Electroweak Penguin
Decays at LHCb
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Outline

- Branching fraction and angular distribution of $b \rightarrow s \mu^+ \mu^-$ processes:
  - Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ (based on 3 fb$^{-1}$).
  - Angular analysis of $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ (based on 5 fb$^{-1}$)
- Branching fraction of $b \rightarrow d \mu^+ \mu^-$ processes:
  - Evidence for $B_s \rightarrow \overline{K}^{*0} \mu^+ \mu^-$ (based on 4.6 fb$^{-1}$)

More information can be found at
http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_RD.html
Electroweak penguin decays

- Flavour changing neutral current transitions that only occur at loop order (and beyond) in the SM.

- New particles can also contribute:

  enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles.

SM diagrams involve the charged current interaction.
Expected $d\Gamma/dq^2$ spectrum

Photon pole enhancement (no pole for $B \rightarrow P \ell \ell$ decays)

Spectrum dominated by narrow charmonium resonances. (vetoed in data)

Form-factors from LCSR calculations

Form-factors from Lattice QCD

Long distance contributions from $c\bar{c}$ above open charm threshold

Typically removed in analyses

Parameterisation

$4\left[ m(\mu) \right]^2$ dimuon mass squared
• We already have precise measurements of branching fractions from the Run1 data, with at least comparable precision to SM expectations:

[We have data on the branching fractions for $B^+ \to K^+ \mu^+ \mu^-$ and $B^0 \to K^0 \mu^+ \mu^-$, with measurements at LHCb and CMS.]

• SM predictions have large theoretical uncertainties from hadronic form factors (3 for $B \to K$ and 7 for $B \to K^*$ decays). For details see [Bobeth et al JHEP 01 (2012) 107] [Bouchard et al. PRL111 (2013) 162002] [Altmannshofer & Straub, EPJC (2015) 75 382].
Branching fraction measurements

Measure smaller branching fractions than predicted by the SM
Angular observables

- Multibody final-states:
  - Angular distribution provides many observables that are sensitive to BSM physics.
  - Constraints are orthogonal to branching fraction measurements, both in their impact in global fits and in terms of experimental uncertainties.

eg $B \rightarrow K^{*0} \mu^+ \mu^-$ decay described by three angles and $q^2$. 

(a) $\theta_K$ and $\theta_\ell$ definitions for the $B^0$ decay

(b) $\phi$ definition for the $B^0$ decay

(c) $\phi$ definition for the $\bar{B}^0$ decay
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular distribution

Complex angular distribution:

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\Omega} \bigg|_p = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l \right.$$ 

$$- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi$$ 

$$+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi$$ 

$$+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi$$ 

$$+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]$$

fraction of longitudinal polarisation of the $K^*$

forward-backward asymmetry of the dilepton system

The observables depend on form-factors for the $B \rightarrow K^*$ transition plus the underlying short distance physics (Wilson coefficients).

Experiments can reduce the complexity by folding the angular distribution, see [LHCb, PRL 111 (2013) 191801]
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular observables


Form-factor “free” observables

- In QCD factorisation/SCET there are only two form-factors:
  - One is associated with $A_0$ and the other $A_{\parallel}$ and $A_{\perp}$.
- Can then construct ratios of observables which are independent of these soft form-factors at leading order, e.g.
  \[ P'_5 = S_5 / \sqrt{F_L (1 - F_L)} \]

- $P'_5$ is one of a set of so-called form-factor free observables that can be measured [Descotes-Genon et al. JHEP 1204 (2012) 104].
Effective theory

- Can write a Hamiltonian for an effective theory of $b \rightarrow s$ processes:

\[ \mathcal{H}_{\text{eff}} = -\frac{4 G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) \mathcal{O}_i(\mu), \]

\[ \Delta \mathcal{H}_{\text{eff}} = \frac{\kappa_{\text{NP}}}{\Lambda_{\text{NP}}^2} \mathcal{O}_{\text{NP}} \]

$k_{\text{NP}}$ can have all/some/none of the suppression of the SM, e.g. MFV inherits SM CKM suppression.

$c.f.\text{ Fermi theory of weak interaction where at low energies:}$

\[ \lim_{q^2 \rightarrow 0} \left( \frac{g^2}{m_W^2 - q^2} \right) = \frac{g^2}{m_W^2} \]

i.e. the full theory can be replaced by a 4-fermion operator and a coupling constant, $G_F$. 

**Local 4 fermion operators with different Lorentz structures**

**Wilson coefficient (integrating out scales above $\mu$)**

**NP scale**

**NP can modify SM contribution or introduce new operators**

**c.f. Fermi theory of weak interaction where at low energies:**
Global fits

- Several attempts to interpret our results through global fits to $b \to s$ data.

Data are consistent between experiments/measurements and favour a modified vector coupling ($C_9^{NP} \neq 0$) at 4-5$\sigma$. 

[W. Altmannshofer et al. EPJC 77 (2017) 377]
$\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ decay

- First observed by the CDF collaboration in [PRL 107 (2011) 201802]
- Decay has unique phenomenology:
  - Diquark pair as a spectator rather than single quark;
  - $\Lambda_b$ can be produced polarised in $pp$ collisions;
  - and the $\Lambda$ baryon decays via the weak interaction.
- Based on [JHEP 06 (2015) 115], expect signal predominantly at low hadronic-recoil ($15 < q^2 < 20$ GeV$^2$/c$^4$).

Figure and SM prediction from: [Detmold et al. Phys.Rev. D93 (2016) 074501]

Data from: [LHCb, JHEP 06 (2015) 115]
$\Lambda_b \to \Lambda \mu^+ \mu^-$ angular distribution

• If the $\Lambda_b$ is produced polarised the decay is described by 5 angles and normal-vector, $\hat{n}$.

• Large number of observables:

$$\frac{d^5 \Gamma}{d\Omega} = \frac{3}{32\pi^2} \sum_{i}^{34} K_i(q^2) f_i(\Omega)$$

where $K_{11} - K_{34}$ are zero if the $\Lambda_b$ is unpolarised. [Blake et al. JHEP 11 (2017) 138]

• Determine observables using the method of moments and a set of orthogonal weighing functions.

• Correct for angular efficiency using per-candidate weights determined on simulated phasespace events.

• Analysis cross-checked using $B^0 \to J/\psi K_S$ and $\Lambda_b \to J/\psi \Lambda$ decays selected in same way as the signal.
$\Lambda_b \to \Lambda \mu^+ \mu^-$ angular distribution

• Large asymmetries on both the lepton- and hadron-side:

\[
A_{FB}^{\ell} = -0.39 \pm 0.04 \text{ (stat)} \pm 0.01 \text{ (syst)}
\]
\[
A_{FB}^{h} = -0.30 \pm 0.05 \text{ (stat)} \pm 0.02 \text{ (syst)}
\]
\[
A_{FB}^{\ell h} = +0.25 \pm 0.04 \text{ (stat)} \pm 0.01 \text{ (syst)}
\]

• Hadron-side asymmetry due to the weak decay of the $\Lambda$ baryon.

Consistent with SM predictions

[PRD 93 (2016) 074501] ($A_{FB}^{\ell h}$ is $\sim 2\sigma$ from its prediction)
$b \rightarrow d \mu^+ \mu^-$ transitions

- Decays are strongly suppressed in the SM, due to the small size of $V_{td}$, with branching fractions of $\mathcal{O}(10^{-8})$.
- We already have access to $b \rightarrow d \mu^+ \mu^-$ processes in the Run 1 data set:

\[
\frac{\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)} \Rightarrow |V_{td}/V_{ts}| = 0.20 \pm 0.02
\]

[Du et al. PRD 93 (2016)034005]
$B_s \rightarrow \bar{K}^{*0} \mu^+ \mu^-$

- Could be used in conjunction with $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ to determine $|V_{td}/V_{ts}|$.
- Need good mass resolution to separate the Bs and $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays.
- Perform a search for the decay using a data set corresponding to 4.6fb$^{-1}$ (3fb$^{-1}$ + 1.6fb$^{-1}$).
\( B_s \rightarrow \bar{K}^*0 \mu^+ \mu^- \) branching fraction

- Analysis binned in 4 bins of NN response.
- Signal yield determined from a simultaneous fit to the NN response bins.
- Normalise signal using \( B^0 \rightarrow J/\psi K^*0 \) and \( f_s/f_d \) from [LHCb-CONF-2013-011].
- Find first evidence for the decay with a significance of 3.4\( \sigma \).
- Resulting branching is:

\[
\mathcal{B}(B_s \rightarrow \bar{K}^*0 \mu^+ \mu^-) = [2.9 \pm 1.0 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.3 \text{ (norm)}] \times 10^{-8}
\]

- Consistent with SM predictions, see e.g. [EPJC 73 (2013) 2593, arXiv:1803.05876]
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⇒ Consistent with SM predictions, see e.g. [EPJC 73 (2013) 2593, arXiv:1803.05876]
Summary

• FCNC processes provide powerful constraints on extensions of the SM.
• Large $b\bar{b}$ cross-section at the LHC provides large samples of “rare” decay processes.
• Several interesting tensions are seen in data on $b\rightarrow s\ell^+\ell^-$ processes.
Summary

• Huge progress expected in the next five years with new data from the LHC experiments and from Belle II.
$B_s \rightarrow \bar{K}^{*0} \mu^+ \mu^-$
$B_s \rightarrow J/\psi \bar{K}^{*0}$

![Graphs showing the decay of $B_s$ to $J/\psi \bar{K}^{*0}$](image)

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Operators

- Different processes are sensitive to different 4-fermion operators. Can exploit this to over-constrain the system.

\[ O_7 = \left( \frac{m_b}{e} \right) (\bar{s}\sigma^{\mu\nu} P_R b F_{\mu\nu}) \]

- photon (constrained by radiative decays and \( b \to s\ell^+\ell^- \) processes at small \( q^2 \))

\[ O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^{\mu}\ell) \]

- vector current (constrained by \( b \to s\ell^+\ell^- \) processes)

\[ O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^{\mu}\gamma_5\ell) \]

- axial vector current (constrained by leptonic decays and \( b \to s\ell^+\ell^- \) processes)

\[ O_S = (\bar{s}P_R b)(\bar{\ell}\ell) \]

- scalar and pseudoscalar operators (constrained primarily by leptonic decays)

\[ O_P = (\bar{s}P_R b)(\bar{\ell}\gamma_5\ell) \]

- e.g.

\[ B_s^0 \to \mu^+\mu^- \text{ constrains } C_{10} - C'_{10}, \; C_S - C'_{S}, \; C_P - C'_{P} \]

\[ B^+ \to K^+\mu^+\mu^- \text{ constrains } C_9 + C'_9, \; C_{10} + C'_{10} \]

\[ B^0 \to K^{*0}\mu^+\mu^- \text{ constrains } C_7 \pm C'_7, \; C_9 \pm C'_9, \; C_{10} \pm C'_{10} \]

The primes denote right-handed counterparts of the operators whose contribution is small in the SM.
Interpretation of global fits

Optimist’s view point

Vector-like contribution could come from e.g. new tree level contribution from a $Z'$ with a mass of a few TeV.

Pessimist’s view point

Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon?

More work needed from experiment/theory to disentangle the two
What can we learn from the data?

- If we are underestimating $c\bar{c}$ contributions then naively expect to see the shift in $C_9$ get larger closer to the narrow charmonium resonances.

No clear evidence for a rise in the data (but more data is needed).
SM contributions

- Interested in new short distance contributions.
- We also get long-distance hadronic contributions.
- Need estimate of non-local hadronic matrix elements [Khodjamirian et al. JHEP 09 (2010) 089]

Short distance part integrates out (as a Wilson coefficient)
Theoretical Framework

• In leptonic decays the matrix element for the decay can be factorised into a leptonic current and $B$ meson decay constant:

$$\langle \ell^+ \ell^- | j_\ell j_q | B_q \rangle = \langle \ell^+ \ell^- | j_\ell | 0 \rangle \langle 0 | j_q | B_q \rangle$$

$$\approx \langle \ell^+ \ell^- | j_q | 0 \rangle \cdot f_{B_q}$$

• In semileptonic decays, the matrix element can be factorised into a leptonic current times a form-factor:

$$\langle \ell^+ \ell^- M | j_\ell j_q | B \rangle = \langle \ell^+ \ell^- | j_\ell | 0 \rangle \langle M | j_q | B_q \rangle$$

$$\approx \langle \ell^+ \ell^- | j_\ell | 0 \rangle \cdot F(q^2) + O(\Lambda_{QCD}/m_B)$$

however this factorisation is not exact (due to hadronic contributions).
Can select a clean sample of signal events using multivariate classifier.

2398 ± 57 candidates in $0.1 < q^2 < 19$ GeV$^2$ after removing the $J/\psi$ and $\psi(2S)$.

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

combinatorial background
Systematic uncertainty on branching fraction measurements

- Normalise measurements to $B \to J/\psi X$ control channel.
  - Cancels luminosity/cross-section/efficiency scale uncertainties.
- Use $B^0 \to K^{*0} \mu^+ \mu^-$ at LHCb as an example of what systematic uncertainties are important:

  | Source                      | $F_S|_{644}^{1200}$ | $d\mathcal{B}/dq^2 \times 10^{-7} (e^4/\text{GeV}^2)$ |
  |-----------------------------|---------------------|------------------------------------------------------|
  | Data-simulation differences | 0.008–0.013         | 0.004–0.021                                          |
  | Efficiency model            | 0.001–0.010         | 0.001–0.012                                          |
  | S-wave $m_{K\pi}$ model     | 0.001–0.017         | 0.001–0.015                                          |
  | $B^0 \to K^{*(892)^0}$ form factors | –               | 0.003–0.017                                          |
  | $\mathcal{B}(B^0 \to J/\psi (\to \mu^+ \mu^-)K^{*0})$ | –               | 0.025–0.079                                          |

Uncertainty on $\mathcal{B}(B \to J/\psi X)$ normalisation modes is already a limiting factor. Encourage Belle II to update these measurements!
Resonant contributions

- With the large LHC datasets can also explore the shape of the $d\Gamma/dq^2$ spectrum in detail.
- See evidence for broad charmonium states and light quark contributions.
- Can determine relative magnitude/phases of the different contributions.

- Data could be used to exclude models proposing new GeV-scale particles as an explanation for $R_K/R_{K^*}$. [F. Sala & D. Straub, arXiv:1704.06188]
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular observables


- SM predictions based on
  [Altmannshofer & Straub, EPJC 75 (2015) 382]
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular analysis

• Typically integrate over all but one angle or perform angular folding to reduce the number of observables.

• LHCb has performed the first full angular analysis of the decay.

→ Access the full set of angular observables and their correlations.

• Experiments need good control of detector efficiencies and to understand background from decays where the $K\pi$ is in an S-wave configuration.

• Use $B^0 \rightarrow J/\psi K^{*0}$ as a control channel to understand the acceptance of the detector.
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ example fit

\[ m(K^+\pi^-\mu^+\mu^-) \ [\text{MeV}/c^2] \]

\[ \cos \theta_K \]

\[ \cos \theta_l \]
Angular distribution of $B^+ \rightarrow K^+ \ell^+ \ell^-$ is a null test of SM, but can be sensitive to new scalar/pseudoscalar/tensor contributions, e.g. [F. Beaujean et al. EPJC 75 (2015) 456]

Combination $B(B_s \rightarrow \mu^+ \mu^-)$ $F_H[B^+ \rightarrow K^+ \mu^+ \mu^-]$
$B_s \rightarrow \phi \mu^+ \mu^- \text{ decay rate}$

- Large tension between the SM prediction and the data at low $q^2 (\sim 3\sigma)$.

SM predictions based on
[Altmannshofer & Straub, arXiv:1411.3161]
Rare leptonic decays

- $B_{(s,d)} \rightarrow \mu^+ \mu^-$ are golden modes to study at the LHC.
  - CKM suppressed, loop suppressed and helicity suppressed.
  - Powerful probe of models with new enhanced (pseudo)scalar interactions, e.g. SUSY at high $\tan \beta$.

\[
\frac{\mathcal{B}(B_q \rightarrow \ell^+ \ell^-)_{\text{NP}}}{\mathcal{B}(B_q \rightarrow \ell^+ \ell^-)_{\text{SM}}} = \frac{1}{|C_{10}^{\text{SM}}|^2} \left\{ \left(1 - 4 \frac{m_\ell^2}{m_{B_q}} \right) \left| \frac{m_{B_q}}{2m_\ell} (C_S - C_S') \right|^2 \right. \\
\left. + \left| \frac{m_{B_q}}{2m_\ell} (C_P - C_P') + (C_{10} - C_{10}') \right|^2 \right\}
\]
Recent LHCb analysis using run 1 and 2 data (3fb$^{-1}$ + 1.4fb$^{-1}$) provided the first single experiment observation of $B_s \rightarrow \mu^+ \mu^-$ at more than 7$\sigma$. [LHCb, PRL 118 (2017) 191801]
$B_S \rightarrow \mu^+ \mu^-$

- Recent LHCb analysis using run 1 and 2 data (3fb$^{-1}$ + 1.4fb$^{-1}$) provided the first single experiment observation of $B_S \rightarrow \mu^+ \mu^-$ at more than 7σ.  
  [LHCb, PRL 118 (2017) 191801]

- Measurements are all consistent with the SM expectation.
  - Can exclude large scalar contributions.

- Branching fraction predicted precisely in the SM with a ~6% uncertainty.

-Time integrated SM prediction
  [C. Bobeth et al. PRL112 (2014)101801]

- Branching fraction $\Gamma_B / \Gamma_s$ from Lattice QCD

- $f_{B_s}$ decay constant from Lattice QCD

- CKM elements

- $v_{cb}$
  - 3.6%
  - 0.11%
  - 0.33%
  - 0.49%

- $m_s$
  - 1.5%

- $\Delta l / \Gamma_s$
  - 0.5%

- $\gamma$
  - 3.2%
Effective lifetime

- The untagged time dependent decay rate is
  \[
  \Gamma[B_s(t) \to \mu^+ \mu^-] + \Gamma[\bar{B}_s(t) \to \mu^+ \mu^-] \propto e^{-t/\tau_{B_s}} \left\{ \cosh \left( \frac{\Delta \Gamma_s}{2} t \right) + A_{\Delta \Gamma} \sinh \left( \frac{\Delta \Gamma_s}{2} t \right) \right\}
  \]

- \( A_{\Delta \Gamma} \) provides additional separation between scalar and pseudoscalar contributions.

- In the SM \( A_{\Delta \Gamma} = 1 \) such that the system evolves with the lifetime of the heavy \( B_s \) mass eigenstate.
The $A_{\Delta \Gamma}$ parameter modifies the effective lifetime of the decay:

$$\tau_{\text{eff}} = \frac{\tau_{B_s}}{1 - y_s^2} \left( \frac{1 + 2A_{\Delta \Gamma} y_s + y_s^2}{1 + A_{\Delta \Gamma} y_s} \right)$$

where $y_s = \tau_{B_s} \frac{\Delta \Gamma}{2}$

- LHCb have performed a first measurement of $\tau_{\text{eff}}$, giving

$$\tau[B_s^0 \to \mu^+ \mu^-] = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

**NB** Not yet sensitive to $A_{\Delta \Gamma}$ (the stat. uncertainty is larger than the change in the lifetime from $\Delta \Gamma_s$). This will become more interesting during runs 3 and 4.
$B_{(s,d)} \rightarrow \tau^+ \tau^-$

- LHCb performs a search for $B_{(s,d)} \rightarrow \tau^+ \tau^-$ decays using $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$.
  - Exploit the $\tau^- \rightarrow a_1(1260)\nu_\tau$ and $a_1(1260)^- \rightarrow \rho(770)^0 \pi^-$ decays to select signal/control regions of dipion mass.
- Fit Neural network response to discriminate signal from background.
  - Ditau mass is not a good discriminator due to missing neutrino energy.
- LHCb sets limits on:
  \[
  \mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) < 6.8 \times 10^{-3} \text{ (95\% CL)} \\
  \mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) < 2.1 \times 10^{-3} \text{ (95\% CL)}
  \]