CP violation in beauty and charm decays at Belle and Belle II

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Introduction

- Big Bang created equal amounts of matter and antimatter
  - ➔ Nowadays we only observe matter

- Process to produce such an asymmetry: Baryogenesis
  - ➔ Requires *CP* violation

- Standard Model (SM) allows for *CP* violation via irreducible complex phase in CKM matrix

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\lambda-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

- Not “strong” enough to explain the observed asymmetry
  - ➔ Measurements of large *CP* violation ⟶ new physics

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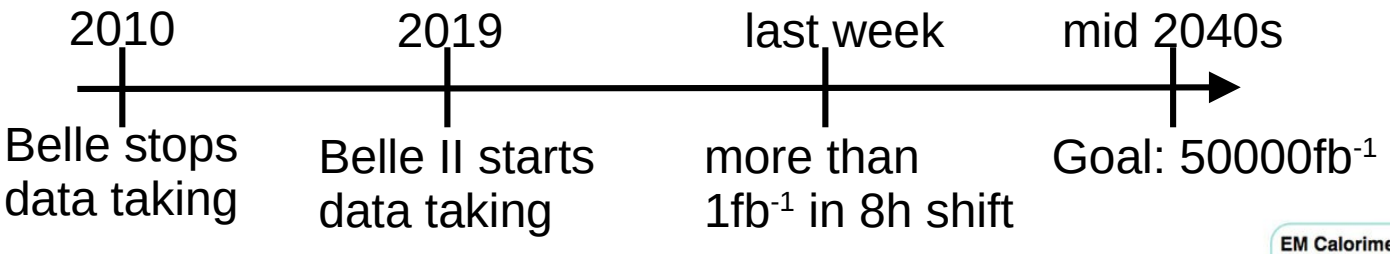
Today:

- Direct *CP* violation in c-quark decays: $\Xi_c^+ \to \Sigma^+ h^+ h^-$, $\Lambda_c^+ \to p h^+ h^-$ and $D^0 \to \pi^+ \pi^- \pi^0$
- Time dep. *CP* violation in b-quark decays: $B^0 \to K_S^0 \pi^+ \pi^- \gamma$

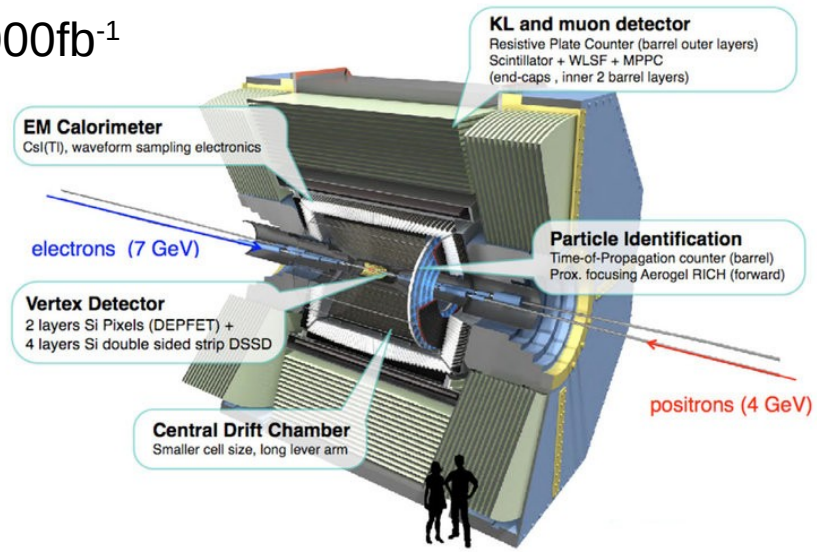
SuperKEKB and Belle II

- SuperKEKB: Asymmetric e^+e^- collisions at and near $\Upsilon(4S)=10.58\,\mathrm{GeV}$ resonance
  - Belle collected $\sim 1000\,\mathrm{fb}^{-1}$
  - Belle II collected $\sim 640\,\mathrm{fb}^{-1}$ (ongoing data-taking right now)
    - World record luminosity $L_{peak}=5.2\times10^{34}\,\mathrm{cm}^{-2}s^{-1}$

$\sigma(e^+e^-\to b\bar{b})=1.1\,nb$
$\sigma(e^+e^-\to c\bar{c})=1.3\,nb$
$\sigma(e^+e^-\to u\bar{u},d\bar{d},s\bar{s})=1.7\,nb$
$\sigma(e^+e^-\to\tau\to\bar{\tau})=0.8\,nb$



- Belle II detector: Upgrade of Belle detector
  - New pixel detector
    - ➔ Excellent vertex reconstruction
  - Clean e^+e^- environment
    - ➔ Excellent neutral reconstruction (e.g. K_S^0,π^0,γ)



Direct *CP* violation in $\Lambda_c^+ \to p h^+ h^-$ and $\Xi_c^+ \to \Sigma^+ h^+ h^-$

Belle II: 428 fb^{-1}

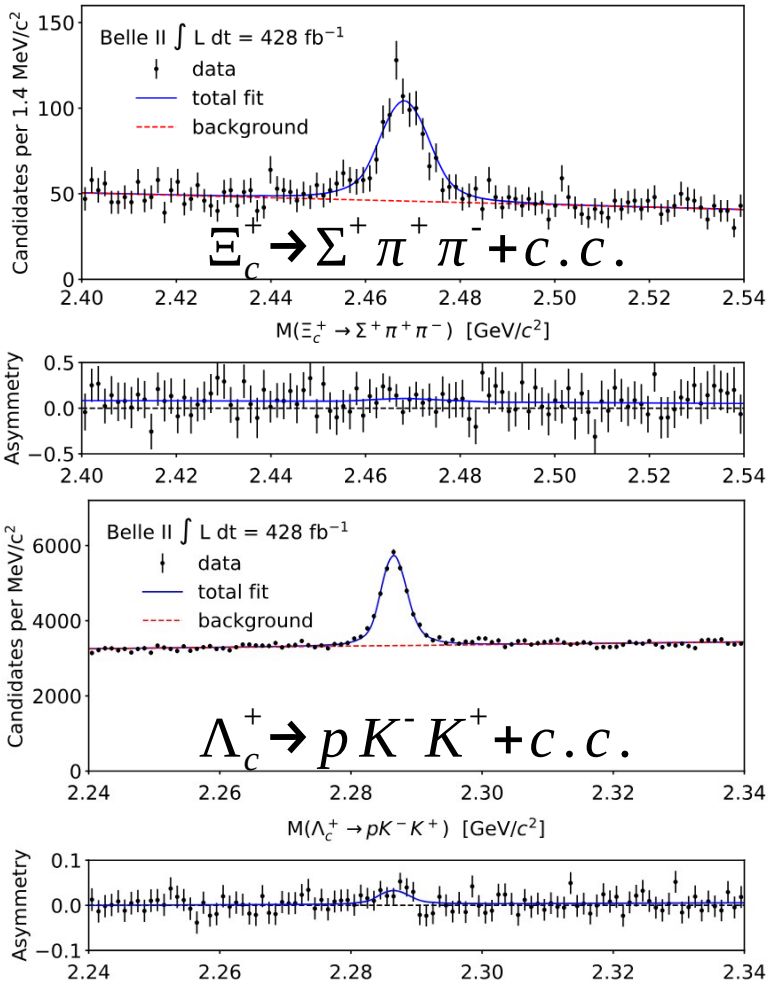
Direct *CP* violation in $\Xi_c^+ \to \Sigma^+ h^+ h^-$ and $\Lambda_c^+ \to p h^+ h^- (h = \pi, K)$

- Direct *CP* violation $A_{CP} = \frac{\Gamma(P \to f) - \Gamma(\bar{P} \to \bar{f})}{\Gamma(P \to f) + \Gamma(\bar{P} \to \bar{f})}$
- First measurements of *CP* violation in charmed baryon decays to hadronic three-body final states
- SM-test of *U*-spin symmetry ([PRD 99.033005](), [EPJC 79, 429]())

$$A_{CP}(\Xi_c^+ \to \Sigma^+ \pi^+ \pi^-) - A_{CP}(\Lambda_c^+ \to p K^+ K^-) = 0$$

$$A_{CP}(\Xi_c^+ \to \Sigma^+ K^+ K^-) - A_{CP}(\Lambda_c^+ \to p \pi^+ \pi^-) = 0$$

- Corrected for detector and production induced asymmetries
- Signal yields determined in unbinned fits of the baryon invariant mass



PRD 113, 032017

Direct *CP* violation in $\Xi_c^+ \to \Sigma^+ h^+ h^-$ and $\Lambda_c^+ \to p h^+ h^- (h = \pi, K)$

Results:

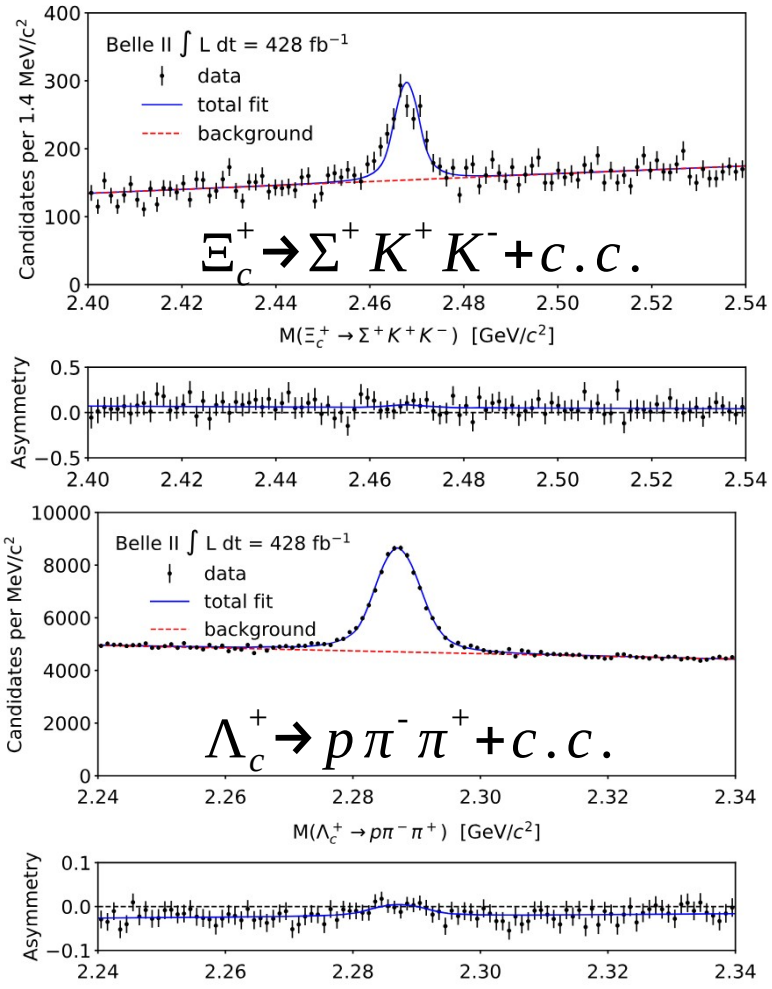
$$A_{CP}(\Xi_c^+ \to \Sigma^+ K^+ K^-) = (3.7 \pm 6.6 \pm 0.6)\%$$
$$A_{CP}(\Xi_c^+ \to \Sigma^+ \pi^+ \pi^-) = (9.5 \pm 6.8 \pm 0.5)\%$$
$$A_{CP}(\Lambda_c^+ \to p K^+ K^-) = (3.9 \pm 1.7 \pm 0.7)\%$$
$$A_{CP}(\Lambda_c^+ \to p \pi^+ \pi^-) = (0.3 \pm 1.0 \pm 0.2)\%$$

from which we derive

$$A_{CP}(\Xi_c^+ \to \Sigma^+ \pi^+ \pi^-) - A_{CP}(\Lambda_c^+ \to p K^+ K^-) = (13.4 \pm 7.0 \pm 0.9)\%$$

$$A_{CP}(\Xi_c^+ \to \Sigma^+ K^+ K^-) - A_{CP}(\Lambda_c^+ \to p \pi^+ \pi^-) = (4.0 \pm 6.6 \pm 0.7)\%$$

- No *CP* violation observed
- Consistent with SM *U*-symmetry



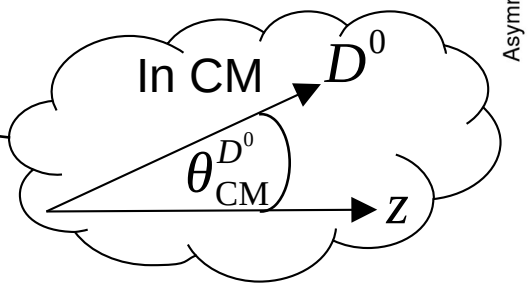
PRD 113, 032017

Direct *CP* violation in $D^0 \to \pi^+ \pi^- \pi^0$

Belle II: 428 fb^{-1}

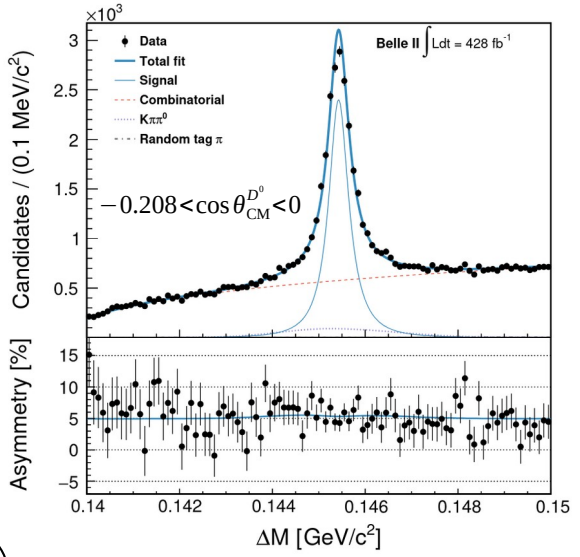
Direct *CP* violation in $D^0 \to \pi^+ \pi^- \pi^0$

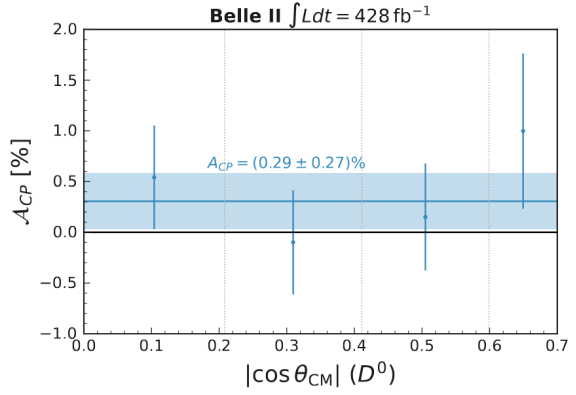
- Flavor of D^0 tagged in $D^{*+} \to D^0 [\to \pi^+ \pi^- \pi^0] \pi^+$ (or $D^{*-} \to \overline{D}^0 [\to \pi^+ \pi^- \pi^0] \pi^-$)
- Corrected for detector induced asymmetries
- Signal yields determined in unbinned fits to $M(D^0)$ and $\Delta M = M(D^{*+}) - M(D^0)$ in bins of $\cos\theta^{D^0}_{\mathrm{CM}}$



$$A_{CP} = (0.29 \pm 0.27 \pm 0.13)\%$$

- Consistent with *CP* symmetry
- **34%** more precise than current best (BaBar: PRD 78, 051102) despite only 10% more data





arXiv.2510.21224

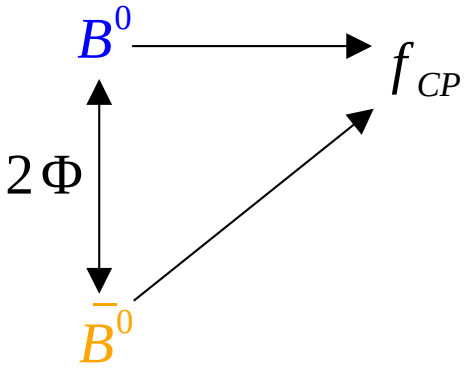
Time dependent *CP* violation in $B^0 \to K^0_S \pi^+ \pi^- \gamma$

Belle: 711 fb^{-1} + Belle II: 365 fb^{-1}

Mixing-induced CP violation

- Neutral particle being able to oscillate into its anti-particle gives rise to mixing-induced *CP* violation

- Mixing-induced *CP* violation

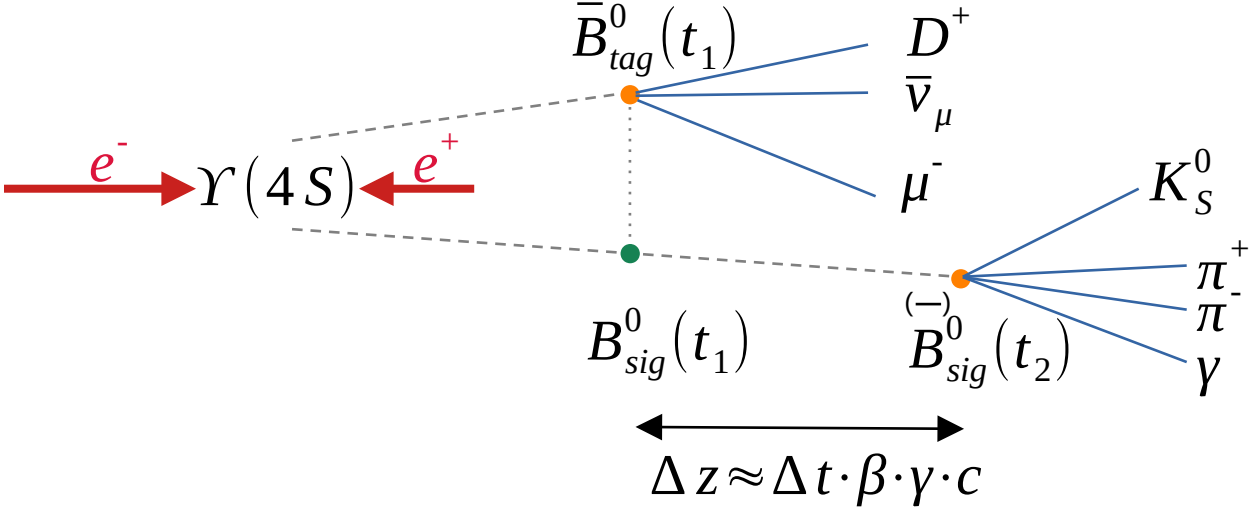


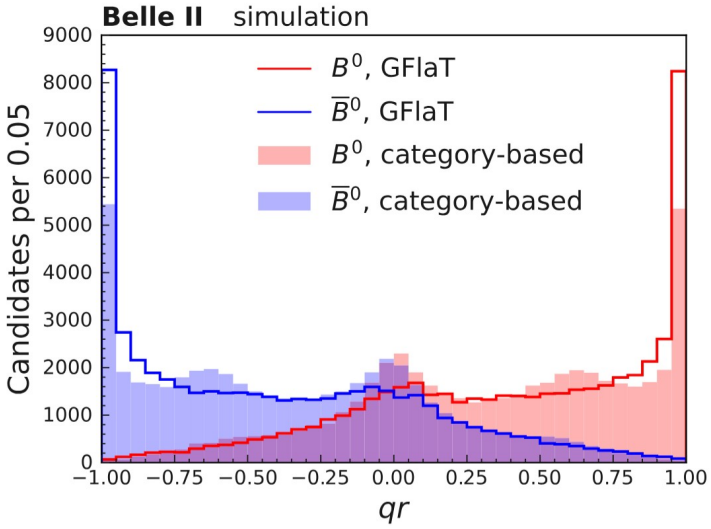
$$A_{CP}(\Delta t) = \frac{\Gamma(\bar{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\bar{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})}(\Delta t) = S_{CP} \cdot \sin(\Delta m_d \Delta t) - C_{CP} \cdot \cos(\Delta m_d \Delta t)$$

mixing induced CP violation

direct CP violation

Time dependent *CP* violation measurements



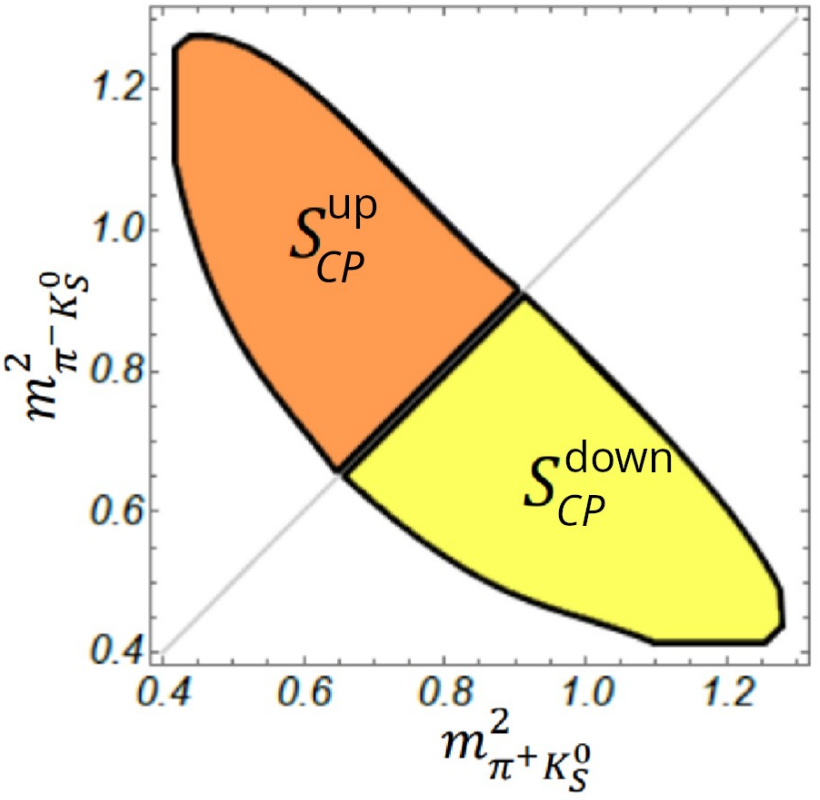


PRD 110, 012001

Requirement	Belle	Belle II
Good vertex resolution	$\Delta z \approx 200\,\mu m$	$\Delta z \approx 130\,\mu m$
High tagging efficiency	$\epsilon_{tag} \approx 30\,\%$	$\epsilon_{tag} \approx 37\,\%$

Time dependent *CP* violation in $B^0 \to K^0_S \pi^+ \pi^- \gamma$

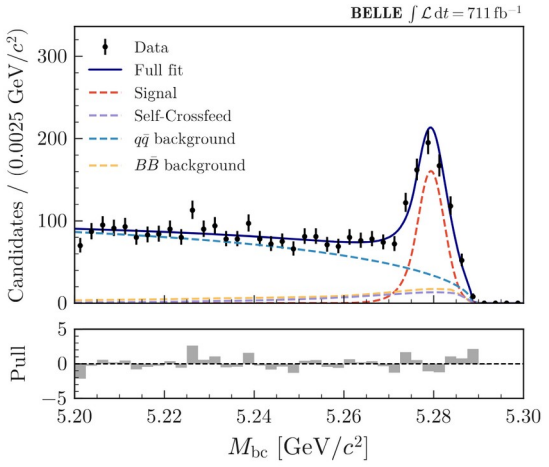
- Only $B^0 \to K^0_S \rho^0 [\to \pi^+ \pi^-]$ true *CP* eigenstate f_{CP}
- $B^0 \to f_{CP} \gamma$ photon dominantly left-handed
  - SM predicts S≈0
- Contributions from non-CP eigenstates, e.g. $K^{*+-} \pi^{-+}$ can be disentangled in amplitude analysis (not done here)
- We measure S_{CP}, C_{CP} and S^+_{CP}, S^-_{CP}
  - $S^+_{CP} = S^{up}_{CP} + S^{down}_{CP}$
  - $S^-_{CP} = S^{up}_{CP} - S^{down}_{CP}$
  - Can constrain C_7/C'_7 [JHEP09(2019)034]

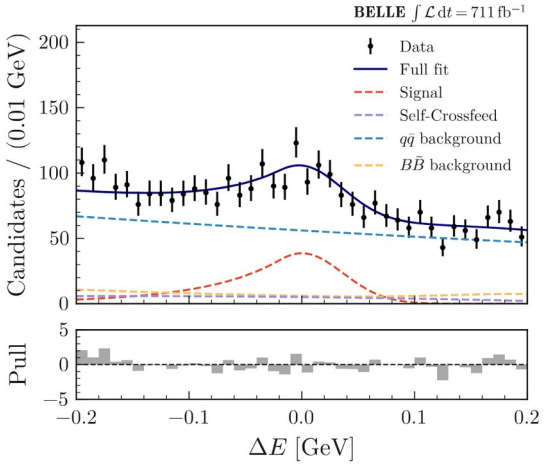


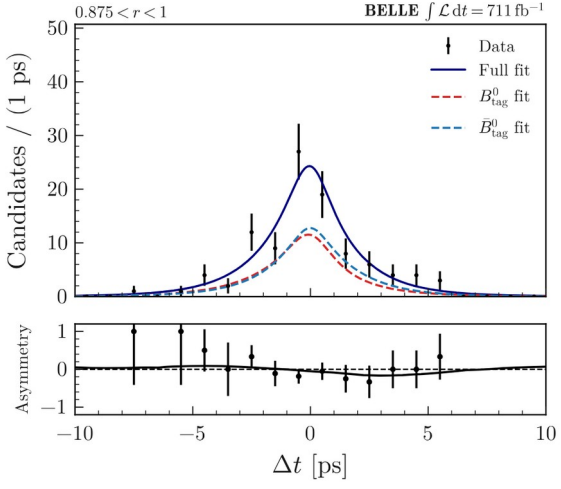
Time dependent *CP* violation in $B^0 \to K^0_S \pi^+ \pi^- \gamma$

- Parameters determined in 3D fit to
  - $M_{bc} = \sqrt{E^{*2}_{beam} - \left|\vec{p}^{\,*}_B\right|^2}$
  - $\Delta E = E^*_B - E^*_{beam}$
  - Δt

$$C = -0.17 \pm 0.09 \pm 0.04$$
$$S = -0.29 \pm 0.11 \pm 0.05$$
$$S^+ = -0.57 \pm 0.23 \pm 0.10$$
$$S^- = 0.31 \pm 0.24 \pm 0.05$$







JHEP01(2026)134

- **Most precise determination**
- Superseding previous Belle (PRL 101, 251601) and BaBar (PRD 93, 052013) measurements by **factor 2**

Summary

- *CP* violation measurements are great probe for new physics
- Belle and Belle II data are analyzed in combined measurements
- Presented two direct *CP* violation searches of c-quark decays
  - → **Worlds most precise determinations**
- Showed time dependent *CP* measurement of $B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma$
  - → Consistent with previous determinations with **factor 2 improvement of uncertainties**
- All presented measurements are statistically limited

Backup

Raw *CP* violation

- We measure: $A_{raw}^{sig} = A_{CP}^{sig} + A^{det} + A^{prod}$

Can be removed by averaging over production angle cosΘ*

- Estimate A^{det} and A^{prod} in control channel (cc): $A_{raw}^{cc} = A_{CP}^{cc} + A^{det} + A^{prod}$

Precisely known

→ Measure: $A_{CP}^{sig} = A_{raw}^{sig} - A_{raw}^{cc} + A_{CP}^{cc}$