KAON 2019

CP violation in beauty and charm at LHC*b*

Marcos Romero, on behalf of the LHC*b* colaboration

IGFAE, Universidade de Santiago de Compostela

Perugia, September 10th

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LHC*b*

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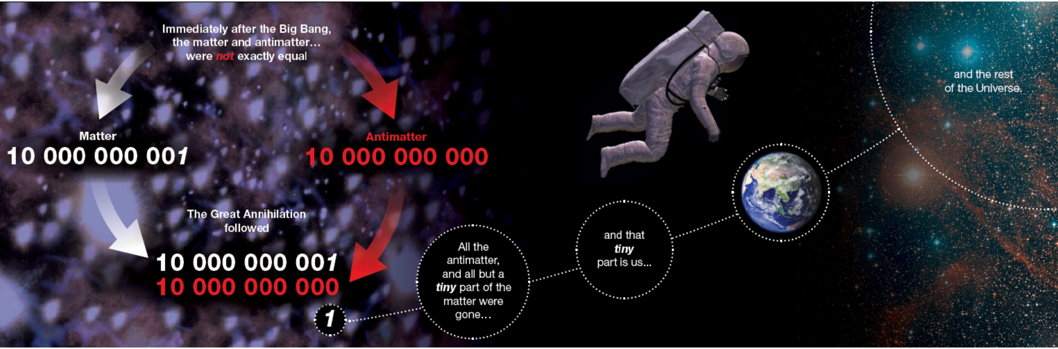
Introduction

Introduction: Why do we study flavour physics?

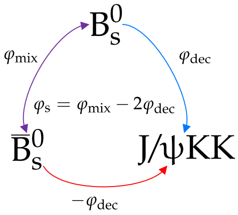


- CPV is necessary condition to baryon asymmetry in the Universe.
- SM includes CPV in de CKM 3×3 matrix through a complex phase.
  - SM CPV is not sufficient to explain matter–antimatter asymmetry.
  - We look for new sources of CPV.
- Looking for SM deviations in an 'indirect' way is complementary to direct production searches

Introduction: CP violation

We need at least 2 competitive interfering amplitudes with different weak (ϕ) and strong (δ) phases. CP violating effects depend on

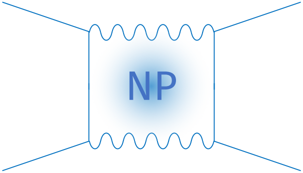
$$\lambda = \frac{q}{p}\frac{\overline{A}}{A}.$$

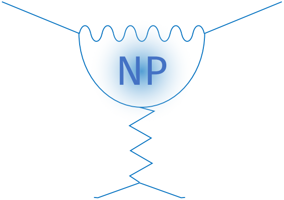


CPV in decay $P(B_s^0 \to f) \neq P(\overline{B}_s^0 \to f)$, thus $|A|^2 \neq |\overline{A}|^2$

CPV in mixing $P(B_s^0 \to \overline{B}_s^0) \neq P(\overline{B}_s^0 \to B_s^0)$, thus $|q/p| \neq 1$.

CPV in interference $P(B_s^0 \to f) \neq P(B_s^0 \to \overline{B}_s^0 \to f)$, thus $\arg(\lambda) \neq 0$.





Beauty physics

Direct CPV: $B^\pm \to \pi^\pm K^+ K^-$ arXiv:1905.09244

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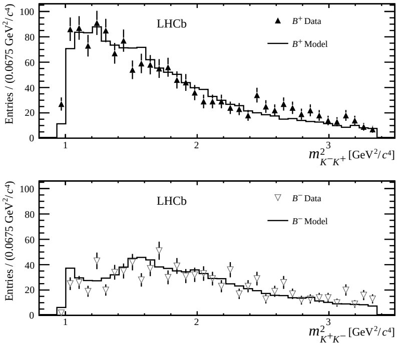
- Using 3 fb^{-1} Run 1 data.
- Separated Dalitz plot analysis for B^+ (2000 events) and B^- (1600 events).
- DP amplitude with seven components, using isobar model.
- Mainly non-resonant and $\rho^0(1450)$ (about 30 % each).



CP asymmetry

The rescattering amplitude, produces a negative CP asymmetry, which is the largest CPV effect from a single amplitude

$$\mathcal{A} = (-66 \pm 4 \pm 2)\%$$

Direct CPV: $B^\pm \to \pi^\pm\pi^+\pi^-$ LHCb-PAPER-2019-017 LHCb-PAPER-2019-018

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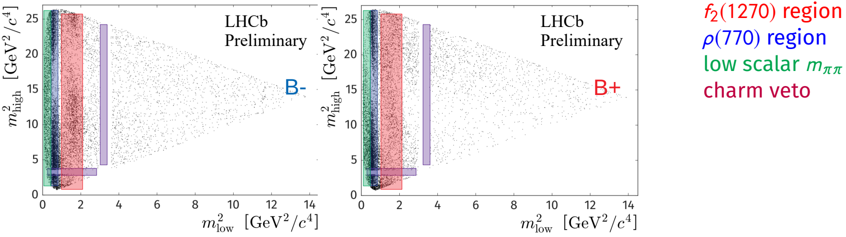
- Using Run 1 data: 3 fb^{-1} (about 20000 signal decays).
- Three different approaches to the complicaded S–wave parametization:

  Isobar Each contribution has a clear physical meaning.
  K–matrix Unitary by construction.
  QMI Fit regions of the Dalitz Plot directly from data.

  All three are in broad agreement.

- Lots of resonances in $\pi^+\pi^-$ pairs:

  Non S–wave $\rho(770)$, $\omega(782)$, $f_2(1270)$, $\rho^0(1450)$ and $\rho^3(1690)$
  S–wave $f_0(500)$, $f_0(980)$, $f_0(1500)$ and $f_0(1710)$



Direct CPV: $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ LHCb-PAPER-2019-017 LHCb-PAPER-2019-018

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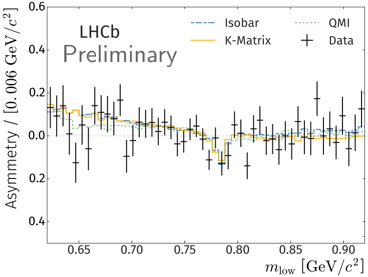
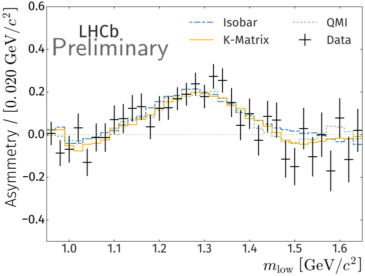
- Three different kinds of CP asymmetries observed:
  1. Huge asymmetry in S–P interference around the $\rho^0(770)$ pole with over 25σ statistical significance. *First observation of CPV in a quasi–two–body interference.*
  2. Large asymmetry in $f_2(1270)$ tensor, with $+10\sigma$. *First CPV involving a tensor.*
  3. Asymmetry in S–wave at low $\pi^+\pi^-$ mass with over 10σ statistical significance. Flip of sign in m_{KK} threshold.
- No asymmetry observed in $\rho - \omega$ mixing.





Direct CPV: $B_u^+ \to J/\psi\rho^+$ Eur. Phys. J. C79 (2019) 537

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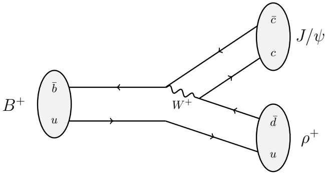
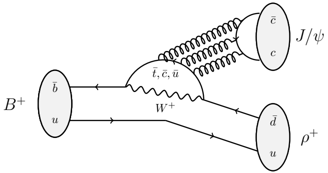
- Using 3 fb^{-1} of Run 1 data.
- BF is measured relative to $B^+ \to J/\psi K^+$ because of the similarity with $B^+ \to J/\psi(\to \mu^+\mu^-)\ \ \rho^+(\to \pi^+\pi^0(\to \gamma\gamma))$



Results

$$\mathcal{B}(B_u^+ \to J/\psi\rho^+) = (3.81^{+0.25}_{-0.24} \pm 0.35) \times 10^{-5}$$

$$\mathcal{A}(B_u^+ \to J/\psi\rho^+) = -0.045^{+0.056}_{-0.057} \pm 0.008$$



- Both are the most precise measurements to date, and compatible with the previous BaBar result *Phys.Rev.D76:031101,2007*.
- This $\mathcal{A}$ value can be used to place penguin constraints in measurements of ϕ_s in $B_s^0 \to J/\psi\phi$.

Mixing–induced CPV: γ status JHEP 08 (2018) 176 JHEP 03 (2018) 059

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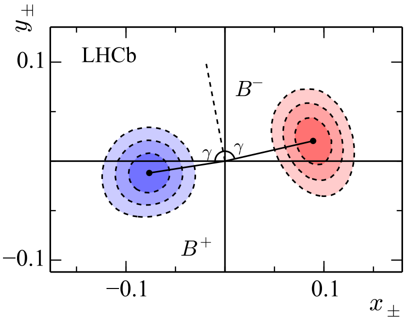
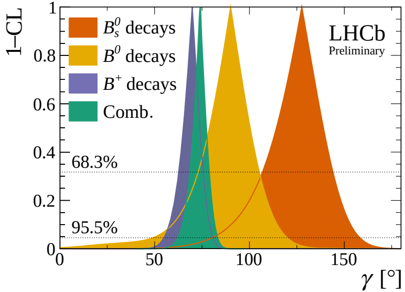
- Phase γ is measured through interference in $B^{\pm} \to DK^{\pm}$ and in $B^0_{d,s}$ decays

Results 2018

LHCb	$\gamma = (74.5^{+5.0}_{-5.8})^{\circ}$
HFLAV	$\gamma = (73.5^{+4.2}_{-5.1})^{\circ}$
UTFIT	$\gamma = (65.8 \pm 2.2)^{\circ}$

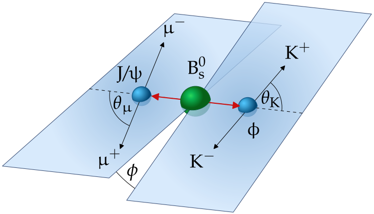
- Both consistent within $\sim 2\sigma$. This is a non trivial test on:
  - KM theory of CPV single-phase hypothesis
  - Contribution of new physics in tree–level diagrams
- Small internal tensions between $B^0_{s,d}$ and $B^{\pm}$.

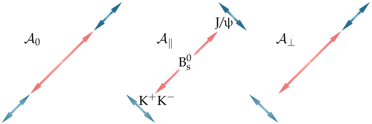




Mixing–induced CPV: neutral B_s^0 decays

- Observable phase is
  $\phi_s = \phi_M - 2\phi_D = \arg(\lambda) = \arg\left(\frac{q}{p}\frac{\overline{A}}{A}\right)$.
- Also important in the decay rate are $\Delta\Gamma$ and Δm.
- NP can appear in ϕ_M.
  - Tree decays ($b \to s\bar{c}c$): no NP in ϕ_D.
  - Loop decays ($b \to s\bar{q}q$, $q = s, d$): potential NP in ϕ_D.
- Deviation of ϕ_s from SM would imply NP.
- Direct CPV posible in $|\lambda| \neq 1$ too.
- S, P and D wave interfering amplitudes.





Mixing–induced CPV: $B_s^0 \to J/\psi K^+ K^-$ Eur. Phys. J. C 79 (2019) 706

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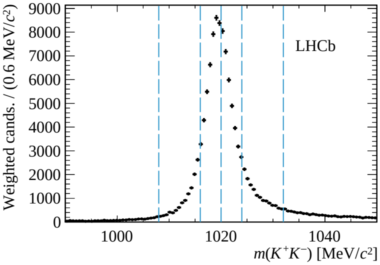
- Using 1.9 (Run 2) fb^{-1} of data (about 117000 events).
- Looking at 990 – 1050 MeV $/c^2$ mass window. Mainly $\phi(1020)$ and modest $f_0(980)$ contribution.
- Average decay–time resolution $\sigma_{\mathrm{eff}} = 45.5\,\mathrm{fs}^{-1}$
- Decay–time and angular efficiencies are estimated with simulation and matched to data
- Four–dimensional amplitude analysis (helicity angles & time). The fit is performed in 6 m_{KK} bins.

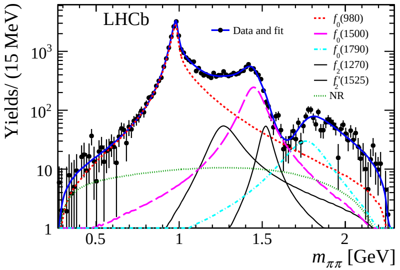


Key parameters

$$\phi_s = -83 \pm 41 \pm 6\,\mathrm{mrad}$$
$$|\lambda| = 1.012 \pm 0.016 \pm 0.006$$
$$\Gamma_s - \Gamma_d = -4.1 \pm 2.4 \pm 1.5\,\mathrm{fs}^{-1}$$
$$\Delta\Gamma_s = 77 \pm 8 \pm 3\,\mathrm{fs}^{-1}$$

Mixing–induced CPV: $B_s^0 \to J/\psi\pi^+\pi^-$ Phys. Lett. B 797 (2019)

- Using 1.9 (Run 2) fb^{-1} of data (about 33000 events).
- Mainly $f_0(980)$ contribution with other S–wave and D–wave amplitudes.
- Average decay–time resolution $\sigma_{\mathrm{eff}} = 41.5\,\mathrm{fs}^{-1}$
- Decay–time and angular efficiencies are estimated with simulation and matched to data
- Five–dimensional amplitude analysis (helicity angles, mass & time).



Key parameters

$$\phi_s = -57 \pm 60 \pm 11\,\mathrm{mrad}$$

$$|\lambda| = 1.01\,^{+0.08}_{-0.06} \pm 0.03$$

$$\Gamma_H - \Gamma_d = -50 \pm 4 \pm 4\,\mathrm{fs}^{-1}$$

Mixing–induced CPV: Status of $\phi_s^{c\bar{c}s}$

- Results are in agreement with previous measurements and the SM prediction.

Average LHC*b*

$$\phi_s = -41 \pm 25\,\text{mrad}$$

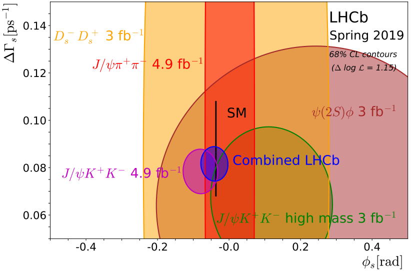
$$\Delta\Gamma_s = 0.0816 \pm 0.0048\,\text{ps}^{-1}$$

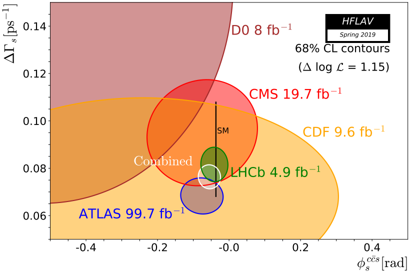
HFLAV combination

$$\phi_s = -55 \pm 21\,\text{mrad}$$

$$\Delta\Gamma_s = 0.0764 \pm 0.0024\,\text{ps}^{-1}$$

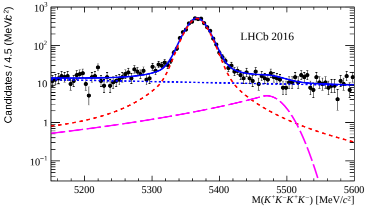
- Reduction on experimental uncertainty of $\sim 30\,\%$ from the average before Moriond 2019, thanks to ATLAS.





Mixing–induced CPV: $B_s^0 \to \phi\phi$ arXiv:1907.10003

- Using 3 (Run 1) + 2 (Run 2) fb^{-1} of data (about 8500 events).
- 4–dimension fit: helicity angles & time.
- Parameters Γ_s, $\Delta\Gamma_s$ and Δm_s are fixed to known values.
- Mainly $\phi(1020)$ and S–wave $f_0(980)$ contribution.
- Detector efficiency and decay–time resolution are determined with simulation.
- Decay–time efficiency determined with data.
- Improvement on exp. unc. in 25% on $\phi_s^{s\bar{s}s}$ and 40 % on $|A_0|^2$ from previous analysis.



Key parameters

$$\phi_s^{s\bar{s}s} = -73 \pm 115 \pm 27\,\text{mrad}$$
$$|\lambda| = 0.99 \pm 0.05 \pm 0.01$$
$$|A_0|^2 = 0.381 \pm 0.007 \pm 0.012$$

$|A_0|^2$ in agreement with QCD predictions.

Mixing–induced CPV: $B^0_{\{s,d\}} \to K^{*0}\overline{K}^{*0}$ JHEP 07 (2019) 032

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- Using 3 (Run 1) fb^{-1} of data.
- 5–dimension fit: helicity angles & 2 $m_{K\pi}$ masses.
- $B^0_{\{s,d\}} \to K^{*0}\overline{K}^{*0}$ are U–spin partners, and can be used to control penguin pollution.

$B^0_d \to K^{*0}\overline{K}^{*0}$

- Untagged and time–integrated analysis.
- Assuming $\Delta\Gamma \approx 0$ and negligible CPV in the mixing and the decay.
- First LHCb analysis

$B^0_s \to K^{*0}\overline{K}^{*0}$

Compatible with TD analysis from *LHCb-PAPER-2017-048*:

$$\phi_s^{s\bar{s}s} = -100 \pm 130 \pm 140\,\text{mrad}$$
$$|\lambda| = 1.035 \pm 0.034 \pm 0.089$$

- Found $|A_0|^2(B^0_d) \gg |A_0|^2(B^0_s)$.
- Measured B^0_s/B^0_d branching–fraction ratio $R^{\text{exp}}_{sd} = 3.43 \pm 0.38$, there is a theoretical prediction $R^{\text{theo}}_{sd} = 16.4 \pm 5.2$, *Phys.Rev.D76:074005,2007.* ⊞

Charm physics

Direct CPV: D^0 decays arXiv:1905.05428

- Using 5.9 fb^{-1} (almost full Run 2) of data.
- Both prompt $m(D^0\pi^+_{\text{soft}})$ and semileptonic $m(D^0)$ tagging were used.
- The raw asymmetry in Cabbibo supressed $D^0 \to h^+h^-$ decays

$$\mathcal{A}(D \to h^+h^-) = \frac{N(D \to f) - N(\bar{D} \to \bar{f})}{N(D \to f) + N(\bar{D} \to \bar{f})} = \mathcal{A}_{\text{CP}} + \mathcal{A}_{\text{detector}} + \mathcal{A}_{\text{production}}$$

includes both physics and detector effects. Then we compute:

$$\Delta\mathcal{A}_{\text{CP}} = \mathcal{A}(K^+K^-) - \mathcal{A}(\pi^+\pi^-) = \mathcal{A}_{\text{CP}}(K^+K^-) - \mathcal{A}_{\text{CP}}(\pi^+\pi^-).$$

- $SU(3)$ symmetry imposes $\mathcal{A}_{\text{CP}}(K^+K^-) = -\mathcal{A}_{\text{CP}}(\pi^+\pi^-)$.
- $\Delta\mathcal{A}_{\text{CP}}$ is primarily sensitive to **direct CPV**.

Direct CPV: D^0 decays arXiv:1905.05428

Combination Run 1 & Run 2

$$\Delta\mathcal{A}_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

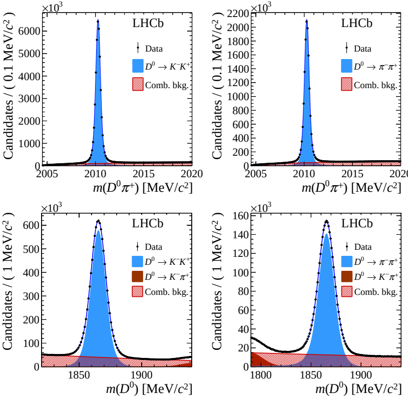
- CPV was observed at 5.3σ statistical significance.
- Result consistent with the SM expectations ($10^{-4} - 10^{-3}$).

Using the latest results†, we get:

$$a^{dir}_{CP} = \Delta\mathcal{A}_{CP} + \frac{\Delta\langle t\rangle}{\tau(D^0)}\mathcal{A}_{\Gamma} = (-15.7 \pm 2.9) \times 10^{-4}$$

prompt

44 M events   14 M events



9 M events   3 M events

semileptonic

† $\frac{\Delta\langle t\rangle}{\tau(D^0)} = \frac{\langle t\rangle_{KK} - \langle t\rangle_{\pi\pi}}{\tau(D^0)} = 0.115 \pm 0.002$ and $\mathcal{A}_{\Gamma} \approx -a^{ind}_{CP} = (-2.8 \pm 2.8) \times 10^{-4}$

Indirect CPV: $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ LHCb-CONF-2019-001

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- New measurement of $\mathcal{A}_\Gamma$ with $1.9\,\text{fb}^{-1}$.
- The asymmetries in the mixing and in the interference are:

Asymmetries 2015–2016

$$\mathcal{A}_\Gamma(K^+K^-) = (1.3 \pm 3.5 \pm 0.7) \times 10^{-4}$$

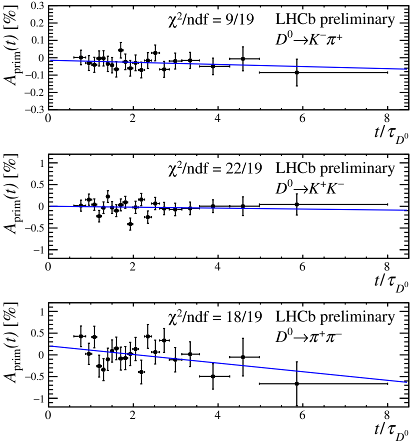
$$\mathcal{A}_\Gamma(\pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}$$

- If we neglect decay phases, then we get a combined value

Combination Run 1 + Run 2

$$\mathcal{A}_\Gamma(K^+K^-+\pi^+\pi^-) = (0.9\pm2.1\pm0.7)\times10^{-4}$$

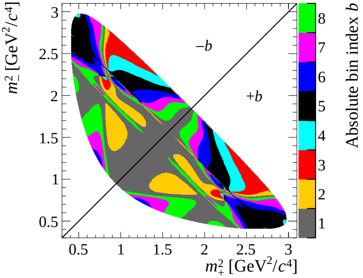
- There is **no evidence** for CPV in mixing or interference.

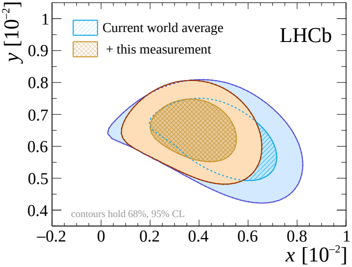


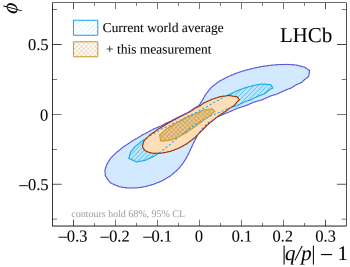
Charm mixing parameters
PRL 122, 231802 (2019)

This is a time–dependent DP analysis using the **bin–flip** method.

- Data is binned in DP coordinates where the binning scheme is chose to have approximately constant strong–phase differences.
- Measure the yield ratio $R^{\pm}_{bj}(x_{CP}, y_{CP}, \Delta x, \Delta y)$ between $[-b, +b]$ bins as function of decay time







Charm mixing parameters

PRL 122, 231802 (2019) PRL 122, 011802 (2019)

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Most precise single–experiment measurements to date.

- Using 3 fb^{-1} of data (2.3 M events) both prompt and semileptonic.

Run 1 data

$$x_{CP} = 0.27 \pm 0.16(\text{stat}) \pm 0.04(\text{syst})\,\%$$

$$\Delta x = -0.053 \pm 0.070(\text{stat}) \pm 0.022(\text{syst})\,\%$$

- First evidence of $x > 0$ when combinating with previous measurements.

- Using 3 fb^{-1} of data coming from semimuonic B decays.

Run 1 data

$$y_{CP} = 0.57 \pm 0.13\,(\text{stat}) \pm 0.09\,(\text{syst})$$

Both fit results compatible with symmetry hypothesis.

$$z_{CP} \pm \Delta z = \left(\frac{q}{p}\right)^{\eta} (y \pm ix) \quad \text{with} \quad x = \frac{\Delta m}{\Gamma} \text{ and } y = \frac{\Delta\Gamma}{2\Gamma}$$

$$x_{CP} = -\Im(z_{CP}),\ y_{CP} = -\Re(z_{CP}),\ \Delta x = -\Im(\Delta z) \text{ and } \Delta y = -\Re(\Delta z)$$

Conclusions

Summary

Beauty part

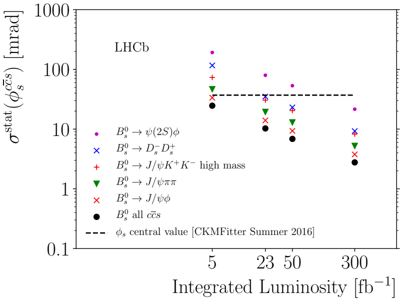
- Time–dependent analyses are compatible with the SM and produce the strongest constraints in the different ϕ_s.
- Very large direct CPV manifestations in DP regions of charmless 3–body decays. Possibly due to strong phases originated in rescattering.
- First observation of CPV involving a tensor.

Charm part

- First observation of CPV in charm decays. Direct CPV found with ΔA_{CP}.
- Most precise determination of mixing parameters x_{CP} and y_{CP} from a single experiment. Also first evidence of $x > 0$.
- All results are statistically limited: large room for improvements with next runs of LHC*b*.

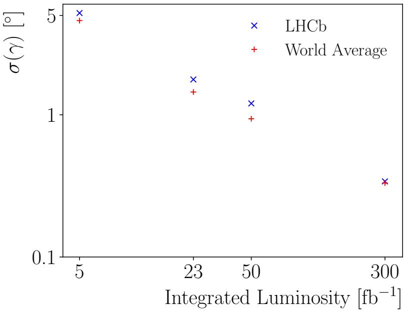
Prospects

Prospects in beauty arXiv:1808.08865



- The expected precision on $\phi_s^{c\bar{c}s}$ after Upgrade II will be $\sim$ 4 mrad from $B_s^0 \to J/\psi\phi$ decays, and $\sim$ 3 mrad from all modes combined: at the same level of nowadays CKMfitter value.

- LHCb is currently dominating CKM phase $\gamma = (74.0 \pm 5.0)^\circ$. Precision on γ after Upgrade II will be 0.35°.



Prospects in charm arXiv:1808.08865

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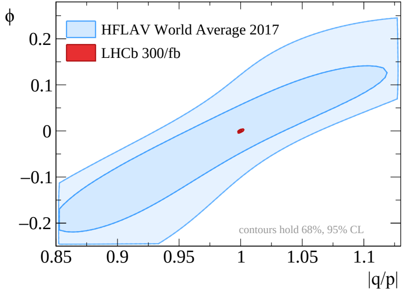

- CPV in A_Γ is predicted in the SM to be 3×10^{-5}. Its smallness may be turned into an advantage after all.
- We are now set for precision studies con CPV in charm. Future measurements with HL–LHC will certainly matter.

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^+K^-$	Yield $D^0 \to \pi^+\pi^-$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.007	0.015
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

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Backup

Abstract

Precision measurements of CP violating observables in the decays of b and c hadrons are powerful probes to search for physics beyond the Standard Model. The most recent results on CP violation in the decay, mixing and interference of both b and c hadrons obtained by the LHCb Collaboration with Run I and years 2015-2016 of Run II are presented, including the first observation of CP violation in the charm system. In particular world best constraints and world first measurements are provided for CKM elements, unitarity angles and charm parameters. We also discuss prospects for future sensitivities.

$R_{\{s,d\}}$

From the V–A structure of the weak interaction and helicity conservation in the strong interaction, the final state of these decays is from QCDF expected to be highly longitudinally polarised (*Z. Phys. C1 (1979) 269*).

The gluonic penguins are quite different CKM elements

$$B_s^0 \text{ decay} \longrightarrow \lambda^2 \cdot P_{tc} + \lambda^4 \cdot P_{uc}$$

$$B_d^0 \text{ decay} \longrightarrow \lambda^3 \cdot P_{ct} + \lambda^3 \cdot P_{ut}$$

As the $|A_0|^2$ for B_s^0 and B_d^0 are so different whilst not expecting so, this translates into a thus unexpected value of

$$R_{sd} = \frac{\mathcal{B}(B_s^0)}{\mathcal{B}(B_d^0)} \frac{f_L(B_s^0)}{f_L(B_d^0)} \frac{1-y^2}{1+y\cos\phi_s}$$