Constraining the CKM Angle $\gamma$ at LHCb

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γ in Tree-Level B Decays

• γ is the least well-constrained angle of the CKM triangle.
• Fits in summer 2012 (before the inclusion of LHCb data) gave:
  \[ \gamma = 66\pm12^\circ \text{ (CKMFitter), } \gamma = 76\pm10^\circ \text{ (UTFit)} \]
• Measurements of γ from B decays mediated only by tree-level transitions provide an “standard candle” for the Standard Model.
• This can be compared with γ values from B decays involving loop-level transitions
  – For example \( B^0 (s) \rightarrow hh' \) decays
• Significant difference between these would indicate New Physics contribution to the loop process.
Menu of Results

• LHCb gamma combination from time-independent methods, using $B^+ \rightarrow D^0 K^+$ and $B^+ \rightarrow D^0 \pi^+$ (Phys. Lett. B 726 (2013) 151), and updated preliminary combination using $B^+ \rightarrow D^0 K^+$ only (LHCb-CONF-2013-006)

• Time-independent $\gamma$ measurement with 3/fb, using $B^+ \rightarrow D^0 K^+$ and $B^+ \rightarrow D^0 \pi^+$ with $D^0 \rightarrow K_S K \pi$ (LHCb-PAPER-2013-068, submitted to Phys. Lett. B)

• First observation of $B_s \rightarrow \bar{D}^0 \varphi$ (Phys. Lett. B 727 (2013) 403)

• Studies of beauty baryon decays to $D^0 ph$ and $\Lambda_c h$ (Phys. Rev. D 89 (2014) 032001)

The LHCb Experiment

- Forward arm spectrometer, optimised for study of $B$ and $D$ decays.
- Collected 1/fb of data at $E_{\text{CM}} = 7$ TeV in 2011 and 2/fb at 8 TeV in 2012

Key capabilities:
- High trigger efficiency, including on purely hadronic final states.
- Excellent Impact Parameter (IP) and Mass Resolution
- Hadronic PID over wide momentum range
Time-Integrated Methods

- Sensitivity to $\gamma$ from interference between $b \to c$ and $b \to u$ transitions at tree level, when $D$ final state is accessible to both $D^0$ and $\bar{D}^0$
- Aside from $\gamma$, have hadronic unknowns $r_{B(D)}$, $\delta_{B(D)}$, where ratio of suppressed to favoured $B(D)$ decay amplitudes is $r_B e^{i(\delta_B - \gamma)} (r_D e^{i\delta_D})$
- Method to extract these hadronic unknowns (and $\gamma$) depends on the $D$ final state

- Three main methods:
  - **ADS**: $D \to$ quasi-flavour-specific state, e.g. $K\pi$, $K\pi\pi\pi$ (Phys. Rev. Lett. 78 (1997) 257, Phys. Rev. D 63 (2001) 036005)
Gamma Combination

• The published LHCb combination uses analyses of $B \rightarrow Dh$ with:
  – $D \rightarrow K \pi, KK$ or $\pi\pi$ using 1/fb (Phys. Lett. B 712 (2012) 203),
  – $D \rightarrow K\pi\pi\pi$ using 1/fb (Phys. Lett. B 723 (2012)) 44),
  – $D \rightarrow K_sKK$ or $K_s\pi\pi$ using 1/fb (Phys. Lett. B 718 (2012) 43),
  – Plus CLEO data on $D \rightarrow K\pi\pi\pi$ strong phase (Phys. Rev. D 80 (2009) 031105)

• The experimental likelihoods are combined as

\[ \mathcal{L}(\alpha) = \prod_i f_i(A_i^{\text{obs}}|A_i(\alpha_i)) \]

where $A$ are the experimental observables ($R_{CP}$, $x_+$, etc) and $\alpha$ are the physics parameters ($\gamma$, $r_B$, etc).

• Confidence intervals are rescaled, to account for undercoverage and neglected correlations between systematics.

• The effects of $D^0-\overline{D^0}$ mixing, and of possible CPV in the $D$ decays, are taken into account.

• 68% CL confidence interval using DK and D$\pi$ is:

$\gamma \in [55.4, 82.3]^{\circ}$
Gamma Combination

- There is also a more recent, preliminary LHCb combination.
- This uses analyses of $B\to DK$ from the same analyses as the published combination, adding the information from an updated analysis with $D\to K_S KK$ or $K_S \pi\pi$ using the 3/fb dataset (LHCb-CONF-2013-004).
- Preliminary result is $\gamma = 67\pm12^\circ$

These results lead to updated CKM fits:

$\gamma = 68.0^{+8.0}_{-8.5}^\circ$ (CKMFitter, FPCP 2013),
$\gamma = 70.1\pm7.1^\circ$ (UTFit, EPS 2013).
Observables for $B^+ \rightarrow D^0(\rightarrow K_S K \pi)h^+$

- This is the first ADS-like analysis to use Singly-Cabibbo-Suppressed (SCS) modes. Label final states as OS or SS comparing $K^\pm$ with $B^\pm$

- Analysing three-body $D$ final state requires knowledge of how the average interference amplitude ($\kappa_{K_S K\pi}$) and strong phase difference ($\delta_{K_S K\pi}$) vary across the $D$ Dalitz plot
  - This is taken from a CLEO-c measurement, Phys. Rev. D 85 (2012) 092016

- Decay rates for $B^+ \rightarrow D^0K^+$ are:
  \[
  \Gamma_{SS, DK}^\pm = z\left[ 1 + r_B^2 r_D^2 + 2 r_B r_D \kappa_{K_S K^0 K\pi}^0 \cos(\delta_B \pm \gamma - \delta_{K_S K^0 K\pi}^0) \right] \\
  \Gamma_{OS, DK}^\pm = z\left[ r_B^2 + r_D^2 + 2 r_B r_D \kappa_{K_S K^0 K\pi}^0 \cos(\delta_B \pm \gamma + \delta_{K_S K^0 K\pi}^0) \right]
  \]

- Measure yield ratios (e.g. $R_{DK/D\pi, SS}$) and charge asymmetries (e.g. $A_{SS,DK}$) between the OS and SS samples, and between $DK$ and $D\pi$ final states.

- Analysis is done across whole Dalitz plane, and in a restricted region around the $K^{*\pm}$ resonance, where the coherence factor $\kappa_{K_S K\pi}$ is higher ($\approx 1.0$ vs $\approx 0.7$).
Results for $B^+ \rightarrow D^0(K^+ S K \pi)h^+$

- Measure 8 yields, with $B^+ \rightarrow D^0K^+$ and $B^+ \rightarrow D^0\pi^+$ separated by OS/SS and charge of $B^\pm$
- Charge-summed yields for OS and SS $D^0K^+$ are 71 and 145 respectively.
- Sensitivity to $\gamma$ appears to be improved by taking $K^{*\pm}$ region, due to higher coherence factor.
- Good prospects for future analysis of $K^{*\pm}$ region with more statistics.
Observation of $B_s \rightarrow \bar{D}^0 \phi$

- Time-dependent analysis of the $B_s \rightarrow \bar{D}^0 \phi$ decay can measure $\gamma$ and $\phi_s$ (Phys. Lett. B 253 (1991) 483).
- Using the now-known sign of $\Delta \Gamma_s$, this determination can be made unambiguous (Phys. Rev. D 85 (2012) 114015).
- A time-independent analysis can also measure $\gamma$, provided enough $D^0$ final states are included (Phys. Rev. D 69 (2004) 113003, Phys. Lett. B 649 (2007) 61). This has advantages for LHCb, as it means flavour-tagging is not required.

• First step is to make the first observation of the decay, using the Cabibbo-favoured $\bar{D}^0 \rightarrow K^+ \pi^-$ decay mode.
Observation of $B_s \rightarrow \overline{D}^0 \phi$

- LHCb searched for $B_s \rightarrow \overline{D}^0 \phi$ with a blind analysis of 1/fb of data.
- First observation of $B_s \rightarrow \overline{D}^0 \phi$ is made, with significance of 6.5σ.

$$N_{B_s \rightarrow \overline{D}^0 \phi} = 43 \pm 8$$

- Branching fraction ($\mathcal{B}$) is measured relative to the $B_d \rightarrow \overline{D}^0 K^{*0}$ decay. Also improve the measurement of $\mathcal{B}(B_s \rightarrow \overline{D}^0 K^{*0})$ relative to $B_d \rightarrow \overline{D}^0 K^{*0}$:

$$\mathcal{B}(B_s^0 \rightarrow \overline{D}^0 \phi) = \left[ 2.3 \pm 0.4 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.2 \left( f_s/f_d \right) \pm 0.3 \left( \mathcal{B}(B^0 \rightarrow \overline{D}^0 K^{*0}) \right) \right] \times 10^{-5},$$

$$\mathcal{B}(B_s^0 \rightarrow \overline{D}^0 K^{*0}) = \left[ 3.3 \pm 0.3 \text{ (stat)} \pm 0.1 \text{ (syst)} \pm 0.3 \left( f_s/f_d \right) \pm 0.5 \left( \mathcal{B}(B^0 \rightarrow \overline{D}^0 K^{*0}) \right) \right] \times 10^{-4}.$$  

- With more data, can add more $D^0$ final states, such as $KK$, $\pi\pi$, $K_S\pi\pi$, …
Baryon Decays to $D^0ph, \Lambda_c h$

- Beauty baryon sector remains largely unexplored.
- Decays such as $\Lambda_b \rightarrow D^0\Lambda$ and $\Lambda_b \rightarrow D^0pK^-$ can be used to measure $\gamma$ (Z. Phys. C 56 (1992) 129, Mod. Phys. Lett. A 14 (1999), Phys. Rev. D 65 (2002) 073029)
- LHCb has studied beauty baryon decays to $D^0ph^-$ and $\Lambda_c h^-$ final states, using 1/fb of data.
- The Caibibbo-favoured final states $D^0 \rightarrow K^-\pi^+$ and $\Lambda_c \rightarrow pK^-\pi^+$ are used.
- Common $pK^-\pi^+h$ final state reduces systematic uncertainties.
- Firstly, use a loose, cut-based selection to measure:

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow D^0p\pi^-) \times \mathcal{B}(D^0 \rightarrow K^-\pi^+)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-) \times \mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)} = 0.0806 \pm 0.0023 \pm 0.0035$$

(factoring out poorly-known $\mathcal{B}(\Lambda_c \rightarrow pK^-\pi^+)$)
Baryon Decays to $D^0p\phi$, $\Lambda_c h$

- Tighter selection (with BDT) used to make the first observations of $\Lambda_b \rightarrow D^0pK^-$ (9.0\(\sigma\)) and $\Xi_b \rightarrow D^0pK^-$ (5.9\(\sigma\)), and measure:

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow D^0 pK^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow D^0 p\pi^-)} = 0.073 \pm 0.008^{+0.005}_{-0.006},$$

$$\frac{f_{\Xi_b} \times \mathcal{B}(\Xi_b^0 \rightarrow D^0 pK^-)}{f_{\Lambda_b} \times \mathcal{B}(\Lambda_b^0 \rightarrow D^0 pK^-)} = 0.44 \pm 0.09 \pm 0.06$$

- The $D^0pK^-$ spectrum can also be used to measure the mass difference:

$$m_{\Xi_b^0} - m_{\Lambda_b^0} = 174.8 \pm 2.4 \pm 0.5 \text{ MeV}/c^2$$

(Systematic is dominated by background modelling in mass fit)

- Combining with the LHCb measurement of $m_{\Lambda_b}$ using $\Lambda_b \rightarrow J/\psi \Lambda$ (PRL 110 (2013) 182001) gives:

$$m_{\Xi_b} = 5794.3 \pm 2.4 \pm 0.7 \text{ MeV}/c^2$$

Most precise to date!
Baryon Decays to Two Charm Hadrons

- Another showcase for LHCb’s capabilities with beauty baryons is the analysis of their decays to pairs of charm hadrons, using 3/fb.
- Events are selected using a BDT trained on signal decays to the relevant single charm hadron: $B_d \rightarrow D^- \pi^+$, $B_s \rightarrow D_s^- \pi^+$ or $\Lambda_b \rightarrow \Lambda_c \pi^-$.  
- Clear first observations are made of the decays $\Lambda_b \rightarrow \Lambda_c D_s^-$ (CF) and $\Lambda_b \rightarrow \Lambda_c D^-$ (SCS), with: 

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} = 0.042 \pm 0.003 \text{ (stat)} \pm 0.003 \text{ (syst)}.$$  

- The $\Lambda_b$ branching fractions can be normalised to $\overline{B_d} \rightarrow D^+ D_s^-$, but the fragmentation fraction ratio $f_{\Lambda_b}/f_d$ is known to depend on the $p_T$ of the b-hadron (LHCb, Phys. Rev. D 85 (2012) 032008)...
Baryon Decays to Two Charm Hadrons

- Adopting the $p_T$-dependence of $f_{\Lambda_b}/f_d$ measured by LHCb using $B_d \to D^- \pi^+$ and $\Lambda_b \to \Lambda_c \pi^-$ (LHCb-PAPER-2012-004, in preparation), the double ratio is measured:
  \[
  \left[ \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}{\mathcal{B}(\bar{B}^0 \to D^+D^-)} \right] / \left[ \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)}{\mathcal{B}(\bar{B}^0 \to D^+\pi^-)} \right] = 0.96 \pm 0.02 \text{ (stat)} \pm 0.06 \text{ (syst)}.
  \]

- In addition, the modes $B_{\{d,s\}} \to \Lambda_c^+ \Lambda_c^-$ are searched for, and no significant signal is found. The following 95% C.L. limits are set:
  \[
  \frac{\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \Lambda_c^-)}{\mathcal{B}(\bar{B}^0 \to D^+D_s^-)} < 0.0022 , \quad \frac{\mathcal{B}(B_s^0 \to \Lambda_c^+ \Lambda_c^-)}{\mathcal{B}(B_s^0 \to D^+D_s^-)} < 0.30
  \]

- Finally, the very similar Q-values of the $\bar{B}_d \to D^+D_s^-$ and $\Lambda_b \to \Lambda_c D_s^-$ decays allows a precise measurement of the mass difference:
  \[
  M(\Lambda_b^0) - M(\bar{B}^0) = 339.72 \pm 0.24 \text{ (stat)} \pm 0.18 \text{ (syst)} \text{ MeV}/c^2
  \]

- Using the World Average $B_d$ mass gives the most precise result to date for the absolute $\Lambda_b$ mass: $M(\Lambda_b^0) = 5619.30 \pm 0.34 \text{ MeV}/c^2$
Summary & Prospects

- Preliminary LHCb $\gamma$ combination with $B^+ \rightarrow D^0 K^+$ decays, using various methods (ADS, GLW, GGSZ) gives $\gamma = 67 \pm 12^\circ$, more precise than the B-factory measurements.
- At the moment, no one method dominates the sensitivity.
- Always looking to add new $B$ decays, and new $D$ final states
  - First constraints on $\gamma$ with $B^+ \rightarrow D^0 (\rightarrow K_S K \pi) h^+$ just submitted to PLB
  - Promising new mode $B_s \rightarrow D^0 \phi$ now observed
- Wealth of measurements now being done with $b$-baryons, may throw up some interesting surprises.
- Stay tuned for more results in the future!
  - Many measurements are awaiting the inclusion of the 2.0/fb collected at 8 TeV in 2012
Gamma Combination

- CLEO-c result on $D \rightarrow K\pi\pi\pi$:

- Other parameters measured:
Helicity Structure for $B_s \rightarrow \overline{D}^0 \phi$

- Distribution of the helicity angle for selected signal events shows that the $B_s$ mass region is dominated by a vector resonance, as expected for a final state. In contrast in the $B_d$ mass region is not.

- The $B_d$ distribution supports what was seen in the LHCb paper on the discovery of the $B_d \rightarrow \overline{D}^0 K^+ K^-$ decay, Phys. Rev. Lett. 109 (2012) 131801.

- The $B_s$ distribution is reinforced by the $m(KK)$ distribution in the $B_s$ region:
Baryon Decays to $D^0\phi h, \Lambda_c h$

- The tighter selection is also applied to the $\Lambda_c h^-$ spectra, to clearly observe $\Lambda_b \rightarrow \Lambda_c K^-$, and find evidence for $\Xi_b \rightarrow \Lambda_c K^-$ (3.3σ):

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} = 0.0731 \pm 0.0016 \pm 0.0016,$$

$$\frac{\mathcal{B}(\Xi_b^0 \rightarrow \Lambda_c^+ K^-) \times \mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+)}{\mathcal{B}(\Xi_b^0 \rightarrow D^0 p K^-) \times \mathcal{B}(D^0 \rightarrow K^- \pi^+)} = 0.57 \pm 0.22 \pm 0.21$$
\[ \Lambda_b \rightarrow D^0 p \phi^- \] Dalitz Plots

**LHCb**

**$D^0 p \pi^-$**

**zoom to low-mass**

$m(p\pi^-)$

**zoom to low-mass**

$m(D^0 p)$

**$D^0 p K^-$**

$m(pK^-)$

$m(D^0 p)$
The "two charm hadrons" analysis also makes the most precise measurement of $\mathcal{B}(B_s \rightarrow D^+ D_s^-)$:

$$\frac{\mathcal{B}(B_s^0 \rightarrow D^+ D_s^-)}{\mathcal{B}(B^0 \rightarrow D^+ D^-)} = 0.038 \pm 0.004 \text{ (stat)} \pm 0.003 \text{ (syst)}.$$  

$$\mathcal{B}(B_s^0 \rightarrow D^+ D_s^-) = (2.7 \pm 0.5) \times 10^{-4}$$