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

Rencontres de Blois
17/05/2023

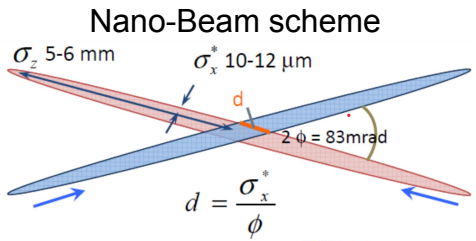
Jakub Kandra
(INFN Padova)
on behalf of Belle II collaboration

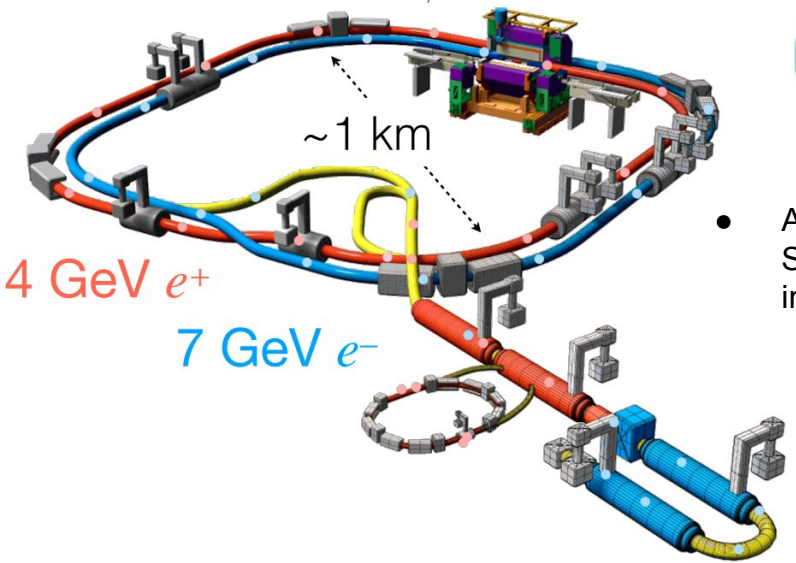
Recent Belle II results

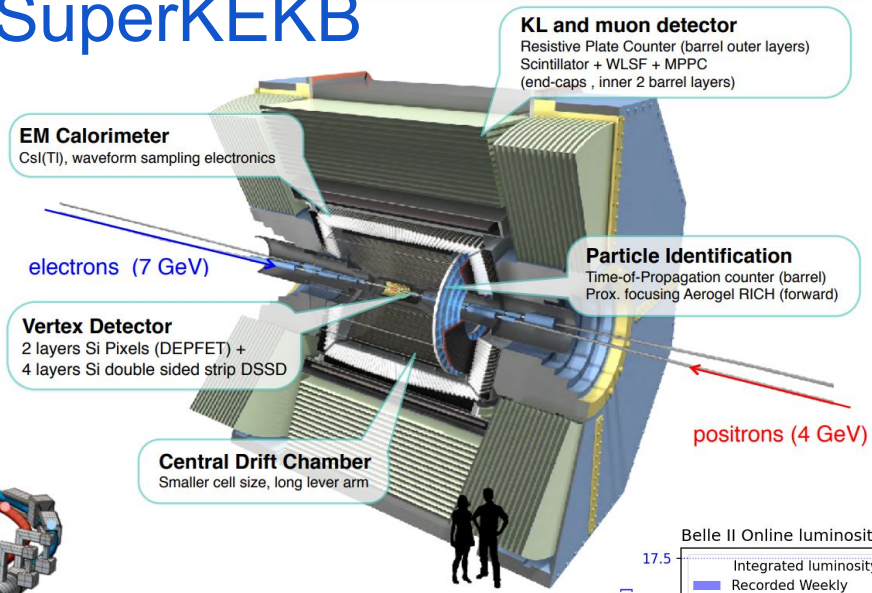
- Belle II detector at SuperKEKB
- Time-dependent CP violation
  - $B^0 \to \phi K_S$
  - $B^0 \to K_S K_S K_S$
  - $B^0 \to K_S \pi^0$
- Charm physics
  - Charm lifetime measurements
  - D^+_s lifetime measurement
  - Charm flavor tagger

Jakub Kandra, INFN Padova

Belle II detector at SuperKEKB

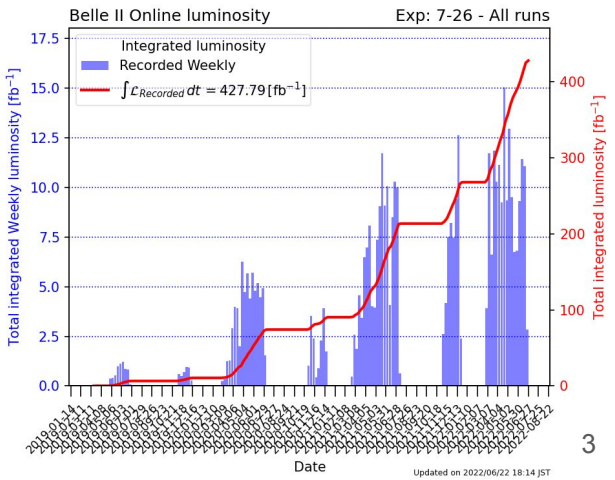






- Excellent vertex resolution
- Efficient neutrals reconstruction (π^0, K_S)
- K/π separation

- Asymmetric e^+e^- collisions at the SuperKEKB accelerator complex in Japan
  - Recorded world's highest instantaneous luminosity (4.7×10^{34} $cm^{-2}s^{-1}$)
  - Collected 362 fb^{-1} dataset at the Y(4S) in 2019-22, corresponding to 387M $B\bar{B}$ pairs



Recent Belle II results

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  - $B^0 \to \phi K_S$
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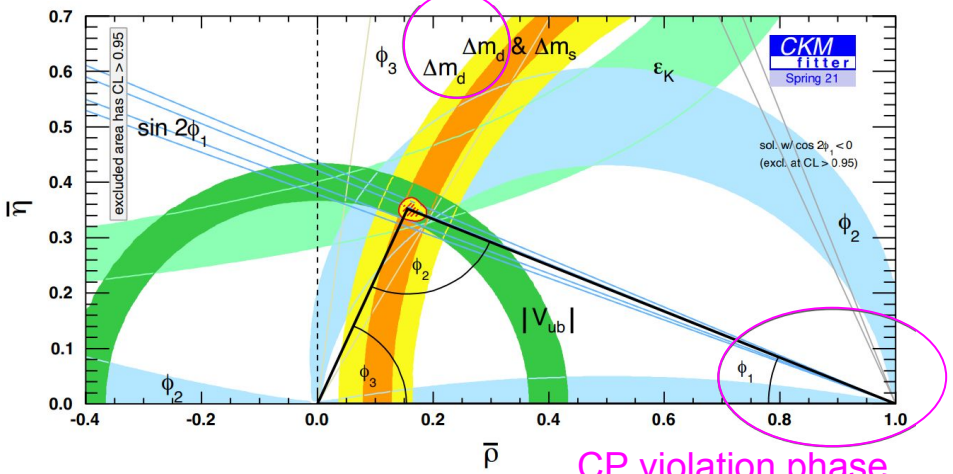
- Charm physics
  - Charm lifetime measurements
  - D^+_s lifetime measurement
  - Charm flavor tagger

Time-dependent CP violation

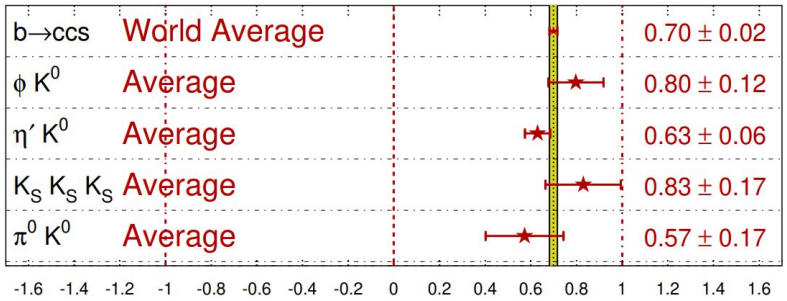
- Measurements of $\sin 2\varphi_1$ in $b \to qqs$ transitions as a probe of beyond SM physics
  - Clean theory prediction (~few %)
  - Loop-suppressed, potentially affected by competing BSM amplitudes
- Experimentally challenging, due to
  - Small BF (~10^{-6}) and neutrals in the final state (K_S, π^0)
  - Sophisticated analysis techniques (tagging and Δt resolution)
- Validated with benchmark mixing and CPV analyses ($B \to D^{(*)}\pi$ and $B \to J/\psi K_S$)

mixing frequency



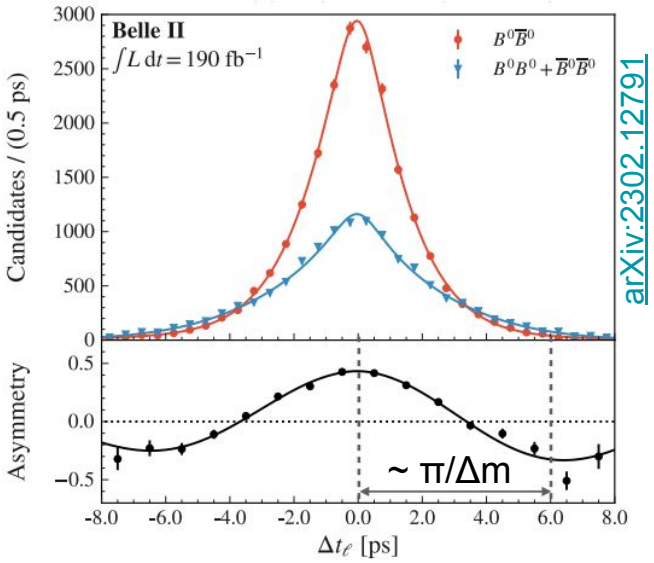
CP violation phase

$$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$$ HFLAV 2021



Δm and sin2φ$_1$

B→D(*)π (flavor specific)

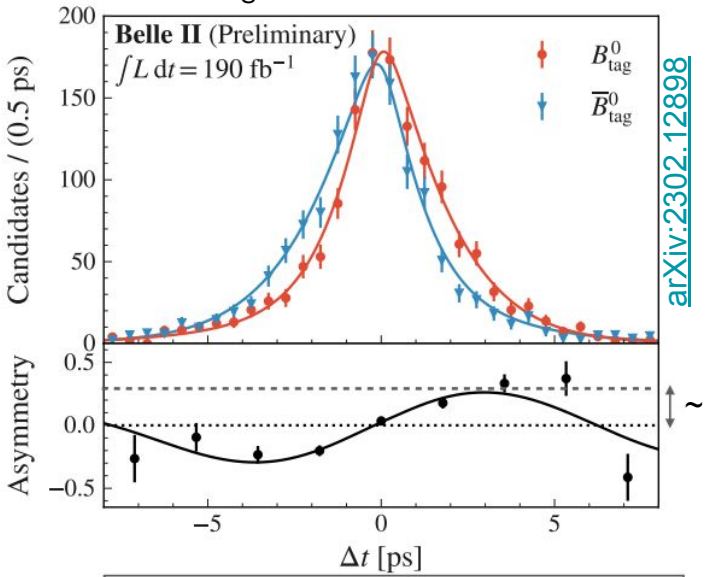


arXiv:2302.12791

$$\tau_{B^0} = (1.499 \pm 0.013 \pm 0.008)\ \text{ps}$$
$$\Delta m_d = (0.516 \pm 0.008 \pm 0.005)\ \text{ps}^{-1}$$

HFLAV: τ = 1.519 ± 0.004 ps,
Δm = 0.5065 ± 0.0019 ps^{-1}

B→J/ψK$_S$ (CP eigenstate)



arXiv:2302.12898

~ sin2φ$_1$ = S$_{CP}$

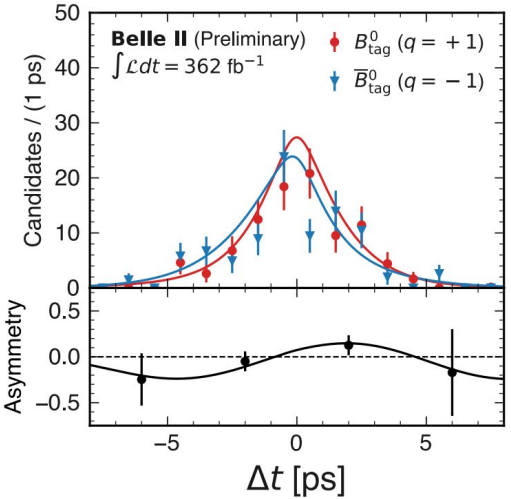
$$S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$$
$$A_{CP} = 0.094 \pm 0.044(\text{stat})\,^{+0.042}_{-0.017}(\text{syst})$$

HFLAV: S$_{CP}$ = 0.699 ± 0.017,
A$_{CP}$ = 0.005 ± 0.015

$B^0 \to \phi K_S$

- Simultaneous Δt fit to extract the CP asymmetries
  - $B \to K^+KK_S$ fixed from HFLAV
  - Validated on the B^+ control sample (null asymmetry)
- Mostly unique to Belle II
  - On par with most precise determinations of A_{CP}
  - 10-20% improvement on S_{CP} for the same signal yield wrt Belle/BaBar determinations

Signal mode ($B^0 \to \phi K_S$)

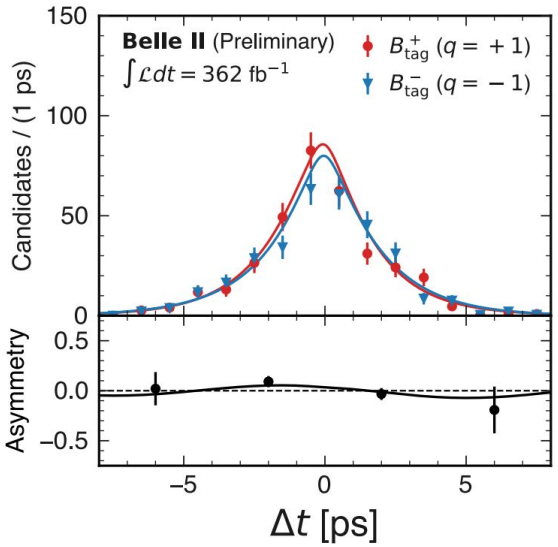


$$A_{CP} = 0.31 \pm 0.20^{+0.05}_{-0.06}$$

$$S_{CP} = 0.54 \pm 0.26^{+0.06}_{-0.08}$$

HFLAV: $S_{CP} = 0.74\ ^{+0.11}_{-0.13}$
$A_{CP} = -0.01 \pm 0.14$

Control channel ($B^+ \to \phi K^+$)



$$A_{CP} = 0.12 \pm 0.10\ (\text{stat.})$$

$$S_{CP} = -0.09 \pm 0.12\ (\text{stat.})$$

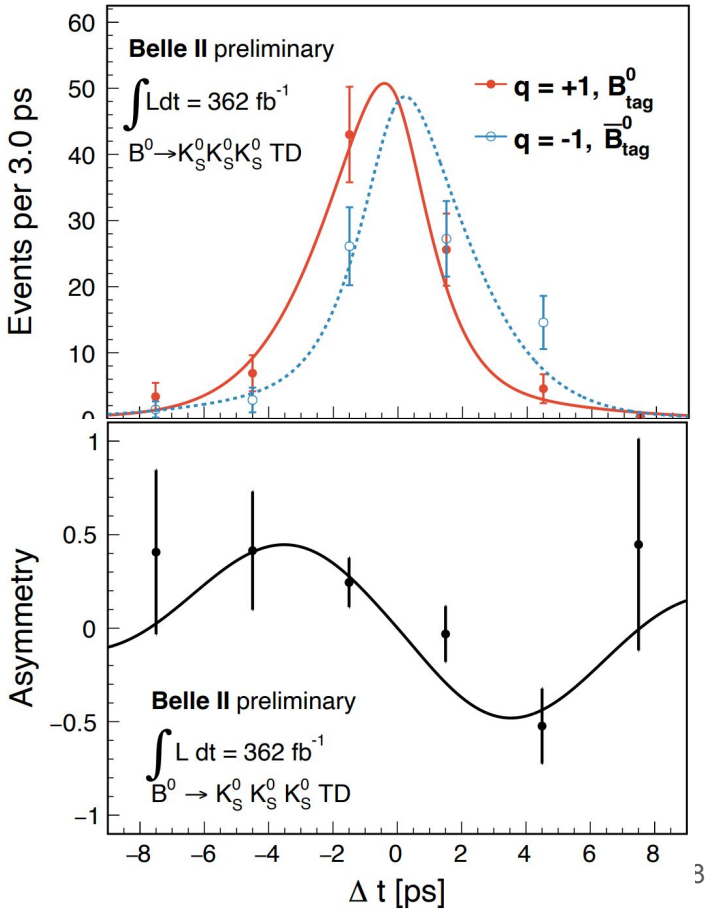
$B^0 \to K_S K_S K_S$

- Simultaneous fit events with and without vertex information and $B^+ \to K_S K_S K^+$
  - Events with vertex information used in the Δt fit for the determination of A_{CP} and S_{CP}
  - Events without vertex information used only to constrain the time integrated asymmetry A_{CP}
  - $B^+ \to K_S K_S K^+$ control sample to constrain background shapes and Δt resolution function
- On par with most precise determination of A_{CP} and unique to Belle II

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

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

HFLAV: S_{CP} = -0.83 ± 0.17, A_{CP} = 0.15 ± 0.12



$B^0 \to K_S \pi^0$

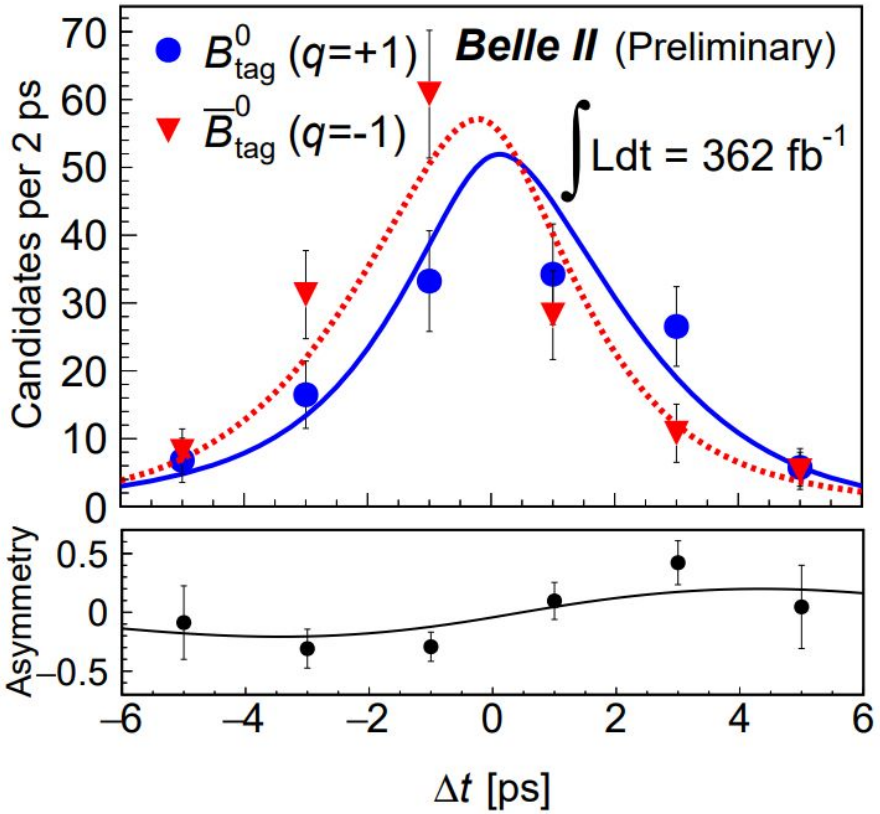
arXiv:2305.07555

- Sensitive to effective value of $\sin 2\varphi_1$ and providing inputs to isospin sum-rule
- Simultaneous fit events with and without vertex information to maximize the sensitivity on A_{CP}
- Competitive with world's best results with much less luminosity

$$A_{CP} = 0.04 \pm 0.15 \pm 0.05$$

$$S_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04$$

HFLAV: $S_{CP} = 0.57 \pm 0.17$, $A_{CP} = -0.01 \pm 0.10$



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- Charm physics
  - Charm lifetime measurements
  - D^+_s lifetime measurement
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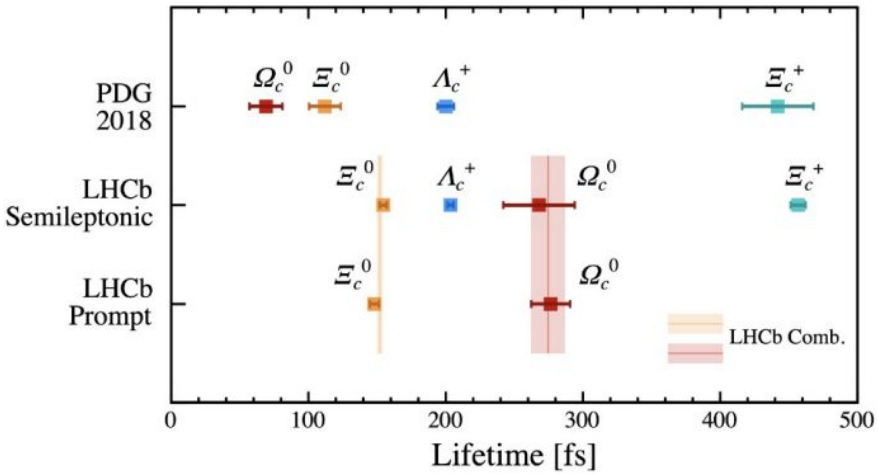
Charm lifetime measurements

- 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
  - The Ω_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

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



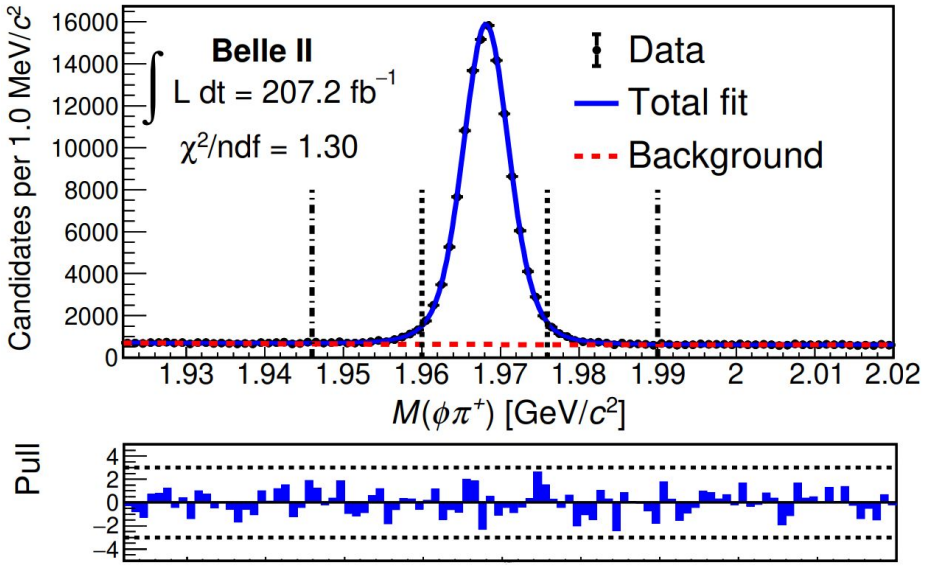
$$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$$

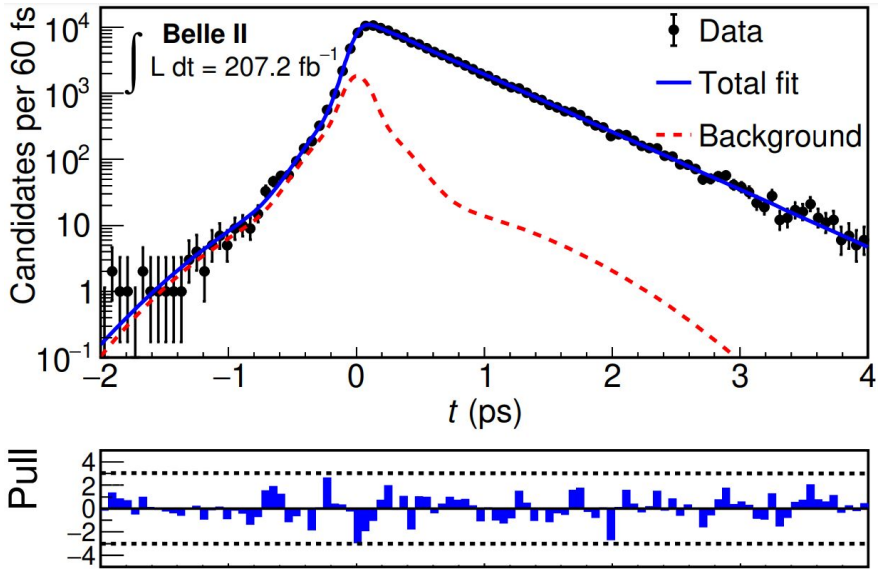
Possible reasons why HQE has initially failed are being debated (Science Bulletin 67 (2022) 445-447, arXiv:2204.11935)

D^+_s lifetime measurement - New for Blois!

$$\tau_{D_s^+} = (498.7 \pm 1.7^{+1.1}_{-0.8})\ \text{fs}$$

- Our sample consists of 116×10^3 $D^+_s \to \phi\pi^+$ ($\phi \to K^+K^-$) decays
- This is the most precise measurement to date and consistent with approximately twice the precision of current world-average value of (504 ± 4) fs.
- It is also consistent with theory predictions ($\tau_{D_s^+} \sim \tau_{D^0}$)



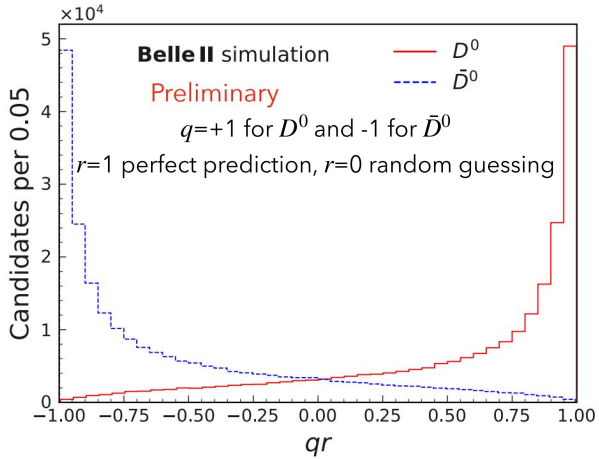


Charm flavor tagger

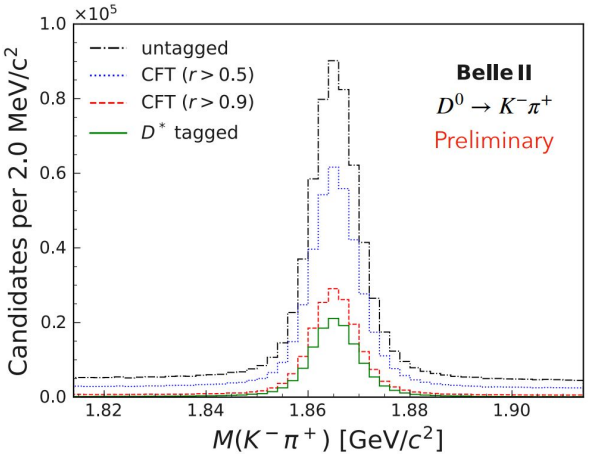
arXiv:2304.02042

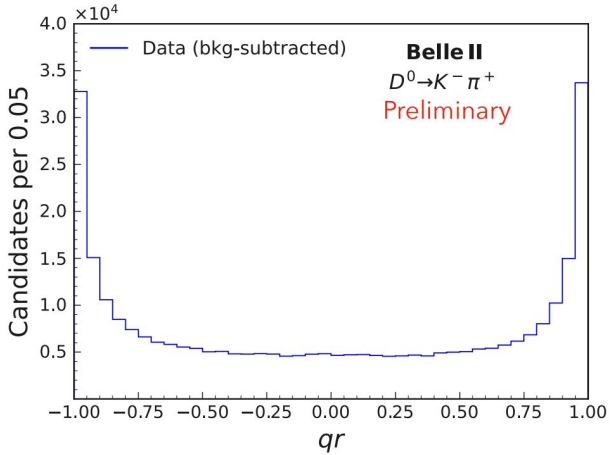
- reconstruct particles most collinear with signal meson
- uses kinematic features (ΔR , recoiling mass) and PID of tagging particles
- based on BDT, predicts (tagging decision *q* and dilution *r*)
- trained using simulation and calibrated with Belle II data

$$\epsilon_{\text{tag}}^{\text{eff}} = \epsilon_{\text{tag}}\langle r^2 \rangle = (47.91 \pm 0.07(\text{stat.}) \pm 0.51(\text{syst.}))\,\%$$



- Double the effective sample size w.r.t D*⁺-tagged events (with larger background level)
- provide discrimination between signal and background
- CFT will increase sensitivity for many charm decays:
  - $D^0 \to \pi^0\pi^0$, $K^0_S K^0_S$, $K\pi^0\pi$, ...



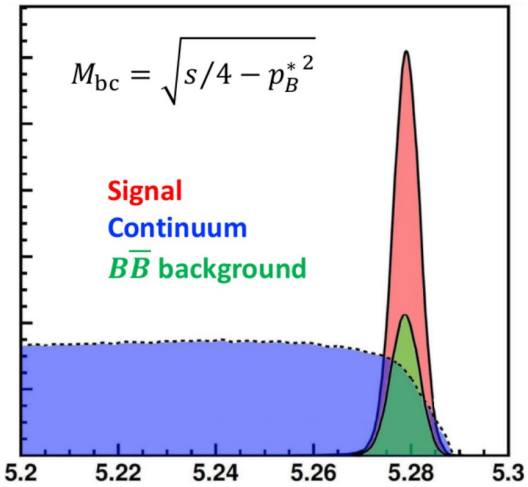


Conclusions and outlook

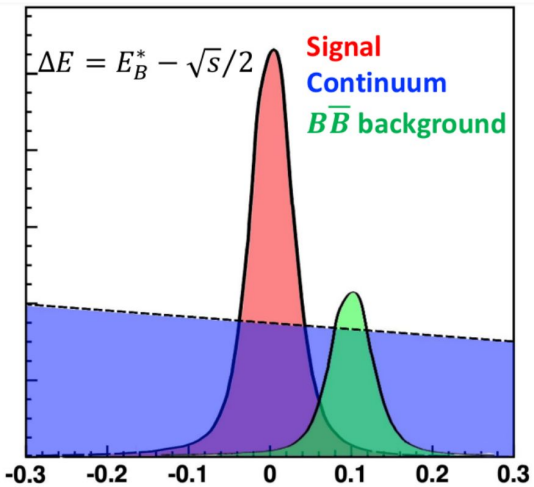
- Time-dependent CP Violation
  a. Results on time-dependent CP observables with penguins
  b. Precision on par with world's best determinations in spite of much less luminosity
  c. These measurements are essential to probe generic BSM physics in loops
  d. Belle II is in a unique position to improve our current experimental knowledge on these modes
- Charm physics:
  a. Charm Flavor Tagger
     - new inclusive algorithm that exploits correlation between signal flavor and charge of tagging particles
     - significantly enlarge the available sample size
  b. D^+_s lifetime measurement - New!
     - The most precise measurement and consistent with twice the precision of current world-average value
     - It is also consistent with theory predictions.

Backup

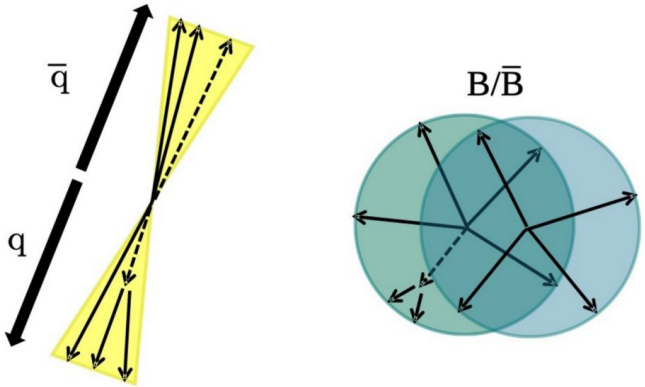
B-factory analysis



Beam-constrained mass [GeV/c2]



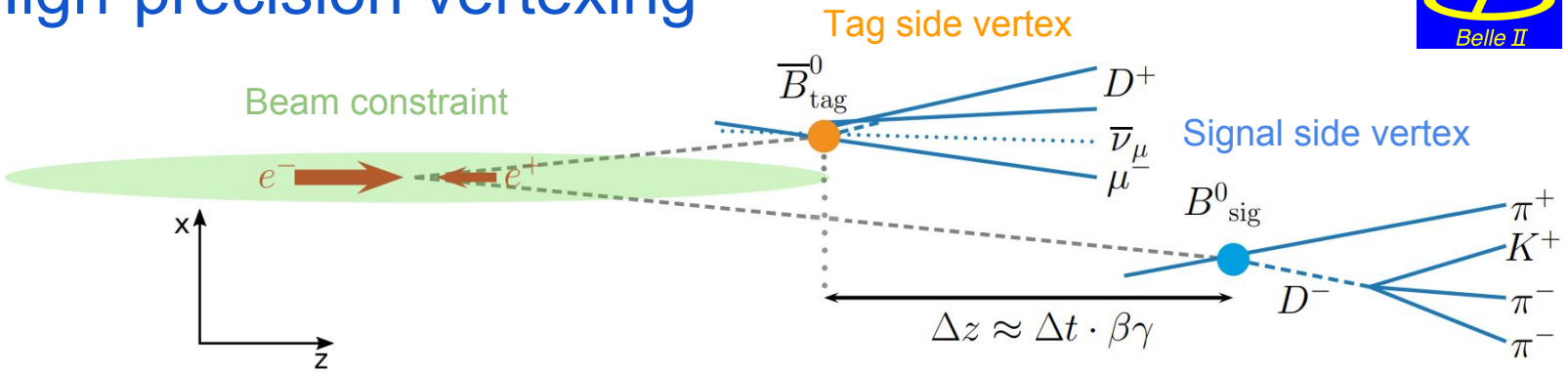
Energy difference [GeV]



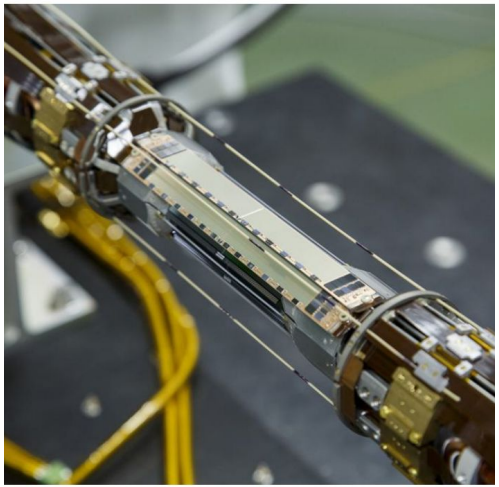
Event shape

- High resolution (~2-10 MeV) high-level analysis variables (M_{bc}, ΔE), separating signal from backgrounds, using to the knowledge of beam energy
- Several event shape variables exploiting the correlations in e^+e^- collision

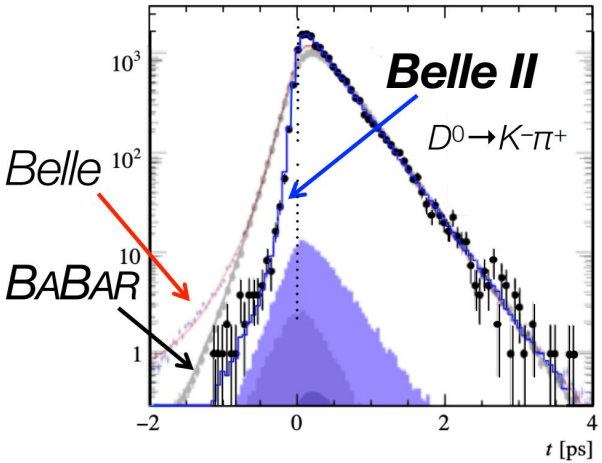
High-precision vertexing



- Measuring the time difference Δt of coherently produced B$\overline{\text{B}}$ pairs from the decay of a Y(4S), boosted along z
- Improved vertex resolution from pixel in spite of lower boost
  - Belle: βγ = 0.43, Δz ≈ 200μm
  - Belle II: βγ = 0.29, Δz ≈ 130μm
- Enhanced Δt resolution from the beam spot profile in combination with the new nano-beam scheme
- Two times better impact parameter resolution than Belle/BaBar shows up in decay-time distribution

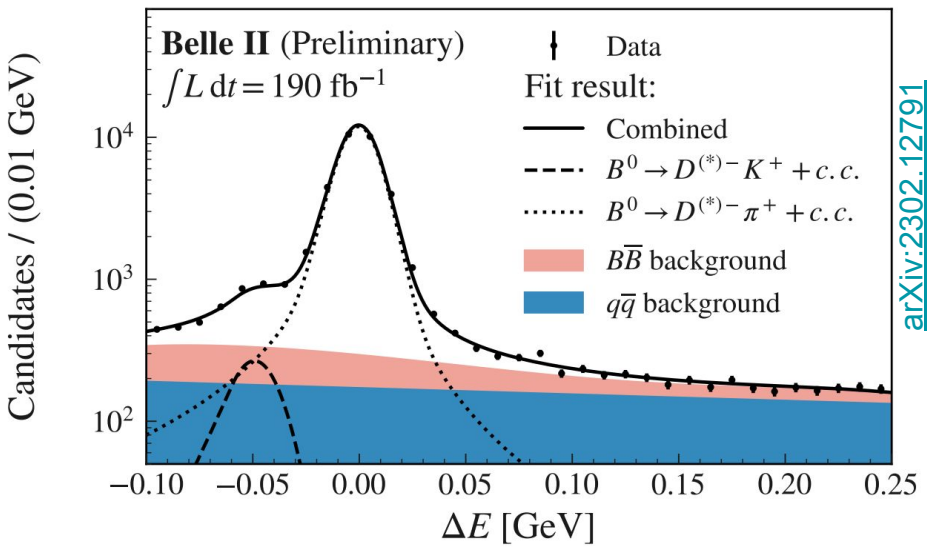


Pixel detector ~ radius 1.3 cm



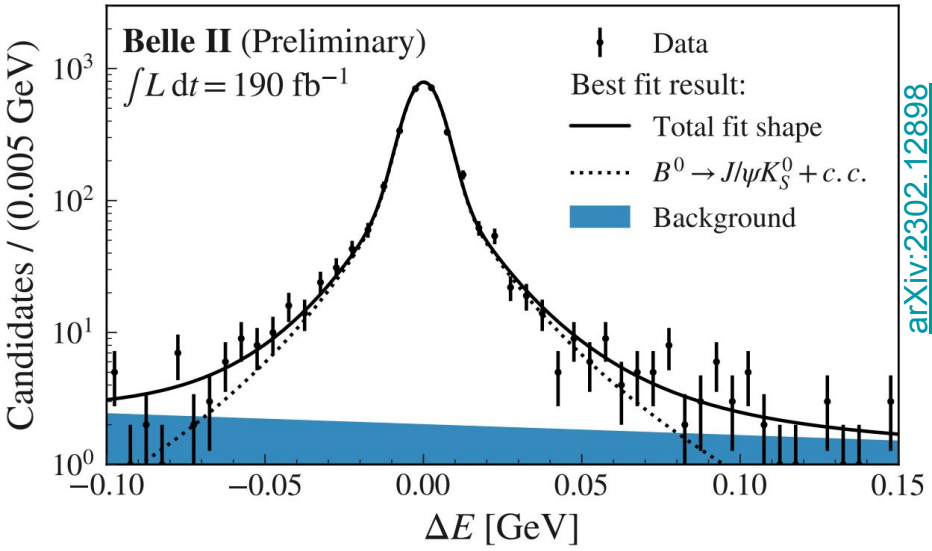
Δm and sin2φ$_1$

Energy difference ~33k B→D(*)π



arXiv:2302.12791

Energy difference ~2.8k B→J/ψK$_S$



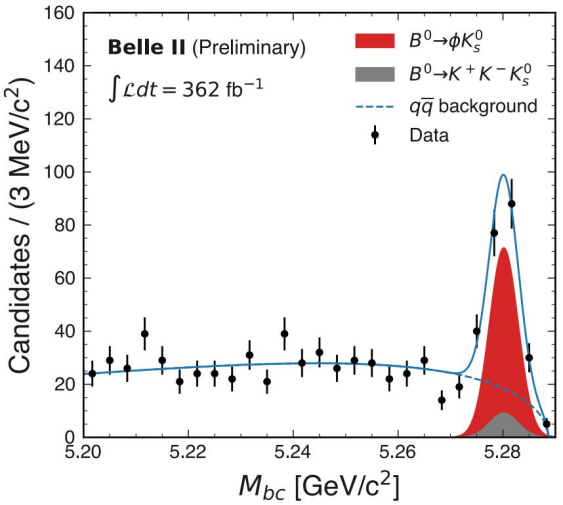
arXiv:2302.12898

- High-yield, low-background modes used for benchmark measurements of time-dependent observables
- Main challenge: accurate understanding of vertex resolution (Δt resolution ~1 ps) and tagging (ε_{tag}~30%)

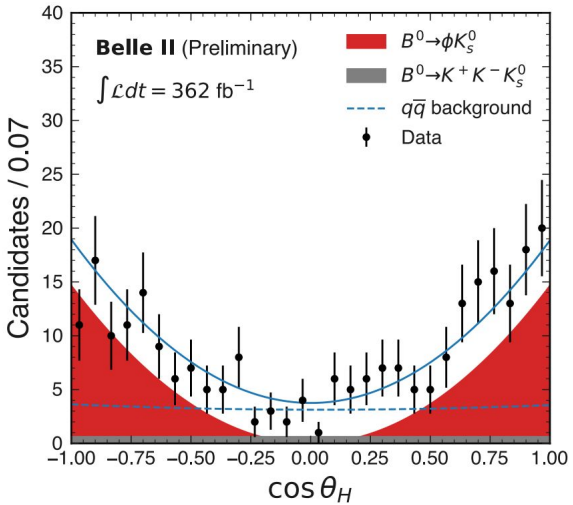
$B^0 \to \varphi K_S$

- Clean experimental signature with similar Δt resolution as $B \to J/\psi K_S$
- Main challenge: dilution from nonresonant decays with opposite CP
- Quasi-two body analysis of resonant $B \to \psi K_S$ decays
  - Non-resonant $B \to K+KK_S$ component disentangled in cosθ
  - Effect of neglecting interference estimated with inputs from previous Dalitz measurements

Beam constraint mass



Cosine of the helicity angle

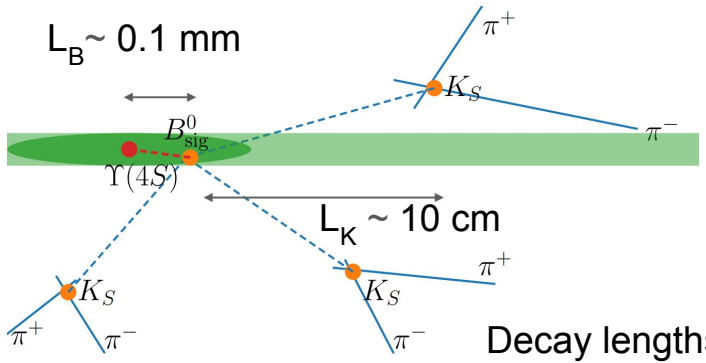


162 ± 17 $B \to \psi K_S$ signal events with 387M $B\bar{B}$ pairs

$B^0 \to K_S K_S K_S$

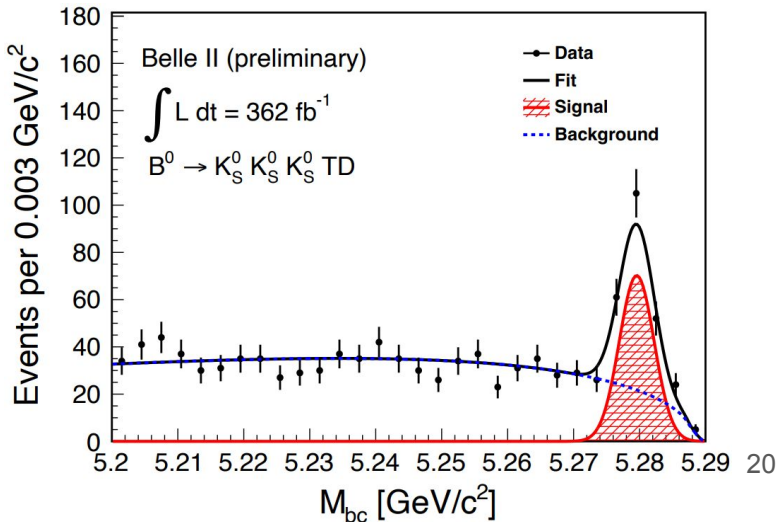
- Same underlying quark transition as $B \to \psi K_S$, w/o contributions from opposite-CP backgrounds
- Main challenge: no prompt tracks to form a vertex
  - Decay vertex reconstruction relies on the Ks trajectory and profile of the interaction point
  - Dataset divided into events with and without vertexing information
- 2 BDTs to suppress fake K_S (kinematic/hits $\pi^{\pm}$ tracks) and continuum (event shape variables)

158^{+14}_{-13} (TD) + 62 ± 9 (TI) $B \to K_S K_S K_S$ signal events with 387M $B\bar{B}$ pairs



Decay lengths (not to scale)

Beam constraint mass



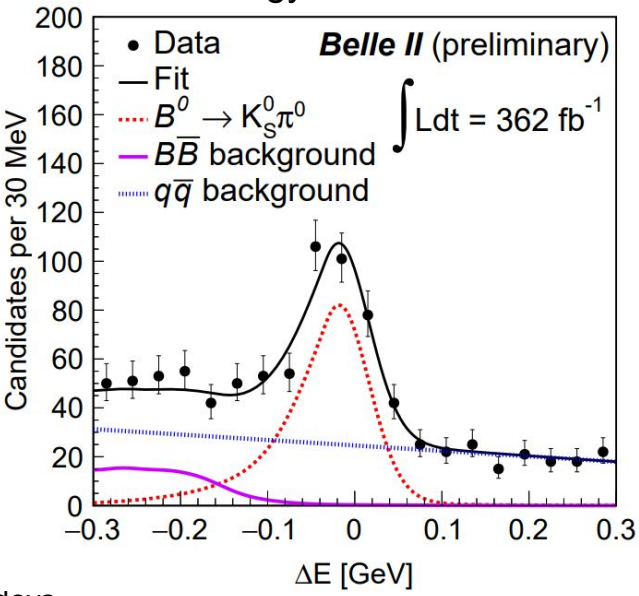
$B^0 \to K_S \pi^0$

arXiv:2305.07555

- Main challenge: no prompt tracks to form a vertex
  - Decay vertex reconstruction relies on the Ks trajectory and profile of the interaction point
  - Poor decay time resolution, need good performance with neutrals
- Validate on $B^0 \to J/\psi K_S$ with K_S only vertex

415 ± 25 $B^0 \to K_S \pi^0$ signal events with 387M $B\bar{B}$ pairs

Energy difference



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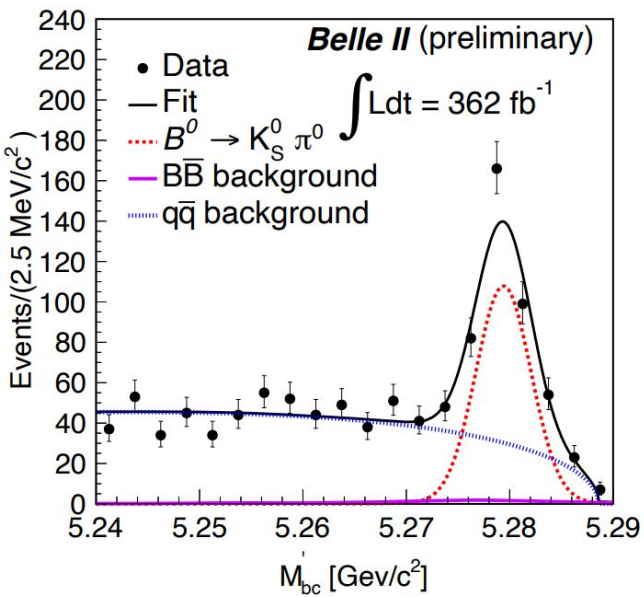
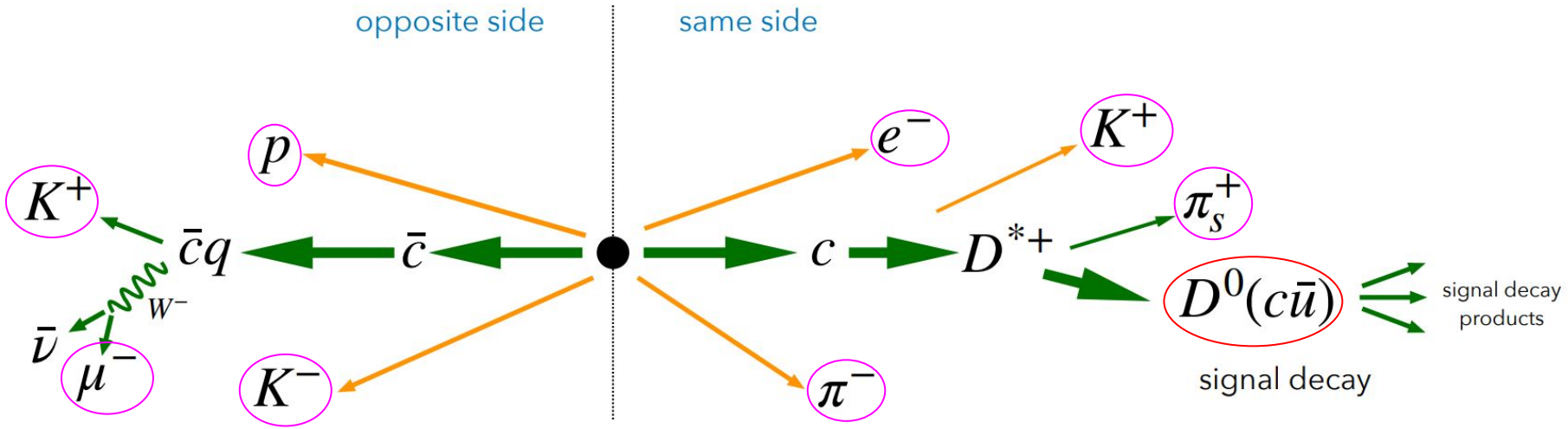


Charm flavor tagger



- e^+e^- → two charm hadrons + fragmentation
  - no entanglement, inaccessible strong phase
- one of main ingredients to any CPV/mixing measurement is flavor tagging
  - standard approach: exclusive reconstruction of strong decay $D^{*+} \to D^0\pi^+$
  - a new more inclusive method is desirable to exploit correlation between signal flavor and charge of tagging particles

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
  - The Ω_c^0 is not the shortest-living charm baryon.
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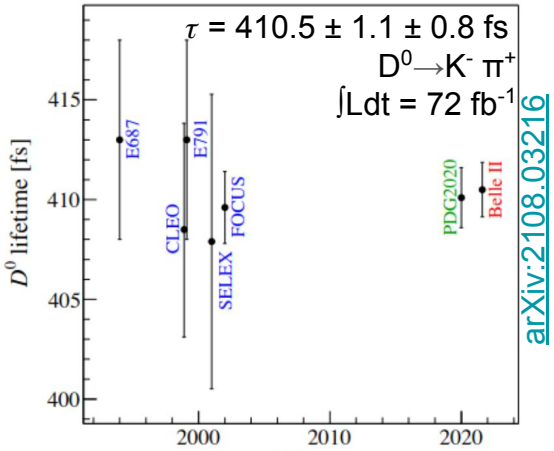
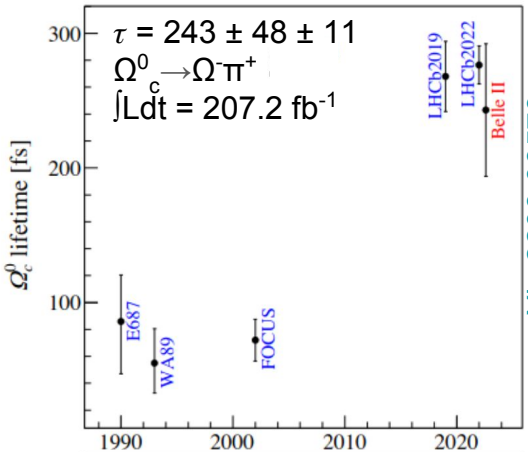
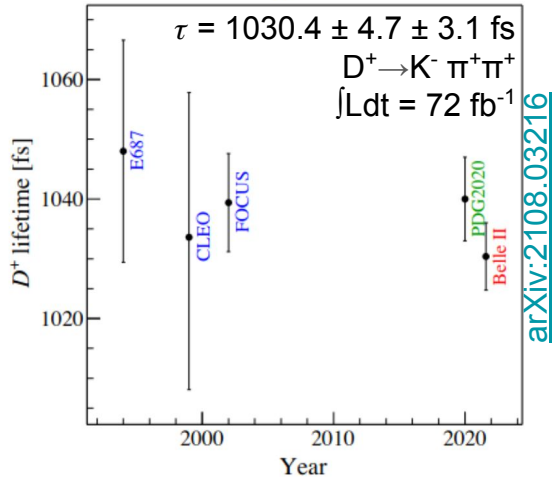
  - Better vertexing performance than Belle/BaBar



arXiv:2108.03216



arXiv:2208.08573



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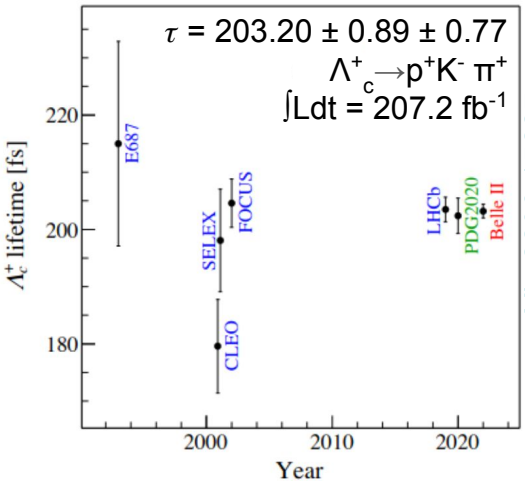

arXiv:2206.15227