Recent measurements of CP violation

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The 29th International Workshop on Weak Interactions and Neutrinos, July3-8, 2023, Zhuhai, China

The Mystery of the Matter Asymmetry

- According to the Big Bang theory, equal amounts of matter and antimatter were initially created in the early Universe. . However, in the current Universe, almost all things consist of only matter.
- CP violation is required to explain the matter- antimatter asymmetry of the Universe.
- The study of CP violation (CPV) is experiment-driven. CP violation was discovered in 1964 in the decays of neutral kaons, which was completely unexpected then.
- To date, CPV has been confirmed in K, B and D meson decays.
- In the Standard Model (SM), CPV is present in the weak interactions via CKM mechanism, it is insufficient to explain the observed matter-antimatter asymmetry in the Universe.
- The SM is incomplete and other sources of CPV must exist.

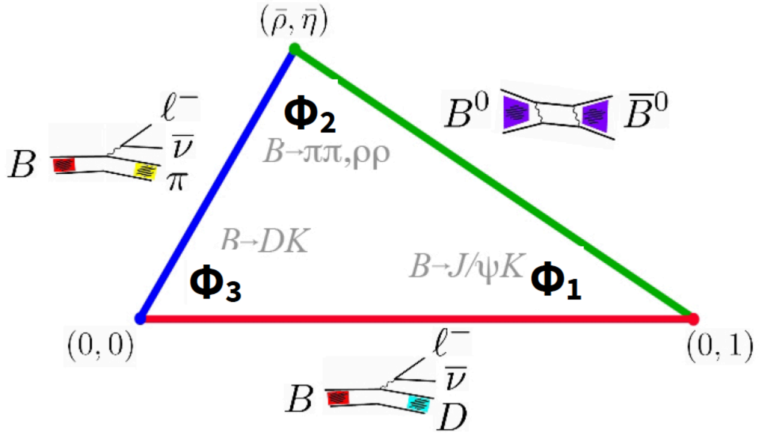
CP violation and the Unitarity Triangle

- In SM, the Kobayashi-Maskawa mechanism provides an elegant and simple explanation of CP violation.
- Wolfenstein parametrization: CKM matrix described by 4 parameters λ, A, ρ, η.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\cong \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



- η is the source of CPV in the SM.
- Key test of the SM: determining accurately the Unitarity Triangle
  - Magnitudes: branching fractions or mixing frequencies
  - Angles (ϕ_1/β, ϕ_2/α, ϕ_3/γ): CP violation measurements in B decays.

Recent CPV measurements

Time-dependent:
- $B^0 \to J/\psi K_S^0$ arXiv:2302.12898
- $B^0 \to \phi K_S^0$ Moriond 2023
- $B^0 \to K_S^0 K_S^0 K_S^0$ Moriond 2023
- $B^0 \to K_S^0 \pi^0$ arXiv:2305.07555

Time-integrated:
- $B^+ \to \pi^+\pi^0$ Moriond 2023
- $B^0 \to \pi^0\pi^0$ arXiv:2303.08354

γ/ϕ_3 measurement :
- $B^+ \to D(K_S^0 K^+\pi^-)K^+$ arXiv: 2306.02940
- $B^+ \to D_{CP} K^+$ Moriond 2023

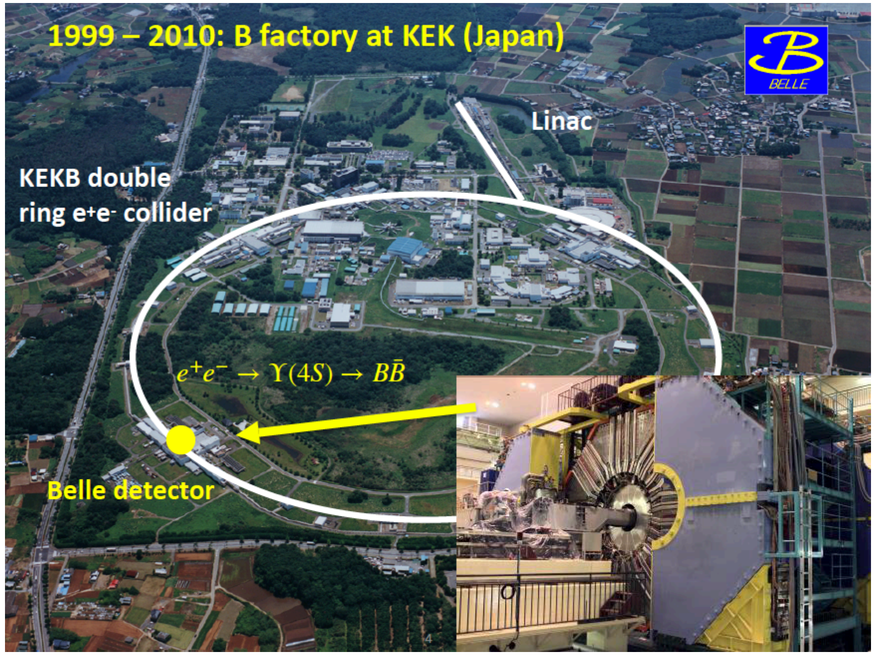
Charm
- T-odd CPV in $D_{(s)}^+$ four-body decays
  PRD 107, 052001 (2023)
  arXiv:2305.12806 arXiv:2305.11405
- $\Lambda_c^+ \to \Lambda h^+$ and $\Lambda_c^+ \to \Xi^0 h^+$
  Sci.Bull. 68 (2023) 583

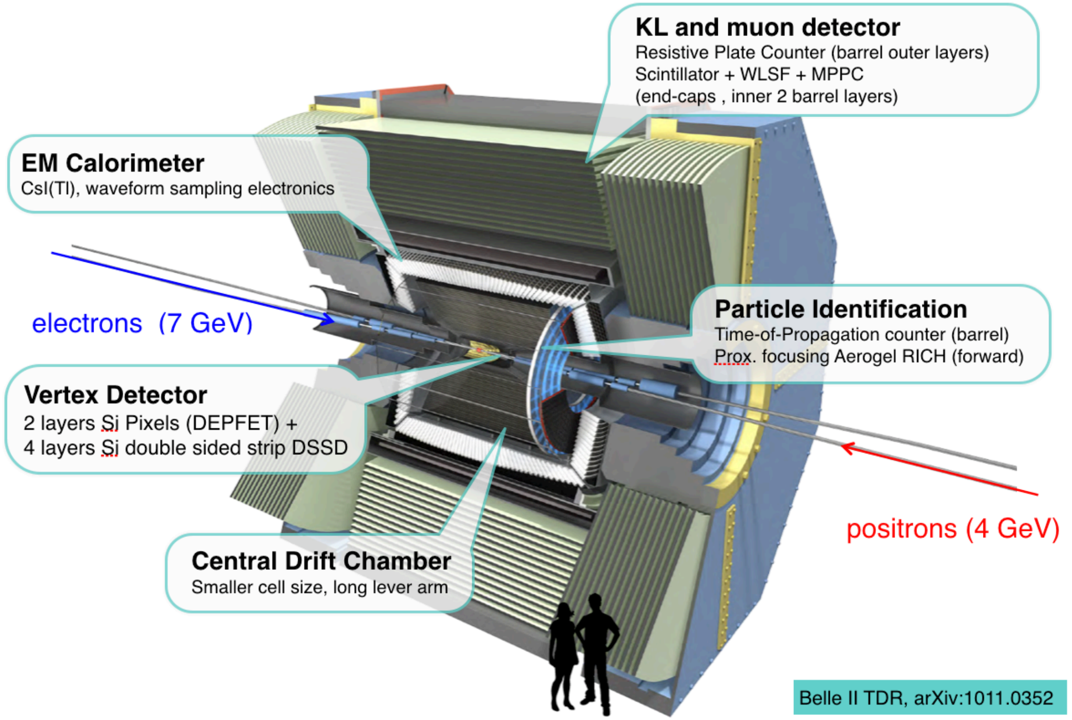
- Recent CPV measurements in the quark sector.

LHCb:
- $B^0 \to \psi K_S^0$ LHCb-Paper-2023-013
- $B^+ \to D(K^-\pi^+\pi^+\pi^-)h^+$
  arXiv:2209.03692
- $B^+ \to D(h^+h^-\pi^+\pi^-)h^+$
  arXiv:2301.10328
- $B_s^0 \to J/\psi K^+K^-$ LHCb-Paper-2023-016
- $B_s^0 \to \phi\phi$ arXiv:2304.06198
- $D^0 \to K^+K^-$ arXiv:2209.03179
- $D_{(s)} \to K^-K^+K^+$ arXiv:2303.04062
- $D^0 \to \pi^-\pi^+\pi^0$ arXiv:2306.12746

BESIII:
- $J/\psi \to \Xi^-\Xi^+$
- Nature 606, 64 (2022)
- $J/\psi \to \Sigma^+\bar{\Sigma}^-$
- arXiv:2304.14655
- $J/\psi \to \Xi^0\bar{\Xi}^0$
- arXiv:2305.09218
- $\psi(3686) \to \Xi^0\bar{\Xi}^0$
- arXiv:2302.09767
- $J/\psi \to \Lambda\bar{\Lambda}$
- PRL 129 (2022) 131801

Belle & Belle II Experiments



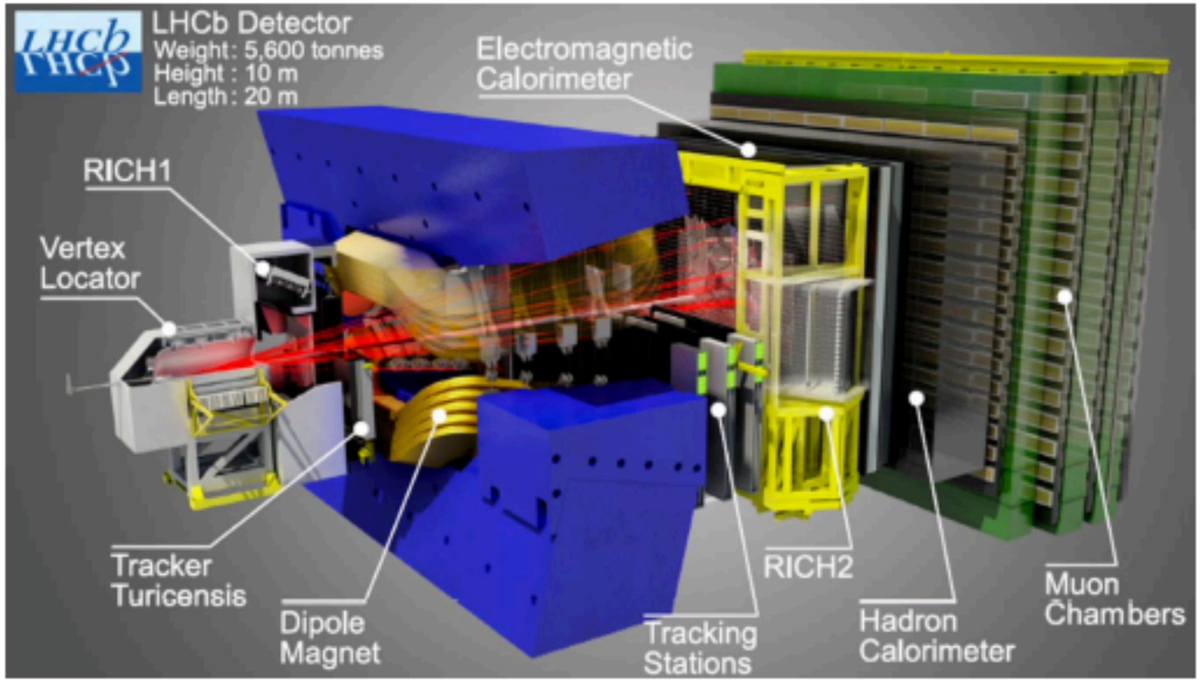


- Asymmetric e^+e^- colliders. B factories, also charm and τ factories.
- Belle → Belle II: e^+ (3.5 GeV) e^- (8 GeV) → e^+ (4 GeV) e^- (7 GeV) . Improved vertex resolution allows lower boost.
- 428 fb^{-1} (362 fb^{-1} at $\Upsilon(4S)$) collected at Belle II so far. Goal: 50 ab^{-1}.
- Record peak luminosity $4.7\times10^{34} cm^{-2}s^{-1}$ at Belle II.

- Silicon detectors for vertex measurement
- Drift chamber for p and dE/dx measurement
- TOP and ARICH counters for particle identification
- EM Calorimeter (ECL) for e^+ and γ reconstruction
- KLM detector for K_L and μ detection

The LHCb Experiment

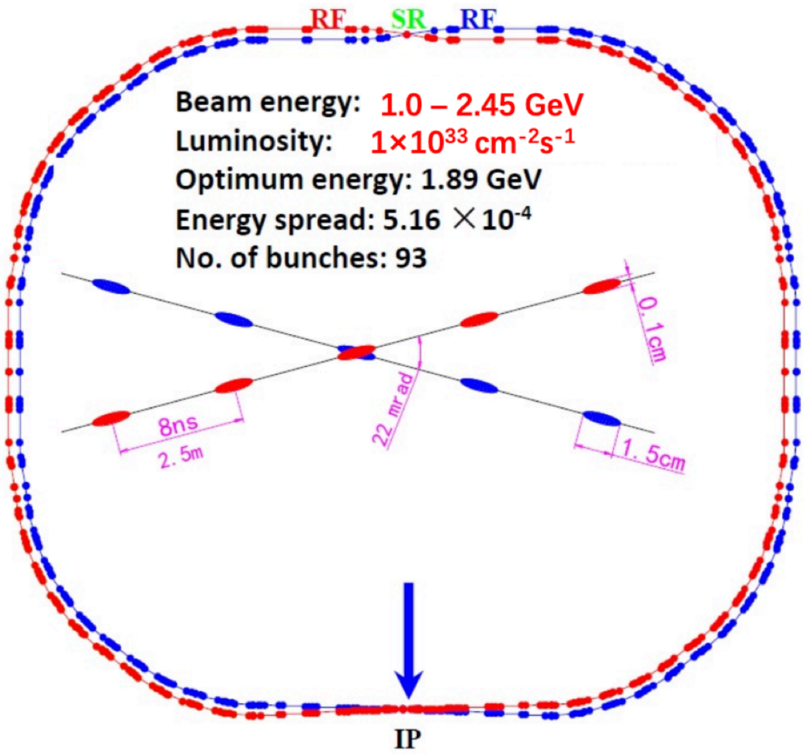
LHCb @ LHC (CERN): pp collisions



Run 1-2 detector

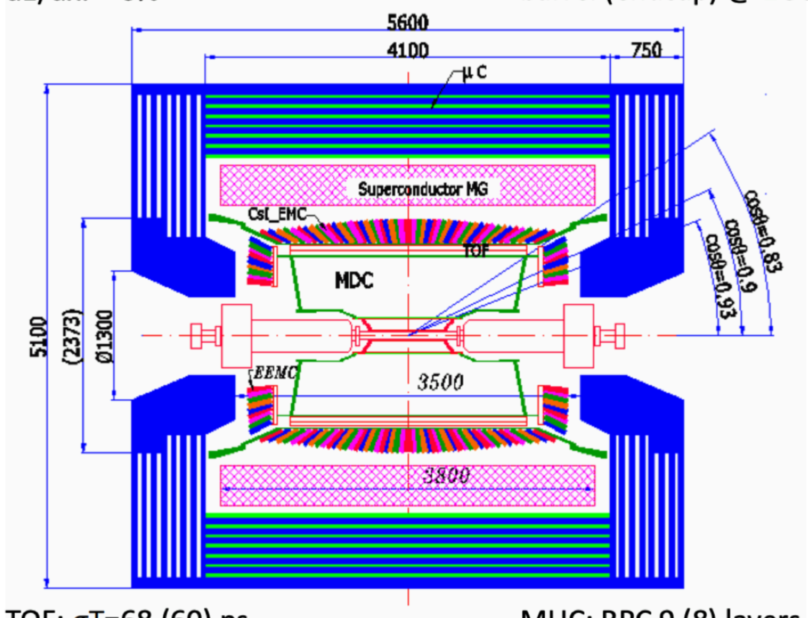
- Forward detector optimized for b and c meson studies.
- Huge b cross-section.
- Excellent vertex resolution and particle identification.
- Events with high multiplicity, reconstruction of neutrals is challenging.
- 9 fb^{-1} accumulated during Run1-2 (2010-2018)
- Run 3 started in 2022 with an upgraded LHCb detector, goal 50 fb^{-1}.

The BESIII Experiment



MDC: Δp/p =0.5% @ 1GeV/c
dE/dx: ~ 6%

EMC: CsI (Tl) 2.5% (5.0%)
barrel (endcap) @ 1GeV



TOF: σT=68 (60) ps
barrel (endcap)

MUC: RPC 9 (8) layers
barrel (endcap)

- Symmetric e^+e^- collider, low background. Charm and τ factory.
- Multipurpose detector with good resolution, near 4π angular coverage.
- World’s largest charmonia data sample.

Time Dependent (TD) CPV measurement at Belle(II)

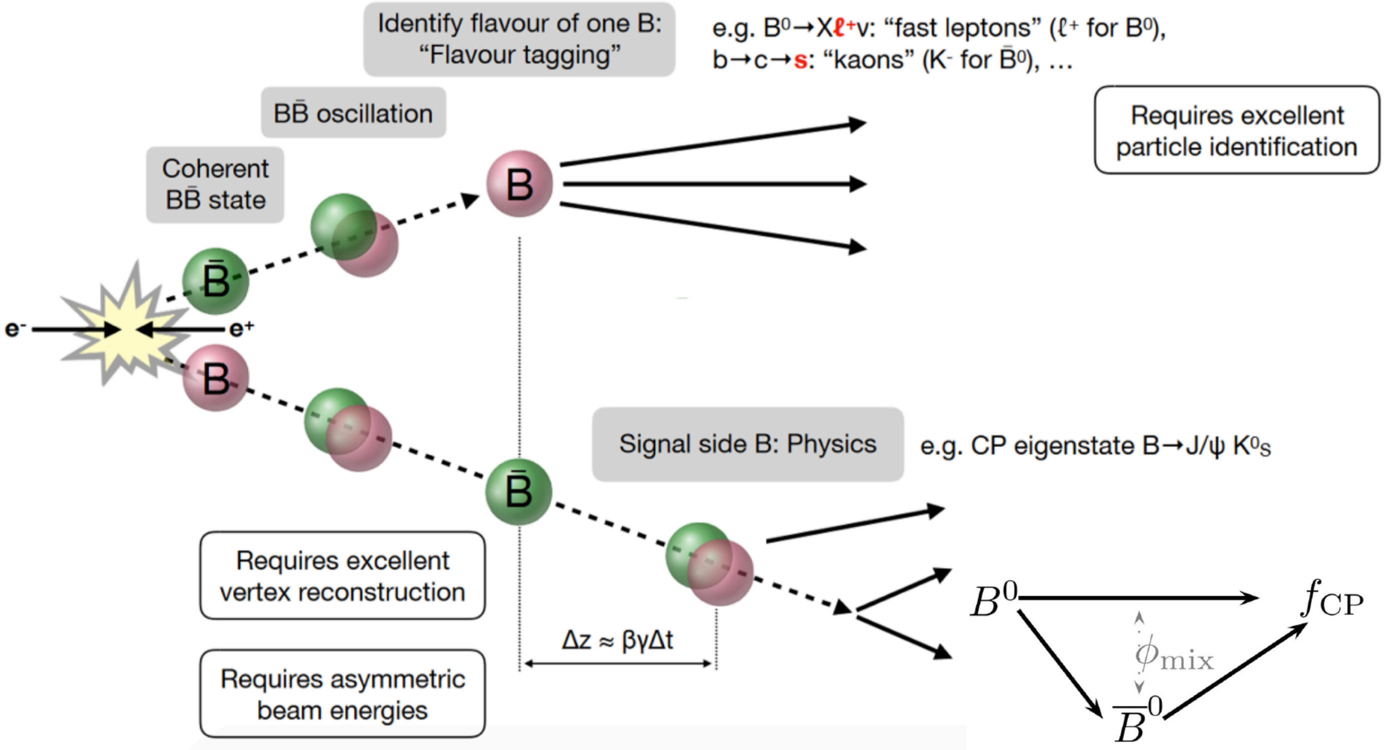
- The CP asymmetry, $A_{CP}(\Delta t)$, of the proper time difference distribution Δt of the two B mesons

The SM predicts A = 0 and S = −η sin 2ϕ₁

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

Mixing-induced CPV

Direct CPV

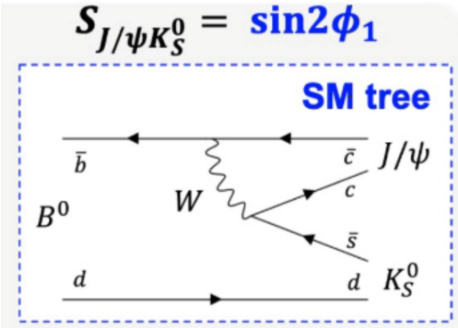


- The $B^0\overline{B^0}$ pairs from Υ(4S) are produced in a coherent, entangled quantum mechanical state. Tagging the flavor the other side B allows to know the flavor of signal side B.
- The distance between signal and tag-side B decay vertices in z direction (Δz) allows Δt to be measured.

TD CPV in $B^0 \to J/\psi K_S^0$

arXiv:2302.12898

Belle II 190 fb^{-1}

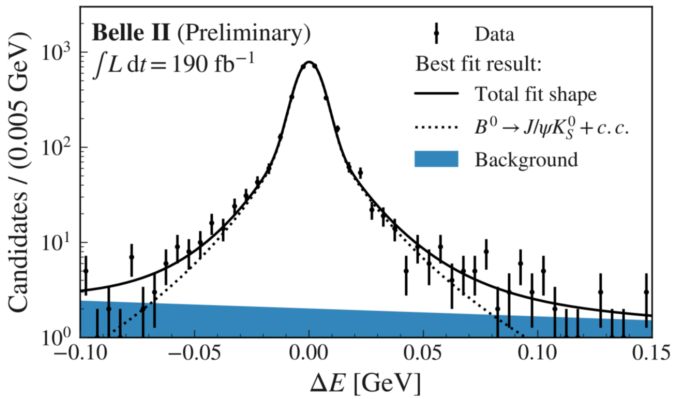


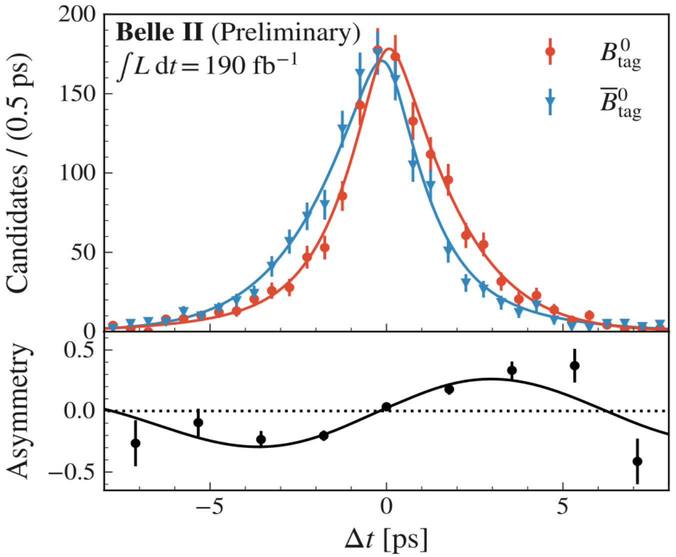
- Tree-dominated $b \to c\bar{c}s$, golden mode
  - small theoretical uncertainty and clean experimental signature.
  - contribution of penguin diagrams with a different CKM phase is expected to be at less than 1% level.
- Fit ΔE distribution and subtract background.
- Fit the sWeighted Δt distribution to extract sin(2β) and A_{CP}.

$$\mathcal{A}(\Delta t) = S_{J/\psi K_S^0} \sin(\Delta m_d \Delta t) + A_{J/\psi K_S^0} \cos(\Delta m_d \Delta t)$$

$$S_{CP} = 0.720 \pm 0.062(\mathrm{stat}) \pm 0.016(\mathrm{syst}),$$

$$A_{CP} = 0.094 \pm 0.044(\mathrm{stat}) {}^{+0.042}_{-0.017}(\mathrm{syst}).$$





- Consistent with the world-average. Statistical uncertainty is twice that of the current most precise determination (from Belle), consistent with a four-times smaller data set.

TD CPV in $b \to sq\bar{q}$

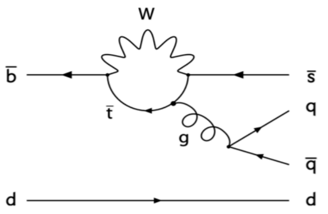
Belle II 362 fb^{-1}
387M $B\bar{B}$ pairs

- Penguin-dominated modes $b \to sq\bar{q}$: $B^0 \to \phi K_S^0$ and $B^0 \to K_S^0 K_S^0 K_S^0$.

$$\mathcal{A}(\Delta t) = S_{sq\bar{q}} \sin(\Delta m_d \Delta t) + A_{sq\bar{q}} \cos(\Delta m_d \Delta t)$$

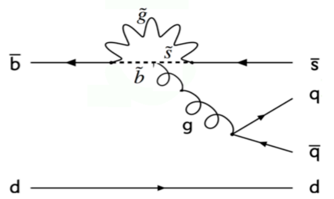
- $S_{sq\bar{q}} \approx -\eta_{CP} S_{J/\psi K_S^0}$ in the SM; discrepancy can arise if NP particle propagated in the $b \to sq\bar{q}$ loop.

Suppressed in SM



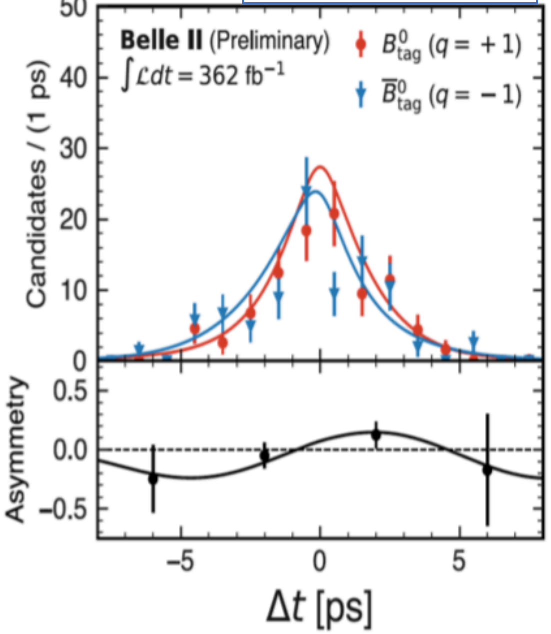
$S_{\text{penguin}} \approx \sin 2\beta$ (SM)
$A_{\text{penguin}} \approx 0$ (SM)

Access to potential BSM physics



$+ \Delta S$ (NP)
$+ \Delta A$ (NP)

$B^0 \to \phi K_S^0$

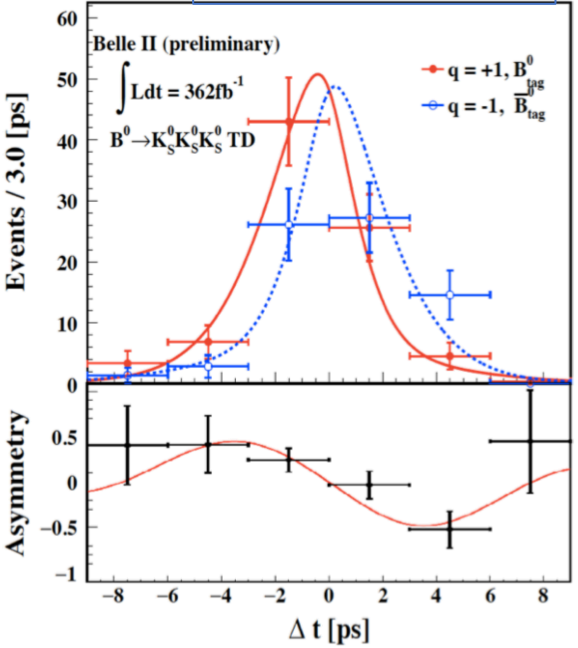


$S_{K_S\phi} = +0.54 \pm 0.26^{+0.06}_{-0.08}$
$A_{K_S\phi} = +0.31 \pm 0.20^{+0.05}_{-0.06}$

- $S_{K_S\phi}$ is consistent with $-\eta_{CP} S_{J/\psi K_S^0}$
- Belle results:

535M $B\bar{B}$ pairs
$S_{K_S\phi} = 0.50 \pm 0.21 \pm 0.06$
657M $B\bar{B}$ pairs
$A_{K_S\phi} = 0.04 \pm 0.20 \pm 0.10$

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



- Challenge: no prompt tracks from vertex
- Decay vertex reconstruction using K_S^0 trajectory and profile of the interaction point.

$S_{3K_S} = -1.37^{+0.35}_{-0.45} \pm 0.03$
$A_{3K_S} = +0.07^{+0.15}_{-0.20} \pm 0.02$

- S_{3K_S} is consistent with $-\eta_{CP} S_{J/\psi K_S^0}$
- Belle (772M $B\bar{B}$ pairs) :
  $S_{3K_S} = -0.71 \pm 0.23 \pm 0.05$
  $A_{3K_S} = 0.12 \pm 0.16 \pm 0.05$

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

arXiv:2305.07555

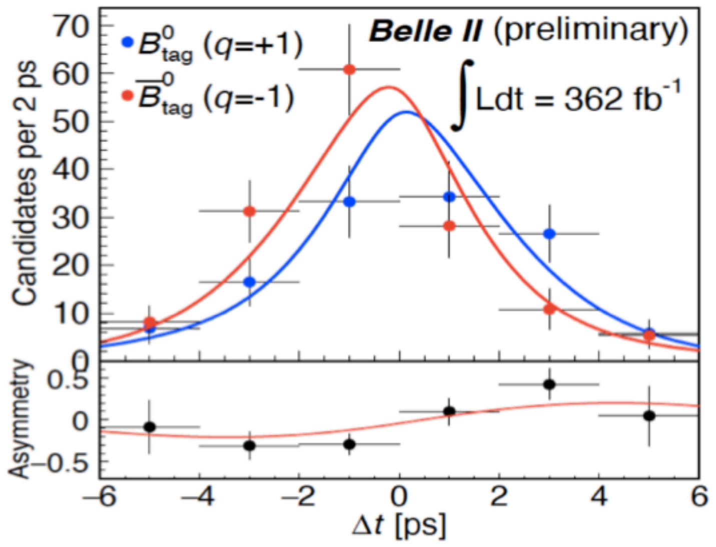
Belle II 362 fb^{-1}

- $B^0 \to K_S^0\pi^0$ proceeds mainly via $b \to sd\bar{d}$ loop amplitude.
- Sensitive to effective value of sin2ϕ_1 and providing inputs to isospin sum-rule

$$I_{K\pi} = \mathcal{B}r(K^+\pi^-)\mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\mathcal{B}r(K^0\pi^+)\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\mathcal{B}r(K^+\pi^0)\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\mathcal{B}r(K^0\pi^0); \quad I_{K\pi}^{SM} = 0$$

M. Gronau, Phys. Lett. B **627**, 82(2005).

- Time dependent $B^0 \to K_S^0\pi^0$: main challenge is the decay vertex reconstruction.
- Validated on $B^0 \to J/\psi K_S^0$ events reconstructed w/o J/ψ vertex.
- Simultaneous time-integrated (40% events without Δt) and time-dependent fit to maximize the sensitivity on A_{CP} .
- Competitive with world's best results with less (60-80%) luminosity.



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

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

combine time-integrated and time-dependent results:

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

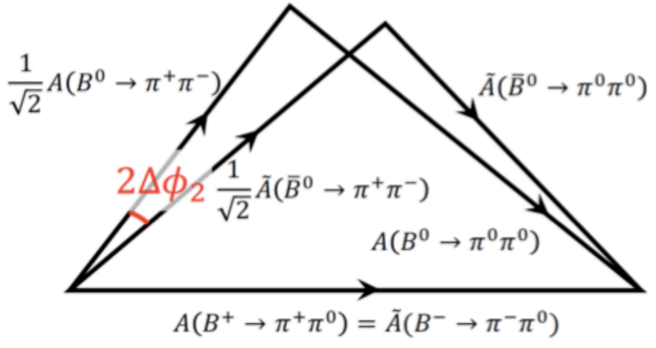
- Combining all $B \to K\pi$ final states at Belle II:

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

CPV in $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$

- The CKM angle ϕ_2 measurement is based on $b \to u$ processes. Significant contributions from penguins ($b \to d$): $\phi^{\text{eff}}{}_2 = \phi_2 + \Delta\phi_2$.
- Penguin and tree contributions can be disentangled using the isospin relations

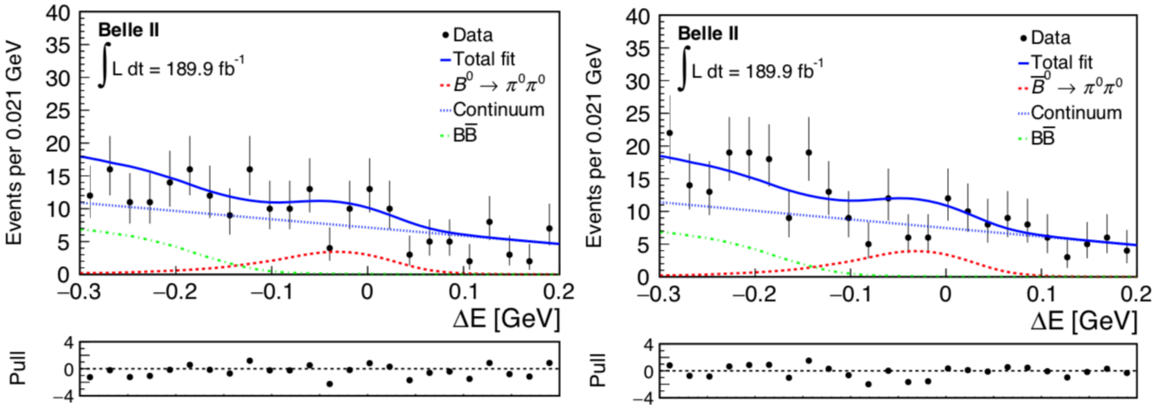
M. Gronau and D. London, Phys Rev. Lett. **65**, 3381 (1990).



$$A^{+0} = \frac{1}{\sqrt{2}}A^{+-} + A^{00} \quad \text{and} \quad \bar{A}^{-0} = \frac{1}{\sqrt{2}}\bar{A}^{+-} + \bar{A}^{00},$$

arXiv:2303.08354

Belle II 189 fb^{-1}

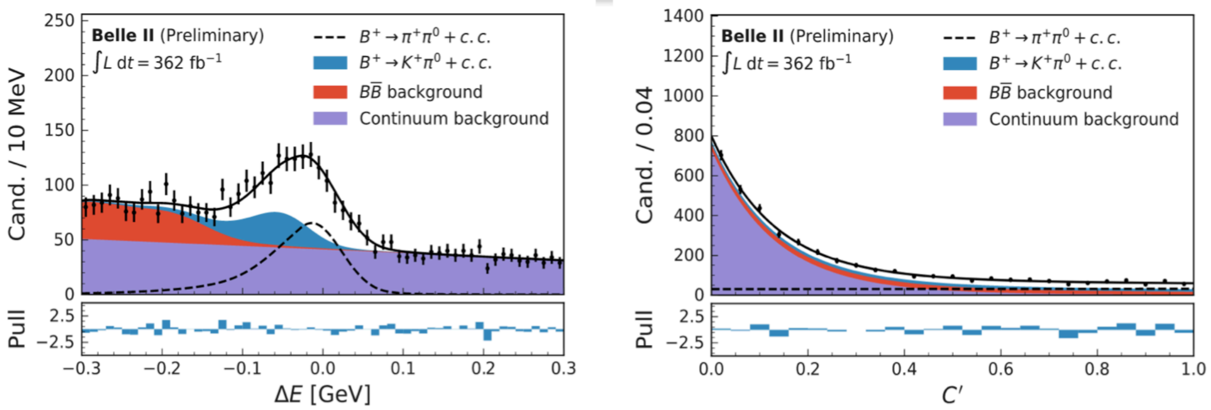


$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07.$$

Belle (772M $B\bar{B}$) : $\mathcal{A}_{CP} = +0.14 \pm 0.36\ (\text{stat.}) \pm 0.10\ (\text{syst.})$

$B^+ \to \pi^+\pi^0$

Belle II 362 fb^{-1}



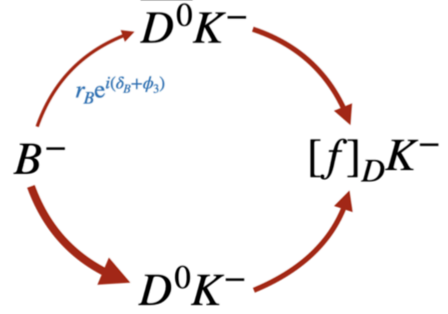
$$A_{CP}(B^+ \to \pi^+\pi^0) = -0.08 \pm 0.05 \pm 0.01$$

Belle (772M $B\bar{B}$) : $A_{CP} = +0.025 \pm 0.043 \pm 0.007$

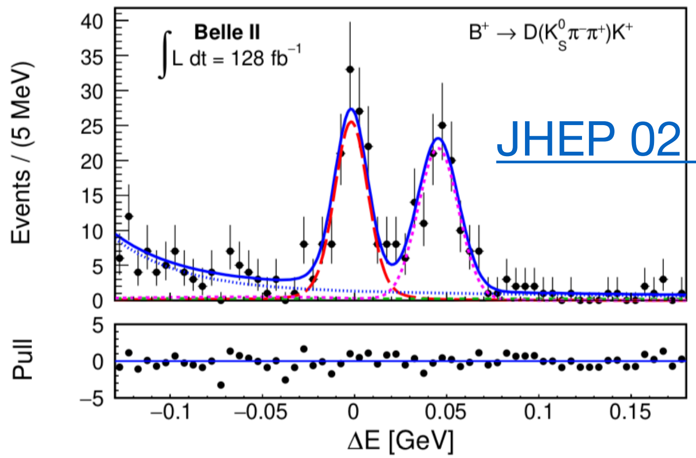
CPV in $B^+ \to DK^+$ (towards ϕ_3/γ)

- ϕ_3/γ is the phase between b → u and b →c transitions.
- The absence of the loop contribution allows extremely clean theoretical prediction of ϕ_3
- Various approaches with different *D* final states:
  - Self-conjugate final states $D^0 \to \mathrm{K_S} h^+ h^-$
  - singly Cabibbo-suppressed $D^0 \to \mathrm{K_S K^+} \pi^-$.
  - CP eigenstates: $\mathrm{D^0} \to K^+K^-, \mathrm{K_S^0}\pi^0$
  - CF and DCS decays: $\mathrm{D^0} \to K^+\pi^-$

Interference between two decays to same final state gives access to phase:



$$\frac{\mathscr{A}^{\text{suppr.}}\left(B^- \to \overline{D}^0 K^-\right)}{\mathscr{A}^{\text{favor.}}\left(B^- \to D^0 K^-\right)} = r_{\mathrm{B}} e^{i(\delta_{\mathrm{B}}+\gamma)}$$



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Current WA dominated by LHCb:

$$\gamma[^\circ] = 65.9\ {}^{+\,3.3}_{-\,3.5}$$

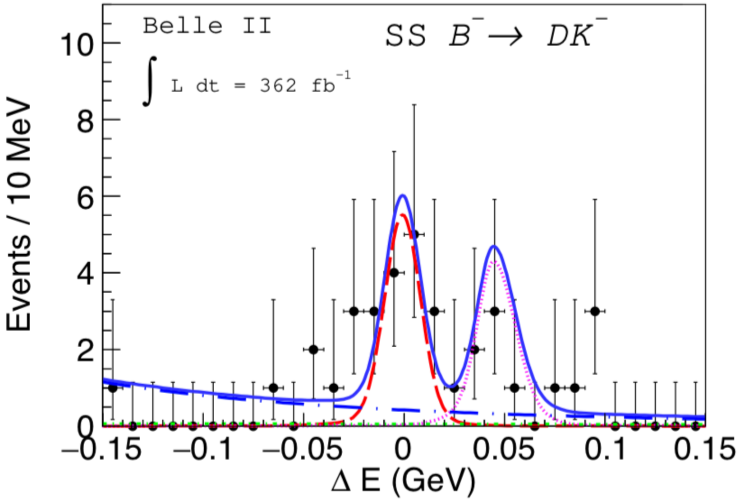
$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ$$

arXiv:2306.02940

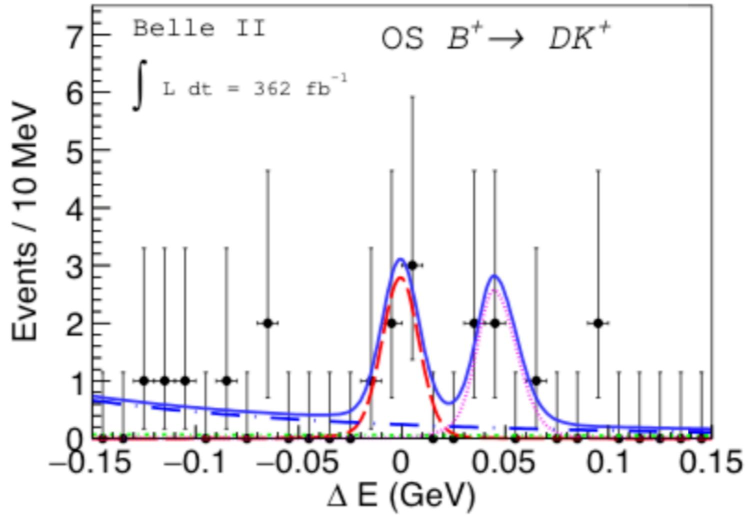
$B^+ \to D(K_S^0 K^+ \pi^-) K^+/\pi^+$

Belle II 362 fb^{-1}
+ Belle 711 fb^{-1}

- $B^\pm \to D(K_S^0 K^\pm \pi^\mp) K^\pm/\pi^\pm$. SS: same sign, OS: opposite sign.
- 2D fit (ΔE, CS') of 8 categories: (+, -) x (SS, OS) x (DK, $D\pi$) in full D phase space and in interference-enhanced $D \to K^* K$ region.
- Model-independent information on the ϕ_3.
- Results consistent with LHCb, but not competitive. Contribute to constrain γ/ϕ_3 in combination with other measurements.



$$
\begin{aligned}
A_{\rm SS}^{DK} &= -0.089 \pm 0.091 \pm 0.011, \\
A_{\rm OS}^{DK} &= 0.109 \pm 0.133 \pm 0.013, \\
A_{\rm SS}^{D\pi} &= 0.018 \pm 0.026 \pm 0.009, \\
A_{\rm OS}^{D\pi} &= -0.028 \pm 0.031 \pm 0.009, \\
R_{\rm SS}^{DK/D\pi} &= 0.122 \pm 0.012 \pm 0.004, \\
R_{\rm OS}^{DK/D\pi} &= 0.093 \pm 0.013 \pm 0.003, \\
R_{\rm SS/OS}^{D\pi} &= 1.428 \pm 0.057 \pm 0.002,
\end{aligned}
$$



$B^+ \to D_{CP} K^+$

Belle II 189 fb^{-1}
+ Belle 711 fb^{-1}

- $B^+ \to D_{CP} K^+$, $D \to K^+K^-$(CP even) , $D \to K_S^0\pi^0$ (CP odd).
- 2D fit (ΔE, CS') of 6 categories: (DK, $D\pi$) x (K^+K^-, $K_S^0\pi^0$, $K^+\pi^-$).

$$\mathcal{R}_{CP\pm} = \frac{\mathcal{B}r(B^- \to D_{CP\pm}K^-) + \mathcal{B}r(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}r(B^- \to D_{\rm flav}K^-) + \mathcal{B}r(B^+ \to D_{\rm flav}K^+)}$$

$$= 1 + r_B^2 + 2r_B \cos\delta_B \cos\phi_3$$

$$\mathcal{A}_{CP\pm} \equiv \frac{\Gamma(B^- \to D_{CP\pm}K^-) - \Gamma(B^+ \to D_{CP\pm}K^+)}{\Gamma(B^- \to D_{CP\pm}K^-) + \Gamma(B^+ \to D_{CP\pm}K^+)}$$

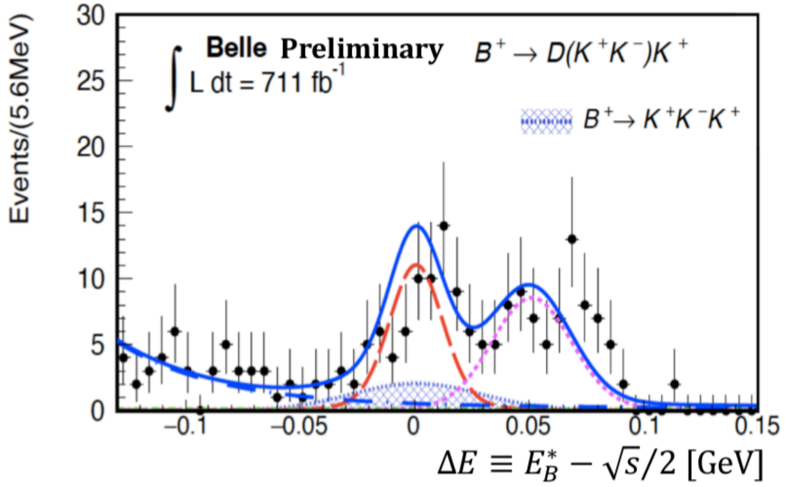
$$= \pm 2r_B \sin\delta_B \sin\phi_3 / \mathcal{R}_{CP\pm}$$

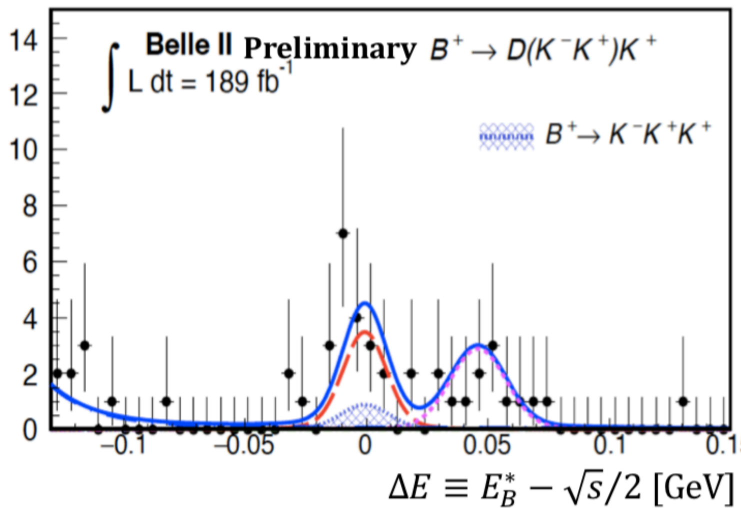
$\boldsymbol{\mathcal{R}_{CP+} = 1.164 \pm 0.081 \pm 0.036}$ $\boldsymbol{\mathcal{R}_{CP-} = 1.151 \pm 0.074 \pm 0.019}$

$\boldsymbol{\mathcal{A}_{CP+} = (+12.5 \pm 5.8 \pm 1.4)\%}$ $\boldsymbol{\mathcal{A}_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%}$

... best $\mathcal{A}_{CP-}$ measurement

$\boldsymbol{4.7^\circ < \phi_3 < 175.8^\circ,\ 0.069 < r_B < 0.560}$ ... @ 95.4% CL





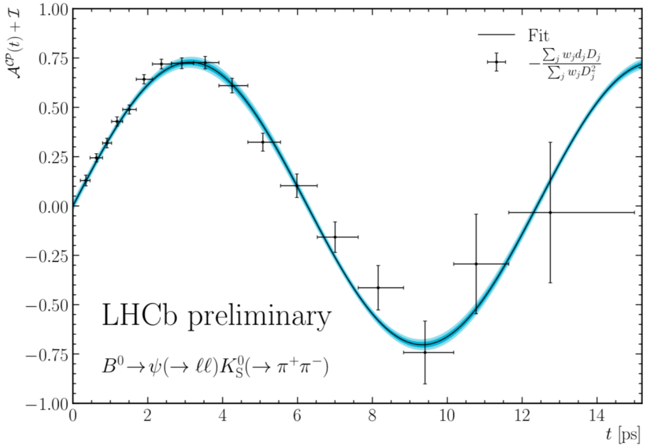
LHCb-Paper-2023-013

TD CPV in $B^0 \to \psi K_S^0$

- Three modes with full Run 2 data
  - $B^0 \to J/\psi(\to \mu\mu) K_S^0(\to \pi^+\pi^-)$ (82 %)
  - $B^0 \to J/\psi(\to ee) K_S^0(\to \pi^+\pi^-)$ (12 %)
  - $B^0 \to \psi(2S)(\to \mu\mu) K_S^0(\to \pi^+\pi^-)$ (6 %)
- From mass fit, *sWeights* are obtained for effective background subtraction in CP fit.

$$P_{B^0,(\bar{B}^0)}(t) \propto (1 \mp \alpha)(1 \mp \Delta\epsilon)(1 \mp S \sin(\Delta m_d t) \pm C \cos(\Delta m_d t))$$

- The most precise single measurement of $\sin(2\phi_1)$ to date.

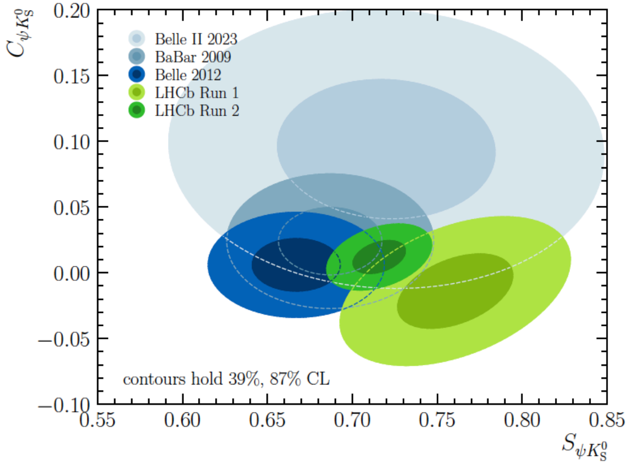


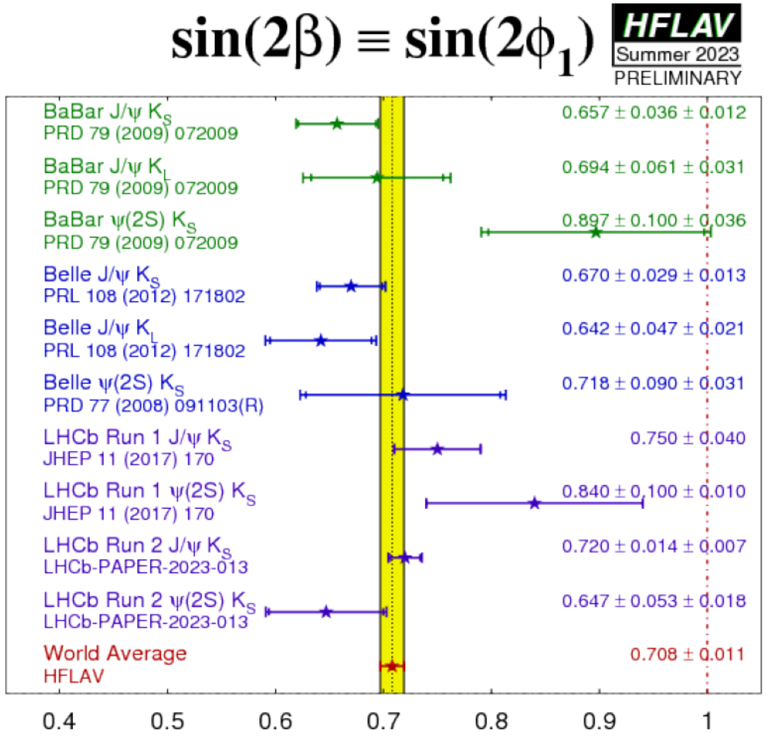
Combined fit result

$$S_{\psi K_S^0}^{\text{Run 2}} = 0.716 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})$$
$$C_{\psi K_S^0}^{\text{Run 2}} = 0.012 \pm 0.012\,(\text{stat}) \pm 0.003\,(\text{syst})$$

New total LHCb combination

$$S_{\psi K_S^0}^{\text{Run 1+2}} = 0.723 \pm 0.014\,(\text{stat+syst})$$
$$C_{\psi K_S^0}^{\text{Run 1+2}} = 0.007 \pm 0.012\,(\text{stat+syst})$$





$B^+ \to D(K^-\pi^+\pi^+\pi^-)h^+$

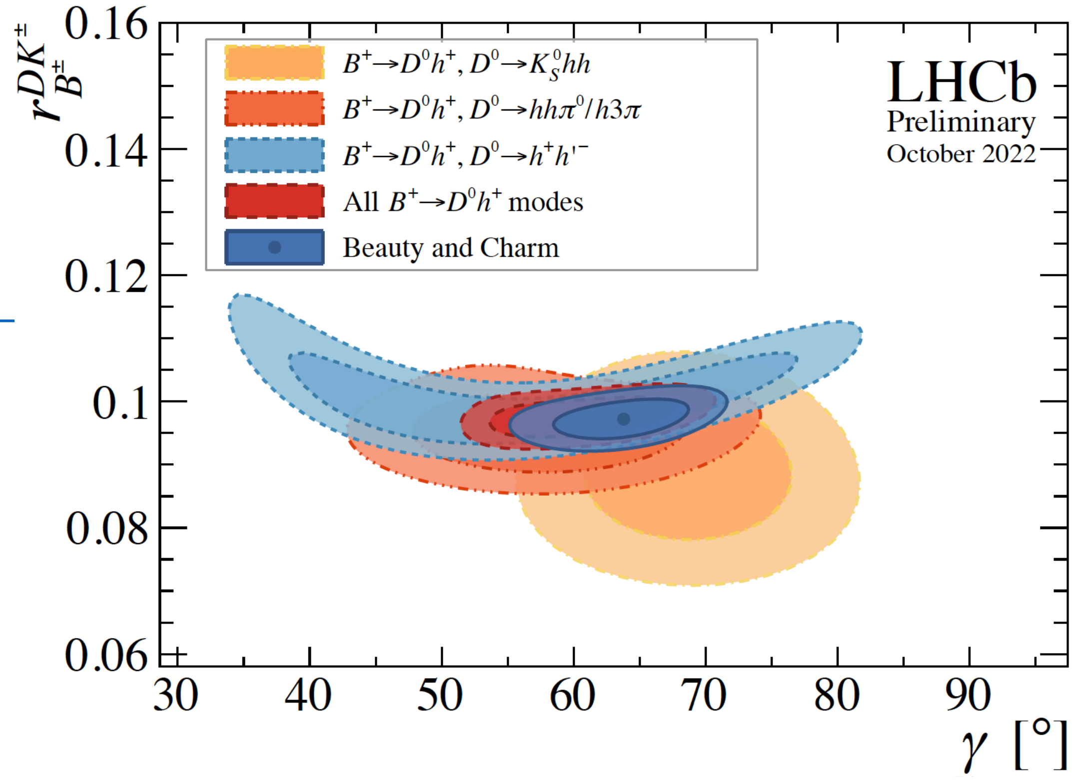
arXiv:2209.03692

- Improved sensitivity can be achieved with binned measurement.
- 4 bins chosen according to LHCb amplitude analysis EPJC 78 (2018) 6, 443
- using external inputs for
  - Hadronic decay parameters from model-independent determinations by CLEO-c and BESIII JHEP 05 (2021) 164
  - $D^0 - \overline{D^0}$ mixing parameters by LHCb PRL 116 (2016) 241801
- 2nd most precise determination of γ from single D-decay mode

$$\gamma = \left(54.8^{+6.0+0.6+6.7}_{-5.8-0.6-4.3}\right)^\circ$$

- New LHCb combination:

$$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^\circ$$



TD CPV in $B_s^0 \to J/\psi K^+ K^-$

LHCb-Paper-2023-016

- Mixing-induced CPV phase ϕ_s in B_s^0 decays through $b \to c\bar{c}s$ transitions.
- Golden mode : $B_s^0 \to J/\psi\phi(K^+K^-)$
- Flavor-tagged time-dependent angular analysis.

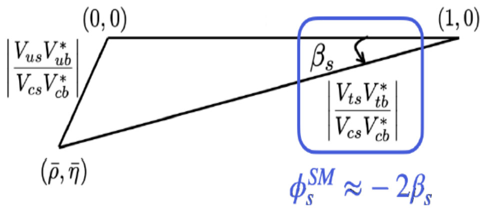
$$A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \to J/\psi KK) - \Gamma(B_s^0 \to J/\psi KK)}{\Gamma(\bar{B}_s^0 \to J/\psi KK) + \Gamma(B_s^0 \to J/\psi KK)} = \eta_f \cdot \sin\phi_s^{\rm obs} \cdot \sin(\Delta m_s t)$$

- CP eigenvalue of the final state $\eta_f = (-1)^L$
- A mixture of CP-even & CP-odd components → angular analysis

ϕ_s [rad]	$-0.039 \pm 0.022 \pm 0.006$
$\lvert\lambda\rvert$	$1.001 \pm 0.011 \pm 0.005$

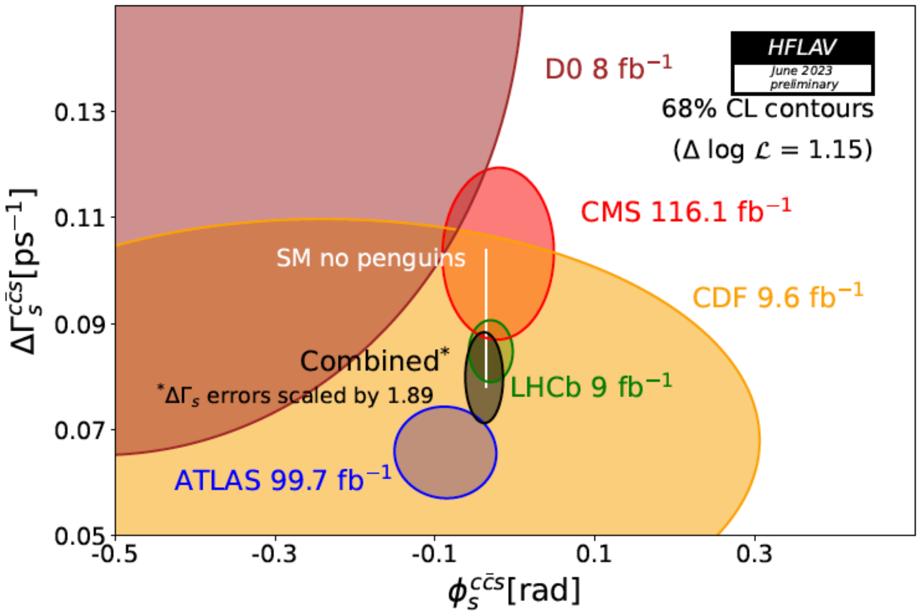
- The most precise measurement of ϕ_s to date.

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



- Combination with all measurements:
- $\phi_s^{J/\psi KK} = -0.050 \pm 0.017$ rad → improved by 23%
- $\phi_s^{c\bar{c}s} = -0.039 \pm 0.016$ rad → improved by 15%
- Consistent with the prediction of Global fits assuming SM:[3]

$$\phi_s^{\rm tree} \approx (-0.0368^{+0.0006}_{-0.0009})\ {\rm rad}$$



TD CPV in $B_s^0 \to \phi\phi$

arXiv:2304.06198

LHCb Run2 data sample

- Penguin-dominated decay $b \to s\bar{s}s$.
- NP could contribute to mixing and penguin processes.
- Three linear polarization states for $\phi\phi$.
- Flavor-tagged time-dependent angular analysis.

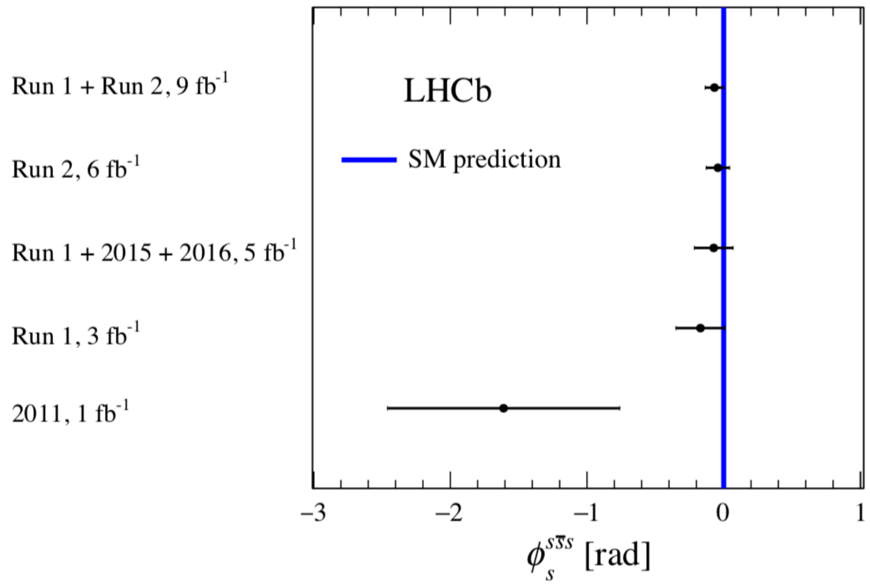
- The most precise measurement of $\phi_s^{s\bar{s}s}$ in penguin dominated decays.
- Agreement with the SM.
- Polarization-dependent CP-violation parameters are measured for the first time.

- polarization independent result:

$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009 \text{ rad},$$
$$|\lambda| = 1.004 \pm 0.030 \pm 0.009,$$

Combination with Run 1 gives:

$$\phi_s^{s\bar{s}s} = (-0.074 \pm 0.069) \text{ rad}$$
$$|\lambda| = 1.009 \pm 0.030$$



CP violation in charm sector

- Charm provides unique gate for study of CP violation in up-type quark decays.
- Due to smallness of involved CKM elements and GIM mechanism, CP violation in charm is predicted to be small: 10^{-4}- 10^{-3}.
- SM calculation dominated by long distance contributions.
- LHCb reported direct CP violation in $D^0 \to h^+h^-$ in March 2019, using the difference between two time-integrated CP-violating asymmetries of Cabibbo-suppressed D^0 decays [Phys. Rev. Lett. 122 (2019) 211803]
- The result challenges predictions based on first- principle QCD dynamics
- Further measurements are needed in charm sector.

$D^0 \to K^+K^-$

arXiv:2209.03179

- Time-integrated CPV measurement in the Cabibbo-suppressed decay $D^0 \to K^+K^-$.
- D^0 mesons originate from promptly produced $D^{*+} \to D^0\pi^+$.

$$A(K^-K^+) \approx \mathcal{A}_{CP}(K^-K^+) + A_{\mathrm{P}}(D^{*+}) + A_{\mathrm{D}}(\pi^+_{\mathrm{tag}})$$

Physical CP asymmetry | Production asy. | Detection asy. of tagging pions

$$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft}) + A(D^+ \to K^-\pi^+\pi^+) - [A(D^+ \to \overline{K}^0\,\pi^+) - A(\overline{K}^0)]$$

Original method (used also in Run 1)

$$A_{CP}(D^0 \to K^-K^+) = +A(D^{*+} \to (D^0 \to K^-K^+)\,\pi^+_{soft}) - A(D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+_{soft}) + A(D_s^+ \to \phi\pi^+) - [A(D_s^+ \to \overline{K}^0\,K^+) - A(\overline{K}^0)]$$

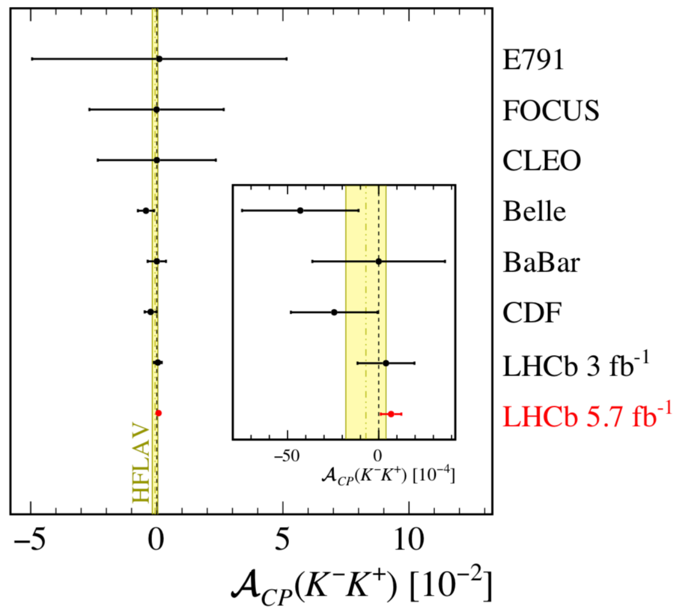
New method

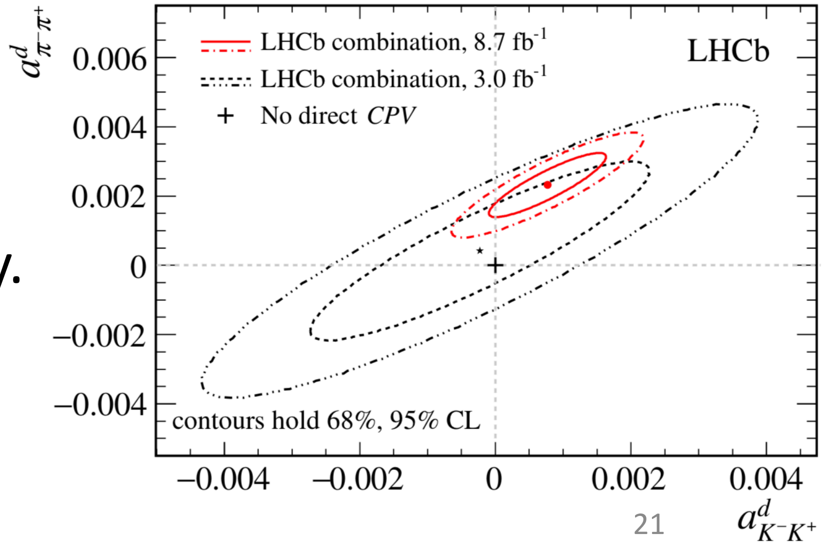
- A combination with the previous LHCb measurements shows the first evidence for direct CP violation in $D^0 \to \pi^+\pi^-$ decay.

$$\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst})] \times 10^{-4}.$$

$$a^d_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4},$$

$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4},$$





$D^0 \to \pi^-\pi^+\pi^0$

arXiv:2306.12746

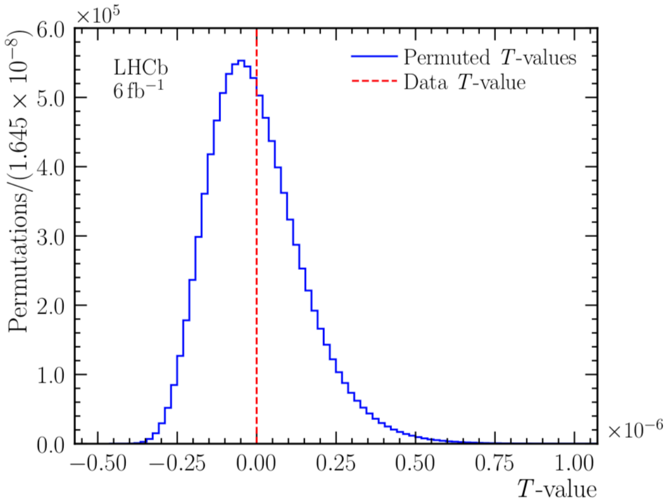
- $D^0 \to \pi^-\pi^+\pi^0$ is similar with $D^0 \to \pi^-\pi^+$. CS decay. Sensitive to interference between tree and penguin diagrams.
- Three-body phase space can enrich local CPV effects.
- The energy test computes the T-value over all D^0- D^0 pairs (n) and $\overline{D^0}$ - $\overline{D^0}$ pairs ($\bar{n}$) and between D^0- $\overline{D^0}$. PhysRevD.84.054015

$$T \equiv \frac{1}{2n(n-1)}\sum_{i,j\neq i}^{n}\psi_{ij} + \frac{1}{2\bar{n}(\bar{n}-1)}\sum_{i,j\neq i}^{\bar{n}}\psi_{ij} - \frac{1}{n\bar{n}}\sum_{i,j}^{n,\bar{n}}\psi_{ij}.$$

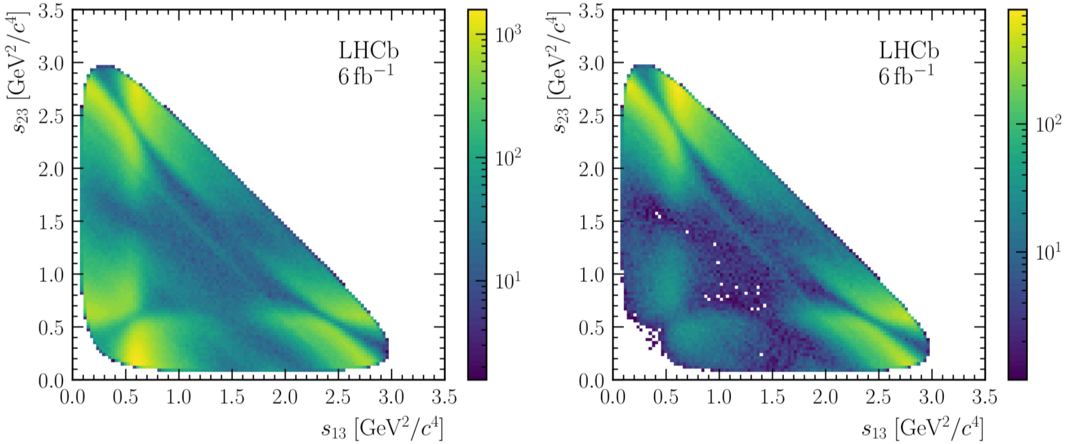
$$\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$$

$$d_{ij}^2 = [(\Delta s_{12})_{ij}^2 + (\Delta s_{13})_{ij}^2 + (\Delta s_{23})_{ij}^2]$$

- The function ψ_{ij} gives a weighted distance between pairs in phase space.
- The tunable parameter δ is optimized to maximize sensitivity to CP violation.



The results are consistent with CP symmetry .



- Background-subtracted signal samples for the resolved (left) and merged (right) π^0.

$D^+_{(s)} \to K^-K^+K^+$

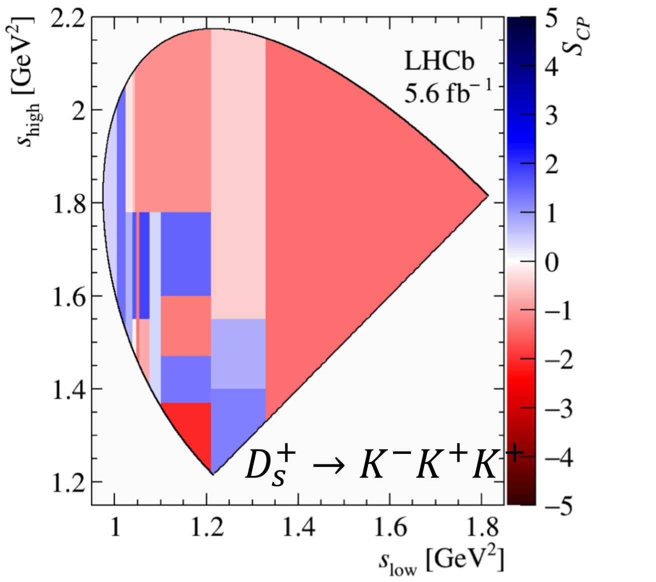
arXiv:2303.04062

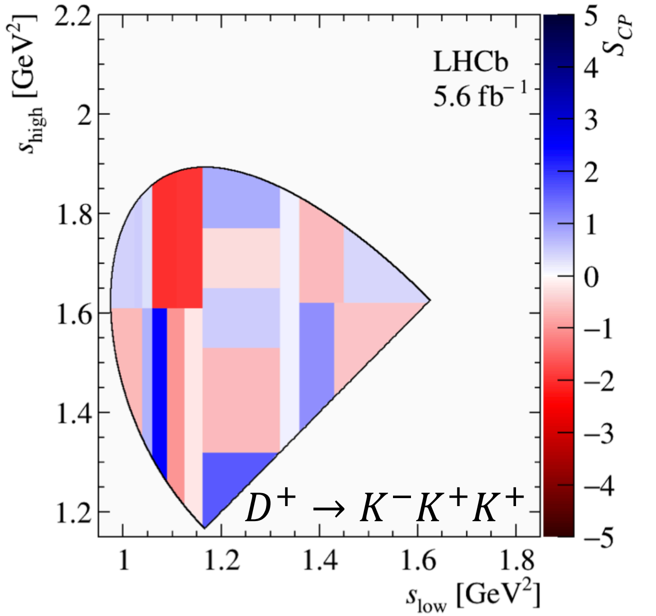
- SCS decay $D_s^+ \to K^-K^+K^+$; DCS decay $D^+ \to K^-K^+K^+$, no CPV in SM.
- Model-independent binned Dalitz-plot analysis.
- Dalitz plot divided in 21 bins that reproduce the pattern of the main resonances ($\simeq$ constant strong phase).
- Fit-per-bin method. Variation of the original Miranda technique: test χ^2 to compare Dalitz distributions of $N^i(D_s^+)$ and $N^i(D_s^-)$ (signal yields obtained by mass fit in each bin)

α takes into account global nuisance asymmetries

$$S^i_{CP} = \frac{N^i(D^+_{(s)}) - \alpha N^i(D^-_{(s)})}{\sqrt{\alpha\left(\delta^2_{N^i(D^+_{(s)})} + \delta^2_{N^i(D^-_{(s)})}\right)}}, \quad \alpha = \frac{\sum_i N^i(D^+_{(s)})}{\sum_i N^i(D^-_{(s)})}, \quad \chi^2 = \sum_i \left(S^i_{CP}\right)^2$$

- No evidence for CP violation is observed in these decays.





T-odd CPV in $D_{(s)}^{+}$ four-body decays

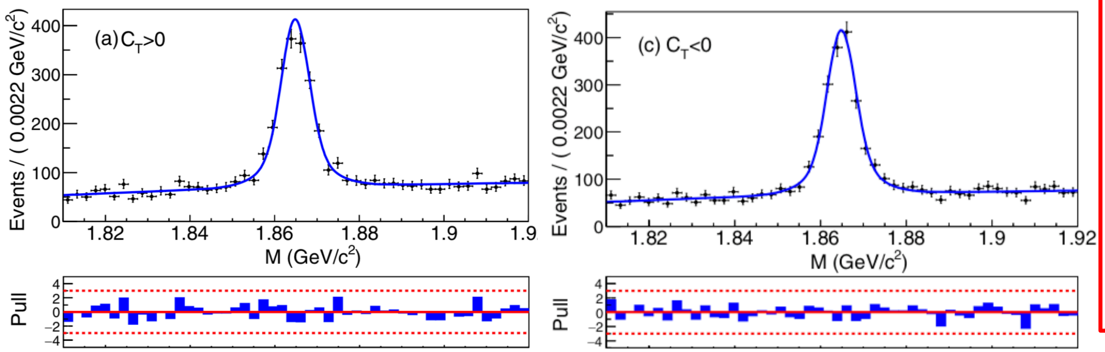
- *T*-odd correlations provides a powerful tool to indirectly search for CP violation under CPT symmetry conservation.
- C_T observable defined by a triple mixed product $C_T = (\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3$, satisfying CP($C_T$)=-C($C_T$)=- $\overline{C}_T$

$$A_T = \frac{\Gamma_+(C_T > 0) - \Gamma_+(C_T < 0)}{\Gamma_+(C_T > 0) + \Gamma_+(C_T < 0)} \qquad \overline{A}_T = \frac{\Gamma_-(-\overline{C}_T > 0) - \Gamma_-(-\overline{C}_T < 0)}{\Gamma_-(-\overline{C}_T > 0) + \Gamma_-(-\overline{C}_T < 0)}$$

- T-odd CP-violating asymmetry is defined as $a_{CP}^{T\text{-odd}} = \frac{1}{2}(A_T - \overline{A}_T)$

- All results consistent with zero CP Violation.

$D^0 \to K_S^0 K_S^0 \pi^+\pi^-$ PRD 107, 052001 (2023)

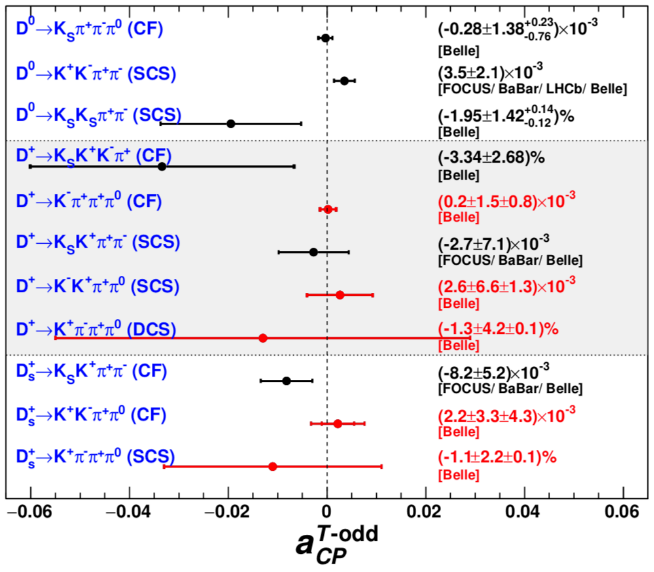


$$A_{CP}(D^0 \to K_S^0 K_S^0 \pi^+\pi^-) = [-2.51 \pm 1.44(\text{stat})\,^{+0.11}_{-0.10}(\text{syst})]\%.$$

$$a_{CP}^T(D^0 \to K_S^0 K_S^0 \pi^+\pi^-) = [-1.95 \pm 1.42(\text{stat})\,^{+0.14}_{-0.12}(\text{syst})]\%.$$

- α_{CP}^T is proportional to $\sin\phi\cos\delta$, ϕ and δ are the weak and strong phase differences.
- A_{CP} (α_{CP}^T) is sensitive to δ=π(0).

$D_{(s)}^+ \to K^\pm h^\mp \pi^+\pi^0$ arXiv:2305.12806



$D_{(s)}^+ \to K^+ K_S h^- h^-$ arXiv:2305.11405

$$a_{CP}^{T\text{-odd}}(D^+ \to K^+ K_S^0 \pi^+\pi^-) = (0.34 \pm 0.87 \pm 0.32)\%$$
$$a_{CP}^{T\text{-odd}}(D_s^+ \to K^+ K_S^0 \pi^+\pi^-) = (-0.46 \pm 0.63 \pm 0.38)\%$$
$$a_{CP}^{T\text{-odd}}(D^+ \to K^+ K^- K_S^0 \pi^+) = (-3.34 \pm 2.66 \pm 0.35)\%,$$

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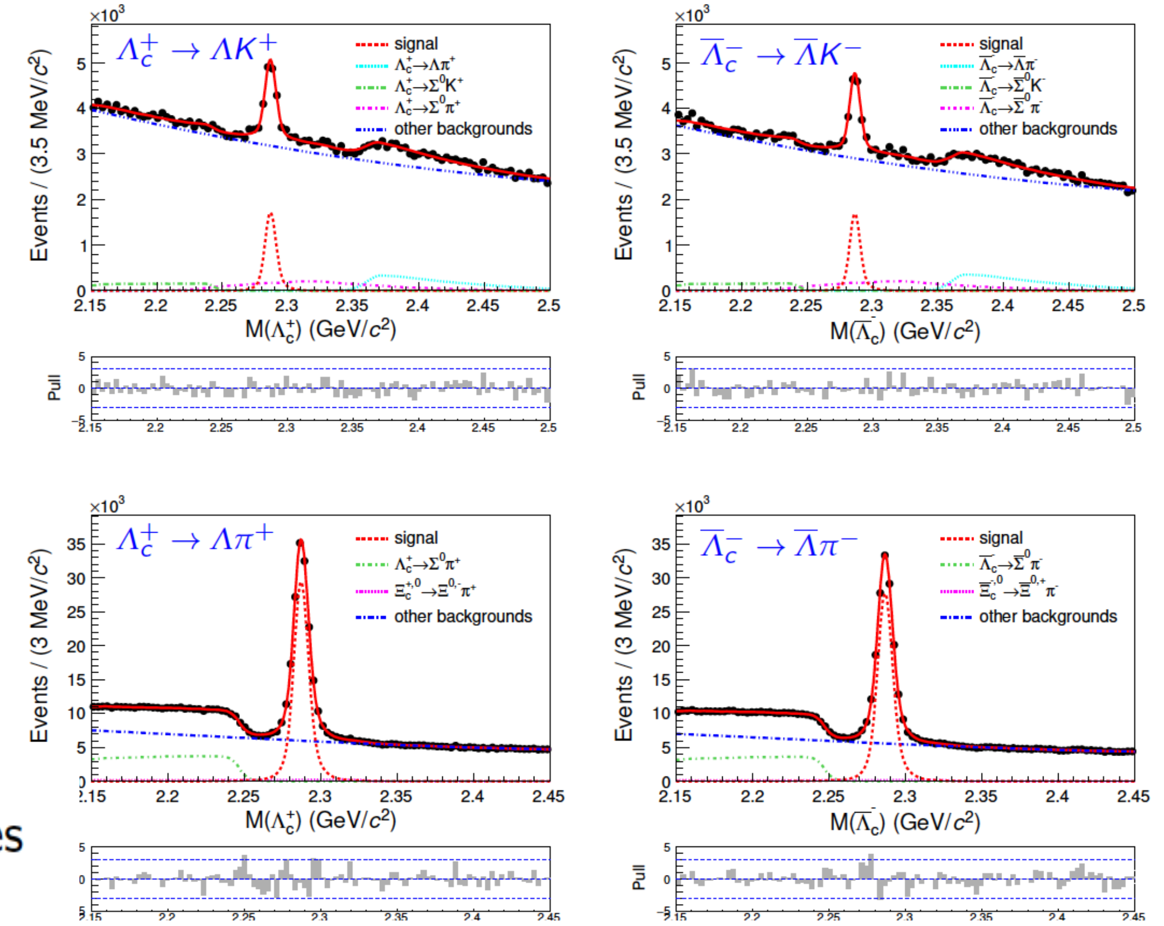
CPV in $\Lambda_c^+ \to \Lambda h^+$ and $\Lambda_c^+ \to \Sigma^0 h^+$ $(h = K, \pi)$

- Baryogenesis, the process by which the baryon-antibaryon asymmetry of the universe developed, is directly related to baryon CPV.
- To date, CPV has been confirmed in the open-flavored meson sector (K, D and B mesons), but not in the baryon sector.

$$A_{\rm raw}(\Lambda_c^+ \to \Lambda K^+) \approx A_{CP}^{\Lambda_c^+ \to \Lambda K^+} + A_{CP}^{\Lambda \to p\pi^-} + A_\varepsilon^{\Lambda} + A_\varepsilon^{K^+} + A_{\rm FB}^{\Lambda_c^+}$$

$$\begin{aligned} & A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda K^+) - A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda \pi^+) \\ = & A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) - A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda \pi^+). \end{aligned}$$

- Simultaneous fit on the $A_\varepsilon^{h^+}$-weighted $\Lambda_c^\pm$ samples gives
  $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1)\%$
  $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4)\%$,
  first CPV result of charmed baryon SCS two-body decays.



A_{CP}^{α} in $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$

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- The decay asymmetry parameter α was introduced by Lee and Yang to study the parity-violating and parity-conserving amplitudes in weak hyperon decays.

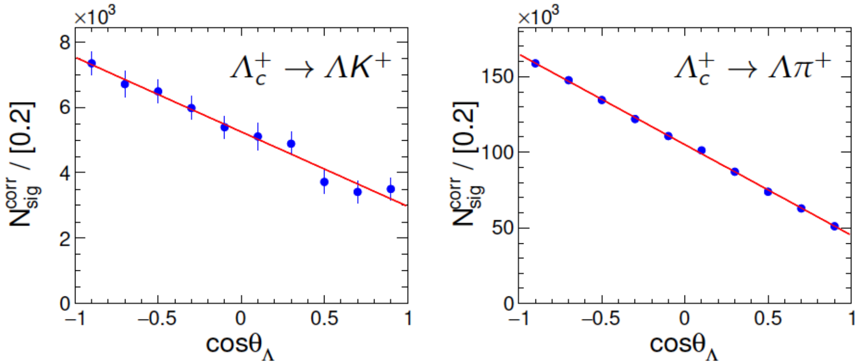
$$\frac{dN(\Lambda_c^+ \to \Lambda h^+)}{d\cos\theta_\Lambda} \propto 1 + \alpha_{\Lambda_c^+}\alpha_- \cos\theta_\Lambda$$

$$\frac{dN(\Lambda_c^+ \to \Sigma^0 h^+)}{d\cos\theta_{\Sigma^0}\, d\cos\theta_\Lambda} \propto 1 - \alpha_{\Lambda_c^+}\alpha_- \cos\theta_{\Sigma^0} \cos\theta_\Lambda$$

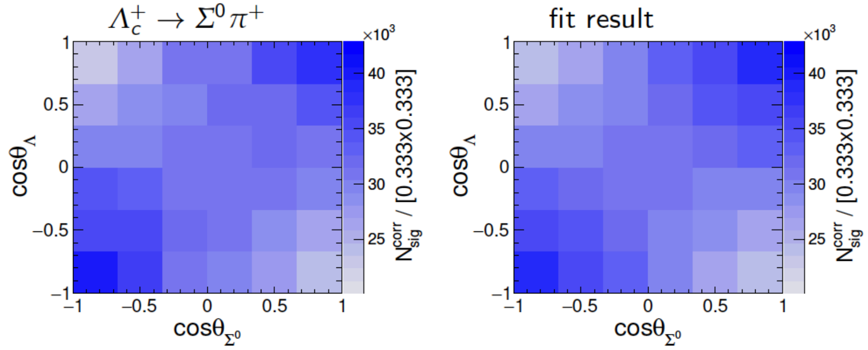
- The α-induced CP asymmetry:

$$A_{CP}^{\alpha} \equiv \frac{\alpha_{\Lambda_c^+} - \widehat{CP}\alpha_{\Lambda_c^+}\widehat{CP}^{\dagger}}{\alpha_{\Lambda_c^+} + \widehat{CP}\alpha_{\Lambda_c^+}\widehat{CP}^{\dagger}} = \frac{\alpha_{\Lambda_c^+} + \alpha_{\overline{\Lambda}_c^-}}{\alpha_{\Lambda_c^+} - \alpha_{\overline{\Lambda}_c^-}}$$

► $\cos\theta_\Lambda$ distributions of $\Lambda_c^+ \to \Lambda h^+$ after efficiency correction, fitted with $1 + \alpha_{\Lambda_c^+}\alpha_- \cos\theta_\Lambda$



► $(\cos\theta_\Lambda, \cos\theta_{\Sigma^0})$ 2D distributions of $\Lambda_c^+ \to \Sigma^0 h^+$ after efficiency correction, fitted with $1 - \alpha_{\Lambda_c^+}\alpha_- \cos\theta_{\Sigma^0}\cos\theta_\Lambda$



Channel	$k = \alpha_{\Lambda_c^+}\alpha_-$	$\bar{k} = \alpha_{\Lambda_c^-}\alpha_+$	$\alpha_{\Lambda_c^+}$	$\alpha_{\overline{\Lambda}_c^-}$	A_{CP}^{α}	W.A. A_{CP}^{α}	our $A_{CP}^{\alpha}(\Lambda \to p\pi^-)$
$\Lambda_c^+ \to \Lambda K^+$	-0.418 ± 0.053	-0.442 ± 0.053	$-0.566 \pm 0.071 \pm 0.028$	$0.592 \pm 0.070 \pm 0.079$	$-0.023 \pm 0.086 \pm 0.071$	−	−
$\Lambda_c^+ \to \Lambda \pi^+$	-0.582 ± 0.006	-0.565 ± 0.006	$-0.784 \pm 0.008 \pm 0.006$	$0.754 \pm 0.008 \pm 0.018$	$+0.020 \pm 0.007 \pm 0.013$	-0.07 ± 0.22	$+0.017 \pm 0.007 \pm 0.012$
$\Lambda_c^+ \to \Sigma^0 K^+$	-0.43 ± 0.18	-0.37 ± 0.21	$-0.58 \pm 0.24 \pm 0.09$	$0.49 \pm 0.28 \pm 0.14$	$+0.08 \pm 0.35 \pm 0.14$	−	−
$\Lambda_c^+ \to \Sigma^0 \pi^+$	-0.340 ± 0.016	-0.358 ± 0.017	$-0.452 \pm 0.022 \pm 0.023$	$0.473 \pm 0.023 \pm 0.035$	$-0.023 \pm 0.034 \pm 0.030$	−	$-0.026 \pm 0.034 \pm 0.030$

combined: $+0.013 \pm 0.007 \pm 0.011$

- No evidence of CPV in baryon (Λ_c^+ and Λ) decays is found.

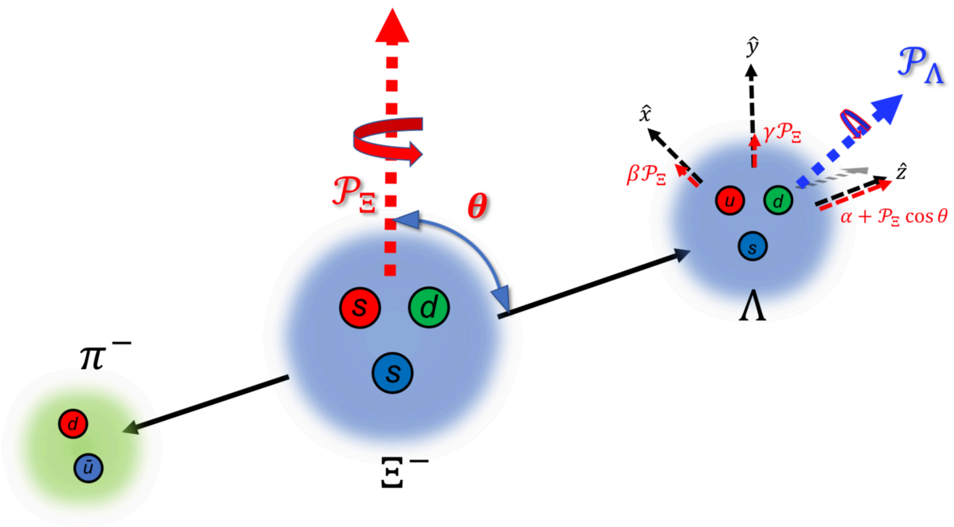
CP symmetry test with entangled baryons

Nature 606, 64 (2022)

- $J/\psi \to \Xi^-\Xi^+ \to \Lambda\pi^-\Lambda\pi^+$

- Self analyzing hyperons: daughter particles are emitted according to polarization of mother hyperon.
- From decay amplitudes one can construct CP-odd decay parameters α_Ξ, β_Ξ, γ_Ξ

$$\beta_\Xi = \sqrt{1-\alpha_\Xi^2}\sin\phi_\Xi;\ \gamma_\Xi = \sqrt{1-\alpha_\Xi^2}\cos\phi_\Xi$$



$$A_{CP}^{Y} = \frac{\alpha_Y + \bar{\alpha}_Y}{\alpha_Y - \bar{\alpha}_Y}, \quad \Delta\phi_{CP} = \frac{\phi_Y + \bar{\phi}_Y}{2}$$

$$A_{CP}^{\Xi} \approx -\tan(\delta_P - \delta_S)\tan(\xi_P - \xi_S)$$

strong phase diff. weak phase diff.

Longitudinal polarization of Λ governed by α_Ξ; ϕ_Ξ gives rotation of P_Λ with respect to P_Ξ

ϕ_Ξ allows for new CP test: $\Delta\phi_\Xi = (\phi_\Xi + \overline{\phi_\Xi})/2$

$J/\psi \rightarrow \Xi^-\bar{\Xi}^+ \rightarrow \Lambda\pi^-\bar{\Lambda}\pi^+$

- Nine-dimensional phase space given by nine helicity angles

$$\boldsymbol{\xi} = (\theta, \theta_\Lambda, \varphi_\Lambda, \theta_{\bar{\Lambda}}, \varphi_{\bar{\Lambda}}, \theta_p, \varphi_p, \theta_{\bar{p}}, \varphi_{\bar{p}}).$$

- Eight free global parameters determined by maximum log likelihood method: $\boldsymbol{\omega} = (\alpha_\psi, \Delta\Phi, \alpha_\Xi, \phi_\Xi, \bar{\alpha}_\Xi, \bar{\phi}_\Xi, \alpha_\Lambda, \bar{\alpha}_\Lambda)$
- The formalism exploits polarization, entanglement and sequential decays

$$\mathcal{W}(\boldsymbol{\xi};\boldsymbol{\omega}) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} \sum_{\mu'\nu'=0}^{3} a^{\Xi}_{\mu\mu'} a^{\bar{\Xi}}_{\nu\nu'} a^{\Lambda}_{\mu'0} a^{\bar{\Lambda}}_{\nu'0}$$

$$C_{\mu\nu}(\theta; \alpha_\psi, \Delta\Phi)$$

Parameter	This work	Previous result
A^{Ξ}_{CP}	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–
$\Delta\phi^{\Xi}_{\mathrm{CP}}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad	–
$A^{\Lambda}_{\mathrm{CP}}$	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$ [14]

Other CP symmetry test in hyperon decays

- $J/\psi \to \Lambda\bar{\Lambda}$ Phys.Rev.Lett. 129 (2022) 131801
  - 1×10^{10} J/ψ events

$$A_{CP} = (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+) = -0.0025 \pm 0.0046 \pm 0.0012$$

- $J/\psi \to \Sigma^+\bar{\Sigma}^-$ arXiv:2304.14655
  - 1×10^{10} J/ψ events
  - First study to test CP symmetry in the hyperon to neutron decay, and result is consistent with CP-conservation.

- J/ψ ($\psi(3686)$) $\to \Xi^0\,\bar{\Xi}^0$
  - 1×10^{10} J/ψ events; 4×10^{8} $\psi(3686)$ events
  - Results are consistent with CP-conservation.

arXiv:2305.09218

A^{Ξ}_{CP}	$(-5.4 \pm 6.5 \pm 3.1) \times 10^{-3}$
$\Delta\phi^{\Xi}_{CP}$(rad)	$(-0.1 \pm 6.9 \pm 0.9) \times 10^{-3}$
A^{Λ}_{CP}	$(6.9 \pm 5.8 \pm 1.8) \times 10^{-3}$

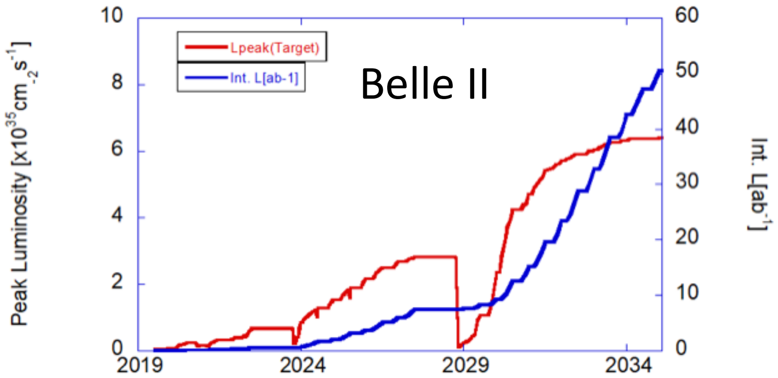
arXiv:2302.09767

A^{Ξ}_{CP}	$-0.007 \pm 0.082 \pm 0.025$
$\Delta\phi^{\Xi}_{CP}$	$-0.079 \pm 0.082 \pm 0.010$

Summary

- CP violation is being tested in broad physics programs at different experiments.
- We are in the era of seeking for new physics corrections to SM CPV.
- No evidence for new CPV physics so far.
- More results from Belle II/LHCb/BESIII (etc.) are anticipated.
  - Belle II: 428 fb^{-1} recorded. Goal: 50 ab^{-1}.
  - LHCb: 9 fb^{-1} in Run1-2. More than 5 times luminosity during Runs 3–4.
  - BESIII: collected 1.0×10^{10} J/ψ events, rich program using entangled hyperon pairs.
- Large datasets will allow for unprecedented reach on precise CPV measurements.

LHCb

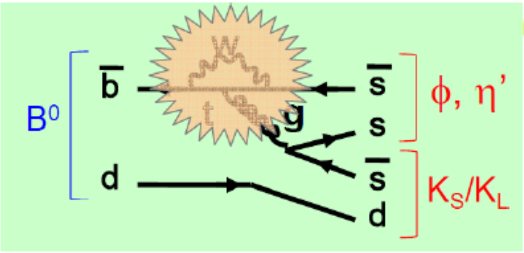


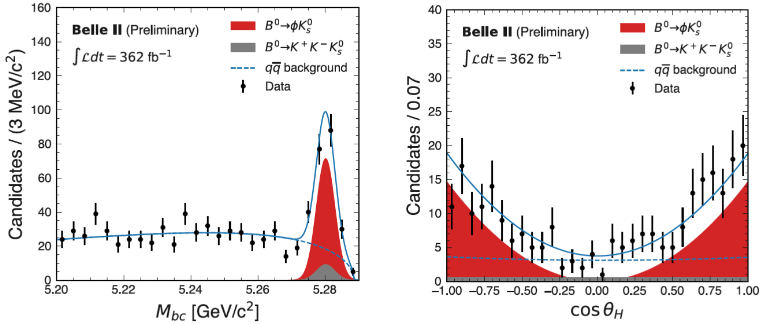
Extra

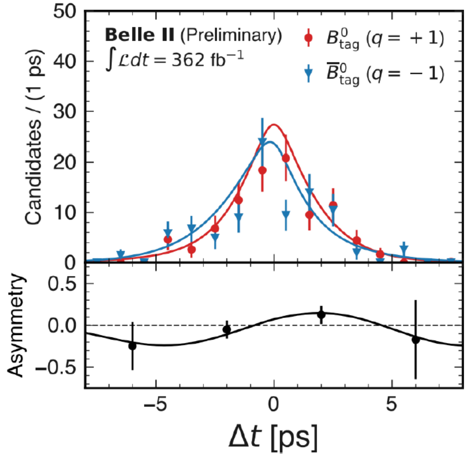
TD CPV in $B^0 \to \phi K_S^0$

- Penguin-dominated modes $b \to q\bar{q}s$.
- Clean experimental signature with similar Δt resolution as $B^0 \to J/\psi K_S$.
- Main challenge: dilution from non-resonant decays with opposite CP
- Non-resonant $B^0 \to K^+K^-K_S^0$ component disentangled in $\cos\theta$.
- Simultaneous Δt fit to extract the CP asymmetries.
  - $B^- \to K^+K^-\mathrm{K_S}$ fixed from HFLAV.
  - Validated on the B^- control sample (null asymmetry).
- 162 ± 17 signal yields.

b→s (B → φK⁰, η'K⁰)





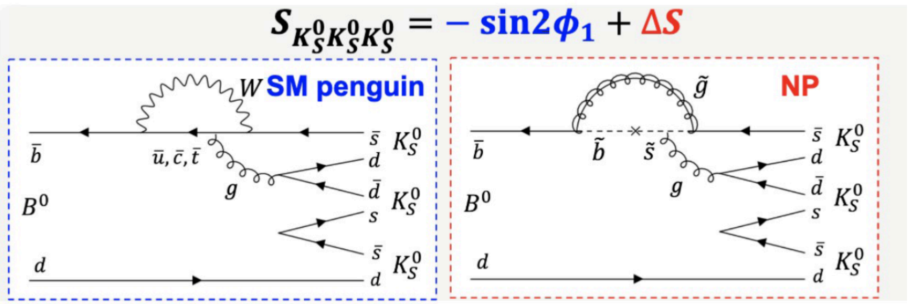


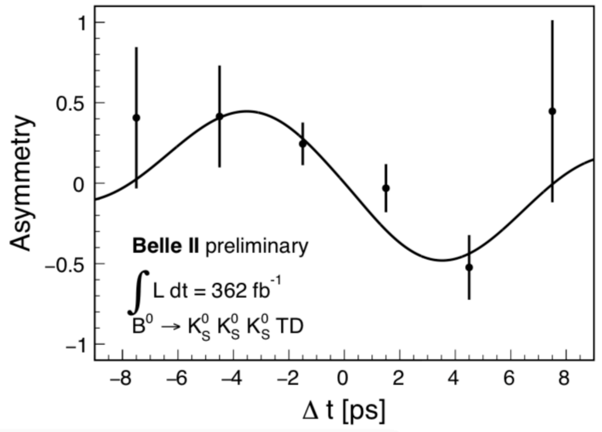
$A_{CP} = 0.31 \pm 0.20^{+0.05}_{-0.06}$ $\quad A_{CP}^{w.a.} = -0.01 \pm 0.14$

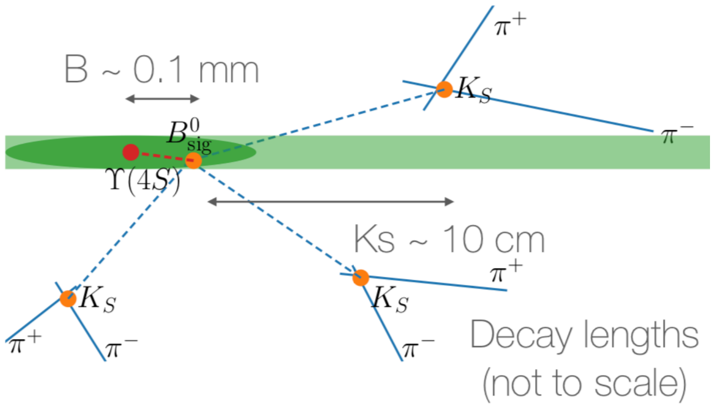
$S_{CP} = 0.54 \pm 0.26^{+0.06}_{-0.08}$ $\quad S_{CP}^{w.a.} = 0.59 \pm 0.14$

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

- Penguin process suppressed in the SM, sensitive to new physics.
- Same underlying quark transition as $B^0 \to \phi K_S^0$, no contribution from opposite-CP backgrounds.
- Challenge: no prompt tracks to from a vertex. K_S^0 flies 10 cm on average.
- Reconstruct $B^+ \to K_S^0 K_S^0 K^+$ as control mode, remove vertex information from K^+.
- Simultaneous fit on control sample to constrain background shapes and Δt resolution function.
- 3D fit (invariant mass, CS output and Mbc) to extract signal yields.
- Dataset divided into events with (TD) and without (TI) information from the vertex detector.
- 158^{+14}_{-13} (TD) and 62 ± 9 (TI) $B^0 \to K_S^0 K_S^0 K_S^0$ signal evens with 387M $B\bar{B}$ pairs.
- TI events used only to constrain the time-integrated asymmetry A_{CP}.







$$\sin(2\beta)^{\text{eff}} = 1.36^{+0.35}_{-0.45}\,(\text{stat.}) \pm 0.03\,(\text{syst.})$$

$$A_{CP} = 0.07^{+0.15}_{-0.20}\,(\text{stat.}) \pm 0.02\,(\text{syst.})$$

Test iso-spin symmetry in $\mathrm{B} \rightarrow K\pi$

Moriond 2023

- From the iso-spin symmetry in the SM:

Phys.Lett.B 627 (2005) 82

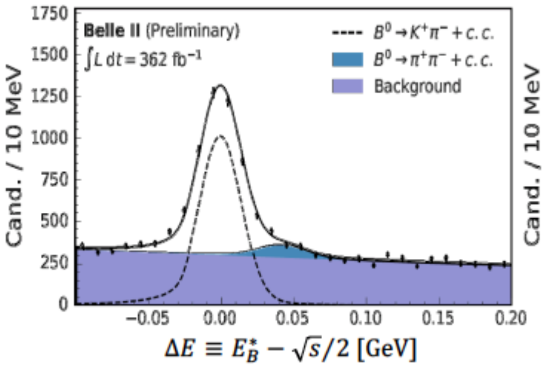
Isospin sum-rule: relation among the products of $\mathcal{B}r$ and $\mathcal{A}_{CP}$ for $B \rightarrow K\pi$

$$I_{K\pi} = \mathcal{B}r(K^+\pi^-)\mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\mathcal{B}r(K^0\pi^+)\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\mathcal{B}r(K^+\pi^0)\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\mathcal{B}r(K^0\pi^0); \quad I_{K\pi}^{SM} = 0$$

M. Gronau, Phys. Lett. B **627**, 82(2005).

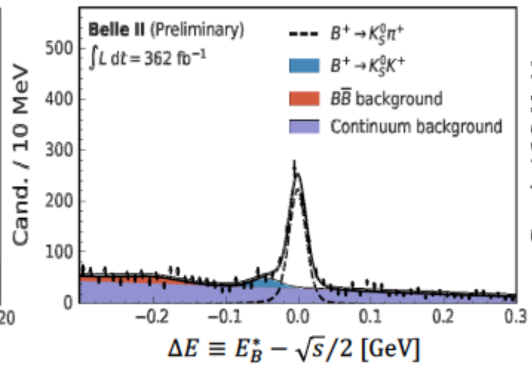
- Belle II can measure all the observables.

$B^0 \rightarrow K^+\pi^-$ results



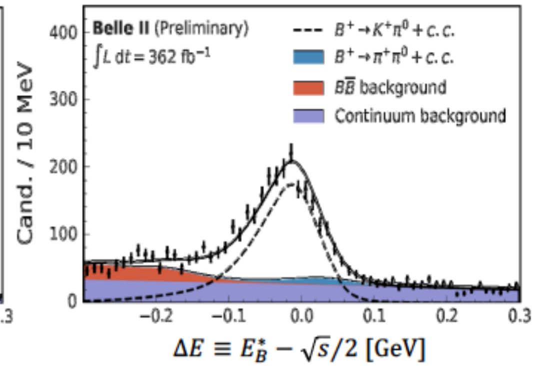
$\mathcal{B}r = (20.7 \pm 0.4 \pm 0.6)\times10^{-6}$
$\mathcal{A}_{CP} = -0.07 \pm 0.02 \pm 0.01$

$B^+ \rightarrow K^0_S\pi^+$ results



$\mathcal{B}r = (24.4 \pm 0.7 \pm 0.9)\times10^{-6}$
$\mathcal{A}_{CP} = -0.05 \pm 0.03 \pm 0.01$

$B^+ \rightarrow K^+\pi^0$ results



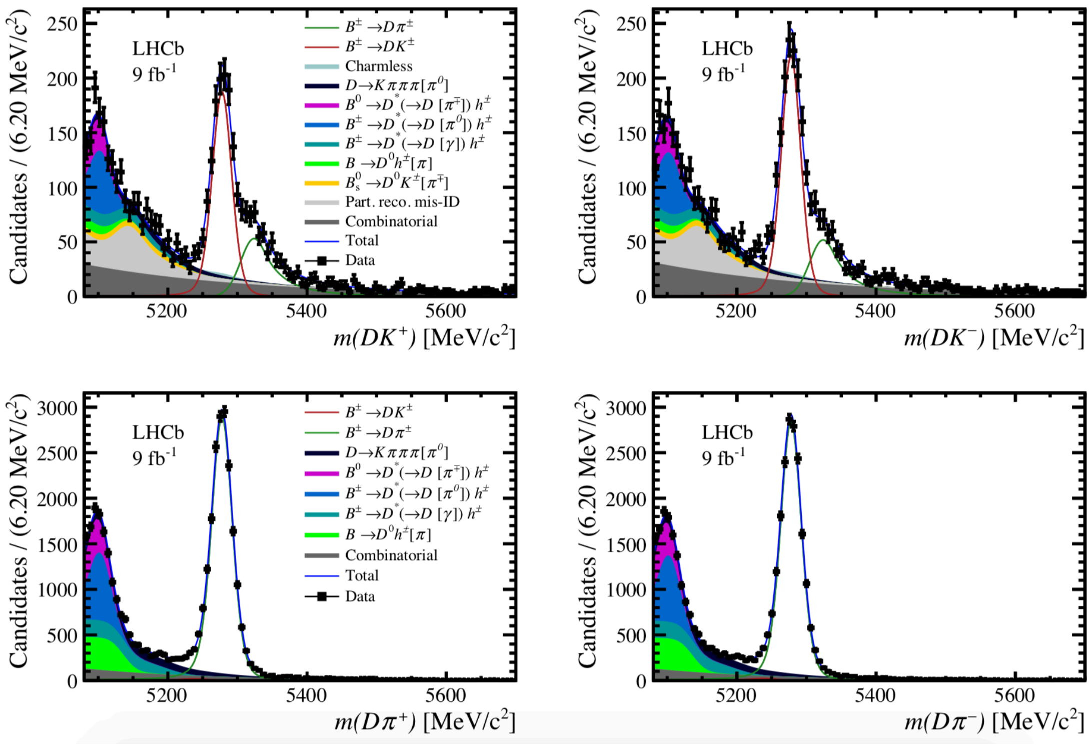
$\mathcal{B}r = (14.2 \pm 0.4 \pm 0.9)\times10^{-6}$
$\mathcal{A}_{CP} = +0.01 \pm 0.03 \pm 0.01$

CPV in $B^+ \to D(h^+h^-\pi^+\pi^-)h^+$

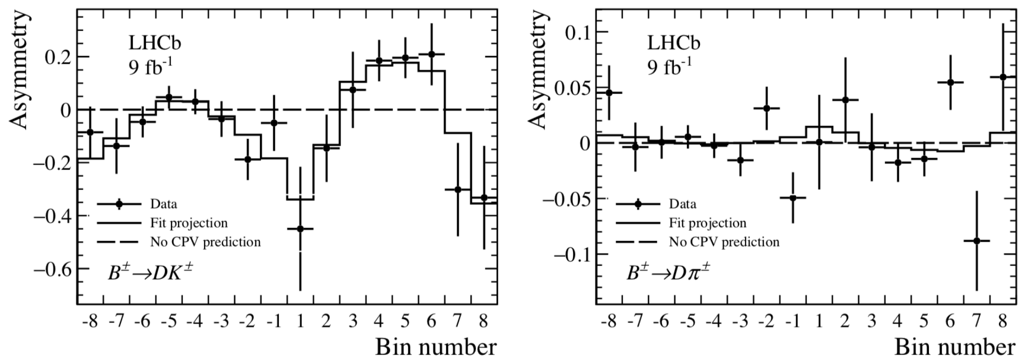
arXiv:2301.10328

- First study of CP violation in $B^+ \to D(K^+K^-\pi^+\pi^-)h^+$ and updated for $B^+ \to D(\pi^+\pi^-\pi^+\pi^-)h^+$.
- Global phase-space integrated measurement for $B^+ \to [K^+K^-\pi^+\pi^-]_D\, h^+$ and $B^+ \to [\pi^+\pi^-\pi^+\pi^-]_D\, h^+$.
- Binned measurement for $[K^+K^-\pi^+\pi^-]_D$. Sensitive to the local CP asymmetries.
- External information on charm-decay parameters, taken from LHCb amplitude analysis. JHEP 02 (2019) 126
- Precision will improve after charm model-independent measurements.

LHCb Run 1 + Run 2 data sample

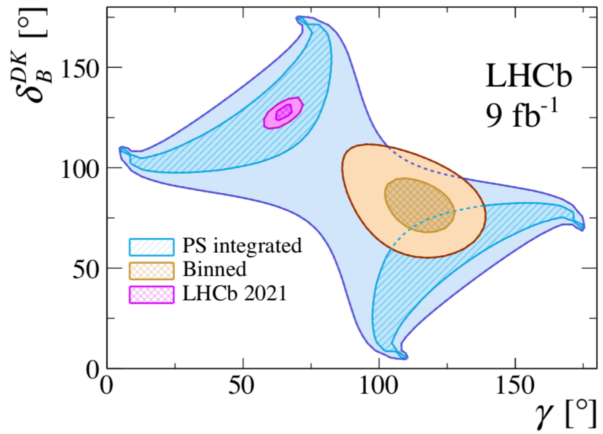


Fractional bin asymmetries:



model-dependent γ:

$$\gamma = (116^{+12}_{-14})^\circ$$



Other topics

- CP violation in the lepton sector
  - neutrino mass eigenstates mismatch weak eigenstates
  - analogue to CKM matrix: PMNS matrix

In the 3-Flavor PMNS model:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- CP violation in QCD
  - QCD Lagrangian can contain CP violating relative phase $\bar{\theta}$
  - measurement of neutron electric dipole moment
  - Axion ALPs search