Rare decays and LFU tests at LHCb Upgrade II

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New Physics searches in rare B decays

Flavour Changing Neutral Currents are suppressed in the SM,

- only occur at loop level
- GIM suppressed
- left-handed chirality

but this is **not necessarily true** in a New Physics scenario.

Study many different kind of observables ($B$’s, angular observables, LFU tests) with different sensitivities to NP.
Model independent NP search - Effective Theory

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \frac{e^2}{16\pi^2} V_{tb} V_{tq}^* \sum_i C_i \mathcal{O}_i + \text{h.c.} \]

- **Radiative decays**
  - \( B^0 \to K^{*0} \gamma \) ...

- **Very rare decays**
  - \( B^0 \to \mu^+ \mu^- \)
  - \( B_s^0 \to \mu^+ \mu^- \)

- **Electroweak penguins**
  - \( B^0 \to K^{*0} \mu^+ \mu^- \)
  - \( B^+ \to K^+ e^+ e^- \)
  - \( B^+ \to \pi^+ \mu^+ \mu^- \) ...
LHCb upgrade plan

- Run 1 & Run 2: 9 fb$^{-1}$
- Run 3 & Run 4 (Upgrade I): 50 fb$^{-1}$ ($\mathcal{L} = 2 \times 10^{33} \text{ cm}^2\text{s}^{-1}$)
- Run 5 (Upgrade II): 300 fb$^{-1}$ ($\mathcal{L} = 2 \times 10^{34} \text{ cm}^2\text{s}^{-1}$)
Very rare decays

- Very suppressed $\Rightarrow$ Need as much statistics as possible
- These analysis will be still statistically limited with the Upgrade II sample
$B^0_{(s)} \rightarrow \mu^+\mu^-$ branching fractions

- Precisely predicted in the SM
  \[ B_{SM}(B^0 \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9} \]
  \[ B_{SM}(B^0_s \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10} \]

- Latest measurements from LHCb
  \[ B(B^0_s \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \]
  \[ B(B^0 \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-10} @ 95\% \text{ CL} \]

- With 300 fb$^{-1}$ the uncertainty on $B(B^0_s \rightarrow \mu^+\mu^-) \sim 0.16 \times 10^{-9}$ (1.8%)
  - Statistical uncertainty \sim 1.8% 
  - Dominant syst. $f_s/f_d$ will scale with luminosity
  - Expected total syst. \sim 4%

- For the ratio of $B$'s of $B^0$ over $B^0_s$ ($r$), LHCb could reach $\sigma(r) \sim 10\%$

P. Álvarez Cartelle (Imperial College London) Rare decays and LFU @ Upgrade II
$B^0_s \rightarrow \mu^+ \mu^-$ effective lifetime

- Extremely clean theoretically and has complementary sensitivity to scalar operators
  - In the SM, only the heavy $B^0_s$ eigenstate couples to $\mu \mu$ ($\tau_{\mu \mu}^{SM} = \tau_H$)
- Recent LHCb measurement: $\tau_{\mu \mu} = 2.04 \pm 0.44 \pm 0.05$ ps
- Could reach $\sim 2\%$ uncertainty with 300 fb$^{-1}$

![Effective lifetime fit](image)

[PRL 118, 191801 (2017)]

[PRL 109, 041801 (2012)]
Other very rare decays

- Other $B_{(s)} \rightarrow \ell^+ \ell^-$ will still be far from the SM predictions
  - $B^0_s \rightarrow e^+ e^-$: $[4 - 11] \times 10^{-9}$ (exp. Run 1) $\rightarrow [3 - 9] \times 10^{-10}$ (exp. Run 5)
  - $B^0_s \rightarrow \tau^+ \tau^-$: $6.8 \times 10^{-3}$ (Run 1) $\rightarrow 3 \times 10^{-4}$ (exp. Run 5)

- For lepton flavour violating modes such as $B_{(s)} \rightarrow e\mu$, $B^+ \rightarrow K^+ e\mu$ or $\tau \rightarrow \mu\mu\mu$ limit improvements $\sim$ one order of magnitude are expected
  - Limits in $B \rightarrow K^{(*)} e\mu$ and $B \rightarrow K^{(*)} \tau\mu$ will probe the region of interest of the models currently developed for explaining the B anomalies

- Reconstruction of electrons and taus would benefit from the removal of the RF foil and the enhanced low momentum tracking [LHCb, EOI for phase II upgrade, CERN-LHCC-2017-003]
Rare charm and strange decays

- Large cross-section for strange and charm hadrons
- Strange decays: sensitivity will improved significantly already Upgrade I with full software trigger
  - Will get best limits in $K_S^0 \rightarrow \mu^+ \mu^-$, $K_S^0 \rightarrow \pi^0 \mu^+ \mu^-$
  - Proposed specialised processors for downstream track finding would increase efficiency for these decays

- In charm decays:
  - Expect order of magnitude improvement in sensitivity to SD contributions
  - More observables accesible: $A_{FB}$, $A_{CP}$
Electroweak penguins
Interesting set of tensions with the SM predictions

- Branching fractions measurements of $B \rightarrow K^{(*)} \mu^+ \mu^-$, $B_s \rightarrow \phi \mu^+ \mu^-$, $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ ...

- Angular analyses of $B_s \rightarrow \phi \mu^+ \mu^-$, $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ and $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Lepton flavour universality tests in $B^+ \rightarrow K^+ l^+ l^-$ and $B^0 \rightarrow K^{*0} l^+ l^-$
$b \to s\mu^+\mu^-$ branching fractions

- Upgrade II will bring better control over the shape of $d\mathcal{B}/dq^2$
- In terms of systematic uncertainty, the knowledge on $\mathcal{B}(B \to J/\psi X)$ modes used for normalisation is already a limiting factor (Belle 2!)
- Run 1 precision on $B$'s is already at the level of the theory uncertainty for the SM predictions
$b \to s \mu^+ \mu^-$ angular analyses

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

- Give access to observables with reduced dependence on hadronic effects [JHEP 1204 (2012) 104]
- LHCb finds deviation from the SM prediction at the level of $3.4\sigma$

Hadronic uncertainties

Global fits of Wilson Coefficients to $b \to s\mu^+\mu^-$ data rely on theory predictions for $B \to X_s$ form-factors.

Anomalies in $b \to s\mu^+\mu^-$ have exposed theory limitations: debate on whether uncertainties related to $c\bar{c}$-loop contributions are under control.

Need to improve theory alongside with experimental precision to profit from Upgrade II!

[S. Descotes-Genon et al. JHEP06 (2016) 092]
Angular analyses prospects

- With 300 fb$^{-1}$ (e.g. $\sim 440,000 \ B^0 \rightarrow K^{*0}\mu^+\mu^-$ candidates), we can use our to help improving the theory prediction:
  - precise determination of angular observables in narrow bins of $q^2$, or
  - extract information on the form-factors from the fit to the data
Angular analyses prospects: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Parameterise and fit for form-factors together with Wilson Coefficients in a $q^2$-unbinned approach
  - Hurth et al, JHEP11(2017)176,
  - Chrzaszcz et al, 1805.06378,
  - Blake et al, EPJC(2018)78:453

- Important to maintain performance for $\mu$ channels (PID, mass resolution, vertex isolation)

- Systematics:
  - Assumptions from modelling of form-factors/resonances
  - Understanding the angular acceptance will need of large MC samples (fast MC)
  - Control angular distribution of the background with data

$C_{9NP}^{NP} = -1.4$

$C_{9NP}^{NP} = -C_{10NP}^{NP} = -0.7$
Angular analyses prospects: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- For $C_9, C_{10}$ form factor uncertainties cause saturation at $\sim 30 \text{ fb}^{-1}$
  - Will need theory to improve too to push this further
- Will be able to probe $C'_9, C'_10$ to high precision
- Different NP scenarios can be cleanly separated
Testing MFV with $b \to d \ell^+ \ell^-$ decays

- CKM-suppressed equivalent of $b \to s \ell^+ \ell^-$, several observations already with Run1, 2015 and 2016 data

- With $\mathcal{B}(B \to \pi\mu\mu)/\mathcal{B}(B \to K\mu\mu)$ and form-factors from the lattice, can access $|V_{td}/V_{ts}|$ only with penguins
  - With 300 fb$^{-1}$, expect factor 10 improvement in experimental error precision, but requires also improvements in the lattice calculation
Testing MFV with $b \to d\ell^+\ell^-$ decays (II)

Upgrade II will allow also angular analyses of $b \to d\ell^+\ell^-$ transitions

- Angular analysis of $B^0_s \to \bar{K}^*0\mu\mu$ with comparable precision to Run 1 $B^0 \to K^*0\mu^+\mu^-$
- For the $B^0$ equivalent, $B^0 \to \rho^0\mu\mu$, flavour tagging is needed: tagging efficiency still limiting factor in phase II

[JHEP 07 (2018) 020]

P. Álvarez Cartelle (Imperial College London)

Rare decays and LFU @ Upgrade II
Lepton flavour universality tests

Ratios of branching fractions between muons and electrons are theoretically pristine

\[
R_X = \frac{BR(B \rightarrow X\mu^+\mu^-)}{BR(B \rightarrow Xe^+e^-)} \overset{\text{SM}}{\approx} 1
\]

→ Essentially free from QCD uncertainties, QED effects can be \(\mathcal{O}(10^{-2})\)

[JHEP 07 (2007) 040], [EPJC 76 (2016) 8,440]
Lepton Flavour Universality tests - prospects

[Upgrade II physics case, LHCb-PUB-2018-009]

- Precision driven by the electron modes
  - Substantial gain in expected yields in Upgrade II
  - Projections based on same performance going forward

- Statistical power opens the door to measuring different channels with good precision ($R_{\phi}$, $R_{\Lambda}$) and even access CKM-suppressed version ($R_{\pi}$).

  → Different $R_X$ sensitive to different combinations of Wilson coefficients, allow separation of NP scenarios

<table>
<thead>
<tr>
<th>Yield</th>
<th>Run 1 result</th>
<th>9 fb$^{-1}$</th>
<th>23 fb$^{-1}$</th>
<th>50 fb$^{-1}$</th>
<th>300 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to K^+ e^+ e^-$</td>
<td>254 ± 29 [274]</td>
<td>1 120</td>
<td>3 300</td>
<td>7 500</td>
<td>46 000</td>
</tr>
<tr>
<td>$B^0 \to K^{*0} e^+ e^-$</td>
<td>111 ± 14 [275]</td>
<td>4 90</td>
<td>1 400</td>
<td>3 300</td>
<td>20 000</td>
</tr>
<tr>
<td>$B^0_s \to \phi e^+ e^-$</td>
<td>–</td>
<td>80</td>
<td>230</td>
<td>530</td>
<td>3 300</td>
</tr>
<tr>
<td>$\Lambda^0_b \to p K^+ e^+ e^-$</td>
<td>–</td>
<td>120</td>
<td>360</td>
<td>820</td>
<td>5 000</td>
</tr>
<tr>
<td>$B^+ \to \pi^+ e^+ e^-$</td>
<td>–</td>
<td>20</td>
<td>70</td>
<td>150</td>
<td>900</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$R_X$ precision</th>
<th>Run 1 result</th>
<th>9 fb$^{-1}$</th>
<th>23 fb$^{-1}$</th>
<th>50 fb$^{-1}$</th>
<th>300 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_K$</td>
<td>0.745 ± 0.090 ± 0.036 [274]</td>
<td>0.043</td>
<td>0.025</td>
<td>0.017</td>
<td>0.007</td>
</tr>
<tr>
<td>$R_{K^{*0}}$</td>
<td>0.69 ± 0.11 ± 0.05 [275]</td>
<td>0.052</td>
<td>0.031</td>
<td>0.020</td>
<td>0.008</td>
</tr>
<tr>
<td>$R_{\phi}$</td>
<td>–</td>
<td>0.130</td>
<td>0.076</td>
<td>0.050</td>
<td>0.020</td>
</tr>
<tr>
<td>$R_{pK}$</td>
<td>–</td>
<td>0.105</td>
<td>0.061</td>
<td>0.041</td>
<td>0.016</td>
</tr>
<tr>
<td>$R_{\pi}$</td>
<td>–</td>
<td>0.302</td>
<td>0.176</td>
<td>0.117</td>
<td>0.047</td>
</tr>
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Lepton Flavour Universality tests - prospects

- Precision driven by the electron modes
  - Substantial gain in expected yields in Upgrade II
  - Projections based on same performance going forward
- Statistical power opens the door to measuring different channels with good precision ($R_\phi$, $R_\Lambda$) and even access CKM-suppressed version ($R_\pi$).

  $\Rightarrow$ Different $R_X$ sensitive to different combinations of Wilson coefficients, allow separation of NP scenarios
- Differences in the angular distributions for electron/muon final states are also theoretically clean

- Sensitivity to different combinations of Wilson Coefficients
Detector considerations

- Main experimental challenges related to large amount of bremsstrahlung emitted by the electrons in the detector ⇒ Degraded momentum, and mass/$q^2$ resolution
  - Perform recovery of brem. photon clusters in ECAL (for $E_T > 75\text{ MeV}$)

- Can we maintain ability to reconstruct the brem. photons in a busier environment? Improve?
  - Reduce the amount of material in the detector
  - Improve ECAL granularity and energy resolution

- Largest systematic uncertainties will still scale with luminosity, e.g. for $R_K$:
  - modelling of partially reconstructed backgrounds (study them in data)
  - corrections to simulation (data-driven)
Radiative decays
Radiative decays

- Will improve precision in $B$'s, $CP$ asymmetries and photon polarisation
- Large statistics will give access to $b \rightarrow d\gamma$ transitions, which have smaller $B$'s but where $CP$ asymmetries are expected to be larger
- Challenging analyses:
  - Invariant mass resolution dominated by photon reconstruction
    - control partially reconstructed backgrounds
  - Large photon backgrounds
    - $\pi^0 \rightarrow \gamma\gamma$ reconstructed as single cluster
    - Combinatorial, $O(10)$ reconstructed photons per event
- Performance improvements needed in many analyses to profit from statistics in phase II
Summary

- The LHCb phase II upgrade will enable the study of highly suppressed decay modes
  - Will approach the SM predictions ($B^0_s \rightarrow \mu\mu$) or be sensitive to possible NP effects in several channels (LFV)

- $b \rightarrow s\ell\ell$ transitions will not be “rare” any more
  - Branching fractions and angular observables might reach current SM precision by the end of Run 2
  - Still plenty of very clean observables to keep looking at (LFU)
  - Large samples will open new analysis possibilities that could help improve SM predictions

- Many radiative decays analyses will be systematics-limited by the end of phase I
  - The improved ECAL can greatly enhance our capabilities
Backup
$b \to d\ell^+\ell^-$ transitions

- As for $B_d \to \mu^+\mu^- / B_s \to \mu^+\mu^-$ and $\Delta m_d / \Delta m_s$, ratio of $b \to s$ and $b \to d$ decays is a test of MFV

- EW penguins have additional uncertainty from ratio of form factors, will need improvements from Lattice too

FNAL/MILC PRD93,113016 (2016)
LFU prospects

- For ratios of $B$'s (e.g. $R_K$, $R_{K^*0}$) we could reach 1-2% precision
  - For comparison Belle 2 expects to reach a precision of 4-5% with a 50 ab$^{-1}$ dataset [S. Sandilya at CKM 2016]

- Angular analyses with electrons have orthogonal systematics with respect to $R_X$'s and these can also be kept under control
- Expect good sensitivity to differences in the angular distributions for electron/muon final states

[LHCb, EOI for phase II upgrade CERN-LHCC-2017-003]
LFU with $b \rightarrow c \ell \nu$ decays

- We also have hints of $\mu - \tau$ non-universality in semileptonic $X_b \rightarrow X_c \ell \nu$
- Difficult measurement due to missing neutrinos, but Run 1 demonstrated LHCb’s potential in this area
LFU with $b \rightarrow c\ell\nu$ decays - prospects

Phase-II will substantially benefit $R(X_c)$ measurements of $B_s$, $\Lambda_b$, $B_c$ hadrons

Complementary sensitivity to NP

- What can we do better?
  - Reduction of background from additional charged tracks can be achieved with better vertex resolution
  - Neutral isolation to reject background with neutrals could benefit from an upgraded calorimeter
Photon polarisation - $B^0_s \rightarrow \phi\gamma$

- Tagged time dependent analysis of $B^0_s \rightarrow \phi\gamma$

$$\Gamma \sim e^{-\Gamma t}[\cosh(\frac{\Delta \Gamma t}{2}) - A^\Delta \sinh(\frac{\Delta \Gamma t}{2})$$

$$\pm C \cos(\Delta mt) \mp S \sin(\Delta mt)]$$

- $A^\Delta$ and $S$ sensitive to the photon polarisation
- Expected sensitivity of Run 2 analysis $\sim 0.3$

- With 300 fb$^{-1}$:
  - $\sigma(A^\Delta) \sim 0.02$ (stat)
  - Need to work on reducing systematics from lifetime acceptance ($\sigma(A^\Delta)$)
  - Uncertainties on $C$, $S$ dominated by proper time resolution
Photon polarisation - Baryonic decays

- Angular analysis of $\Lambda_b \rightarrow \Lambda \gamma$
  - Run 1 + Run 2: Expected sensitivity $\sigma(a_\gamma) < 0.2$
  - With 300 fb$^{-1}$:
    - Expected $\sigma(a_\gamma)_{\text{stat}} \sim 0.01$
    - Acceptance modeling will be dominant uncertainty
    - Would benefit from improved downstream track reconstruction