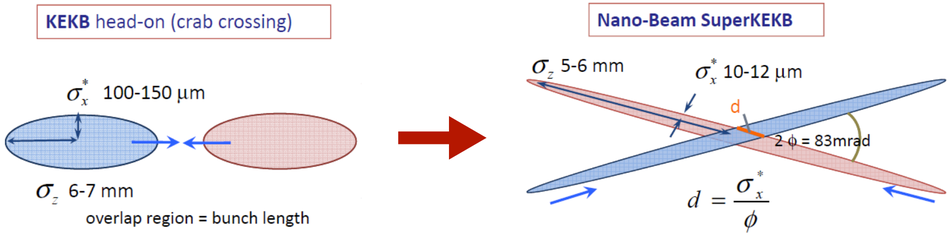
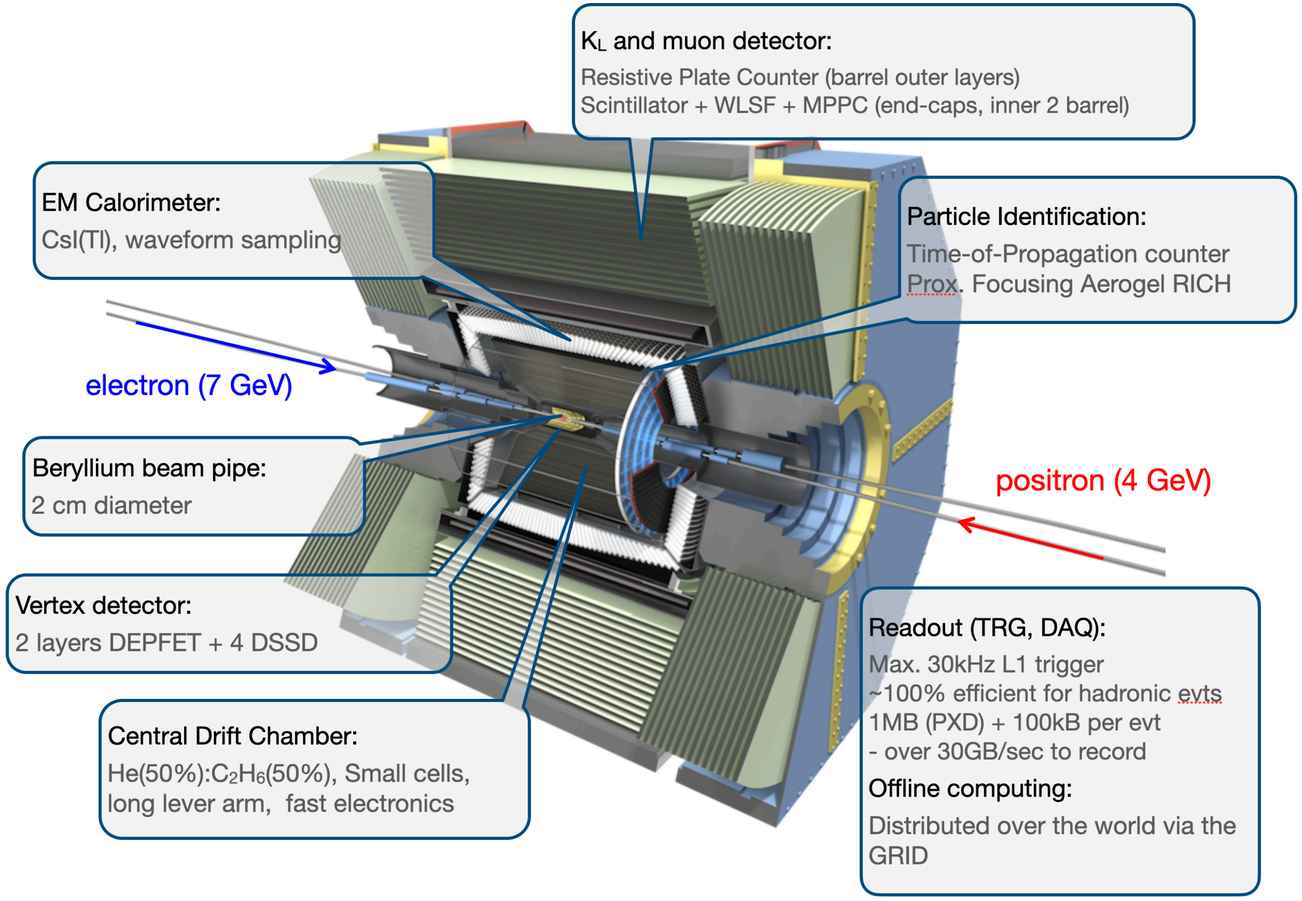
Recent Belle II results on time-dependent CP violation and charm physics

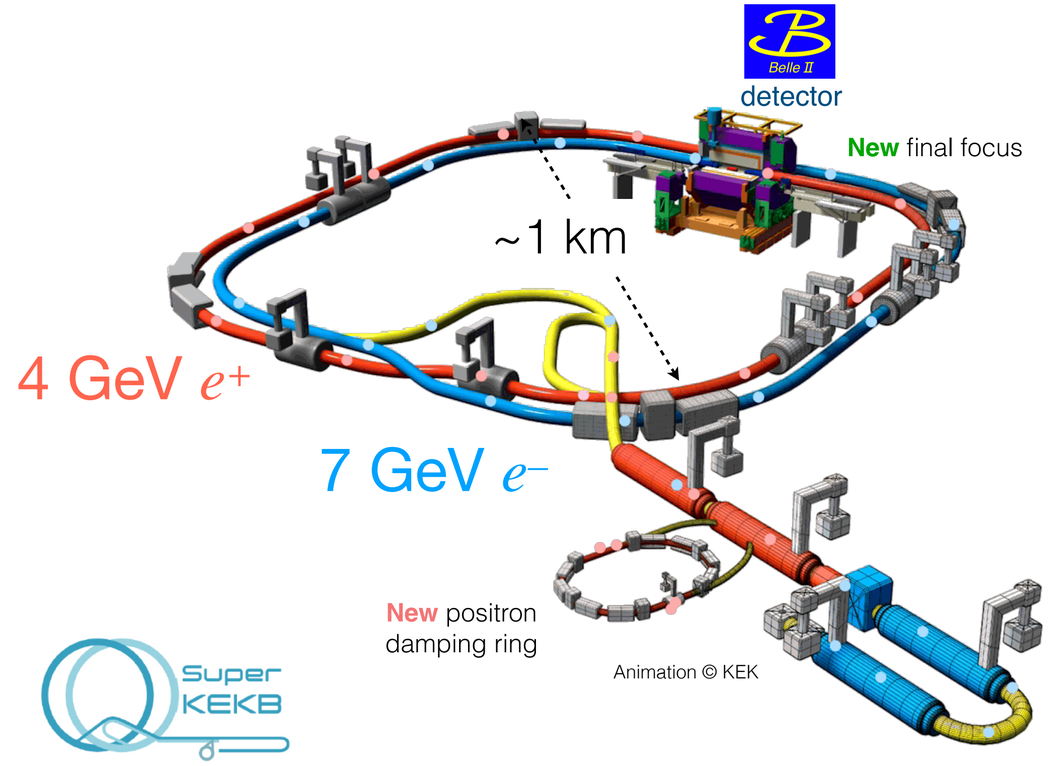
Jake Bennett
University of Mississippi
FPCP 2023 - Lyon, France

SuperKEKB

High-luminosity Super B factory



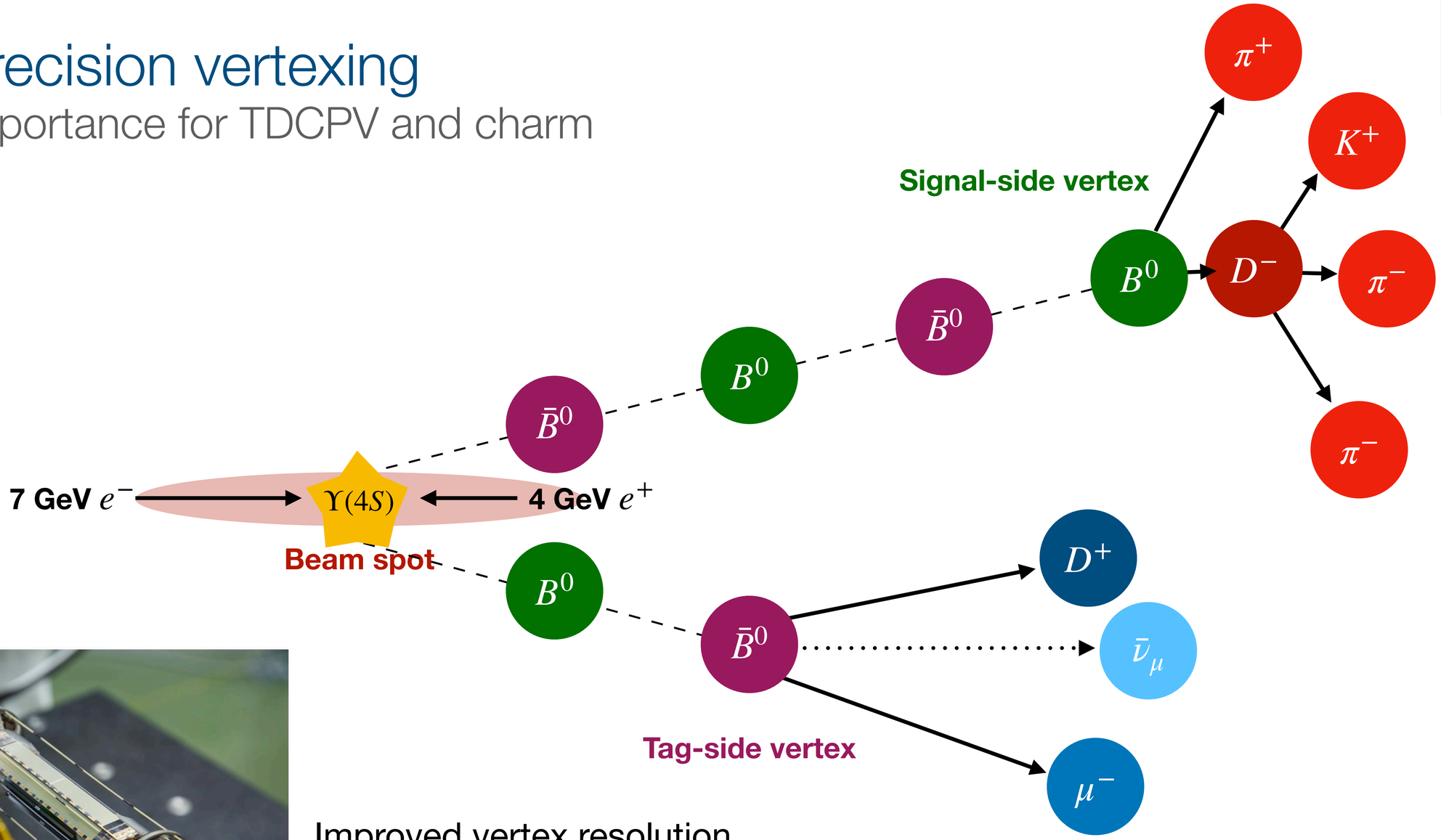


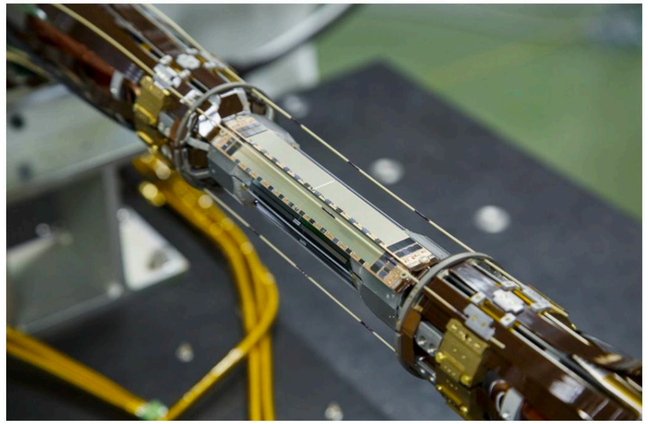


$$u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ \ell^+\ell^- \leftarrow e^+e^- \rightarrow \Upsilon(\mathrm{nS}) \rightarrow B^{(*)}\bar{B}^{(*)}$$

High-precision vertexing

and its importance for TDCPV and charm





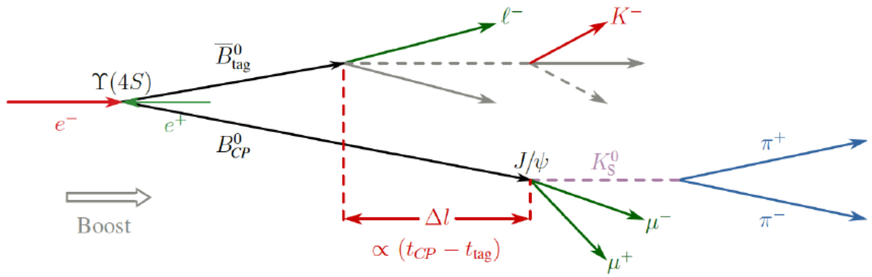
Improved vertex resolution
due to pixel detector
(despite lower boost)

Identifying new CP-violating phases in the quark sector

High sensitivity to New Physics

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_d}}{4\tau_d}\left\{1 + q\left[A_{CP}\cos(\Delta m_d \Delta t) + S_{CP}\sin(\Delta m_d \Delta t)\right]\right\}$$

$A_{CP} \approx 0$ in the SM $\qquad$ $S_{CP} \approx \sin 2\beta$ in the SM

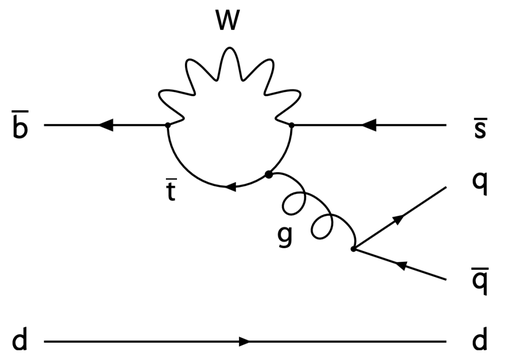


- Some experimentally challenging modes:
  - Fully hadronic final state with neutrals (Unique to Belle II)
  - Low purity → dedicated continuum suppression algorithms

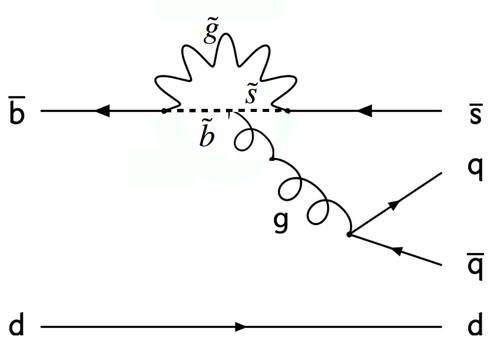
$S_{\rm penguin} \approx$ $\sin 2\beta$ (SM)

$A_{\rm penguin} \approx$ 0 (SM)

Suppressed in SM



Access to potential BSM physics



+ ΔS (NP)

+ ΔA (NP)

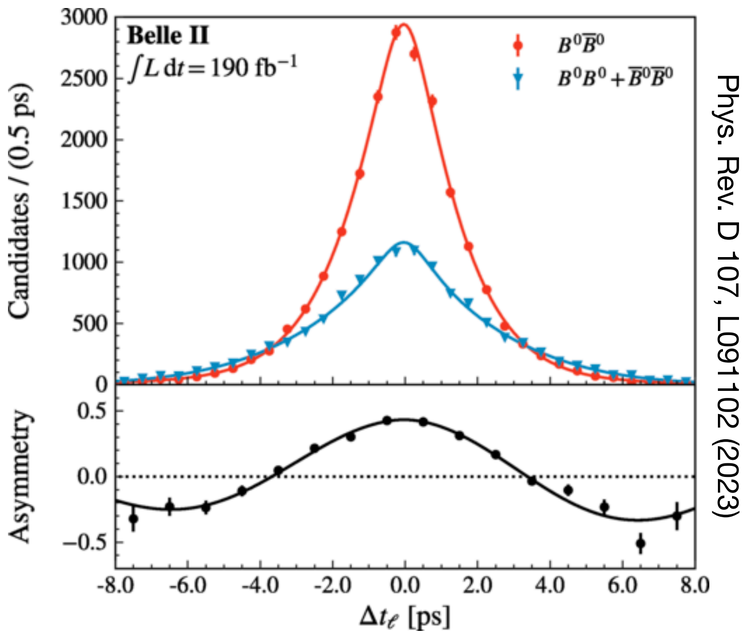
$\sin 2\beta/\phi_1$

The bread-and-butter for B factories

More details by J. Skorupa on Thursday

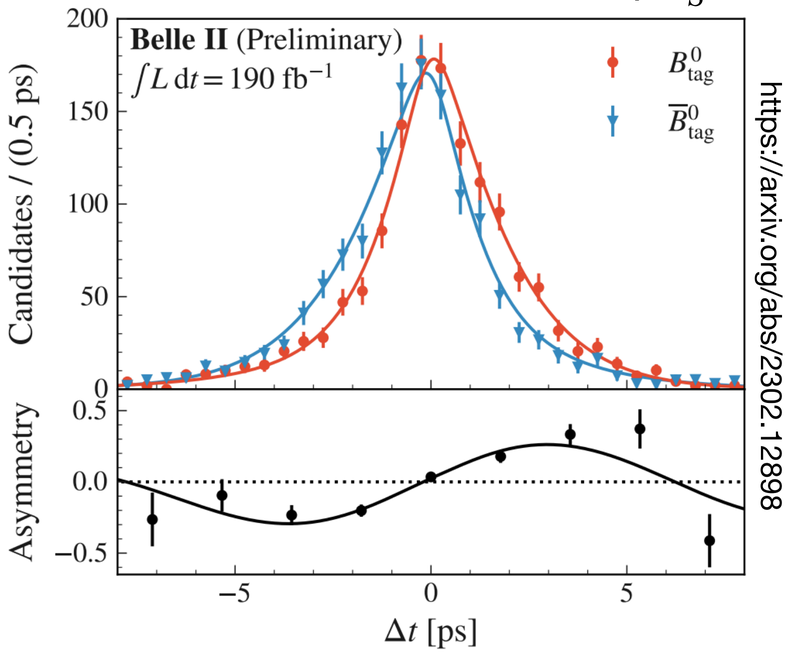
- SM measurement, but important analysis to refine all our tools for future measurement sensitive to NP (e.g. $B^0 \to K^0_S K^0_S K^0_S$ - see following): we are ready!
- Essential to validate Δt resolution (~1 ps) & flavor tagger (ϵ_{tag} ~ 30%) performance for TDCPV analyses

33k events from $B^0 \to D^{(*)-}\pi^+$



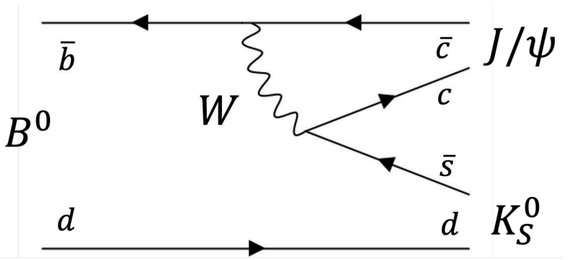
Phys. Rev. D 107, L091102 (2023)

2.8k events from $B^0 \to J/\psi K^0_S$



https://arxiv.org/abs/2302.12898

Reference mode for measurement of β with gluonic penguins



$\tau_{B^0} = 1.499 \pm 0.013 \pm 0.008$ ps w.a. 1.519 ± 0.004 ps

$\Delta m_d = 0.516 \pm 0.008 \pm 0.005\ \text{ps}^{-1}$ w.a. $0.5065 \pm 0.0019\ \text{ps}^{-1}$

$S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$ w.a. 0.698 ± 0.017

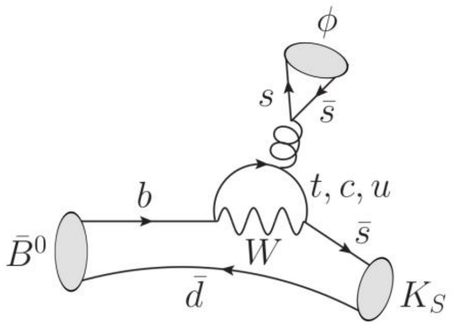
$A_{CP} = 0.094 \pm 0.044(\text{stat})^{+0.042}_{-0.017}(\text{syst})$ w.a. -0.005 ± 0.015

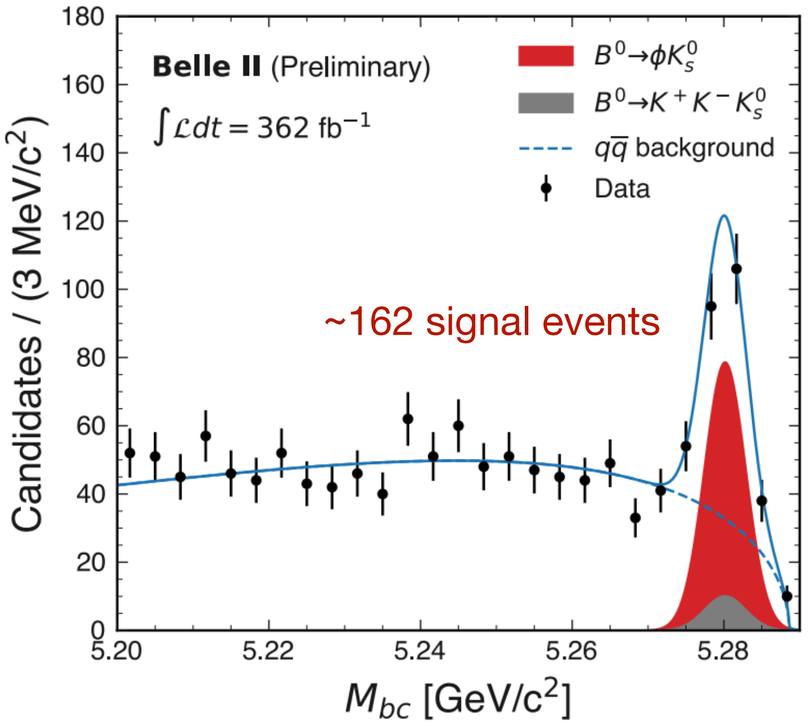
Recent results
in time-dependent CP violation

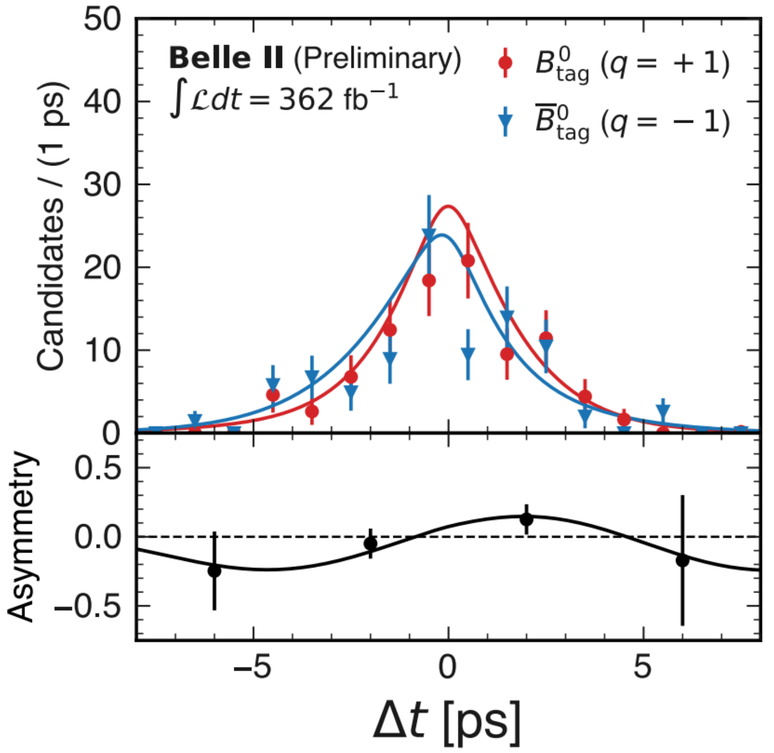
$B^0 \to \phi K^0_S$ on par with best measurements

- Clean experimental signature
- Calibration of resolution and tagging with $B \to D^*\pi$
- Validated with $B^+ \to \phi K^+$ (null asymmetry test)
- 4D fit: (M_{bc}, O'_{CS}, $\cos(\theta)$, Δt)

Continuum suppression BDT output







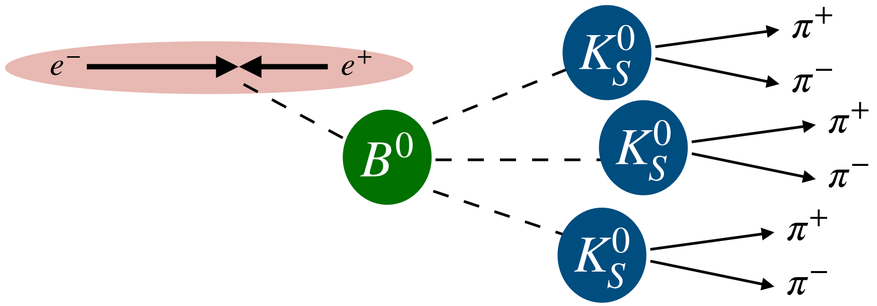
$$A_{CP} = 0.31 \pm 0.20^{+0.05}_{-0.06} \qquad A^{w.a.}_{CP} = -0.01 \pm 0.14$$

$$S_{CP} = 0.54 \pm 0.26^{+0.06}_{-0.08} \qquad S^{w.a.}_{CP} = 0.59 \pm 0.14$$

Recent results
in time-dependent CP violation

$B^0 \to K^0_S K^0_S K^0_S$ on par with best measurements

- Complex vertexing (only displaced tracks!)
- 3D signal fit: (M_{bc}, M_B, O'_{CS}) simultaneous fit with
  - $B^+ \to K^0_S K^0_S K^+$ (background, Δt calibration)
  - time-ind $B^0 \to K^0_S K^0_S K^0_S$ for A_{CP} constraint
- Δt fit to extract A_{CP} and S_{CP}



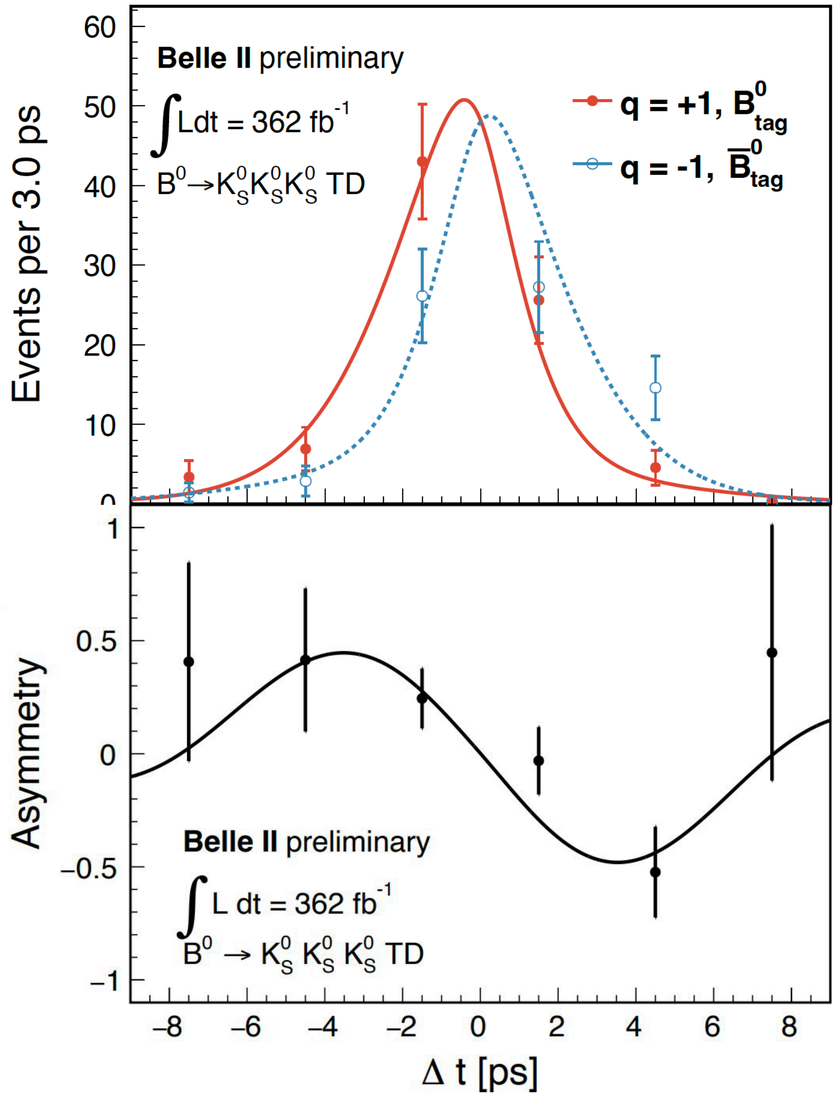
(K^0_S flight distance ~10 cm)

$$A_{CP} = 0.07^{+0.15}_{-0.20} \pm 0.02$$

$$S_{CP} = -1.37^{+0.35}_{-0.45} \pm 0.03$$

$$A_{CP}^{w.a.} = 0.15 \pm 0.12$$

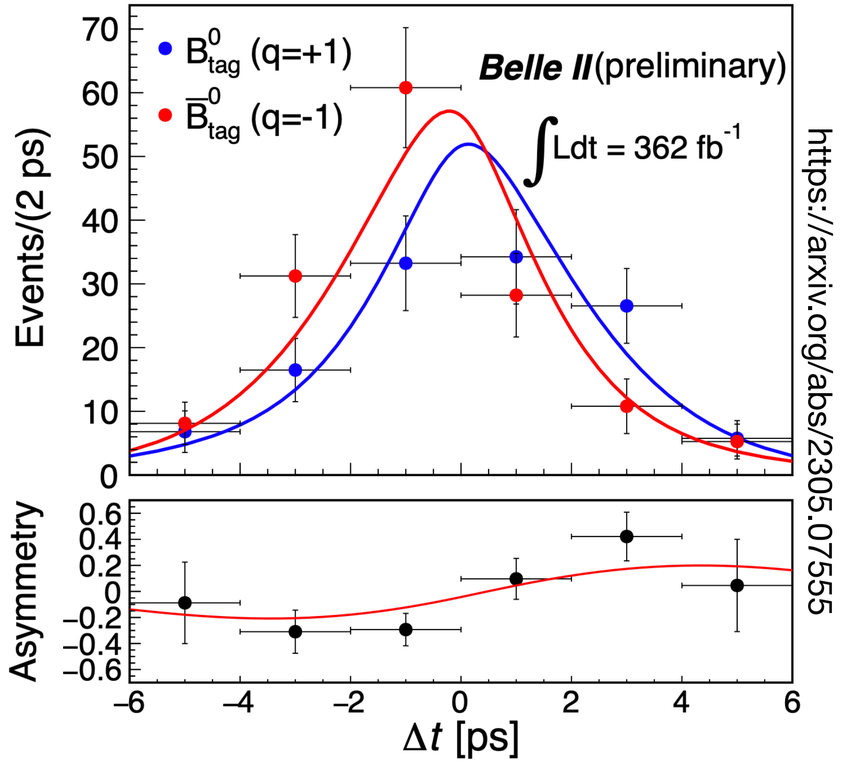
$$S_{CP}^{w.a.} = -0.83 \pm 0.17$$



Recent results
in time-dependent CP violation

More details by S. Raiz next session

$B^0 \to K^0_S\pi^0$ on par with best measurements



$$A_{CP} = 0.04 \pm 0.15 \pm 0.05 \qquad A_{CP}^{w.a.} = 0.00 \pm 0.13$$

$$S_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04 \qquad S_{CP}^{w.a.} = 0.58 \pm 0.17$$

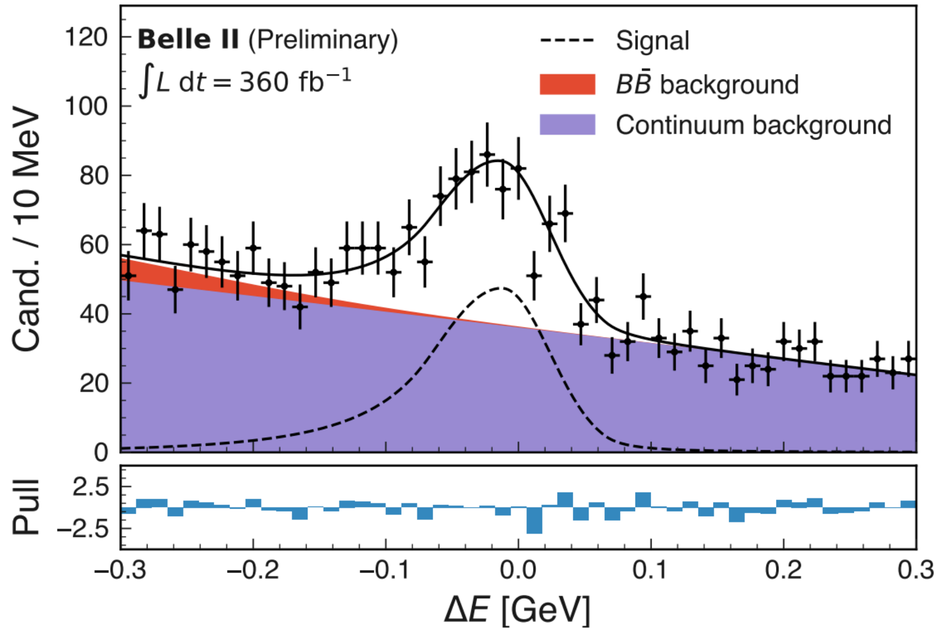
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+} \cdot \frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0} \cdot \frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0} \cdot \frac{\mathcal{B}_{K^0\pi^0}}{\mathcal{B}_{K^+\pi^-}} \approx 0$$

- Combine $B^0 \to K^0_S\pi^0$ with time-integrated analysis:

$$A_{CP}^{K^0_S\pi^0} = -0.01 \pm 0.12 \pm 0.05 \qquad w.a. = -0.0 \pm 0.13$$

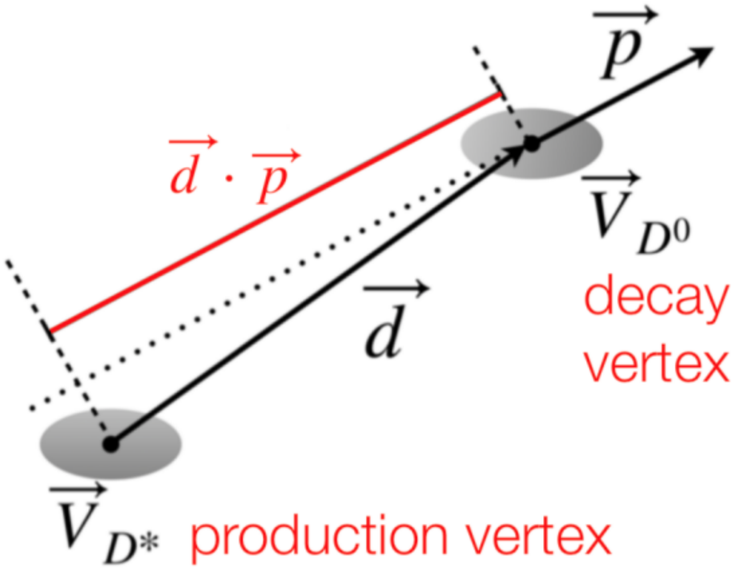
- Combining all $B \to K\pi$ final states at Belle II:

$$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05 \qquad w.a. = 0.13 \pm 0.11$$



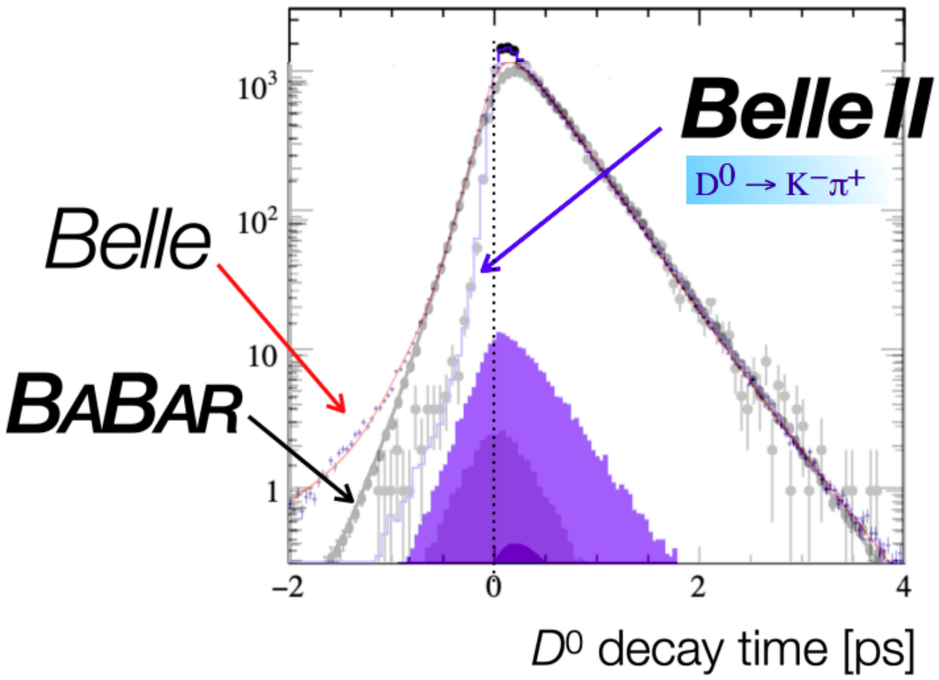
Precise charm lifetime measurements

Leveraging the excellent detector performance



- Lifetimes from distance between production and decay vertices
  - Decay times become negative due to resolution (tool to understand resolution)
  - High precision measurements probe beam spot and alignment calibration

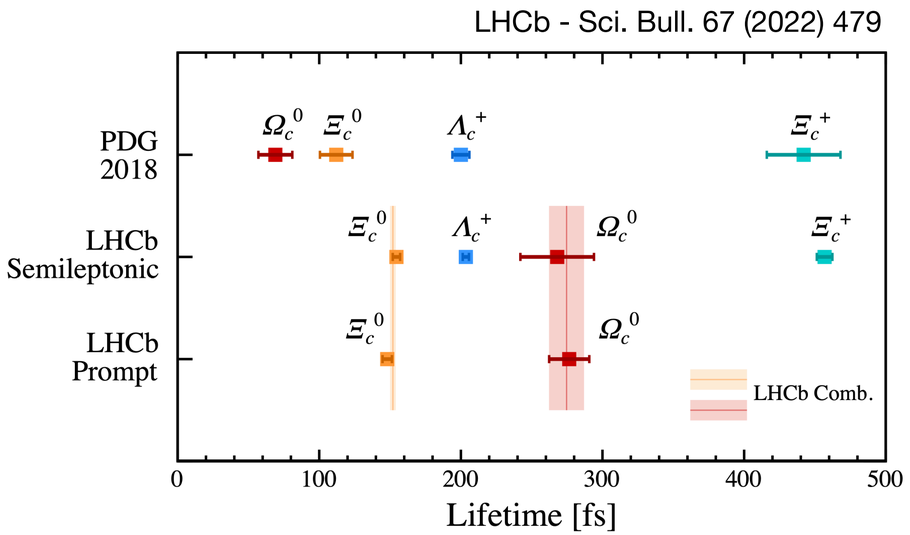
$$t = \frac{m_D}{p}\left(\vec{d} \cdot \hat{p}\right)$$



- Belle II can make precision, absolute lifetime measurements
  - Large samples of exclusive charm decays *without lifetime-biasing triggers and selections*
  - Precise calibration of final state particle momenta
  - Excellent vertex detector alignment
  - Very good vertex resolution, small beam size

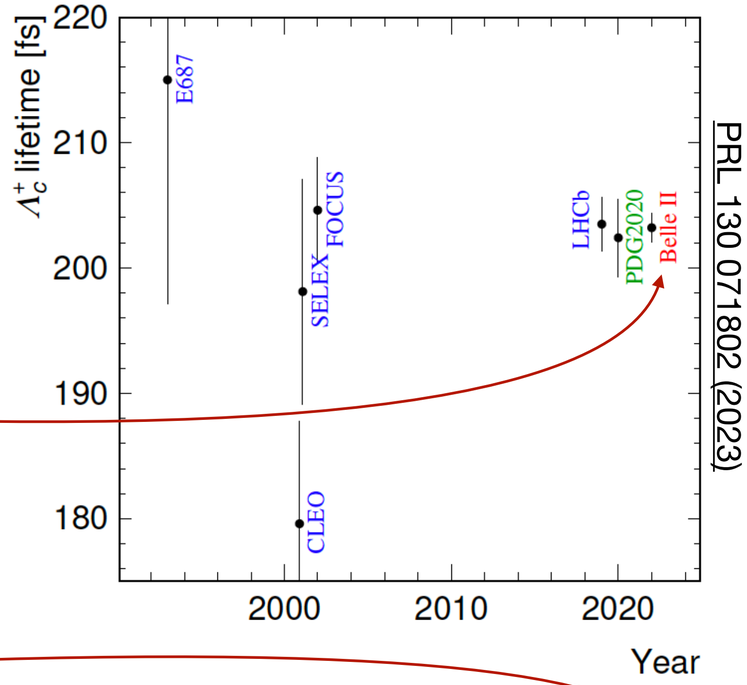
Charmed baryon lifetimes at Belle II

Confirming recent upheaval

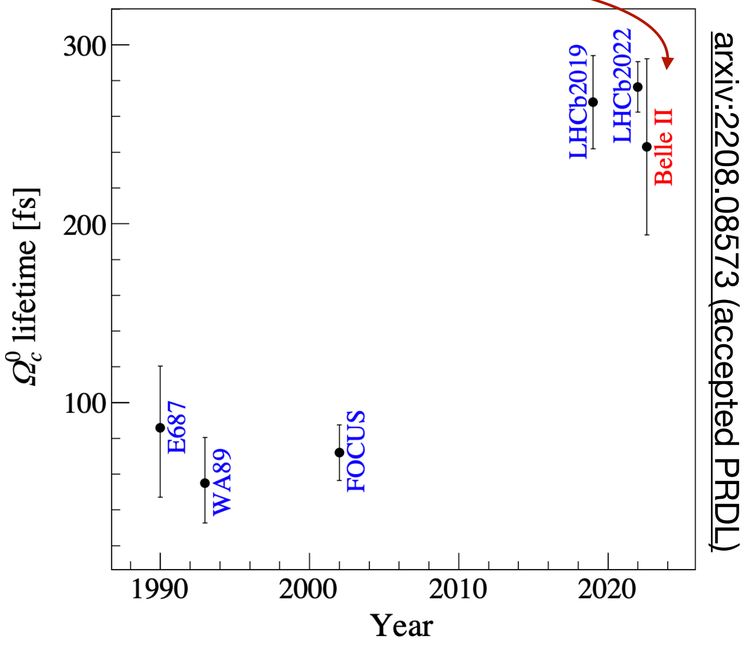


$$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$$

- World's best measurement of the Λ_c^+ lifetime
- Confirmed LHCb measurement for Ω_c^0 lifetime that challenged earlier determinations and HQE expectations
- More confirmation of the excellent performance and alignment of the Belle II vertex detector



PRL 130 071802 (2023)

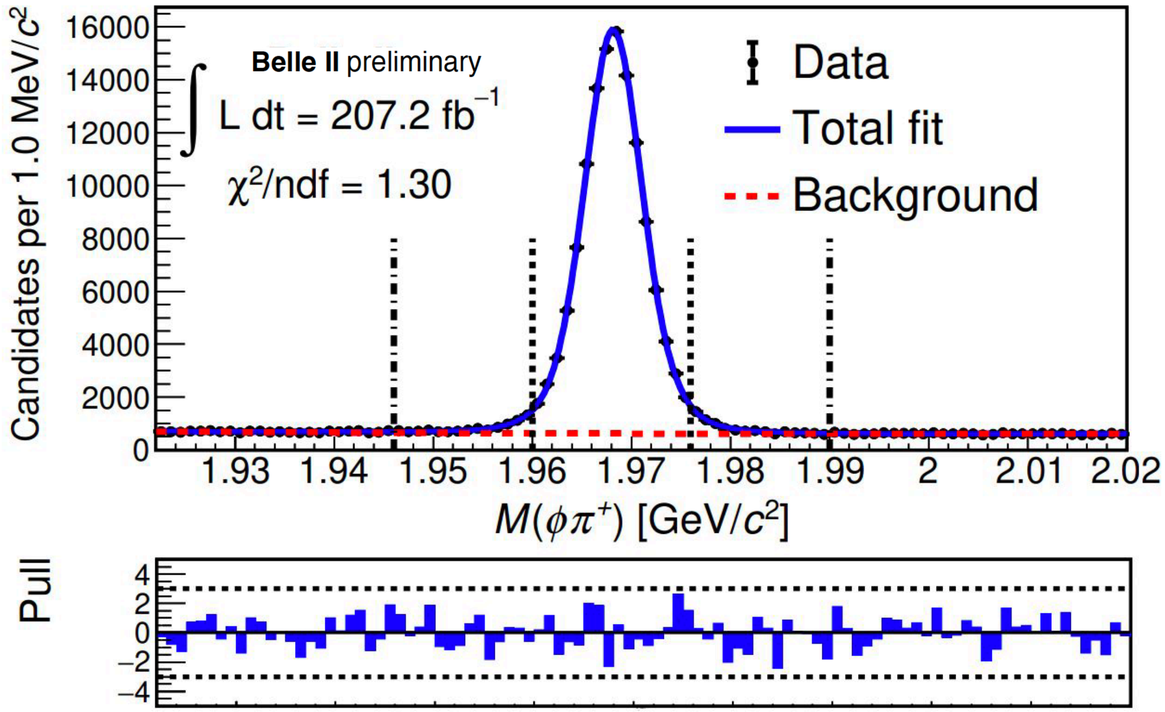


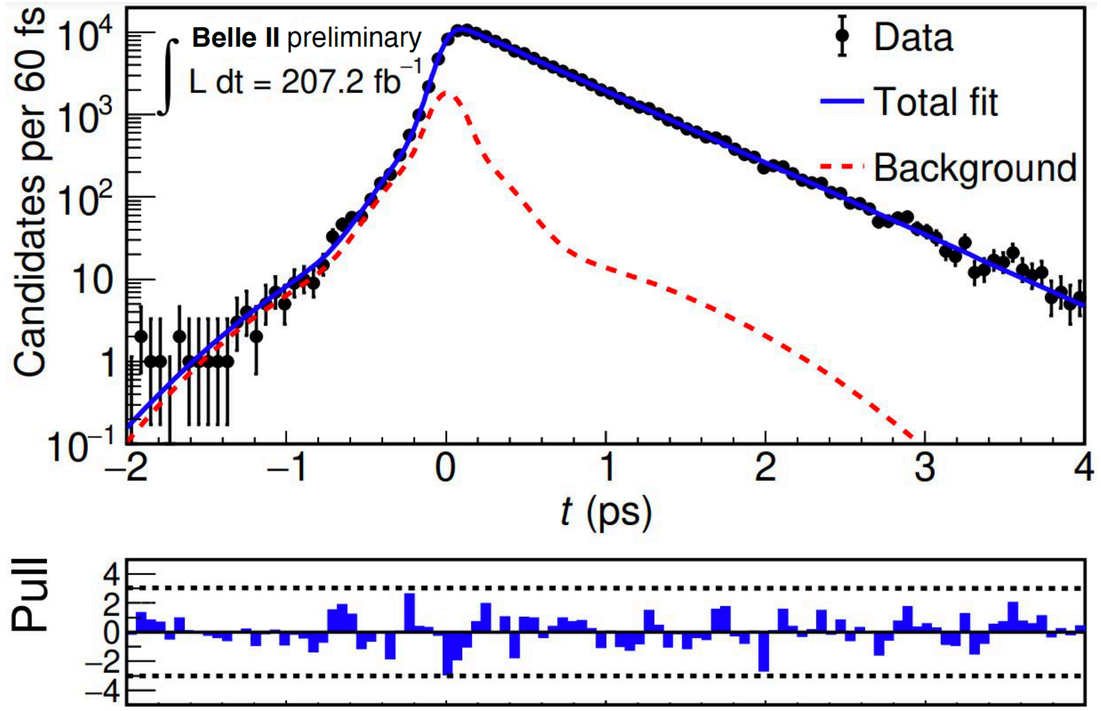
arxiv:2208.08573 (accepted PRDL)

Another world-leading lifetime measurement

D_s lifetime measurement

- Measured $\tau_{D_s^+} = (498.7 \pm 1.7^{+1.1}_{-0.8})$ fs using 116×10^3 $D_s^+ \to \pi^+[\phi \to K^+K^-]$ decays
  - Consistent with by about twice as precise as current world-average (504 ± 4) fs
  - Also consistent with theory predictions ($\tau_{D_s^+} \sim \tau_{D^0}$)

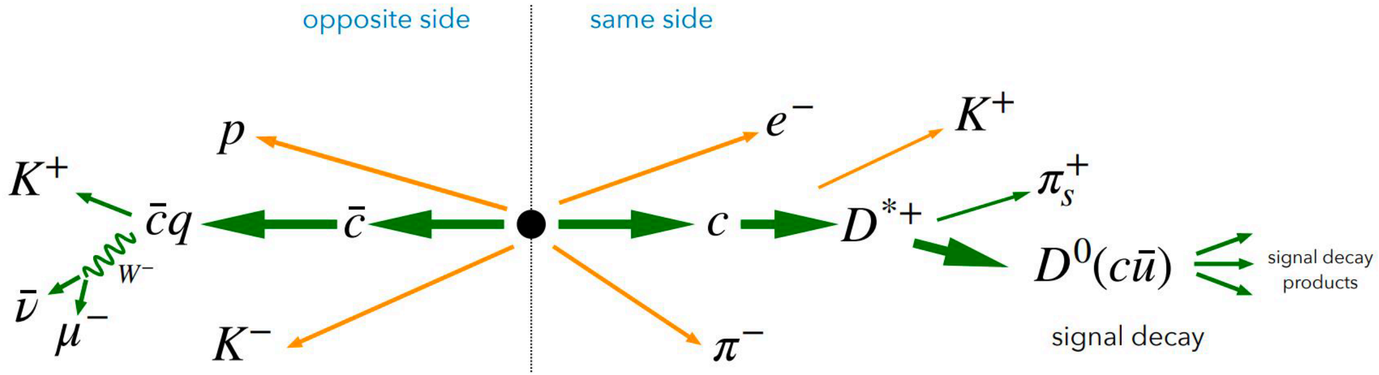




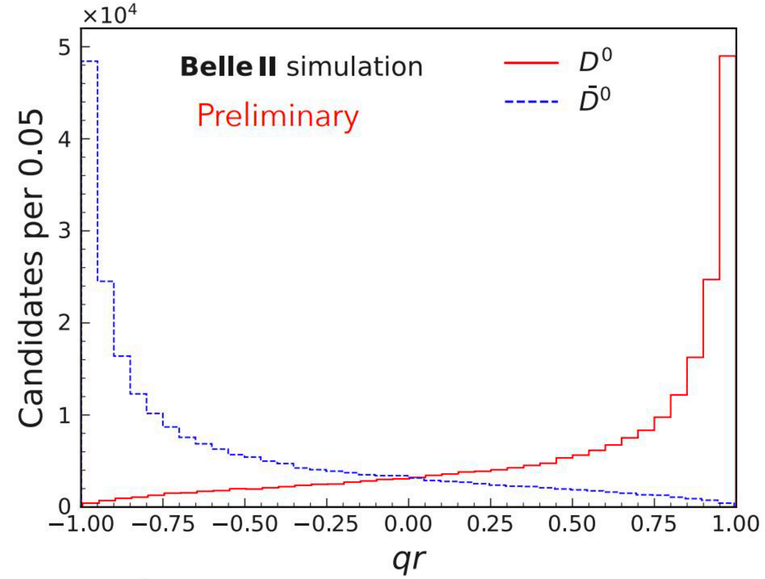
Charm flavor tagger (CFT)

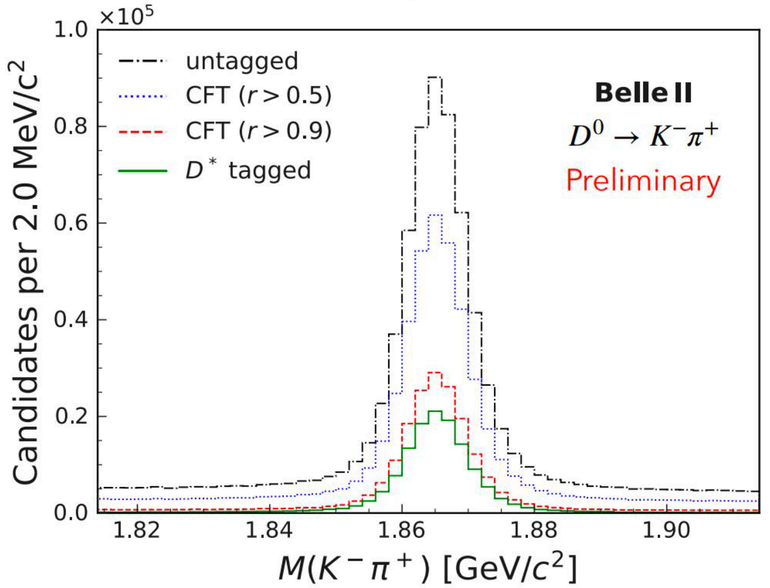
Novel method to identify production flavor of neutral charmed mesons

- CPV in charm: only up-type quark forming a meson mixing system
- CFT exploits correlation between the flavor of a reconstructed neutral D meson and the electric charges of the rest of the event



- Tagging decision (q) chosen to be +1 (-1) for D^0 ($\bar{D}^0$), dilution factor (r) close to one for perfect prediction, zero for random guess
- Effective tagging efficiency $\epsilon_{\text{tag}}^{\text{eff}} = (47.91 \pm 0.07(\text{stat}) \pm 0.51(\text{syst}))\,\%$, independent of decay mode
- Approximately doubles effective size of many CPV, mixing measurements
- Basic principles can be used at other experiments





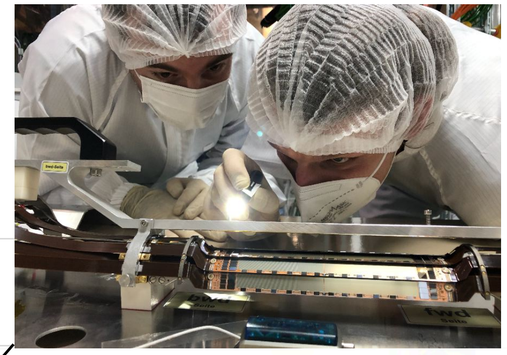
https://arxiv.org/abs/2304.02042

Summary

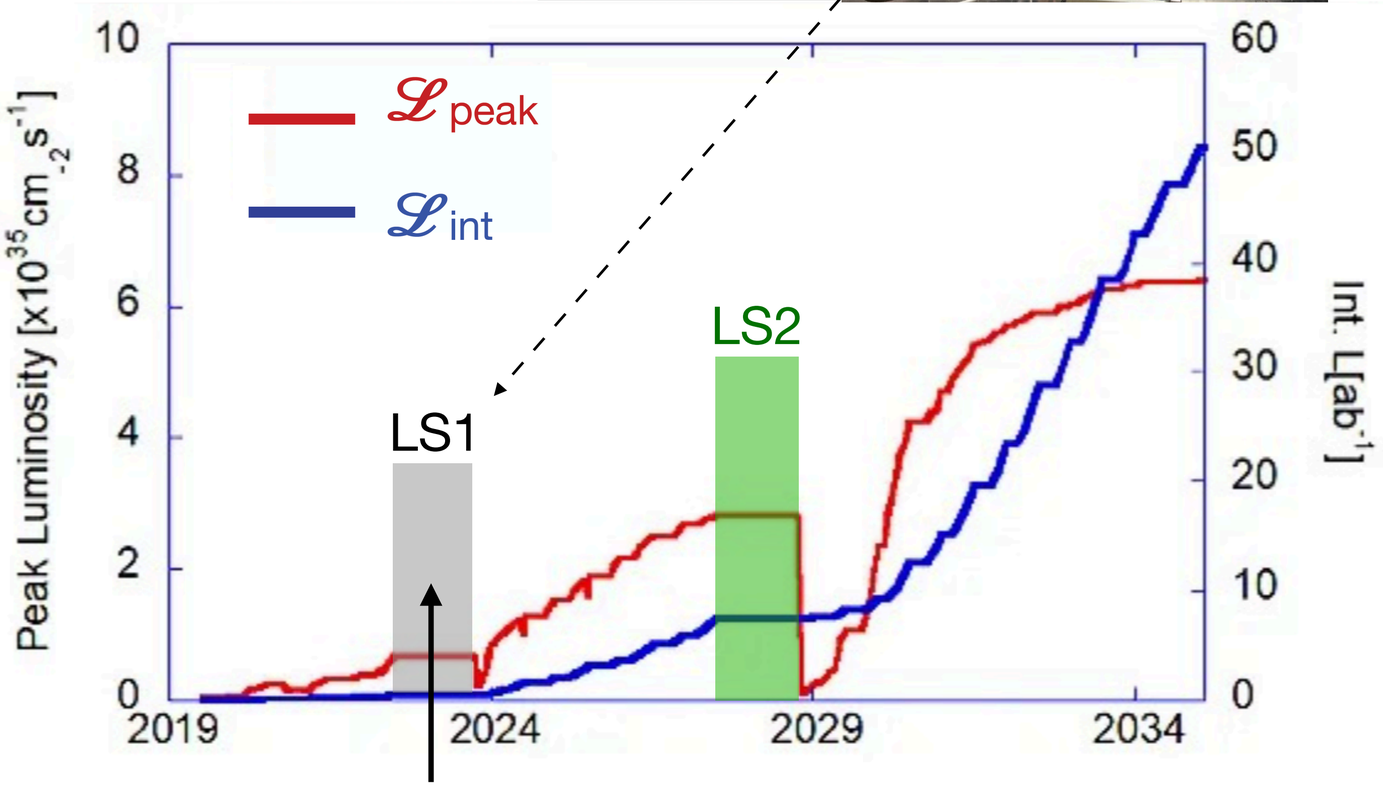
- Upgraded SuperKEKB accelerator, improved Belle II detector, refined analysis techniques
- The physics program of Belle II has outstanding potential for discovering BSM physics over the next decade
  - Broad program of fundamental weak interaction measurements
  - New Physics discoveries possible in searches unique to Belle II
  - New tools and techniques enhance Belle II physics capabilities
- With half the dataset of previous B-factories, Belle II is already producing competitive results
- Only 0.5% of target integrated luminosity collected so far - much more to come!

The road to 50 ab^{-1}

Until 2035



PXD arrives at KEK for testing



You are here:

$\mathscr{L}_{\text{int}} = 424\ \text{fb}^{-1}$ (~half the Belle dataset)

$\mathscr{L}_{\text{peak}} = 4.7 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ (world record!) ~5x $\mathscr{L}$(PEP-II)

- Long Shutdown 1 (LS1)
  - Ongoing since summer 2022
  - Maintenance and upgrade of machine and detector
  - Data taking will resume in early 2024
- Long Shutdown 2 (LS2)
  - To be confirmed
  - Upgrade of the SuperKEKB interaction region to enable $\mathscr{L}_{\text{peak}} = 6 \times 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$
- Key challenge to increasing beam currents and squeezing beam-size at interaction point: beam-beam blowup