Measurement of γ in $B^0 \rightarrow DK^{*0}$ decays at the LHCb experiment

IOP HEPP & APP 2019

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CP violation in the Standard Model

- The CKM matrix gives amplitudes for transitions between *d*-type and *u*-type quarks:

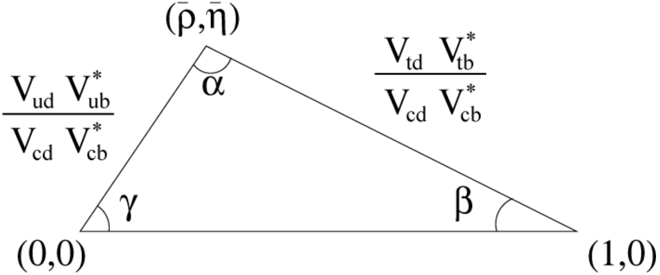
$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

- The matrix can be parametrised to have a single complex phase, which is the only source of *CP* violation in the Standard Model:

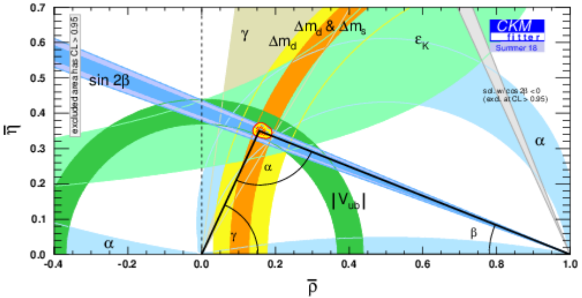
$$V_{\mathrm{CKM}} = \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}(\lambda^4)$$

The Unitarity Triangle

- According to the Standard Model CKM matrix is **unitary** since there are no flavour-changing couplings apart from $W^{\pm}$.
- We get constraints such as $V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$.
- This defines a **triangle** with angles of similar size:



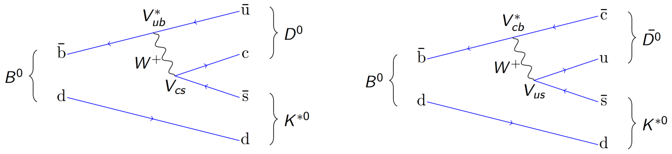
Direct and indirect measurements of γ



- We measure γ directly using **tree-level** decays (unlikely to be affected by new physics). The current LHCb average is $\gamma = (74.0^{+5.0}_{-5.8})^\circ$[LHCb-CONF-2018-002].
- Indirect measurements depend on **loop diagrams**, and give $\gamma = (65.64^{+0.97}_{-3.42})^\circ$[CKMFitter 2018]. Disagreement between the direct and indirect values would be evidence for new physics!

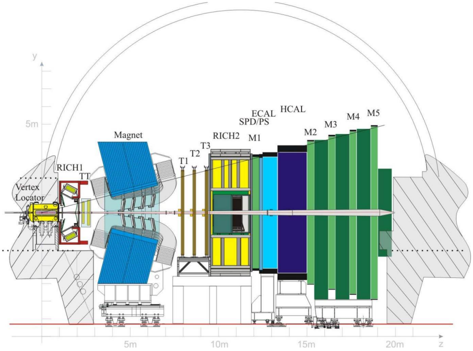
$B^0 \to DK^{*0}$ decays

- Most γ analyses use $B^- \to DK^-$ (one diagram colour-suppressed). Here we use $B^0 \to DK^{*0}$, where both diagrams are colour-suppressed:



(a) $b \to u$ (b) $b \to c$

- This means a smaller decay rate, but larger interference effects.
- Decay rate depends on:
  1. Weak-phase difference, γ;
  2. Amplitude ratio, r_B (~ 0.3, vs. ~ 0.1 for $B^- \to DK^-$);
  3. Strong-phase difference, δ_B;
  4. Coherence factor, κ, to account for non-K^{*0} contributions to $B^0 \to DK^+\pi^-$ ($= 0.958^{+0.005}_{-0.046}$ [PRD 93 (2016) 112018]).



- Use 5fb^{-1} of data collected at LHCb between 2011 and 2016.
- Reconstruct D mesons in 7 final states: K^+K^-, $\pi^+\pi^-$, $K^\pm\pi^\mp$ (previously measured in Run 1 [PRD 90 (2014) 112002]), $\pi^+\pi^-\pi^+\pi^-$ and $K^\pm\pi^\mp\pi^+\pi^-$ (first measurement).
- Measure *CP* observables and extract constraints on γ, r_B and δ_B.

The GLW modes

- We study the CP-even D final states $(K^+K^-, \pi^+\pi^-)$ using the GLW method. Measure the asymmetry:

$$\mathcal{A}_{CP}^{hh} \equiv \frac{\Gamma(\bar{B}^0 \to D(h^+h^-)\bar{K}^{*0}) - \Gamma(B^0 \to D(h^+h^-)K^{*0})}{\Gamma(\bar{B}^0 \to D(h^+h^-)\bar{K}^{*0}) + \Gamma(B^0 \to D(h^+h^-)K^{*0})}$$

- Also measure the ratio w.r.t. the Cabibbo favoured $(D \to K^-\pi^+)$ channel:

$$\mathcal{R}_{CP}^{hh} \equiv \frac{\Gamma(\bar{B}^0 \to D(h^+h^-)\bar{K}^{*0}) + \Gamma(B^0 \to D(h^+h^-)K^{*0})}{\Gamma(\bar{B}^0 \to D(K^-\pi^+)\bar{K}^{*0}) + \Gamma(B^0 \to D(K^+\pi^-)K^{*0})} \times \frac{BF(D^0 \to K^-\pi^+)}{BF(D^0 \to h^+h^-)}$$

- We can extend the method to the quasi-GLW mode $\pi^+\pi^-\pi^+\pi^-$, using the fractional CP-even content: $F_+^{4\pi} = 0.759 \pm 0.023$ [JHEP 01 (2018) 144].

The ADS modes

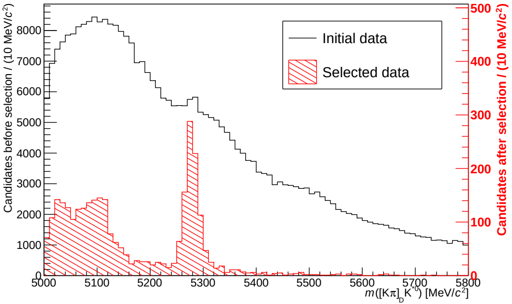
- There are two categories of $D \to K^{\pm}\pi^{\mp}$ decays:
  1. **Favoured**, when final-state kaons have the same charge ($K\pi$);
  2. **Suppressed**, when final-state kaons have the opposite charge (πK).
- We measure the ratios $\mathcal{R}^{\pm}$ (more experimentally robust than $\mathcal{A}_{ADS}$ and $\mathcal{R}_{ADS}$):

$$\mathcal{R}_{+}^{\pi K} = \frac{\Gamma(B^0 \to D(\pi^+K^-)K^{*0})}{\Gamma(B^0 \to D(K^+\pi^-)K^{*0})}$$

$$\mathcal{R}_{-}^{\pi K} = \frac{\Gamma(\bar{B}^0 \to D(\pi^-K^+)\bar{K}^{*0})}{\Gamma(\bar{B}^0 \to D(K^-\pi^+)\bar{K}^{*0})}$$

- This method is extended to the quasi-ADS modes, $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$, using an additional coherence factor $\kappa_D^{K3\pi} = 0.43^{+0.17}_{-0.13}$ [PLB 757 (2016) 520].

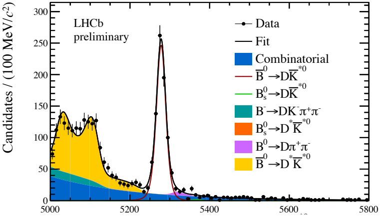
Data selection



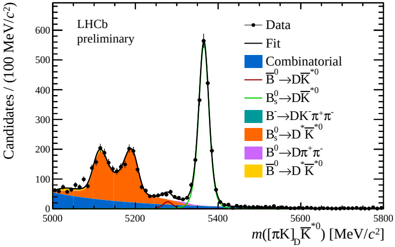
- Mass windows on D and K^{*0} mesons
- Boosted Decision Trees to reduce combinatorial background
- Particle ID information to separate D decay categories
- Vetos on specific physics backgrounds

Example (ADS mass fits):

Favoured ($K\pi$):



Suppressed (πK):

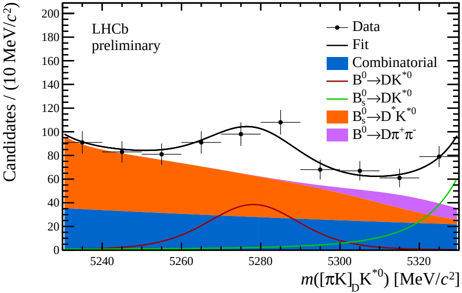


Fit components:

1. Signal $B^0 \to DK^{*0}$
2. $B_s^0 \to DK^{*0}$
3. Combinatorial background
4. $B^0 \to D^*K^{*0}$ (part reco)
5. $B_s^0 \to D^*K^{*0}$ (part reco)
6. $B^+ \to DK^+\pi^-\pi^+$ (part reco)
7. $B^0 \to D\pi^+\pi^-$ (mis-ID)

Preliminary results: $K^{\pm}\pi^{\mp}$ NEW!

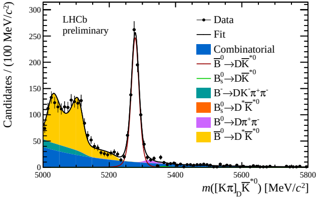
The suppressed mode (πK) is observed for the first time, to a significance of 5.8σ.

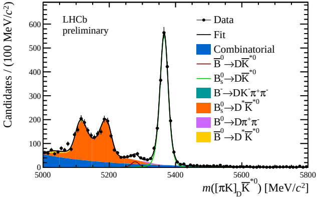


Signal region of the πK invariant mass fit

Preliminary results: $K^{\pm}\pi^{\mp}$ NEW!

$\bar{B}^0 \to D(K^{\mp}\pi^{\pm})\bar{K}^{*0}$



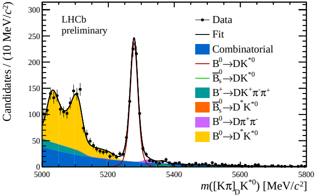


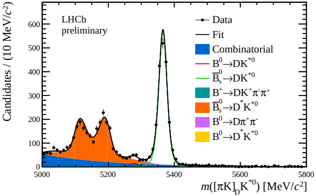
Favoured yield: 786 ± 24

Suppressed yield: 76 ± 12

$\mathcal{R}_{-}^{\pi K} = 0.095 \pm 0.021 \pm 0.002$

$B^0 \to D(K^{\pm}\pi^{\mp})K^{*0}$





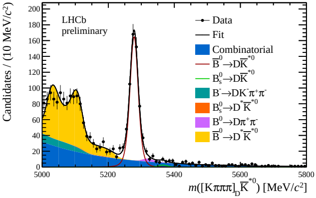
Favoured yield: 754 ± 24

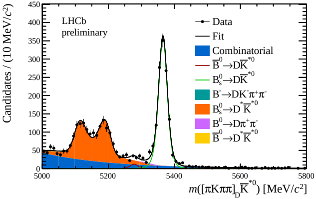
Suppressed yield: 47 ± 11

$\mathcal{R}_{+}^{\pi K} = 0.074 \pm 0.026 \pm 0.002$

Preliminary results: $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ NEW!

$\bar{B}^0 \to D(K^{\mp}\pi^{\pm}\pi^{+}\pi^{-})\bar{K}^{*0}$



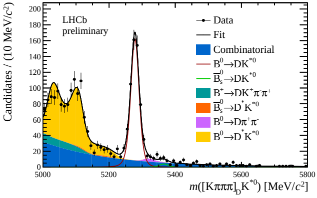


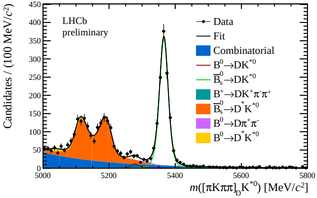
Favoured yield: 557 ± 21

Suppressed yield: 41 ± 10

$\mathcal{R}_{-}^{\pi K\pi\pi} = 0.072 \pm 0.025 \pm 0.003$

$B^0 \to D(K^{\pm}\pi^{\mp}\pi^{+}\pi^{-})K^{*0}$





Favoured yield: 548 ± 20

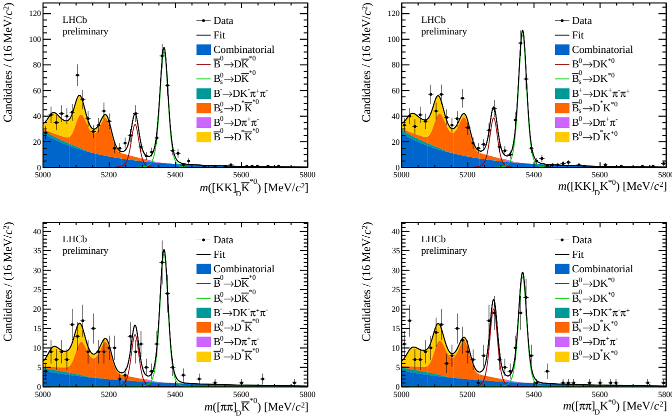
Suppressed yield: 40 ± 10

$\mathcal{R}_{+}^{\pi K\pi\pi} = 0.074 \pm 0.026 \pm 0.002$

Suppressed mode significance: 4.4σ.

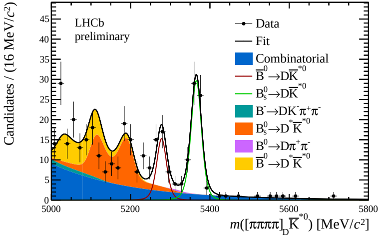
Preliminary results: K^+K^- and $\pi^+\pi^-$ NEW!

$\bar{B}^0 \to D(h^+h^-)\bar{K}^{*0}$ $\quad$ $B^0 \to D(h^+h^-)K^{*0}$



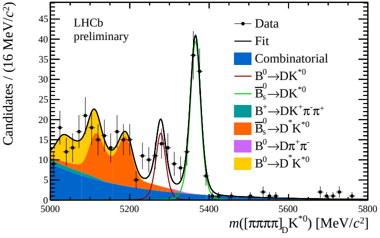
$$\mathcal{A}_{CP}^{KK} = -0.051 \pm 0.101 \pm 0.008$$
$$\mathcal{R}_{CP}^{KK} = 0.918 \pm 0.099 \pm 0.020$$
$$\mathcal{A}_{CP}^{\pi\pi} = -0.182 \pm 0.142 \pm 0.008$$
$$\mathcal{R}_{CP}^{\pi\pi} = 1.315 \pm 0.194 \pm 0.029$$

$\bar{B}^0 \to D(\pi^+\pi^-\pi^+\pi^-)\bar{K}^{*0}$



Signal yield: 32 ± 7

$B^0 \to D(\pi^+\pi^-\pi^+\pi^-)K^{*0}$



Signal yield: 35 ± 8

$$\mathcal{A}_{CP}^{4\pi} = -0.026 \pm 0.151 \pm 0.013$$

$$\mathcal{R}_{CP}^{4\pi} = 1.012 \pm 0.165 \pm 0.037$$

Signal significance 8.4σ (First observation!)

Summary of results NEW!

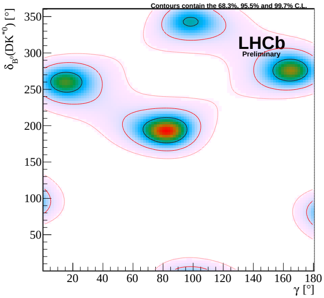
Summary of preliminary results:

$$
\begin{aligned}
\mathcal{A}_{CP}^{KK} &= -0.051 \pm 0.101 \pm 0.008 \\
\mathcal{A}_{CP}^{\pi\pi} &= -0.182 \pm 0.142 \pm 0.008 \\
\mathcal{R}_{CP}^{KK} &= 0.918 \pm 0.099 \pm 0.020 \\
\mathcal{R}_{CP}^{\pi\pi} &= 1.315 \pm 0.194 \pm 0.029 \\
\mathcal{A}_{CP}^{4\pi} &= -0.026 \pm 0.151 \pm 0.013 \\
\mathcal{R}_{CP}^{4\pi} &= 1.012 \pm 0.165 \pm 0.037 \\
\mathcal{R}_{+}^{\pi K} &= 0.064 \pm 0.021 \pm 0.002 \\
\mathcal{R}_{-}^{\pi K} &= 0.095 \pm 0.021 \pm 0.002 \\
\mathcal{R}_{+}^{\pi K\pi\pi} &= 0.074 \pm 0.026 \pm 0.002 \\
\mathcal{R}_{-}^{\pi K\pi\pi} &= 0.072 \pm 0.025 \pm 0.003
\end{aligned}
$$

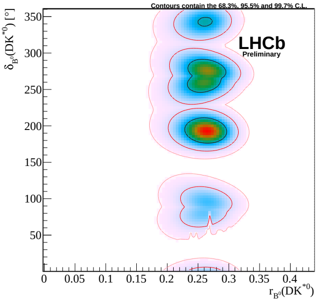
The dominant systematics are:

- GLW asymmetries ($\mathcal{A}_{CP}$): Production and detection asymmetry corrections.
- GLW ratios ($\mathcal{R}_{CP}$): Branching fraction normalisation, selection efficiency correction.
- ADS ratios ($\mathcal{R}^{\pm}$): Fixed parameters in invariant mass fit.

γ interpretation NEW!



δ_B vs. γ



δ_B vs. r_B

- Two solutions in $\gamma - \delta_B$ space are compatible with the current LHCb measurement, $\gamma = 74.0^{+5.0}_{-5.8}$. No strong γ constraint since we saw no significant CP violation.
- We measure $r_B = 0.265 \pm 0.023$, significantly improving upon the previous measurement (0.240 ± 0.052). This will have a strong impact on LHCb and world γ averages.

Conclusion

- Decays of $B^0 \to DK^{*0}$ with $D \to \pi^+\pi^-\pi^+\pi^-$ and the suppressed mode $D \to \pi K$ are observed to $> 5\sigma$ for the first time.
- CP observables are measured and interpreted in terms of γ, r_B and δ_B. The resulting constraints are found to be consistent with expectation.
- Further $B^0 \to DK^{*0}$ analyses with different D modes and utilising the full Run-2 data set will improve constraints and break degeneracies.
- Paper coming very soon! (LHCb-PAPER-2019-021)