Early charm physics results from Belle II and prospects

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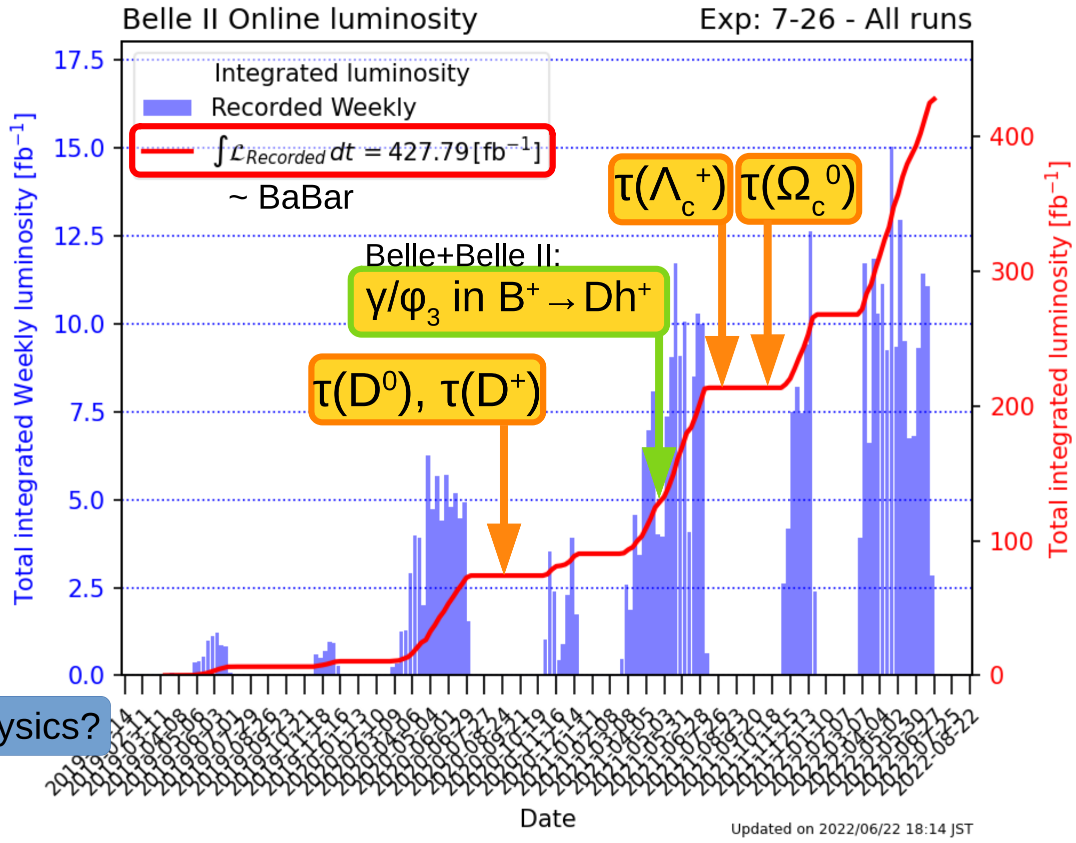
Charm at Super-B-Factory

- A lot of charm hadrons produced by SuperKEKB
  - Prompt in $e^+e^- \to c\bar{c}$ (1.3 nb)
  - Secondary in $\Upsilon(4S) \to B \to D$ (1.1 nb)
  - Clean collision environment
    - Well-defined initial state, no pile-up
- Opportunities for charm physics
  - CP-V measurements, searches for rare and forbidden decays, New Physics? spectroscopy, lifetimes of charm mesons and baryons

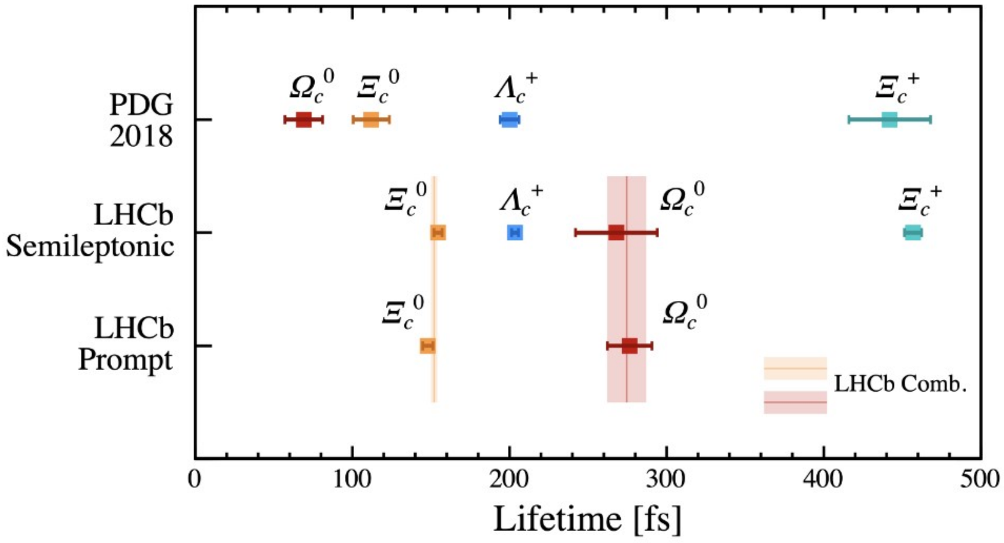


Better understanding of strong interactions at low E? → improve models used for BSM searches

Motivations for charm lifetime measurements

- Beauty and charm hadron lifetimes predicted by heavy quark expansion (HQE)
  - Charm is challenging (higher-order corrections + QCD contributions)
  - Improvements important for reliable predictions in flavor physics
- Charm lifetime hierarchy recently reshuffled by LHCb
  - Surprise: $\mathbf{\Omega_c^0}$ is not the shortest-living charm baryon!?
  - All lifetimes relative to D^+
- Belle II reach is unique!
  - Can save and reconstruct large samples of exclusive charm decays without the need to use lifetime-biasing triggers and selections
  - Better vertexing performance than Belle/BaBar

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



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

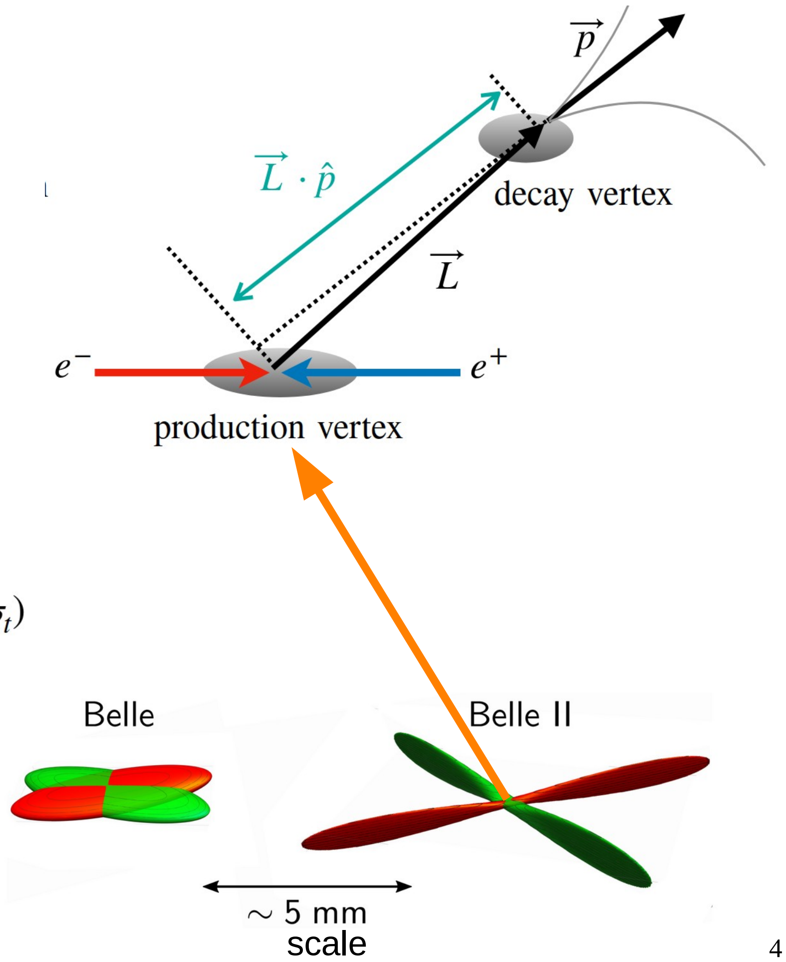
Possible reasons why HQE has initially failed are being debated (Science Bulletin 67 (2022) 445-447, arXiv:2204.11935)

Lifetime measurements @ Belle II

- Fully reconstructed decays to charged particles, no lifetime-biasing selections
- Signal and background fractions from mass fit, lifetime-biasing decays from B's removed by kinematic cut
- Lifetime from unbinned maximum likelihood fit to distribution of the reconstructed decay time and its uncertainty:

Production vertex constrained by measured primary interaction point (*beamspot*)

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



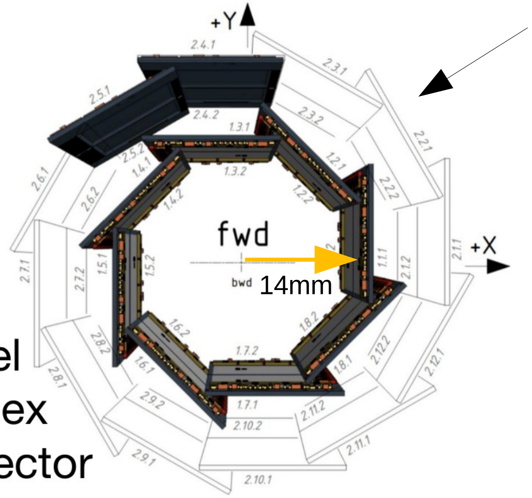
$$\mathrm{PDF}(t,\sigma_t) = (1-\mathrm{f_b})\int_0^\infty e^{-t_{\mathrm{true}}/\tau} R(t - t_{\mathrm{true}}\,|\,b, s\sigma_t)\,dt_{\mathrm{true}}\mathrm{PDF_{sig}}(\sigma_t) + \mathrm{f_b}\mathrm{PDF_{bkg}}(t,\sigma_t)$$

- Excellent decay time resolution thanks to super-small luminous region (**nano-beam**) used as a constraint + new pixel vertex detector (1st layer 14 mm from collision) resolution

Significant resolution improvement to Belle/BaBar

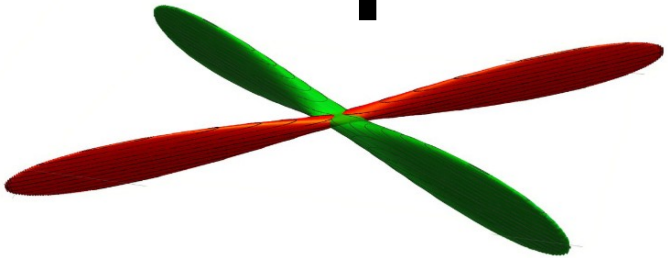
Impact parameter resolution in radial/longitudinal direction of 10/15 µm (at high momenta) (about twice better than Belle)

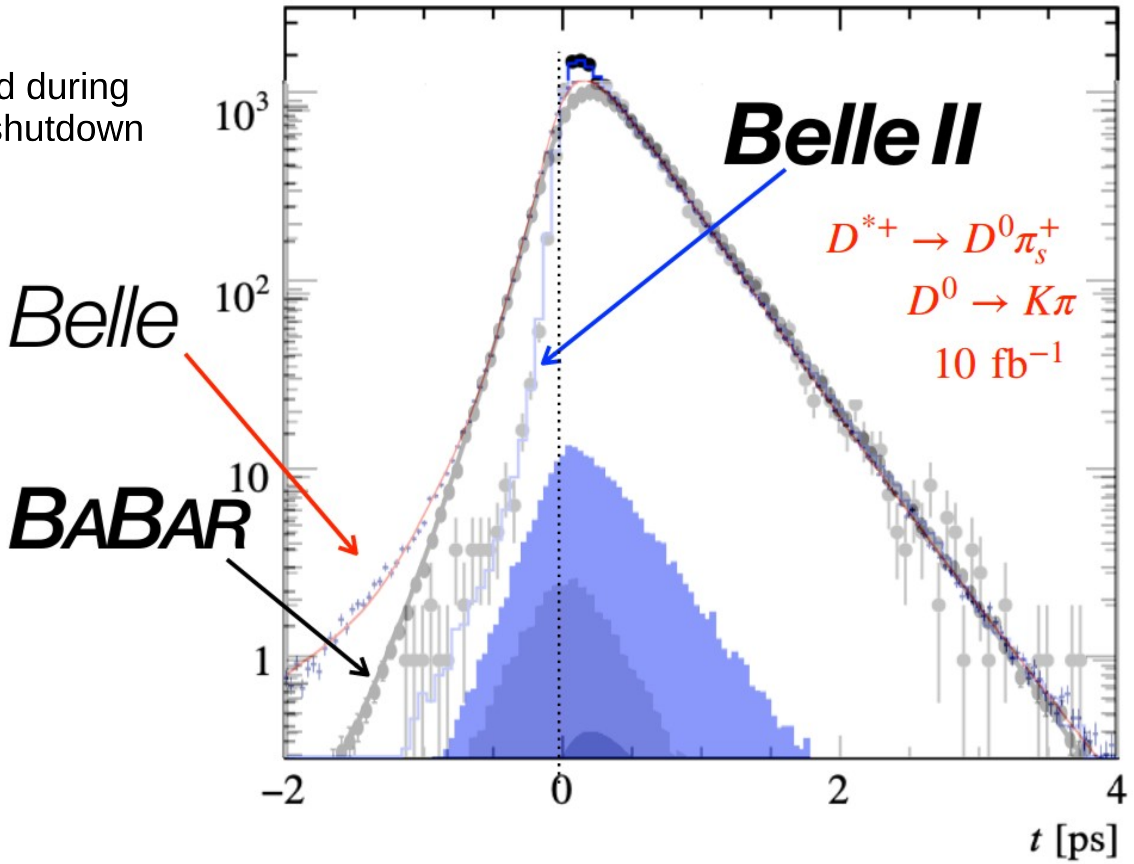
To be installed during current long shutdown



Pixel vertex detector

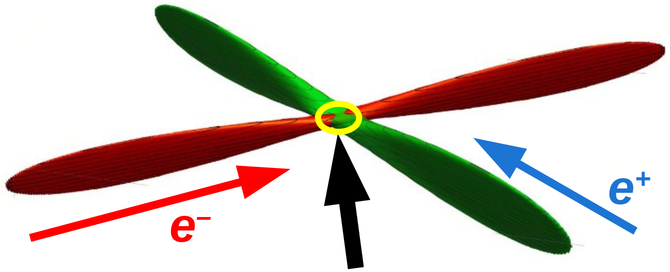
+





Precision lifetimes: Ingredients

Interaction region calibration



$\sigma_{Y'} = 0.2\mu\text{m}, \sigma_{X'} = 13\mu\text{m}, \sigma_{Z'} = 320\mu\text{m}$

3D Gaussian PDF width, position and orientation in space calibrated every 30 minutes

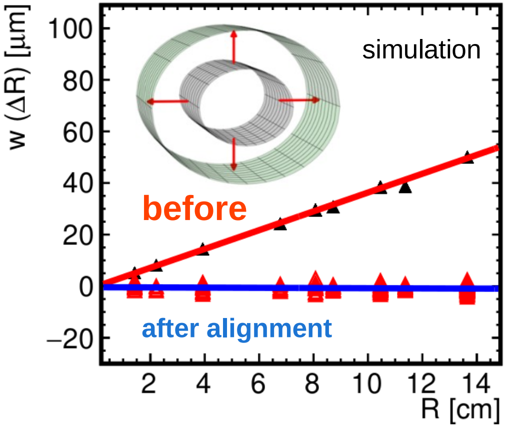
Based on high-stat di-muon events

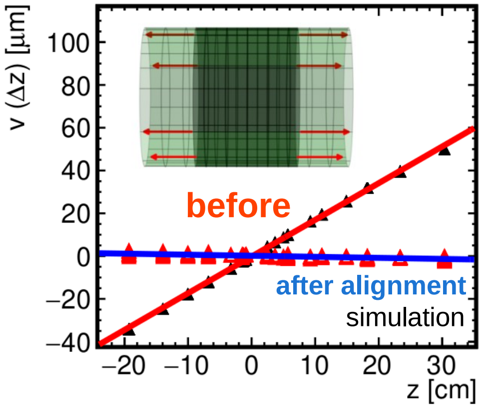
Tracker alignment

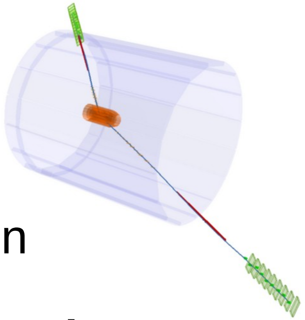
Simultaneous global and local alignment of pixels, strips (up to 4th order surface defomations) and wire chamber (60k parameters) from tracks

+ Run-dependent alignment (also for pixel sensors)

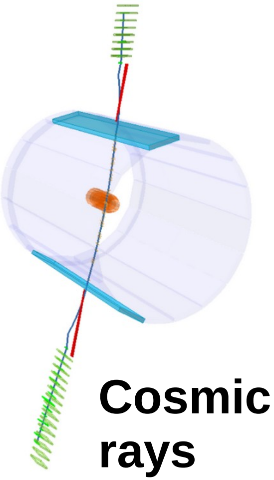
Data-driven and MC-driven misalignment estimates for systematics



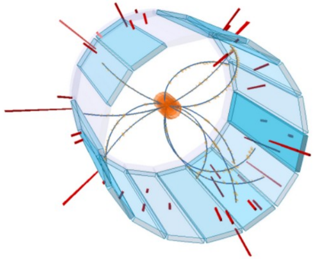




Di-muon events



Cosmic rays



Hadronic events + off-IP events

D^0/D^+ Lifetime Measurement

- 171×10^3 and 59×10^3 signal events for neutral and charged D

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

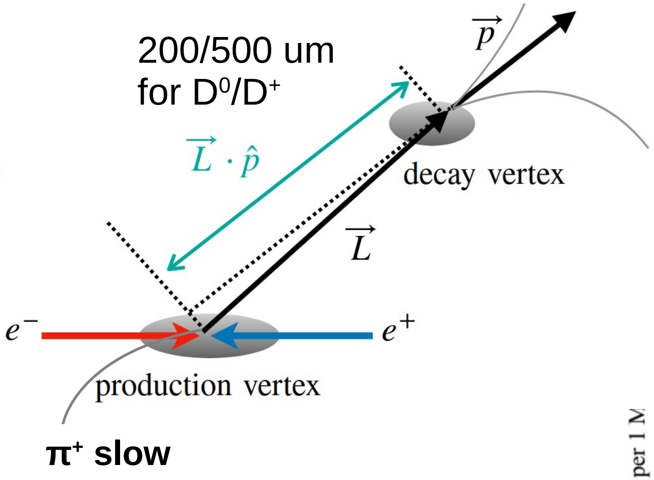
$$D^{*+} \to (D^+ \to K^-\pi^+\pi^+)\pi^0$$

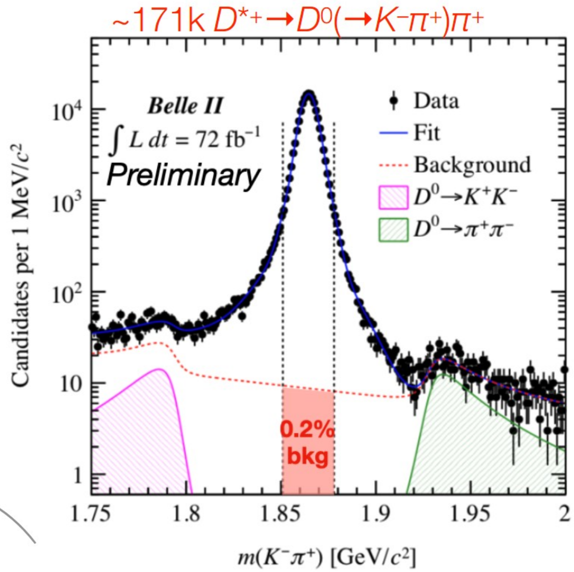
- B → D decays removed using

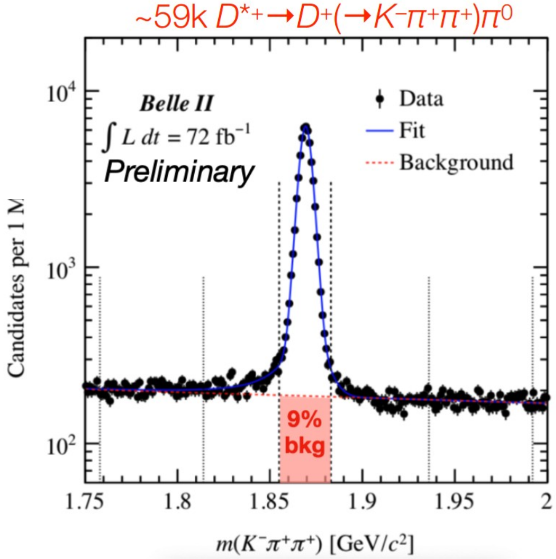
$$p^{\mathrm{CMS}}(D^{*+}) > 2.5(2.6)\ \mathrm{GeV}/c \text{ for } D^0(D^+)$$

- High purity
  - Background neglected for D^0 (systematics)
  - From simultaneous sideband fit for D^+

prompt + 2 lifetime components







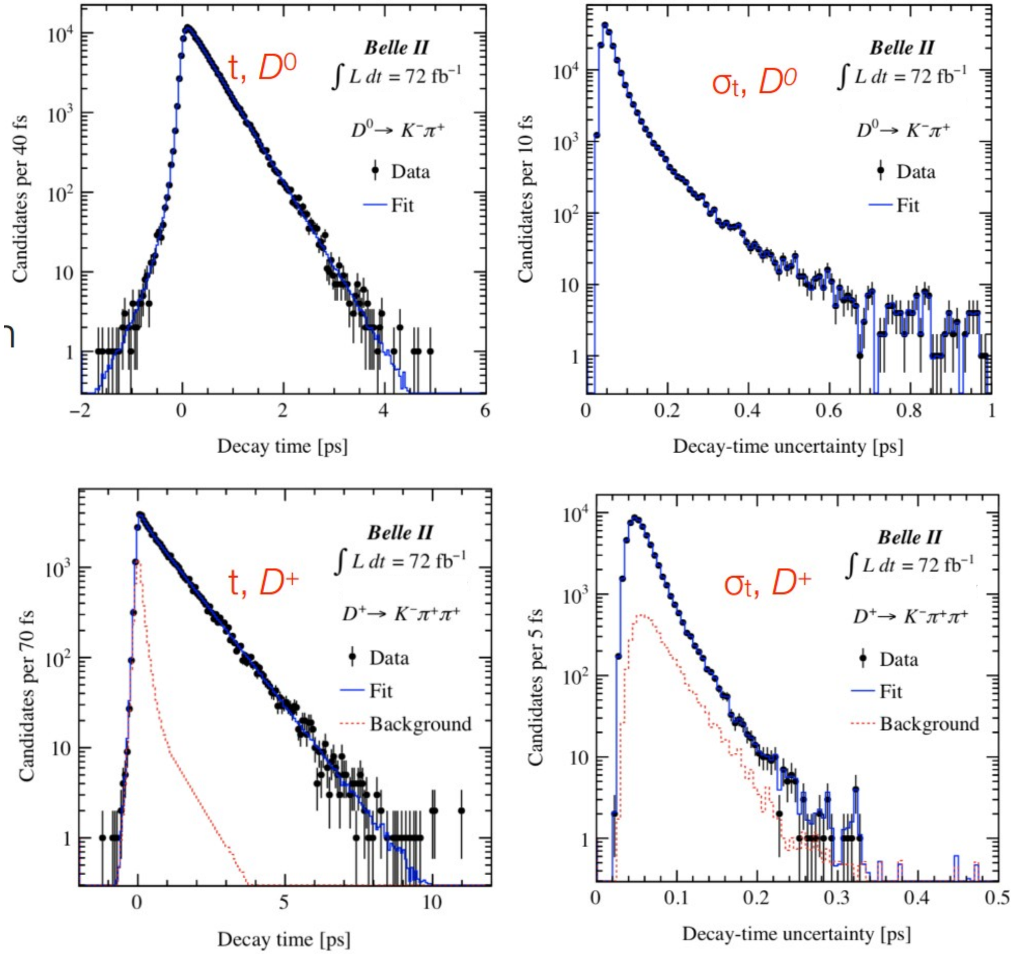
D^0/D^+ Lifetime Measurement

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

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

- Most precise to date and consistent with WA, improving LHCb reference
- Only preliminary alignment used
- Demonstrates excellent vertexing

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



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

Lifetime of Λ_c^+

- Reconstructed low-background sample

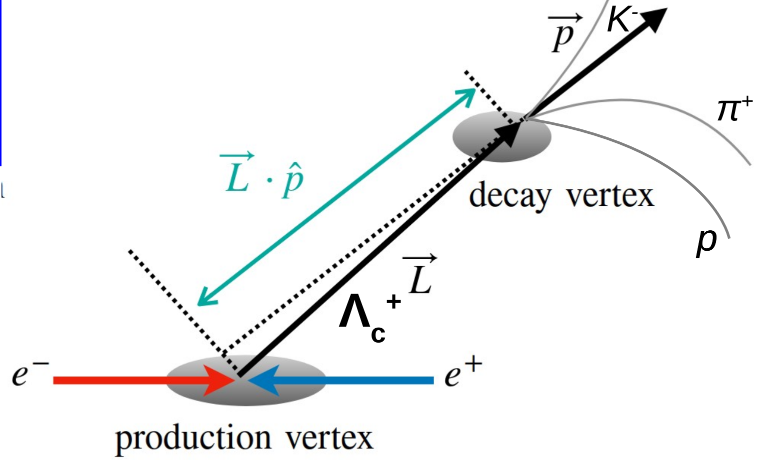
$$\Lambda_c^+ \to pK^-\pi^+$$

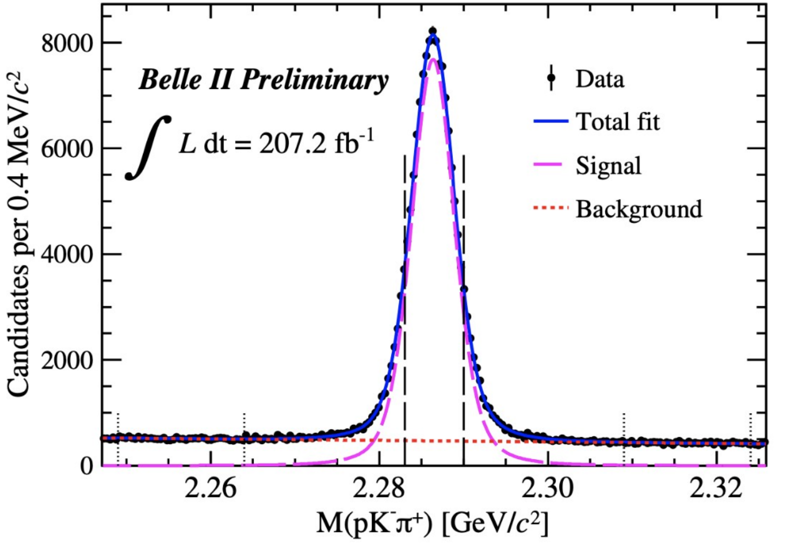
- 116×10³ signal events with 7.5% background in the signal region

- Potential lifetime-biasing backgrounds

decay	BR	τ
$\Xi_c^0 \to \Lambda_c^+\pi^-$	0.55 ± 0.20 % (LHCb)	153 ± 6 fs
$\Xi_c^+ \to \Lambda_c^+\pi^0$	1.11 % (theory pred.)	456 ± 5 fs

- not taken into account in previous measurements
- conservative estimate of yields by fits to Λ_c^+ impact parameter distribution
- vetos applied on $M(pK^-\pi^+\pi^-)$-$M(pK^-\pi^+)$
  $M(pK^-\pi^+\pi^0)$ - $M(pK^-\pi^+)$
- remaining bias evaulated by mixing signal with generic MC → half as correction, half as systematics



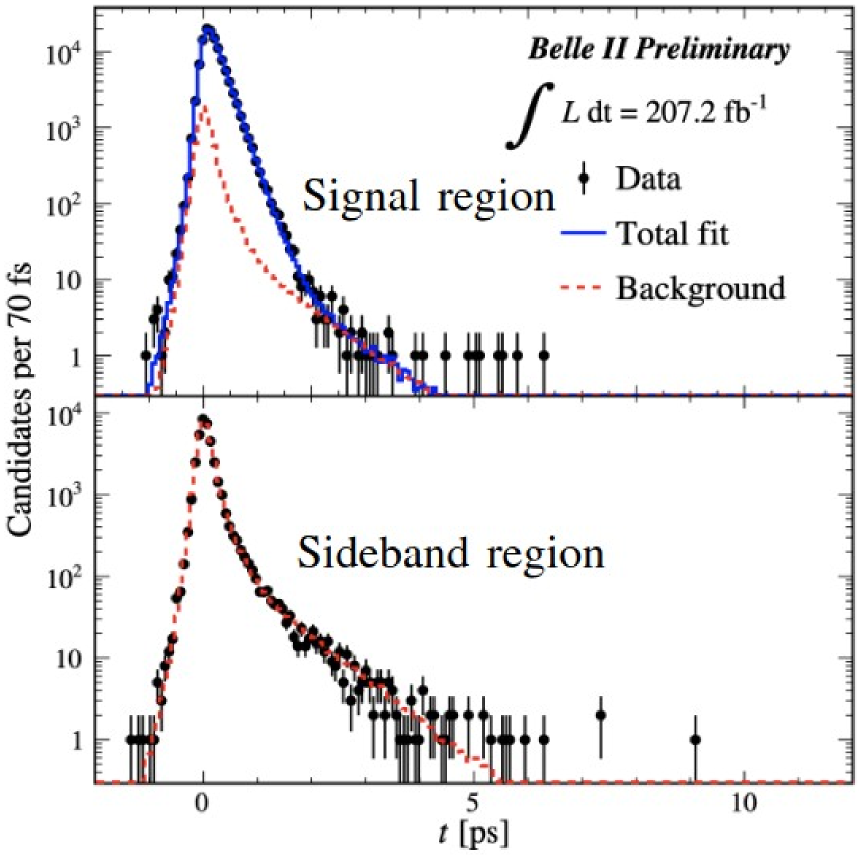


Lifetime of Λ_c^+

$$\tau(\Lambda_c^+) = 203.2 \pm 0.9(\text{stat.}) \pm 0.8(\text{syst.})\ \text{fs}$$

- Consistent with current WA and most precise to date
- Dominant systematics: resolution modeling and alignment
  - Reprocessing alignment for part of the dataset

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

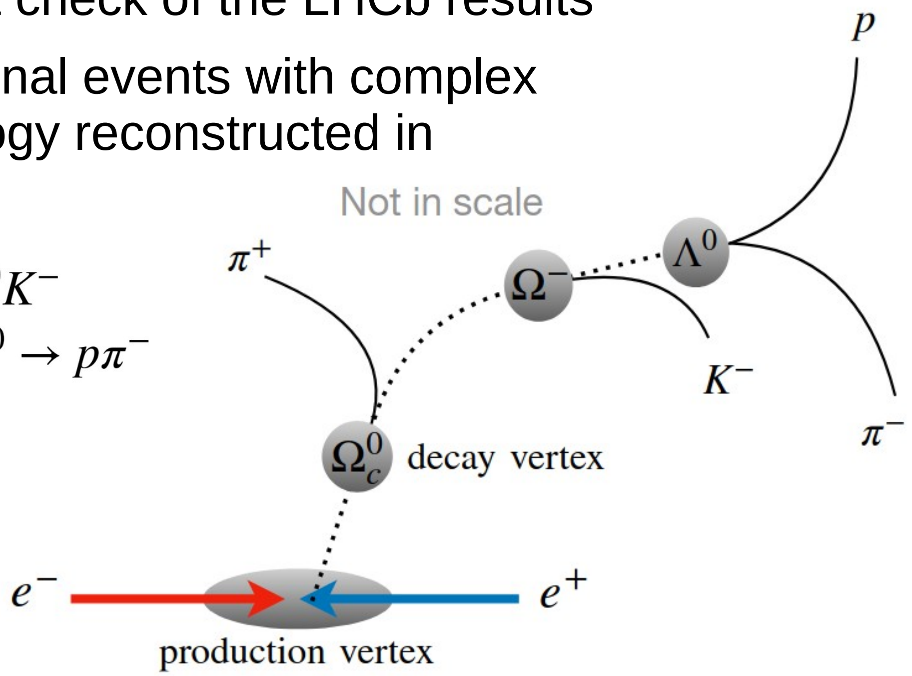


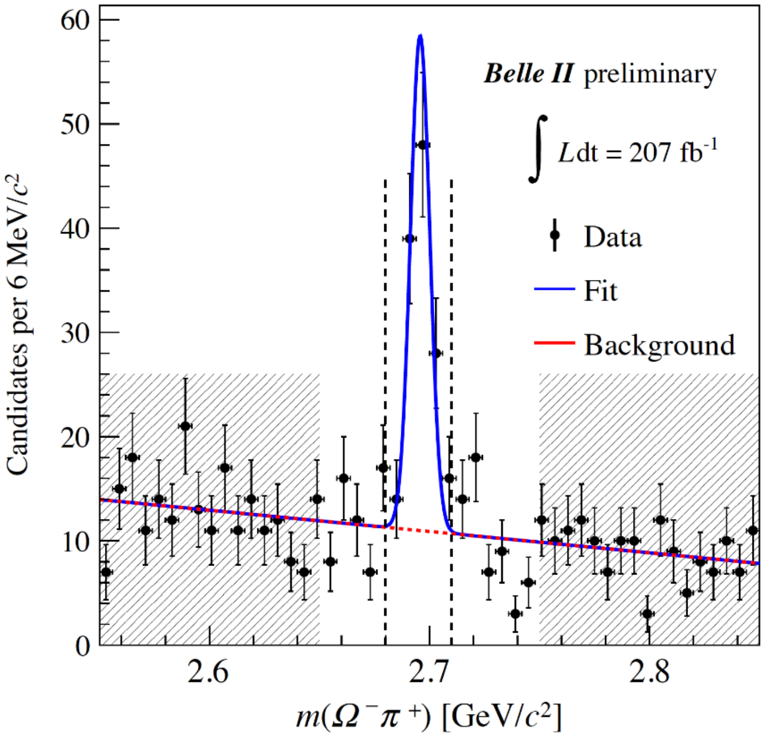
https://arxiv.org/abs/2206.15227 Accepted by Physical Review Letters

Lifetime of Ω_c^0

- Independent check of the LHCb results
- About 90 signal events with complex decay topology reconstructed in

$$\Omega_c^0 \to \Omega^-\pi^+$$
$$\Omega^- \to \Lambda^0 K^-$$
$$\Lambda^0 \to p\pi^-$$



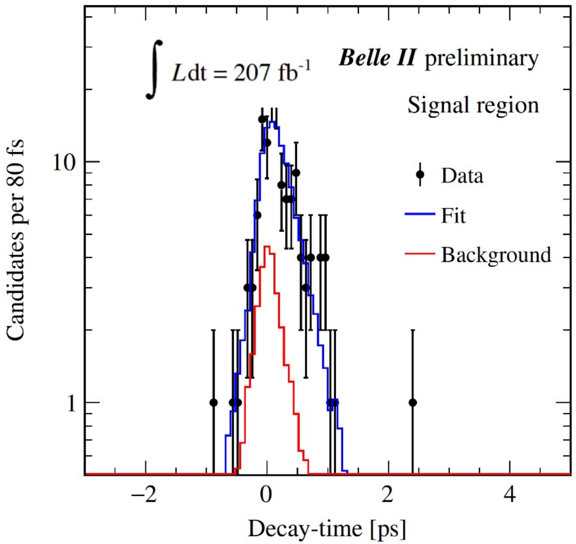


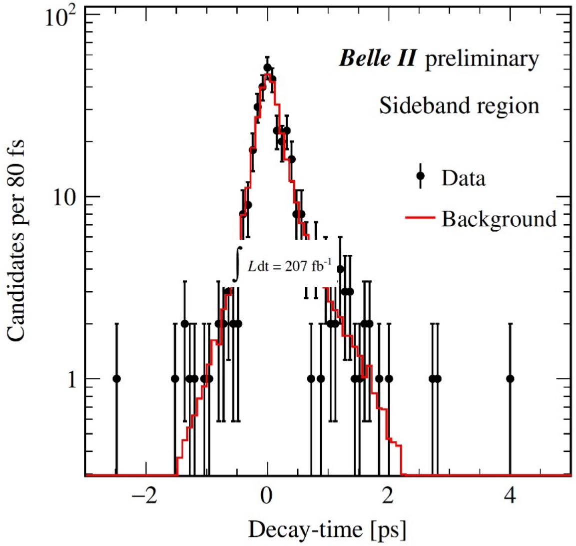
- 33% background contamination in the signal region
  - Prompt + lifetime components

Lifetime of Ω_c^0

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

- Consistent with LHCb average
  - 3.4σ tension with pre-LHCb
  - Demonstration of vertexing capabilities in complex decay topologies
- Limited by statistics
  - Systematics dominated by background and resolution model





Source	Uncertainty (fs)
Fit bias	3.4
Resolution model	6.2
Background model	8.3
Detector alignment	1.6
Momentum scale	0.2
Input charm masses	0.2
Total	11.0

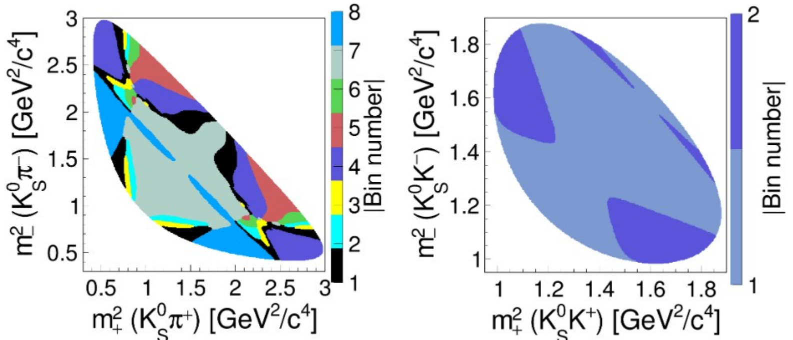
https://arxiv.org/abs/2208.08573 Accepted by Physical Review D Letters

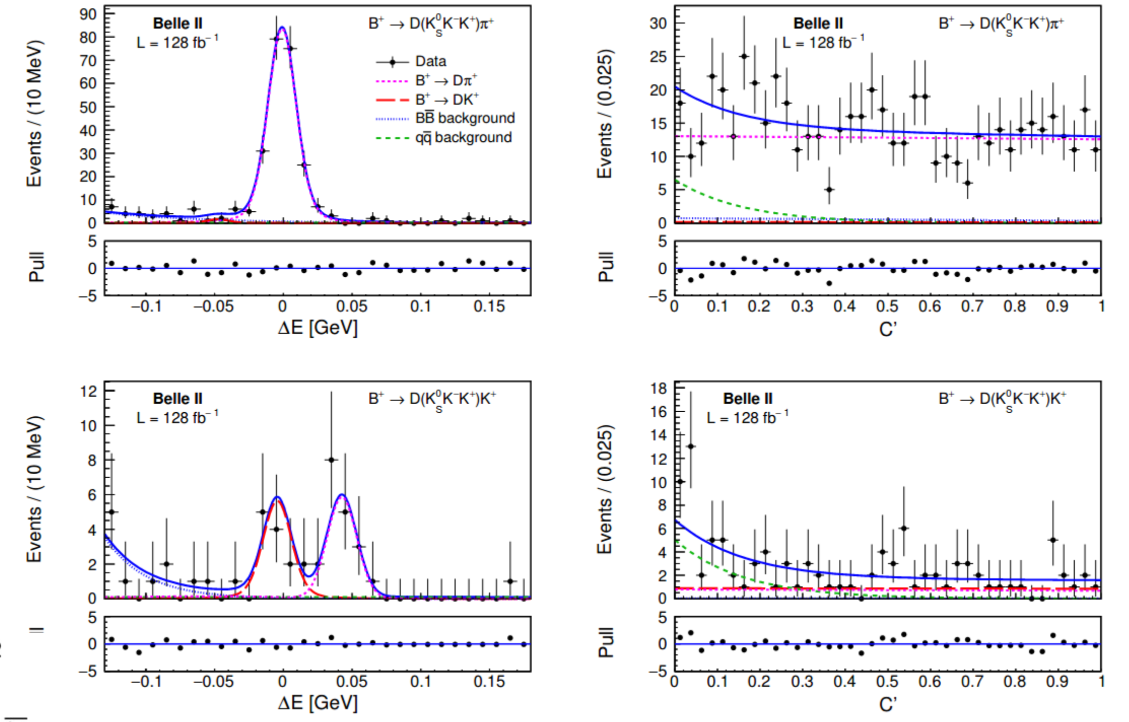
Towards precision CP-V: γ/φ_3

Combined analysis of Belle and Belle II data to determine the CKM angle ϕ_3 using $B^+ \to D(K_S^0 h^- h^+)h^+$ decays

Motivation: Constrain BSM physics by comparing direct (tree … 3° error) and indirect (loops … 0.9° error) determination of γ/φ_3

- First physics paper combining Belle (711 fb^{-1}) and Belle II (128 fb^{-1}) data
- Model-independent Dalitz plot analysis

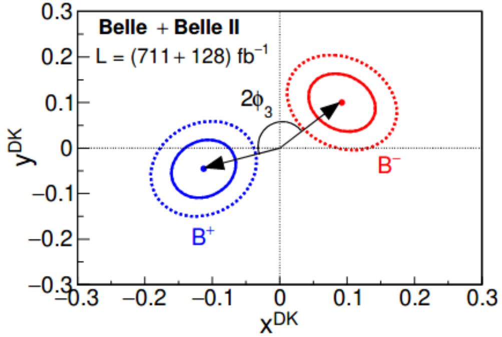




$$\Delta E = \sum_i E_i^* - E_{\text{beam}}^*,$$

Transformed FastBDT output

Towards precision CP-V: γ/φ_3



The two interfering decays sensitive to ϕ_3 are $B^+ \to \bar{D}^0 K^+$ and $B^+ \to D^0 K^+$

CKM & color suppressed

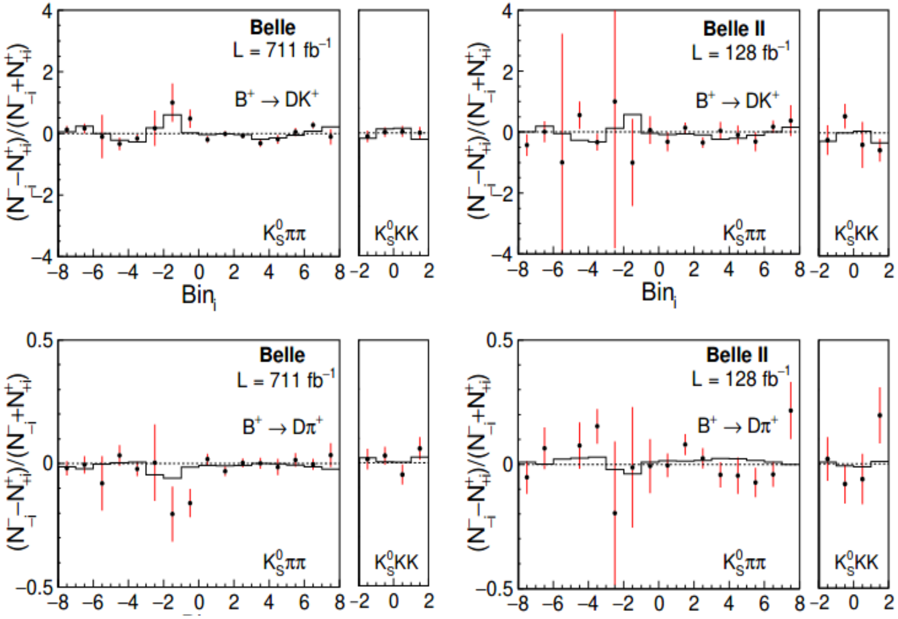
$$A_{B^+}\left(m_-^2, m_+^2\right) \propto A_{\bar{D}}\left(m_-^2, m_+^2\right) + r_B^{DK} e^{i\left(\delta_B^{DK} - \phi_3\right)} A_D\left(m_-^2, m_+^2\right)$$

External strong phase inputs (CLEO + BESIII)

$$\begin{aligned} \phi_3 &= (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ\,, \\ r_B^{DK} &= 0.129 \pm 0.024 \pm 0.001 \pm 0.002, \\ \delta_B^{DK} &= (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ\,. \end{aligned}$$

WA: $(66.2^{+3.4}_{-3.2})^\circ$

JHEP 02 (2022) 063



Improved precision with respect to Belle for r & δ, almost none for φ_3 (slightly different central value from Belle II)

Net improvements w.r.t. Belle at given luminosity. At 10/fb … < 4° stat. error

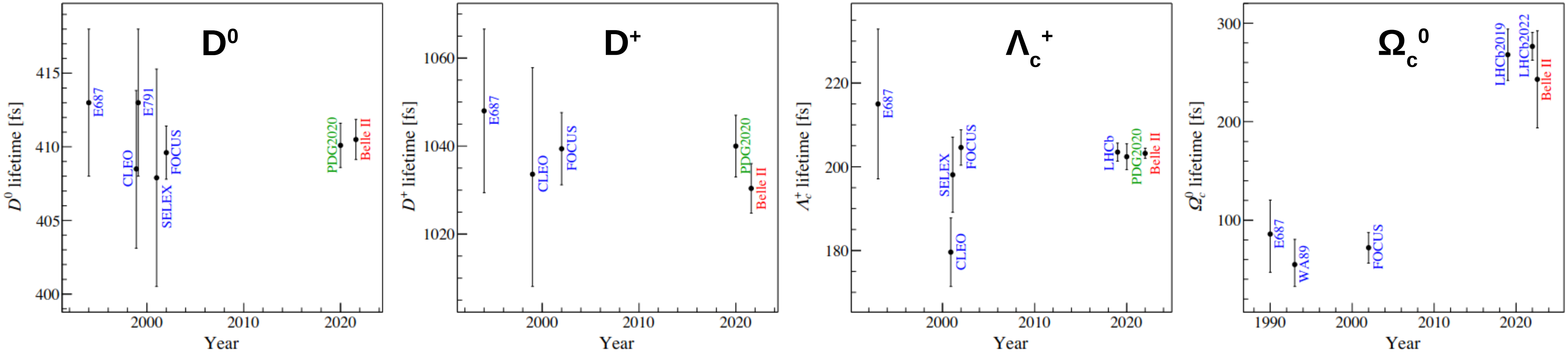
Charm prospects: Time-integrated CP-V

- Similarly to Belle, Belle II can contribute to more precise CP violation measurements in charm decays
- Direct CP-V precision to reach O(10^{-4}) for the full dataset
- Belle II input is crucial in channels with neutrals in the final state

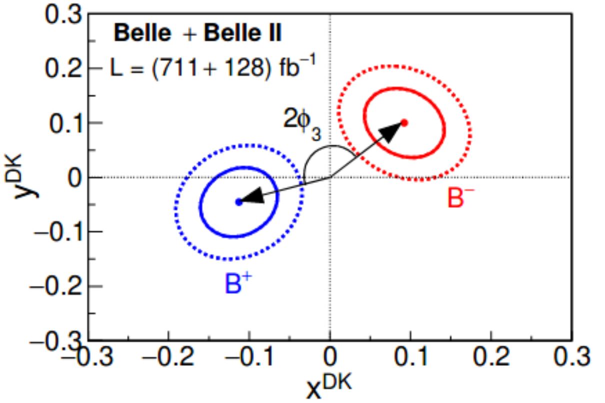
Direct CP-V in charm: extrapolations from Belle to Belle II:

	Direct (time-integrated) CP Violation in %			$5\ \text{ab}^{-1}$	$50\ \text{ab}^{-1}$
$D^0 \to K^+K^-$	A_{CP}	0.976	$-0.32 \pm 0.21 \pm 0.09$	± 0.10	± 0.03
$D^0 \to \pi^+\pi^-$	A_{CP}	0.976	$+0.55 \pm 0.36 \pm 0.09$	± 0.16	± 0.05
$D^0 \to \pi^0\pi^0$	A_{CP}	0.966	$-0.03 \pm 0.64 \pm 0.10$	± 0.28	± 0.09
$D^0 \to K_S^0\pi^0$	A_{CP}	0.966	$-0.21 \pm 0.16 \pm 0.07$	± 0.08	± 0.02
$D^0 \to K_S^0 K_S^0$	A_{CP}	0.921	$-0.02 \pm 1.53 \pm 0.17$	± 0.66	± 0.23
$D^0 \to K_S^0\eta$	A_{CP}	0.791	$+0.54 \pm 0.51 \pm 0.16$	± 0.21	± 0.07
$D^0 \to K_S^0\eta'$	A_{CP}	0.791	$+0.98 \pm 0.67 \pm 0.14$	± 0.27	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	A_{CP}	0.532	$+0.43 \pm 1.30$	± 0.42	± 0.13
$D^0 \to K^+\pi^-\pi^0$	A_{CP}	0.281	-0.60 ± 5.30	± 1.26	± 0.40
$D^0 \to K^+\pi^-\pi^+\pi^-$	A_{CP}	0.281	-1.80 ± 4.40	± 1.04	± 0.33
$D^+ \to \phi\pi^+$	A_{CP}	0.955	$+0.51 \pm 0.28 \pm 0.05$	± 0.12	± 0.04
$D^+ \to \pi^+\pi^0$	A_{CP}	0.921	$+2.31 \pm 1.24 \pm 0.23$	± 0.54	± 0.17
$D^+ \to \eta\pi^+$	A_{CP}	0.791	$+1.74 \pm 1.13 \pm 0.19$	± 0.46	± 0.14
$D^+ \to \eta'\pi^+$	A_{CP}	0.791	$-0.12 \pm 1.12 \pm 0.17$	± 0.45	± 0.14
$D^+ \to K_S^0\pi^+$	A_{CP}	0.977	$-0.36 \pm 0.09 \pm 0.07$	± 0.05	± 0.02
$D^+ \to K_S^0 K^+$	A_{CP}	0.977	$-0.25 \pm 0.28 \pm 0.14$	± 0.14	± 0.04
$D_s^+ \to K_S^0\pi^+$	A_{CP}	0.673	$+5.45 \pm 2.50 \pm 0.33$	± 0.93	± 0.29
$D_s^+ \to K_S^0 K^+$	A_{CP}	0.673	$+0.12 \pm 0.36 \pm 0.22$	± 0.15	± 0.05

Summary



- World-leading charm lifetime measurements
  - Important to validate/challenge/improve HQE and strong interactions description for future precision measurements
  - Demonstrate excellent vertexing capabilities, paving way for precise time-dependent measurements
- Independent confirmation of Ω_c^0 lifetime from LHCb and new charm baryon lifetime hierarchy
- Most precise γ/φ_3 from B-Factories using $B^+ \to D(K_S h^+ h^-)h^+$ and Belle+Belle II data
- More data on tape, and much more to come! Belle II will give a crucial contribution via measurements with channels with neutrals in the final states:
  - Prospects for direct CP asymetries in charm, charmonium spectroscopy, rare and forbidden decays, time-dependent analyses; B → charm



Thank you for your attention!

BACKUP

Channel	Observable	Belle/BaBar measurement		Scaled	
		$\mathcal{L}$ [ab^{-1}]	Value	5 ab^{-1}	50 ab^{-1}
Leptonic decays					
	μ^+ events		492 ± 26	2.7k	27k
$D_s^+ \to \ell^+ \nu$	τ^+ events	0.913	2217 ± 83	12.1k	121k
	f_{D_s}		2.5%	1.1%	0.34%
$D^+ \to \ell^+ \nu$	μ^+ events	—	—	125	1250
	f_D	—	—	6.4%	2.0%
Rare and radiative decays					
$D^0 \to \rho^0 \gamma$	A_{CP}		$+0.056 \pm 0.152 \pm 0.006$	± 0.07	± 0.02
$D^0 \to \phi \gamma$	A_{CP}	0.943	$-0.094 \pm 0.066 \pm 0.001$	± 0.03	± 0.01
$D^0 \to \overline{K}^{*0} \gamma$	A_{CP}		$-0.003 \pm 0.020 \pm 0.000$	± 0.01	± 0.003
Mixing and indirect (time-dependent) CP violation					
$D^0 \to K^+ \pi^-$	x'^2 (%)	0.976	0.009 ± 0.022	± 0.0075	± 0.0023
(no CPV)	y' (%)		0.46 ± 0.34	± 0.11	± 0.035
(CPV allowed)	$\lvert q/p \rvert$	World avg. [230]	$0.89^{+0.08}_{-0.07}$	± 0.20	± 0.05
	ϕ (°)	with LHCb	$-12.9^{+9.9}_{-8.7}$	$\pm 16°$	$\pm 5.7°$
$D^0 \to K^+ \pi^- \pi^0$	x''	0.384	$2.61^{+0.57}_{-0.68} \pm 0.39$	—	± 0.080
	y''		$-0.06^{+0.55}_{-0.64} \pm 0.34$	—	± 0.070
	x (%)		$0.56 \pm 0.19^{+0.04}_{-0.08}{}^{+0.06}_{-0.08}$	± 0.16	± 0.11
$D^0 \to K_S^0 \pi^+ \pi^-$	y (%)	0.921	$0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.07}$	± 0.10	± 0.05
	$\lvert q/p \rvert$		$0.90^{+0.16}_{-0.15}{}^{+0.05}_{-0.04}{}^{+0.06}_{-0.05}$	± 0.12	± 0.07
	ϕ (°)		$-6 \pm 11 \pm 3^{+3}_{-4}$	± 8	± 4
Direct (time-integrated) CP violation in %					
$D^0 \to K^+ K^-$	A_{CP}	0.976	$-0.32 \pm 0.21 \pm 0.09$	± 0.10	± 0.03
$D^0 \to \pi^+ \pi^-$	A_{CP}	0.976	$+0.55 \pm 0.36 \pm 0.09$	± 0.16	± 0.05
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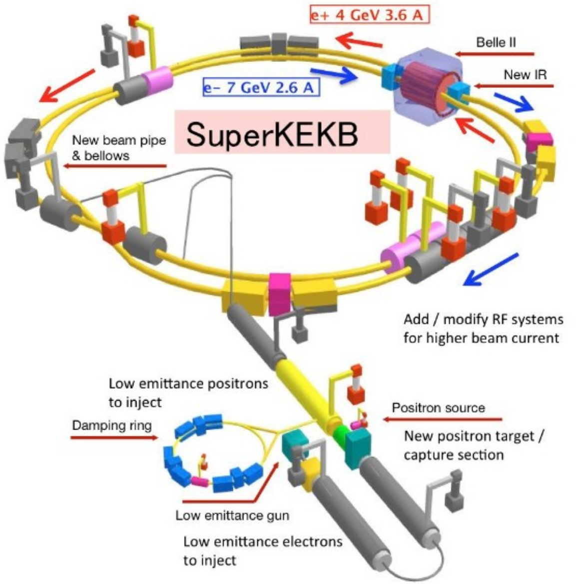
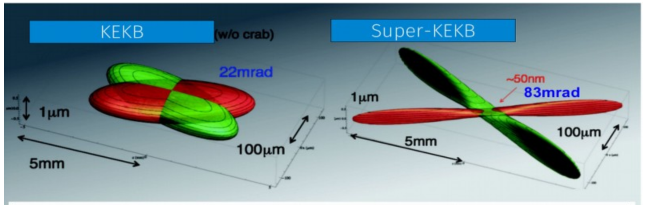
$D^0 \to K^+ \pi^- \pi^0$	A_{CP}	0.281	-0.60 ± 5.30	± 1.26	± 0.40
$D^0 \to K^+ \pi^- \pi^+ \pi^-$	A_{CP}	0.281	-1.80 ± 4.40	± 1.04	± 0.33
$D^+ \to \phi \pi^+$	A_{CP}	0.955	$+0.51 \pm 0.28 \pm 0.05$	± 0.12	± 0.04
$D^+ \to \pi^+ \pi^0$	A_{CP}	0.921	$+2.31 \pm 1.24 \pm 0.23$	± 0.54	± 0.17
$D^+ \to \eta \pi^+$	A_{CP}	0.791	$+1.74 \pm 1.13 \pm 0.19$	± 0.46	± 0.14
$D^+ \to \eta' \pi^+$	A_{CP}	0.791	$-0.12 \pm 1.12 \pm 0.17$	± 0.45	± 0.14
$D^+ \to K_S^0 \pi^+$	A_{CP}	0.977	$-0.36 \pm 0.09 \pm 0.07$	± 0.05	± 0.02
$D^+ \to K_S^0 K^+$	A_{CP}	0.977	$-0.25 \pm 0.28 \pm 0.14$	± 0.14	± 0.04
$D_s^+ \to K_S^0 \pi^+$	A_{CP}	0.673	$+5.45 \pm 2.50 \pm 0.33$	± 0.93	± 0.29
$D_s^+ \to K_S^0 K^+$	A_{CP}	0.673	$+0.12 \pm 0.36 \pm 0.22$	± 0.15	± 0.05

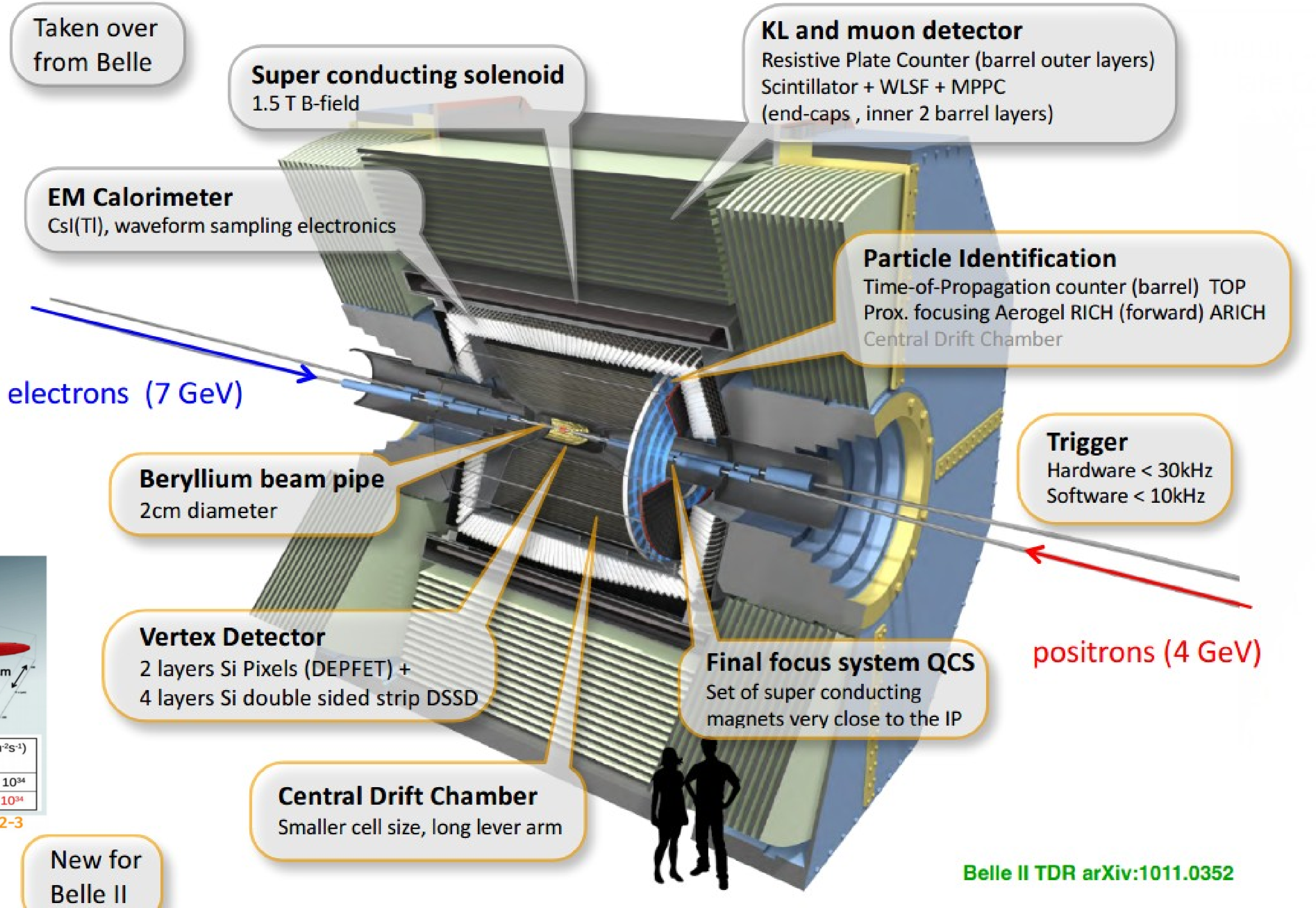
Belle II @ SuperKEKB





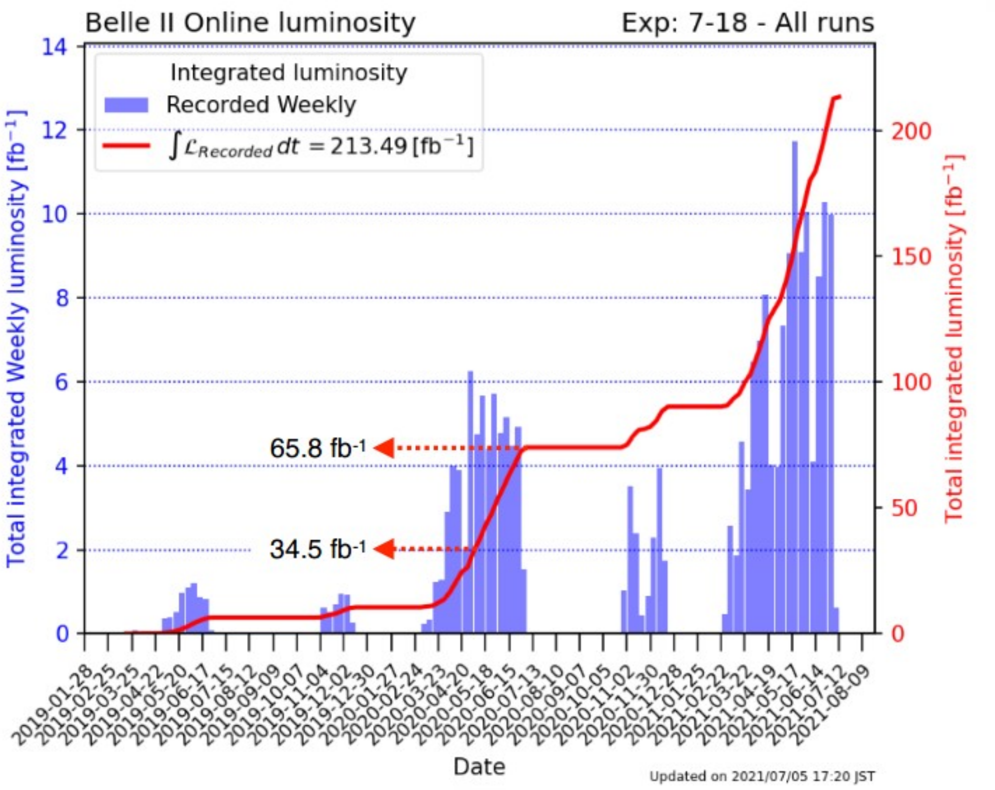
	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

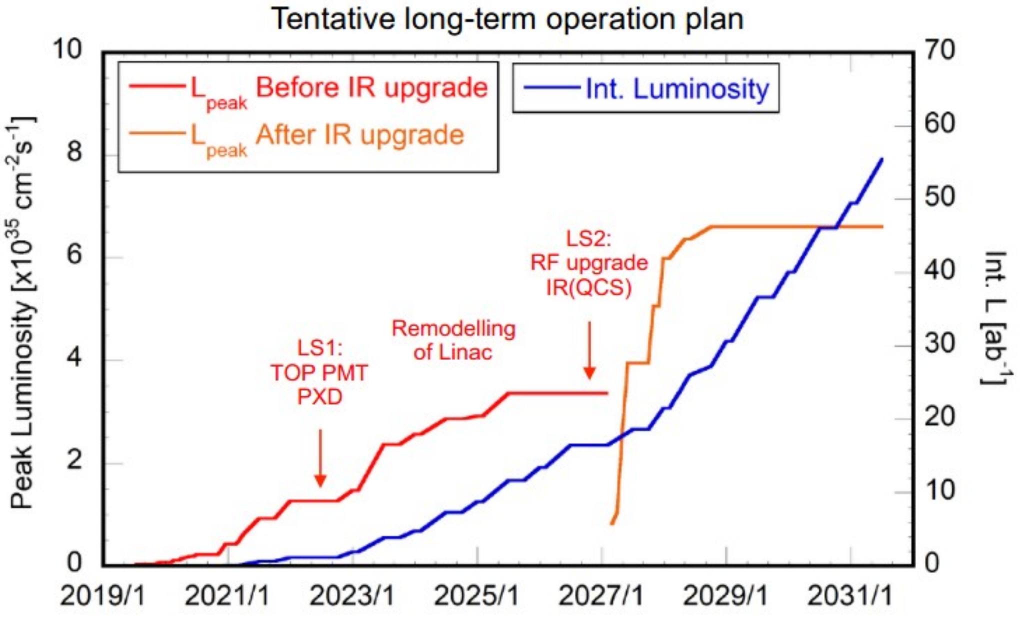
factor 20 factor 2-3



Belle II TDR arXiv:1011.0352

Integrated luminosity and long-term plan

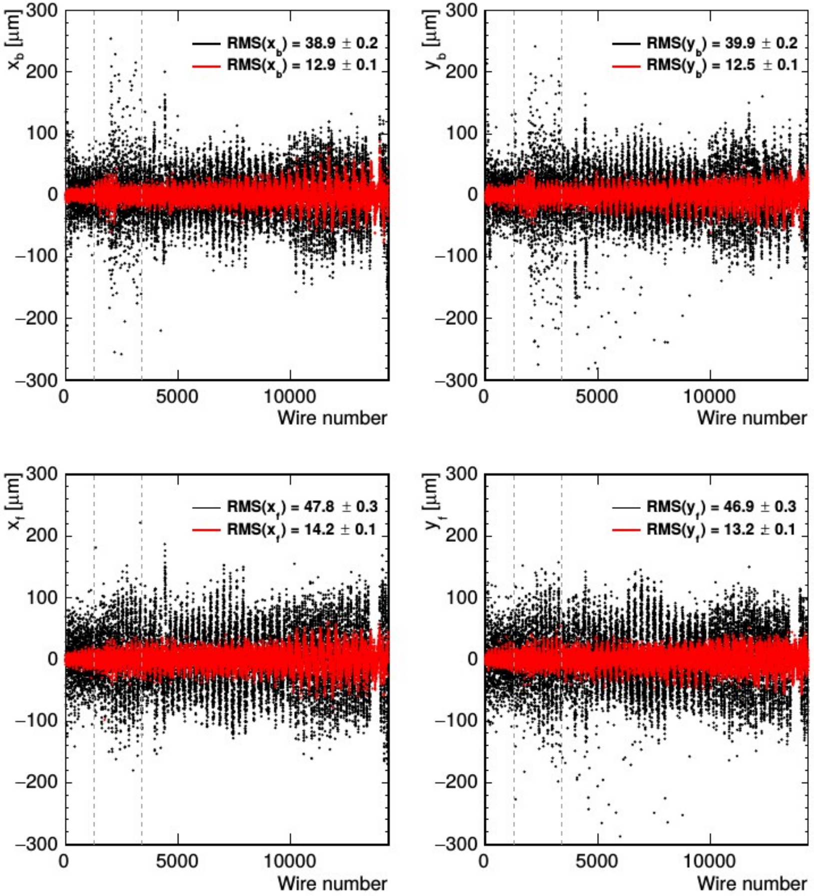




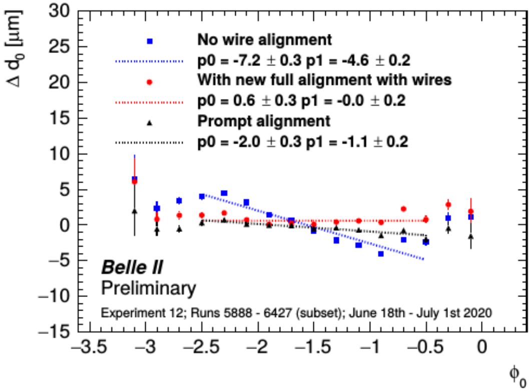
Much more data to come in future ...

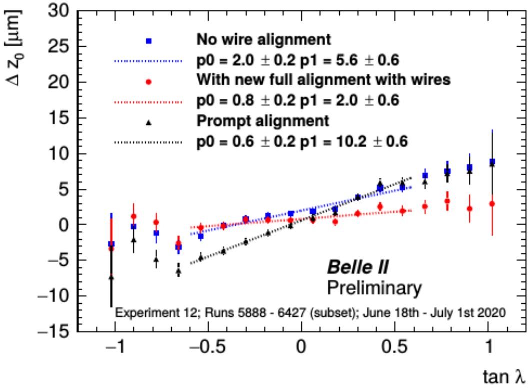
Systematics & Alignment

Alignment of realistic wire misalignment:



Alignment further improves after full reprocessing





Full simultaneous re-alignment with up to 60k parameters of VXD and drift chamber

+ run-dependent alignment of large structures and pixel sensors

Lifetime fit for D mesons

Lifetime extracted by 2D UML fit to decay time and its uncertainty. All parameters extracted directly from the data.

resolution function — fixed from data (binned template)

$$\mathrm{pdf}(t, \sigma_t \,|\, \tau, b, s) \propto \int_0^{\inf} e^{-t_{\mathrm{true}}/\tau} \underbrace{R(t - t_{\mathrm{true}} \,|\, \sigma_t, b, s)}_{\text{resolution function}} dt_{\mathrm{true}} \; \underbrace{pdf(\sigma_t)}_{\text{fixed from data (binned template)}}$$

resolution function

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

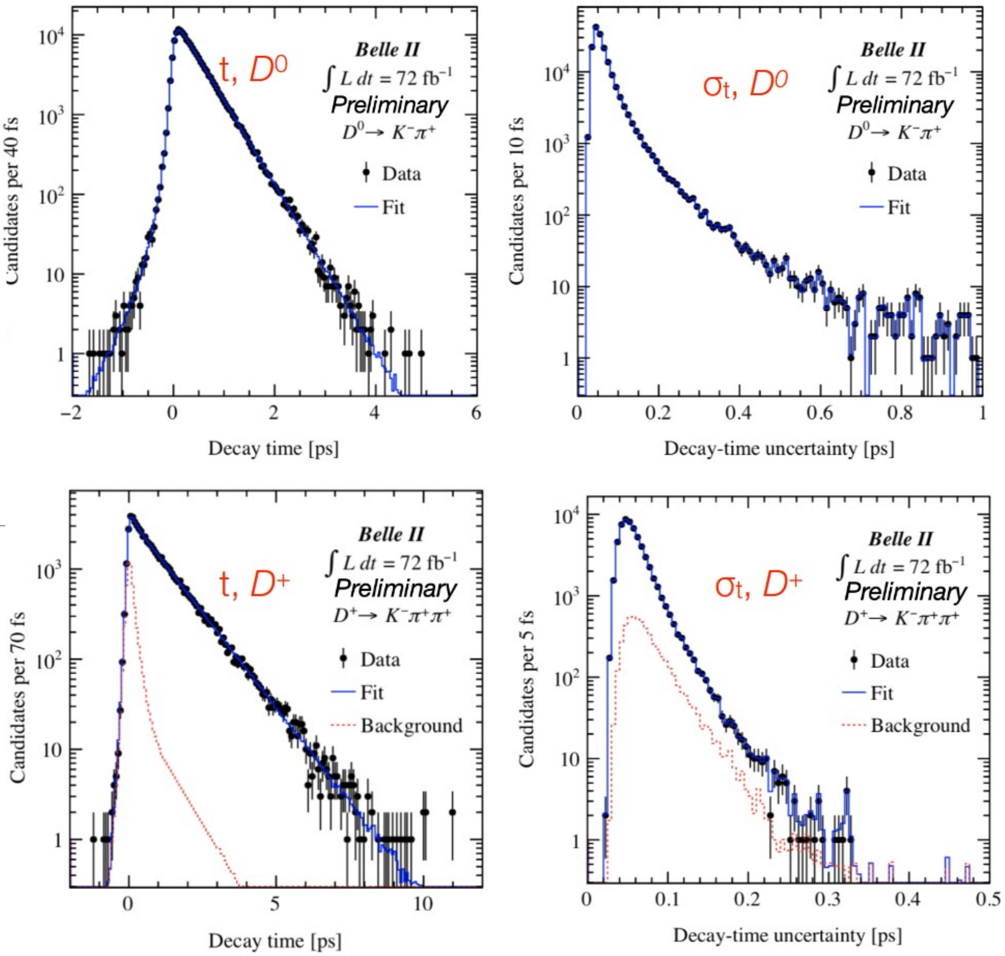
b = bias
s = proper time uncertainty scaling factor

Empirical model for background from data side-bands. Fitted simultaneously with signal region. Bkg fraction fixed to result of mass fit

$$\mathrm{pdf}_{\mathrm{bkg}}(t, \sigma_t) = \mathrm{pdf}_{\mathrm{bkg}}(t \,|\, \sigma_t)\; \mathrm{pdf}_{\mathrm{bkg}}(\sigma_t)$$

zero-lifetime component — lifetime#1 component — lifetime#2 component

$$\mathrm{pdf}_{\mathrm{bkg}}(t|\sigma_t) = \underbrace{(1 - f_{bl})R(t \,|\, b + \boxed{b_{\mathrm{bkg}}}, s\sigma_t)}_{\text{zero-lifetime component}} + f_{bl}\Big[\underbrace{f_{bl1}\mathrm{pdf}_{bl1}(t \,|\, \sigma_t, \boxed{\tau_{b1}}, b + b_{\mathrm{bkg}}, s)}_{\text{lifetime\#1 component}} + \underbrace{(1 - f_{bl1})\mathrm{pdf}_{bl2}(t \,|\, \sigma_t, \boxed{\tau_{b2}}, b + b_{\mathrm{bkg}}, s)}_{\text{lifetime\#2 component}}\Big]$$

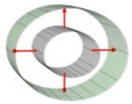
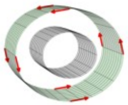
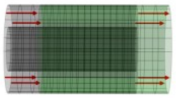
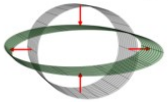
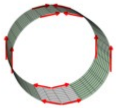
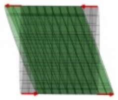
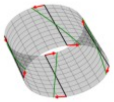
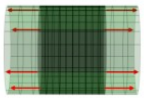


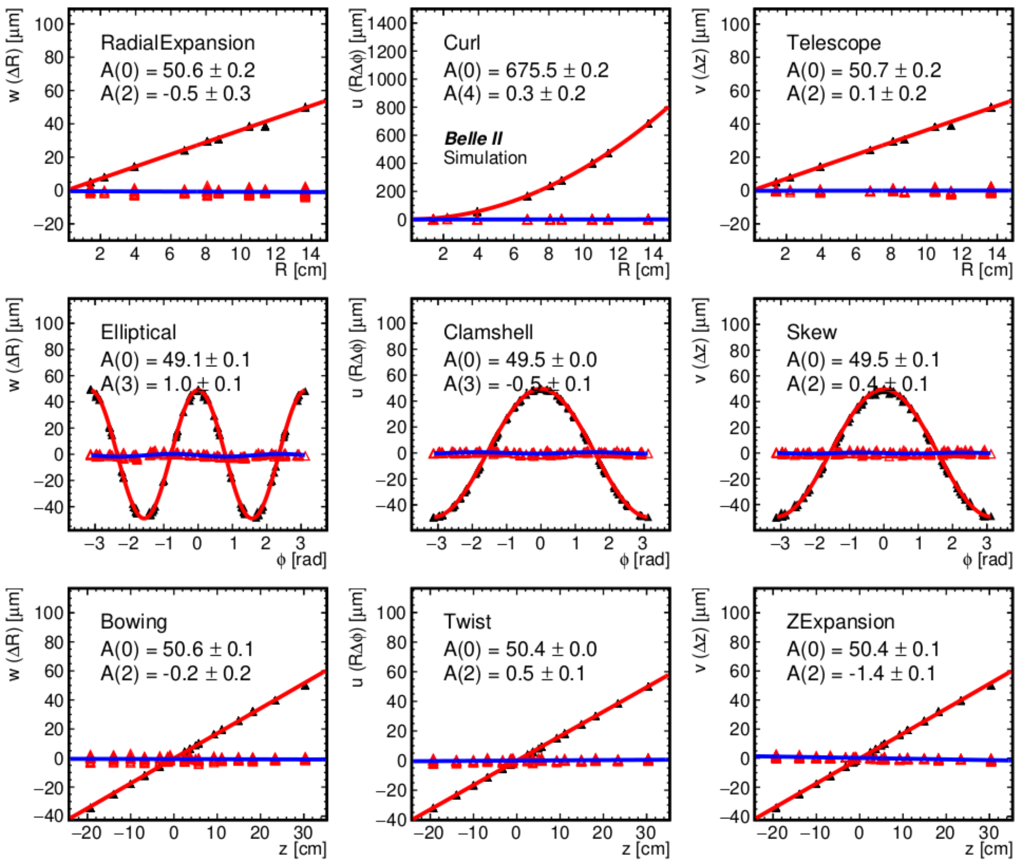
LHCb-Belle II Comparison

Observable	Current Belle/ Babar	2019 LHCb	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})	LHCb (23 fb^{-1})	Belle II Upgrade (250 ab^{-1})	LHCb upgrade II (300 fb^{-1})
CKM precision, new physics in CP Violation							
$\sin 2\beta/\varphi_1$ ($B \to J/\psi K_S$)	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/φ_3	13°	5.4°	4.7°	1.5°	1.5°	0.4°	0.4°
α/φ_2	4°	–	2	0.6°	–	0.3°	–
$\lvert V_{ub}\rvert$ (Belle) or $\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ (LHCb)	4.5%	6%	2%	1%	3%	<1%	1%
φ_s	–	49 mrad	–	–	14 mrad	–	4 mrad
$S_{CP}(B \to \eta' K_S$, gluonic penguin)	0.08	○	0.03	0.015	○	0.007	○
$A_{CP}(B \to K_S \pi^0)$	0.15	–	0.07	0.04	–	0.02	–
New physics in radiative & EW Penguins, LFUV							
$S_{CP}(B_d \to K^* \gamma)$	0.32	○	0.11	0.035	○	0.015	○
$R(B \to K^* l^+ l^-)$ ($1<q^2<6$ GeV$^2/c^2$)	0.24	0.1	0.09	0.03	0.03	0.01	0.01
$R(B \to D^* \tau \nu)$	6%	10%	3%	1.5%	3%	<1%	1%
$Br(B \to \tau \nu)$, $Br(B \to K^* \nu\nu)$	24%, –	–	9%, 25%	4%, 9%	–	1.7%, 4%	–
$Br(B_d \to \mu\mu)$	–	90%	–	–	34%	–	10%
Charm and τ							
$\Delta A_{CP}(KK-\pi\pi)$	–	8.5×10^{-4}	–	5.4×10^{-4}	1.7×10^{-4}	2×10^{-4}	0.3×10^{-4}
$A_{CP}(D \to \pi^+\pi^0)$	1.2%	–	0.5%	0.2%	–	0.1%	–
$Br(\tau \to e \gamma)$	$<120\times10^{-9}$	–	$<40\times10^{-9}$	$<12\times10^{-9}$	–	$<5\times10^{-9}$	–
$Br(\tau \to \mu\mu\mu)$	$<21\times10^{-9}$	$<46\times10^{-9}$	$<3\times10^{-9}$	$<3\times10^{-9}$	$<16\times10^{-9}$	$<0.3\times10^{-9}$	$<5\times10^{-9}$

arXiv: 1808.08865 (Physics case for LHCb upgrade II), PTEP 2019 (2019) 12, 123C01 (Belle II Physics Book)

Sensitivity of VXD to systematic (weak mode) misalignments

	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** $\Delta r = c_{scale} \cdot \|z\|$ 	**Twist** $r\Delta\phi = c_{scale} \cdot z$ 	**Z expansion** $\Delta z = c_{scale} \cdot z$ 



Lifetime of Λ_c^+