Measurements of time-dependent CP violation in B decay at Belle and Belle II

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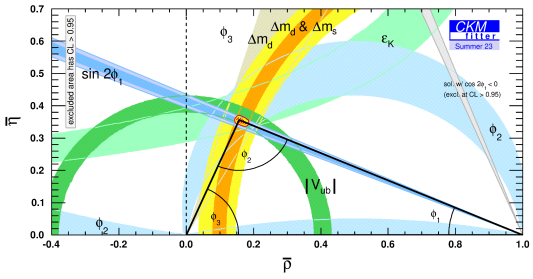
EPS-HEP 2025

07 July 2025

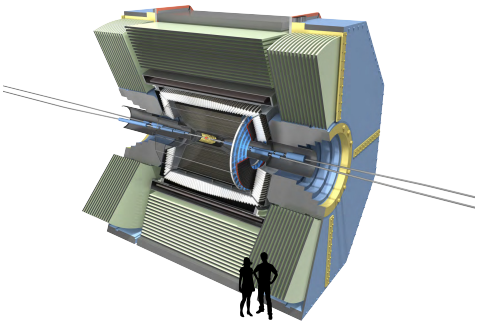
Introduction

- CKM matrix describes transition probabilities between quark flavor states in the Standard Model.
- Unitarity of CKM matrix represented by triangles in complex plane.
- Over-constrain the triangle
  $\rightarrow$ any deviation from triangle hints towards New Physics.
- To date, no significant deviations from the Standard Model $\rightarrow$ more precise measurements needed (e.g. Belle II, LHCb).



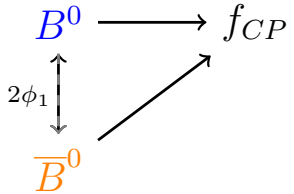
SuperKEKB and Belle II

- SuperKEKB: Asymmetric e^+e^- collision at the $\Upsilon(4S)$ energy.
  - Run 1: Collected $365\ \mathrm{fb}^{-1}$ on-resonance data, corresponding to $387\mathrm{M}\ B\bar{B}$ pairs.
  - Achieved world record instantaneous luminosity of $5.1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
  - Run2: data-taking ongoing.
- Belle II: Upgrade of all purpose Belle detector.
  - New pixel detector close to interaction region $\rightarrow$ Improved vertex resolution.
  - Efficient reconstruction of neutral particles (e.g. K_S, π^0).
  - Known initial conditions (ideal for decays with missing energy).



Mixing-Induced CP Violation

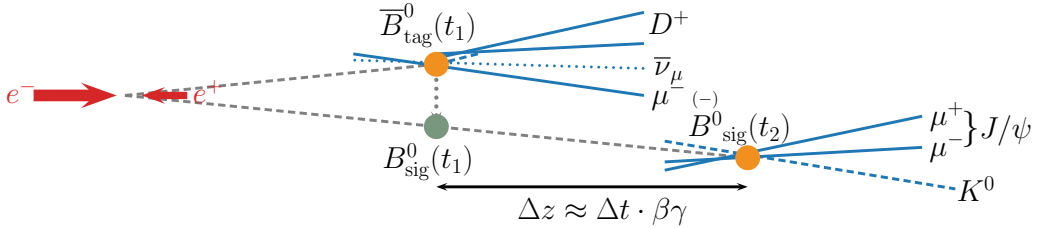
Interference of mixing and decay amplitudes lead to mixing-induced CP violation.
ϕ_1 contributes as the mixing phase $|V_{td}|e^{i\phi_1}$ in B meson mixing.
Decay to CP eigenstate f_{CP}.



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

S_{CP}: mixing-induced CP asymmetry C_{CP}: direct CP asymmetry

Time-Dependent CP Measurements at Belle II



Critical for good time-dependent measurements at Belle II:

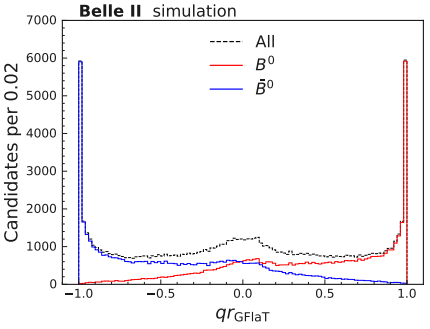
1. Good vertex resolution compensating for lower boost (Belle II: $\Delta z \approx 130 \mu m$, Belle: $\Delta z \approx 200 \mu m$).
2. High tagging efficiency due to entanglement (Belle II: $\epsilon_{tag} = (37.4 \pm 0.5)\%$, Belle: $\epsilon_{tag} = (30.1 \pm 0.4)\%$)

GNN Flavor Tagger (GFlaT)

arXiv:2402.17260

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

$\rightarrow$ Improved tagging efficiency leads to $\sim 18\%$ more effective data compared to conventional flavor tagger!



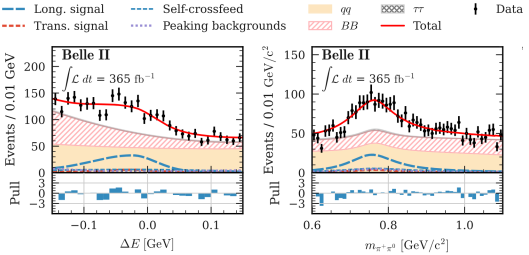
All analyses presented today use GFlaT!

$B^0 \to \rho^+\rho^-$: Physics and Analysis

PhysRevD.111.092001

Measure ϕ_2 from time-dependent analysis of $b \to u\bar{u}d$ transitions.
Pollution from $b \to d$ penguin amplitude: $S_{CP} = \sqrt{1 - C_{CP}^2}\sin(2\phi_2 + \Delta\phi_2)$.
$P \to VV$ decay: one longitudinal and two transverse polarization states
$\to$ measure longitudinal polarization fraction f_L from decay (helicity) angle distributions of $\rho^\pm$ mesons.

- $\rho^\pm \to \pi^\pm\pi^0$: good Δt resolution from 2 prompt tracks.
- Challenge: large combinatorial backgrounds from low energy photons
  $\to$ train classifier to distinguish correct and fake photons.
- Signal extraction fit in ΔE, $\cos\theta_{\rho^\pm}$, $m_{\pi^\pm\pi^0}$, $q\bar{q}$ background suppression variable.



$\Delta E = E^*_B - E^*_{\text{beam}}$

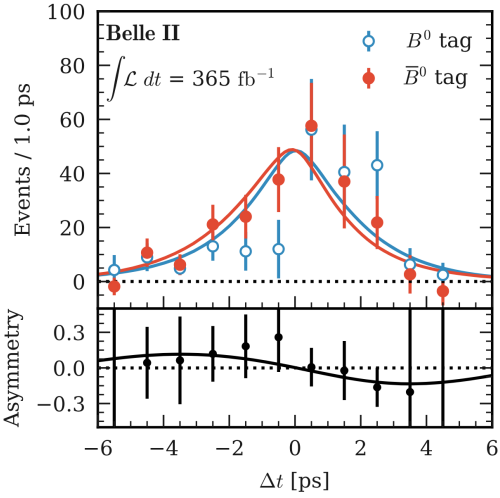
$B^0 \to \rho^+\rho^-$: Results

PhysRevD.111.092001

- Use signal weighting from previous fit to extract C_{CP} and S_{CP} from fit of Δt in bins of GFlaT output.

$$\mathcal{B} = (2.89^{+0.23+0.29}_{-0.22-0.27}) \times 10^{-5}$$
$$f_L = 0.921^{+0.024+0.017}_{-0.025-0.015}$$
$$C_{CP} = -0.02 \pm 0.12^{+0.06}_{-0.05}$$
$$S_{CP} = -0.26 \pm 0.19 \pm 0.08$$

On par with world's best measurements.
Perform isospin analysis combining $B \to \rho\rho$ and $B \to \pi\pi$ results (details on $B^0 \to \pi^0\pi^0$ in Xiaodong's talk) to extract $\phi_2 = (92.6^{+4.5}_{-4.7})^\circ$.

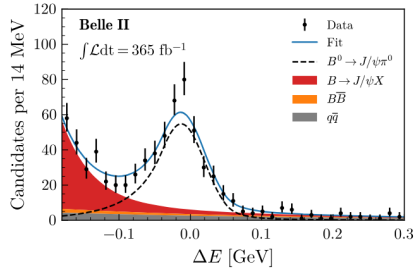


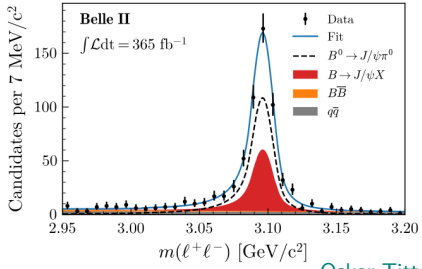
$B^0 \to J/\psi\pi^0$: Physics and Analysis

PhysRevD.111.012011

Measurements of ϕ_1 in $b \to c\bar{c}s$ transitions are shifted by penguin contributions.
Use $B^0 \to J/\psi\pi^0$ which proceeds via a $b \to c\bar{c}d$ transition to constrain resulting shift.
$\phi_d^{eff} = 2\phi_1 + \Delta\phi_d$, with $\Delta\phi_d \approx 0.5°$.

- $J/\psi \to \ell^+\ell^-$ ($\ell = e/\mu$) gives experimentally clean signal.
- Challenge: reconstruction of π^0: $B \to J/\psi X$ backgrounds.
- Signal extraction fit in ΔE and $m(\ell^+\ell^-)$ with shapes controlled from $B^0 \to J/\psi K_S^0$ and $B^+ \to J/\psi K^{*+}$ decays.





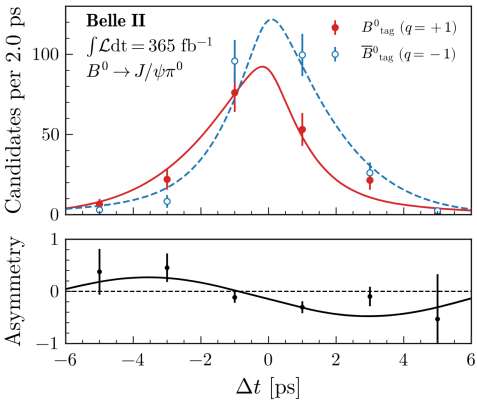
$B^0 \to J/\psi\pi^0$: Results

PhysRevD.111.012011

- Use signal weighting from previous fit to extract C_{CP} and S_{CP} in signal region from fit of Δt in bins of GFlaT output.

$$\mathcal{B} = (2.00 \pm 0.12 \pm 0.09) \times 10^{-5}$$
$$C_{CP} = 0.13 \pm 0.12 \pm 0.03$$
$$S_{CP} = -0.88 \pm 0.17 \pm 0.03$$

First observation (with 5σ) of mixing-induced CP violation in $B^0 \to J/\psi\pi^0$ from a single measurement!
Already used to constrain $\Delta\phi_d$: arXiv:2501.09414



$B^0 \to J/\psi\omega$

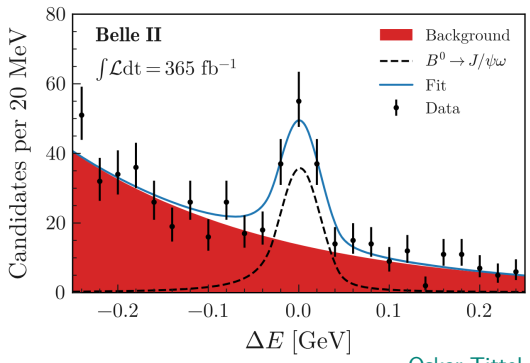
PhysRevD.111.032012

$B^0 \to J/\psi\omega$, like $B^0 \to J/\psi\pi^0$, proceeds via a $b \to c\bar{c}d$ transition.
Channel can be used to constrain shift in ϕ_1 due to penguin contributions and as control channel for decays mediated by $b \to d\ell^+\ell^-$ transitions.
$P \to VV$ decay: measure longitudinal polarization fraction in the future.

- Challenge: reconstruction of $\omega \to \pi^+\pi^-\pi^0$
  $\to$ use BDT to suppress backgrounds from fake ω candidates.

$$\mathcal{B} = (2.16 \pm 0.30 \pm 0.14) \times 10^{-5}$$

First observation of this decay, with 6.5σ significance!
Most precise result to date!



Conclusion

- The presented results are competitive with world's best measurements or world leading.
- Many channels only accessible at Belle II
- Precision achieved by detector (e.g. PXD) and software (e.g. GFlaT) improvements.
- After problems with data taking in 2024, improved detector and accelerator understanding.