Prospects for measuring CP violating asymmetries at LHCb

Jim Libby, The University Of Oxford, on behalf of the LHCb collaboration

• An overview of LHCb and its advantages
  • Trigger
  • Particle ID
  • Proper time resolution

• Specific examples in several channels (see N. Ellis talk for others)

• Summary and conclusions
LHCb motivation and overview

At a luminosity of $2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ ⇒

$$4.5 \times 10^{11} \ B_d + \bar{B}_d \ 	ext{and} \ 1.3 \times 10^{11} \ B_s + \bar{B}_s \ 	ext{per year}$$

Statistics allow accurate measurements of $\alpha, \beta, \gamma, \delta\gamma$ and $x_s$ in modes with small branching fraction ($O(10^{-5})$) ⇒

• Over constraint of unitarity triangles

LHCb: dedicated experiment to exploit this potential

Optimised for B-physics:

• Forward geometry: correlated production, low $p_t$ thresholds, Roman Pot vertex

• ‘Low’ luminosity: optimised for single interactions
Experimental requirements for LHCb physics

Efficient trigger for non-leptons

- $B_d^0 \rightarrow D^* \pi, D^* 3\pi (\gamma)$
- $B^0_s \rightarrow D_s \pi (\chi_s)$
- $B_d^0 \rightarrow \rho^+ \rho^- (\gamma)$
- $B_d^0 \rightarrow K^{*0} K^{*0} (\gamma)$

Distinguish $\pi/K$

- $B_d^0 \rightarrow DK^{*0} (\gamma)$
- $B \rightarrow K^* \gamma$ (rare decay)
- $B_s^0 \rightarrow K^+ K^- (\gamma)$
- $B_s^0 \rightarrow K^{*+} K^{*-} (\gamma)$
- $B_s^0 \rightarrow \pi^+ \pi^- (\alpha, \gamma)$

Resolve $\chi_s$

- $B_d^0 \rightarrow J/\psi K_s (\beta)$
- $B_d^0 \rightarrow J/\psi \rho^0 (\delta \gamma)$
- $B_s^0 \rightarrow J/\psi K_s (\gamma)$

Lepton Trigger

- $B_s^0 \rightarrow \mu^+ \mu^- (\text{rare decay})$

Channels discussed in this talk

Hence need for:

- efficient trigger for hadrons and leptons
- $\tau$ resolution
- particle ID (RICH)

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Triggering on B events at LHC

Trigger is primary challenge:

- $\sigma_{\text{inel}}/\sigma_{\text{bb}} \approx 160$, 25 ns between interactions and low branching fractions eg $B \rightarrow \pi \pi \approx 5 \times 10^{-6}$

Pre-trigger (level 0)

- suppression ×40 and latency 4 µs
- high $p_t \mu^\pm$, $e^\pm$, $\gamma$ and hadrons
- pile up veto (9.3 MHz)

Vertex trigger (level 1)

- suppression ×25 and latency 500 µs
- step 1) search in 2d projection for high impact parameter tracks
- step 2) Try to find 3d vertices using tracks from 1
- + Level 0 combined with vertex tracking

High level triggers (level 2 and 3)

- suppression ×8 and ×25
- level 2) refined vertex trigger
- level 3) start of offline reconstruction

Trigger efficiency $\sim 30\%$
for ‘useful’ b-events
in most channels of interest
LHCb Vertex Locator (VELO)

TP design: 17 stations distributed along 1m

- Stations mounted in Roman pots and withdrawn during injection $\Rightarrow$ 1cm from beam during physics
- Si strip detectors (double-metal readout)
- Radiation damage may lead to replacement after a few years - open geometry makes this practical

Proper time resolution of 43 fs $\Rightarrow$ sensitivity to $B_s$ oscill. up to $x_s \sim 75$ in 1 year.

Reduced dilution in $B_s$ modes of interest

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Hadron ID

Two reasons why hadron ID is very important to LHCb

1) Suppress background in certain final states (e.g. $B_s \rightarrow D_s K$) ⇒ (high momentum $K/\pi$ separation)

2) Flavour tag of identified $K^\pm$ from accompanying $B$ (b$\rightarrow$ c$\rightarrow$s) (low momentum $K/\pi$ separation)

IMPORTANT for hadron triggered events

Requires $K/\pi$ separation range of $1 < p < 100$ GeV/c ⇒ RICHes

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LHCb RICH system

3 different radiators gives large range of $\pi/K$ separation

Pattern recognition algorithms designed for high multiplicity LHC environment

Upstream- RICH1
$(1 < p < 70 \text{ GeV/c})$

Downstream - RICH2
$(20 < p < 100 \text{ GeV/c})$
$B_d \rightarrow \pi^+ \pi^-$

$B_d \rightarrow \pi^+ \pi^-$ would be the ideal decay in which to measure $\alpha$: 

$$A(t) = A_{\text{dir}} \cos(\Delta M t) + A_{\text{mix}} \sin(\Delta M t)$$

2 PROBLEMS

1. Two-body background ($B_d \rightarrow K\pi$, $B_s \rightarrow K\pi$ and $B_s \rightarrow K\bar{K}$) which can have own CP asymmetry

$\Downarrow$ RICH extracts pure sample to study with background at a negligible levels

2. $A_{\text{dir}}$ and $A_{\text{mix}}$ are related to $\alpha$ and 2 variables which depend on the Penguin process $\Rightarrow |P/T|$ and $\delta_{P-T}$

Fixing $|P/T|$ and assuming it is known perfectly:

$$\sigma_\alpha \sim 2 - 5^\circ \text{ in 1 year}$$ (depends on parameter values)

However, $|P/T|$ unlikely to be known to better than 10% which gives systematic error of $O(\sigma_\alpha \text{ 1 year})$
$B_d \rightarrow \rho \pi$

Alternative measure of $\alpha$ from the study of $B_d \rightarrow \rho \pi$: $B_d^0 \rightarrow \rho^- \pi^+ \rightarrow \pi^+ \pi^- \pi^0$

**Interferences**

- Strong phase + $\alpha$
- $\alpha$

Time dependent analysis of Dalitz plot leads to determination of $\alpha$, tree and penguin amplitudes.

![Dalitz Plot - $B_d^0 \rightarrow \pi^+ \pi^- \pi^0$](image)

- $\alpha = 1.35$ rad.
- $s^+(\text{Gev}^2/c^4)$
$B_d \to \rho \pi$

- Experimental challenges same as $B \to \pi \pi$ with the addition of reconstruction and association of $\pi^0$
- Full simulation studies performed and LHCb expects to reconstruct 1.3k events per year
- $\sigma_{MB} \sim 50$ MeV and B/S = 0.75
- 9 parameter un-binned likelihood used to extract $\alpha$, tree and penguin parameters
- So far a stand alone simulation study with only Dalitz plot acceptance applied
- Can determine $\alpha$ unambiguously
- Still several systematic problems with acceptance, background, EW penguins, other resonances($\rho^\prime$) to be investigated….

$\sigma_\alpha \sim 3-6^\circ$ in 1 year
-2\beta-\gamma \text{ from } B_d \to D^*-\pi^+ , B_d \to D^- \text{ a}_1

- Theoretically clean $\Rightarrow$ no penguins
- Four time dependent decay rates
- Requires an efficient hadron trigger
- Asymmetry is very small ($O(1\%)$) therefore high statistics required:
  - exclusive $D^*\pi$ reconstruction
    $\sim 80 \text{ k/year with } S/B\sim 12$
  - inclusive $D^*\pi$ reconstruction
    $\sim 260 \text{ k/year with } S/B\sim 3$

Uncertainty due to:

$$|\xi| = |A(B_d \to D^{*+}\pi^-)|/|A(B_d \to D^{*-}\pi^-)|$$

expected to be known to 10 % or better

Addition of $B_d \to D^*_1$ channel ($\sim 360 \text{ k/year}$) will enhance precision but requires full angular analysis
New strategies for measuring CKM phases

Several new strategies for extracting the CKM phases have been studied during recent SM workshop (1 year sensitivities given)

- Combination of $B_d \rightarrow \pi K$ (both charged and neutral B) to extract $\gamma$
  - ambiguous solutions; $\sigma_\gamma = 2^\circ$ to $7^\circ$

Various strategies exploiting U-spin symmetry ($d \leftrightarrow s$)

- Combine $B_s \rightarrow KK$ and $B_d \rightarrow \pi \pi$ to simultaneously extract $\gamma$ and $\beta$:
  - fix $\beta$; $\sigma_\gamma \sim 4^\circ$
  - dependence on $\Delta M_s$ and exactness of U-spin symmetry
- the hadron ID capabilities of LHCb excel ⇒

- Combining $B_{d(s)} \rightarrow D^+_{d(s)} D^-_{d(s)}$ again to extract $\gamma$:
  - $O(100k)$ events per year
  - $\sigma_\gamma$ order a few degrees

- Combining $B_{d(s)} \rightarrow J/\psi K^0_s$ to extract $\gamma$:
  - need to improve S/B

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Summary

• LHCb is a 2nd generation b-sector CP violation experiment:
  – Massive statistics
    • $\sim 10^{12}$ $b\bar{b}$ events per year
    • trigger efficient including hadrons
  – Particle ID
    • Reduces background in many channels to low level
    • good kaon flavour tag
  – Proper time resolution ($\sigma_\tau \sim 40$ fs)
    • Precision measurements in $B_s$ system
• Not mentioned here: systematics, rare decays (N. Ellis) also $B_c$, $B$-baryons, $\tau$ and charm
• Leads to an excellent capability to study CP violation within the SM and beyond
B\(_s\) Oscillations

- Using \(B_s \rightarrow D_s \pi\)
- \(\chi_s\) up to 75 can be measured
- \(\Delta M_s\) up to 48 ps\(^{-1}\)
- For \(\Delta M_s = 20\) ps\(^{-1}\); \(\sigma(\Delta M_s) = 0.011\) ps\(^{-1}\)
- Also precision measurement of \(\Delta \Gamma_s / \Gamma_s\)

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**γ from B_s → D_s K**

- B_s allows new measures of the parameter γ. Asymmetry in B_s, B_s → D_s ±K allows extraction of γ-2δγ (analogue of B_d → D^*-π^+).
- **Require:**
  - » B_s oscillation sensitivity again
  - » Hadron ID ⇒ RICH

LHCb expects 2.5k reconstructed and tagged events per year

\[ \sigma(\gamma-2\delta\gamma)_{1\text{year}} = 6-13^\circ \]

Depends on strong phase difference, γ-2δγ and \(x_s\)

Not discussed further here but γ can also be extracted from B_d → D^0K^*0 and B^± → D^0K^±.
- low rates \((10^{-7}/10^{-8})\) only make these possible at forward experiments with good hadronic ID.
## Trigger performance

### Example decays

<table>
<thead>
<tr>
<th>Channel</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_d \to \pi \pi )</td>
<td>( B_{d} \to J/\psi (\mu\mu)K^0 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Good efficiency in all final states including hadronic
- Suppression distributed amongst levels

<table>
<thead>
<tr>
<th>Pretrigger ( \varepsilon )</th>
<th>76%</th>
<th>88%</th>
<th>54%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex trigger ( \varepsilon ) (Level 1)</td>
<td>48%</td>
<td>50%</td>
<td>56%</td>
</tr>
<tr>
<td>Annual yield after Level 1</td>
<td>54k</td>
<td>203k</td>
<td>17k</td>
</tr>
<tr>
<td>Annual yield after reconstruction and tagging</td>
<td>5k</td>
<td>37k</td>
<td>2.5k</td>
</tr>
</tbody>
</table>

Huge statistics of LHC propagate to analysis