Measurements of the CKM angle $\gamma$ at LHCb

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What is $\gamma$?

- Least well measured CKM angle
- No top quark coupling in its definition, $\gamma = \arg \left[ -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right]$
- New physics expected to enter in loops
  - Measure $\gamma$ at tree and loop level and compare them!
  - Theoretically clean

Direct: $\gamma = (72.1^{+5.4}_{-5.8})^\circ$

Indirect: $\gamma = (65.3^{+1.0}_{-2.5})^\circ$

$B^{\pm} \rightarrow D^0 K^{\pm}$ ADS/GLW

- Well established tree-level modes for $\gamma$ measurement
  - **GLW**: Interference between $B^- \rightarrow DK^-$ and $B^- \rightarrow \bar{D}K^-$, with $CP$ eigenstate decay e.g. $D \rightarrow KK, \pi\pi$ ($D = D^0/\bar{D}^0$)
  - **ADS**: Additional $\gamma$ sensitivity with non-$CP$ eigenstate $D$ decay e.g. $D \rightarrow K\pi$

**GLW**: $B^{\pm} \rightarrow [\pi^\pm \pi^\mp]_D h^{\pm}$

**ADS**: $B^{\pm} \rightarrow [\pi^\pm K^\mp]_D h^{\pm}$

During 2015 and 2016 (Run 2), an additional 2 fb$^{-1}$ was taken at $\sqrt{s} = 13$ TeV

- Dataset roughly doubled
- GLW modes ($KK, \pi\pi$) measured again in Run 1 + Run 2 data

\begin{align*}
B^{\pm} \to D^{0}h^{\pm} \text{ 2-body GLW update (preliminary)}

A_{KK}^{K\pi} &= -0.019 \pm 0.005 \text{ (stat.)} \pm 0.002 \text{ (syst.)} \\
A_{K\pi}^{KK} &= -0.008 \pm 0.003 \text{ (stat.)} \pm 0.002 \text{ (syst.)} \\
A_{KK}^{K\pi} &= +0.126 \pm 0.014 \text{ (stat.)} \pm 0.001 \text{ (syst.)} \\
A_{K\pi}^{\pi\pi} &= -0.008 \pm 0.006 \text{ (stat.)} \pm 0.002 \text{ (syst.)} \\
A_{K\pi}^{\pi\pi} &= +0.115 \pm 0.025 \text{ (stat.)} \pm 0.008 \text{ (syst.)} \\
R_{KK}^{KK} &= 0.988 \pm 0.015 \text{ (stat.)} \pm 0.013 \text{ (syst.)} \\
R_{\pi\pi}^{\pi\pi} &= 0.992 \pm 0.027 \text{ (stat.)} \pm 0.032 \text{ (syst.)}
\end{align*}

Tension between $A_{KK}^{K\pi}$ and $A_{K\pi}^{\pi\pi}$ in Run 1 analysis has eased - $A_{KK}^{K\pi}$ in Run 1 and Run 2 compatible at 2.6$\sigma$
What else can we do?

- Alternative approach to $B^\pm \rightarrow D^0 K^\pm$ - add a star! ⋆
- $B^\pm \rightarrow D^0 (K^{*\pm} \rightarrow K_s^0 \pi^\pm)$ with $D^0 \rightarrow \phi\phi$ ADS/GLW
- Analysis close to finalisation: 4 fb$^{-1}$ shown at CKM

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[LHCb-CONF-2016-014] 4
\[ B^\pm \rightarrow D^{*0} K^\pm \] with \[ D^{*0} \rightarrow D^0 \pi^0 / D^0 \gamma \]

- Theoretically similar to \( B^\pm \rightarrow D^0 h^\pm \), with an interesting extra feature
  - \( \pi^0 \) and \( \gamma \) variants of the decay have an exact strong phase difference of \( \pi \) [Phys. Rev. D 70, 091503(R)]

- Measure both \( B^\pm \rightarrow D^{*0} (\rightarrow D^0 \pi^0) K^\pm \) and \( B^\pm \rightarrow D^{*0} (\rightarrow D^0 \gamma) K^\pm \) decays to determine \( r_{D^{*0}K}^B, \delta_{D^{*0}K}^B, \gamma \)

- **Experimental challenge:** \( \pi^0 / \gamma \) reconstruction is difficult and has limited efficiency at LHCb [Int. J. Mod. Phys. A 30, 1530022 (2015)]
Partially reconstructed $B^\pm \rightarrow D^{*0}h^\pm$ [LHCb-PAPER-2017-021]

- **Solution:** completely ignore the $\pi^0$ and $\gamma$ from the $D^{*0}$!
  - No penalty from $\pi^0/\gamma$ reconstruction efficiency
  - Select signal candidates identically to $B^\pm \rightarrow D^0h^\pm$

- Fit variable is $m(D^0h) \Rightarrow$ uniquely related to angular properties of $D^{*0}$ decay daughters
  - Different mass and spin of $\pi^0$ and $\gamma$ lets you tell their $m(D^0h)$ distributions apart - **central idea of the analysis**

![Analytical PDF fits](image)

Analytical PDF fits to $B^\pm \rightarrow D^{*0}(\rightarrow D^0\pi^0)K^\pm$ (left) and $B^\pm \rightarrow D^{*0}(\rightarrow D^0\gamma)K^\pm$ (right) simulated decays
Sources of background [LHCb-PAPER-2017-021]

- $B^0 \rightarrow D^*^- (\rightarrow D^0 \pi^-) h^+$
- $B^\pm \rightarrow D^0 h^\pm \pi^0$
- $B^0_s \rightarrow D^0 K \pi$
- $B \rightarrow D^* h^\pm X \quad X = \pi^0, \pi^\pm, \gamma$
$B^\pm \rightarrow D^{(*)0} h^\pm$ with $D^0 \rightarrow K\pi$ [LHCb-PAPER-2017-021]

NEW

\begin{align*}
B^\pm \rightarrow (D^{*0} \rightarrow D^{0}\pi^0) h^\pm & \quad \text{LHCb preliminary} \\
B^0 \rightarrow (D^{*\mp} \rightarrow D^{0}\pi^\mp) h^\pm & \quad \text{LHCb preliminary} \\
B^\pm \rightarrow (D^{*0} \rightarrow D^{0}\gamma) h^\pm & \quad \text{LHCb preliminary} \\
B^\pm \rightarrow D^0 h^\pm \pi^0 & \quad \text{Part. reco. mis-ID}
\end{align*}
$B^\pm \to D^{(*)0} h^\pm$ with $D^0 \to KK$ [LHCb-PAPER-2017-021] NEW

LHCb preliminary

$B^\pm \to [K^+K^-]_p K^\pm$

$B^\pm \to [K^+K^-]_p \pi^\pm$

$B^\pm \to D^0 h^\pm \pi^0$

$B \to D^* h^\pm \pi$

$B \to D^0 h^\pm \pi$

$B^\pm \to D^0 h^\pm \pi^0$

$B^\pm \to D^0 \pi^\pm$

$B^\pm \to DK^\pm$

Part. reco. mis-ID

Combinatorial
\[ B^\pm \rightarrow D^{(*)0} h^\pm \quad \text{with} \quad D^0 \rightarrow \pi \pi \]
• $B^\pm \rightarrow D^{*0} h^\pm$ modes measured for the first time at LHCb with a brand new technique!
  • Currently GLW modes are included - ADS under investigation
  • Fully reconstructed $B^\pm \rightarrow D^0 h^\pm$ results (Slide 3) are measured with the same fit

<table>
<thead>
<tr>
<th>$B^\pm \rightarrow D^{*0} K^\pm$ results (preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_K^{K\pi,\gamma} = +0.001 \pm 0.022$ (stat.) $\pm 0.007$ (syst.)</td>
</tr>
<tr>
<td>$A_K^{K\pi,\pi^0} = +0.006 \pm 0.012$ (stat.) $\pm 0.004$ (syst.)</td>
</tr>
<tr>
<td>$A_K^{CP,\gamma} = +0.273 \pm 0.093$ (stat.) $\pm 0.040$ (syst.)</td>
</tr>
<tr>
<td>$A_K^{CP,\pi^0} = -0.151 \pm 0.033$ (stat.) $\pm 0.013$ (syst.)</td>
</tr>
<tr>
<td>$R^{CP,\gamma} = 0.909 \pm 0.087$ (stat.) $\pm 0.099$ (syst.)</td>
</tr>
<tr>
<td>$R^{CP,\pi^0} = 1.138 \pm 0.029$ (stat.) $\pm 0.082$ (syst.)</td>
</tr>
</tbody>
</table>
Measuring $r_B^{D*K}$, $\delta_B^{D*K}$, $\gamma$ [LHCb-PAPER-2017-021]

- 6 partially reconstructed GLW $CP$ observables used to constrain the fundamentals
  - Determine profile likelihood contours for $r_B^{D*K}$, $\delta_B^{D*K}$ and $\gamma$
  - Measurements included in new LHCb $\gamma$ combination (along with $B^\pm \rightarrow D^0 K^\pm$ GLW)

- $r_B^{D*K}$ and $\delta_B^{D*K}$ align with HFLAV GGSZ averages [arXiv:1612.07233]
- $\gamma$ within 1$\sigma$ of current LHCb combination [JHEP 12 (2016) 087]
  - Hope to further improve precision with addition of ADS modes
Latest LHCb $\gamma$ combination [LHCb-CONF-2017-004]

NEW

- Includes the following updates since last combination:
  - $B^\pm \rightarrow D^0 K^{*\pm}$ ADS/GLW [LHCb-CONF-2016-014] NEW
  - $B^\pm \rightarrow D^{*0} K^{*\pm}$ GLW [LHCb-PAPER-2017-021] NEW
  - $B_s^0 \rightarrow D_s^{\mp} K^{\pm}$ TD [LHCb-CONF-2016-015] 1 fb$^{-1}$ → 3 fb$^{-1}$
  - $B^\pm \rightarrow D^0 K^{\pm}$ GLW [LHCb-PAPER-2017-021] 3 fb$^{-1}$ → 5 fb$^{-1}$

$$\gamma = (76.8^{+5.1}_{-5.7})^\circ \text{ (preliminary)}$$
Summary

- LHCb continues to drive forward $\gamma$ precision through studying tree-level $B^{\pm}$ decays
- In addition to $B^{\pm} \rightarrow D^0 K^{\pm}$, great progress has been made on $B^{\pm} \rightarrow D^0 K^{*\pm}$ and $B^{\pm} \rightarrow D^{*0} K^{\pm}$
  - These brand new modes at LHCb contribute important information in the latest $\gamma$ combination
- Addition of more Run 2 data (2017 & 2018) promises further excitement ahead - stay tuned!
Backup
Run 1 LHCb $\gamma$ combination [JHEP 12 (2016) 087]

- Single most precise $\gamma$ measurement from a single experiment
  - $\gamma = (72.2^{+6.8}_{-7.3})^\circ$
- Includes Run 1 $B^\pm \to D^0 K^\pm$ ADS/GLW and GGSZ
- Now being updated with $B^\pm \to D^0 K^*\pm$ ADS/GLW, $B^\pm \to D^{(*)0} K^\pm$ GLW and $B^0_s \to D_s^{\mp} K^\pm$
Time-dependent $B^0_s \to D^\mp_s K^{\pm}$ [LHCb-CONF-2016-015]

\[
\gamma = (127^{+17}_{-22})^\circ
\]
\[
\delta_{D_s K} = (358^{+15}_{-16})^\circ
\]
\[
r_{D_s K} = 0.37^{+0.10}_{-0.09}
\]

- **Input:** $\phi_s = -0.010 \pm 0.039$ rad [Phys. Rev. Lett. 114, 041801 (2015)]
- **3.6\sigma** evidence of $CP$ violation in $B^0_s \to D^\mp_s K^{\pm}$
- **2.2\sigma** compatibility with LHCb time-integrated $\gamma$ combination
GGSZ modes

- LHCb has a suite of completed 3 fb$^{-1}$ GGSZ analyses:
  - $B^\pm \rightarrow D^0 K^\pm$ with $D^0 \rightarrow K^0_s \pi^+\pi^-$, $K^0_s K^+K^-$ [JHEP 10 (2014) 097]
  - MD $B^0 \rightarrow D^0 K^*0$ with $D^0 \rightarrow K^0_s \pi^+\pi^-$ [JHEP 08 (2016) 137]
  - MI $B^0 \rightarrow D^0 K^*0$ with $D^0 \rightarrow K^0_s \pi^+\pi^-$, $K^0_s K^+K^-$ [JHEP 06 (2016) 131]

- $B^\pm \rightarrow D^0 K^\pm$ update is active using Run 1 + Run 2 data

$\text{MD } B^0 \rightarrow D^0 K^*0$ with $D^0 \rightarrow K^0_s \pi^+\pi^-$ [JHEP 08 (2016) 137]
Summer 2017 HFLAV averages - $B^\pm \rightarrow D_{CP}K^\pm$

### $D_{CP} K A_{CP^+}$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>0.25 ± 0.06 ± 0.02</td>
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<tr>
<td>Belle</td>
<td>0.06 ± 0.14 ± 0.05</td>
</tr>
<tr>
<td>CDF</td>
<td>0.39 ± 0.17 ± 0.04</td>
</tr>
<tr>
<td>LHCb KK</td>
<td>0.13 ± 0.01 ± 0.00</td>
</tr>
<tr>
<td>LHCb $\pi\pi$</td>
<td>0.12 ± 0.03 ± 0.01</td>
</tr>
<tr>
<td>Average</td>
<td>0.13 ± 0.01</td>
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</tbody>
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### $D_{CP} K R_{CP^+}$

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<tr>
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<tbody>
<tr>
<td>BaBar</td>
<td>1.18 ± 0.09 ± 0.05</td>
</tr>
<tr>
<td>Belle</td>
<td>1.13 ± 0.16 ± 0.08</td>
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<tr>
<td>CDF</td>
<td>1.30 ± 0.24 ± 0.12</td>
</tr>
<tr>
<td>LHCb KK</td>
<td>0.99 ± 0.01 ± 0.01</td>
</tr>
<tr>
<td>LHCb $\pi\pi$</td>
<td>0.99 ± 0.03 ± 0.03</td>
</tr>
<tr>
<td>Average</td>
<td>1.00 ± 0.02</td>
</tr>
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</table>
Summer 2017 HFLAV averages - $B^\pm \to D^*_CP K^\pm$

### $D^*_CP K A_{CP+}$

<table>
<thead>
<tr>
<th>Experiment</th>
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<th>Error</th>
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<tbody>
<tr>
<td>BaBar</td>
<td>-0.11 ± 0.09 ± 0.01</td>
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</tr>
<tr>
<td>Belle</td>
<td>-0.20 ± 0.22 ± 0.04</td>
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<tr>
<td>LHCb</td>
<td>-0.15 ± 0.03 ± 0.01</td>
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<tr>
<td>Average</td>
<td>-0.14 ± 0.03</td>
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### $D^*_CP K A_{CP-}$

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<tbody>
<tr>
<td>BaBar</td>
<td>0.06 ± 0.10 ± 0.02</td>
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<tr>
<td>Belle</td>
<td>0.13 ± 0.30 ± 0.08</td>
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<tr>
<td>LHCb</td>
<td>0.27 ± 0.09 ± 0.04</td>
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<tr>
<td>Average</td>
<td>0.15 ± 0.07</td>
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### $D^*_CP K R_{CP+}$

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<tbody>
<tr>
<td>BaBar</td>
<td>1.31 ± 0.13 ± 0.03</td>
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<tr>
<td>Belle</td>
<td>1.41 ± 0.25 ± 0.06</td>
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<tr>
<td>LHCb</td>
<td>1.14 ± 0.03 ± 0.08</td>
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<tr>
<td>Average</td>
<td>1.21 ± 0.07</td>
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### $D^*_CP K R_{CP-}$

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<td>BaBar</td>
<td>1.09 ± 0.12 ± 0.04</td>
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<tr>
<td>Belle</td>
<td>1.15 ± 0.31 ± 0.12</td>
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<tr>
<td>LHCb</td>
<td>0.91 ± 0.09 ± 0.10</td>
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<tr>
<td>Average</td>
<td>1.04 ± 0.09</td>
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