Angular analysis of $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$ with the ATLAS Experiment

Tamsin Nooney

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Motivation and background

Analysis Strategy:

- Angular analysis parameterisation
- Monte Carlo and backgrounds
- Fit infrastructure and validation

Summary
Why $B_d^0 \rightarrow K^{*0} \mu^+\mu^-$?

The (semi-)rare decay $B_d^0 \rightarrow K^{*0} \mu^+\mu^-$ is a FCNC decay and thus proceeds via several competing loop diagrams in the Standard Model, allowing for substantial new physics contributions.

➔ Able to test the SM (QCD, effective theories etc.).
➔ We can indirectly search for new physics at scales beyond the reach of the LHC.
What are we measuring?

The decay $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$, where $K^{*0} \rightarrow K^+ \pi^-$, is described by four kinematic variables:

1) The invariant mass $q^2$ of the dimuon system.
2) $\theta_L$
3) $\theta_K$
4) $\phi$

Three angles describing the geometrical configuration of the final state as shown.

The angular distribution is factorised in terms of the helicity angle distributions according to a chosen angular PDF and any observables of interest are extracted.
The differential decay rate of $B_d^0 \rightarrow K^0* \mu^+ \mu^-$:

$$\frac{1}{d(\Gamma + \Gamma)/dq^2} \frac{d^3(\Gamma + \Gamma)}{d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell ight. \\
- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \\
+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

- $F_L$ is the longitudinal polarisation of the $K^{*0}$.
- $A_{FB}$ is the forward-backward asymmetry of the muons.
- $S_i$ represent different combinations of the $K^{*0}$ spin amplitudes.
The two 1D PDFs used to extract the parameters $F_L(q^2)$ and $A_{FB}(q^2)$ in 2011 analysis:

\[
\frac{1}{\Gamma} \frac{d^2 \Gamma}{d \cos \theta_\ell dq^2} = \frac{3}{4} F_L(q^2) (1 - \cos^2 \theta_\ell) + \frac{3}{8} (1 - F_L(q^2)) (1 + \cos^2 \theta_\ell) + A_{FB}(q^2) \cos \theta_\ell,
\]

\[
\frac{1}{\Gamma} \frac{d^2 \Gamma}{d \cos \theta_K dq^2} = \frac{3}{2} F_L(q^2) \cos^2 \theta_K + \frac{3}{4} (1 - F_L(q^2)) (1 - \cos^2 \theta_K).
\]

➔ The product of these distributions is an approximation of the true angular distribution. We aim to generalise away from this form for that reason.

➔ Fitting to $f(\cos \theta_\ell)f(\cos \theta_K)$ improves the precision on $F_L$, but also introduces a small bias on that quantity.

✗ Incomplete information.
✗ Form factor (FF) dependent observables at leading order.
The 2011 analysis described in ATLAS-CONF-2013-038 used two 1D PDFs to extract the angular distribution parameters $F_L(q^2)$ and $A_{FB}(q^2)$.

Total signal event yield of 454 using 4.9 fb$^{-1}$ of data.

The angular observables are compared to SM predictions [C. Bobeth et al. arXiv:1105.2659].

<table>
<thead>
<tr>
<th>$q^2$ range (GeV$^2$)</th>
<th>$N_{sig}$</th>
<th>$A_{FB}$</th>
<th>$F_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00 &lt; $q^2$ &lt; 4.30</td>
<td>19 ± 8</td>
<td>0.22 ± 0.28 ± 0.14</td>
<td>0.26 ± 0.18 ± 0.06</td>
</tr>
<tr>
<td>4.30 &lt; $q^2$ &lt; 8.68</td>
<td>88 ± 17</td>
<td>0.24 ± 0.13 ± 0.01</td>
<td>0.37 ± 0.11 ± 0.02</td>
</tr>
<tr>
<td>10.09 &lt; $q^2$ &lt; 12.86</td>
<td>138 ± 31</td>
<td>0.09 ± 0.09 ± 0.03</td>
<td>0.50 ± 0.09 ± 0.04</td>
</tr>
<tr>
<td>14.18 &lt; $q^2$ &lt; 16.00</td>
<td>32 ± 14</td>
<td>0.48 ± 0.19 ± 0.05</td>
<td>0.28 ± 0.16 ± 0.03</td>
</tr>
<tr>
<td>16.00 &lt; $q^2$ &lt; 19.00</td>
<td>149 ± 24</td>
<td>0.16 ± 0.10 ± 0.03</td>
<td>0.35 ± 0.08 ± 0.02</td>
</tr>
<tr>
<td>1.00 &lt; $q^2$ &lt; 6.00</td>
<td>42 ± 11</td>
<td>0.07 ± 0.20 ± 0.07</td>
<td>0.18 ± 0.15 ± 0.03</td>
</tr>
</tbody>
</table>
2011 results

$F_L$ and $A_{FB}$ as a function of $q^2$ measured by ATLAS (black dots) with the results of other experiments shown in conjunction [ATLAS-CONF-2013-038].

For 2012 data, we will do 2D and 3D fits to get the full set of observables.

BaBar Collaboration [arXiv:0804.4412]  
CDF Collaboration [arXiv:1108.0695]  
Belle Collaboration [arXiv:0904.0770]  
LHCb Collaboration [LHCb-CONF-2012-00]
Traditional angular analysis

We will perform the traditional full angular analysis of the data using:

\[
\frac{1}{\Gamma} \frac{d^5 \Gamma}{d \cos \theta_L d \cos \theta_K d \phi dq^2} = \frac{9}{16 \pi} \left\{ \left( \frac{2 F_S(q^2)}{3} + \frac{4 A_S(q^2)}{3} \cos \theta_K (1 - \cos^2 \theta_L) \right) \\
+ (1 - F_S(q^2)) \left( \frac{2 F_L(q^2)}{3} \cos^2 \theta_K (1 - \cos^2 \theta_L) + \frac{1 - F_L(q^2)}{2} (1 - \cos^2 \theta_K)(1 + \cos^2 \theta_L) \right) \\
+ \frac{1 - F_L(q^2)}{2} A_T(q^2) (1 - \cos^2 \theta_K)(1 - \cos^2 \theta_L) \cos 2\phi \\
+ \frac{4 A_{FB}(q^2)}{3} (1 - \cos^2 \theta_K) \cos \theta_L \\
+ A_{Im}(q^2) (1 - \cos^2 \theta_K)(1 - \cos^2 \theta_L) \sin 2\phi \right\}\]

➔ Can add a scalar component to the fit introducing two new parameters.
➔ The full distribution introduces two additional parameters to extract.
➔ 6 observables of interest are: \( F_L, A_{FB}, F_S, A_S, A_T, A_{Im} \).

✔ Complete information.
✗ FF dependent observables at leading order.
Optimised observable analysis

We will perform a FF independent analysis:

\[
\frac{1}{(\Gamma + \bar{\Gamma})} \frac{d^4(\Gamma + \bar{\Gamma})}{d\cos\theta_i d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2\theta_K + F_L \cos^2\theta_K + \frac{1}{4} (1 - F_L) \sin^2\theta_K \cos 2\theta_i - F_L \cos^2\theta_K \cos 2\theta_i + S_3 \sin^2\theta_K \sin^2\theta_i \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_i \cos \phi + S_5 \sin 2\theta_K \sin \theta_i \cos \phi + S_6 \sin^2\theta_K \cos \theta_i + S_7 \sin 2\theta_K \sin \theta_i \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_i \sin \phi + S_9 \sin^2\theta_K \sin^2\theta_i \sin 2\phi \right].
\]

➔ In addition to $F_L$, we can measure the FF independent parameters.

\[
P_i'(s,c) = \frac{S_i^{(s,c)}}{\sqrt{F_L(1 - F_L)}}
\]

➔ 9 observables to measure in total.

➔ Can reduce the number of observables directly by **folding** the differential decay rate and exploiting the symmetries in the angular expressions, e.g.:

✔ Complete information.
✔ FF independent observables at leading order.
Optimised observable analysis

We will perform a FF independent analysis:

\[
\frac{1}{(\Gamma + \bar{\Gamma})} \frac{d^4(\Gamma + \bar{\Gamma})}{d\cos \theta_i d\cos \theta_K d\phi dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \\
+ \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_i - F_L \cos^2 \theta_K \cos 2\theta_i \\
+ S_3 \sin^2 \theta_K \sin^2 \theta_i \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_i \cos \phi \\
+ S_5 \sin 2\theta_K \sin \theta_i \cos \phi + S_6 \sin^2 \theta_K \cos \theta_i + S_7 \sin 2\theta_K \sin \theta_i \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_i \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_i \sin 2\phi \right].
\]

➔ In addition to $F_L$, we can measure the FF independent parameters.

➔ Can reduce the number of observables directly by **folding** the differential decay rate and exploiting the symmetries in the angular expressions, e.g.:

\[
\phi \rightarrow -\phi \quad \text{if} \quad \phi < 0 \\
\theta_\ell \rightarrow \pi - \theta_\ell \quad \text{if} \quad \theta_\ell > \frac{\pi}{2}
\]

➔ Obtain a formula with only $S_5$ among the $S_i$ observables

✔ Complete information.

✔ FF independent observables at leading order.
The CP asymmetry, $A_{CP}$, for $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$ is defined as:

$$A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$$

The data gives us:

$$N_{obs} = (1 - \omega)N + \overline{\omega}\overline{N} \quad \text{and} \quad \overline{N}_{obs} = (1 - \overline{\omega})\overline{N} + \omega N$$

Hence:

$$A_{CP} = \frac{(1 - \Delta\omega)\overline{N}_{obs} - (1 + \Delta\omega)N_{obs}}{(1 - \overline{\omega} - \omega)(\overline{N}_{obs} + N_{obs})}$$

$A_{CP}$ is predicted to be of the order $<10^{-2}$ in the SM. [Christoph Bobeth et al. JHEP07(2008)106]

The measurement is sensitive to physics beyond the SM.
Monte Carlo and backgrounds

Signal:

➔ Generated using Pythia.
➔ $\cos \theta_K$, $\cos \theta_L$ and $\phi$ have non trivial acceptances to be extracted.

Backgrounds:

➔ Extensive studies of potential background modes of concern.

➔ $B^+ \rightarrow (J/\psi, \psi(2S)) K^{*+}$
  Expect combinatorial background.

➔ $B_d \rightarrow (J/\psi, \psi(2S)) K^*$
  Resonant regions = control sample.

➔ $B_s \rightarrow (J/\psi, \psi(2S)) \phi$
  Expect feed through to be small given $B_s$ vs $B_d$ mass difference.

➔ $c\bar{c} \rightarrow \mu^+\mu^-X$
  To study backgrounds above open charm threshold.
→ New fitting machinery in place with the possibility of implementing the different parametrisations.

→ The new fit framework means we can work in two main directions, and quickly change between sub-configurations:

1) Traditional angular fit configuration:
2) Form Factor Independent angular fit configuration.

→ Will move to a 1 step fit paradigm.

→ Possibility of adapting to fine binning (c.f. LHCb’s results shown at Moriond ’15).

→ $A_{CP}$ can be studied.
The analysis of these data can provide a number of results:

- Traditional angular analysis.
- Form factor independent angular analysis.
- $A_{CP}$ measurement.
- Differential branching fraction.

Monte Carlo has been produced for the main backgrounds.

Ntuple production is under way.

A lot of development effort has gone into the fit infrastructure.

Traditional and form factor independent PDFs have been set up and are ready for use.