Rare FCNC $t$, $b$ and $c$ decays

T. Blake on behalf of the LHCb collaboration including results from ATLAS and CMS
Outline

1. Why are FCNC $t$, $b$ and $c$ decays interesting?
2. The very rare decays $B_{(s,d)}^0 \rightarrow \mu^+ \mu^-$. 
3. Photon polarisation in $b \rightarrow s \gamma$ decays.
4. Branching fractions and angular distributions of $b \rightarrow s \ell^+ \ell^-$ decays.
5. Rare $c$ and $t$ decays.

- For more details see the talks in the heavy flavour/top sessions by F. Scuri, F. Ligabue, M. de Cian, J. F. Kamenik and W. Altmannshofer.
In the SM only the charged current interaction is flavour changing.

- All other interactions are flavour conserving.

Flavour changing $b \rightarrow s$ and $b \rightarrow d$ transitions only occur at loop order in the SM.

- SM contribution is suppressed.
$b \rightarrow s \mu^+ \mu^-$ example

Standard Model

T. Blake

Rare FCNC decays
$b \rightarrow s \mu^+ \mu^-$ example

Standard Model

```
\begin{align*}
b & \quad W^- \quad s \\
t & \quad \gamma, Z^0 & \mu^+ \\
\mu^- & \\
\end{align*}
```

“New physics” (loop order)

```
\begin{align*}
b & \quad \tilde{\chi}^0_0 \quad s \\
\tilde{d}_i & \quad \gamma, Z^0 & \mu^+ \\
\mu^- & \\
\end{align*}
```

- Sensitivity to the different SM & NP contributions through decay rates, angular observables and CP asymmetries.
$b \rightarrow s \mu^+ \mu^-$ example

Standard Model

```
\begin{align*}
  b & \rightarrow W^- & s \\
  t & \rightarrow \mu^+ & \gamma, Z^0 \\
  b & \rightarrow t & s \\
  W^- & \rightarrow W^+ & \nu & \mu^+ \\
  \end{align*}
```

“New physics” (loop order and at tree level)

```
\begin{align*}
  b & \rightarrow \tilde{\chi}^0 & s \\
  d_i & \rightarrow \mu^+ & \gamma, Z^0 \\
  b & \rightarrow \tilde{d}_i & s \\
  \tilde{g} & \rightarrow \mu^+ & H^0 \\
  b & \rightarrow t & s \\
  H^- & \rightarrow H^+ & \nu & \mu^+ \\
  \end{align*}
```

- Sensitivity to the different SM & NP contributions through decay rates, angular observables and CP asymmetries.
$B_{s,d}^0 \rightarrow \mu^+ \mu^-$
$B_s^0 \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$

- $B^0$ and $B_s^0 \rightarrow \mu^+ \mu^-$ are both GIM (loop) and helicity suppressed in the SM.
- Sensitive to contributions from (pseudo)scalar sector → interesting probe of NP models with extended Higgs sectors (e.g. MSSM, 2HDM, . . .)

e.g. in MSSM, branching fraction scales approximately as $\tan^6 \beta / M_A^4$

- Predicted precisely in the SM:
  \[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9} \]

[Bobeth et al. PRL 112 101801 (2014)]

NB $B(B^0 \rightarrow \mu^+ \mu^-)$ suppressed by $|V_{td}/V_{ts}|^2$. 

T. Blake Rare FCNC decays 5 / 31
$B_s^0 \to \mu^+\mu^-$ searches

- Background rejection key for rare decay searches $\rightarrow$ use multivariate classifiers (BDTs) and tight particle identification requirements.

Calibrate the BDT response on MC (CMS) or $B \to hh$ data (LHCb).

Branching fraction normalised w.r.t. $B^+ \to J/\psi K^+$ (and $B^0 \to K^+\pi^-$ at LHCb).
$B_s^0 \rightarrow \mu^+ \mu^-$ at LHCb and CMS

- In 3 fb$^{-1}$ LHCb sees evidence for $B_s^0 \rightarrow \mu^+ \mu^-$ at 4.0$\sigma$
  with $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9^{+1.1+0.3}_{-1.0-0.1}) \times 10^{-9}$. [PRL 111 (2013) 101805]

- In 20 fb$^{-1}$ CMS sees evidence for $B_s^0 \rightarrow \mu^+ \mu^-$ at 4.3$\sigma$
  with $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$. [PRL 111 (2013) 101805]
Naïve combination of CMS and LHCb results gives:

\[ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9} \]
\[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.6 \pm 1.6) \times 10^{-10} \]

\[ \rightarrow B_s^0 \rightarrow \mu^+ \mu^- \] is observed at more than 5\(\sigma\)

- Work is ongoing to do a proper combination of the two results.
- Unfortunately, measured BF s are consistent with SM expectations.
Photon polarisation in \( b \to s \gamma \)
Photon polarisation in $b \rightarrow s \gamma$ decays

- $B^0 \rightarrow K^{*0}\gamma$ was the first penguin decay ever observed, by CLEO in 1992. [PRL 71 (1993) 674]
- We already know from the B-factories that inclusive & exclusive $b \rightarrow s \gamma$ branching fractions are compatible with SM expectations.
- What else do we know?

$\Rightarrow$ In the SM, photons from $b \rightarrow s \gamma$ decays are predominantly left-handed ($C_7/C'_7 \sim m_b/m_s$) due to the charged-current interaction.

- Can test $C_7/C'_7$ using:
  - Mixing-induced CP violation [Atwood et al PRL 79 (1997) 185-188],
  - $\Lambda_b^0$ baryons [Hiller & Kagan PRD 65 (2002) 074038],
OR $B \rightarrow K^{**}\gamma$ decays such as $B^+ \rightarrow K_1(1270)\gamma$.


- Can infer the photon polarisation from the up-down asymmetry of the photon direction in the $K^+\pi^-\pi^+$ rest-frame. Unpolarised photons would have no asymmetry.

- This is conceptionally similar to the Wu experiment, which first observed parity violation.
At LHCb we look at $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ decays using calorimeter photons.

Observe $\sim 13,000$ signal candidates in 3 fb$^{-1}$.

There are a large number of overlapping resonances in the $m(K^+ \pi^- \pi^+)$ mass spectra. No attempt is made to separate these in the analysis, we simply bin in 4 bins of $m(K^+ \pi^- \pi^+)$.
Best fit, Fit with \((C'_7 - C_7)/(C'_7 + C_7) = 0\)
Combining the 4 bins, the photon is observed to be polarised at 5.2\(\sigma\).

Unfortunately you need to understand the hadronic system to know if the polarisation is left-handed, as expected in the SM.

→ First observation of photon polarisation in \(b \to s\gamma\) decays
$b \to s \ell^+ \ell^- \text{ decays}$
Can also probe photon polarization using virtual photons in $b \rightarrow s \ell^+ \ell^-$ decays, e.g. through the angular distribution of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay.

Also sensitive to new left- and right-handed vector currents.

Decay described by three angles ($\theta_\ell, \theta_K, \phi$) and the dimuon invariant mass squared, $q^2$.

Analyses are performed in bins of $q^2$. 
Angular distribution depends on 11 angular terms:

\[
\frac{d^4\Gamma[B^0 \rightarrow K^{*0}\mu^+\mu^-]}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi} \left[ J_1^s \sin^2 \theta_K + J_1^c \cos^2 \theta_K + J_2^s \sin^2 \theta_K \cos 2\theta_\ell + J_2^c \cos^2 \theta_K \cos 2\theta_\ell + \\
J_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + \\
J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + J_6 \cos^2 \theta_K \cos \theta_\ell + J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + \\
J_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + J_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
\]

where the \( J_i \)'s are bilinear combinations of seven decay amplitudes \( A_{L,R}^L, A_{L,R}^R, A_0^{L,R} \& A_t \) (\( L/R \) for the chirality of the \( \mu^+\mu^- \) system).

- Large number of terms, simplified by angular folding, e.g. \( \phi \rightarrow \phi + \pi \)
  if \( \phi < 0 \) to cancel terms in \( \cos \phi \) and \( \sin \phi \) (LHCb).
**Angular distribution depends on 11 angular terms:**

\[
\frac{d^4\Gamma[B^0 \to K^{*0} \mu^+ \mu^-]}{d \cos \theta_\ell \ d \cos \theta_K \ d \phi \ dq^2} = \frac{9}{32\pi} \left[ J_1^s \sin^2 \theta_K + J_1^c \cos^2 \theta_K + J_2^s \sin^2 \theta_K \cos 2\phi + J_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\ell \right.
\]

\[
\left. + J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + J_6 \cos^2 \theta_K \cos \theta_\ell + J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + J_8 \sin 2\theta_K \sin \theta_\ell \sin \phi + J_9 \sin 2\theta_K \sin^2 \theta_\ell \cos \phi \right].
\]

where the \( J_i \)'s are bilinear combinations of seven decay amplitudes \( A_{L,R}^{L,R}, A_0^{L,R} \) & \( A_t \) (\( L/R \) for the chirality of the \( \mu^+ \mu^- \) system).

- Large number of terms, simplified by angular folding, e.g. \( \phi \to \phi + \pi \) if \( \phi < 0 \) to cancel terms in \( \cos \phi \) and \( \sin \phi \) (LHCb).
\( B^0 \to K^{*0} \mu^+ \mu^- \) angular distribution

depends on 11 angular terms:

\[
\begin{align*}
&J_1^s \sin^2 \theta_K + J_1^c \cos^2 \theta_K + J_2^s \sin^2 \theta_K \cos 2\theta_\ell + J_2^c \cos^2 \theta_K \cos 2\theta_\ell + J_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + J_6 \cos^2 \theta_K \cos \theta_\ell + J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + J_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \\
\end{align*}
\]

where the \( J_i \)'s are bilinear combinations of seven decay amplitudes \( A^{L,R}_L, A^{L,R}_R, A^{L,R}_0 \ & A_t \) (\( L/R \) for the chirality of the \( \mu^+ \mu^- \) system).

- Large number of terms, simplified by angular folding, e.g. \( \phi \to \phi + \pi \) if \( \phi < 0 \) to cancel terms in \( \cos \phi \) and \( \sin \phi \) (LHCb).

Altmannshofer et al. [JHEP 01 (2009) 019]
Angular distribution depends on 11 angular terms:

\[
\frac{d^4\Gamma[B^0 \rightarrow K^{*0} \mu^+ \mu^-]}{d \cos \theta_\ell \, d \cos \theta_K \, d \phi \, dq^2} = \frac{9}{32\pi} \left[ J_1^s \sin^2 \theta_K + J_1^c \cos^2 \theta_K + J_2^s \sin^2 \theta_K \cos 2\theta_\ell + J_2^c \cos^2 \theta_K \cos 2\theta_\ell + J_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + J_6 \cos^2 \theta_K \cos \theta_\ell + J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + J_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
\]

where the $J_i$'s are bilinear combinations of seven decay amplitudes $A_{L,R}^L, A_{L,R}^R, A_0^{L,R} \& A_t$ ($L/R$ for the chirality of the $\mu^+ \mu^-$ system).

Large number of terms, simplified by angular folding, e.g. $\phi \rightarrow \phi + \pi$ if $\phi < 0$ to cancel terms in $\cos \phi$ and $\sin \phi$ (LHCb).
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular distribution

OR by integrating over two of the three angles (ATLAS and CMS):

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\phi} = \frac{1}{2\pi} (1 + S_3 \cos 2\phi + A_9 \sin 2\phi),$$

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta_K} = \frac{3}{2} F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L)(1 - \cos^2 \theta_K),$$

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta_\ell} = \frac{3}{4} F_L (1 - \cos^2 \theta_\ell) + \frac{3}{8} (1 - F_L)(1 + \cos^2 \theta_\ell) + A_{FB} \cos \theta_\ell.$$

Leaves 4 observables:

- $A_{FB}$ Dimuon forward-backward asymmetry.
- $F_L$ Fraction of longitudinal $K^{*0}$ polarisation.
- $A_{T/S3}^2$ Asymmetry sensitive to the (virtual) photon polarisation.
- $A_9$ A CP asymmetry.
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular distribution (part 1)

ATLAS (prelim.) [ATLAS-CONF-2013-038], CMS 5.2 fb$^{-1}$ [PLB 727 (2013) 77], LHCb 1 fb$^{-1}$ [JHEP 08 (2013) 131]

Theory prediction from Bobeth et al. [JHEP 07 (2011)] and references therein.
Can also apply different angular foldings to access different angular terms \([PRL 111 191801 (2013)]\).

SM predictions from \([\text{Decotes-Genon et al. JHEP 05 (2013) 137}]\)

Focus on observables where leading form-factor uncertainties cancel, e.g. \(P'_{4,5} = S_{4,5}/\sqrt{F_L(1 - F_L)}\).

In 1 \(fb^{-1}\), LHCb observes a local discrepancy of 3.7\(\sigma\) in \(P'_5\) (probability that at least one bin varies by this much is 0.5%).
Understanding the $P'_5$ anomaly?

- **Decotes-Genon, Matias & Virto** perform a global fit to the available $b \rightarrow s \gamma$ and $b \rightarrow s \ell^+ \ell^-$ data → $4.5\sigma$ discrepancy from SM. Fit favours $C_9^{\text{NP}} \approx -1.5$ (non-SM vector current).
  
  [PRD 88 074002 (2013)]

- **Altmannshofer & Straub** perform a global analysis and find discrepancies at the level of $3\sigma$. Data best described by modified $C_9$ (and $C'_9$). Data can be explained by introducing a flavour-changing $Z'$ boson at $\mathcal{O}(1\,\text{TeV})$.
  
  [EPJC 73 2646 (2013)]
Gaul, Goertz & Haisch also favour $Z'$, but with mass $O(7 \text{ TeV})$. [JHEP 01 (2014) 069]

Beaujean, Bobeth & van Dyk float form-factor uncertainties as nuisance parameters and find the discrepancy can be reduced to $2\sigma$. [arXiv:1310.2478].

Jaeger & Camalich also explore form-factor uncertainties and try to address their size in the large recoil region. [JHEP 05 (2013) 043]

In general:

~> Difficult to explain data in SUSY scenarios or using partial compositeness (why only $C_9^{(i)}$?).

~> Data can be described using $Z'$ with flavour violating couplings, but mass must be $O(7 \text{ TeV})$ to avoid direct limits and limits from mixing ($\Delta m_s$).

~> Could we just be underestimating the theory uncertainties?
Differential branching fraction of $B \rightarrow K^{(*)} \mu^+ \mu^-$

- If $C_9^{NP} = -1.5$, then expect to see a suppression of the rate of $B \rightarrow K^{(*)} \mu^+ \mu^-$ decays.

- Can reconstruct the $K^{(*)}$ as either $K^+$, $K_S^0$, $K^{*+}$ ($\rightarrow K_S^0 \pi^+$) or $K^{*0}$. $K_S^0$ and $K^{*+}$ modes are experimentally challenging due to the long $K_S^0$ lifetime.

- We see large signals for all four $K^{(*)}$ modes in the $3 \text{ fb}^{-1}$ LHCb dataset [arXiv:1403.8044].

- Look at $dB/dq^2$, using $B \rightarrow J/\psi K^{(*)}$ decays to normalise the branching fraction.
Differential branching fraction of $B \to K(\ast)\mu^+\mu^-$

LHCb 1 fb$^{-1}$ ($B^0 \to K^0\mu^+\mu^-$) [JHEP 08 (2013)]
LHCb 3 fb$^{-1}$ [arXiv:1403.8044]
CMS 5.2 fb$^{-1}$ [PLB 727 (2013) 77]

- SM predictions based on
  [JHEP 07 (2011) 067], [JHEP 01 (2012) 107].
- Lattice input from

SM predictions based on
[JHEP 07 (2011) 067], [JHEP 01 (2012) 107].
Lattice input from
Differential branching fraction of $B \to K^{(*)} \mu^+ \mu^-$

- $C_9^{NP} = -1.0, C_9' = 1.2$

Horgan et al [arXiv:1310.3887]

- SM predictions based on
  [JHEP 07 (2011) 067], [JHEP 01 (2012) 107].

- Lattice input from

LHCb 1 fb

CMS 5.2 fb

$B^0 \to K^{*0} \mu^+ \mu^-$

LCSR Lattice Data

$B^0 \to K^0 \mu^+ \mu^-$

LCSR Lattice Data

$B^+ \to K^+ \mu^+ \mu^-$

LHCb
Lepton universality?

- If a $Z'$ is responsible for the anomaly in $P_5'$, does it couple equally to all flavours of leptons?
- Dominant SM processes couple with equal strength to leptons:

\[
R_K = \frac{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (d\mathcal{B}[B^+ \rightarrow K^+ \mu^+ \mu^-]/dq^2) dq^2}{\int_{q^2=1 \text{ GeV}^2/c^4}^{q^2=6 \text{ GeV}^2/c^4} (d\mathcal{B}[B^+ \rightarrow K^+ e^+ e^-]/dq^2) dq^2} = 1 \pm \mathcal{O}(10^{-3}) .
\]

- Selection of the $B^+ \rightarrow K^+ e^+ e^-$ decay is experimentally challenging, due to bremsstrahlung emission from the $e^{\pm}$.

\[B^+ \rightarrow J/\psi (\rightarrow e^+ e^-) K^+ \text{ and } B^+ \rightarrow K^+ e^+ e^- \text{ candidates triggered by the } e^{\pm}.\]
Correct for bremsstrahlung using calorimeter photons (with $E_T > 75$ MeV).

Migration of events into/out-of the $1 < q^2 < 6 \text{GeV}^2/c^4$ window is corrected using MC.

Take double ratio with $B^+ \to J/\psi K^+$ decays to cancel possible systematic biases.

In 3 fb$^{-1}$ LHCb determines $R_K = 0.745^{+0.090}_{-0.074}\text{(stat)}^{+0.036}_{-0.036}\text{(syst)}$ which is consistent with SM at 2.6$\sigma$. 

LHCb-PAPER-2014-024 [Preliminary],
Belle [PRL 103 (2009) 171801],
BaBar [PRD 86 (2012) 032012]
FCNC charm decays
FCNC charm decays

- Effective GIM cancellation due to presence of $b-, s-, d$-quark in loop.
  
  e.g. $\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) \approx 10^{-18}$ in SM.

- Long distance contributions.

- Exploit small $\Delta m$ in $D^{*\pm}$ decays to suppress backgrounds.

- Experimental precision limited by hadronic $\pi \rightarrow \mu$ mis-id.
Using 1 fb$^{-1}$ LHCb sets a limit of:

$$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 6.8 \times 10^{-9} \text{ at 95% CL}$$

Limit on LD from $D^0 \rightarrow \gamma \gamma$

- Belle 90% CL
- CDF 90% CL (360 pb$^{-1}$)
- CMS 90% CL (90 pb$^{-1}$)
- LHCb 95% CL (1.0 fb$^{-1}$)

Belle
[PRD 81 (2010) 091102]

CDF
[PRD 82 (2010) 091105]

CMS
[CMS-PAS-BPH-11-017]

LHCb
[PLB 725 (2013) 15-24]
\[ D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^- \] at LHCb

- Can also look at other c → u decays, e.g. \( D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^- \).
- Background from light resonances.

Set limits in 1 fb\(^{-1}\) of

\[ \mathcal{B}(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 8.3 \times 10^{-8} \]
\[ \mathcal{B}(D_s^+ \rightarrow \pi^+ \mu^+ \mu^-) < 4.1 \times 10^{-7} \]

at 95% CL

Improving existing limits by 50x.
... or 4-body decays of $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ [PLB 728 (2014) 234-243]

\[
\text{low } m(\mu^+\mu^-) \quad \rho/\omega \quad \phi \quad \text{high } m(\mu^+\mu^-)
\]

Signal, $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ background

- Using 1 fb$^{-1}$ of integrated luminosity, LHCb sets a limit of:
  \[
  \mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) < 5.5 \times 10^{-7} \text{ at } 90\%
  \]

  c.f. SM predictions of $\mathcal{O}(10^{-9})$, improving on previous limits by 50x.
FCNC top decays
Effective GIM cancellation leads to $\mathcal{B}(t \to Z^0 q) < 10^{-14}$ in the SM, see e.g. [ActaPhys. Polon. B35 (2004) 2671-2694]

CMS perform a search for $t \to Z^0 j$ with $Z^0 \to \ell^+ \ell^-$, where $j$ is a jet, reconstructing the other top through $t \to Wb$. [PRL 112 171802 (2014)]

CMS sets a limit of $\mathcal{B}(t \to Z^0 q) < 5 \times 10^{-4}$ at 95\% CL

Earlier ATLAS results using 2011 dataset in [JHEP 09 (2012) 139]
Can also set limits on FCNC top coupling by looking at top production, e.g. anomalous single top production through $q g \rightarrow t$.

Search carried out by the ATLAS collaboration, with $t \rightarrow Wb$, sets limits of:

$$B(t \rightarrow ug) < 5.7 \times 10^{-5} \text{ at 95\% CL}$$

$$B(t \rightarrow cg) < 2.7 \times 10^{-4} \text{ at 95\% CL}$$
Large $b$ and $c$ and $t$ production cross section makes the LHC an excellent flavour factory.

Are we starting to see some tension with the SM in $b \rightarrow s \ell^+ \ell^-$ decays?

Many analyses are still to be updated with the full Run I dataset. Many new results to come.

I don’t have time to talk about $\mathcal{CP}$, isospin asymmetries, LFV or LNV decays. More details in the parallel sessions.
Constraints

- Flavour constraints depend heavily on model assumptions. Will just pick one example of a concrete model, the CMSSM, from [Mahmoudi arXiv:1310.2556].

allowed, $\mathcal{B}(b \to s\gamma)$, $\mathcal{B}(B^0_s \to \mu^+\mu^-)$, $A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$, – direct searches

- Flavour constraints exclude the the whole $m_0 : m_{\frac{1}{2}}$ plane at large $\tan\beta$ and are comparable to direct searches at $\tan\beta \approx 30$. 
Can exploit correlations with other flavour observables, e.g. $B_s^0$ mixing phase $\phi_s$. 

T. Blake

Rare FCNC decays

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$B_s^0 \rightarrow \mu^+\mu^-$ progress with time

![Graph showing progress over time with data points for various experiments such as Belle, L3, CLEO, UA1, ARGUS, ATLAS, CMS, LHCb, D0, BABAR, and EPS2013. The graph includes 95% CL or measurement values.]
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ at LHCb

Using 1 fb$^{-1}$ of integrated luminosity

$B^0 \rightarrow K^{*0} J/\psi$ 

$B^+ \rightarrow K^+ \pi^- \pi^+ \mu^+ \mu^-$ 

Signal
Perform measurements in six bins of $q^2 = m_{\mu^+\mu^-}^2$.

The binning scheme was originally optimised for the Belle experiment (not particularly optimal for the LHC experiments).
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ at ATLAS and CMS

ATLAS

 CMS

Large data sets are also available at ATLAS [ATLAS-CONF-2013-038] and CMS [PLB 727 (2013) 77].

$J/\psi$ and $\psi(2S)$ leakage
In the SM expect the partial widths of $B^+ \to K^+ \mu^+ \mu^-$ and $B^0 \to K^0 \mu^+ \mu^-$ to be almost identical

$$A_I = \frac{\Gamma[B^+ \to K^+ \mu^+ \mu^-] - \Gamma[B^0 \to K^0 \mu^+ \mu^-]}{\Gamma[B^+ \to K^+ \mu^+ \mu^-] + \Gamma[B^0 \to K^0 \mu^+ \mu^-]} \approx 0$$

In our 1 fb\(^{-1}\) dataset, LHCb found $A_I < 0$ at $4.4\sigma$.

Updating the measurement to the full 3 fb\(^{-1}\) dataset. Still favour negative $A_I$, but $A_I$ is compatible with $A_I = 0$ at $1.5\sigma$. 

Belle [PRL 103 (2009) 171801]

BaBar [PRD 86 (2012) 032012]
Single angle and two parameters describe the decay:

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_l} = \frac{3}{4} (1 - F_H) + \frac{1}{2} F_H + A_{FB} \cos \theta_l
\]

\(F_H\) corresponds to the fractional contribution of (pseudo)scalar and tensor operators to \(\Gamma\).

Angular distribution is only +ve for \(A_{FB} \leq F_H/2\) and \(F_H \geq 0\).

Unfortunately the angular distribution is insensitive to \(C_9^{NP}\).

It is also consistent with the SM expectation of \(A_{FB} \approx 0\) and \(F_H \approx 0\).
Anatomy of the $B^0 \to K^{*0} \mu^+ \mu^-$ decay

No photon ($C_7$) enhancement of $B \to K \mu^+ \mu^-$ decays at low $q^2$.
**c\bar{c}** contributions at high $q^2$

- $B^+ \rightarrow K^+ \mu^+ \mu^-$ data shows clear resonant structure.
- First observation of $B^+ \rightarrow \psi(4160)K^+$ and $\psi(4160) \rightarrow \mu^+ \mu^-$.  
  [PRL 111 (2013) 112003]

- Beylich, Buchalla & Feldman Theory calculations take $c\bar{c}$ contributions into account (through an OPE) but not their resonant structure.  
  [EPJC 71 (2011) 1635]
Normalise the observed event yields w.r.t. \( B^0 \rightarrow K^{*0} J/\psi \) to determine \( d\mathcal{B}/dq^2 \).

- Sensitivity of \( d\mathcal{B}/dq^2 \) to NP contributions limited by hadronic uncertainties.

- With larger datasets also need to consider S-wave interference under the \( K^{*0} \) from \( B^0 \rightarrow K^+ \pi^- \mu^+ \mu^- \) (and \( B^0 \rightarrow K^+ \pi^- J/\psi \)).

\[
\begin{array}{c}
B^0 \rightarrow K^{*0} \mu^+ \mu^- \\
\text{differential branching fraction}
\end{array}
\]
Angular observables $J_i(q^2)$ for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

\[ J_1^i = \frac{3}{4} \left\{ \frac{(2 + \beta^2_\mu)}{4} |A^L_\parallel|^2 + |A^L_\perp|^2 + (L \rightarrow R) \right\} + \frac{4m^2_\mu}{q^2} \Re(A^L_\perp A^R_\perp + A^L_\parallel A^R_\parallel) \]

\[ J_2^i = \frac{3\beta^2_\mu}{16} \left\{ |A^L_\parallel|^2 + |A^L_\perp|^2 + (L \rightarrow R) \right\} \]

\[ J_3^i = \frac{3\beta^2_\mu}{4} \left\{ |A^L_\parallel|^2 - |A^L_\perp|^2 + (L \rightarrow R) \right\} \]

\[ J_4^i = \frac{3\beta^2_\mu}{4\sqrt{2}} \left\{ \Re(A^L_\parallel A^L_\perp) + (L \rightarrow R) \right\} \]

\[ J_5^i = \frac{3\sqrt{2}\beta^2_\mu}{4} \left\{ \Re(A^L_\parallel A^L_\perp) - (L \rightarrow R) \right\} \]

\[ J_6^i = \frac{3\beta^2_\mu}{2} \left\{ \Re(A^L_\parallel A^L_\perp) - (L \rightarrow R) \right\} \]

\[ J_7^i = \frac{3\sqrt{2}\beta^2_\mu}{4} \left\{ \Im(A^L_\parallel A^L_\perp) - (L \rightarrow R) \right\} \]

\[ J_8^i = \frac{3\beta^2_\mu}{4\sqrt{2}} \left\{ \Im(A^L_\parallel A^L_\perp) + (L \rightarrow R) \right\} \]

\[ J_9^i = \frac{3\beta^2_\mu}{4} \left\{ \Im(A^L_\parallel A^L_\perp) + (L \rightarrow R) \right\} \]

For completeness

$J_i$ depend on 7 complex amplitudes: $A^L_\parallel, A^L_\perp, A^R_\parallel, A^R_\perp, A^L_0, A^R_0, A_t$
At “leading order”

\[
A^L_{\perp} = N \sqrt{2} \left\{ \left[ (C_9^{\text{eff}} + C_9'^{\text{eff}}) \mp (C_{10}^{\text{eff}} + C_{10}'^{\text{eff}}) \right] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} \left( C_7^{\text{eff}} + C_7'^{\text{eff}} \right) T_1(q^2) \right\}
\]

\[
A^L_{\parallel} = -N \sqrt{2} \left[ (C_9^{\text{eff}} - C_9'^{\text{eff}}) \mp (C_{10}^{\text{eff}} - C_{10}'^{\text{eff}}) \right] \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} \left( C_7^{\text{eff}} - C_7'^{\text{eff}} \right) T_2(q^2)
\]

\[
A^L_{0} = -\frac{N}{2m_{K^*} \sqrt{q^2}} \left\{ \left[ (C_9^{\text{eff}} - C_9'^{\text{eff}}) \mp (C_{10}^{\text{eff}} - C_{10}'^{\text{eff}}) \right] \left[ (m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*}) A_1(q^2) - \frac{A_2(q^2)}{m_B + m_{K^*}} \right]
\]

\[
+ 2m_b(C_7^{\text{eff}} - C_7'^{\text{eff}}) \left[ (m_B^2 + 3m_{K^*}^2 - q^2) T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2} T_3(q^2) \right] \right\}
\]

\[
A_t = \frac{N}{\sqrt{q^2}} \sqrt{\lambda} \left\{ 2(C_{10}^{\text{eff}} - C_{10}'^{\text{eff}}) + \frac{q^2}{m_{\mu}} (C^{\text{eff}}_P - C^{\text{eff}}'_P) \right\} A_0(q^2)
\]

\[
A_S = -2N \sqrt{\lambda} (C_S - C_S) A_0(q^2)
\]

- \( C_i \) are Wilson coefficients that we want to measure (they depend on the heavy degrees of freedom).
- \( A_0, A_1, A_2, T_1, T_2 \) and \( V \) are form-factors (these are effectively nuisance parameters).
Comments on angular distribution

- The L & R indices refer to the chirality of the leptonic system.
  - Different due to the axial vector contribution to the amplitudes.

- If $C_{10} = 0$, $A_{0,||,\perp}^L = A_{0,||,\perp}^R$ and the angular distribution reduces to the one for $B^0 \to K^{*0} J/\psi$.

- Zero-crossing point of $A_{FB}$ comes from interplay between the different vector-like contributions.

- In the SM there are 7 different amplitudes that contribute, corresponding to different polarisations states:
  
  - $K^{*}$ on-shell $\to$ 3 polarisation states $\epsilon_{K^*}(m = +, -, 0)$
  - $V^*$ off-shell $\to$ 4 polarisation states $\epsilon_{K^*}(m = +, -, 0, t)$

- $A_t$ corresponds to a longitudinally polarised $K^*$ and time-like $\mu^+\mu^-$. It’s suppressed, so can be neglected.
$B_S^0 \to \mu^+ \mu^-$ and $B^0 \to \mu^+ \mu^-$

- $B^0$ and $B_S^0 \to \mu^+ \mu^-$ are both GIM (loop) and helicity suppressed in the SM.
- Sensitive to contributions from (pseudo)scalar sector → interesting probe of NP models with extended Higgs sectors (e.g. MSSM, 2HDM, ...).
- e.g. in MSSM, branching fraction scales approximately as $\tan^6 \beta / M_A^4$.
- More generally:

$$B(B^0 \to \mu^+ \mu^-) \approx \frac{G_F \alpha^2 M^3 f^2_{B_q} \tau_{B_q}}{64 \pi^3 \sin^4 \theta_W} |V_{tb} V_{tq}|^2 \left(1 - \frac{4 m^2_\mu}{M^2_{B_q}}\right)^{1/2} M_{B_q} \times \left[\left(1 - \frac{4 m^2_\mu}{M^2_B}\right) |C_S - C'_S|^2 + |(C_P - C'_P) + \frac{2 m_\mu}{M_B} (C_{10} - C'_{10})|^2 \right]$$
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$q^2$ [GeV$^2$/c$^4$] vs. $m(K^+\mu^+\mu^-)$ [MeV/c$^2$]

LHCb (a)

$q^2$ [GeV$^2$/c$^4$] vs. $m(K^+e^+e^-)$ [MeV/c$^2$]

LHCb (b)