Angular analysis of the decay $B_d \rightarrow K^* \mu^+ \mu^-$ at LHCb

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Introduction

- Flavour changing neutral current decay ($\rightarrow$ loop), described by 3 angles ($\theta_l$, $\phi$, $\theta_K$) and di-$\mu$ invariant mass $q^2$
- Sensitive to magnetic and vector and axial semi-leptonic penguin operators
- Many observables where hadronic uncertainties cancel
  - Forward-backward asymmetry $A_{FB}$ of $\theta_l$ distribution (zero-crossing point)
- Pre-EPS measurements from Babar, Belle and CDF

BABAR: PRL 102, 091803 (2009); CDF: Note 10047 (2010); Belle: PRL 103, 171801 (2009)
Strategy

• Select signal events
• Correct for the effect of the reconstruction and selection requirements – “acceptance effect” – using simulation
  – Model independent correction
  – Validate by performing angular analysis of $B_d \rightarrow K^* J/\psi$ control channel, where physics parameters known from elsewhere
  – Check simulation with a range of control channels
• Fit for observables

• First measurements from LHCb from $309 \text{ pb}^{-1}$ data taken in 2011
• Focus on theoretically clean angular observables e.g. $A_{FB}$, $F_L$ and $d\Gamma/dq^2$
Selection

- Selection:
  - Remove c$\bar{c}$ resonances
    - $2946 < m_{\mu\mu} < 3176$ MeV/c$^2$
    - $3586 < m_{\mu\mu} < 3776$ MeV/c$^2$
  - Treat peaking backgrounds with a specific set of criteria
    ($\rightarrow$ residual backgrounds $\sim$3% of signal)
  - Combinatorial backgrounds reduced with a Boosted Decision Tree (BDT) selection

- Use Belle $q^2$ binning and an (overlapping) $1 < q^2 < 6$ GeV$^2$/c$^4$ bin favoured by theorists
Boosted Decision Tree

• Train BDT on 2010 data i.e. totally independent of 2011 data sample
  – Signal sample – $B_d \rightarrow K^* J/\psi$ data
  – Bkgrd sample – $B_d \rightarrow K^* \mu\mu$ mass sideband events

• Resulting selection
  – Background-to-signal ratio ~0.3
    Comparable to B-factories
  – Does not induce further biases in $\cos\theta_L$, $\cos\theta_K$ and $q^2$ cf reconstruction
    biases introduced are primarily from detector geometry – easy to model
Acceptance Correction

- Correct angular and $q^2$ distributions for the effect of the detector and selection

- To be model independent, use an event-by-event weight which is determined on the basis of the $\theta_L$, $\theta_K$, $q^2$ of the signal candidates that are found

- Simulation quality verified with range of control channels ($B_d \rightarrow K^* J/\psi$, $J/\psi \rightarrow \mu\mu$, $D^* \rightarrow D^0(K\pi)\pi$)
  - Tracking efficiency
  - Hadron (mis-)identification probabilities
  - Muon (mis-)identification
  - Overall momentum and $\eta$ distributions

Weight depends on $\cos \theta_K$

Vast majority of events have weights $\sim 1$
Fit Procedure and Validation

• Simultaneous fit to the 1d projections of $\cos \theta_L$, $\cos \theta_K$ and $m_{K\pi\mu\mu}$ in bins of $q^2$
  - Events weighted according to acceptance correction
  - Use Bayesian approach to construct stat. errors with flat prior over physical region
  - Systematics effects are very small and can be reduced with further data
  - Cross-check with a simple counting approach (don’t use angular distributions)

• Validate fitting on $B_d \to K^*J/\psi$
  - $A_{FB}$ consistent with zero, as expected
  - s-wave contribution induces an asymmetry in $\cos \theta_K$ distribution, $A_{FB}^K$
  - Acceptance correction makes $\cos \theta_K$ asymmetric→symmetric
  - Variation of $A_{FB}^K$ with $m_{K\pi}$ matches BaBar data( **) across $m_{K\pi}$ range

( **) BABAR: PRD 76, 031102 (2007)
$B_d \rightarrow K^{*}\mu\mu$ yields

$0.00 < q^2 < 2.00 \text{ GeV}^2/c^4$

$2.00 < q^2 < 4.30 \text{ GeV}^2/c^4$

$4.30 < q^2 < 8.68 \text{ GeV}^2/c^4$

$10.09 < q^2 < 12.86 \text{ GeV}^2/c^4$

$14.18 < q^2 < 16.00 \text{ GeV}^2/c^4$

$16.00 < q^2 < 19.00 \text{ GeV}^2/c^4$
$B_d \rightarrow K^{*\mu\mu}$ yields

<table>
<thead>
<tr>
<th>$q^2$ (GeV$^2$)</th>
<th>$n_{stg}$</th>
<th>$n_{bkg}$</th>
<th>significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 &lt; q^2 &lt; 2$</td>
<td>$40.9 \pm 7.5$</td>
<td>$14.4 \pm 8.5$</td>
<td>7.7</td>
</tr>
<tr>
<td>$2 &lt; q^2 &lt; 4.3$</td>
<td>$23.3 \pm 6.2$</td>
<td>$15.3 \pm 8.6$</td>
<td>4.9</td>
</tr>
<tr>
<td>$4.3 &lt; q^2 &lt; 8.68$</td>
<td>$93.3 \pm 11.3$</td>
<td>$30.0 \pm 12.5$</td>
<td>11.7</td>
</tr>
<tr>
<td>$10.09 &lt; q^2 &lt; 12.9$</td>
<td>$57.3 \pm 8.8$</td>
<td>$18.6 \pm 9.7$</td>
<td>9.3</td>
</tr>
<tr>
<td>$14.18 &lt; q^2 &lt; 16$</td>
<td>$42.2 \pm 6.8$</td>
<td>$3.6 \pm 4.7$</td>
<td>10.1</td>
</tr>
<tr>
<td>$16 &lt; q^2 &lt; 19$</td>
<td>$48.1 \pm 7.8$</td>
<td>$6.7 \pm 6.4$</td>
<td>9.2</td>
</tr>
<tr>
<td>$1 &lt; q^2 &lt; 6$ GeV$^2$</td>
<td>$70.0 \pm 10.2$</td>
<td>$32. \pm 3.2$</td>
<td>9.4</td>
</tr>
<tr>
<td>Full</td>
<td>$302.3 \pm 20.1$</td>
<td>$91.0 \pm 5.4$</td>
<td>–</td>
</tr>
</tbody>
</table>
$A_{FB}$ Measurement

Theory predictions from C.Bobeth et al.,
arXiv:1105.0376v2
In $1<q^2<6$ GeV$^2/c^4$ bin,
- $A_{FB} = -0.10 \pm 0.14 \pm 0.05$
  c.f. Belle $0.26^{+0.27}_{-0.30} \pm 0.07$

Theory predictions from C.Bobeth et al., arXiv:1105.0376v2
$F_L$ Measurement

Theory predictions from C. Bobeth et al., arXiv:1105.0376v2
In $1 < q^2 < 6 \text{ GeV}^2/\text{c}^4$ bin,

- $F_L = 0.57^{+0.11}_{-0.10} \pm 0.03$
- c.f. Belle $0.67 \pm 0.23 \pm 0.07$

Theory predictions from C. Bobeth et al., arXiv:1105.0376v2
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Conclusions

• Angular analysis of $B_d \rightarrow K^* \mu^+ \mu^-$
  – $A_{FB}$, $F_L$ and $d\Gamma/dq^2$ measured as function of $q^2$ with 309pb$^{-1}$ of LHCb data taken in 2011
  – All three measurements show good agreement with the SM, no evidence for a large asymmetry in the low $q^2$ region as hinted at by previous experiments
  – Errors smaller than previous measurements and are statistically dominated
Backup
Search for $B^+ \rightarrow \pi^- \mu^+ \mu^+$ and $B^+ \rightarrow K^- \mu^+ \mu^+$

- Lepton Flavour Violating decays
  - $(\Delta L=2)$ strictly forbidden in SM
  - Sterile Majorana $\nu$ of mass $O(1\text{GeV}/c^2)$ could enhance BR significantly

- Analysis Strategy
  - Tight selection, use ‘opposite sign’ $B^+ \rightarrow K^- \mu^+ \mu^-$ decays as a proxy for signal
  - Normalise to $B^+ \rightarrow J/\psi K^+$
  - Detector performance measured from control channels used to estimate peaking background

- Observed signal / background
  - $<0.3$ (0.1) background events expected in $\pi\mu\mu$ ($K\mu\mu$)
  - Zero events observed in both signal and mass sideband regions
Search for $B^+ \rightarrow \pi^+ \mu^+ \mu^+$ and $B^+ \rightarrow K^- \mu^+ \mu^+$

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  - Normalise to $B^+ \rightarrow J/\psi K^+$
  - Detector performance measured from control channels used to estimate peaking bkgrd

- Observed signal / background
  - $<0.3$ (0.1) bkgrd evts expected in $\pi \mu \mu$ ($K \mu \mu$)
  - Zero events observed in both signal and mass sideband regions

Observed limit @ 90% CL
$BR(B^+ \rightarrow K^- \mu^+ \mu^+) < 4.3 \times 10^{-8}$
$BR(B^+ \rightarrow \pi^+ \mu^+ \mu^+) < 4.5 \times 10^{-8}$

Factor 40(30) improvement cf previous best limit (CLEO)
• Search for $B^+ \rightarrow \pi^- \mu^+ \mu^+$, $B^+ \rightarrow K^- \mu^+ \mu^+$
  
  – Observed limit @ 90% CL
    • $\text{BR}(B^+ \rightarrow K^- \mu^+ \mu^+) < 4.3 \times 10^{-8}$
    • $\text{BR}(B^+ \rightarrow \pi^- \mu^+ \mu^+) < 4.5 \times 10^{-8}$

  – Factor 40(30) improvement cf previous best limit (CLEO)
Peaking Backgrounds

• A number of vetos are introduced to deal with peaking bkgrds e.g.
  – $B_s \rightarrow \phi \mu^+ \mu^-$ with $K \rightarrow \pi$
  – $B_d \rightarrow K^*J/\psi$ with $\pi(K) \rightarrow \mu$ and $\mu \rightarrow \pi(K)$ swaps [evades $J/\psi$ vetos]
  – $B_d \rightarrow K^*\mu\mu$ with $K \rightarrow \pi$ and $\pi \rightarrow K$

  Completely negligible impact on signal

• Residual background (after application of BDT selection also):

<table>
<thead>
<tr>
<th>Source</th>
<th>Quantity</th>
<th>Signal Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \rightarrow \phi \mu^+ \mu^-$</td>
<td>2.3</td>
<td>0.1</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^*0J/\psi$</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^*0\mu^+ \mu^-$</td>
<td>1.2</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.2</strong></td>
<td><strong>0.5</strong></td>
</tr>
</tbody>
</table>

→ residual background is ~3% of signal – only ~0.7% of this can affect asymmetry - $B_d \rightarrow K^*\mu\mu$ background flips B and B
Likelihoods

$1 < q^2 < 6 \text{ GeV}^2/c^4$
Likelihoods

0 < q^2 < 2 GeV^2/c^4

2 < q^2 < 4.3 GeV^2/c^4

4.3 < q^2 < 8.68 GeV^2/c^4

10.09 < q^2 < 12.9 GeV^2/c^4

14.18 < q^2 < 16 GeV^2/c^4

16 < q^2 < 19 GeV^2/c^4
Errors and Physical Region

• Angular equations → pdf negative if $A_{FB} < 3/4(1-F_L)$

• Statistical errors
  – Use Bayesian approach to construct errors with flat prior over physical region
    • The central value quoted is that with the largest likelihood
    • Errors estimated by performing a profile-likelihood scan over the plane and integrating a 68% CL region of the likelihood distribution

• Systematics effects are small and can be reduced with further data