Measurement of the CKM angle \( \gamma \) with the model-independent GGSZ method in \( B^\pm \rightarrow D K^\pm \) decays

Faye Cheung
University of Oxford

Institute of Physics
Particle, Astroparticle and Nuclear Physics meeting
30\(^{\text{th}}\) March – 2\(^{\text{nd}}\) April 2015
CKM angle $\gamma$

Unitarity relation: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

Can be verified by checking if direct and indirect measurements of $\gamma$ are consistent

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

World average from **direct** and **indirect** measurements

\[
\gamma = \left( 73.2^{+6.3}_{-7.0} \right)^\circ
\]

\[
\gamma = \left( 66.9^{+1.0}_{-3.7} \right)^\circ
\]

CKMfitter Jan ’15 update

- $\gamma$ is unique: the only unitarity angle that can be determined from direct measurements with *no penguin pollution*
- While indirect measurement contains loop (and potential New Physics!) contributions

✈ Vital goal of LHCb (and flavour physics!) is to measure tree-level $\gamma$ to degree-level precision
Tree-level $\gamma$ from $B^{\pm} \rightarrow DK^{\pm}$

... where $D$ is an admixture of $D^0$ and $\bar{D}^0$ decaying to same final state

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

Weak phase difference between $b \rightarrow u$ and $b \rightarrow c$

$B^- \rightarrow B^+, \gamma \rightarrow -\gamma$$

$\Rightarrow$ CP violation

Hadronic terms determined experimentally

$$r_B \sim 0.1$$

$r_B$ = size of interference

$= \text{sensitivity to } \gamma$

$\delta_B$: relative strong phase

depending on final state, require external input from charm experiments or amplitude model for $r_D$ and/or $\delta_D$
'GGSZ' final state


**Multi-body D decay**
Complication: $\delta_D$ varies with phase space
$\Rightarrow$ decay rate varies with final-state kinematics

Visualise phase space with Dalitz plot:

$$ (m_2^-, m_2^+) \equiv (m^2(K_S^0 h^-), m^2(K_S^0 h^+)) $$

**Two methods at LHCb**

**Model-dependent**
Fit data to an amplitude model to provide $\delta_D$


**Model-independent**
Use external measurements of $\delta_D$ from quantum-correlated $\psi(3770) \rightarrow D\bar{D}$ decays by CLEO-c in binned regions of Dalitz plot

*JHEP 10 (2014) 097*

- ✓ systematic due to $\delta_D$ is data-driven
- ✓ counting experiment: simplifies analysis and reduces CPU time
- ✗ not optimal use of statistics due to binning
Model-independent method

Decay rate to bin $i$:

$$N_{\pm i}(B^-) \propto \left( F_{\mp i} + (x_-^2 + y_-^2)F_{\mp i} + 2\sqrt{F_{i}F_{-i}}(x_-c_i \pm y_-s_i) \right)$$

$$N_{\pm i}(B^+) \propto \left( F_{\mp i} + (x_+^2 + y_+^2)F_{\mp i} + 2\sqrt{F_{i}F_{-i}}(x_+c_i \pm y_+s_i) \right)$$

- $c_i, s_i$: cos, sin $\delta_D$ weighted by $D$ decay rate, integrated in bin
- External input from CLEO-c

\[ F_i \]
fractional yield of flavour-tagged $D^0 \to K^0_S h^+h^-$ in bin

\[ x_\pm = r_B \cos(\delta_B \pm \gamma) \]
\[ y_\pm = r_B \sin(\delta_B \pm \gamma) \]

Measure with a flavour-tagged control mode which has same efficiency profile as signal

Extract from simultaneous fit to all bins

all we need to know are the relative yields of the signal and control mode in each bin!

\[ r_B e^{i(\delta_B - \gamma)} \]
\[ r_D e^{i\delta_D} \]

\[ D^0 K^- \]
\[ B^- \]
\[ f(D)K^- \]
LHCb detector

Analysis presented uses 3 fb\(^{-1}\) of \(pp\) data collected in Run 1 and is made possible by...

- **VELO (VErtex LOcater)**
  - B meson flight distance ~1 cm,
  - impact parameter resolution ~20 \(\mu\)m: powerful discriminator of \(B\) mesons and essential for triggers and offline selection

- **RICH I & II**
  - Particle identification: \(\pi, K, p, e, \mu\)
  - differentiates various \(B, D\) final states

- **LHCb trigger**
  - 45% of hardware trigger bandwidth dedicated to hadronic trigger

\[2 < \eta < 5\]
Measurement of relative yields

\[ N_{\pm i}(B^-) \propto \left( F_{\pm i} + (x^2 + y^2) F_{\mp i} + 2\sqrt{F_i F_{-i}} (x_{-c_i} \pm y_{-s_i}) \right) \]

2580 signal decays selected

Example fit for \( K_S \pi \pi \)

- \( D K^\pm \)
- \( D \pi^\pm \)
- Combinatorial
- Part. reco.

Low level of cross-feed from the higher BR \( D \pi \) decay

Flavour-tagged decay from LHCb data:

\[ B^0 \rightarrow (D^{*+} \rightarrow D^0 \pi^+) \mu^- \bar{\nu}_\mu \]

High yield, high purity, negligible mistag of \( D^0 \) flavour

\[ m(D^{*\pm}) - m(D^0) \]

\[ m(D^0) \]
Fit to CP observables

Data and fit expectations are compatible
Results are consistent with CP violation hypothesis
Fit to $CP$ observables

\[ x_\pm = r_B \cos(\delta_B \pm \gamma) \]
\[ y_\pm = r_B \sin(\delta_B \pm \gamma) \]

Most accurate measurement of these $CP$ observables to date

\[ x_+ = (-7.7 \pm 2.4 \pm 1.0 \pm 0.4) \times 10^{-2} \]
\[ y_+ = (-2.2 \pm 2.5 \pm 0.4 \pm 1.0) \times 10^{-2} \]
\[ x_- = (2.5 \pm 2.5 \pm 1.0 \pm 0.5) \times 10^{-2} \]
\[ y_- = (7.5 \pm 2.9 \pm 0.5 \pm 1.4) \times 10^{-2} \]

\[ \gamma = (62^{+15}_{-14})^\circ \]
\[ \delta_B = (134^{+14}_{-15})^\circ \]
\[ r_B = (8.0^{+1.9}_{-2.1}) \times 10^{-2} \]

Precision from single measurement matches that of BaBar, Belle $\gamma$ combinations

Statistical uncertainties

2D confidence intervals @ 39.3, 86.5, 98.9%

3D confidence intervals @ 19.9, 74.9, 98.1% projected onto 2D

LHCb

Experimental systematic

due to $\delta_D$ measurements

Faye Cheung, University of Oxford
Future prospects

• The $B \to DK$ GGSZ model-independent analysis currently offers the best precision in $\gamma$ from a single direct measurement

$$\gamma = (62^{+15}_{-14})^\circ$$

• In limit of high statistics, error due to $\delta_D$ obtained at CLEO-c will result in $\sigma(\gamma) \to 2^\circ$

• Updated measurements of $\delta_D$ from BES-III experiment will reduce systematics further when they are made available

• This method will continue to be a key player in measuring $\gamma$ at degree-level precision
Dalitz plot efficiency

- Need to account for non-uniform selection efficiency in Dalitz plot due to kinematics of trigger and selection

- Automatically taken into account if source of $F_i$ has same efficiency distribution

- Apply correction factor to account for <10% difference between hadronic and semi-leptonic modes caused by use of different triggers

- Alternative is to use simulated data and amplitude model to get $F_i$ but difficult to get simulation correct in hadronic environment
Systematics

Table 4: Summary of statistical, experimental, and strong-phase, uncertainties on $x_\pm$ and $y_\pm$ in the case where both $D \to K_S^0\pi^+\pi^-$ and $D \to K_S^0K^+K^-$ decays are included in the fit. All entries are given in multiples of $10^{-2}$.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma(x_+)$</th>
<th>$\sigma(x_-)$</th>
<th>$\sigma(y_+)$</th>
<th>$\sigma(y_-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>2.4</td>
<td>2.5</td>
<td>2.5</td>
<td>2.9</td>
</tr>
<tr>
<td>Efficiency corrections</td>
<td>0.9</td>
<td>0.9</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Mass fit PDFs</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Shape of $D\pi^\pm$ mis-identified as $DK^\pm$</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Shape of partially reconstructed backgrounds</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>$c_i$, $s_i$ bias due to efficiency</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Migration</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Bias correction</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Total experimental</td>
<td>1.0</td>
<td>1.0</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Strong-phase-related uncertainties</td>
<td>0.4</td>
<td>0.5</td>
<td>1.0</td>
<td>1.4</td>
</tr>
</tbody>
</table>