Recent time-dependent measurements of CP violation at Belle II

Oskar Tittel, on behalf of the Belle II collaboration

EPS-HEP 2023

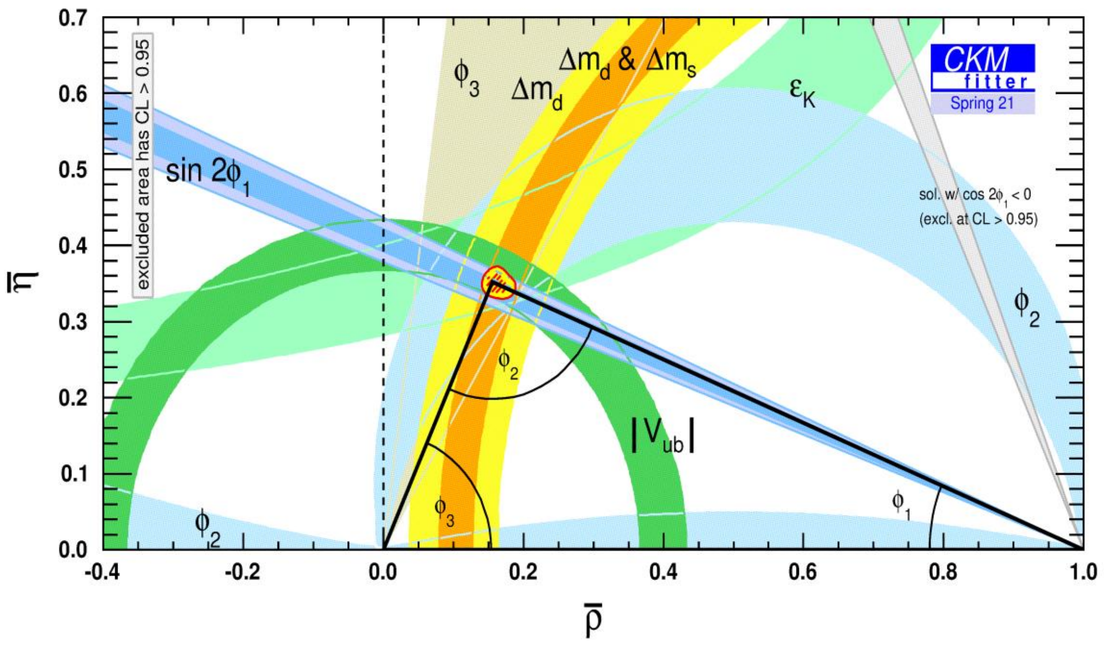
22.08.2023

The B-Meson System CKM Triangle

CKM triangle closed in the SM
→ tensions may hint towards new physics (NP)

Precise measurements by BaBar, Belle and LHCb result in
$\Phi_1 = (22.2 \pm 0.7)^\circ$ (HFLAV)

Check for agreement in channels which are sensitive to NP

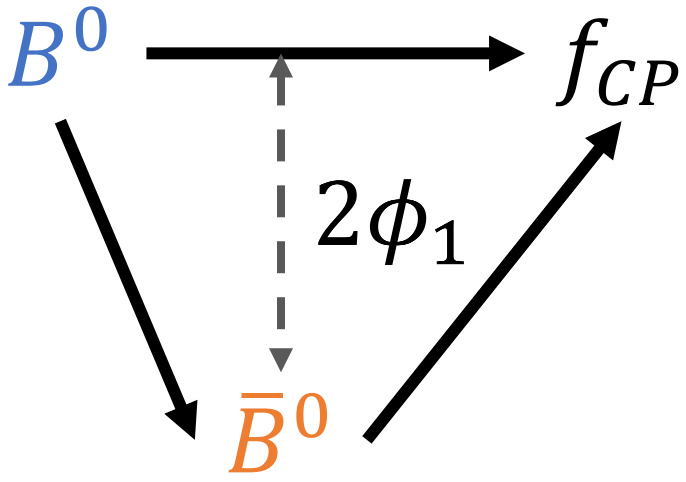


$$\boxed{\Phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \cong \arg(V_{td})}$$

Mixing-Induced CP-Violation

Interference of mixing and decay amplitudes lead to mixing-induced CPV

Φ_1 contributes as the mixing phase $|V_{td}|e^{i\phi_1}$

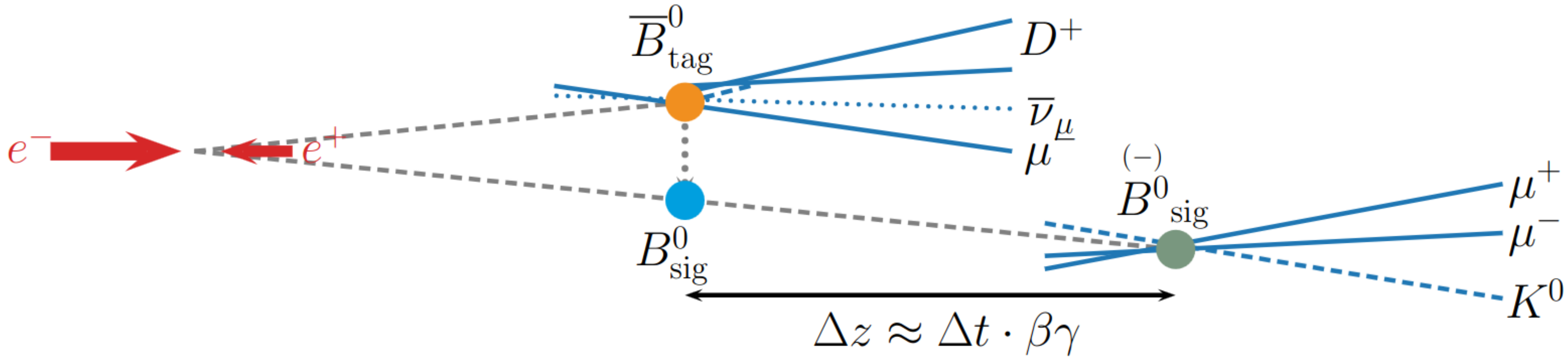


$$\mathcal{A}_{CP}(t) = \frac{N(\bar{B}^0 \to f_{CP}) - N(B^0 \to f_{CP})}{N(\bar{B}^0 \to f_{CP}) + N(B^0 \to f_{CP})}(t) = S_{CP}\sin(\Delta m_d t) - C_{CP}\cos(\Delta m_d t)$$

S_{CP}: mixing-induced asymmetry

C_{CP}: direct asymmetry

Time Dependent CP Measurements at Belle II



Critical for good time-dependent measurements:

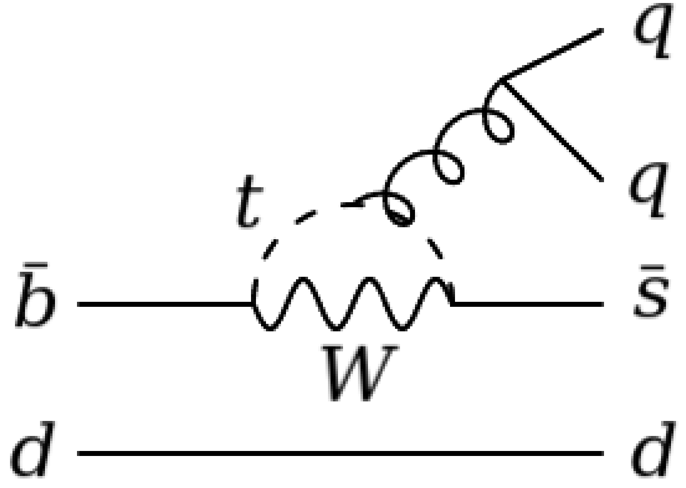
1. Good vertex resolution (Belle II: $\Delta z \approx 130\mu m$, Belle: $\Delta z \approx 200\mu m$)
2. High tagging efficiency (Belle II: $\varepsilon_{tag} = (31.7 \pm 0.4)\%$, Belle: $\varepsilon_{tag} = (30.1 \pm 0.4)\%$)

Today: three new Belle II results using the full dataset ($362\mathrm{fb}^{-1}$)

Hadronic Penguins

FCNC not allowed in SM at tree level

→ decay via loop-suppressed $\bar{\mathrm{b}} \rightarrow \bar{\mathrm{s}}\mathrm{q}\bar{\mathrm{q}}$ transition
→ sensitive to NP



Example: $B^0 \rightarrow \eta' \mathrm{K}_S$

Relatively high BF wrt. other penguin mediated decays to CP-eigenstates

$\sin 2\phi_1 = S_{CP}\ \ \mathcal{O}(\sim 1\%)$ (arXiv:hep-ph/0505075)

New for EPS!

$B^0 \to \eta' K_S$

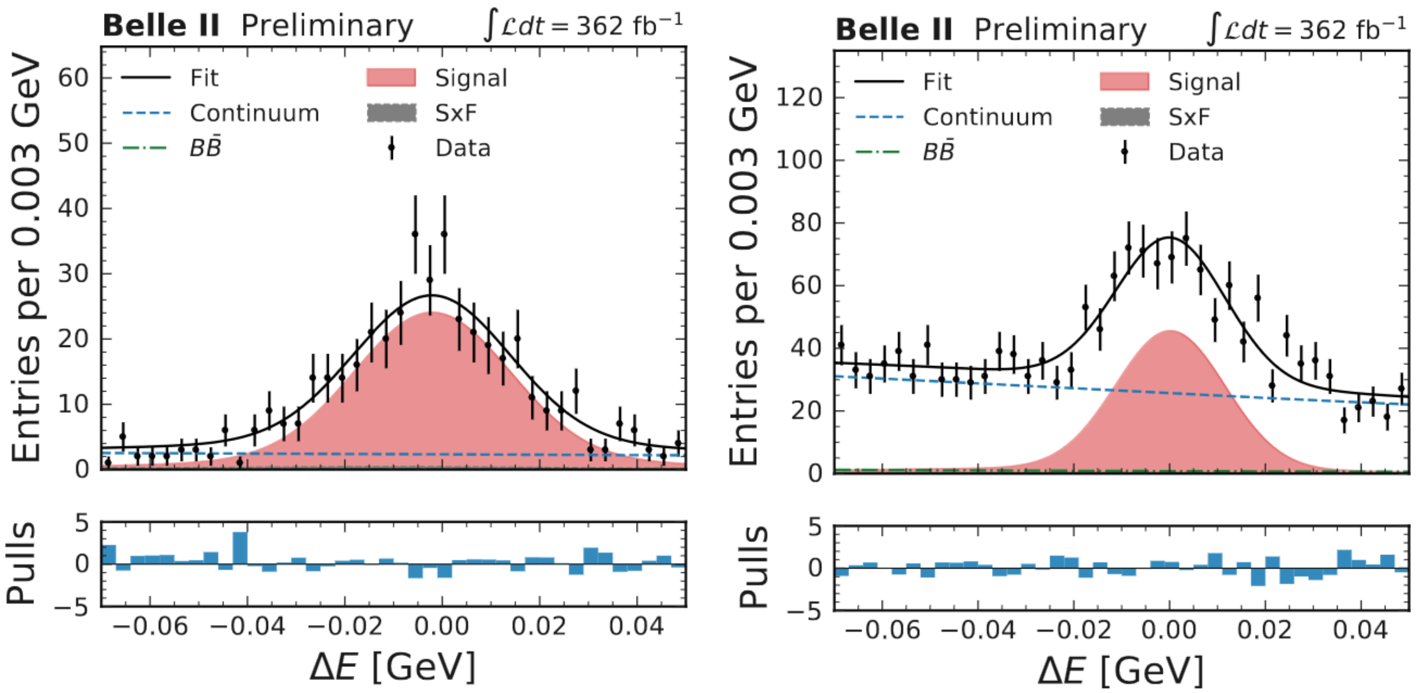
Consider sub-channels $\eta'[\to \eta(\gamma\gamma)\pi^+\pi^-]$ and $\eta'[\to \rho(\pi^+\pi^-)\gamma]$

Challenge: high backgrounds from random combination of tracks from $q\bar{q}$ events

Train event-shape MVA to suppress this background

Signal extraction: $\boxed{n_{sig} = 829 \pm 35}$

$\eta'[\to \eta\pi^+\pi^-]$ $\eta'[\to \rho\gamma]$



$$\Delta E = E_B^* - E_{\text{beam}}^*$$

New for EPS! $B^0 \to \eta' K_S$

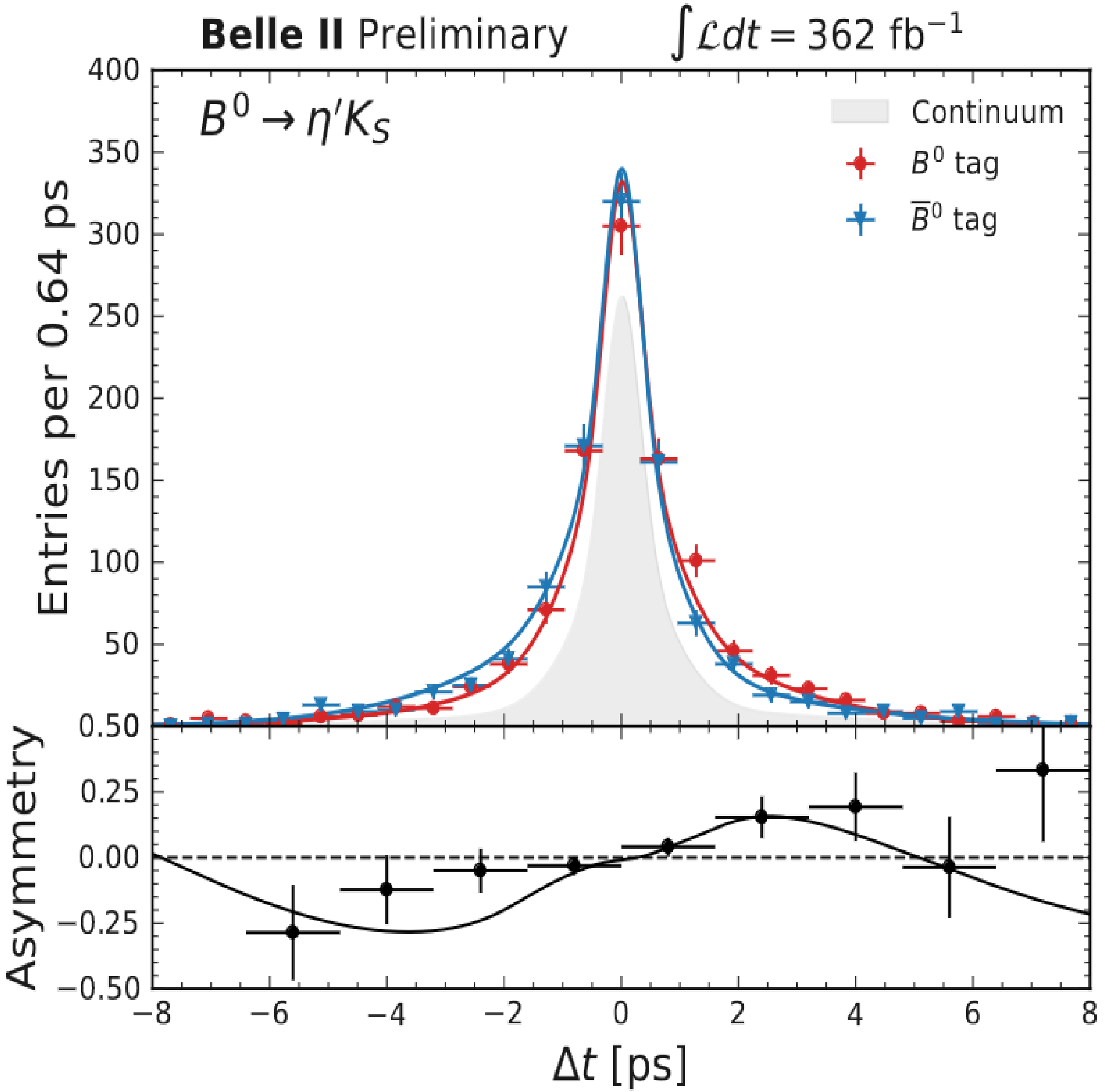
Background Δt shape controlled from sideband

S_{CP} and C_{CP} extracted from fit in signal region with background parameters fixed from first step

Fit validated with $B^{\pm} \to \eta' K^{\pm}$

Unique at Belle II

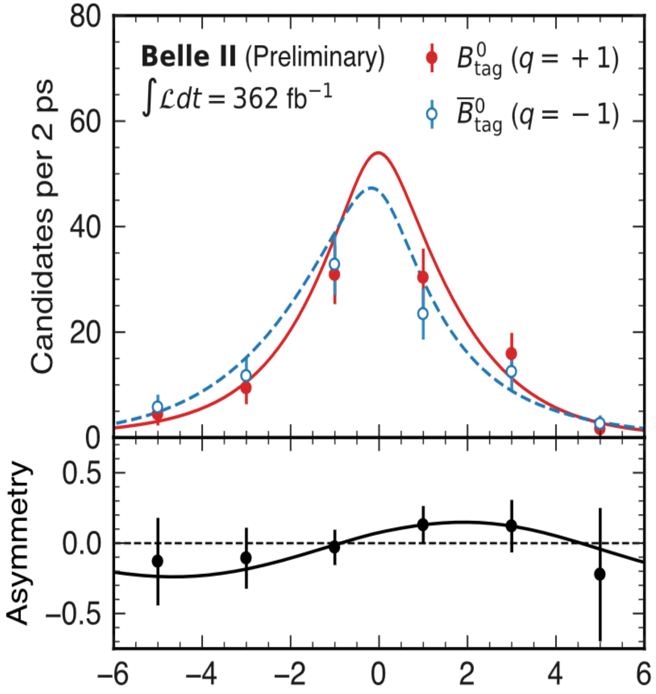
$$C_{CP} = 0.19 \pm 0.08 \pm 0.03$$
$$S_{CP} = 0.67 \pm 0.10 \pm 0.04$$



HFLAV: $C_{CP} = -0.05 \pm 0.04$ $S_{CP} = 0.63 \pm 0.06$

Other Hadronic Penguin Results

$B^0 \to \varphi K_S$

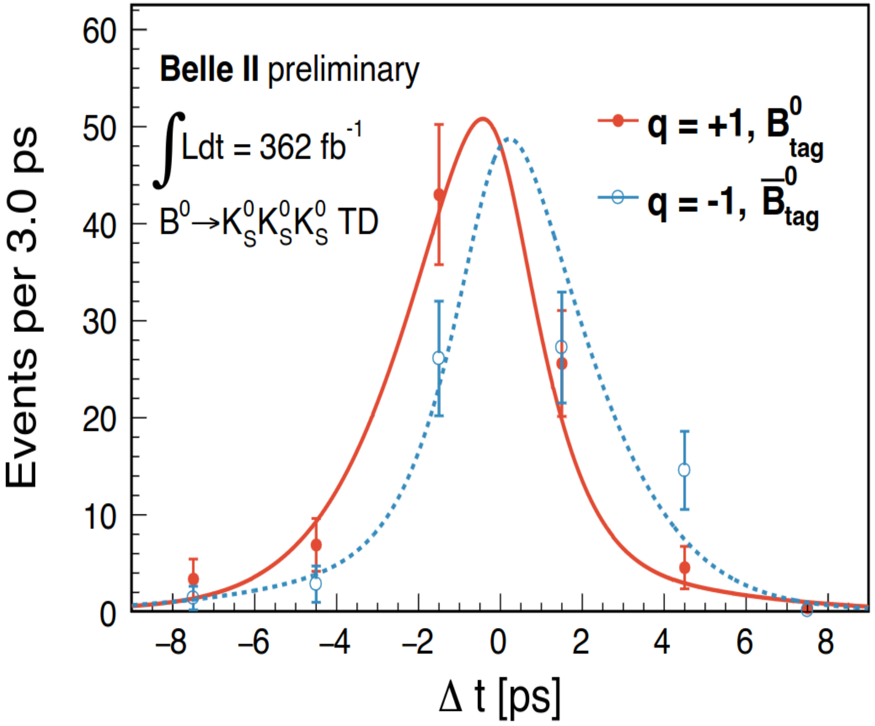


arXiv:2307.02802

$$C_{CP} = -0.31 \pm 0.20 \pm 0.05$$
$$S_{CP} = \quad 0.54 \pm 0.26^{+0.06}_{-0.08}$$

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

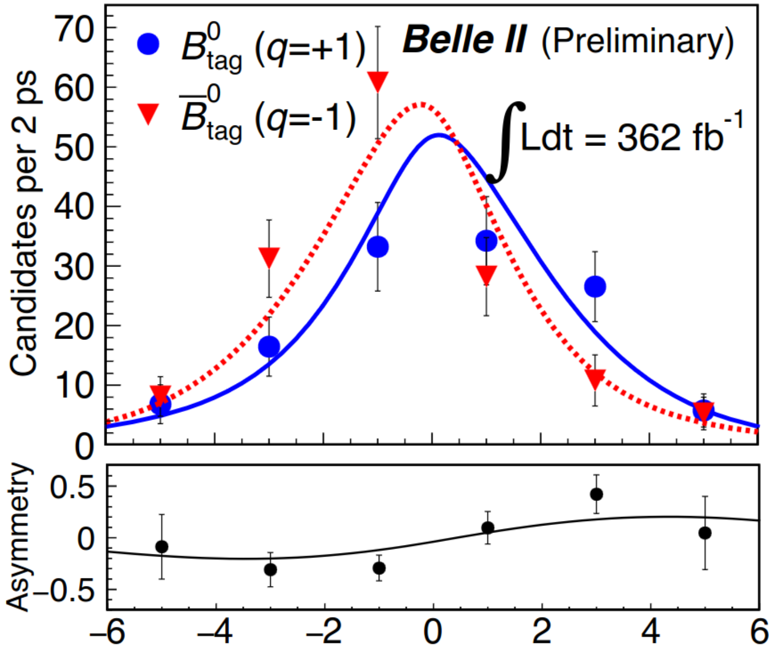
$B^0 \to K_S K_S K_S$



$$C_{CP} = -0.07 \pm 0.20 \pm 0.05$$
$$S_{CP} = -1.37^{+0.35}_{-0.45} \pm 0.03$$

HFLAV: $C_{CP} = -0.15 \pm 0.12$ $S_{CP} = -0.83 \pm 0.17$

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

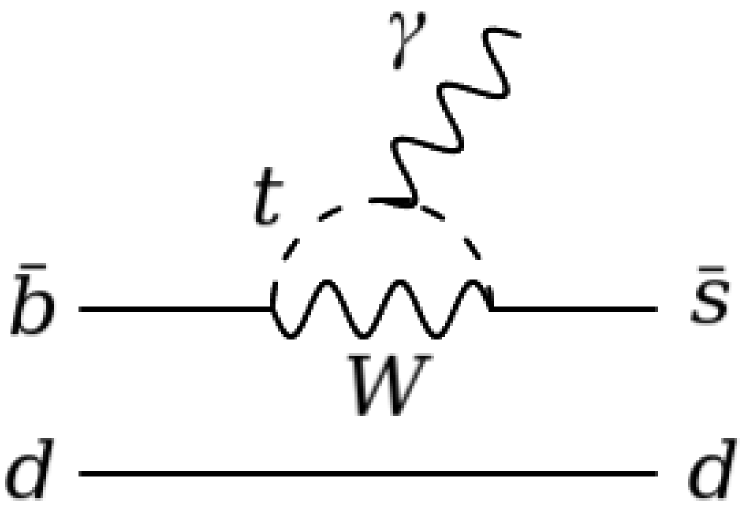


arXiv:2305.07555

$$C_{CP} = -0.04 \pm 0.15 \pm 0.05$$
$$S_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04$$

HFLAV: $C_{CP} = 0.01 \pm 0.10$ $S_{CP} = 0.57 \pm 0.17$

Radiative Penguins



Polarization of photon strongly constrains flavor

→ final state no CP eigenstate

→ SM: S_{CP} helicity suppressed

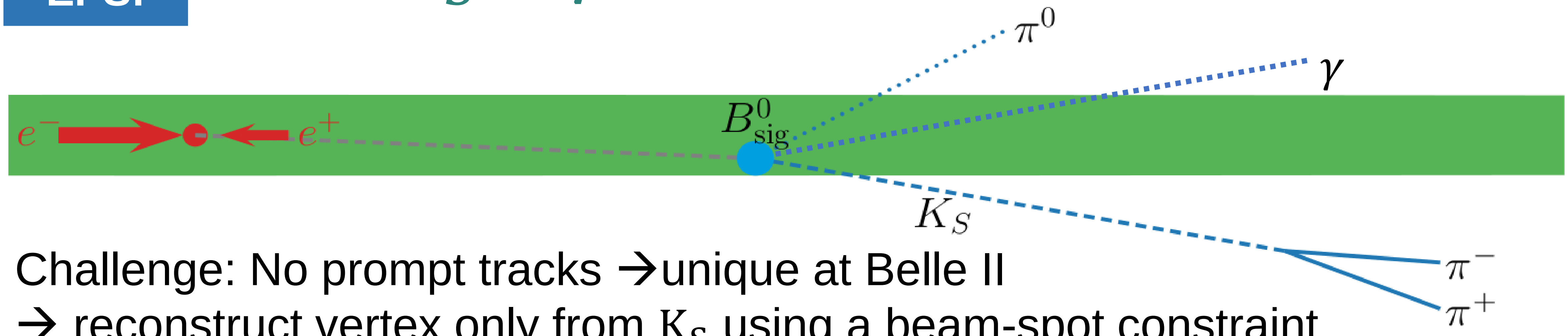
NP processes could contribute to a significant mixing-induced CP violation

Example: $B^0 \to K_S \pi^0 \gamma$

Theory: $S_{CP} = -0.035 \pm 0.017$ (arXiv:hep-ph/0406055)

New for EPS!

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



Challenge: No prompt tracks →unique at Belle II
→ reconstruct vertex only from K_S using a beam-spot constraint

Candidates with poor vertex reconstruction are used to measure C_{CP} in a time-integrated way

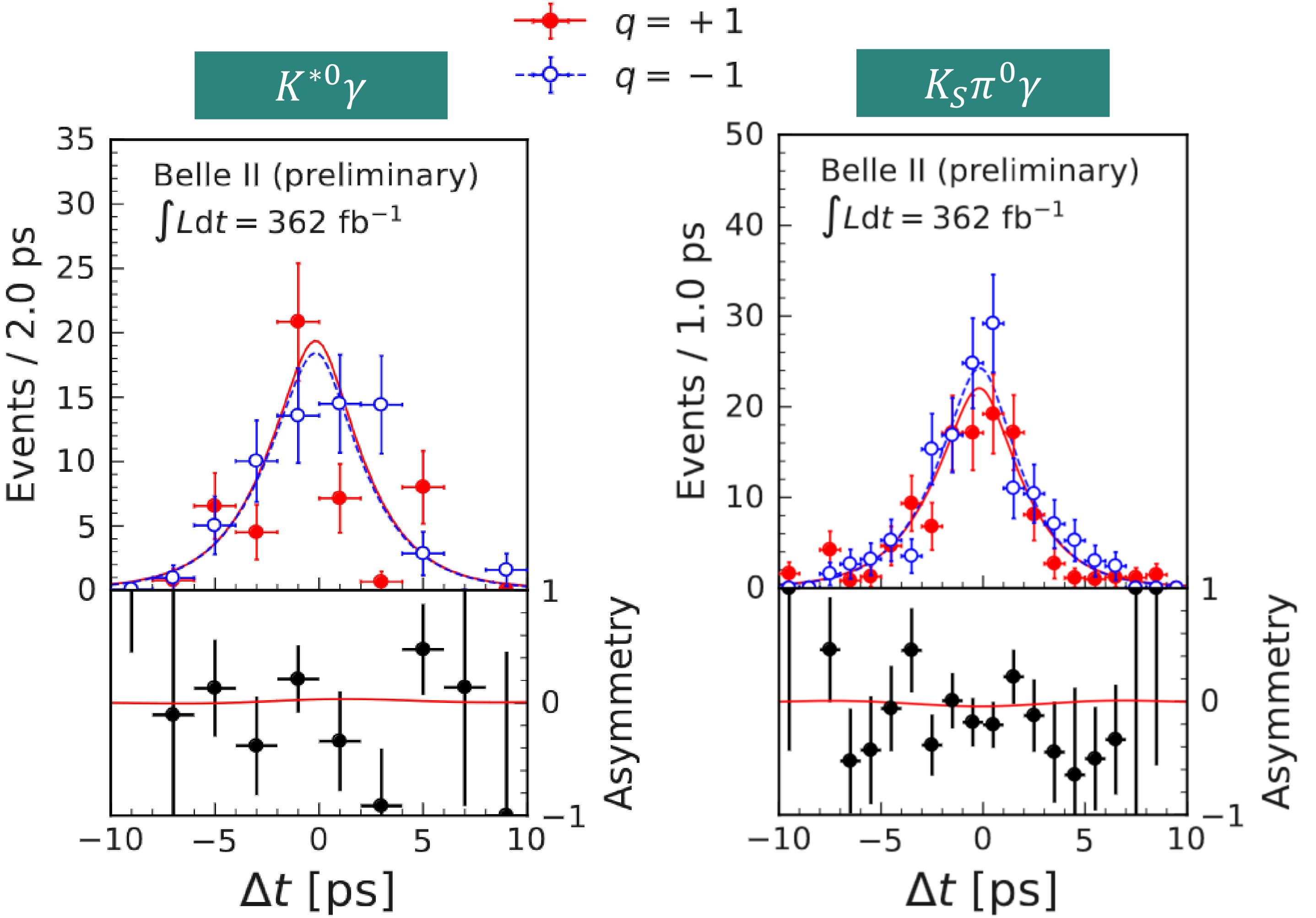
High multiplicity coming from fake beam background π^0
→ select single one using MVA methods

New for EPS!

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

Consider exclusive decay to $K^{*0}(\to K_S\pi^0)\gamma$ and inclusive decay to $K_S\pi^0\gamma$ separately

Channel	$K^{*0}\gamma$	$K_S\pi^0\gamma$
$M_{K_S\pi^0}$-region $[\frac{GeV}{c^2}]$	$]0.8, 1.0[$	$[0.6, 0.8]$or $[1.0, 1.8]$
Signal yield	385 ± 24	171 ± 23



$$C_{CP} = 0.10 \pm 0.13 \pm 0.03$$
$$S_{CP} = 0.00^{+0.27+0.03}_{-0.26-0.04}$$

$$C_{CP} = -0.06 \pm 0.25 \pm 0.07$$
$$S_{CP} = 0.04^{+0.45}_{-0.44} \pm 0.10$$

Most precise result up to date!

HFLAV:

$K^{*0}\gamma$: $C_{CP} = -0.04 \pm 0.14$ $S_{CP} = -0.16 \pm 0.22$

$K_S\pi^0\gamma$: $C_{CP} = -0.07 \pm 0.12$ $S_{CP} = -0.15 \pm 0.20$

*The HFLAV $K_S\pi^0\gamma$ values include $K^{*0}\gamma$

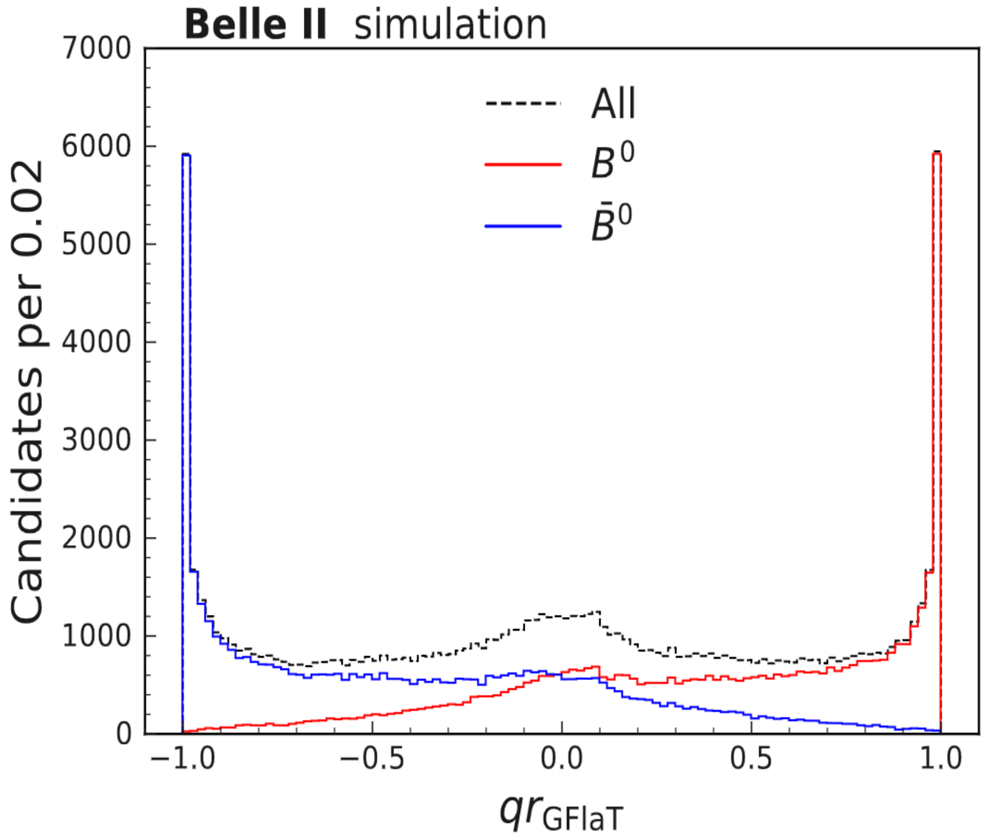
New for EPS!

GNN Flavor Tagger (GFlaT)

New flavor tagger (GFlaT) based on graph neural network (GNN), which uses interrelational information between particles, developed in Belle II

Conv. FT: $\epsilon_{tag} = (31.68 \pm 0.45 \pm 0.41)\ \%$
GFlaT: $\epsilon_{tag} = (37.40 \pm 0.43 \pm 0.34)\ \%$

→ ~18% more effective data due to increase in tagging efficiency compared to conventional flavor tagger!



New for EPS! $B^0 \to J/\psi K_S$

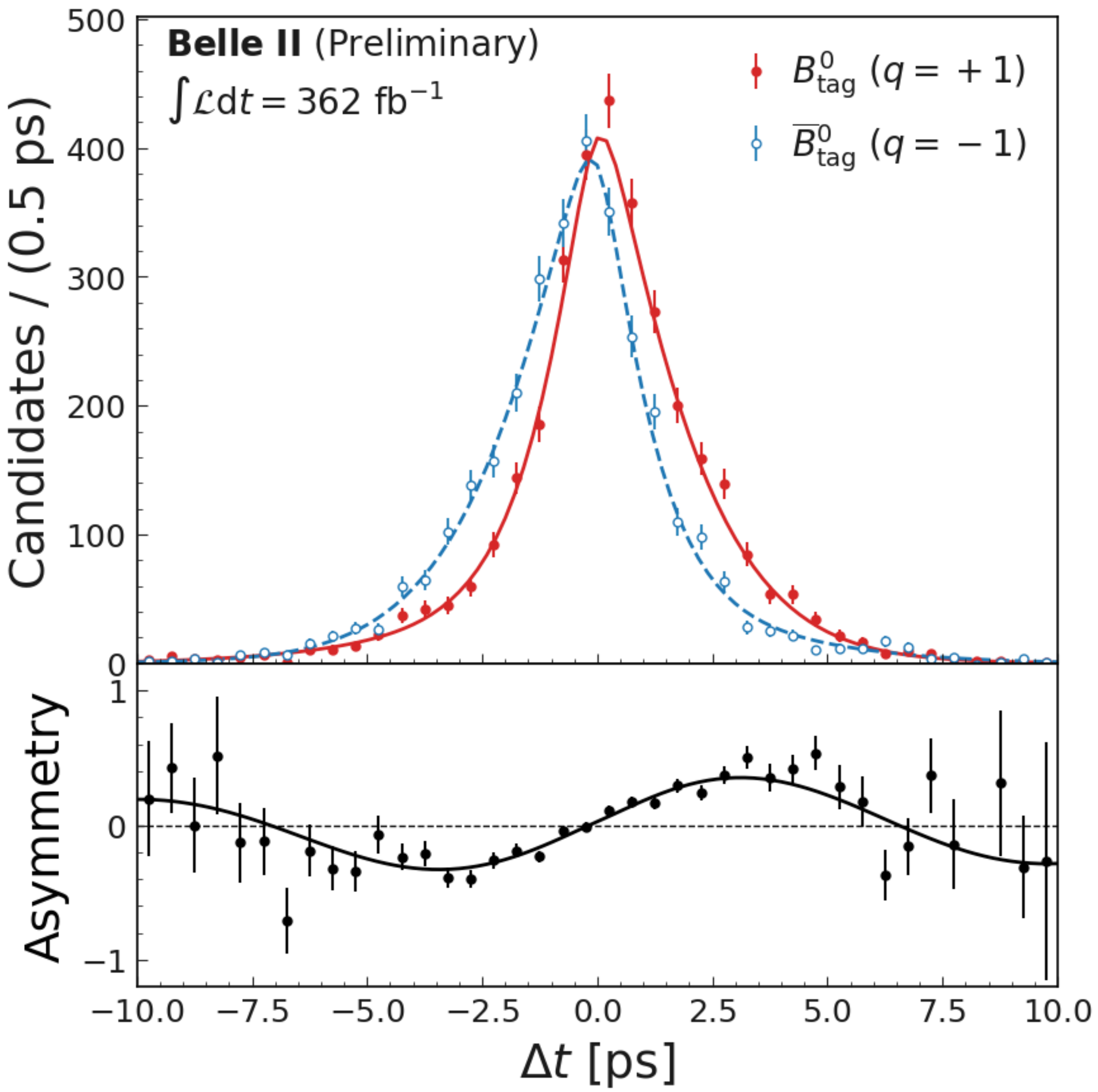
SM measurement with large BF and experimentally clean signature

Validate FT performance

$\sim$8 % reduction in statistical uncertainty due to GFlaT

$$C_{CP} = -0.035 \pm 0.026 \pm 0.012$$
$$S_{CP} = \quad 0.724 \pm 0.035 \pm 0.014$$

HFLAV: $C_{CP} = 0.000 \pm 0.020$ $S_{CP} = 0.695 \pm 0.019$



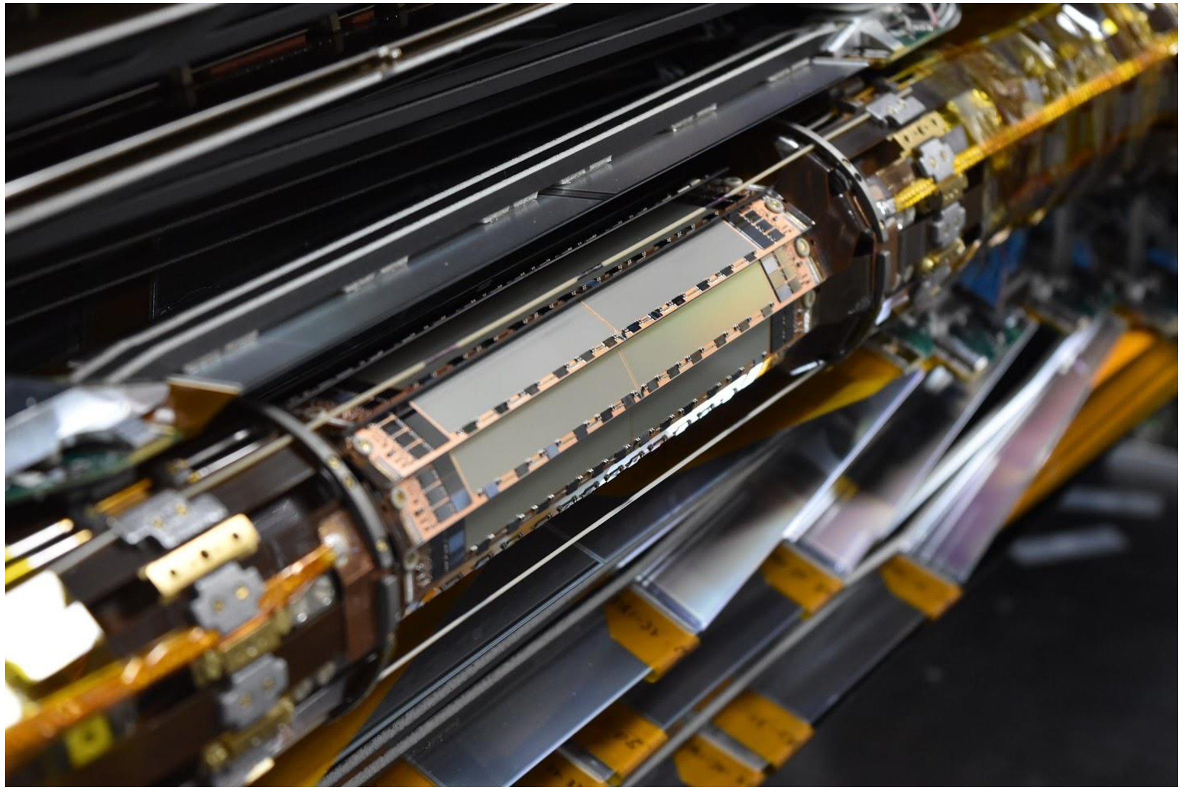
Conclusion

Presented 6 TD results from 2023 including 3 new results:

1. Several results already on par with best measurement or world leading
2. Many channels unique to Belle II

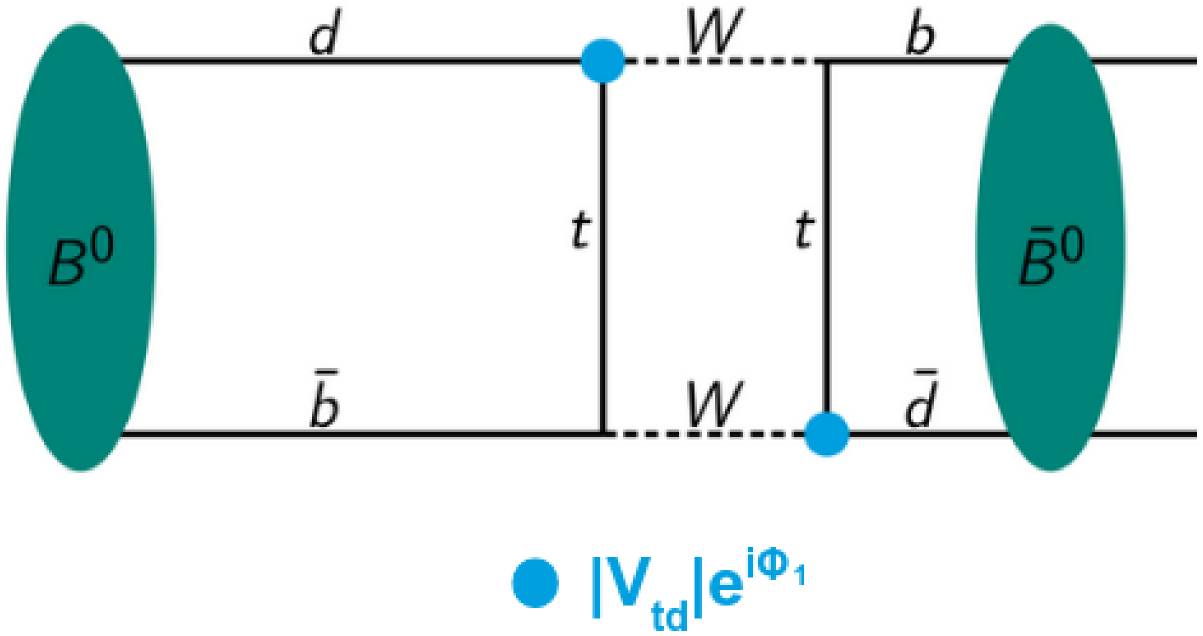
Prospects:

1. More data: restart data taking this winter
2. Better control: software (GFlaT) and hardware (new pixel vertex detector) improvements ready for new run



Backup

B-Meson Mixing



Moriond 23: $K_S K_S K_S$

No contributions from opposite-CP backgrounds

Main challenge: no prompt tracks
→vertex reconstruction from K_S trajectories

Unique at Belle II

$$C_{CP} = -0.07 \pm 0.20 \pm 0.05$$
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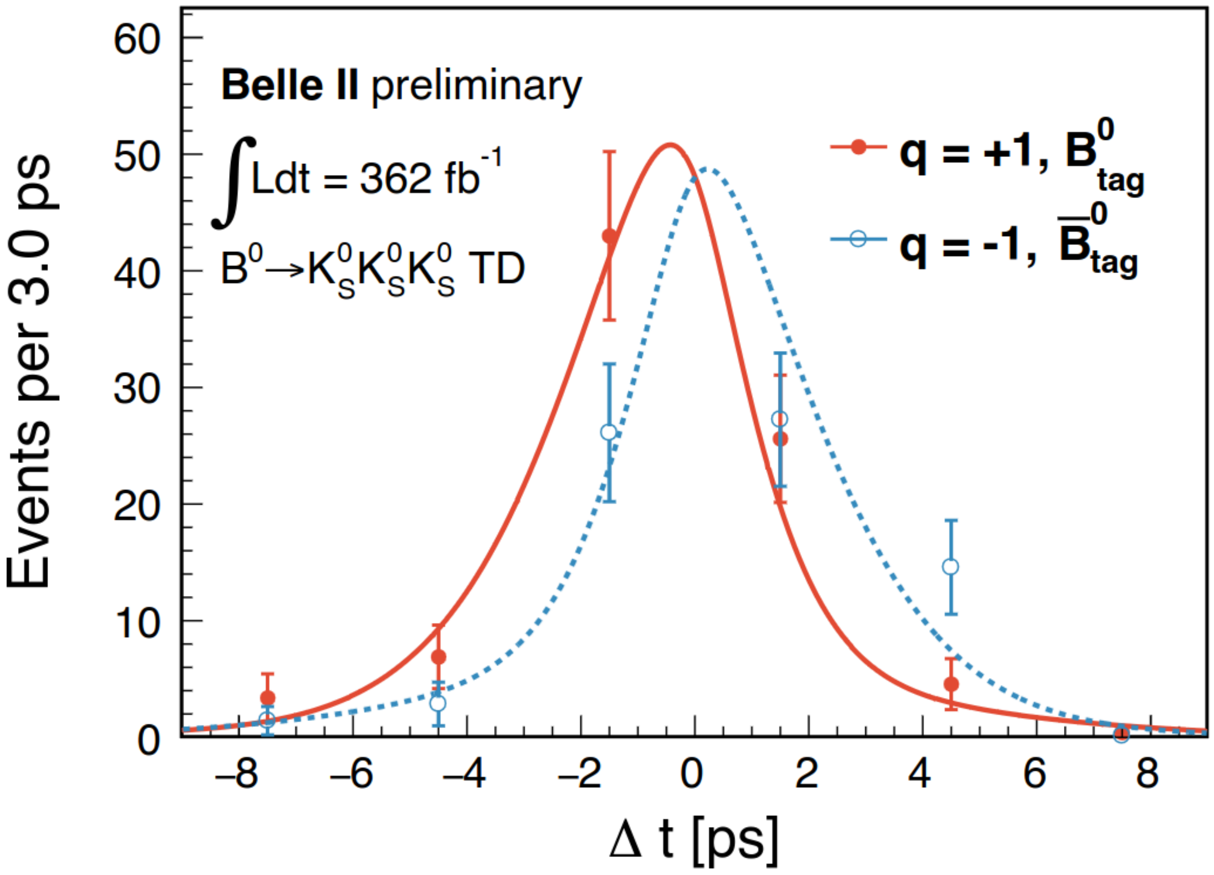
HFLAV: $C_{CP} = -0.15 \pm 0.12$ $S_{CP} = -0.83 \pm 0.17$



Moriond 23: φK_S

Clean experimental signature due to two prompt tracks from $\varphi \rightarrow K^+K^-$

Main challenge: non-resonant backgrounds with opposite-CP

Results competitive with best measurements

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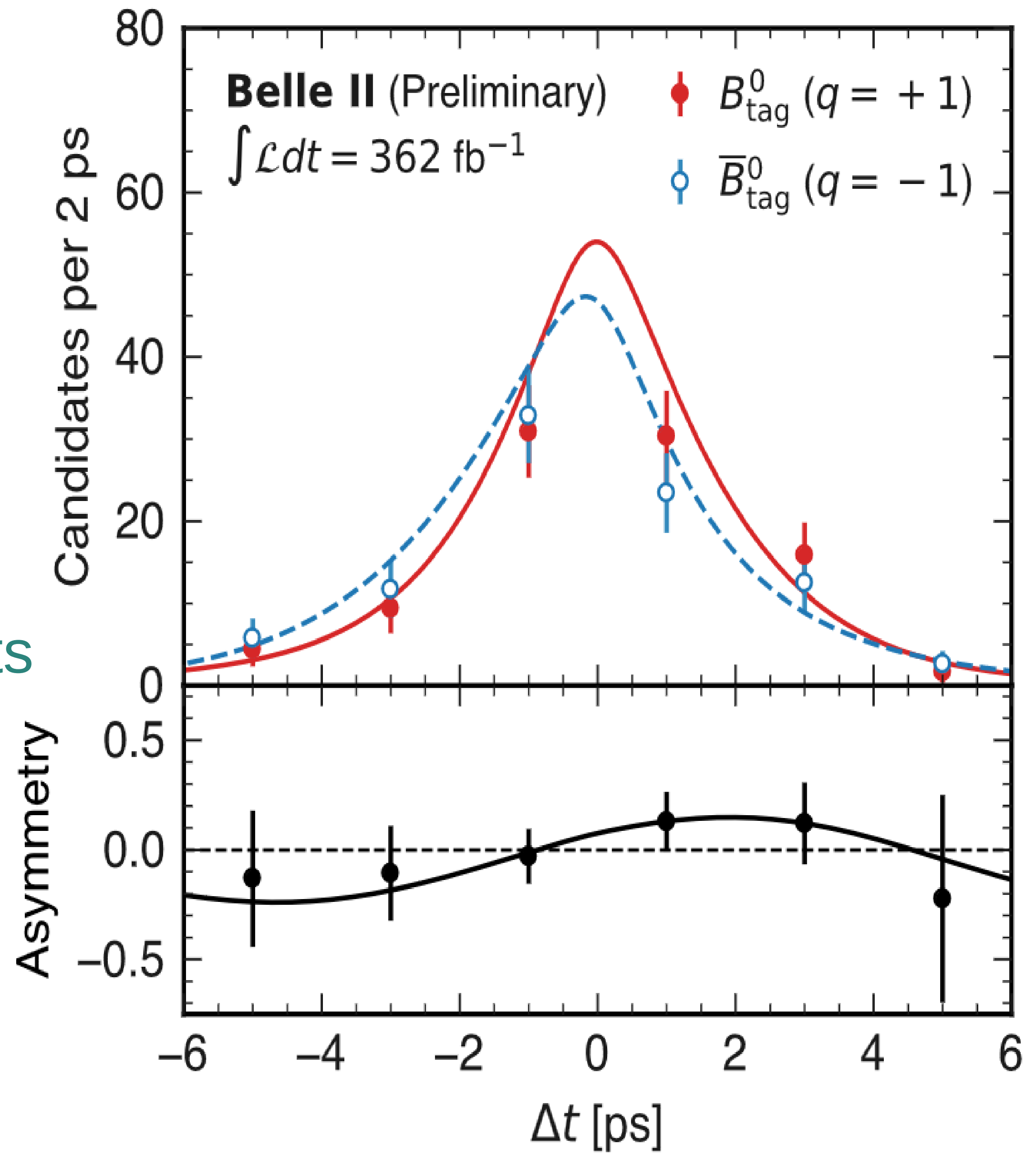
HFLAV: $C_{CP} = 0.01 \pm 0.14$ $S_{CP} = 0.74^{+0.11}_{-0.13}$



CB FT Perfomance