Precision measurements of the Cabibbo-Kobayashi-Maskawa angle $\gamma$ at LHCb

Donal Hill on behalf of the LHCb collaboration
CERN seminar
10 October 2017
• It’s that time of year again - many congratulations to all of those involved on LIGO and VIRGO

• Spare a thought for the C in CKM, who didn’t win the Nobel prize in 2008 along with K & M

• Today’s talk is dedicated to Cabibbo, and to everyone else who hasn’t won a Nobel prize!

“I’ve already got the prize. The prize is the pleasure of finding the thing out…” - R. P. Feynman
The CKM matrix and the weak force

\[ V_{\text{CKM}} = \begin{bmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{bmatrix} \]

- Connects \( u \)- and \( d \)- type quarks via the weak force
- Each element related to a transition probability, \(|V_{ij}|^2\)
- \( 3 \times 3 \) unitary matrix is parameterised by three rotation angles and one complex phase
  - Phase changes sign under the \( CP \) operator
  - In SM, this phase is the single source of quark sector \( CP \) violation
The Unitarity Triangle

- **Unitary matrix:** $\sum_j |V_{ij}|^2 = \sum_i |V_{ij}|^2 = 1$

- Any dot product of two columns is zero

- Take first and third columns:
  - $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
  - Equation of a triangle in the complex plane!

- **The Unitarity Triangle - 3 angles of similar size**
The Unitarity Triangle is built assuming unitarity i.e. no other flavour changing couplings apart from $W^\pm$

- New Physics could violate unitarity

Need to over-constrain all sides and angles with independent measurements

- See if the various constraints agree
- Is unitarity valid?
Is The Unitarity Triangle actually a triangle?

\[ \alpha = \arg \left[ -\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right] \quad \beta = \arg \left[ -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right] \quad \gamma = \arg \left[ -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right] \]

- Global CKM fits performed using information from many measurements
  - Measuring \( \beta \) and \( \gamma \) is an important part of this process
  - Let’s explore \( \beta \) first as an example

![Image of the Unitarity Triangle with additional annotations]
CKM angle $\beta$

$$\beta = \arg \left[ -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right]$$

- Contains couplings to the top quark
  - Interested in looking at $V_{tb}$ compared to $V_{td}$
  - How can we access this?

- Via a handy box diagram!
  - This diagram is responsible for $B^0/\bar{B}^0$ oscillations
  - Can measure $\beta$, knowing $K^0$ CP violation
CKM angle $\beta$

- If $V_{td} \neq V_{td}^*$:
  - $\Gamma(B^0 \rightarrow f_{CP}) \neq \Gamma(\bar{B}^0 \rightarrow f_{CP})$
  - Example: $f_{CP} = J/\psi K^0_s$
  - Shows up as $CP$ violation in mixing

- Well studied by the $B$ factories and LHCb - time dependent $CP$ violation
  - Amplitude of oscillation is $\sin(2\beta)$ (diluted by tagging)

What about $\gamma$?

$$\gamma = \arg \left[ -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right]$$

- No top quark in the definition of $\gamma$
  - This time, we don’t need a box diagram
  - Can measure purely with tree level decays

- Look for direct $CP$ violation by comparing $V_{ub}$ and $V_{cb}$
  - How do we do that?
Measuring $\gamma$ with $B^- \rightarrow DK^-$ decays

- Ideal laboratory is $B^- \rightarrow DK^-$
  - $D = D^0$ or $\bar{D}^0$ decaying to the same final state

- There are two competing diagrams
  - Each of them has an amplitude $A$

- One diagram is suppressed by a factor $r_B$

- The diagrams have a relative phase $\theta$

\[ A \sim 1 \]

\[ A \sim r_B e^{i\theta} \]
Measuring $\gamma$ with $B^- \rightarrow DK^-$ decays

- $\theta$ contains two parts
  - $\delta_B$ which covers QCD - strong phase
  - Other part is the weak phase - let’s suggestively call it $\gamma$

- Weak phase $\gamma$ in $B^- \rightarrow DK^-$ decays is the same as the CKM angle $\gamma$ within $10^{-4}$

- $B^- \rightarrow DK^-$ decays are a theoretically super-clean probe of $\gamma$
  - Non-tree SM diagrams contribute $\leq O(10^{-7})$

From amplitudes to decay rates - the GLW method

• Two possible $B^- \to DK^-$ paths: add ’em up then square!

$$\Gamma \propto |1 + r_B e^{i\theta}|^2 = 1 + r_B^2 + 2r_B \cos (\theta)$$

• $\gamma$ is the $CP$ violating phase $\Rightarrow$ changes sign under charge conjugation

• Different decay rates for $B^+$ and $B^-$

• This is the GLW method

$$\Gamma(B^- \to DK^-) \propto 1 + r_B^2 + 2r_B \cos (\delta_B - \gamma)$$

$$\Gamma(B^+ \to DK^+) \propto 1 + r_B^2 + 2r_B \cos (\delta_B + \gamma)$$
The ADS method

- **ADS method**: choose a $D$ decay with amplitude ratio ($r_D$) and phase ($\delta_D$)
  - Pick one where $r_D \sim r_B$
  - For $B^- \to DK^-$, $r_B \sim 0.1$
  - Nice choice is $D \to K\pi$, $r_D \sim 0.06$

- **Bigger interference effect $\Rightarrow$ larger $B^+/B^-$ differences**

  \[
  \Gamma(B^- \to DK^-) \propto r_D^2 + r_B^2 + 2 r_D r_B \cos(\delta_B + \delta_D - \gamma)
  \]

  \[
  \Gamma(B^+ \to DK^+) \propto r_D^2 + r_B^2 + 2 r_D r_B \cos(\delta_B + \delta_D + \gamma)
  \]
The ADS method

- Measure rates of $B^+$ and $B^-$ decays separately and build asymmetries

$$A = \frac{\Gamma(B^- \rightarrow [\pi^- K^+]_D K^-) - \Gamma(B^+ \rightarrow [\pi^+ K^-]_D K^+)}{\Gamma(B^- \rightarrow [\pi^- K^+]_D K^-) + \Gamma(B^+ \rightarrow [\pi^+ K^-]_D K^+)}$$

- Also interested in rate of suppressed decays compared to their doubly-favoured counterparts, $B^\pm \rightarrow [K^\pm \pi^\mp]_D K^\pm$

$$R = \frac{\Gamma(B^- \rightarrow [\pi^- K^+]_D K^-) + \Gamma(B^+ \rightarrow [\pi^+ K^-]_D K^+)}{\Gamma(B^- \rightarrow [\pi^+ K^-]_D K^-) + \Gamma(B^+ \rightarrow [\pi^- K^+]_D K^+)}$$

- Both $A$ and $R$ contain information about $\gamma$
\[ B^\pm \rightarrow [\pi^\pm K^\mp]_D K^\pm \]  

(Run 1: 3 fb \(^{-1}\)) [LHCb-PAPER-2016-003]

- \( B^\pm \rightarrow DK^\pm \) CP violation significance \(- 8\sigma\)
- First observation of CP violation in a single \( B^\pm \rightarrow Dh^\pm \) decay \((h = \pi, K)\)
Constraining $\gamma$ across many final states

• No single method can tell us everything e.g. ADS doesn’t give a single $\gamma$ solution

• Real power comes from **combining lots of $D$ modes**

• LHCb made great strides with $B^\pm \to D K^\pm$ on several fronts in Run 1:
  - GLW: $D \to KK, \pi\pi, \pi\pi\pi\pi, KK\pi^0, \pi\pi\pi^0$
  - ADS: $D \to \pi K, \pi K\pi\pi, \pi K\pi^0$
  - GGSZ: $D \to K_s^0\pi\pi, K_s^0 K K$
  - GLS: $D \to K_s^0 K \pi$

• **Is there anything else out there?**
More data! The Run 2 era is well underway

- LHCb collected 2 fb$^{-1}$ in 2015-2016
  - Just crossed 1 fb$^{-1}$ in 2017
  - Luminosity levelling to achieve desired performance

- Increased statistics not just coming from extra fb$^{-1}$:
  - Improved software HLT performance
  - Increased $B$ production cross-section at $\sqrt{s} = 13$ TeV
New modes! $B^{\pm} \rightarrow DK^{*\pm}$ (5 fb$^{-1}$) [LHCb-PAPER-2017-030]

- Add a star to the $K$ - select $K^{*\pm} \rightarrow K_s^0 \pi^\pm$
- Challenging final state
  - Two extra tracks compared to $B^{\pm} \rightarrow DK^\pm, D \rightarrow hh$
  - $K_s^0 \rightarrow \pi\pi$: efficiency $\sim 10\%$
  - Select within $K^*(892)$ window

- **Interesting feature** - no background from misidentified $D\pi$-type decays
  - Measure only $B^{\pm} \rightarrow DK^{*\pm}$ across various 2- and 4-body $D$ final states
  - Follow the same formalism as $B^{\pm} \rightarrow DK^\pm$ - rates and asymmetries
$B^\pm \to DK^{\ast\pm}$  (5 fb$^{-1}$) [LHCb-PAPER-2017-030]
\[ B^\pm \rightarrow DK^{\ast \pm} (5 \text{ fb}^{-1}) \]

- 12 CP observables used to determine the fundamental parameters \( r_B^{DK^{\ast}} \), \( \delta_B^{DK^{\ast}} \), \( \gamma \)
- This mode will become valuable for constraining \( \gamma \) in future, as more data and \( D \) modes are added
$B^{\pm} \rightarrow D^{*0} K^{\pm}$ with $D \rightarrow KK, \pi\pi$ (GLW)

- Theoretically similar to $B^{\pm} \rightarrow DK^{\pm}$, with interesting extra features
  - Two $\gamma$-sensitive sub-decays: $D^{*0} \rightarrow D\pi^0$ and $D^{*0} \rightarrow D\gamma$
  - $\pi^0$ and $\gamma$ variants have $180^\circ$ $\delta_D$ difference - opposite $CP$
    - [Phys. Rev. D 70, 091503(R)]
  - Gives us access to a $CP$-odd mode at LHCb

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

- Same formalism as $B^{\pm} \rightarrow DK^{\pm}$ - measure rates and asymmetries
Experimental challenge

- Soft neutral reconstruction is difficult at LHCb, and has limited efficiency \([\text{LHCb-DP-2014-002}]\)
  - \(\epsilon(\pi^0) \sim 4\%\)
  - \(\epsilon(\gamma) \sim 20\%\)

- Expect lower statistics than in \(B^\pm \to DK^\pm\) case
  - Is there anything we can do to get around this limitation?
Partial reconstruction approach

- Don’t consider the soft neutral at all!
  - Partially reconstruct and select identically to $B^\pm \rightarrow DK^\pm$
  - No statistics loss due to $\epsilon(\pi^0)$ or $\epsilon(\gamma)$

- BDT trained on combinatorial background in data and $B^\pm \rightarrow DK^\pm$ signal MC
  - Efficiencies very similar for $B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D^*0K^\pm$

- All signal modes end up in the same event sample
  - Differentiate between them based on their $m(DK)$

![Background rejection versus Signal efficiency](chart1)

![TMVA overtraining check for classifier: BDTG](chart2)
The $m(DK)$ distribution

- Fit variable is $m(DK) \Rightarrow$ uniquely related to angular properties of $D^{*0}$ decay daughters
  - Different mass and spin of $\pi^0$ and $\gamma$ - different $m(DK)$
  - Parabolic distributions:
    - double peak for $B^\pm \rightarrow (D^{*0} \rightarrow D\pi^0)K^\pm$
    - single wide peak for $B^\pm \rightarrow (D^{*0} \rightarrow D\gamma)K^\pm$

![Graphs showing $\pi^0$ and $\gamma$ distributions](image)
Detector resolution effects

- Detector isn’t perfect - convolve parabolas with a double Gaussian resolution function
  - Modelled on the $B^\pm \to DK^\pm$ peak resolution

- Distinctive distributions for $D^{*0} \to D\pi^0$ and $D^{*0} \to D\gamma$
  - Both sit lower in mass than the $B^\pm \to DK^\pm$ peak (red region)
  - In previous 3 fb$^{-1}$ $B^\pm \to DK^\pm$ analysis, these decays were background $> 5000$ MeV/$c^2$
Fits to $B^\pm \rightarrow D^{*0} K^\pm$ simulation

- Custom RooFit PDFs authored to model the distributions
  - Parabolic function convolved with a double Gaussian
  - Shape parameters determined from fits to selected signal MC

- **Mission:** measure $B^\pm \rightarrow D K^\pm$, $B^\pm \rightarrow (D^{*0} \rightarrow D\pi^0)K^\pm$ and $B^\pm \rightarrow (D^{*0} \rightarrow D\gamma)K^\pm$ in a single fit after common $DK^\pm$ candidate selection
In reality, there are more $B$ decays than our $B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D^{*0}K^\pm$ friends!

Several other partially reconstructed decays sit in the same invariant mass region as the signals.

Extensive simulation studies performed to understand the $m(DK)$ distributions of each background.

<table>
<thead>
<tr>
<th>Fully reco. signal</th>
<th>Partially reco. signal</th>
<th>Partially reco. bkg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \rightarrow DK^\pm$</td>
<td>$B^\pm \rightarrow (D^{*0} \rightarrow D\pi^0)K^\pm$</td>
<td>$B^0 \rightarrow (D^{*-} \rightarrow D\pi^-)K^+$</td>
</tr>
<tr>
<td>$B^\pm \rightarrow (D^{*0} \rightarrow D\gamma)K^\pm$</td>
<td>$B^\pm \rightarrow DK^{\pm} \pi^0$</td>
<td>$B^0 \rightarrow DK^{\pm} \pi^\mp$</td>
</tr>
<tr>
<td>$\bar{B}^0_s \rightarrow DK^{\pm} \pi^\mp$</td>
<td>$B \rightarrow (D^* \rightarrow DX)K^{\pm}Y$</td>
<td></td>
</tr>
</tbody>
</table>
Background shapes

\[ B^0 \rightarrow (D^{*-} \rightarrow D\pi^-)K^+ \]

\[ B^\pm \rightarrow DK^\pm \pi^0 \]

\[ \bar{B}_s^0 \rightarrow DK^\pm \pi^{-} \]

\[ B \rightarrow (D^{*} \rightarrow DX)K^\pm Y \]
$m(Dh^\pm)$ fit, $D \to K^\pm \pi^\mp$ (5 fb$^{-1}$) [LHCb-PAPER-2017-021]

- Favoured mode data helps us understand the signal and background contributions

![Graph showing data distributions for $m(Dh^\pm)$ and $m(D\pi)$](attachment:graph.png)

- $B^\pm \to D K^\pm$
- $B^\pm \to D\pi^\pm$
- $B^\pm \to (D^{*0} \to D\pi^0) h^\pm$
- $B^\pm \to (D^{*0} \to D\gamma) h^\pm$
- $B^0 \to (D^{*-} \to D\pi^-) h^+$
- $B^\pm \to Dh^{\pm} \pi^0$
- $B \to (D^* \to DX) h^\pm Y$

Particle misidentification

Simultaneous fit to $m(DK)$ and $m(D\pi)$ - split based upon particle ID requirement
Crosscheck results \((5 \text{ fb}^{-1})\) [LHCb-PAPER-2017-021]

- Fit measures several branching fractions
  - All agree with current world averages \((< 1.3\sigma)\)
  - Validation of the partial reconstruction method

<table>
<thead>
<tr>
<th>Observable</th>
<th>This result</th>
<th>World average</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathcal{B}(B^\pm \rightarrow D^{*0} K^\pm) / \mathcal{B}(B^\pm \rightarrow D^{*0} \pi^\pm))</td>
<td>((7.93 \pm 0.57)%)</td>
<td>((8.11 \pm 0.77))%</td>
</tr>
<tr>
<td>(\mathcal{B}(B^\pm \rightarrow D^{*0} \pi^\pm))</td>
<td>((4.66 \pm 0.27) \times 10^{-3})</td>
<td>((5.18 \pm 0.26) \times 10^{-3})</td>
</tr>
<tr>
<td>(\mathcal{B}(D^{*0} \rightarrow D^{0} \pi^0))</td>
<td>(0.636 \pm 0.015)</td>
<td>(0.647 \pm 0.009)</td>
</tr>
</tbody>
</table>
Making a $\gamma$-sensitive measurement

- What we really want to measure is $CP$ violation!
  - $\gamma$ causes a difference in $B^+$ and $B^-$ decay rates

- Split data by $B$ charge and measure charge asymmetries
  - Correct all raw asymmetries for $B^\pm$ production asymmetry and additional detection asymmetry effects

- Also interested in relative rates
  - Rate of $B^\pm \to D^{*0}K^\pm$ compared to $B^\pm \to D^{*0}\pi^\pm$
  - Rates of $CP$ mode decays ($D \to KK, \pi\pi$) compared to favoured mode ($D \to K\pi$)
$m(Dh^\pm)$ fit, $D \rightarrow K^\pm\pi^\mp$ (5 fb$^{-1}$) [LHCb-PAPER-2017-021]
**CP observables** \((CP = KK, \pi\pi)\)

- Measure \(\pi^0\) and \(\gamma\) asymmetries in favoured and \(CP\) modes
  - 4 observables - \(A_{K\pi}^{\pi^0}, A_{K\pi}^{\gamma}, A_{CP}^{\pi^0}, A_{CP}^{\gamma}\)

- Measure rates of \(B^\pm \rightarrow D^{*0}([CP]_D\pi^0)K^\pm\) and \(B^\pm \rightarrow D^{*0}([CP]_D\gamma)K^\pm\) compared to favoured mode counterparts
  - 2 observables - \(R_{CP}^{\pi^0}, R_{CP}^{\gamma}\)

- Strong phase difference of 180° between \(\pi^0\) and \(\gamma\) sub-decays: effectively measuring \(R_{CP}^{\pm}\) and \(A_{CP}^{\pm}\)

\[
R_{CP}^{\pi^0} \equiv R_{CP}^+ = 1 + r_B^2 + 2r_B \cos(\delta_B) \cos(\gamma)
\]
\[
R_{CP}^{\gamma} \equiv R_{CP}^- = 1 + r_B^2 - 2r_B \cos(\delta_B) \cos(\gamma)
\]
\[
A_{CP}^{\pi^0} \equiv A_{CP}^+ = +2r_B \sin(\delta_B) \sin(\gamma)/R_{CP}^+
\]
\[
A_{CP}^{\gamma} \equiv A_{CP}^- = -2r_B \sin(\delta_B) \sin(\gamma)/R_{CP}^-
\]
$m(Dh^\pm)$ fit, $D \rightarrow K^+K^-$ (5 fb$^{-1}$) [LHCb-PAPER-2017-021]
$m(Dh^\pm) \text{ fit, } D \to K^+K^- \quad (5 \text{ fb}^{-1})$ [LHCb-PAPER-2017-021]
$m(Dh^\pm)$ fit, $D \rightarrow K^+K^-$ (5 fb$^{-1}$) [LHCb-PAPER-2017-021]
$m(Dh^\pm)$ fit, $D \to \pi^+\pi^-$ (5 fb$^{-1}$) [LHCb-PAPER-2017-021]
$m(Dh^\pm)$ fit, $D \to \pi^+\pi^-$ (5 fb$^{-1}$) [LHCb-PAPER-2017-021]
$m(Dh^\pm)$ fit, $D \rightarrow \pi^+\pi^-$ (5 fb$^{-1}$) [LHCb-PAPER-2017-021]
**CP observable results (5 fb$^{-1}$)** [LHCb-PAPER-2017-021]

- $B^{\pm} \rightarrow D^{*0} h^{\pm}$ modes measured for the first time at LHCb and using a brand new technique!
- Currently **GLW** modes are included - **ADS** under investigation
- Fully reconstructed $B^{\pm} \rightarrow D^{0} h^{\pm}$ results are measured with the same fit

### $B^{\pm} \rightarrow D^{*0} K^{\pm}$ results [LHCb-PAPER-2017-021]

<table>
<thead>
<tr>
<th>$A_{K}^{K \pi, \gamma}$</th>
<th>$+0.001 \pm 0.021$ (stat) $\pm 0.007$ (syst)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{K}^{K \pi, \pi^0}$</td>
<td>$+0.006 \pm 0.012$ (stat) $\pm 0.004$ (syst)</td>
</tr>
<tr>
<td>$A_{K}^{CP, \gamma}$</td>
<td>$+0.276 \pm 0.094$ (stat) $\pm 0.047$ (syst)</td>
</tr>
<tr>
<td>$A_{K}^{CP, \pi^0}$</td>
<td>$-0.151 \pm 0.033$ (stat) $\pm 0.011$ (syst)</td>
</tr>
<tr>
<td>$R_{CP, \gamma}$</td>
<td>$0.902 \pm 0.087$ (stat) $\pm 0.112$ (syst)</td>
</tr>
<tr>
<td>$R_{CP, \pi^0}$</td>
<td>$1.138 \pm 0.029$ (stat) $\pm 0.016$ (syst)</td>
</tr>
</tbody>
</table>
• Important not to forget the $B^\pm \to DK^\pm$ GLW updates!
  • World-best measurements supersede those in 3 fb$^{-1}$ analysis
  • Consistent picture between previous results and this update
  • Improved precision as expected from increased statistics

• Statistical precision approaching level of systematics in some observables - future work to drive down systematics

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<th>$B^\pm \to DK^\pm$ results</th>
<th>[LHCb-PAPER-2017-021]</th>
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<tbody>
<tr>
<td>$A_K^{K\pi} = -0.019 \pm 0.005$ (stat) $\pm 0.002$ (syst)</td>
<td></td>
</tr>
<tr>
<td>$A_K^{KK} = +0.126 \pm 0.014$ (stat) $\pm 0.002$ (syst)</td>
<td></td>
</tr>
<tr>
<td>$A_K^{\pi\pi} = +0.115 \pm 0.025$ (stat) $\pm 0.007$ (syst)</td>
<td></td>
</tr>
<tr>
<td>$R_K^{KK} = 0.988 \pm 0.015$ (stat) $\pm 0.011$ (syst)</td>
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</tr>
<tr>
<td>$R_K^{\pi\pi} = 0.992 \pm 0.027$ (stat) $\pm 0.015$ (syst)</td>
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Determining $\gamma$, $r_{B}^{D^*K}$ and $\delta_{B}^{D^*K}$ ($5 \text{ fb}^{-1}$) [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 $\gamma$

- $r_{B}^{D^*K}$ and $\delta_{B}^{D^*K}$ align with HFLAV GGSZ averages [arXiv:1612.07233]

- $\gamma$ within 1σ of 2016 LHCb combination [LHCb-PAPER-2016-032]
  - Will further improve precision with addition of ADS modes
LHCb $\gamma$ combination [LHCb-CONF-2017-004]

- Perform a statistical combination using observables from several LHCb analyses
  - Many hadronic parameters, but critically $\gamma$ is common to all

- Previous combination based entirely on Run 1 measurements [LHCb-PAPER-2016-032]

- An update has been performed, which includes the following:
  - $B^\pm \rightarrow DK^\pm$ GLW (5 fb$^{-1}$) $\rightarrow$ 3 fb$^{-1}$ → 5 fb$^{-1}$
  - $B^\pm \rightarrow D^{*0} K^\pm$ GLW (5 fb$^{-1}$) NEW
  - $B^\pm \rightarrow DK^{*\pm}$ ADS/GLW (5 fb$^{-1}$) NEW
  - Time-dependent $B^0_s \rightarrow D^- s K^+$ (3 fb$^{-1}$) $\rightarrow$ 1 fb$^{-1}$ → 3 fb$^{-1}$
Updated combination results [LHCb-CONF-2017-004]

- Profile likelihood contours have shrunk after updating $B^\pm \rightarrow DK^{\pm}$ GLW and adding new information

OLD

NEW

![Diagram showing updated combination results with profile likelihood contours for different decay modes, including blue, pink, orange, and green regions representing different combinations.]
• New combination supersedes previous - most precise measurement of $\gamma$ from a single experiment

• Uncertainty reduced by $\sim 1.7^{\circ}$ relative to previous combination

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

• Current HLFAV average (inc. BaBar and Belle): $\gamma = (76.2^{+4.7}_{-5.0})^{\circ}$
Outlook for $\gamma$ at the end of Run 2

- LHCb has more to say on $\gamma$ before Run 2 wraps up

- Several key measurements are underway, to name a few:
  - $B^\pm \rightarrow DK^\pm$ ADS UPDATE
  - $B^\pm \rightarrow DK^\pm$ GGSZ UPDATE
  - $B^0 \rightarrow DK^{*0}$ ADS/GLW UPDATE
  - $B^\pm \rightarrow DK^{*\pm}$ GGSZ NEW
  - $B^\pm \rightarrow D^{*0} K^\pm$ ADS NEW

- Increased statistical power of Run 1 + Run 2 dataset will improve $\gamma$ precision even further
  - Plenty to stay tuned for in the coming months!
What does it all mean?

- **Main idea**: compare $\gamma$ measured in tree level decays with the value inferred from indirect global fits
- Loop processes, which give $\beta$, $\Delta m_s$ & $\Delta m_d$, are NP sensitive
- Indirect $\gamma$ precision $\sim 2^\circ$ - limited by QCD theory uncertainty in $B^0/\bar{B}^0$ [MILC]
  - We must strive to push tree level $\gamma$ below this
  - **Does the Unitarity Triangle close?**
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  - **Does the Unitarity Triangle close?**
Comparison with world averages $\gamma$

Latest LHCb combination (direct) $\gamma = (76.8^{+5.1}_{-5.7})^\circ$

HFLAV 2017 world average (direct) $\gamma = (76.2^{+4.7}_{-5.0})^\circ$

CKMfitter 2016 world average (indirect) $\gamma = (65.3^{+1.0}_{-2.5})^\circ$

- Can’t say anything definitive with current precision, but...
  - LHCb combination is $\sim 2\sigma$ higher than indirect world average

- Strongly motivates the continued pursuit of $\gamma$ with trees
  - LHCb is in a strong position to improve $\gamma$ precision further
  - Will high central value of tree level $\gamma$ persist?
Another kid on the block

- Belle II due to start taking data next year
  - Aiming for 50 ab$^{-1}$ by 2025
  - **Expecting $\sim 2^\circ$ single experiment precision on $\gamma$ by the end of running** [I. Komarov, EPS 2017, Venice]

- Belle II has some advantages to help it compete with the power of LHCb statistics:
  - Higher sensitivity to neutrals ($\pi^0$, $\gamma$): $CP$-odd $D \rightarrow K_s^0 \pi^0$
  - Full event interpretation: semi-leptonic modes ($|V_{ub}|$)

- LHCb will retain the advantage of superior statistics in fully charged modes: $D \rightarrow KK, \pi\pi, \pi K$ e.t.c.
Belle II and LHCb upgrade $\gamma$ sensitivity

- Assuming 10 fb$^{-1}$ BESIII dataset to provide input on GGSZ $c_i$ & $s_i$
  - Belle II expect 3° precision from $B^{\pm} \rightarrow DK^{\pm}$ GGSZ alone
  - Combining with all other $D$ modes gives 1.6°

- LHCb will work hard to compete well into the upgrade era
  - 1.5° by end of Run 3 ($\sim$ 22 fb$^{-1}$, 2024) [arXiv:1709.10308]
  - < 1° by end of Run 4 ($\sim$ 50 fb$^{-1}$, 2029) [arXiv:1709.10308]
  - $\sim$ 0.4° in Phase II upgrade ($\sim$ 300 fb$^{-1}$, 2034) [CERN-LHCC-2017-003]

\[\begin{array}{c|c|c|c|c|c|c|c|c}
\text{Uncertainty} & \gamma & \phi & 0 & 2 & 4 & 6 & 8 & 10 \\
\end{array}\]
Summary

• $\gamma$ is a cornerstone of the Standard Model
  • Measured precisely using tree level $B$ decays with negligible theoretical uncertainty

• LHCb keeps making world-best measurements of $\gamma$ across a range of interesting modes
  • New techniques like $B^{\pm} \rightarrow D^{*0} K^{\pm}$ partial reconstruction help squeeze the most out of the data

• Many updates to come as we approach the end of Run 2
  • Entering an exciting phase in CKM precision measurements!
Backup
Time-dependent $B_s^0 \rightarrow D_s^- K^+$ (3 fb$^{-1}$) [LHCb-CONF-2016-015]

- Time-dependent $CP$ asymmetries - measure interference between mixing and decay
- $\gamma$ sensitive measurement
  - Assume no NP and no penguin pollution
  - Plug in $\phi_s = -0.010 \pm 0.039$ rad [LHCb-PAPER-2014-059]

- Flavour-tagged analysis measures $CP$ parameters from fit to decay time distribution

![LHCb Preliminary](image-url)

![LHCb Preliminary](image-url)
Time-dependent $B_s^0 \rightarrow D_s^- K^+$ (3 fb$^{-1}$) [LHCb-CONF-2016-015]

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

- **Input:** $\phi_s = -0.010 \pm 0.039$ rad [LHCb-PAPER-2014-059]
- **3.6\sigma** evidence of $CP$ violation in $B_s^0 \rightarrow D_s^\mp K^\pm$
- **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 \(D^0 \rightarrow K_s^0 \pi^+\pi^-\), \(K_s^0 K^+K^-\) [JHEP 10 (2014) 097]
  - MD \(B^0 \rightarrow D^0 K^*^0\) with \(D^0 \rightarrow K_s^0 \pi^+\pi^-\) [JHEP 08 (2016) 137]
  - MI \(B^0 \rightarrow D^0 K^*^0\) with \(D^0 \rightarrow K_s^0 \pi^+\pi^-\), \(K_s^0 K^+K^-\) [JHEP 06 (2016) 131]

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

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

For $D_{CP} K A_{CP^+}$:

- **BaBar**: $0.25 \pm 0.06 \pm 0.02$
- **Belle**: $0.06 \pm 0.14 \pm 0.05$
- **CDF**: $0.39 \pm 0.17 \pm 0.04$
- **LHCb KK**: $0.13 \pm 0.01 \pm 0.00$
- **LHCb ππ**: $0.12 \pm 0.03 \pm 0.01$
- **Average**: $0.13 \pm 0.01$

For $D_{CP} K R_{CP^+}$:

- **BaBar**: $1.18 \pm 0.09 \pm 0.05$
- **Belle**: $1.13 \pm 0.16 \pm 0.08$
- **CDF**: $1.30 \pm 0.24 \pm 0.12$
- **LHCb KK**: $0.99 \pm 0.01 \pm 0.01$
- **LHCb ππ**: $0.99 \pm 0.03 \pm 0.03$
- **Average**: $1.00 \pm 0.02$

PRELIMINARY
Summer 2017 HFLAV averages - $B^\pm \rightarrow D^{*}_{CP}K^\pm$

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

- **BaBar**
  - PRD 78, 092002 (2008)
  - $-0.11 \pm 0.09 \pm 0.01$

- **Belle**
  - PRD 73 (2006) 051106
  - $-0.20 \pm 0.22 \pm 0.04$

- **LHCb**
  - LHCb-PAPER-2017-021
  - $-0.15 \pm 0.03 \pm 0.01$

- **Average**
  - HFLAV correlated average
  - $-0.14 \pm 0.03$

### $D^{*}_{CP} K A_{CP-}$

- **BaBar**
  - PRD 78, 092002 (2008)
  - $0.06 \pm 0.10 \pm 0.02$

- **Belle**
  - PRD 73 (2006) 051106
  - $0.13 \pm 0.30 \pm 0.08$

- **LHCb**
  - LHCb-PAPER-2017-021
  - $0.27 \pm 0.09 \pm 0.04$

- **Average**
  - HFLAV correlated average
  - $0.15 \pm 0.07$

### $D^{*}_{CP} K R_{CP+}$

- **BaBar**
  - PRD 78, 092002 (2008)
  - $1.31 \pm 0.13 \pm 0.03$

- **Belle**
  - PRD 73 (2006) 051106
  - $1.41 \pm 0.25 \pm 0.06$

- **LHCb**
  - LHCb-PAPER-2017-021
  - $1.14 \pm 0.03 \pm 0.08$

- **Average**
  - HFLAV correlated average
  - $1.21 \pm 0.07$

### $D^{*}_{CP} K R_{CP-}$

- **BaBar**
  - PRD 78, 092002 (2008)
  - $1.09 \pm 0.12 \pm 0.04$

- **Belle**
  - PRD 73 (2006) 051106
  - $1.15 \pm 0.31 \pm 0.12$

- **LHCb**
  - LHCb-PAPER-2017-021
  - $0.91 \pm 0.09 \pm 0.10$

- **Average**
  - HFLAV correlated average
  - $1.04 \pm 0.09$
Systematic uncertainties

- Analysis measures **ratios of very similar final states** - large degree of systematic uncertainty cancellation

- Some residual effects remain:
  - Fixed shape parameters from MC fits
  - Use of MC to determine efficiencies
  - Fixed background yields using PDG branching fractions
  - Data-driven method to measure particle ID efficiencies

- All systematics relate to use of **fixed parameters** in the fit
  - Run the fit many times and vary their values ⇒ variation in observable results assigned as systematics