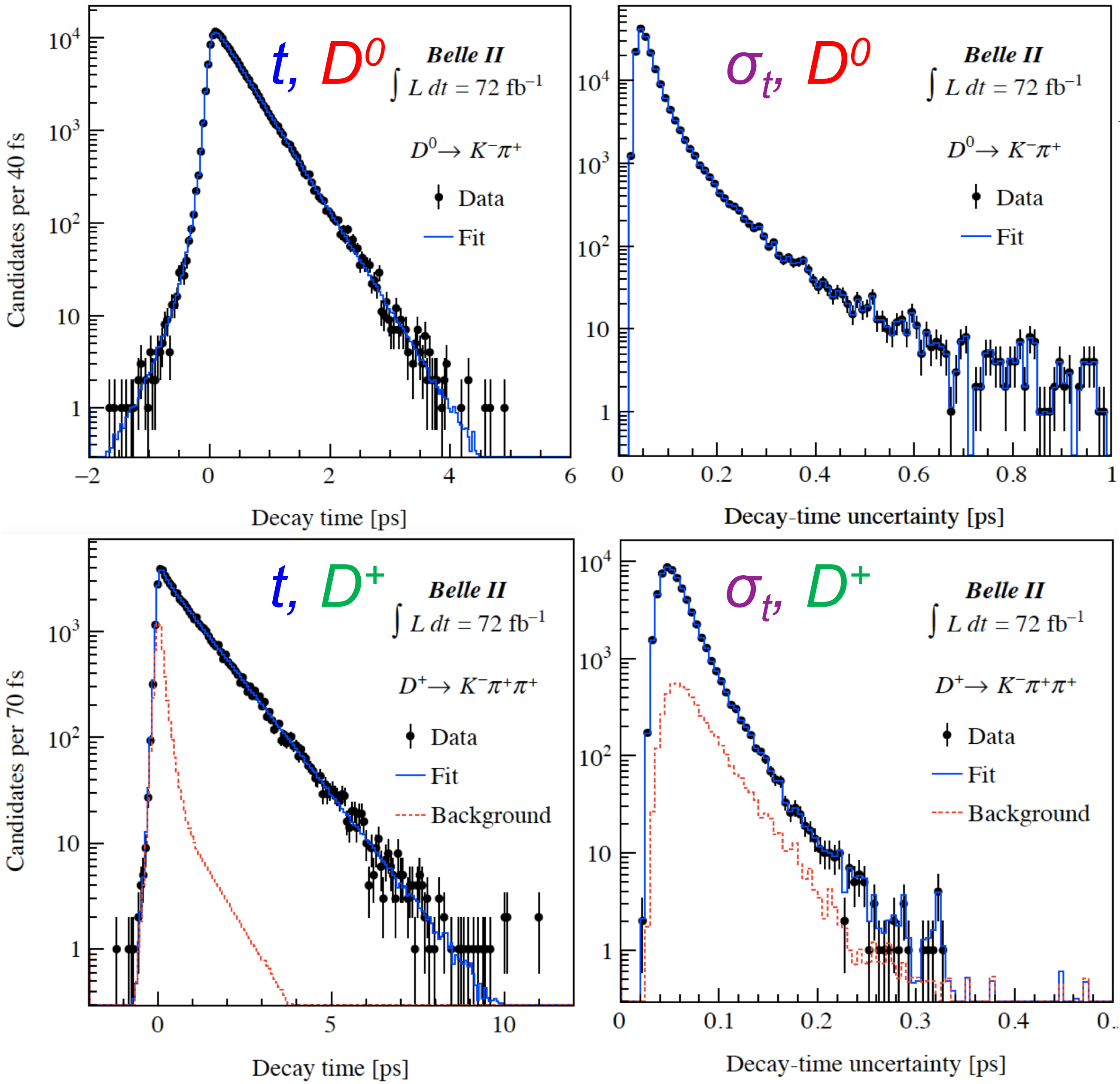
$$\text{pdf} = (1 - f_{\text{bgd}})\ \text{pdf}_{\text{signal}}(t, \sigma_t | \tau, b, s) + f_{\text{bgd}}\ \text{pdf}_{\text{bgd}}(t, \sigma_t | \tau_{b1}, \tau_{b2}, b_{\text{bgd}}, s)$$

$$\text{pdf}_{\text{bgd}}(t, \sigma_t | \tau_{b1}, \tau_{b2}, b_{\text{bgd}}, s) = \text{pdf}_{\text{bgd,t}}(t, \sigma_t | \tau_{b1}, \tau_{b2}, b_{\text{bgd}}, s)\ \text{pdf}_{\text{bgd},\sigma}(\sigma_t)$$

- *Background pdf (t and σ_t) determined from D^+ mass sidebands*
  - *Assume SB events are a good representation of bgd in signal region*
  - *Empirical bgd model with lifetime and prompt components*
- *Signal region and SBs fit simultaneously*
  - *All shape parameters are free*
  - *Bgd fraction fixed to D^+ mass fit value*



D lifetime fits – *unbinned ML fits to t and σ_t distributions*



Resolution function and bgd parameters determined from data

- *t resolution ~ 60-70 fs*
- *MC used for validation and syst. error estimation*

Blind analysis

- *selection, validation, crosschecks and assessment of systematic errors performed before unblinding*
- *except 2019 data (~13% of the sample) which was unblinded for ICHEP 2020*

Systematic uncertainties

- *Lifetime measurements are still statistically limited*
- *Dominant systematic error sources are vertex detector alignment and background*
  - *Background uncertainty dominated my data-MC agreement of t distribution in SBs*
  - *Alignment uncertainty estimated from measuring lifetimes in various mis-aligned MC samples*

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
Statistical error	1.1	4.7

Dominant systematic uncertainties can be reduced in future measurements

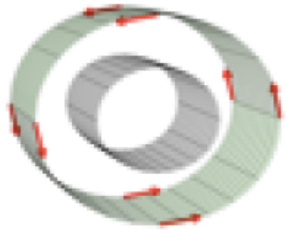
- *Decrease background in signal regions and add a D^0 bgd pdf*
- *Improved alignment algorithm (already employed for most recent data)*

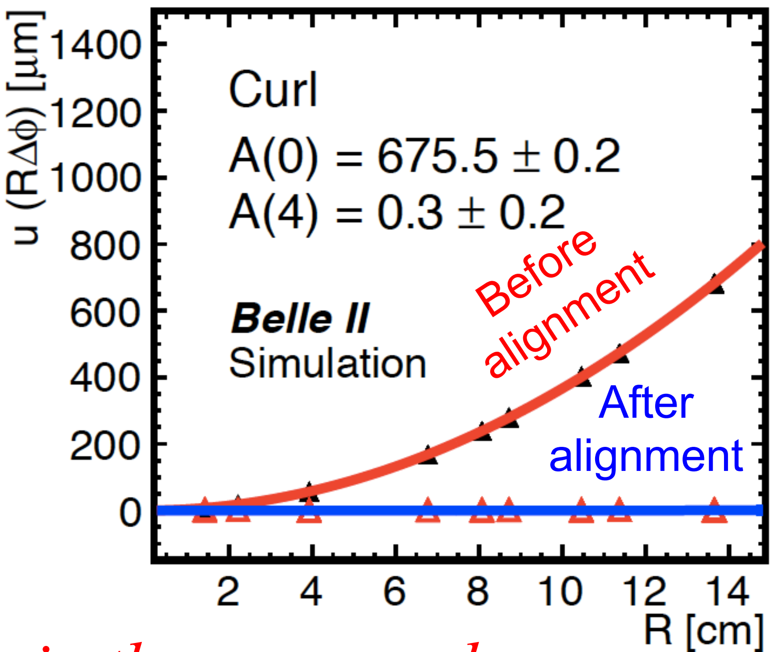
(Mis) alignment uncertainties

- *2 sources of systematic uncertainties due to misalignment*
  - ***Stat. uncertainty** in alignment constants from limited alignment sample size is estimated from day-to-day variations between alignments in data*
  - ***Syst. uncertainty** in alignment constants from residual misalignments not corrected for by the alignment algorithm (9 different weak-mode deformations: radial/longitudinal expansion, telescope, curl, …) is estimated from MC simulation of a misaligned detector*

Curl

$$r\Delta\phi = c_{scale} \cdot r + c_0$$





- *For each source the largest variation in the measured lifetimes is taken as the corresponding syst. uncertainty*

Cross-checks

- Fully-simulated events & Toy MC
- Comparison of fitted lifetimes in data subsamples
  - 6 different data taking periods
  - 10 bins of polar angle $\cos\theta$
  - 10 bins of azimuthal angle φ
  - 10 bins of D momentum
  - On vs. off $\Upsilon(4S)$ data
  - All lifetime variations are compatible with statistical fluctuations
- Also measured D^0 lifetime with D^*-tagged $D^0 \to K^-\pi^+\pi^-\pi^+$ decays (using the same technique as for $D^0 \to K^-\pi^+$)
  - 146k signal events, 0.8% bkg in the signal region
  - different kinematics, different resolution model
  - similar precision as in $D^0 \to K^-\pi^+$, channel
  - $D^0 \to K^-\pi^+\pi^-\pi^+$ and $D^0 \to K^-\pi^+$ blind results agree within 0.8 σ (stat. only)

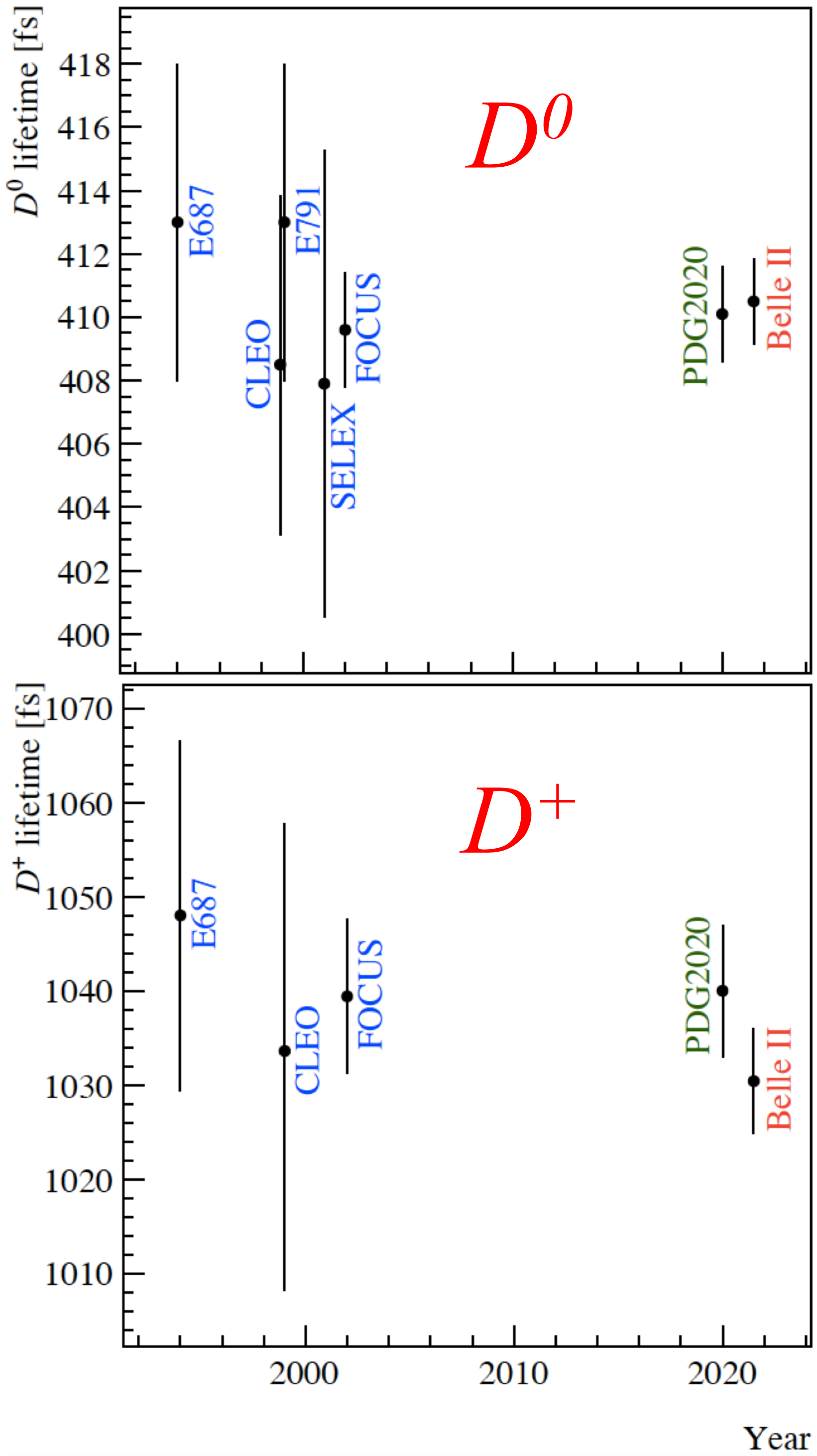
Results

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

$$\tau(D^+)/\tau(D^+) = 2.510 \ \pm 0.015$$
(accounted for correlated systematic uncertainties)

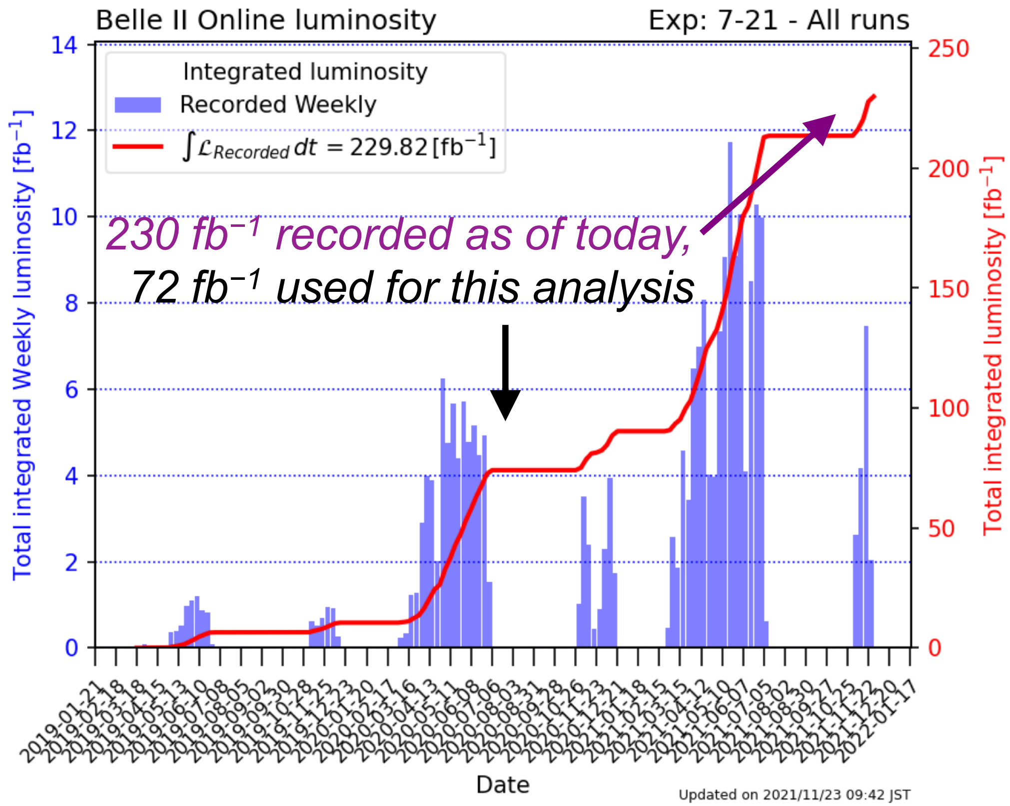
- *Measurements consistent with world averages, and more precise*
- *Few ‰ systematic uncertainties (2‰ and 3‰ for D^0 and D^+, resp.) demonstrate excellent performance and understanding of the Belle II detector*
- *Paper just published in PRL !*

Phys. Rev. Lett. 127, 211801 (2021)



Conclusions & Outlook

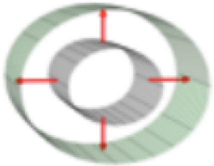
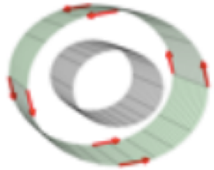
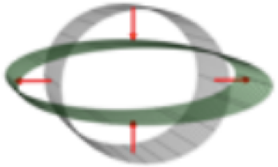
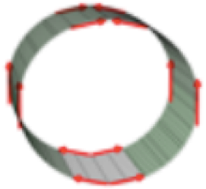
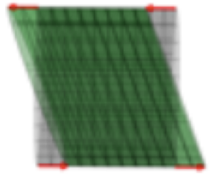
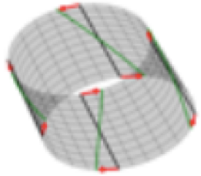
- *Belle II has measured the world's most precise D^0 and D^+ lifetimes at an e^+e^- collider with 2-3‰ accuracy*
  - *Different systematic uncertainties than in previous best measurement*
- *Excellent understanding of Belle II's vertexing capabilities will allow many more precision time-dependent measurements*
  - *E.g. neutral D and B CP violation and mixing*



Belle II has just started its physics program:
Expect a factor 750 more data over the next decade !

Bonus Slides

Weak modes of vertex detector misalignment

	Δr	$r\Delta\phi$	Δz
r	**Radial expansion** $\Delta r = c_{scale} \cdot r$ 	**Curl** $r\Delta\phi = c_{scale} \cdot r + c_0$ 	**Telescope** $\Delta z = c_{scale} \cdot r$ 
ϕ	**Elliptical expansion** $\Delta r = c_{scale} \cdot \cos(2\phi) \cdot r$ 	**Clamshell** $\Delta\phi = c_{scale} \cdot \cos(\phi)$ 	**Skew** $\Delta z = c_{scale} \cdot \cos(\phi)$ 
z	**Bowing** $\Delta r = c_{scale} \cdot \lvert z \rvert$ 	**Twist** $r\Delta\phi = c_{scale} \cdot z$ 	**Z expansion** $\Delta z = c_{scale} \cdot z$