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

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

\[ b \rightarrow s \mu^+ \mu^- \] example

\[ b \rightarrow t \gamma, Z^0 \] (left)

\[ b \rightarrow W^- \nu, W^+ \mu^- \] (right)
\[ b \rightarrow s \mu^+ \mu^- \text{ example} \]

Standard Model

```
\begin{array}{c}
b \quad W^- \quad s \\
\quad t \quad \mu^+ \\
\gamma, Z^0 \\
\quad \mu^- \\
\end{array}
```

```
\begin{array}{c}
b \quad W^- \quad W^+ \\
\quad t \quad \nu \quad \mu^+ \\
\quad \mu^- \\
\end{array}
```

“New physics” (loop order)

```
\begin{array}{c}
b \quad \tilde{\chi}^0 \quad s \\
\quad d_i \quad \mu^+ \\
\gamma, Z^0 \\
\quad \mu^- \\
\end{array}
```

```
\begin{array}{c}
b \quad \tilde{g} \\
\quad d_i \\
\gamma, Z^0 \\
\quad H^0 \\
\quad \mu^- \\
\end{array}
```

```
\begin{array}{c}
b \quad t \\
\quad \tilde{H}^- \\
\quad \tilde{H}^+ \\
\quad \mu^+ \\
\quad \mu^- \\
\end{array}
```

- Sensitivity to the different SM & NP contributions through decay rates, angular observables and CP asymmetries.
Standard Model

\[ b \rightarrow s \mu^+ \mu^- \]

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

- 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 $|V_{td}/V_{ts}|^2$. 
Background rejection key for rare decay searches → use multivariate classifiers (BDTs) and tight particle identification requirements.

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

Branching fraction normalised w.r.t. $B^+ \rightarrow J/\psi K^+$ (and $B^0 \rightarrow K^+ \pi^-$ at LHCb).
\[ B_{s}^0 \rightarrow \mu^+ \mu^- \text{ at LHCb and CMS} \]

- In 3 fb\(^{-1}\) LHCb sees evidence for \( B_{s}^0 \rightarrow \mu^+ \mu^- \) at 4.0\(\sigma\) with \( \mathcal{B}(B_{s}^0 \rightarrow \mu^+ \mu^-) = (2.9^{+1.1}_{-1.0} + 0.3) \times 10^{-9} \). [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:

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

\[ \rightarrow B_s^0 \rightarrow \mu^+ \mu^- \text{ is observed at more than } 5\sigma \]

- Work is ongoing to do a proper combination of the two results.
- Unfortunately, measured BF 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.

\[\Rightarrow\] Can test $C_7/C_7'$ using:

\[\Rightarrow\] Mixing-induced CP violation \[Atwood et al PRL 79 (1997) 185-188\],

\[\Rightarrow\] $\Lambda_b^0$ baryons \[Hiller & Kagan PRD 65 (2002) 074038\],
OR $B \rightarrow K^{*\ast} \gamma$ 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 \((C'_7 - C_7)/(C'_7 + C_7) = 0\)

\[
\frac{1}{N} \times \frac{dN}{d\cos \theta} \quad \text{LHCb}
\]

- [1.1,1.3] GeV/c²

- [1.3,1.4] GeV/c²

- [1.4,1.6] GeV/c²

- [1.6,1.9] GeV/c²
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 $b \rightarrow s\gamma$ decays
$b \rightarrow s \ell^+ \ell^-$ decays
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular distribution

- Can also probe photon polarisation 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:

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

where the \( J_i \)'s are bilinear combinations of seven decay amplitudes \( A_L^L, A_L^R, A_R^L, A_R^R \) & \( A_t \) (\( L/R \) 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).
Angular distribution depends on 11 angular terms:

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

where the $J_i$'s are bilinear combinations of seven decay amplitudes $A^{L,R}_\parallel$, $A^{L,R}_\perp$, $A^{L,R}_0$ & $A_t$ ($L/R$ 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).
\[ B^0 \to K^{*0} \mu^+ \mu^- \text{ angular distribution} \]

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 \( A_{L,R}^{L,R}, A_{L,R}^0, A_t \) (\( L/R \) 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).
Angular distribution depends on 11 angular terms:

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

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. \( \phi \to \phi + \pi \) if \( \phi < 0 \) to cancel terms in \( \cos \phi \) and \( \sin \phi \) (LHCb).
\[ B^0 \to K^{*0} \mu^+ \mu^- \text{ angular distribution} \]

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

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\phi} = \frac{1}{2\pi} \left( 1 + S_3 \cos 2\phi + A_9 \sin 2\phi \right),
\]

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

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

Leaves 4 observables:

- \( A_{FB} \) Dimuon forward-backward asymmetry.
- \( F_L \) Fraction of longitudinal \( K^{*0} \) polarisation.
- \( A^2_T / S_3 \) 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)].

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 3.7σ 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 $b \to s\gamma$ and $b \to s\ell^+\ell^-$ data → 4.5σ 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 3σ. 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)]
Understanding the $P'_5$ anomaly?

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

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

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

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

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

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
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 [PRL 111 (2013) 162002], [arXiv:1310.3887].
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:

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

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

$B^+ \to J/\psi (\to e^+ e^-) K^+$ and $B^+ \to K^+ e^+ e^-$ candidates triggered by the $e^\pm$. 

![Graphs showing candidates distribution](image-url)
Lepton universality?

- Correct for bremsstrahlung using calorimeter photons (with $E_T > 75$ MeV).
- Migration of events into/out-of the $1 < q^2 < 6$ GeV$^2/c^4$ window is corrected using MC.
- Take double ratio with $B^+ \rightarrow J/\psi K^+$ 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
Effective GIM cancellation due to presence of $b-$, $s-$, $d$-quark in loop.

\[ \mathcal{B}(D^0 \to \mu^+ \mu^-) \approx 10^{-18} \text{ in SM.} \]

Long distance contributions.

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

Experimental precision limited by hadronic $\pi \to \mu$ mis-id.
$D^0 \rightarrow \mu^+ \mu^-$ at LHCb and CMS

- 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]
Can also look at other $c \to u$ decays, e.g. $D_{(s)}^+ \to \pi^+ \mu^+ \mu^-$.  

× Background from light resonances.

Set limits in 1 fb$^{-1}$ of

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

at 95% CL

Improving existing limits by 50x.
... or 4-body decays of $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$

\[ \text{Signal, } D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^- \text{ background} \]

- 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 $\mathcal{B}(t \rightarrow Z^0 q) < 10^{-14}$ in the SM, see e.g. [ActaPhys. Polon. B35 (2004) 2671-2694]

CMS perform a search for $t \rightarrow Z^0 j$ with $Z^0 \rightarrow \ell^+ \ell^-$, where $j$ is a jet, reconstructing the other top through $t \rightarrow Wb$.

CMS sets a limit of $\mathcal{B}(t \rightarrow Z^0 q) < 5 \times 10^{-4}$ 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 \( qg \to t \).

Search carried out by the ATLAS collaboration, with \( t \to Wb \), sets limits of:

\[
\mathcal{B}(t \to ug) < 5.7 \times 10^{-5} \text{ at 95\% CL}
\]

\[
\mathcal{B}(t \to cg) < 2.7 \times 10^{-4} \text{ at 95\% CL}
\]
Summary

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 $b \to s \ell^+ \ell^-$ 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].

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

- Flavour constraints exclude the whole \( m_0 : m_{1/2}^2 \) 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 $\phi_s$. 
$B_s^0 \rightarrow \mu^+ \mu^-$ progress with time

![Graph showing $B_s^0 \rightarrow \mu^+ \mu^-$ decay progress over time with data points from various experiments such as Belle, L3, CDF, UA1, CLEO, ARGUS, ATLAS, CMS, LHCb, D0, and BABAR. The graph includes BR UL (95% CL) or measurement values on a logarithmic scale ranging from $10^{-10}$ to $10^{-4}$ with markers for different experiments, and a timeline from 1985 to 2015. The standard model predictions for $B_s^0 \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$ decay are also indicated.]
Using 1 fb$^{-1}$ of integrated luminosity

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ at LHCb

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

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

$B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$
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

- Large data sets are also available at ATLAS [ATLAS-CONF-2013-038] and CMS [PLB 727 (2013) 77].
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]
$B^+ \rightarrow K^+ \mu^+\mu^-$ angular distribution

- 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 $F_H \approx 0$. 

\[\text{[arXiv:1403.8045]}\]
All reconstructed tracks

Only well reconstructed tracks with $p_T > 500$ MeV
Anatomy of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay

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

- \( B^+ \to K^+ \mu^+ \mu^- \) data shows clear resonant structure.

- First observation of \( B^+ \to \psi(4160)K^+ \) and \( \psi(4160) \to \mu^+ \mu^- \).
  [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. $B^0 \to K^{*0} J/\psi$ 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 $B^0 \to K^+ \pi^- \mu^+ \mu^-$ (and $B^0 \to K^+ \pi^- J/\psi$).

LHCb 1 fb$^{-1}$ [JHEP 08 (2013)]
CMS 5.2 fb$^{-1}$ [PLB 727 (2013) 77]
Angular observables $J_i(q^2)$ for $B^0 \to K^{*0} \mu^+ \mu^-$

$$
J_i^s = \frac{3}{4} \left\{ \frac{(2 + \beta_\mu^2)}{4} \left[ |A_{\perp}|^2 + |A_{\parallel}|^2 + (L \to R) \right] + \frac{4m_\mu^2}{q^2} \Re(A_{\perp}^L A_{\perp}^{R*} + A_{\parallel}^L A_{\parallel}^{R*}) \right\} \\
J_i^c = \frac{3}{4} \left\{ |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2} \left[ |A_t|^2 + 2\Re(A_0^L A_0^{R*}) \right] \right\} \\
J_2^s = \frac{3\beta_\mu^2}{16} \left\{ |A_{\perp}|^2 + |A_{\parallel}|^2 + (L \to R) \right\} \\
J_2^c = -\frac{3\beta_\mu^2}{4} \left\{ |A_0^L|^2 + (L \to R) \right\} \\
J_3 = \frac{3\beta_\mu^2}{8} \left\{ |A_{\perp}|^2 - |A_{\parallel}|^2 + (L \to R) \right\} \\
J_4 = \frac{3\beta_\mu^2}{4\sqrt{2}} \left\{ \Re(A_0^L A_0^{L*}) + (L \to R) \right\} \\
J_5 = \frac{3\sqrt{2}\beta_\mu}{4} \left\{ \Re(A_0^L A_{\perp}^{L*}) - (L \to R) \right\} \\
J_6 = \frac{3\beta_\mu}{2} \left\{ \Re(A_{\parallel}^L A_{\perp}^{L*}) - (L \to R) \right\} \\
J_7 = \frac{3\sqrt{2}\beta_\mu}{4} \left\{ \Im(A_0^L A_{\perp}^{L*}) - (L \to R) \right\} \\
J_8 = \frac{3\beta_\mu^2}{4\sqrt{2}} \left\{ \Im(A_0^L A_{\perp}^{L*}) + (L \to R) \right\} \\
J_9 = \frac{3\beta_\mu^2}{4} \left\{ \Im(A_{\parallel}^L A_{\perp}^{L*}) + (L \to R) \right\}
$$

For completeness, $J_i$ depend on 7 complex amplitudes: $A_{\parallel}^{L,R}$, $A_{\perp}^{L,R}$ and $A_0^{L,R}$, $A_t$.
\( B^0 \to K^{*0} \mu^+ \mu^- \) decay amplitudes

At “leading order”

\[
A_{\perp}^{L(R)} = N \sqrt{2} \lambda \left\{ \left[ (C_9^{\text{eff}} + C_{9'}^{\text{eff}}) \mp (C_{10}^{\text{eff}} + C'_{10}^{\text{eff}}) \right] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} (C_7^{\text{eff}} + C'_7^{\text{eff}}) T_1(q^2) \right\}
\]

\[
A_{\parallel}^{L(R)} = -N \sqrt{2} (m_B^2 - m_{K^*}^2) \left\{ \left[ (C_9^{\text{eff}} - C_{9'}^{\text{eff}}) \mp (C_{10}^{\text{eff}} - C'_{10}^{\text{eff}}) \right] \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} (C_7^{\text{eff}} - C'_7^{\text{eff}}) T_2(q^2) \right\}
\]

\[
A_0^{L(R)} = -\frac{N}{2m_{K^*} \sqrt{q^2}} \left\{ \left[ (C_9^{\text{eff}} - C_{9'}^{\text{eff}}) \mp (C_{10}^{\text{eff}} - C'_{10}^{\text{eff}}) \right] [(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*}) A_1(q^2) - \lambda \frac{A_2(q^2)}{m_B + m_{K^*}}] \right. \\
+ \left. 2m_b (C_7^{\text{eff}} - C'_{7}^{\text{eff}}) [(m_B^2 + 3m_{K^*}^2 - q^2) T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2} T_3(q^2)] \right\}
\]

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

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

- \( C_i \) 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 \( C_{10} = 0 \), \( A_{0,\parallel,\perp}^L = A_{0,\parallel,\perp}^R \) 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.
\[ B_s^0 \rightarrow \mu^+ \mu^- \text{ and } B^0 \rightarrow \mu^+ \mu^- \]

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

\[
B(B_q^0 \rightarrow \mu^+ \mu^-) \approx \frac{G_F \alpha^2 M_B^3 f_{B_q}^2 \tau_{B_q}^0}{64 \pi^3 \sin^4 \theta_W} |V_{tb} V_{tq}^*|^2 \left( 1 - \frac{4 m_{\mu}^2}{M_{B_q}^2} \right) \frac{1}{2} M_{B_q}^0 \times \left[ \left( 1 - \frac{4 m_{\mu}^2}{M_B^2} \right) |C_S - C'_S|^2 + |(C_P - C'_P) + \frac{2 m_{\mu}}{M_B} (C_{10} - C'_{10})|^2 \right]
\]