Measurement of γ in $B^0 \to DK^{*0}$ decays

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Hannah Pullen

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University of Oxford

Introduction

1. **What is γ and why do we want to measure it?**
   - i The CKM matrix and unitarity triangle
   - ii Indirect and direct measurements
   - iii γ measurements at LHCb
2. **ADS/GLW analysis of $B^0 \to DK^{*0}$ decays**
   - i The ADS and GLW methods
   - ii Run 1 results
   - iii Updated analysis invariant mass fits

What is γ and why do we want to measure it?

The CKM matrix

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

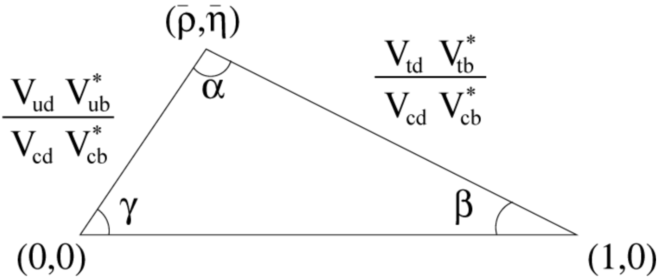
$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

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

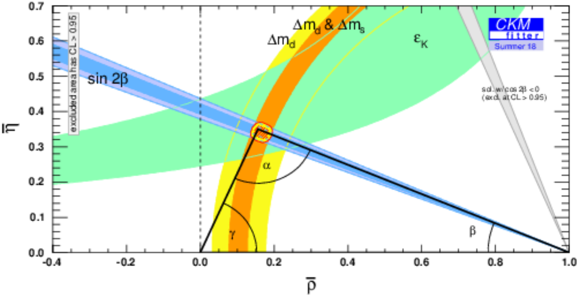
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

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:

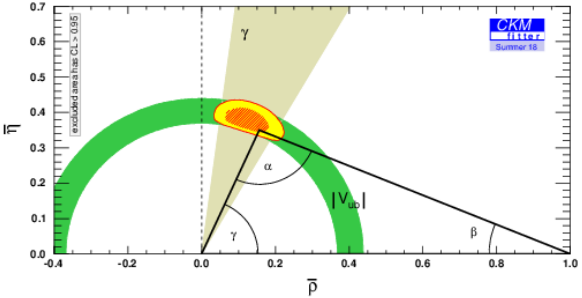


Measuring γ indirectly



- We can measure certain triangle parameters from $B^0 \to J/\psi K_s^0$ decays and $B^0_{(s)}$ mixing.
- This gives us an indirect measurement of $\gamma = (65.64^{+0.97}_{-3.42})^\circ$.
- However, these decays involve **box diagrams**, so are susceptible to effects from **new physics**.

Measuring γ directly



- We can also measure γ directly using **tree-level** decays only. This is unlikely to be affected by new physics.
- This direct measurement gives $\gamma = (72.1^{+5.4}_{-5.7})^\circ$ (v.s. $(65.64^{+0.97}_{-3.42})^\circ$ indirect).
- Disagreement between the direct and indirect measurements would be **evidence for new physics**!

$B \to DK$ decays

$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- This can be measured directly using $B \to DK$ decays, where D is a superposition of $D^0(c\bar{u})$ and $\bar{D}^0(\bar{c}u)$ mesons.
- These contain interference between $b \to u$ and $b \to c$ transitions.
- There are several categories of $B \to DK$ decay:
  1. **GLW**: $D \to h^+h^-$, $h = (\pi, K)$
  2. **ADS**: $D \to K^+\pi^-$
  3. **GGSZ**: $D \to K_s^0 h^+h^-$, $h = (\pi, K)$
  4. **GLS**: $D \to K_s^0 K^+\pi^-$

Direct γ measurements at LHCb

The current LHCb measurement is $\gamma = (74.0^{+5.0}_{-5.8})^\circ$. This comes from a variety of analyses of $B \to DK$ decays:

Run 1 only:	$B^+ \to DK^+$ ADS and GLS, $B^+ \to DK^+\pi^-\pi^+$, $B^0 \to DK^{*0}$ ADS/GLW[1], $B^0 \to DK^{*0}$ GGSZ, $B^0 \to DK^+\pi^-$ GLW-Dalitz, $B_s^0 \to D_s^\mp K^\pm$, $B^0 \to D^\pm\pi^\mp$.
Run 1 & 2:	$B^+ \to DK^+$ GLW and GGSZ, $B^+ \to D^*K^+$, $B^+ \to DK^{*+}$

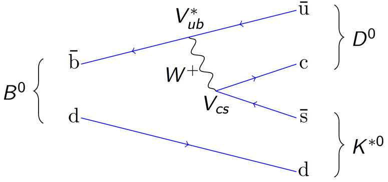
- $B^0 \to DK^{*0}$ ADS/GLW decays have been studied in Run 1 [Phys. Rev. D90 (2014) 112002, arXiv:1407.8136].
- I am updating this result to include 2015 + 2016 data.
- The full $DK\pi$ phase space can also be exploited, and has been studied in a Run 1 analysis [Phys. Rev. D93 (2016) 112018, arXiv:1602.03455].

[1] GLW result superseded by $B^0 \to DK\pi$ Dalitz analysis

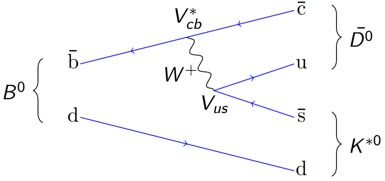
ADS/GLW analysis of $B^0 \to DK^{*0}$

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

- Use the interference between $b \to u$ and $b \to c$ transitions to measure γ. Amplitude ratio $r_B \simeq 0.22$.
- Both diagrams are **colour suppressed**. In $B^+ \to DK^+$, only one diagram is colour suppressed so r_B is smaller ($\simeq 0.10$)
- $B^0 \to DK^{*0}$ therefore has lower overall statistics, but higher sensitivity to CP violation.

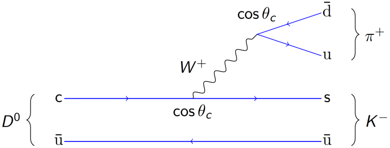


$\mathcal{A} \sim r_B e^{i(\gamma+\delta_B)}$



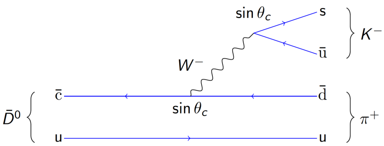
$\mathcal{A} \sim 1$

- For interference we require a final state common to both D^0 and $\bar{D}^0$.
- One such state is $K^{\pm}\pi^{\mp}$ (the "ADS" modes):



Cabibbo-favoured

$\mathcal{A} \sim 1$



Doubly Cabibbo-suppressed

$\mathcal{A} \sim r_D e^{-i\delta_D}$

ADS favoured and suppressed modes

We have $D \to K^{\pm}\pi^{\mp}$ and $K^{*0} \to K^{+}\pi^{-}$ (or $\bar{K}^{*0} \to K^{-}\pi^{+}$).
There are two possible final states:

1. D and K^{*0} daughters with the **same sign**.
   ($b \to c$ followed by favoured D decay) +
   ($b \to u$ followed by suppressed D decay).
   Higher statistics, low γ sensitivity.
2. D and K^{*0} daughters with the **opposite sign**.
   ($b \to c$ followed by suppressed D decay) +
   ($b \to u$ followed by favoured D decay).
   Lower statistics, high γ sensitivity.

ADS observables

1. Same-sign (**favoured**) mode:
   $A(B^0 \to D[K^+\pi^-]K^{*0}[K^+\pi^-]) \propto 1 + r_B r_D e^{i(\gamma+\delta_B-\delta_D)}$
2. Opposite-sign (**suppressed**) mode:
   $A(B^0 \to D[K^-\pi^+]K^{*0}[K^+\pi^-]) \propto r_B e^{i(\gamma+\delta_B)} + r_D e^{-i\delta_D}$

We can extract constraints on (γ, r_B, δ_B) by measuring the suppressed to favoured yield ratios:

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

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

These are related to the physics parameters via:

$$\mathcal{R}^\pm = \frac{r_B^2 + r_D^2 + 2\kappa r_B r_D \cos(\delta_B + \delta_D \pm \gamma)}{1 + r_B^2 r_D^2 + 2\kappa r_B r_D \cos(\delta_B - \delta_D \pm \gamma)}$$

The GLW method

We also look at the CP-even final states, $D \to h^+h^-$ $(h = K, \pi)$.

1. Measure the CP **asymmetry**:

$$\mathcal{A}_{CP+} = \frac{\Gamma(\bar{B}^0 \to D(hh)K^{*0}) - \Gamma(B^0 \to D(hh)K^{*0})}{\Gamma(\bar{B}^0 \to D(hh)K^{*0}) + \Gamma(B^0 \to D(hh)K^{*0})}$$
$$\simeq 2\kappa r_B \sin(\delta_B)\sin(\gamma)$$

2. Measure the **ratio** w.r.t. the favoured ADS mode:

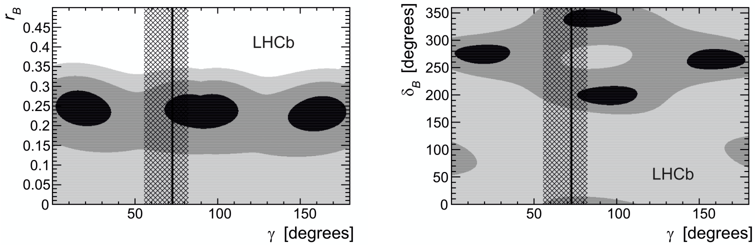
$$\mathcal{R}_{CP+} = \frac{\Gamma(\bar{B}^0 \to D(hh)K^{*0}) + \Gamma(B^0 \to D(hh)K^{*0})}{\Gamma(\bar{B}^0 \to D(K\pi)K^{*0}) + \Gamma(B^0 \to D(K\pi)K^{*0})} \times \frac{\mathcal{B}(D \to K\pi)}{\mathcal{B}(D \to hh)}$$
$$\simeq 1 + r_B^2 + 2\kappa r_B \cos(\delta_B)\cos(\gamma)$$

Results from Run 1

Measurements from 2011 + 2012 ($3\,\text{fb}^{-1}$):

$$\mathcal{R}^{+} = 0.06 \pm 0.03 \pm 0.01 \qquad \mathcal{R}^{-} = 0.06 \pm 0.03 \pm 0.01$$
$$\mathcal{A}^{KK} = -0.20 \pm 0.15 \pm 0.02 \qquad \mathcal{A}^{\pi\pi} = -0.09 \pm 0.22 \pm 0.02$$
$$\mathcal{R}^{KK} = 1.05^{+0.17}_{-0.15} \pm 0.04 \qquad \mathcal{R}^{\pi\pi} = 1.21^{+0.28}_{-0.25} \pm 0.05$$

This provides a measurement of $r_B = 0.240^{+0.055}_{-0.048}$ and constraints on γ and δ_B:



The suppressed ADS mode is observed at a significance of 2.9σ.

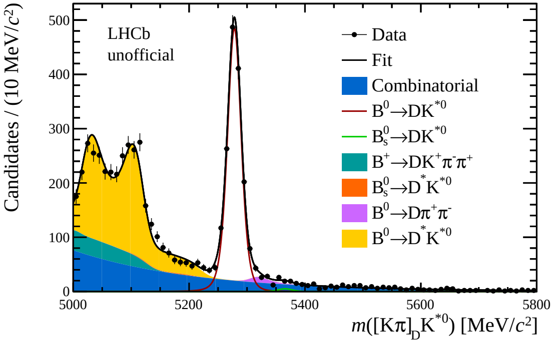
Run 1 + Run 2 update

- I am reanalysing the Run 1 data and adding **2015 + 2016**.
  - Updated selection, including a new Boosted Decision Tree with better discriminating variables.
  - Improved invariant mass fit.
- I also add the **four-body modes** $D \to K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$ and $D \to \pi^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$ for the first time.
- Analysis currently under review and will be published soon.

The favoured ADS mode

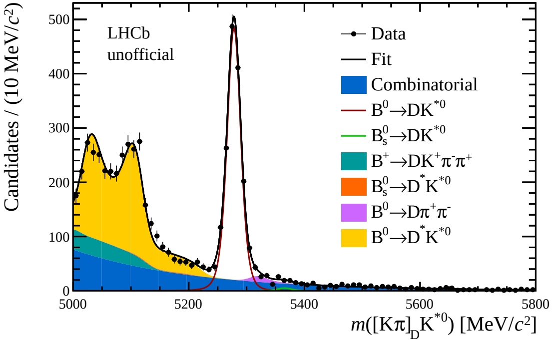
Run 1 + Run 2 data ($= 5\,\text{fb}^{-1}$). Mass fit components:

- **Signal**: $B^0 \to DK^{*0}$ and $B_s^0 \to DK^{*0}$.
- **Partially reconstructed**: $B^0 \to D^* K^{*0}$, $B_s^0 \to D^* K^{*0}$ and $B^+ \to DK^+\pi^-\pi^+$.
- **Other**: Misidentified $B^0 \to D\pi^+\pi^-$ and combinatorial background.



The favoured ADS mode

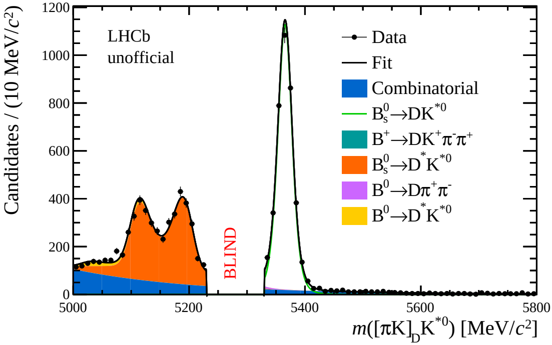
- **Run 1 only**: 774.9 signal events.
- **Run 1 + Run 2**: 1540.8 signal events.
- Higher statistics and higher purity in updated analysis.



The suppressed ADS mode

Run 1 + Run 2 data ($= 5\text{fb}^{-1}$). Mass fit components:

- **Signal**: $B^0 \to DK^{*0}$ (BLIND) and $B_s^0 \to DK^{*0}$.
- **Partially reconstructed**: $B^0 \to D^* K^{*0}$, $B_s^0 \to D^* K^{*0}$ and $B^+ \to DK^+\pi^-\pi^+$.
- **Other**: Misidentified $B^0 \to D\pi^+\pi^-$ and combinatorial background.

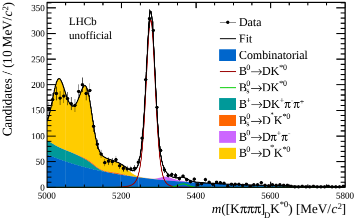


Four-body ADS modes

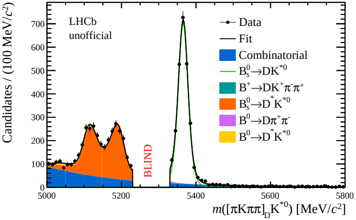
We can extend the ADS method to four-body final states, $D \to K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$. Same observables $\mathcal{R}^{\pm}$, with a few changes:

$$\mathcal{R}^{\pm} = \frac{r_B^2 + \left(r_D^{K3\pi}\right)^2 + 2\kappa r_B r_D^{K3\pi}\kappa_{K3\pi}\cos(\delta_B + \delta_D^{K3\pi} \pm \gamma)}{1 + r_B^2\left(r_D^{K3\pi}\right)^2 + 2\kappa r_B r_D^{K3\pi}\kappa_{K3\pi}\cos(\delta_B - \delta_D^{K3\pi} \pm \gamma)}$$

My analysis measures these observables for the first time at LHCb.



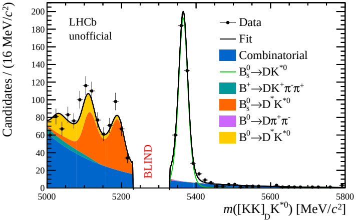
Favoured (1101.8 events)



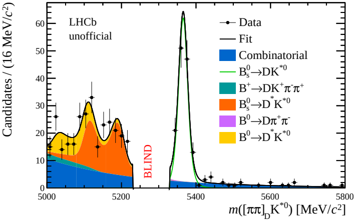
Suppressed

The KK and $\pi\pi$ modes

Use $D \to h^+h^-$ decays to measure $\mathcal{A}_{CP+}$ and $\mathcal{R}_{CP+}$.



$D \to K^+K^-$



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

More to come

This 2011 - 2016 analysis of $B^0 \to DK^{*0}$ will be published very soon!
Many other developments using Run 1 + Run 2 data are still to come:

- Full 2017 + 2018 update of ADS/GLW $B^0 \to DK^{*0}$ analysis;
- GGSZ $B^0 \to DK^{*0}$ analysis;
- Many more full Run 2 analyses of other $B \to DK$ decays.

We hope to bring the uncertainty on γ down to around 3° - 4° with Run 2 data, and to an even better precision with Run 3 onwards.