Electroweak penguin decays as probes of physics beyond the Standard Model

Mitesh Patel (Imperial College London)
LHC Seminar, 8th May 2012

on behalf of the LHCb Collaboration
The interest in EW penguins

- Standard Model has no tree level Flavour Changing Neutral Currents (FCNC)

- FCNC only occur as loop processes, proceed via penguin or box diagrams – sensitive to contributions from new (virtual) particles

  $\rightarrow$ Probe masses $> E_{CM}$ of the accelerator

- e.g. $B^0 \rightarrow K^*\gamma$ decay
A historical example – $B^0 \rightarrow K^{*0} \gamma$

- **In SM**: occurs through a dominating $W$-$t$ loop
- **Possible NP diagrams**:
- Observed by CLEO in 1993, two years before the direct observation of the top quark
  - $BR$ was expected to be $(2-4) \times 10^{-4}$
  - measured $BR = (4.5 \pm 1.7) \times 10^{-4}$

Theoretical Foundation

• The Operator Product Expansion is the theoretical tool that underpins rare decay measurements – rewrite SM Lagrangian as:

\[ \mathcal{L} = \sum_i C_i O_i \]

- “Wilson Coefficients” \( C_i \)
  • Describe the short distance part, can compute perturbatively in given theory
  • Integrate out the heavy degrees of freedom that can't resolve at some energy scale \( \mu \)
- “Operators” \( O_i \)
  • Describe the long distance, non-perturbative part involving particles below the scale \( \mu \)
  • Account for effects of strong interactions and are difficult to calculate reliably

→ Form a complete basis – can put in all operators from NP/SM

• In certain observables the uncertainties on the operators cancel out – are then free from theoretical problems and measuring the Wilson Coefficients tells us about the heavy degrees of freedom – independent of model
Observables in EW penguin decays

• Measuring branching fraction of EW penguin decays → information on mass, coupling

• Can also make a different class of measurements – probe the helicity structure:
  – If decay mediated by Z boson – expect L&R-handed contributions, measure ratio of the two
  – If decay mediated by NP – ????

• Have two options:
  – (Only states with same polarisation/helicity can interfere) → measure time dependent CP violation where tag if have a B or a \( \bar{B} \)
  – Use self-tagging channels e.g. sign of \( K^\pm \) from \( K^{*0} \rightarrow K\pi \) decay indicates whether had a B or \( \bar{B} \) → angular analysis
Outline

• The LHCb detector and trigger

• Angular analysis of the decay $B^0 \rightarrow K^* \mu \mu$

• The search for the decay $B^+ \rightarrow \pi^+ \mu \mu$

• The isospin asymmetry in $B \rightarrow K^* \mu \mu$ and $B \rightarrow K \mu \mu$ decays
  – Shown in public for first time … interesting results

• $A_{CP}$ in $B^0 \rightarrow K^{*0} \gamma$

(All results from the full 1fb$^{-1}$ of integrated luminosity collected in 2011)
The Experimental Environment

- LHC produces a huge number of B decays
  - $\sigma(b\bar{b}) = 280\mu b$ @ LHC, 7TeV (**)
    (approx. linear with energy)
  - $\sigma(b\bar{b}) = 0.001\mu b$ @ B factories

- At the LHC $\sigma(pp, \text{ inelastic}) @ \sqrt{s}=7$ TeV $\sim 60$ mb, only 1/200 events contains a b quark, looking for BR $\sim 10^{-6}$-$10^{-9}$ - enormous demands on detector and trigger

$\rightarrow$ The LHCb experiment

The LHCb Experiment

- b production predominately at small polar angles 
  → forward spectrometer
The LHCb Experiment

- **B lifetime → displaced secondary vertex**
  - Need few interactions/event → operate at luminosity 10–50 times lower than central detectors
  - Vertex detector capable of picking out the displaced vertex
The LHCb Experiment

- B lifetime $\rightarrow$ displaced secondary vertex
  - Need few interactions/event $\rightarrow$ operate at luminosity 10–50 times lower than central detectors
  - Vertex detector capable of picking out the displaced vertex

![Diagram of LHCb Experiment](image-url)
The LHCb Experiment

- Precision momentum resolution → mass resolution

<table>
<thead>
<tr>
<th></th>
<th>LHCb</th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum Resolution</td>
<td>$\delta p/p = 0.4-0.6%$</td>
<td>$\delta p_T/p_T = 1-3%$</td>
<td>$\delta p_T/p_T = 5-6%$</td>
</tr>
<tr>
<td>Mass resolution $J/\psi \rightarrow \mu \mu$</td>
<td>13 MeV/c$^2$</td>
<td>28 MeV/c$^2$ (*)</td>
<td>46 MeV/c$^2$ (**)</td>
</tr>
</tbody>
</table>

The LHCb Experiment

- Events dominated by pions – separating kaons ($\rightarrow$RICH 1,2) produced in B events and muons ($\rightarrow$M1-5) critical
The LHCb Experiment

- Events dominated by pions – separating kaons ($\rightarrow$RICH 1,2) produced in B events and muons ($\rightarrow$M1-5) critical
The LHCb Trigger

- Small event size (60kB) → large bandwidth
- Allows low thresholds

<table>
<thead>
<tr>
<th><strong>L0 Hardware</strong></th>
<th>“high $p_T$” signals in calorimeter and muon systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HLT1 Software</strong></td>
<td>Partial reconstruction, selection based on one or two (dimuon) displaced tracks, muon ID</td>
</tr>
<tr>
<td><strong>HLT2 Software</strong></td>
<td>Global reconstruction (very close to offline) dominantly inclusive signatures – use MVA</td>
</tr>
</tbody>
</table>

+ Global Event Cuts for events with high multiplicity

<table>
<thead>
<tr>
<th><strong>Overall efficiency</strong></th>
<th>Charm</th>
<th>Had. B</th>
<th>Lept. B</th>
</tr>
</thead>
<tbody>
<tr>
<td>~10%</td>
<td>~40%</td>
<td>~75-90%</td>
<td></td>
</tr>
</tbody>
</table>
$B^0 \rightarrow K^{*} \mu \mu$
$B^0 \rightarrow K^* \mu \mu$

- Flavour changing neutral current $\rightarrow$ loop
- Sensitive to interference between $O_{7\gamma}$, $O_{9,10}$ and their primed counterparts
- Exclusive decay $\rightarrow$ theory uncertainty from form factors
- Decay described by three angles, $\theta_l$, $\theta_K$ and $\phi$, and $q^2 = m^2_{\mu\mu}$, self-tagging $\rightarrow$ angular analysis allows to probe helicity
- Multitude of angular observables in which uncertainties cancel to some extent e.g. $A_{FB}$ – asymmetry in $\theta_l$ distribution
\[ B^0 \rightarrow K^*_0 \mu\mu \text{ – angular analysis} \]

- Full angular distribution:
  \[
  \frac{d^4 \Gamma}{d \cos \theta_\ell d \cos \theta_K d \phi dq^2} \propto I_1 \sin^2 \theta_K + I_2 \cos^2 \theta_K + (I_5 \sin^2 \theta_K + I_7 \cos^2 \theta_K) \cos 2\theta_\ell \\
  + I_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi \\
  + I_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \\
  + (I_6 \sin^2 \theta_K \cos^2 \theta_K + I_8 \cos^2 \theta_K) \cos \theta_\ell + I_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\
  + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + I_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi
  \]

- Apply "folding" technique: \( \phi \rightarrow \phi + \pi \) for \( \phi < 0 \). This cancels terms with \( I_4, I_5, I_7, I_8 \)

- Fitting these angles allows access to angular observables where the hadronic uncertainties are under control:
  - \( F_L \), the fraction of \( K^{*0} \) longitudinal polarisation
  - \( A_{FB} \), the forward-backward asymmetry – and zero-crossing point
  - \( S_3 \propto A^2_T(1-F_L) \), the asymmetry in \( K^{*0} \) transverse polarisation
  - \( A_{IM} \), a T-odd CP asymmetry
\[ B^0 \rightarrow K^{*0}\mu\mu \text{ – angular analysis} \]

- Full angular distribution:

\[
\frac{d^4 \Gamma}{d \cos \theta_\ell \, d \cos \theta_K \, d \phi \, dq^2} \propto F_L \cos^2 \theta_K + \frac{3}{4} \left(1 - F_L\right) \left(1 - \cos^2 \theta_K\right) + \\
F_L \cos^2 \theta_K (2 \cos^2 \theta_\ell) + \\
\frac{1}{4} \left(1 - F_L\right) \left(1 - \cos^2 \theta_K\right) (2 \cos^2 \theta_\ell - 1) + \\
S_3 (1 - \cos^2 \theta_K) (1 - \cos^2 \theta_\ell) \cos 2\phi + \\
\frac{4}{3} A_{FB} (1 - \cos^2 \theta_K) \cos \theta_\ell + \\
A_{IM} (1 - \cos^2 \theta_K) (1 - \cos^2 \theta_\ell) \sin 2\phi
\]

- Apply "folding" technique: \( \phi \rightarrow \phi + \pi \) for \( \phi < 0 \). This cancels terms with \( I_4, I_5, I_7, I_8 \).

- Fitting these angles allows access to angular observables where the hadronic uncertainties are under control:
  - \( F_L \), the fraction of \( K^{*0} \) longitudinal polarisation
  - \( A_{FB} \), the forward-backward asymmetry – and zero-crossing point
  - \( S_3 \propto A_T^2 (1 - F_L) \), the asymmetry in \( K^{*0} \) transverse polarisation
  - \( A_{IM} \), a T-odd CP asymmetry
The interest in $B^0 \to K^* \mu \mu$

- Observables highly sensitive to NP contributions to $C_7^{(')}$, $C_9^{(')}$, $C_{10}^{(')}$

W. Altmannshofer et al. [arXiv:0801.1214]

- $A_{FB}$ zero crossing point particularly well predicted by theory
(Pre-LHC) Experimental Status

- Babar, Belle, and CDF have all measured angular asymmetry $A_{FB}$:

  - Measurements look consistent with each other but errors still large

  ![Graph showing measurements and theoretical predictions]

  Theory prediction from C. Bobeth et al. [arXiv:1105.0376] (and ref. therein)

LHCb Event Selection

- Use a Boosted Decision Tree to make event selection
  - Signal sample – $B^0 \rightarrow K^* J/\psi$ data (~100× more statistics than signal)
  - Bkgrd sample – $B^0 \rightarrow K^* \mu\mu$ mass sideband events
  - Use information about the event kinematics, vertex and track quality, impact parameter and particle identification information

- Remove $m_{\mu\mu}$ regions containing $B^0 \rightarrow K^* J/\psi, B^0 \rightarrow K^* \Psi(2S)$

- Number of peaking backgrounds treated with specific vetos
  - e.g. $B^0 \rightarrow K^* J/\psi$ with $\pi \leftrightarrow \mu$ swap
  → total peaking bkgrds <2% of signal
LHCb Event Selection

• With 1.0 fb$^{-1}$ find 900±34 signal events (BaBar + Belle + CDF ~ 600)
• B/S≈0.25 in region 5230 < m$_{K\pi\mu\mu}$ < 5330 MeV/c$^2$
• Selection does not induce further biases in angles and q$^2$ cf reconstruction/trigger – biases that are 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

- Use a binned acceptance correction derived from LHCb simulation

- Simulation quality verified with range of control channels which are selected from the data ($B^0 \rightarrow K^* J/\psi$, $J/\psi \rightarrow \mu\mu$, $D^* \rightarrow D^0(K\pi)\pi$)
  - Tracking efficiency
  - Hadron (mis-)identification probabilities
  - Muon (mis-)identification
  - Overall momentum and $\eta$ distributions
Fit Procedure and Validation

• Perform a unbinned maximum-likelihood fit to the mass and $(\theta_l, \theta_K, \phi)$ distribution in bins of $q^2$

• Toy simulation studies used to verify behaviour of fit

• Also validated on data using $B^0 \rightarrow K^* J/\psi$
  – $A_{FB}$ consistent with zero, as expected
  – s-wave contribution induces an asymmetry in $\cos \theta_K$ distribution, $A_{FB}^K$
  – Variation of $A_{FB}^K$ with $m_{K\pi}$ matches BaBar data (**) across $m_{K\pi}$ range

(**) BABAR: PRD 76, 031102 (2007)
Systematics

- Consider effects that are $q^2$-dependent or modify the angular distribution and might be incorrectly modelled by the simulation
  - Uncertainties on all of the data-driven corrections
  - Inclusion of an S-wave component
  - Knowledge of the detector acceptance
  - Variation of mass resolution with $q^2$
  - Uncertainty from $B(B^0 \rightarrow K^*J/\psi(\rightarrow \mu\mu))$
  - Variation of level/shape of residual peaking backgrounds
  - ...

- Effects are small, measurements are statistically dominated
Event yields

- Observe events with $>>5\sigma$ significance in each $q^2$ bin

LHCb-CONF-2012-008
Angular Analysis Results: $A_{FB}$

- Data points are centred at the average $q^2$ of events in the relevant bin, as measured from the data.
- Error bars include systematic uncertainties.
- Theory prediction from C. Bobeth et al. [arXiv:1105.0376] (and references therein) – no prediction in region between resonances.
- Most precise measurements to-date - consistent with the SM prediction.
The zero-crossing point, $q_0^2$, extracted through a 2D fit to the forward- and backward-going $m_{K\pi\mu\mu}$ and $q^2$ distributions.

- The world's first measurement of $q_0^2$, at $q_0^2 = 4.9^{+1.1}_{-1.3}$ GeV$^2$/c$^4$.

Angular Analysis Results : $S_3$

- $S_3 \propto A_T^2 (1 - F_L)$, the asymmetry in $K^{*0}$ transverse polarisation
Angular Analysis Results: $F_L, A_{\text{Im}}$

- $F_L$, the fraction of $K^{*0}$ longitudinal polarisation
- $A_{\text{Im}}$, a T-odd CP asymmetry
- No theory prediction for $A_{\text{Im}}$ – expected to be $O(10^{-3})$ in SM
B^0 \rightarrow K^*\mu\mu and B_s \rightarrow \phi\mu\mu differential BF measurements

- Differential branching fraction is extracted by fitting the mass distribution and normalising to B^0 \rightarrow K^*J/\psi, B_s \rightarrow \phi J/\psi
- B^0 \rightarrow K^*\mu\mu : 900\pm34 signal events
- B_s \rightarrow \phi\mu\mu : 77\pm10 signal events
- These are the most precise measurements to-date and are consistent with SM expectations [J.Phys.G G29 (2003) 1103–1118]
Constraints on $C_7$, $C_9$, $C_{10}$


Varying 1 Wilson coefficient at a time. $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$

*preliminary*
Constraints on $C_7$, $C_9$, $C_{10}$

*preliminary*

Varying 1 Wilson coefficient at a time. $C_i = C_i^{SM} + C_i^{NP}$

- Good agreement with SM expectations
- Complementarity between observables crucial to break degeneracies
Impact – with tree level FV


Results can be interpreted as bounds on the scale of new physics:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{j=7,9,10} \frac{e^{i\phi_j}}{\Lambda_j^2} O_j$$

~tree level generic flavour violation
Impact – with loop CKM-like FV


Results can be interpreted as bounds on the scale of new physics:

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} - \sum_{j=7,9,10} \frac{V_{tb} V_{ts}^* e^{i\phi_j}}{16\pi^2} \frac{1}{\Lambda_j^2} \theta_j \]

- Loop level CKM-like flavour violation

- Bounds are weaker in the presence of CP violation beyond the CKM
- Reason: only CP-averaged observables
- Measurement of CP asymmetries would be welcome
$B^0 \rightarrow K^*\mu\mu$ – Outlook

- Measurement of $B^0 \rightarrow K^*\mu\mu$ CP asymmetry in progress

- More data will enable a full angular fit to extract complete information from $B^0 \rightarrow K^*\mu\mu$ decays
  → host of theoretically well calculable observables

- Angular analysis of $B^+ \rightarrow K^+\mu\mu$ decays also in progress

W. Altmannshofer et. al. [arXiv:0801.1214]
The search for $B^+ \rightarrow \pi^+ \mu^+ \mu^-$
The search for $B^+ \rightarrow \pi^+ \mu^+ \mu^-$

- The $B^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay is a $b \rightarrow d$ transition

- In the SM the branching fraction is $\sim 25x$ smaller than the well known $B^+ \rightarrow K^+ \mu^+ \mu^-$ ($b \rightarrow s$) transition and can be enhanced in new physics models

- SM prediction: $B(B^+ \rightarrow \pi^+ \mu^+ \mu^-) = (1.96 \pm 0.21) \times 10^{-8}$ (*)

- Previous best limit from Belle: $B(B^+ \rightarrow \pi^+ \mu^+ \mu^-) < 6.9 \times 10^{-8}$ (90% CL) (**) 

- While ratio CKM elements $V_{ts}/V_{td}$ known from oscillation measurements, this decay probes $V_{ts}/V_{td}$ in above penguin decays

- Measure branching fraction to determine coupling

(*) Hai-Zhen et al., Comm in Theo Ph 50 (2008) 696
Motivation – tension in the CKM picture

- Tension between $\sin 2\beta$ and $V_{ub}|_{B\rightarrow\tau\nu}$ measurements and global fit
- Information from comparing angle to opposite side
- LHCb will improve measurement angle $\gamma$ → alternative measurements of $V_{ts}/V_{td}$ also of interest
**B^+ → π^+μ^+μ^- Analysis**

- **Main issue**: separating $B^+ → π^+μ^+μ^-$ from misidentified $B^+ → K^+μ^+μ^-$

- **Use BDT to make selection**:
  - kinematic properties of the $B$ candidate and daughters
  - particle identification information handled separately
  - $B^+ → (J/ψ, Ψ(2S))K^+$ vetoes
  - peaking backgrounds negligible

- **Fitting**
  - Use $B^+ → J/ψK^+$ events to define signal shape and, under $π^+μ^+μ^-$ hypothesis, shape of mis-identified events
  - Components for partial reconstructed $B$ decays and combinatorial bkgrd
  - Validate by separating $B^+ → J/ψK^+$ and $B^+ → J/ψπ^+$ decays
  - Normalise branching fraction using $B^+ → J/ψK^+$
Result

• With 1.0 fb$^{-1}$ LHCb finds $25.3^{+6.7}_{-6.4}$ B$^+\rightarrow\pi^+\mu^+\mu^-$ signal events
  – 5.2$\sigma$ excess above background

• $\mathcal{B}(B^+\rightarrow\pi^+\mu^+\mu^-) = (2.4\pm0.6\text{(stat)}\pm0.2\text{(syst)})\times10^{-8}$, within $1\sigma$ of SM pred.
• The rarest B decay ever observed

[LHCb-CONF-2012-006]
Isospin Asymmetry in $B \rightarrow K^{(*)} \mu^+ \mu^-$

- Results shown in public for first time
- Will shortly be available in LHCb paper: LHCb-PAPER-2012-011
Isospin Asymmetry

• The isospin asymmetry of $B \rightarrow K^{(*)}\mu^+\mu^-$, $A_I$ is defined as:

$$A_I = \frac{B(B^0 \rightarrow K^{(*)0} \mu^+\mu^-) - \frac{\tau_0}{\tau_+} B(B^\pm \rightarrow K^{(*)\pm} \mu^+\mu^-)}{B(B^0 \rightarrow K^{(*)0} \mu^+\mu^-) + \frac{\tau_0}{\tau_+} B(B^\pm \rightarrow K^{(*)\pm} \mu^+\mu^-)}$$

can be more precisely predicted than the branching fractions.

• $A_I$ is expected to be very close to zero in the SM e.g. for $B \rightarrow K^{(*)}\mu^+\mu^-$:

Asymmetry has been measured in $K^{*\gamma}$ decay modes, agrees with SM.
Experimental Status

- CDF, Belle and Babar have all measured $A_I$:

- For $B \rightarrow K^* \mu^+\mu^-$ results are consistent with the SM
- There is still some tension for $B \rightarrow K \mu^+\mu^-$
- Deficit in $K_{S}\mu\mu$ events $\rightarrow$ large negative $A_I$ (with large uncertainty)

Experimental Status

- CDF, Belle, and BaBar have all measured $A_I$.
- For $B \rightarrow K^\ast \mu$ results are consistent with the SM.
- There is still some tension for $B \rightarrow K \mu^+ \mu^-$
- Deficit in $K_{S} \mu \mu$ events $\rightarrow$ large negative $A_I$ (with large uncertainty).

LHCb Analysis

- Measure differential branching fraction of four decay modes:
  - $B^+ \rightarrow (K^{*+} \rightarrow K_S^0 \pi^+) \mu^+ \mu^-$
  - $B^0 \rightarrow (K^0 \rightarrow K_S^0) \mu^+ \mu^-$
  - $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
  - $B^+ \rightarrow K^+ \mu^+ \mu^-$

- $K_S^0$ are reconstructed through the $K_S^0 \rightarrow \pi^+ \pi^-$ decay mode

- The $K^{*+}$ and $K_S^0$ channels have a lower reconstruction efficiency and a lower visible branching fraction

- The $K^{*0}$ and $K^+$ channels much more copious
LHCb Analysis

- The channels involving a $K_S^0$ are split into two categories based on how the $K_S^0$ is reconstructed – “long” (L) and “downstream” (D)
  - L-events have less background – use cut-based selection
  - D-events – use BDT selection
  - Insofar as possible, use similar selections for $K^+$ channels

- Correction for detector and selection effects again made with simulation (verified to reproduce the data)

- $B \rightarrow K^{(*)}(J/\psi \rightarrow \mu^+\mu^-)$ decays are used to normalise branching fraction for each decay to cancel systematic uncertainties

- Determine $A_i$ by combining the likelihoods of the relevant decay modes
\[ B(B^+ \rightarrow K^{*+}\mu^+\mu^-) \]

- LHCb measurement: \[ B(B^+ \rightarrow K^{*+}\mu^+\mu^-) = (1.16 \pm 0.19) \times 10^{-6} \]
- Cf. PDG \[ B(B^+ \rightarrow K^{*+}\mu^+\mu^-) = (1.16 \pm 0.30) \times 10^{-6} \]
\begin{align*}
\frac{dBF}{q^2}(B^+ \rightarrow K^{*+}\mu^+\mu^-)
\end{align*}

- Measurements are consistent with the SM:

\( A_1 \) for \( B \rightarrow K^* \mu^+ \mu^- \)

- \( A_1 \) for \( B \rightarrow K^* \mu^+ \mu^- \) is consistent with zero, as predicted by the SM
- LHCb results in agreement with previous measurements

![Graphs showing the \( A_1 \) for \( B \rightarrow K^* \mu^+ \mu^- \) as a function of \( q^2 \) with data points and error bars from LHCb, CDF, BELLE, and BaBar.]
$B(B^0 \rightarrow K^0 \mu^+ \mu^-)$

- Assuming a factor two for $K^0 \rightarrow K^0_S$ and accounting for $K_S^0 \rightarrow \pi^+ \pi^-$ branching fraction:
- LHCb measurement:
  $B(B^0 \rightarrow K^0 \mu^+ \mu^-) = (3.1^{+0.7}_{-0.6}) \times 10^{-7}$
- cf PDG
  $B(B^0 \rightarrow K^0 \mu^+ \mu^-) = (4.5\pm1.1) \times 10^{-7}$
  $B(B^0 \rightarrow K^0 l^+ l^-) = (3.1^{+0.8}_{-0.7}) \times 10^{-7}$
- $5.7\sigma$ excess above background

Preliminary
There is a deficit of $B^0 \rightarrow K^0 \mu^+ \mu^-$ signal in the $q^2$ regions which are not adjacent to the charmonium resonances.

A_1 for B→K\mu^+\mu^-

- As a result, A_1 for B→K\mu^+\mu^- tends to sit below the SM prediction
- Results agree with previous measurements but nearly all measurements of A_1 are negative
- Ignoring the small correlation of (syst) errors between each q^2 bin, the significance of the deviation from zero integrated across q^2 is 4.4\sigma (from LHCb alone)
Cross checks

- Hard to imagine some exp’tal issue that affects the $K^0$ decays but not the $K^{*+}(\rightarrow K^0\pi^+)$

- Normalise BF to $J/\psi K^+$ and $J/\psi K^0$ – is only the shape of the relative efficiency that the measurement is sensitive to
  - Most significant effect seen in $A_1$ is at high $q^2$ – where efficiency is very close to that in $J/\psi$ regions
  - At low $q^2$, harder $K_{S0}$, longer flight distance, decay beyond tracking stations and are not reconstructed – essentially geometry
$A_{CP}(B^0 \rightarrow K^{*\gamma})$
$A_{CP}(B^0 \rightarrow K^*\gamma)$

- CLEO’s 10 events in 1993 → LHCb’s 5300 in 2011
  - Can expect another two orders of magnitude increase in the next decade with LHCb upgrade
- Probe CP violation in $b \rightarrow s\gamma$ via the exclusive mode $B^0 \rightarrow K^*\gamma$
  - SM prediction: $A_{CP} = -0.006 \pm 0.004$
    (Previous best measurement: $A_{CP} = -0.016 \pm 0.022 \pm 0.007$ [BaBar])
- Fit for raw asymmetry
  - Subtract $B^0$ production asymmetry, $K\pi$ detection asymmetry
- $A_{CP}(B^0 \rightarrow K^*\gamma) = -0.008 \pm 0.017$ (stat) $\pm 0.009$ (syst)
Conclusions

• World’s most precise measurements of angular observables and differential branching fraction in $B^0 \rightarrow K^* \mu^+ \mu^-$ decays
  – Scale of any NP contributions $O(10 \text{TeV})$ or NP has CKM like flavour suppression

• First observation of $B^+ \rightarrow \pi^+ \mu\mu$, consistent with SM expectation

• Isospin asymmetry $A_I$ [LHCb-PAPER-2012-011 to be submitted to JHEP]
  – $B \rightarrow K^* \mu^+ \mu^-$, $A_I$ results consistent with zero, as expected in SM
  – $B \rightarrow K \mu^+ \mu^-$, $A_I$ results sit below the SM expectation in the $q^2$ region below $4.3 \text{ GeV}^2/c^4$ and above $16 \text{ GeV}^2/c^4$

• $A_{CP}$ in $B^0 \rightarrow K^* \gamma$ in good agreement with SM

• LHCb will improve these measurements and has many more measurements in prospect with the 2012 data
Backup
<table>
<thead>
<tr>
<th>$q^2$ (GeV$^2$/c$^4$) range</th>
<th>Signal Yield</th>
<th>Background Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4m^2_\mu &lt; q^2 &lt; 2.00$</td>
<td>$162.4 \pm 14.2$</td>
<td>$27.7 \pm 3.8$</td>
</tr>
<tr>
<td>$2.00 &lt; q^2 &lt; 4.30$</td>
<td>$71.4 \pm 10.7$</td>
<td>$37.1 \pm 4.1$</td>
</tr>
<tr>
<td>$4.30 &lt; q^2 &lt; 8.68$</td>
<td>$270.5 \pm 18.8$</td>
<td>$58.8 \pm 5.5$</td>
</tr>
<tr>
<td>$10.09 &lt; q^2 &lt; 12.90$</td>
<td>$167.0 \pm 14.9$</td>
<td>$41.7 \pm 4.5$</td>
</tr>
<tr>
<td>$14.18 &lt; q^2 &lt; 16.00$</td>
<td>$113.0 \pm 11.7$</td>
<td>$17.1 \pm 3.0$</td>
</tr>
<tr>
<td>$16.00 &lt; q^2 &lt; 19.00$</td>
<td>$115.0 \pm 12.4$</td>
<td>$23.9 \pm 3.6$</td>
</tr>
<tr>
<td>$1.00 &lt; q^2 &lt; 6.00$</td>
<td>$195.2 \pm 16.9$</td>
<td>$75.8 \pm 6.0$</td>
</tr>
<tr>
<td>$4m^2_\mu &lt; q^2 &lt; 19.00$</td>
<td>$900.0 \pm 34.4$</td>
<td>$206.2 \pm 10.3$</td>
</tr>
</tbody>
</table>

Table 1: The signal and background yields resulting from a fit to the $K^+\pi^-\mu^+\mu^-$ invariant mass distributions of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ candidates in the six $q^2$-bins used in the analysis, the theoretically ‘favoured’ $1 < q^2 < 6$ GeV$^2$/c$^4$ range and in the full $q^2$-range.

<table>
<thead>
<tr>
<th>$q^2$ range (GeV$^2$/c$^4$)</th>
<th>$dBF dq^2$ ($\times 10^{-7}$ GeV$^{-2}$c$^4$)</th>
<th>$A_{FB}$</th>
<th>$F_L$</th>
<th>$A_{im}$</th>
<th>$2S_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.05 &lt; q^2 &lt; 2.00$</td>
<td>$0.68 \pm 0.07 \pm 0.05$</td>
<td>$0.00^{+0.08}<em>{-0.07}^{+0.11}</em>{-0.09}$</td>
<td>$0.31^{+0.07}<em>{-0.05}^{+0.09}</em>{-0.06}$</td>
<td>$0.06^{+0.11}<em>{-0.06}^{+0.13}</em>{-0.09}$</td>
<td>$0.02^{+0.20}<em>{-0.05}^{+0.22}</em>{-0.13}$</td>
</tr>
<tr>
<td>$2.00 &lt; q^2 &lt; 4.30$</td>
<td>$0.30 \pm 0.05 \pm 0.02$</td>
<td>$-0.20^{+0.06}<em>{-0.05}^{+0.09}</em>{-0.07}$</td>
<td>$0.74^{+0.09}<em>{-0.06}^{+0.09}</em>{-0.07}$</td>
<td>$-0.02^{+0.10}<em>{-0.06}^{+0.12}</em>{-0.08}$</td>
<td>$-0.05^{+0.18}<em>{-0.06}^{+0.12}</em>{-0.10}$</td>
</tr>
<tr>
<td>$4.30 &lt; q^2 &lt; 8.68$</td>
<td>$0.54 \pm 0.05 \pm 0.05$</td>
<td>$0.16^{+0.05}<em>{-0.06}^{+0.10}</em>{-0.07}$</td>
<td>$0.57^{+0.05}<em>{-0.05}^{+0.10}</em>{-0.06}$</td>
<td>$0.02^{+0.07}<em>{-0.06}^{+0.13}</em>{-0.05}$</td>
<td>$0.18^{+0.13}<em>{-0.07}^{+0.15}</em>{-0.09}$</td>
</tr>
<tr>
<td>$10.09 &lt; q^2 &lt; 12.89$</td>
<td>$0.50 \pm 0.06 \pm 0.04$</td>
<td>$0.27^{+0.06}<em>{-0.06}^{+0.10}</em>{-0.07}$</td>
<td>$0.49^{+0.06}<em>{-0.07}^{+0.10}</em>{-0.06}$</td>
<td>$-0.01^{+0.11}<em>{-0.11}^{+0.07}</em>{-0.11}$</td>
<td>$-0.22^{+0.20}<em>{-0.13}^{+0.17}</em>{-0.13}$</td>
</tr>
<tr>
<td>$14.18 &lt; q^2 &lt; 16.00$</td>
<td>$0.59 \pm 0.07 \pm 0.04$</td>
<td>$0.40^{+0.04}<em>{-0.05}^{+0.07}</em>{-0.06}$</td>
<td>$0.35^{+0.07}<em>{-0.06}^{+0.07}</em>{-0.06}$</td>
<td>$-0.01^{+0.08}<em>{-0.07}^{+0.07}</em>{-0.07}$</td>
<td>$0.04^{+0.15}<em>{-0.09}^{+0.19}</em>{-0.19}$</td>
</tr>
<tr>
<td>$16.00 &lt; q^2 &lt; 19.00$</td>
<td>$0.44 \pm 0.05 \pm 0.03$</td>
<td>$0.30^{+0.07}<em>{-0.07}^{+0.10}</em>{-0.08}$</td>
<td>$0.37^{+0.06}<em>{-0.07}^{+0.10}</em>{-0.06}$</td>
<td>$0.06^{+0.09}<em>{-0.07}^{+0.10}</em>{-0.10}$</td>
<td>$-0.47^{+0.21}<em>{-0.10}^{+0.23}</em>{-0.15}$</td>
</tr>
<tr>
<td>$1.00 &lt; q^2 &lt; 6.00$</td>
<td>$0.42 \pm 0.04 \pm 0.04$</td>
<td>$-0.18^{+0.06}<em>{-0.06}^{+0.10}</em>{-0.08}$</td>
<td>$0.66^{+0.06}<em>{-0.06}^{+0.07}</em>{-0.08}$</td>
<td>$0.07^{+0.07}<em>{-0.07}^{+0.10}</em>{-0.09}$</td>
<td>$0.10^{+0.15}<em>{-0.10}^{+0.18}</em>{-0.16}$</td>
</tr>
</tbody>
</table>

Table 2: Central values for, and statistical and systematic uncertainties on, the differential branching fraction, $A_{FB}$, $F_L$, $A_{im}$ and $S_3$ in bins of $q^2$. The first uncertainty is statistical and the second systematic.
<table>
<thead>
<tr>
<th>Background</th>
<th>Background Level (%)</th>
<th>Signal Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ (with $K \leftrightarrow \pi$)</td>
<td>$0.85 \pm 0.02$</td>
<td>$0.11$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{*0} J/\psi$ (with $\pi \leftrightarrow \mu$)</td>
<td>$0.27 \pm 0.08$</td>
<td>$0.05$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{*0} J/\psi$ (with $K \leftrightarrow \mu$)</td>
<td>$0.00 \pm 0.00$</td>
<td>$0.03$</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow \phi \mu^+ \mu^-$</td>
<td>$1.23 \pm 0.50$</td>
<td>$0.32$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+ \mu^+ \mu^-$</td>
<td>$0.14 \pm 0.03$</td>
<td>$-$</td>
</tr>
<tr>
<td>Total</td>
<td>$2.49 \pm 0.51$</td>
<td>$0.52$</td>
</tr>
</tbody>
</table>
Theoretical control of form factors

- Recent paper uses experimental results to make a fit to the form factor ratios $V/A_1$ and $A_1/A_2$ - green bands show the 1 and $2\sigma$ contours
- Blue band shows form factor ratio extracted from light cone sum rules
- Red and orange points show ratio extracted from lattice calculations

The interest in $A_T^2$

- $C_7$ and $C_7'$ are constrained by $b \to s \gamma$ processes. Even in the SM-like allowed region can still have large sensitivity to $C_7'$ through $A_T^2$
- $S_3$ is related to $A_T^2$ through $S_3 = 1/2(1-F_L)A_T^2$

[S. Descotes-Genon et. al., arXiv:1104.3342]
Muon Triggers

• ~1 kHz given to the muon lines
• \( p_T \) cuts on muon lines kept very low \( \rightarrow \) trigger efficiency very high

| L0 Hardware | Single-\( \mu \): \( p_T > 1.5 \text{ GeV}/c \)
| Di – \( \mu \): 2 clean muons \( p_T1 > 0.56 \text{ GeV}/c \)
| \( p_T2 > 0.48 \text{ GeV}/c \) |

| HLT1 Software | Single-\( \mu \): \( p_T > 0.8 \text{ GeV}/c \)
| IP > 0.11mm, IPS > 5 |
| Single-\( \mu \): \( p_T > 1.8 \text{ GeV}/c \) (no IP) |

| HLT2 Software | Dimuon: \( M_{\mu\mu} > 4.7 \text{ GeV}/c^2 \)
| Several MVA lines with \( p_T \) and vertex displacement cuts |
| + Global Event Cuts for events with high multiplicity |
Acceptance Correction

• Correct angular and $q^2$ distributions for the effect of the detector and selection
  – $\mu$ p > 3 GeV/c → effect on $\theta_i$
  – IP forward-going hadrons → effect on $\theta_K$

• Use a binned acceptance correction derived from LHCb simulation

• Simulation quality verified with range of control channels ($B_0 \rightarrow K^*J/\psi$, $J/\psi \rightarrow \mu\mu$, $D^* \rightarrow D^0(K\pi)\pi$)
  – Tracking efficiency
  – Hadron (mis-)identification probabilities
  – Muon (mis-)identification
  – Overall momentum and $\eta$ distributions
$B \rightarrow K^* \ell^+ \ell^-$: low vs. high $q^2$

- QCDF: non-factorizable corrections to $O(\alpha_s)$
- LCSR: form factors with correlated uncertainties to all orders in $\Lambda/m_b$
- OPE in powers of $\Lambda_{QCD}/\sqrt{q^2}$
- Non-perturbative corrections beyond form factors negligible
- form factors poorly known

[Beneke et al. (2001, 2004); Ball, Zwicky (2004); Altmannshofer et al. (2008); Khodjamirian et al. (2010)]

[Grinstein, Pirjol (2004); Bharucha et al. (2008); Bobeth et al. (2010); Beylich et al. (2011)]
Operators (1)

- Operators
  
  - Current-current operators \([ (\mathrm{V-A}) ]\)
    
    \[
    Q_1 = (\bar{b}_\alpha \gamma_\mu P_L q_\beta)(\bar{q}_\beta' \gamma^\mu P_L q'_\alpha),
    \]
    
    \[
    Q_2 = (\bar{b}_\gamma \gamma_\mu P_L)(\bar{q}_\gamma' \gamma^\mu P_L q''_\alpha).
    \]

  - Gluonic penguin operators \([ (\mathrm{V-A}) \text{ and } (\mathrm{V+A}) ]\)
    
    \[
    Q_3 = (\bar{b}_\gamma P_L q) \sum_{q'}(\bar{q}_\gamma' \gamma^\mu P_L q'_\alpha),
    \]
    
    \[
    Q_4 = (\bar{b}_\alpha \gamma_\mu P_L q_\beta) \sum_{q'}(\bar{q}_\beta' \gamma^\mu P_L q'_\alpha),
    \]
    
    \[
    Q_5 = (\bar{b}_\gamma P_L q) \sum_{q'}(\bar{q}_\gamma' \gamma^\mu P_R q'_\alpha),
    \]
    
    \[
    Q_6 = (\bar{b}_\alpha \gamma_\mu P_L q_\beta) \sum_{q'}(\bar{q}_\beta' \gamma^\mu P_R q'_\alpha);
    \]
Operators (2)

- Operators
  - Current-current operators \[ (V-A) \]
    \[
    Q_1 = (\bar{b}\gamma_\mu P_L q_\beta)(\bar{q}'_\beta \gamma^\mu P_L q''_\alpha), \\
    Q_2 = (\bar{b}\gamma_\mu P_L q)(\bar{q}'_\gamma \gamma^\mu P_L q'').
    \]
  - Gluonic penguin operators \[ (V-A) \] and \[ (V+A) \]
    \[
    Q_3 = (\bar{b}\gamma_\mu P_L q) \sum_{q'}(\bar{q}'_\gamma \gamma^\mu P_L q'), \\
    Q_4 = (\bar{b}\gamma_\mu P_L q_\beta) \sum_{q'}(\bar{q}'_\gamma \gamma^\mu P_L q''), \\
    Q_5 = (\bar{b}\gamma_\mu P_L q) \sum_{q'}(\bar{q}'_\gamma \gamma^\mu P_R q'), \\
    Q_6 = (\bar{b}\gamma_\mu P_L q_\beta) \sum_{q'}(\bar{q}'_\gamma \gamma^\mu P_R q'').
    \]
Operators (3)

- Electroweak penguin operators

\[
Q_7 = \frac{3}{2} \langle \bar{b} \gamma_\mu P_L q \rangle \sum_{q'} e_{q'} (\bar{q}' \gamma^\mu P_R q'),
\]

\[
Q_8 = \frac{3}{2} \langle \bar{b}_\alpha \gamma_\mu P_L q_\beta \rangle \sum_{q'} e_{q'} (\bar{q}'_\beta \gamma^\mu P_R q'_\alpha),
\]

\[
Q_9 = \frac{3}{2} \langle \bar{b} \gamma_\mu P_L q \rangle \sum_{q'} e_{q'} (\bar{q}' \gamma^\mu P_L q'),
\]

\[
Q_{10} = \frac{3}{2} \langle \bar{b}_\alpha \gamma_\mu P_L q_\beta \rangle \sum_{q'} e_{q'} (\bar{q}'_\beta \gamma^\mu P_L q'_\alpha);
\]

- Magnetic penguin operators

\[
Q_{7\gamma} = \frac{e}{8\pi^2} m_b \left[ b_\sigma^{\mu\nu} (1 + \gamma_5) q \right] F_{\mu\nu},
\]

\[
Q_{8g} = \frac{g_5}{16\pi^2} m_b \left[ \bar{b}_\alpha \sigma^{\mu\nu} (1 + \gamma_5) T_{\alpha\beta} q_\beta \right] G^{\alpha}_{\mu\nu};
\]

Helicity flip required
Operators (4)

- **Semi-leptonic penguin operators**

  \[
  Q_{9V} = (\bar{b}\gamma_{\mu}P_Lq)(\ell\gamma^\mu\ell), \\
  Q_{10A} = (\bar{b}\gamma_{\mu}P_Lq)(\ell\gamma^\mu\gamma_5\ell), \\
  Q_S = (\bar{b}\gamma_{\mu}P_Rq)(\ell\ell), \\
  Q_P = (\bar{b}\gamma_{\mu}P_Rq)(\ell\gamma_5\ell),
  \]

- Here,
  - \(Q_{9V}\) represents cases with leptons in a vector final state
  - \(Q_{10A}\) represents cases with leptons in an axial final state

- \(Q_{S,P}\) only relevant for \(B\to ll\) decays

- Note haven’t drawn out the box diagram

- Throughout, (with NP) operators could be replaced with a right-handed version \(Q'\) where instead of \(P_L\), have \(P_R\)