Mixing and CP violation in B and D meson systems at LHCb

Anita Nandi
On behalf of the LHCb collaboration

University of Oxford

8 March 2017

Introduction

- Studying CP violation in b and c hadrons gives great **insight into the CKM matrix**
- Overconstraining the matrix $\rightarrow$ potential **signs of New Physics**
- To study CP violation $\rightarrow$ collect data using the LHCb detector:

Run	Year	Luminosity	COM energy
Run 1	2011	1fb^{-1}	7 TeV
	2012	2fb^{-1}	8 TeV
Run 2	2015	0.3fb^{-1}	13 TeV
	2016	1.5fb^{-1}	13 TeV
	2017-18	$\sim 3.2\text{fb}^{-1}$	13 TeV

- At 13 TeV b and c production **cross sections are higher** and **improved triggers** mean that most HF decays gain *at least* a **factor 2 in yield** per fb^{-1} in Run 2 compared to Run 1

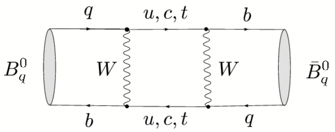
CP violation

There are **three types** of CP violation:

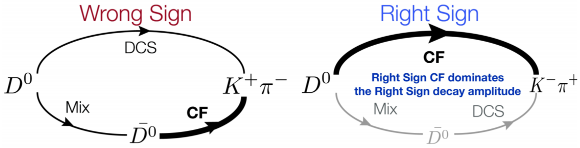
- **Direct** CP violation (in decay)

$$\Gamma(B^- \to DK^-) \neq \Gamma(B^+ \to DK^+)$$

- **Indirect** CP violation (in mixing)



- CP violation from **interference between mixing and decay**



Overview

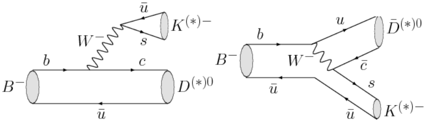
1. Combined measurement of CKM angle γ
2. Charm mixing and CPV in $D^0 \to K^{\pm}\pi^{\mp}$
3. Measurement of A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
4. Search for phase-space dependent CPV in $D^0 \to \pi^+\pi^-\pi^+\pi^-$
5. Further prospects for CP violation

Combined measurement of CKM angle γ

Combined measurement of CKM angle γ (JHEP 12 (2016) 087)

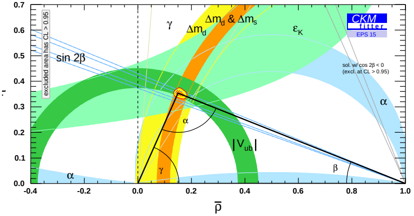
- **Direct measurements** of γ extracted only from tree level processes

e.g.



$$\gamma = (72.2^{+6.8}_{-7.3})^\circ$$

- **Indirect measurement** from global fits to CKM triangle



$$\gamma = (66.85^{+0.94}_{-3.44})^\circ$$

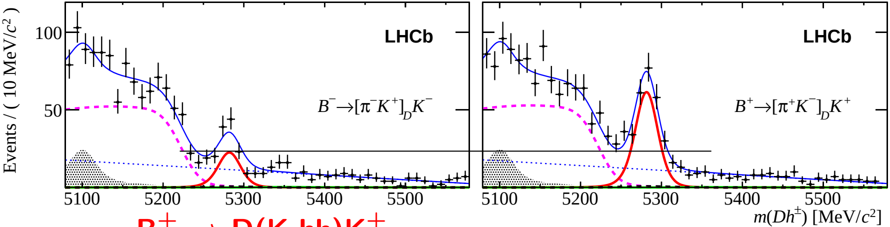
- **Precision to the level of $\sim 1^\circ$** from direct measurements could reveal inconsistencies $\rightarrow$ possible New Physics

Combined measurement of CKM angle γ (JHEP 12 (2016) 087)

- A wide range of γ sensitive mode are targeted at LHCb
- Investigating as many modes as possible improves the sensitivity to γ

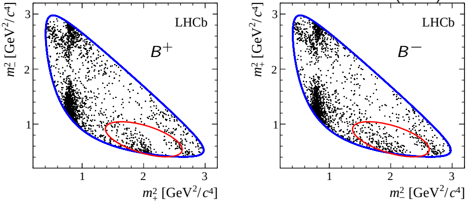
$B^{\pm} \to D(hh)K^{\pm}$

PLB 760 (2016)



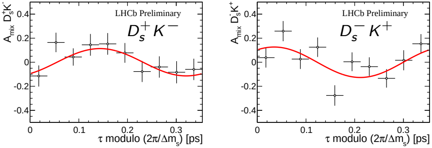
$B^{\pm} \to D(K_s hh)K^{\pm}$

*JHEP*10(2014)097



$B_s^0 \to D_s^{\pm}K^{\mp}$

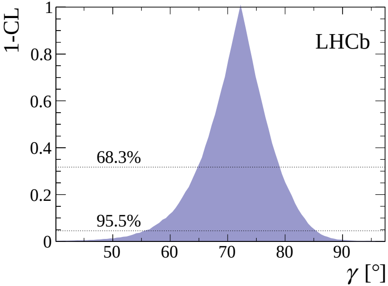
LHCb-CONF-2016-015, CKM 2016



And many more...

Combined measurement of CKM angle γ (JHEP 12 (2016) 087)

- Combine observables from a **wide range of γ sensitive decays**
- **External inputs** from HFAG, CLEO and LHCb are used in the combination
- Use a **frequentist approach**, construct a likelihood function
- Baysian procedure is performed and found consistent

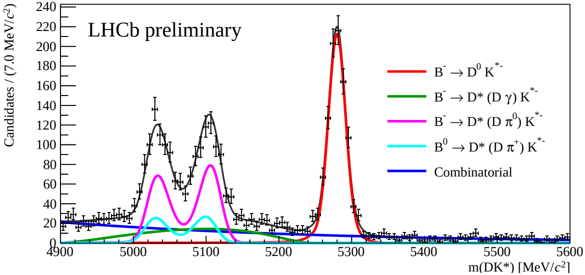


Run 1 data ONLY!

$$\gamma = (72.2^{+6.8}_{-7.3})^{\circ}$$

- **World's most precise direct measurement** of γ from a single experiment

- Performed extensive work on Run 1 data. Now **exploit the expanding Run 2 dataset**
- Expand scope of γ analyses $\rightarrow$ **explore new modes**
- New mode $\mathbf{B^{\pm} \rightarrow D(hh)K^{*\pm}}$ uses **Run 1 and Run 2 data**
- Two-body D decays: $D^0 \rightarrow K^-\pi^+$ (favoured), $K^+K^-, \pi^+\pi^-, K^+\pi^-$

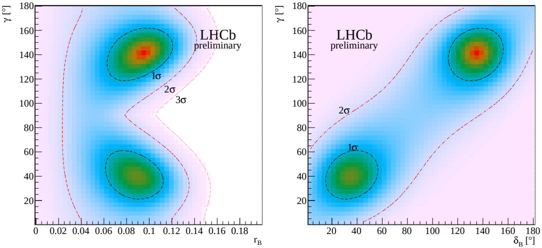


3x the yield per fb^{-1} in Run 2!

- Differences in the **rates of $\mathbf{B^+}$ and $\mathbf{B^-}$** decays gives sensitivity to γ

Future for γ measurements (LHCb-CONF-2016-014, CKM 2016)

- **Simultaneous fit** to the different D modes $\rightarrow$ CP observables
- Interpret in terms of the **physics parameters** r_B, δ_B and γ



- Promising for the sensitivity of future γ measurements
- Use the full 2016 dataset, explore **more D modes** $\rightarrow$ set limits on r_B
- Continue to **expand range of γ sensitive modes**
- Full Run 2 dataset is expected to reduce precision on γ to about 4°

Charm mixing and CPV in $D^0 \to K^{\pm}\pi^{\mp}$

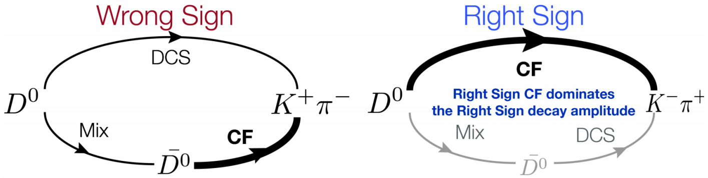
Motivation

- CP violation has not yet been observed in the charm sector
- Improve understanding of mixing in the charm sector

- Flavour and mass eigenstates differ $\to D^0 - \bar{D}^0$ mixing
- Define dimensionless mixing parameters:

$$x = \frac{m_2 - m_1}{\Gamma}, \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} \qquad (|x| \ll 1 \text{ and } |y| \ll 1)$$

$$x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi} \qquad y' = y \cos \delta_{K\pi} - x \sin \delta_{K\pi}$$



Charm mixing and CPV in $D^0 \to K^{\pm}\pi^{\mp}$ (arXiv:1611.06143, submitted to PRD)

- Measurements of the time-dependent ratio of WS-to-RS decay rates:

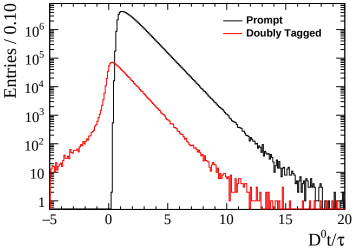
$$R(t)^{\pm} = \underbrace{R_D^{\pm}}_{DCS} + \underbrace{\sqrt{R_D^{\pm}}\, y'^{\pm}\left(\frac{t}{\tau}\right)}_{interference} + \underbrace{\frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}\left(\frac{t}{\tau}\right)^2}_{mixing}$$

$R(t)^{+}$ and $R(t)^{-}$ for initially produced D^0 and $\bar{D}^0$

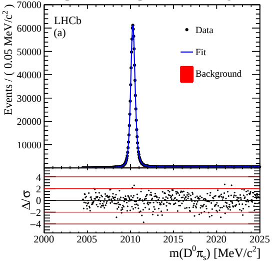
- Fits to RS and WS samples allow extraction of the CP violation and mixing parameters: $R_D^{\pm}$, $(x'^{\pm})^2$ and $y'^{\pm}$

Direct CPV occurs if: $R_D^{+} \neq R_D^{-}$
CPV in mixing occurs if: $x^{+} \neq x^{-}$ and $y^{+} \neq y^{-}$

- Data sample: **Full Run 1 dataset**
- Uses **doubly-tagged (DT)** charm sample from $\bar{B} \to D^{*+}\mu^- X$, $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^\pm\pi^\mp$ → **very pure samples**
- Lower statistics than prompt, but cover a **different region of decay time**

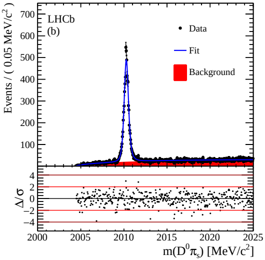


Right Sign decays



1.73×10^6 RS D^{*+} decays

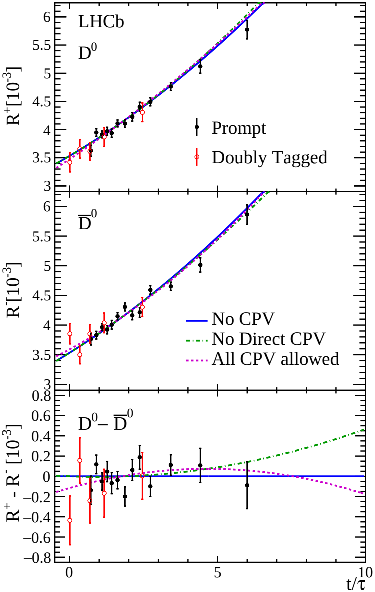
Wrong Sign decays



6.68×10^3 WS D^{*+} decays

Charm mixing and CPV in $D^0 \to K^{\pm}\pi^{\mp}$ (arXiv:1611.06143, submitted to PRD)

- Extract $\mathbf{R^{\pm}}$ **from RS and WS yields** in bins of decay time
- Red points are DT analysis, black points are a previous analysis using prompt charm
- Data is **consistent with the hypothesis of CP symmetry**
- Results from DT analysis are **consistent with the prompt**
- Simultaneous fit to DT and prompt samples → precision of measured parameters **improves by 10-20%** compared to prompt sample only



Measurement of A_Γ in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$

A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ (arXiv:1702.06490, submitted to PRL)

Time dependent CP asymmetry of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$:

$$A_{CP}(t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \approx a_{dir}^f - A_\Gamma \frac{t}{\tau_D}$$

where A_Γ is the **asymmetry between the D^0 and $\bar{D}^0$ effective widths**

$$A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0 \to f} - \hat{\Gamma}_{\bar{D}^0 \to f}}{\hat{\Gamma}_{D^0 \to f} + \hat{\Gamma}_{\bar{D}^0 \to f}}$$

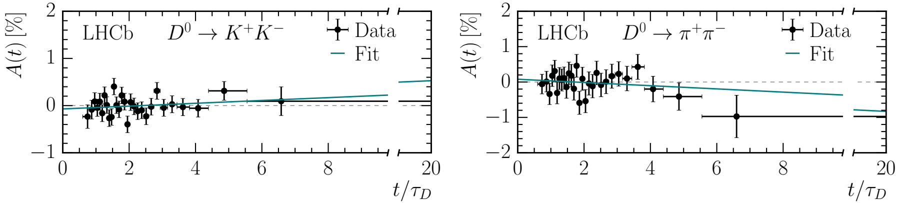
To first order, $a_{dir}^f = 0$ and A_Γ is independent of final state

A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ (arXiv:1702.06490, submitted to PRL)

New method using **full Run 1 dataset**

$$A_{CP}(t) = a_{dir}^{f} - A_\Gamma \frac{t}{\tau_D}$$

- Linear fit to the asymmetry as a function of decay time
- Determine and correct for detector asymmetries



$$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$$
$$A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$$

No evidence for CPV

- Precision improved by almost a **factor of 2** from $1fb^{-1}$ analysis
- Old method was performed, found to be consistent
- Calculate average A_Γ, and combine with muon tagged sample
- **Most precise** A_Γ measurement: $A_\Gamma = (-0.29 \pm 0.28) \times 10^{-3}$

Search for phase-space dependent CPV in $D^0 \to \pi^+\pi^-\pi^+\pi^-$

Search for CPV in $D^0 \to \pi^+\pi^-\pi^+\pi^-$ (arXiv:1612.03207v2, submitted to PLB)

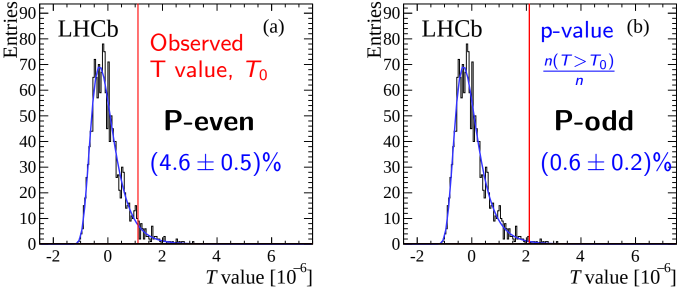
- **Model independent** method to test if data is consistent with no CPV
- **Energy test**: statistical comparison between D^0 and $\bar{D}^0$ based on distances of event pairs in phase space

$$T = \langle d_{ij} \rangle_{DD} + \langle d_{ij} \rangle_{\bar{D}\bar{D}} - \langle d_{ij} \rangle_{D\bar{D}}$$

First application of this test in 4-body decays

- Calculate T-values from randomly separated samples (no CPV)
- 5D phase space: $m^2(\pi\pi)$, $m^2(\pi\pi\pi)$ $\to$ **P-even CPV**
- Separate samples by triple product sign $\to$ **P-odd CPV**

Consistent with CP symmetry



Marginally consistent with CP symmetry

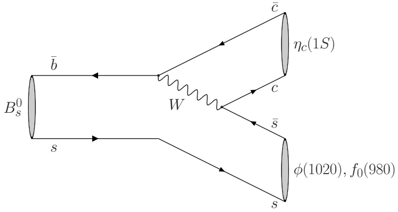
Significance of 2.7σ for CP non-conservation

Further prospects for CP violation

Motivation

- Sensitive to **CP violating phase ϕ_s** (interference between mixing and decay)
- ϕ_s is well predicted in SM and **sensitive to possible NP**
- Purely **CP-even final state** $\to$ no angular analysis required

- Golden channel for ϕ_s ($\approx -2\beta_s$) measurements: $B_s^0 \to J/\psi\phi$
- Superposition of CP-even and CP-odd states $\to$ requires **analysing angular distribution** of final state particles

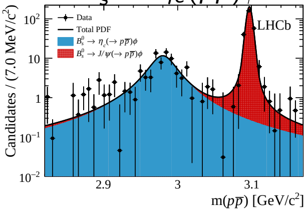


- Not yet enough statistics to perform time-dependent analysis
- Perform **measurement of branching fractions**

$B_s^0 \to \eta_c\phi$ and $B_s^0 \to \eta_c\pi^+\pi^-$ (arXiv:1702.08048, submitted to JHEP)

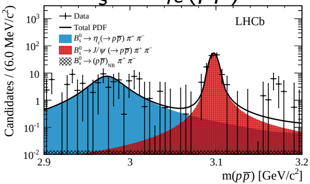
- **Full Run 1 dataset**
- BDT-based selection and PID requirements

$B_s^0 \to \eta_c(p\bar{p})\phi$



- $\mathbf{B_s^0 \to \eta_c\phi}$:
  - η_c reconstructed in $\mathbf{p\bar{p}}$, $\mathbf{K^+K^-\pi^+\pi^-}$, $\mathbf{\pi^+\pi^-\pi^+\pi^-}$, $\mathbf{K^+K^-K^+K^-}$
  - Normalisation channel: $\mathbf{B_s^0 \to J/\psi\phi}$

$B_s^0 \to \eta_c(p\bar{p})\pi^+\pi^-$



- $\mathbf{B_s^0 \to \eta_c\pi^+\pi^-}$:
  - Higher level of combinatoric background
  - η_c reconstructed in $\mathbf{p\bar{p}}$ decay mode
  - Normalisation channel: $\mathbf{B_s^0 \to J/\psi\pi^+\pi^-}$

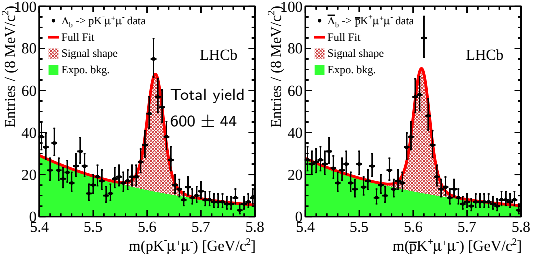
$$\mathcal{B}(B_s^0 \to \eta_c\phi) = (5.01 \pm 0.53 \pm 0.27 \pm 0.63) \times 10^{-4}$$ **Observation**

$$\mathcal{B}(B_s^0 \to \eta_c\pi^+\pi^-) = (1.76 \pm 0.59 \pm 0.12 \pm 0.29) \times 10^{-4}$$ **Evidence**

Motivation

- First evidence for CPV in baryon decays in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ [1]
- FCNC process, loop diagrams → New Physics (NP) [2]
- Limited amount of CPV expected in SM → sensitive to NP

- **Full Run 1 dataset**
- Measure two observables sensitive to CPV: $\Delta\mathcal{A}_{CP}$ and $a_{CP}^{\hat{T}-odd}$



$$\Delta\mathcal{A}_{CP} = (-3.5 \pm 5.0 \pm 0.2) \times 10^{-2}$$
$$a_{CP}^{\hat{T}-odd} = (1.2 \pm 5.0 \pm 0.7) \times 10^{-2}$$

No evidence for CPV found

[1] Charmless b-hadron decays at LHCb, Giulio Dujany. Thursday afternoon

[2] New physics searches with $b \to sll$ transitions and rare decays at LHCb, Kristof De Bruyn. Wednesday afternoon

Conclusions

- World's **most precise direct measurement of** γ continues to improve
- Measurements of CP violation in the charm sector with $D^0 \to K^{\pm}\pi^{\mp}$ and $D^0 \to \pi^+\pi^-\pi^+\pi^-$ are **consistent with CP-symmetry**
- Most precise measurement of A_Γ to date
- Further CPV prospects with $B_s^0 \to \eta_c \phi$ and $B_s^0 \to \eta_c \pi^+\pi^-$, and $\Lambda_b^0 \to pK^-\mu^+\mu^-$
- Many more exciting results to come with **Run 2 data**

Thanks for listening!
Any Questions?

Backups

Charm mixing and CPV in $D^0 \to K^{\pm}\pi^{\mp}$ (arXiv:1611.06143, submitted to PRD)

- Fits performed to extract $R^{\pm}$ in five bins of decay time
- Time dependence of these ratios is fit by minimizing:

$$\chi^2 = \sum_i \underbrace{\left[\left(\frac{r_i^+ - \widetilde{R}(t_i)^+}{\sigma_i^+} \right)^2 + \left(\frac{r_i^- - \widetilde{R}(t_i)^-}{\sigma_i^-} \right)^2 \right]}_{\frac{measured - expected}{error} \text{ for each bin}} + \underbrace{\chi^2_{\epsilon} + \chi^2_{\text{peaking}} + \chi^2_{\text{other}}}_{\text{Gaussian constraints to account for uncertainties: tracking and reconstruction efficiencies and peaking backgrounds}}$$

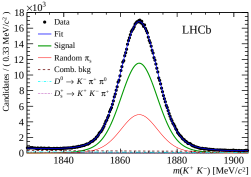
- Three fits are performed:
  - Assumimg **CP symmetry** $(R^+ = R^-, (x'^+)^2 = (x'^-)^2$ and $y'^+ = y'^-)$
  - Requiring CP symmetry in CF and DCS amplitudes $(R^+ = R^-)$ - **no direct CP violation**
  - Allowing **all types of CP violation**

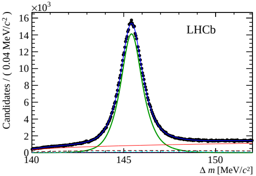
A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ (arXiv:1702.06490, submitted to PRL)

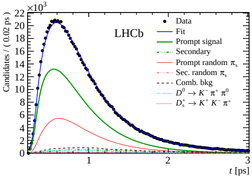
Method 2: Performed on 2012 data, combined with previous 2011 analysis

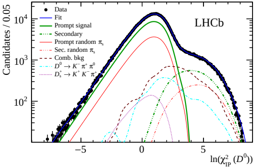
$$A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0\to f} - \hat{\Gamma}_{\bar{D}^0\to f}}{\hat{\Gamma}_{D^0\to f} + \hat{\Gamma}_{\bar{D}^0\to f}}$$

Fits to the D^0 and Δm spectra to determine yields









Simultaneous fit to decay time distribtuion and $ln(\chi^2_{IP}(D^0))$ to extract effective lifetime

Combined Run 1 results:

$$A_\Gamma(K^+K^-) = (-0.14 \pm 0.37 \pm 0.10) \times 10^{-3}$$
$$A_\Gamma(\pi^+\pi^-) = (0.14 \pm 0.63 \pm 0.15) \times 10^{-3}$$