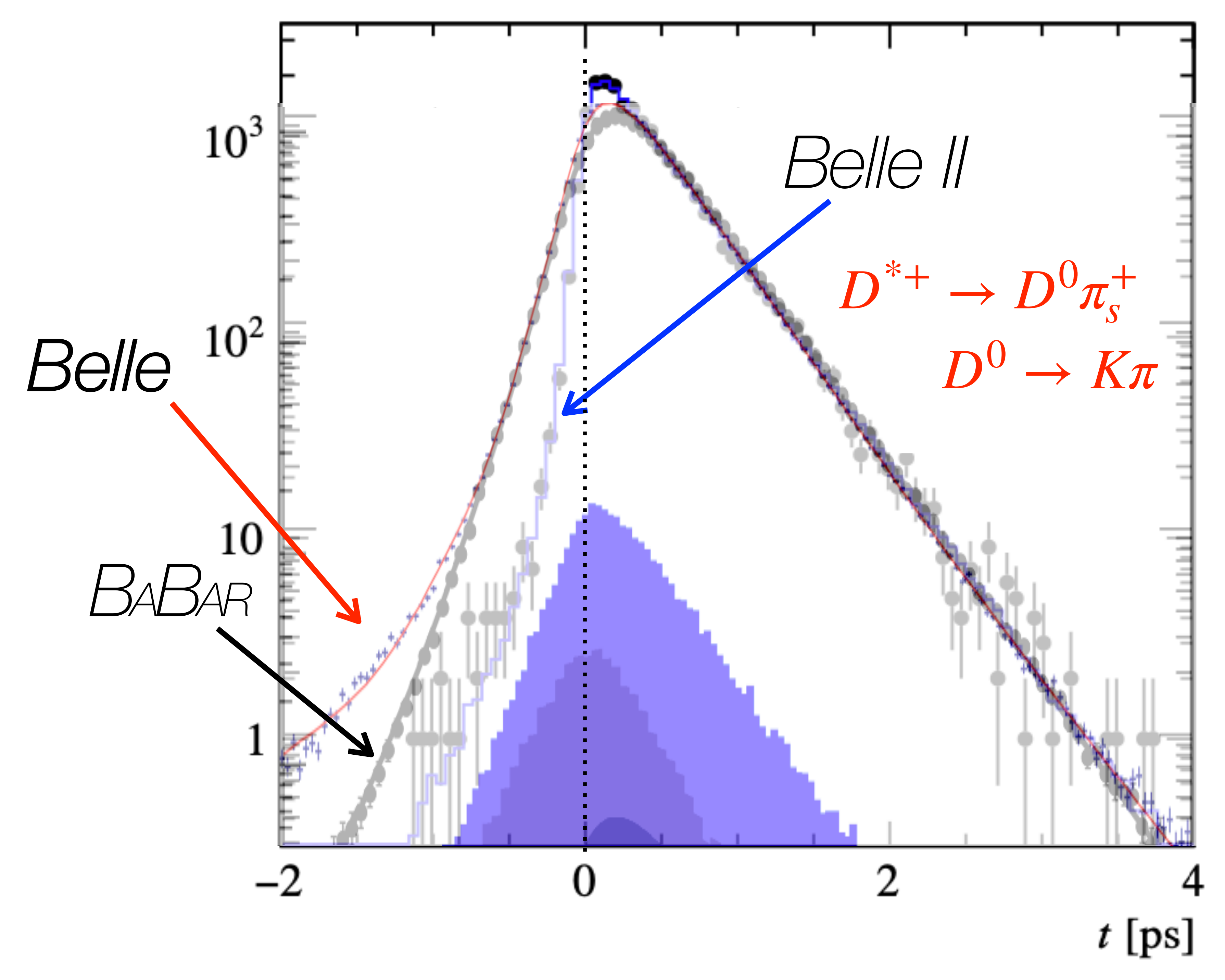
XV International Conference on Heavy Quarks and Leptons, Warwick/online

D meson lifetimes at *Belle II*

HOT TOPIC



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on behalf of the *Belle II* Collaboration

September 13th, 2021

Outline

- *Introduction*
- *Belle II at the High-Luminosity B-Factory SuperKEKB*
- *Measurement of the D^0 and D^+ Lifetimes*
- *Conclusions*

D^0 and D^+ Lifetimes

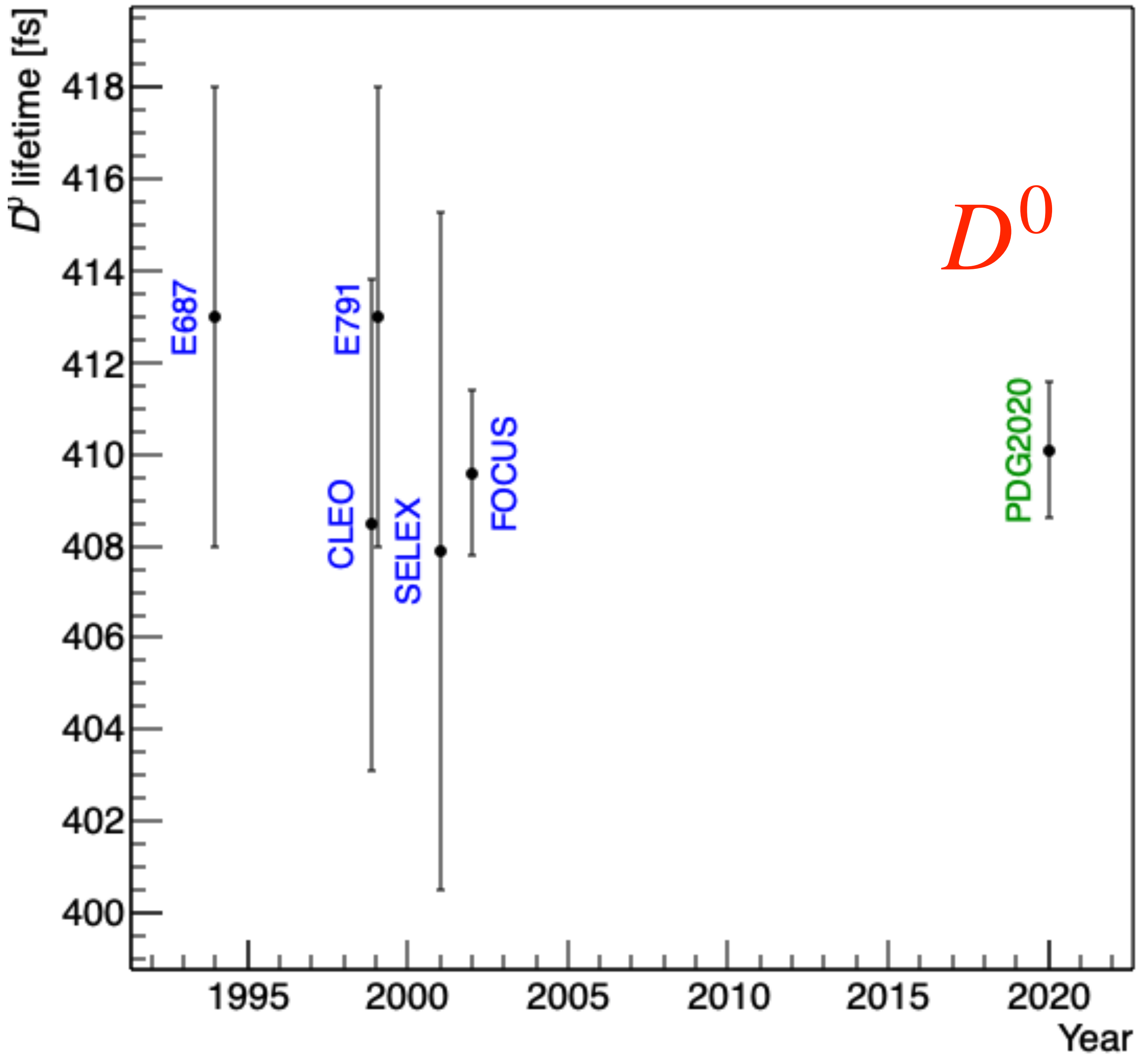
a brief picture

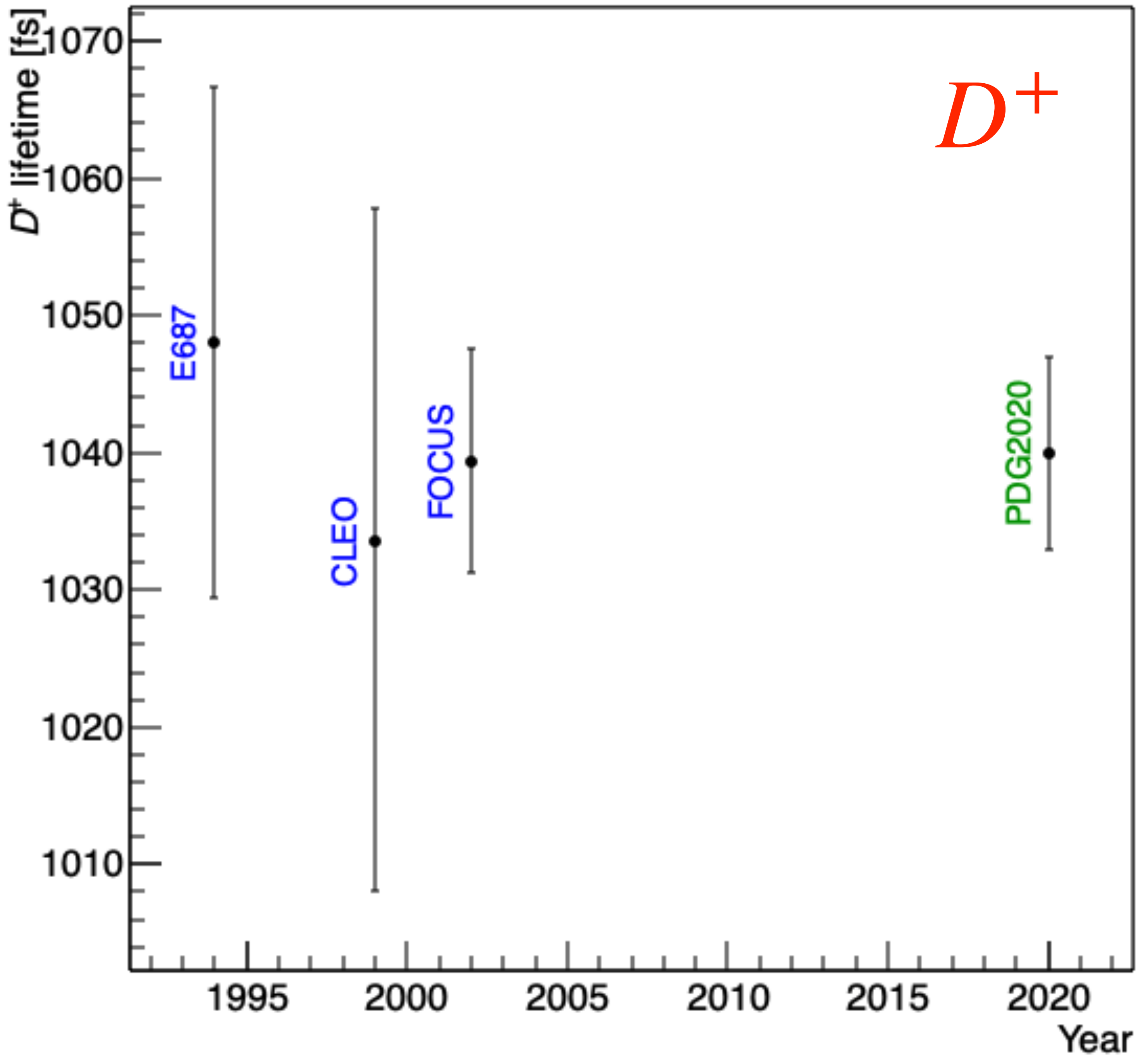
➡ Measured for the first time with ~sub-% precision by FOCUS around 20 years ago arXiv:hep-ex/0203037

➡ No measurements from 1st generation B-Factories Belle and *BaBar*, nor LHCb

- no measurement of charm hadron lifetimes at Belle and *BaBar*
- LHCb uses D^+ lifetime as reference for their charm lifetime measurements

➡ Lifetimes measurements test non-perturbative QCD and provide guidance to describe strong interactions arXiv:1405.3601



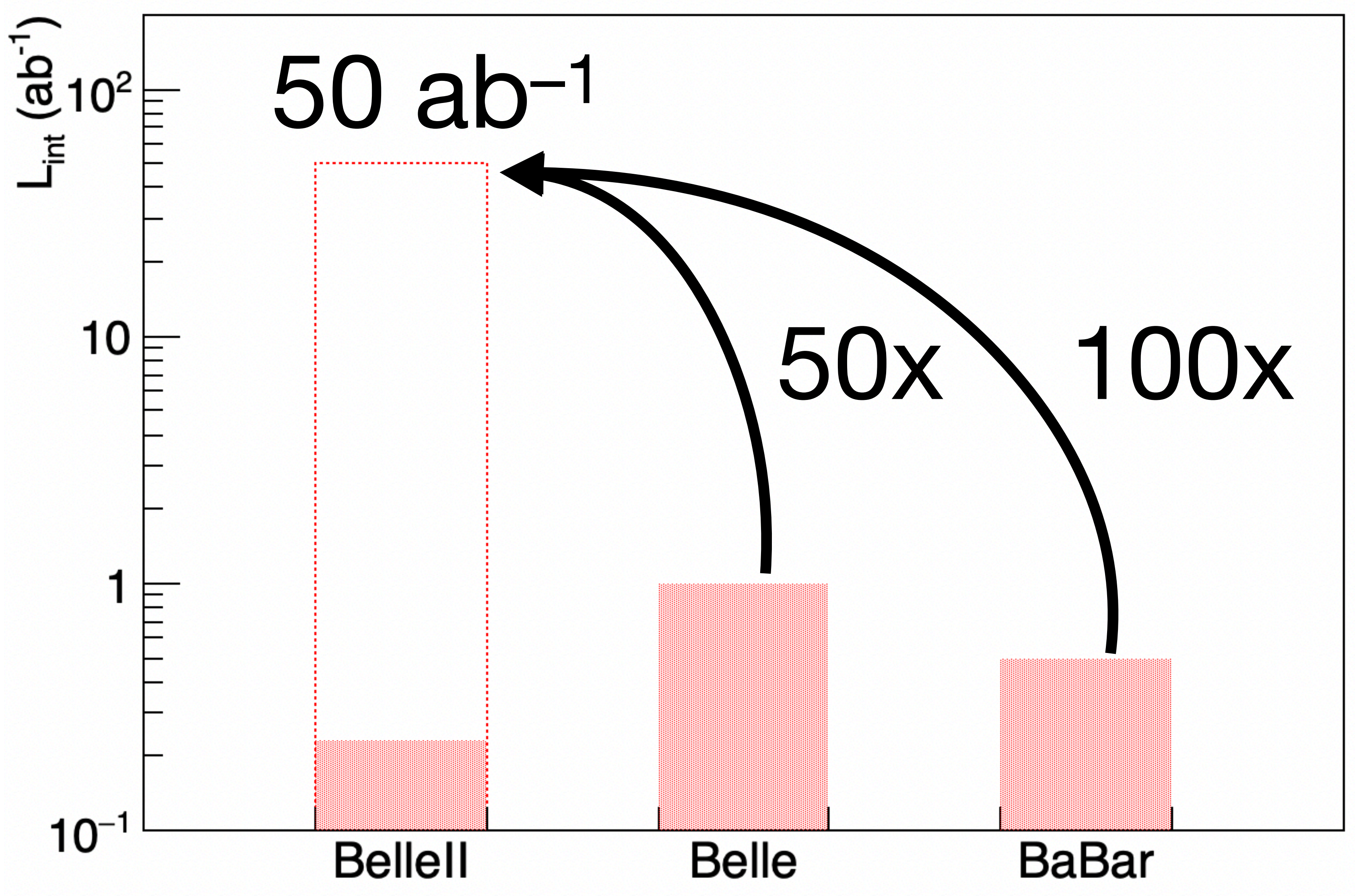


D^0 and D^+ Lifetimes at Belle II

motivation

- ➡ Belle II is a multi-purpose detector installed at the high-luminosity B-Factory SuperKEKB
  - target instantaneous luminosity 30x KEKB/Belle (6×10^{35} $cm^{-2}s^{-1}$)
  - to fully exploit the target 50 ab^{-1}, resolutions must be comparable or better than Belle & systematics under control
- ➡ Data taking started in 2019, collected roughly ~210 fb^{-1}
  - first data crucial to check performance!

INTEGRATED LUMINOSITY



- ➡ D^0 and D^+ lifetime measurements to prove the excellent **vertexing performance** and an achieve an in-depth **understanding of systematic effects** for the **future time-dependent analyses** (CPV/mixing)

Belle II

@ SuperKEKB
High-Luminosity B-Factory

- 2^{nd} generation **asymmetric** e^+e^- collider at the Υ(4S) mass energy
- $\beta\gamma = 0.28$ (0.5x PEP2/*BABAR*, 0.67x KEKB/Belle) enhances the displacements between the B and $\bar{B}$ decay vertices
- 90% solid angle coverage
- excellent vertexing & neutrals reconstruction

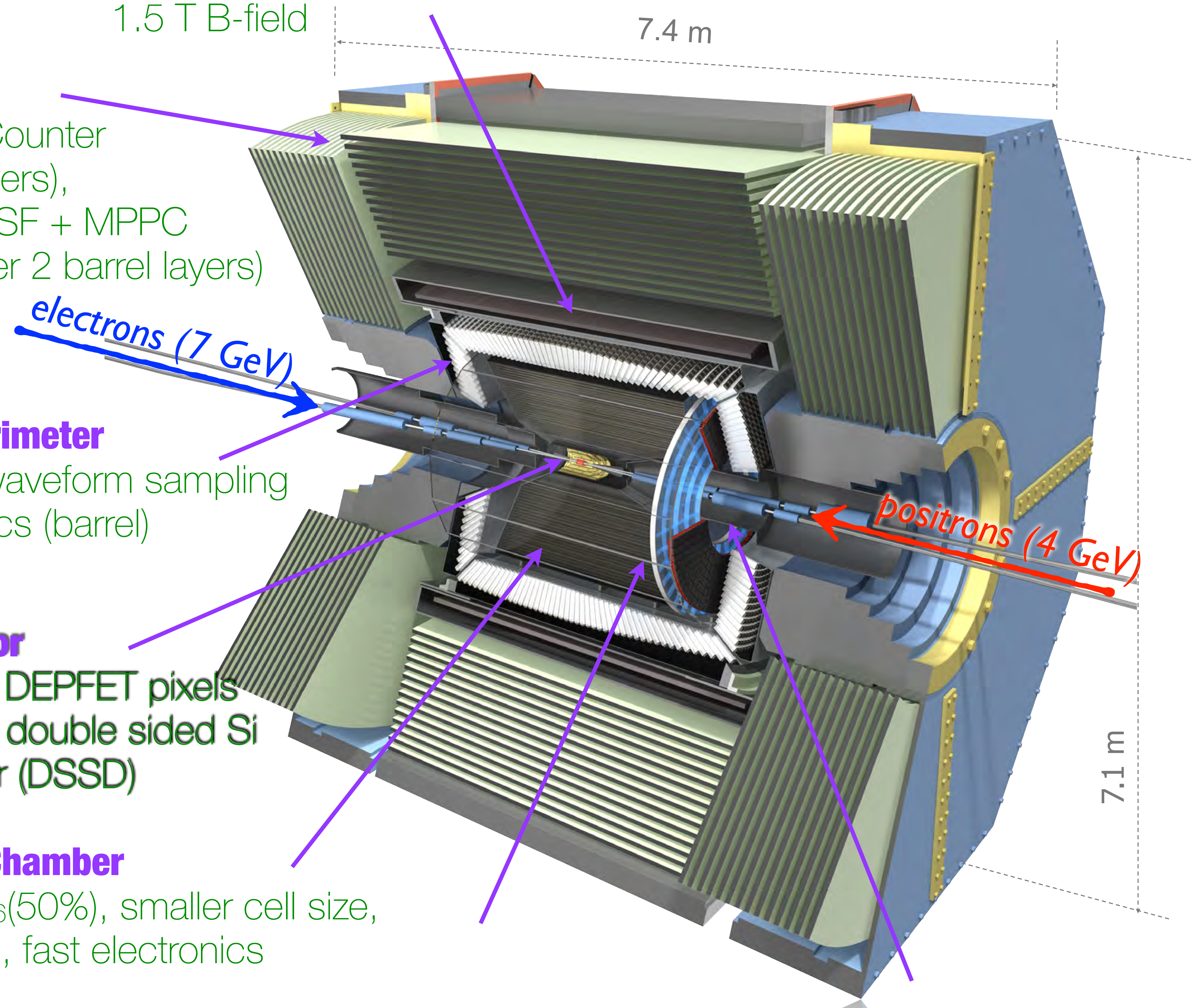
Super-Conducting Solenoid
1.5 T B-field

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

EM Calorimeter
CsI(Tl), waveform sampling
electronics (barrel)

Vertex Detector
PXD: 2 layers DEPFET pixels
SVD: 4 layers double sided Si
strips detector (DSSD)

Central Drift Chamber
He(50%):C_2H_6(50%), smaller cell size,
long lever arm, fast electronics



Trigger
hardware < 30 kHz
software < 10 kHz

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

Final Focus System
set of superconducting
magnets very close to the IP

Belle II TDR

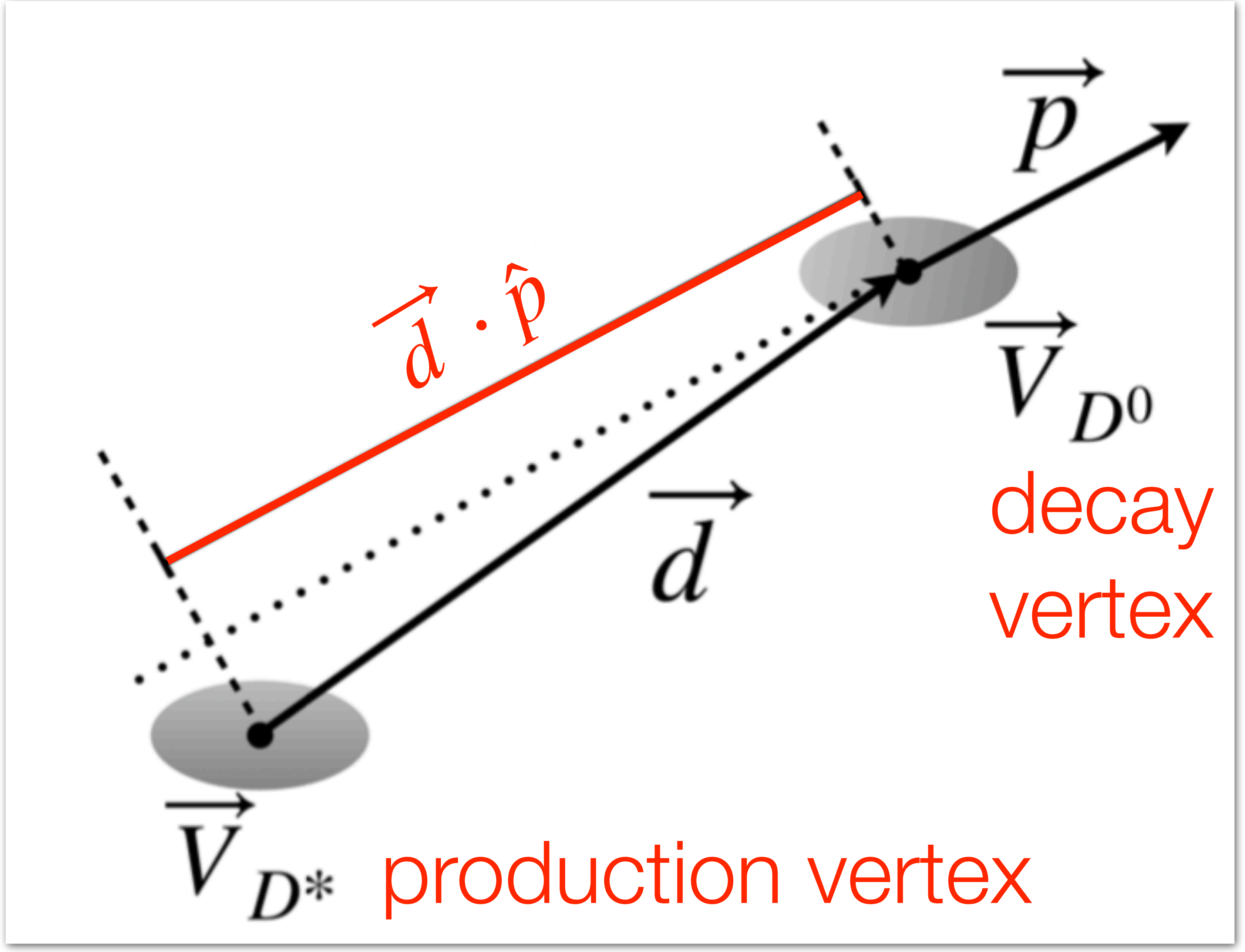
How to Measure the Lifetime

use $e^+e^- \to c\bar{c} \to D^* X$ events

- ➡ Select high-purity signal candidates in D^*-tagged $D^0 \to K\pi$ and $D^+ \to K\pi\pi$
  - avoid selection criteria that bias the D proper time
- ➡ Compute the D proper time t and its uncertainty σ_t from the reconstructed D production and decay vertices and its momentum $\vec{p}$:

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

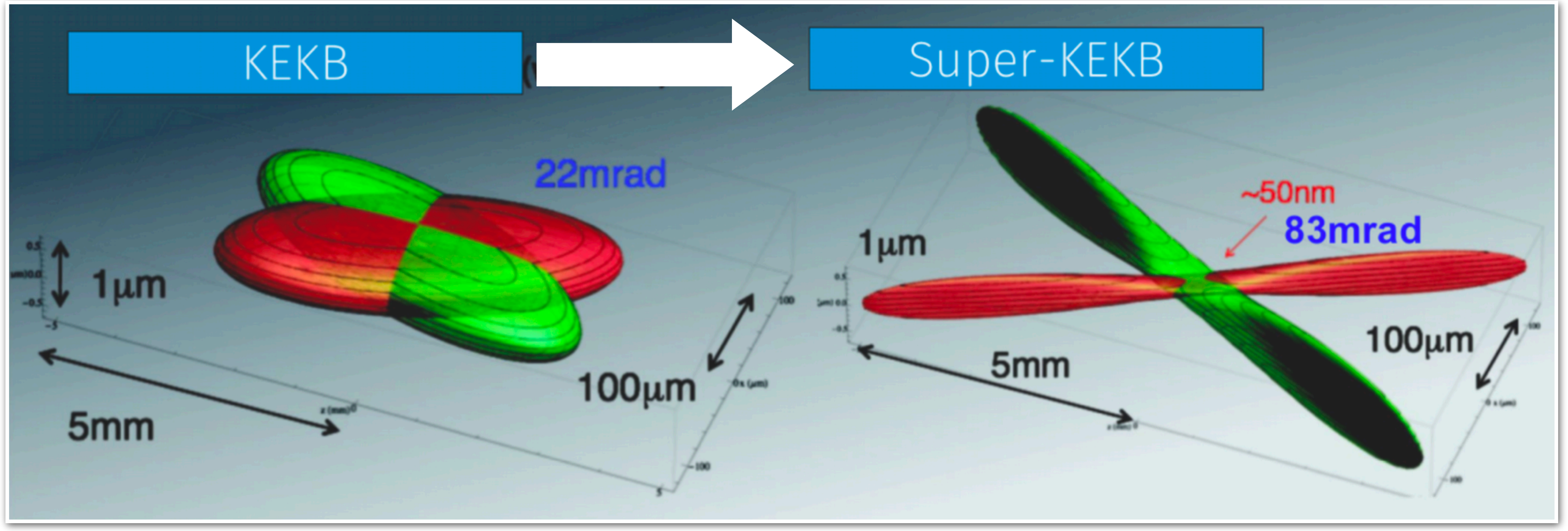
  - production vertex lies inside the e^+e^- interaction region
  - decay vertex is displaced on average by ~200/500 μm for the D^0/D^+
- ➡ Extract the lifetime with a fit to the (t, σ_t) distribution
  - signal & bkg PDFs extracted from data, no input from simulation



Highlight from SuperKEKB

size of the e^+e^- interaction region

- ➡ SuperKEKB implements the "**nano-beam**" scheme (P. Raimondi), needed to reach the target instantaneous luminosity of $6\text{x}10^{35}$ $cm^{-2}s^{-1}$
  - squeeze beams at the interaction point with a set of final focus superconductive magnets
  - typical e^+e^- interaction region sizes (x/y): 10/0.2 μm at *Belle II* vs 100/1 μm at Belle!

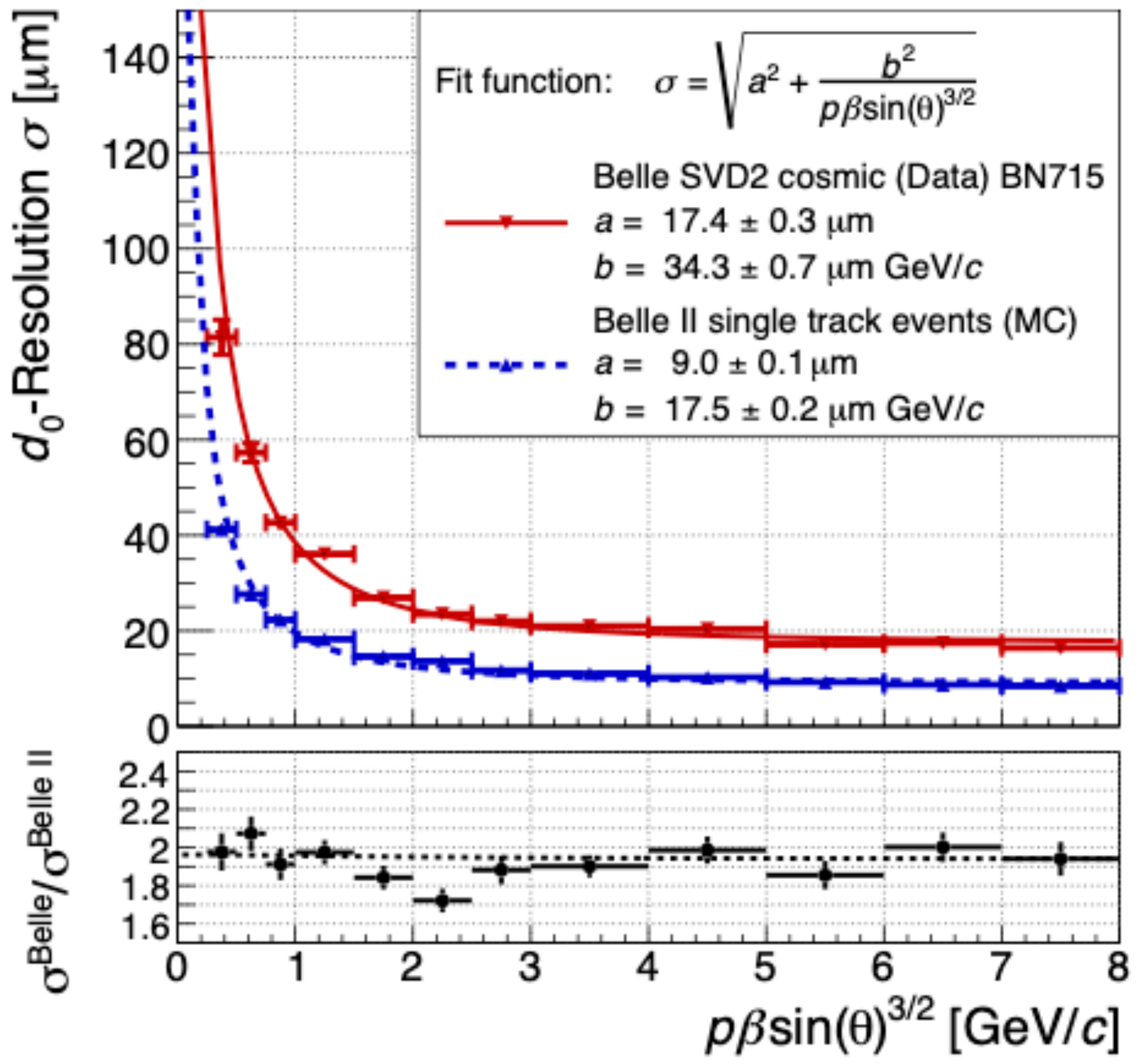


- ➡ Extremely small size of the e^+e^- interaction region allows to apply a **powerful *constraint* on the D production vertex position**
  - periodic track-based calibrations of the position and size of the e^+ e^- interaction region using di-muon samples
- ➡ Will further squeeze the vertical size to increase the luminosity, down to ~ 60 nm

Highlight from Belle II

Verte**X** **D**etector

- ➡ Vertex Detector is composed by
  - 2-layer all-silicon pixel detector (PXD)
  - 4-layer double-sided silicon strip detector (SVD)
- ➡ Innermost PXD layer is only 1.4 cm from the IP (factor 2 nearer than Belle), with very low material budget (0.1% X_0/layer for ⊥ tracks) & excellent hit position resolution
- ➡ Factor 2 improvement in the impact parameter determination wrt Belle and *BABAR*
  - the factor 2 improvement shows up directly in the D proper time resolution (next slide)



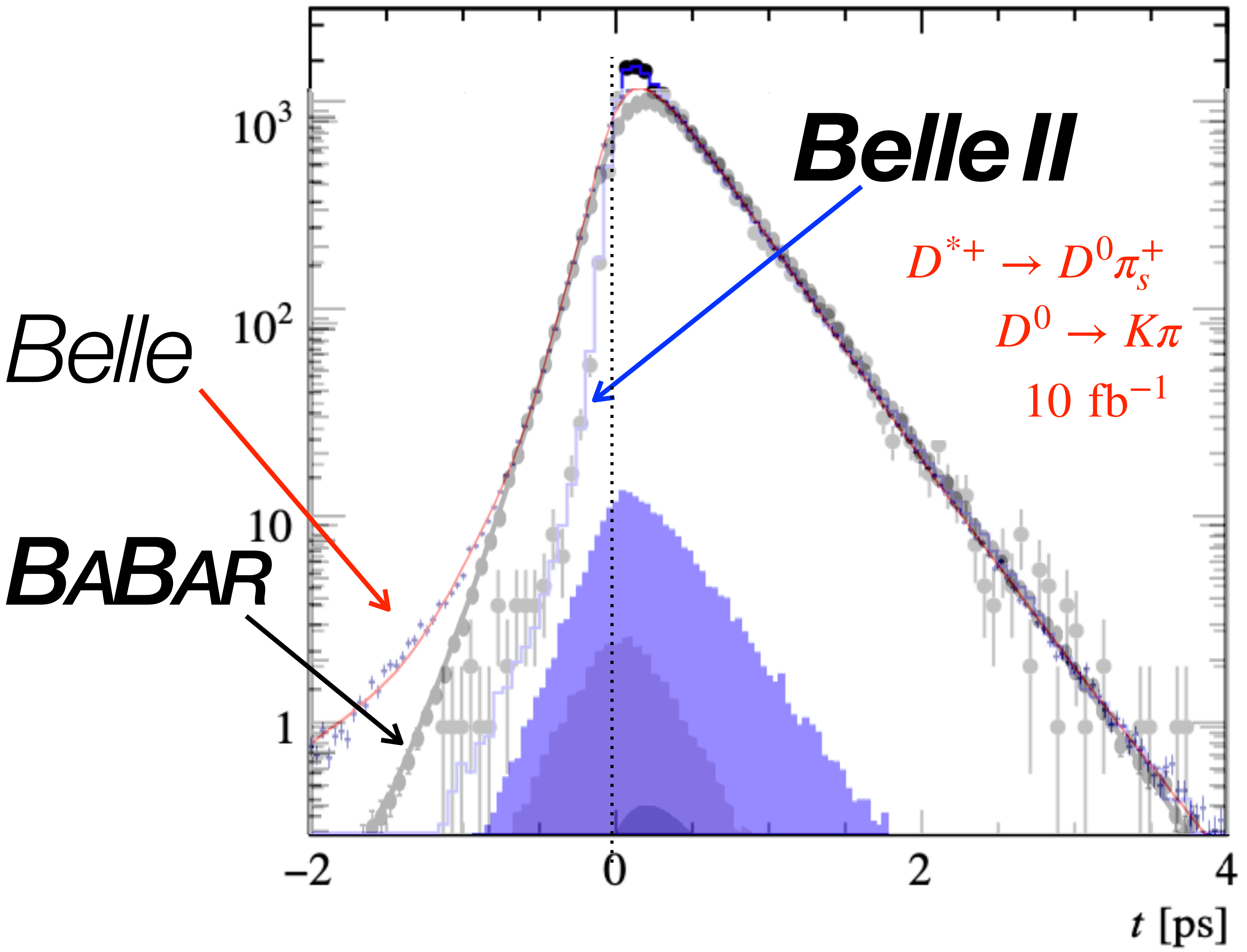
Improved Proper Time Resolution

impact on time-dependent measurements

- ➡ Proper time resolution at *Belle II* is a factor 2 better than *Belle* & BABAR
  - *Belle II* will improve the precision on observables extracted in time-dependent measurements, beyond the increase of luminosity, thanks to the improved resolution
  - there are ongoing studies to quantify the impact on the charm time-dependent measurements (including Dalitz analyses)

Belle II Physics Book

- resolution improvement visible at $t < 0$:



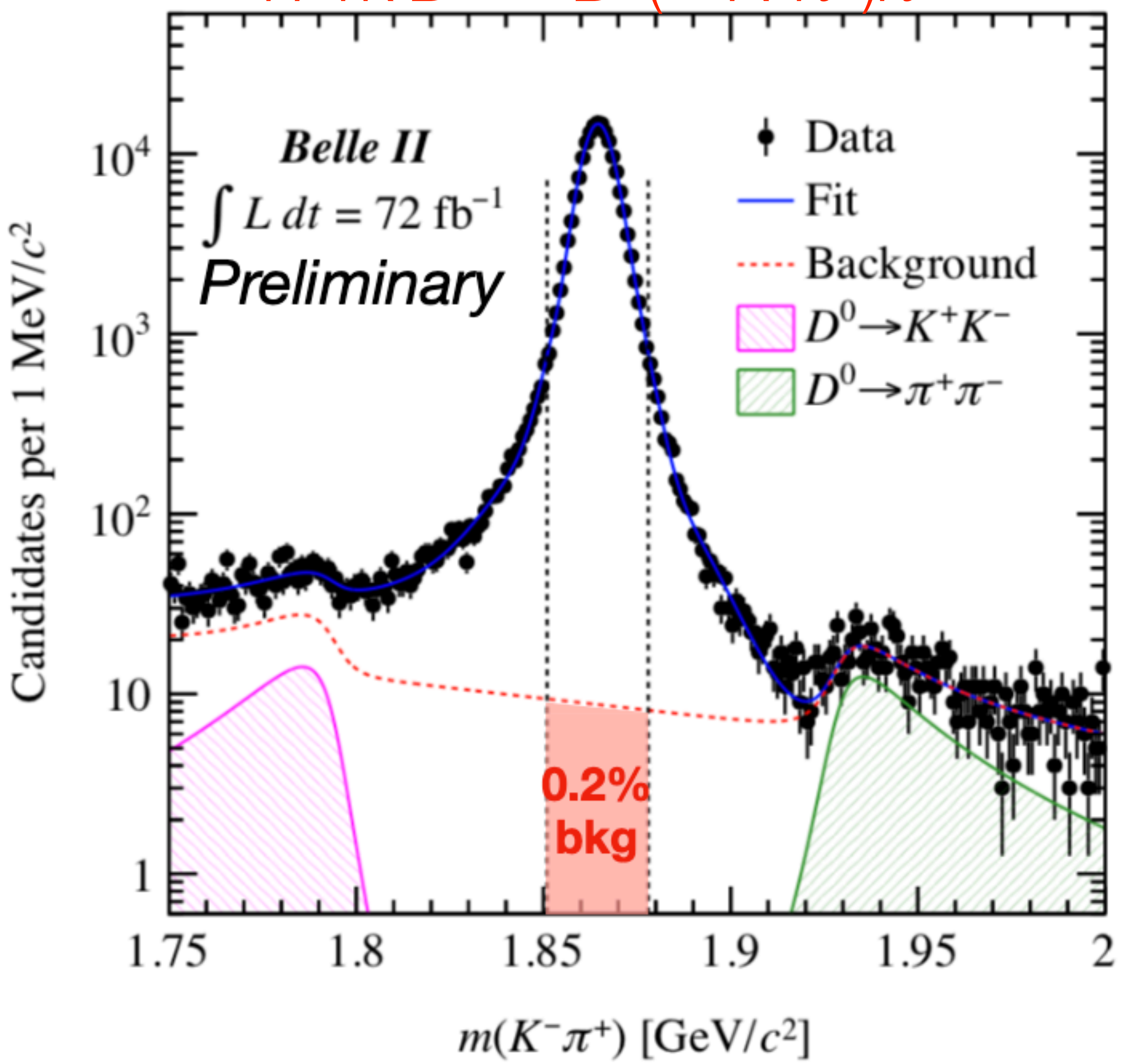
Signal Decays

use 72 fb^{-1} (~1/3 of the data now on disk)

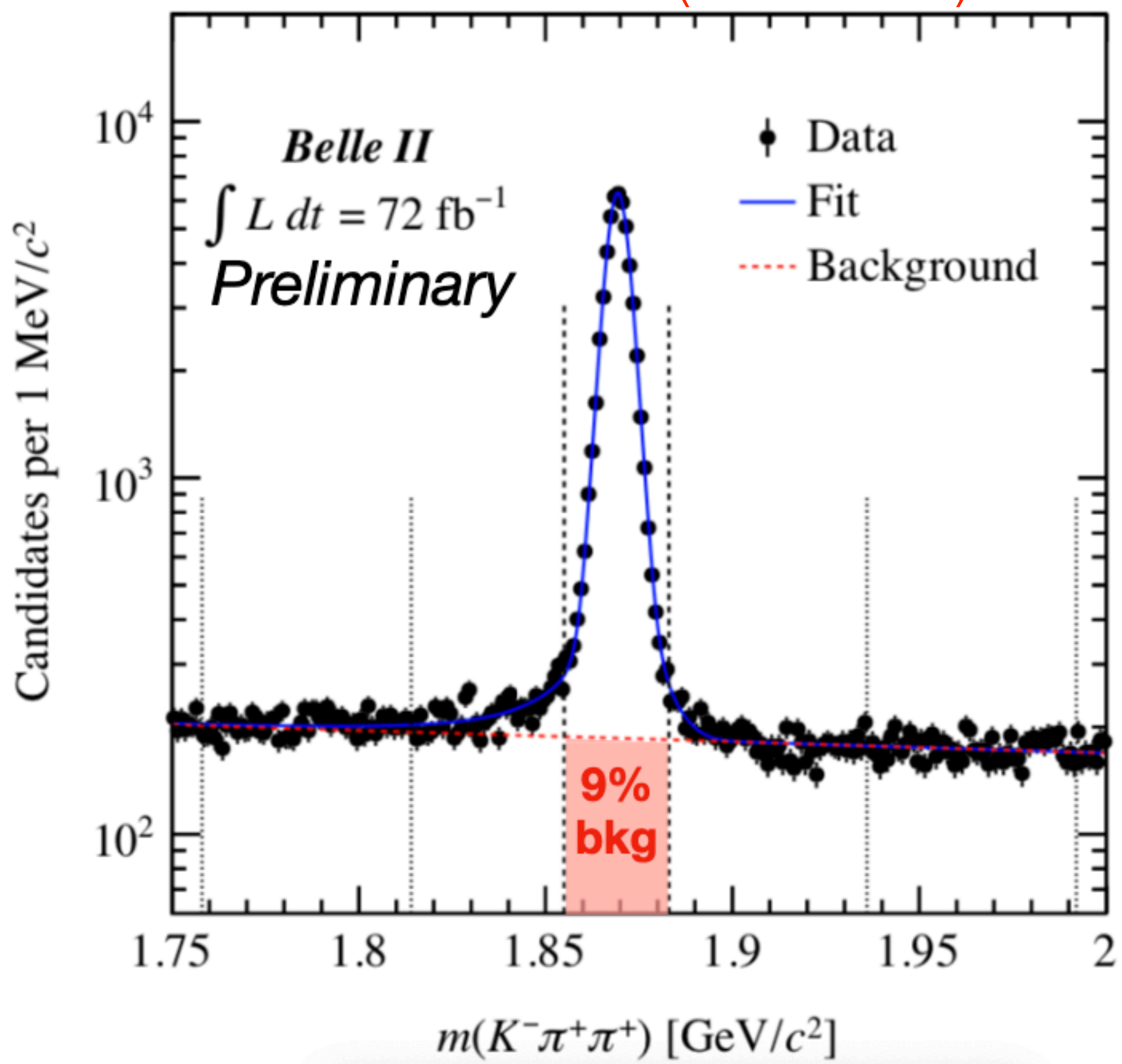
➡ Selected high-purity samples to limit the background-related systematic uncertainty

- removed candidates from B decays to avoid bias on the D production vertex

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



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



Signal PDF

for both D^0 and D^+ channels

- Lifetime extracted with a maximum-likelihood fit to the 2D distribution of proper time (t) and proper-time uncertainty (σ_t)
- Signal PDF is the convolution of an exponential with a resolution function (double/single Gaussian for D^0/D^+)

resolution function *fixed from data (binned template)*

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

resolution function

$$R(t - t_{\mathrm{true}} \,|\, \sigma_t, b, s) = G(t - t_{\mathrm{true}} \,|\, b, s\sigma_t)$$

b = bias

s = proper time uncertainty scaling factor

- Signal PDF validated on simulated data, and with ToyMC
- This is the total PDF for the D^0, where the sub-1% background contamination is ignored

Background Description

only for the D^+ channel

➡ The ~9% background contamination in the signal region can't be ignored → include it in the fit

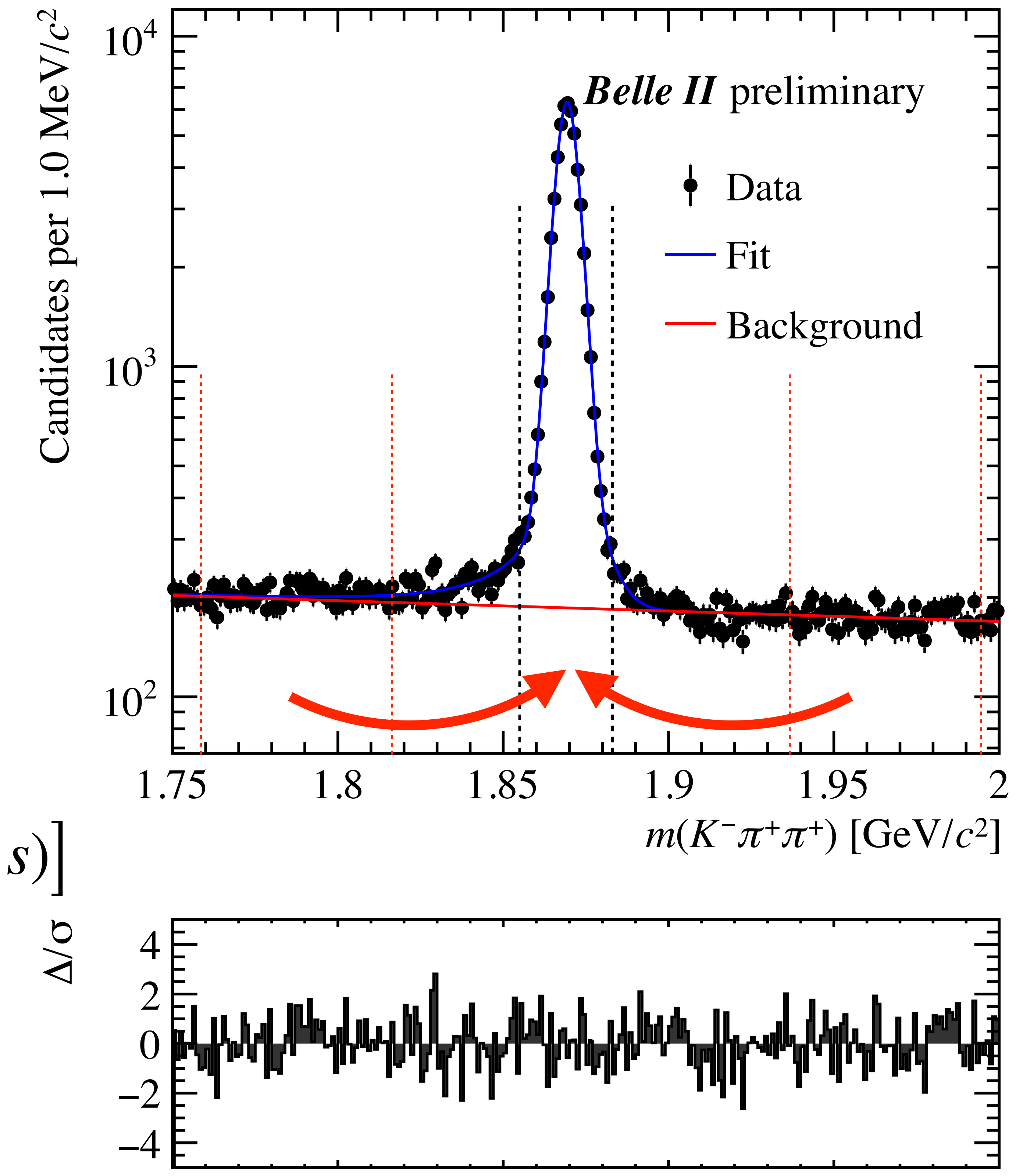
➡ Use an empiric model derived from the data sidebands

- simulation shows that the sidebands represent a good proxy of the background in the signal region
- background PDF: $\text{pdf}_{\text{bkg}}(t, \sigma_t) = \text{pdf}_{\text{bkg}}(t|\sigma_t)\ \text{pdf}_{\text{bkg}}(\sigma_t)$

zero-lifetime component *lifetime#1 component* *lifetime#2 component*

$$\text{pdf}_{\text{bkg}}(t|\sigma_t) = (1-f_{bl})R(t|b+b_{\text{bkg}}, s\sigma_t) + f_{bl}\left[f_{bl1}\text{pdf}_{bl1}(t|\sigma_t, \tau_{b1}, b+b_{\text{bkg}}, s) + (1-f_{bl1})\text{pdf}_{bl2}(t|\sigma_t, \tau_{b2}, b+b_{\text{bkg}}, s)\right]$$

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



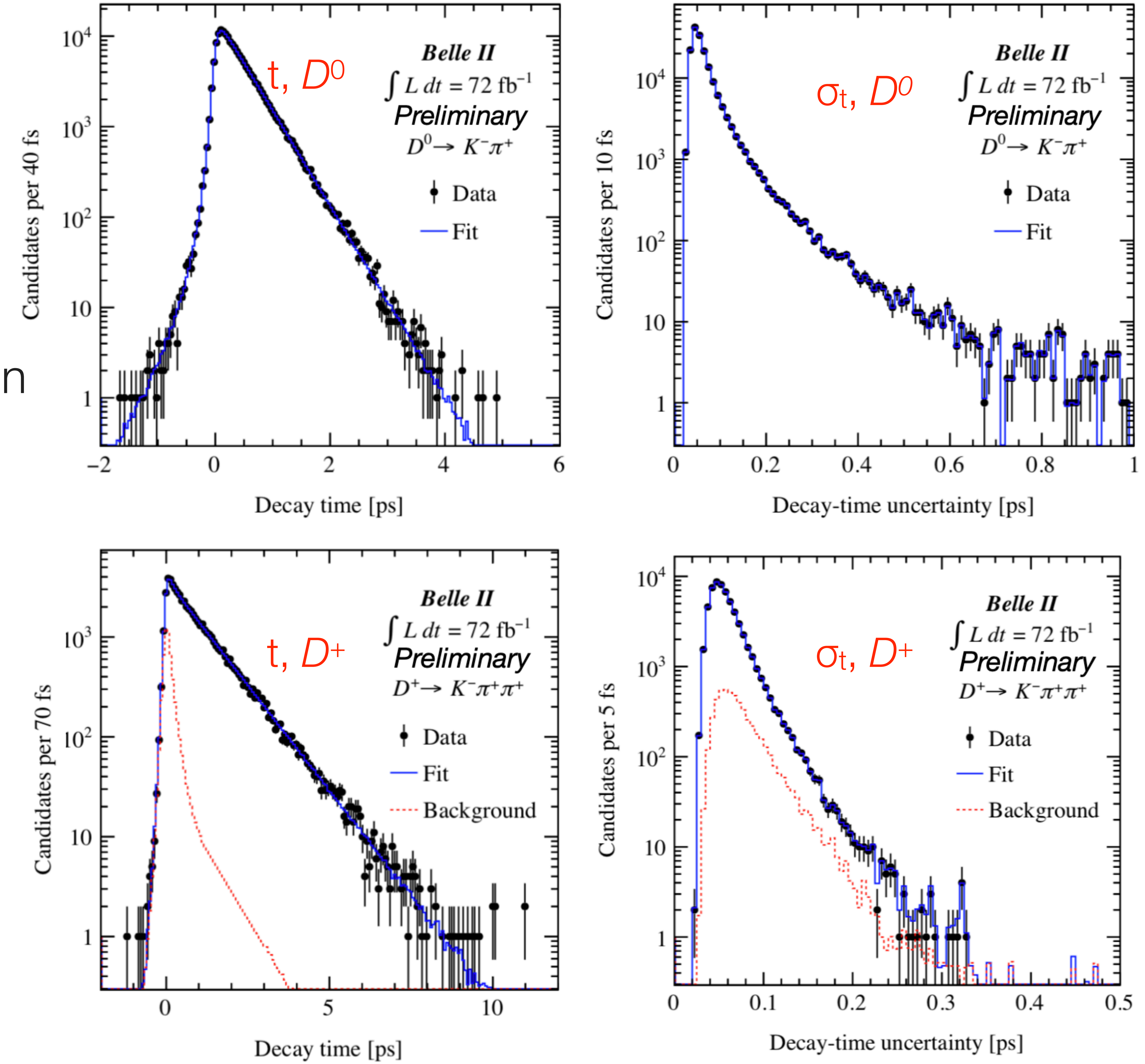
➡ Signal and sideband regions are **fit simultaneously** with all shape parameters free

- the background fraction is constrained to the result of the mass fit

Lifetime Fit

unbinned ML fit to (t,σ_t)

- Resolution and background models extracted on data, no input from simulation
  - resolution ~ 60-70 fs
  - MC just used for validation and to assess a few systematic uncertainties
- Blind analysis:
  - selection, validation, crosschecks and assessment of the systematic uncertainty performed before looking at the lifetime
  - except for 2019 data (~13% of the sample) unblinded since ICHEP 2020 (compatible with WA).



Validation & Crosschecks

before unblinding

- ➡ Full Simulation & Toy MC
- ➡ Data subsamples: split data in bins of D^0 momentum, cosθ, ϕ, run period,… and check that extracted lifetimes are compatible within the statistical uncertainty
- ➡ Measured (blind) D^0 lifetime using same technique as for $D^0 \to K^-\pi^+$, on a different final state: D^*-tagged $D^0 \to K^-\pi^+\pi^-\pi^+$
  - 146k signal events, 0.8% bkg in the signal region
  - different kinematics, different resolution model
  - similar precision to the $D^0 \to K\pi$ *channel*
  - blind results from $D^0 \to K\pi\pi\pi$ and $D^0 \to K\pi$ agrees: $\frac{|\tau_{K\pi} - \tau_{K3\pi}|}{\sqrt{\sigma^2_{K\pi}(\mathrm{stat}) + \sigma^2_{K3\pi}(\mathrm{stat})}} = 0.8$

Systematics Breakdown

total uncertainties are 1.4 fs (D^0) and 5.6 fs (D^+)

- Most critical contribution to the systematic uncertainty comes from the **alignment**
  - affecting the length scale
  - estimated using several different versions of reconstructed misaligned signal MC samples (next slide), from the same generated sample
- Dominant systematics for the D^+ is related to the **backgrounds**
  - to account for imperfect data-MC agreement of the decay-time distribution in the low-mass sideband

Source	Uncertainty (fs)	
	$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$
Statistical	1.1	4.7
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Input charm masses	0.01	0.03
Total systematic	0.8	3.1

- Both the dominant contributions can be improved:
  - reduce bkg contamination in the D^+ signal region
  - improved alignment algorithm already in place

Misalignment Configurations

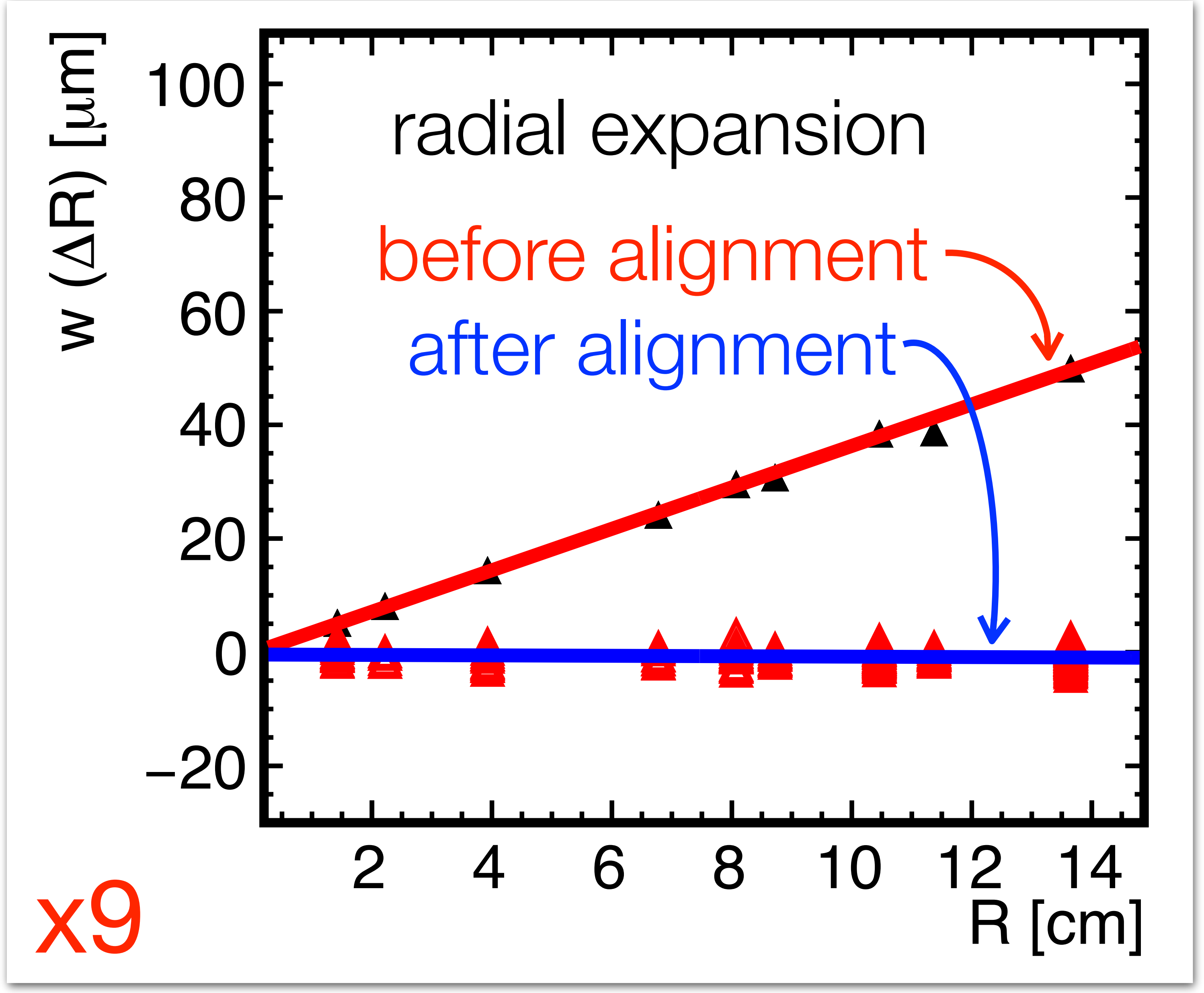
systematic uncertainty estimation

➡ The misalignment configurations are generated in two different ways:

(1) **stat** using **day-to-day difference between alignments in real data** to reproduce similar level of local alignment precision as obtained on an average alignment block

(2) **syst** taking residual misalignments that are not corrected for by the alignment procedure of 9 different **weak-mode deformations** (radial/longitudinal expansion, telescope, curl, …), using the simulation of a misaligned detector

WEAK-MODE DEFORMATION EXAMPLE



➡ The systematic uncertainty is estimated as the sum in quadrature of the largest bias from the day-to-day configurations (stat) and the largest bias from the weak-mode configurations (syst)

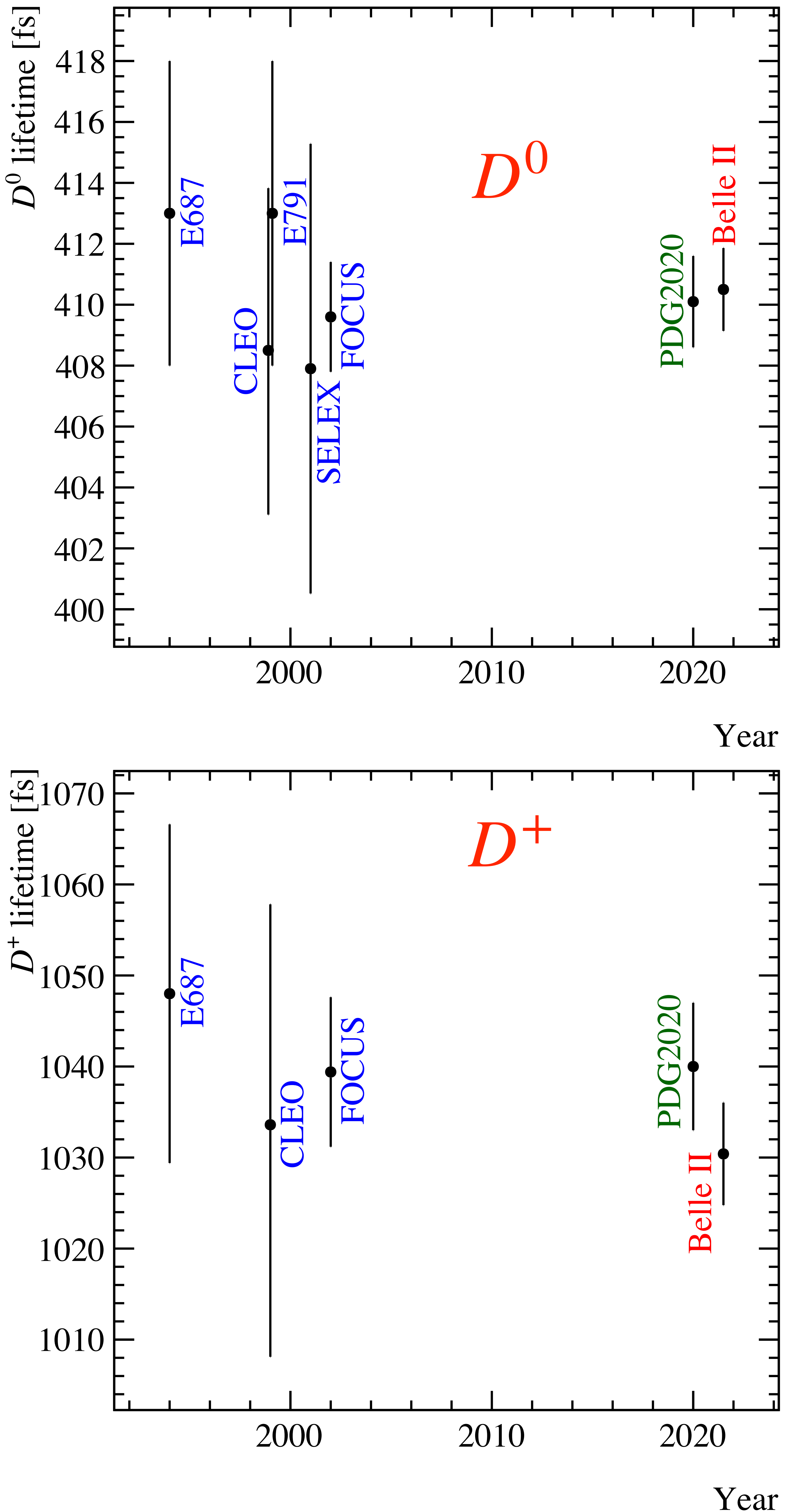
Results

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

$$\tau(D^+)/\tau(D^0) = 2.510 \pm 0.015$$

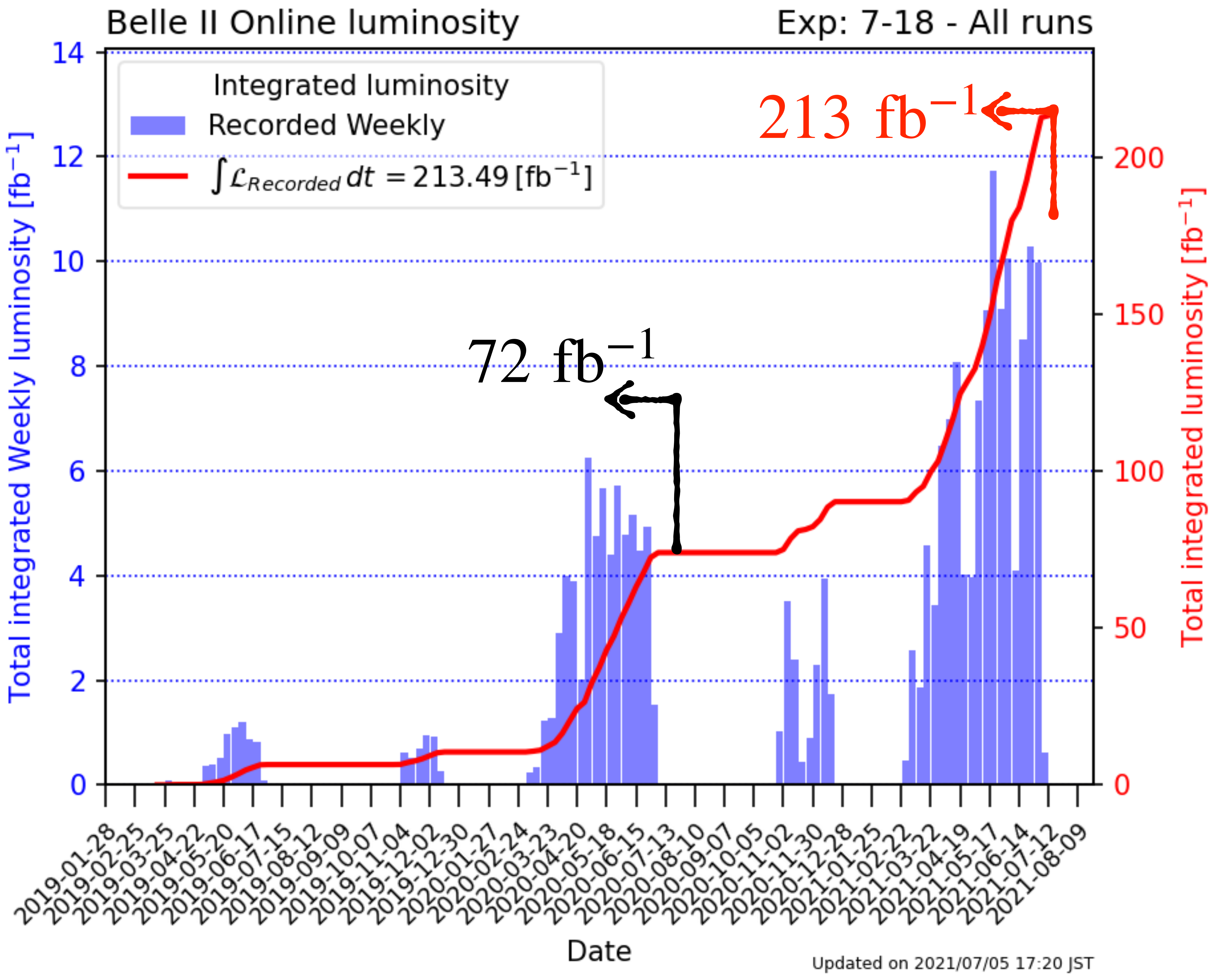
determined considering correlations between (systematic) uncertainties

- ➡ Consistent with current world averages 410.1±1.5 fs (D^0) and 1040±7 fs (D^+).
- ➡ World's most precise measurements of the D^0 and D^+ lifetimes
- ➡ Few ‰ accuracy (3.5‰ for the D^0 and 5.4‰ for the D^+) establishes excellent performance of our detector!
- ➡ submitted to PRL, https://arxiv.org/abs/2108.03216



Conclusions

- World's most precise measurements of the D^0 and D^+ lifetimes, the first one at a B-Factory experiment!
- The expected excellent vertexing performance is established and will guarantee improved precision of time-dependent measurement, beyond the increase of luminosity
- Stay tuned for many results on charm from Belle II in the next years!



Thank you for your attention.