Measurements of $\gamma$ at LHCb with ADS/GLW Strategies

Andrew Powell (University of Oxford)
On behalf of the LHCb collaboration

CKM08 Conference, Rome, September 2008
Outline

• \( B^\pm \rightarrow DK^\pm \) at LHCb
  • Sub-detectors important to this measurement

• Overview of Simulation Data
  • Monte Carlo used within studies reported here

• Selection and Sensitivity Predictions
  • \( B^\pm \rightarrow D(hh)K^\pm \)
  • Four-Body ADS: \( B^\pm \rightarrow D(K\pi\pi\pi)K^\pm \)
  • \( B^0 \rightarrow D(hh)K^{*0} \)

• Summary
\[ B^\pm \rightarrow DK^\pm \] at LHCb

- LHCb statistics will enable full exploitation of all \( B^\pm \rightarrow DK^\pm \) strategies, especially ADS/GLW
  - \( \sigma_{bb} \sim 500 \, \mu b \) at 14 TeV
  - \( L_{int} \sim 2 \times 10^{32} \, \text{cm}^{-2}\text{s}^{-1} \)
  - \( 10^{12} \, bb \) pairs per 2 fb\(^{-1}\) (canonical year)

- Sensitivity to \( \gamma \) dependent on ability to gather high statistics samples of \( B^\pm \rightarrow DK^\pm \) whilst controlling the background

- Good performance is achievable e.g. total efficiency (including acceptance, trigger and selection) for \( B^\pm \rightarrow D(K\pi)K^\pm \) from simulation studies: \( \varepsilon_{Tot} \sim 0.5 \% \)

- Counting experiments – no need for tagging or proper time determination

- \( B^\pm \rightarrow DK^\pm \) performance is reliant upon two vital aspects of the LHCb detector...

<table>
<thead>
<tr>
<th></th>
<th>LHCb</th>
<th>Babar</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^- \rightarrow D(K\pi)K^- ) Fav. Yields</td>
<td>~28,000</td>
<td>918*</td>
<td>1,220*</td>
</tr>
<tr>
<td>Luminosity (fb(^{-1}))</td>
<td>2</td>
<td>420**</td>
<td>710**</td>
</tr>
</tbody>
</table>

*As shown at ICHEP 08
**arXiv:0706.2786v1
The RICH

- Dangerous background from $B^\pm \rightarrow D\pi^\pm$
- $\text{BR}(B^\pm \rightarrow D\pi^\pm) \sim 10 \times \text{BR}(B^\pm \rightarrow DK^\pm)$
- RICH Kaon ID: $\varepsilon_{\text{avg}} > 90\% \quad \forall \text{ momenta}$
- $B/S \leq 0.5$ typical for favoured modes

Tracking System

- Excellent vertex and $p$ determination utilising Si vertex and tracking plane sub-detectors

Vertex Resolutions:
- Primary vertex $\sigma_z \sim 50 \mu m$
- $B$ decay vertex $\sigma_z \sim 200 \mu m$

Mass Resolutions:
- $B^\pm \sim 15 \text{ MeV}$
- $D^0 \sim 6.5 \text{ MeV}$
Simulation Details

• Results presented here from the LHCb Monte Carlo studies
  
  • **Pythia:** Simulation of $pp$ interaction at $\sqrt{s} = 14$ TeV
  • **EvtGen:** $b$-quark evolution and decay
  • **GEANT:** Full detector response simulation
    • + digitisation and trigger simulation packages

• Background estimates for selections from statistically limited $B$-inclusive sample
  • ~34 million $bb$ events within detector geometry
  • Equivalent to ~ 15 mins of LHCb running at nominal luminosity

• While large signal and dominating background samples also generated

• Typical selection requirements imposed upon:
  • Track $|p|$, $p_t$, and RICH PID,
  • Bachelor $K^\pm p_t$ and impact parameter
  • $B$ and $D$ $m_{\text{inv}}$
  • $B$ and $D$ vertex quality ($\chi^2$)
$B^{\pm} \rightarrow D(hh)K^{\pm}$
Two Strategies...

**ADS**

\[ D_{flav} = K^+ \pi, \ K^- \pi^+ \] (4 distinct final states)
- Particular sensitivity with suppressed rate
- Dependence on 5 parameters:
  - \( r_B \)
  - \( \delta_B \)
  - \( N_{K\pi} \) (normalisation)
  - \( \delta_{D(K\pi)} \) … and of course \( \gamma \)

**GLW**

\[ D_{CP} = K^+ K^-, \ \pi \pi^+ \]
- Parameters identical for both final states
  (consider yields together – 2 distinct rates)
- 1 additional parameter:
  - \( N_{hh} \) (normalisation)

**ADS + GLW**

<table>
<thead>
<tr>
<th>( N_{K\pi} )</th>
<th>( N_{hh} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \frac{N_{K\pi}}{N_{hh}} = \frac{BR(D \rightarrow K\pi) \times \epsilon_{K\pi}}{BR(D \rightarrow hh) \times \epsilon_{hh}} ]</td>
<td></td>
</tr>
</tbody>
</table>

- Exploiting relation between \( N_{K\pi} \) and \( N_{hh} \):
  - 5 parameters
  - 6 distinct rates
  - \( \gamma \) solvable!
$B^\pm \to D(hh)K^\pm$ Sensitivity ($2 \text{ fb}^{-1}$)

**Method**
- A $\chi^2$ fit to the 6 rates is performed
- Yield and bkgds as shown in table

**Constraints**
- $\delta_{D(K\pi)} = (22^{+14}_{-16})^\circ$ from CLEO-c*
- Constrain $\delta_{D(K\pi)}$ to $(^+_1^-_{16})^\circ$ of input

**Assumed Inputs**
- $r_B = 0.10$ (UTfit average $0.10 \pm 0.02$)
- $\delta_B = 130^\circ$ (PDG)
- $r_{D(K\pi)} = 0.0616$ (PDG)
- $\delta_{D(K\pi)}$ centred about $(-180)^\circ$
- $\gamma = 60^\circ$

**Results**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Sig. Yield</th>
<th>Bkg Est.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to D(K\pi)K^+$ (fav)</td>
<td>28k</td>
<td>17,520 ± 993</td>
</tr>
<tr>
<td>$B^+ \to D(K\pi)K^+$ (sup)</td>
<td>650**</td>
<td>780 ± 509</td>
</tr>
<tr>
<td>$B^+ \to D(KK)K^+$</td>
<td>3k</td>
<td>3,664 ± 1,026</td>
</tr>
<tr>
<td>$B^+ \to D(\pi\pi)K^+$</td>
<td>1k</td>
<td>3,570 ± 1,480</td>
</tr>
</tbody>
</table>

*Assuming $\delta_D = -158^\circ$
\[ B^\pm \rightarrow D(K3\pi)K^{\pm} \]

- Also an ADS mode
- Although, the D decay is now multi-bodied…
What’s Different?

• First, consider a point \((x)\) in D-decay phase space (akin to that of a 2-body decay (e.g. \(K\pi\))

\[ A_{D^0}(x) = \langle f|D^0 \rangle_{(x)} \]

\[ f(D)K^- \]

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

\[ D^0(x) = \langle f|D^0 \rangle_{(x)} \]

\[ \mathcal{M}^2 \sim |A_{D^0}(x)|^2 + r_B^2 |A_{D^0}(x)|^2 + 2r_B |A_{D^0}(x)||A_{D^0}(x)| \cos(\delta_B - \gamma + \zeta(x)) \]

• This is just the generalised 2-body ADS eqn., but what about multi-body final states…

• Total rate given by integrating over ALL allowable phase space:

\[ \Gamma \propto A_f^2 + r_B^2 \bar{A}_f^2 + 2r_B A_f \bar{A}_f R_f \cos(\delta_B - \gamma + \delta_D) \]

where:

\[ A_f^2 = \int |A_{D^0}(x)|^2 \, dx \]

\[ \bar{A}_f^2 = \int |A_{D^0}(x)|^2 \, dx \]

\[ R_f e^{i\delta_D} = \frac{\int |A_{D^0}(x)||A_{D^0}(x)|e^{i\zeta(x)} \, dx}{A_f \bar{A}_f} \]

\[ 0 \leq R_f \leq 1 \]

The “Coherence Factor”

[Phys Rev. D 68, 033003 (2003)]
Incorporating $K_3\pi$ Multi-Body ADS

Method

• Add these additional 4 rates, incorporating $R_{K_3\pi}$, into the 2-body $\chi^2$ fit
• Yield and bkgds essentially equivalent to $K\pi$

Constraints

• Determination of $R_{K_3\pi}$ possible at CLEO-c (see J. Libby’s talk in previous session)
• Preliminary results shown opposite
• Additional terms added into $\chi^2$ to incorporate constraints 1), 2) & 3)

Assumed Inputs

• $r_{D(K_3\pi)} = 0.0568$ (PDG)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Sig. Yield</th>
<th>Bkg Est.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow D(K_3\pi)K^+$</td>
<td>31k</td>
<td>20,200 ± 2,500</td>
</tr>
<tr>
<td>$B^+ \rightarrow D(K_3\pi)K^+$</td>
<td>530</td>
<td>1,200 ± 360</td>
</tr>
</tbody>
</table>

$<R_{K_3\pi}\cos(\delta^{K_3\pi})> = -0.60 \pm 0.19 \pm 0.24$  1)  
$(R_{K_3\pi})^2 = -0.20 \pm 0.23 \pm 0.09$  2)  
$R_{K_3\pi}\cos(\delta^{K\pi} - \delta^{K_3\pi}) = 0.00 \pm 0.16 \pm 0.07$  3)

[LHCb-2007-004]  
[LHCb-2008-031]
Combining 2 fb\(^{-1}\) Results

**Bottom Line:** Improvement in sensitivity from including \(K3\pi\) mode is equivalent to \(70 – 100\%\) more data after one year of running.

\[\sigma(\gamma) \sim (7.0 – 9.5)^\circ\text{ for 2 fb}^{-1}\]
$B^0 \rightarrow D^0(hh)K^{*0}$

- Can be utilised in a way akin to that of $B^{\pm} \rightarrow D(hh)K^{\pm}$

- Particular sensitivity expected since both diagrams are colour suppressed ($r_{B^0} \sim 0.4$)
$B^0 \to D(hh)K^{*0}$ Sensitivity (2 fb$^{-1}$)

Method
- A $\chi^2$ fit to the 6 rates is performed
- Yield and bkgds as shown in table

Constraints
- $\delta_{D(K\pi)} = (22^{+14}_{-16})^\circ$ from CLEO-c
- Constrain $\delta_{D(K\pi)}$ to ($^{+14}_{-16}$)$^\circ$ of input

Assumed Inputs
- $r_{B^0} = 0.40$
- $r_{D(K\pi)} = 0.0616$ (PDG)
- $\delta_{D(K\pi)}$ centred about (-180)$^\circ$
- $\gamma = 60^\circ$

Results

<table>
<thead>
<tr>
<th>Mode</th>
<th>Sig. Yield</th>
<th>B/S (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to D(K\pi)K^{*0}$ (fav)</td>
<td>3.4k</td>
<td>[0.4, 2.0]</td>
</tr>
<tr>
<td>$B^0 \to D(K\pi)K^{*0}$ (sup)</td>
<td>O(500)</td>
<td>[2.0, 13.0]</td>
</tr>
<tr>
<td>$B^0 \to D(K\bar{K})K^{*0}$</td>
<td>O(500)</td>
<td>[0, 4.0]</td>
</tr>
<tr>
<td>$B^0 \to D(\pi\pi)K^{*0}$</td>
<td>O(100)</td>
<td>[0, 14.0]</td>
</tr>
</tbody>
</table>

Plot taken from G. Marchiori's ICHEP 2008 talk

$\chi^2$ fit to the 6 rates is performed

- Yield and bkgds as shown in table

Constraints
- $\delta_{D(K\pi)} = (22^{+14}_{-16})^\circ$ from CLEO-c
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Assumed Inputs
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Results

<table>
<thead>
<tr>
<th>$\delta_{B^0}$ ($^\circ$)</th>
<th>0</th>
<th>45</th>
<th>90</th>
<th>135</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_\gamma$ ($^\circ$)</td>
<td>6.2</td>
<td>10.8**</td>
<td>12.7**</td>
<td>9.5</td>
<td>5.2</td>
</tr>
</tbody>
</table>

(A phase shift of 180$^\circ$ is required when used within the ADS formalism)

**(Values where the distribution of $\gamma$ fit results returned was non-Gaussian; the RMS values are therefore quoted)**

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[@LHCb-2007-050] [LHCb-2008-031]
Summary

• With just 2 fb\(^{-1}\) of data, LHCb will be able to harness the power of the ADS+GLW methods to perform precision measurements of $\gamma$

$$\sigma_\gamma(B^{\pm}) \sim (7.0 - 9.5)^\circ$$
$$\sigma_\gamma(B^0) \sim (5.0 - 13.0)^\circ$$

• External constraints from CLEO-c hugely important in this measurement ($\delta_{D(K\pi)}$, $R_{K3\pi}$, $\delta_{D(K3\pi)}$)

• Yet more modes to consider:
  • $D \to K\pi\pi^0$ (ADS)
  • $B^\pm \to D^*K^\pm$ (Bondar-Gershon)

• Ultimate precision will be achieved from “global” fit to all LHCb $B^\pm \to DK^\pm$ results (G. Wilkinson’s talk in this session)