Rare decays as sensitive probes for New Physics

Rare decays in the SM

\[ b \to t \to W \to \mu^- \gamma, Z^0 \mu^+ \]

Possible contributions from NP

- Supersymmetry
  \[ b \to \tilde{t} \to W \to \mu^- \mu^+ \]

- Leptoquarks
  \[ b \to \tilde{W} \to \mu^- \mu^+ \]

- New heavy gauge bosons
  \[ b \to Z' \to \mu^+ \mu^- \]

- New rare observables in LHCb Upgrade II

- Rare decays are so called Flavour Changing Neutral Currents
- In the SM: Only allowed via quantum fluctuations (loop suppressed)
- New heavy particles can significantly contribute and change rates and angular distributions
NP contributions and relevant effective couplings

Model independent description in effective field theory

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i \]

\[ \Delta \mathcal{H}_{\text{NP}} = \frac{\kappa}{\Lambda_{\text{NP}}^2} O_i \]

NP can contribute to different operators \( O_i \) depending on its type.

Relevant effective couplings for rare decays:

**Coupling**

**Operator**

\( C_{7}^{(i)} \)

\[ \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_{RL} b) F^{\mu\nu} \]

\( C_{9}^{(i)} \)

\[ (\bar{s}\gamma_{\mu} P_{L} b) (\bar{\mu}\gamma^{\mu}\mu) \]

\( C_{10}^{(i)} \)

\[ (\bar{s}\gamma_{\mu} P_{L} b) (\bar{\mu}\gamma^{\mu}\gamma_{5}\mu) \]

\( C_{S}^{(i)} \)

\[ \frac{m_b}{m_{B}} (\bar{s}P_{RL} b) (\bar{\mu}\mu) \]

\( C_{P}^{(i)} \)

\[ \frac{m_b}{m_{B}} (\bar{s}P_{RL} b) (\bar{\mu}\gamma_{5}\mu) \]
The complementarity of NP searches with rare decays

**Exclusion limits for NP searches**

\[ \mathcal{H}_{\text{NP}} \propto \frac{\kappa}{\Lambda_{\text{NP}}^2} \]

**Rare decays (\( \Delta F = 1 \))**

- **Direct searches**
  - Limited by beam energy, \( \Lambda_{\text{NP}} < \sqrt{s} \)
  - Reach with rare decays scales with \( \sqrt{\kappa/\sigma(C_i)} \)
  - Typically \( \Lambda_{\text{NP}} \propto \sqrt{\kappa/\sigma(C_i)} \propto \sqrt{\kappa} \times 4\int L \, dt \)

**Scenario**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>( \kappa )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree generic</td>
<td>1</td>
</tr>
<tr>
<td>Tree MFV</td>
<td>( V_{tb}V_{ts} )</td>
</tr>
<tr>
<td>Loop generic</td>
<td>( \frac{1}{16\pi^2} )</td>
</tr>
<tr>
<td>Loop MFV</td>
<td>( \frac{V_{tb}V_{ts}}{16\pi^2} )</td>
</tr>
</tbody>
</table>

**CKM-like flavour violation** ↔ **generic flavour violation**
LHCb Upgrade schedule

- **Current status:** 9 fb$^{-1}$ in Run 1+2
- **Upgrade I a+b:** 50 fb$^{-1}$ (Run 3+4 at $\mathcal{L} = 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$)
- **Upgrade II:** 300 fb$^{-1}$ (Run 5 at $\mathcal{L} = 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$)
- **LHCb Upgrade II summarised in EoI** [CERN-LHCC-2017-003] and Physics case [CERN-LHCC-2018-027]
- **Physics of the HL-LHC, WG 4 Flavour** [arxiv:1812.07638]
Typical NP reach of Rare Decays

\[ \Lambda_{NP} \text{ reach with LFU tests } R_K(\ast) \]

Reachable NP scales \( \Lambda_{NP} \propto \sqrt{1/\sigma(C_{NP})} \propto 4\sqrt{\int \mathcal{L} dt} \)

Precision flavour observables probe scales far beyond \( \sqrt{s} = 14 \text{ TeV} \)

Upgrade II can reach a factor 1.9 higher than Upgrade I

---

1 Naive scaling: Assumes identical scaling of systematics
Very Rare Leptonic Decays

LHCb
BDT > 0.5

Candidates / (50 MeV/c^2)

m_{\mu\mu} [MeV/c^2]

- Total
- B^0 \to \mu^+\mu^-
- B^0 \to \mu^+\mu^-
- Combinatorial
- B \to h^+h^-
- B_{(s)}^0 \to \pi^+(K^-)\mu^+\nu_{\mu}
- B_{(s)}^{0(*)} \to \pi^{(*)}\mu^+\mu^-
- \Lambda_b^0 \to p\mu^-\bar{\nu}_\mu
- B_c^+ \to J/\psi\mu^+\nu_{\mu}
The very rare decay $B_s^0 \rightarrow \mu^+ \mu^-$

- Loop- and helicity suppressed with purely leptonic final state: Experimentally and theoretically clean probe of new (pseudo)scalars
- Precise SM prediction [C. Bobeth et al., PRL 112, 101801 (2014)]:
  \[ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9} \quad \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10} \]
- $B_s^0 \rightarrow \mu^+ \mu^-$ sets strong constraint on MSSM $\mathcal{B} \propto \tan^6 \beta/m_A^4$
- First observation of $B_s^0 \rightarrow \mu^+ \mu^-$ ($7.8 \sigma$) by single experiment [PRL 118 (2017) 191801]:
  \[ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.5^{+1.2}_{-1.0}^{+0.2}_{-0.1}) \times 10^{-10} \]
- $B_s^0 \rightarrow \mu^+ \mu^-$ in agreement with SM (and MFV) but stat. limited
**Very rare decays**

\[ B_0^{(s)} \rightarrow \mu^+\mu^- \] in the Upgrade II

### Current Experimental Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronisation fraction ( f_s/f_d )</td>
<td>5.8%</td>
</tr>
<tr>
<td>Normalisation modes</td>
<td>3%</td>
</tr>
<tr>
<td>Particle identification</td>
<td>2%</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>2%</td>
</tr>
</tbody>
</table>

### Current Theory Systematics

- **\( B(B^0 \rightarrow \mu^+\mu^-) \)** will remain stat. dominated with Upgrade II sample
- Projected statistical uncertainty for \( B(B_s^0 \rightarrow \mu^+\mu^-) \) is 1.8%
- Total exp. systematic uncertainty expected to reduce to \( \sim 4\% \)
- Expected total experimental uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>now</th>
<th>23 fb(^{-1})</th>
<th>300 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>absolute uncertainty ( B_s^0 \rightarrow \mu^+\mu^- ) [10(^{-9})]</td>
<td>0.67</td>
<td>0.30</td>
<td>0.16</td>
</tr>
<tr>
<td>rel. uncertainty ( B^0 \rightarrow \mu^+\mu^-/B_s^0 \rightarrow \mu^+\mu^- ) [%]</td>
<td>90%</td>
<td>34%</td>
<td>10%</td>
</tr>
</tbody>
</table>

- Dominant theory uncertainties (\( B_s^0 \) decay constant, CKM elements) also expected to reduce
Very rare decays

$B^0_{s} \rightarrow \mu^+ \mu^-$ lifetime

- $\Gamma(B^0_s(t) \rightarrow \mu^+ \mu^-) \propto \left[ \cosh \left( \frac{y_s t}{\tau_{B_s}} \right) + S_{\mu\mu} \sin(\Delta m_s t) + A_{\Delta \Gamma} \sinh \left( \frac{y_s t}{\tau_{B_s}} \right) \right] e^{-t/\tau_{B_s}}$
- Effective Lifetime probe for NP complementary to $B$
  $\tau_{\mu\mu} = \frac{\tau_{B_s}}{1 - y_s^2} \frac{1+2y_s A_{\Delta \Gamma} + y_s^2}{1+y_s A_{\Delta \Gamma}}$ with $y_s = \tau_{B_s} \frac{\Delta \Gamma}{2} = 0.062 \pm 0.006$
- In the SM: $A_{\Delta \Gamma}^{SM} = 1$, NP models allow $A_{\Delta \Gamma}^{NP} \in [-1, 1]$
- $\tau(B^0_s \rightarrow \tau^+ \tau^-) = 2.04 \pm 0.44 \pm 0.05$ ps [PRL 118 (2017) 191801]
  Compatible with $A_{\Delta \Gamma} = +1 (-1)$ at 1.0 $\sigma$ (1.4 $\sigma$)
- Upgrade II: 2% uncertainty on effective lifetime $\tau_{\mu\mu}$
- Breaks degeneracy between possible contributions from $C_S^{(l)}$ and $C_P^{(l)}$
- Will allow to exclude second solution in $\tan\beta/m_A$ plane
- With tagging power 3.7% measure time-dep. CP-violation $\sigma(S_{\mu\mu}) \sim 0.2$
Electroweak $b \rightarrow s\mu^+\mu^-$ Penguins

$P'_5$ vs $q^2$ [GeV$^2$/c$^4$]

- LHCb data
- ATLAS data
- Belle data
- CMS data
- SM from DHMV
- SM from ASZB
Branching fractions of rare $b \to s \mu^+ \mu^-$ decays

- **Pattern:** Data consistently below SM predictions
- But sizeable hadronic theory uncertainties
- Tensions at $1 - 3 \sigma$ level
Rare $b \to s\mu^+\mu^-$ penguins

Future $b \to s\mu^+\mu^-$ branching fraction measurements

- Experimentally, $\mathcal{B}(b \to s\mu^+\mu^-)$ will be limited by normalisation modes. More precise measurements of these possible by Belle II.
- Asymmetries (experimentally and theoretically) more precise!
  - CP-Asymmetries $A_{CP} = \frac{\Gamma(B \to \bar{K}^{(*)}\mu^+\mu^-) - \Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to \bar{K}^{(*)}\mu^+\mu^-) + \Gamma(B \to K^{(*)}\mu^+\mu^-)}$
  - Isospin-Asymmetries $A_I = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)}\mu^+\mu^-)}$
- Expect percent-level accuracy for these quantities with Upgrade II.

C. Langenbruch (RWTH), TUPFP Durham 2019

New rare observables in LHCb Upgrade II
Rare $b \to s\mu^+\mu^-$ penguins

$b \to d\mu^+\mu^-$ processes

- $B^+ \to \pi^+\mu^+\mu^-$ [JHEP 10 (2015) 034]
- $B_s^0 \to K^{*0}\mu^+\mu^-$ [JHEP 07 (2018) 020]

- $b \to d\mu^+\mu^-$ processes are suppressed wrt. $b \to s\mu^+\mu^-$ by $|V_{td}/V_{ts}|^2$ in the SM (and MFV NP models)
- $N_{\pi\mu\mu} \sim 90$ (Run 1) and $N_{K^{*0}\mu\mu} \sim 40$ (Run 1+2016)
- Upgrade II will provide $N_{\pi\mu\mu} \sim 17\,000$ and $N_{K^{*0}\mu\mu} \sim 4\,300$
- Allows 2\% level precision on $|V_{td}/V_{ts}|$ from rare decays
- Allows for angular analysis of $B_s^0 \to K^{*0}\mu^+\mu^-$ with better precision than Run 1 $B^0 \to K^{*0}\mu^+\mu^-$ result
Angular analyses of $b \to s \mu^+ \mu^-$ decays: $P'_5$ and friends

- $B^0 \to K^{*0} (\to K^+ \pi^-) \mu^+ \mu^-$ exhibits rich angular structure, one example the less form-factor dependent observable $P'_5$
- In $q^2$ bins $[4.0, 6.0]$ and $[6.0, 8.0]$ GeV$^2$/c$^4$ local deviations of 2.8σ and 3.0σ
- LHCb only global $B^0 \to K^{*0} \mu^+ \mu^-$ analysis corresponds to 3.4σ
New rare observables in LHCb Upgrade II

★ Expect $\sim 440000$ $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ candidates in Upgrade II (Roughly corresponds to Run 1 stats for tree-level charmonia modes)
★ Allows for determination of angular observables with unprecedented precision
★ Different NP scenarios can be cleanly separated
- $q^2$-unbinned approaches allow to better exploit the data \[JHEP 11 (2017) 176\]
- Will allow to separate different SM extensions with extremely high precision
- Major challenge to disentangle NP from charm-loop contribution in $C_9$
- Different parameterisations of the charm-loop contributions on the market
  - Parameterisation using Breit-Wigners \[EPJC 78 (2018) 453\]
  - Parameterisation from analyticity \[arXiv:1805.06378\] \[PRD 99 (2019) 013007\]
Lepton Universality Tests in Rare Decays

![Graph showing $R_{K^0}$ vs $q^2$]
Lepton universality tests in rare decays: $R_K$, $R_{K^*}$

$R_X$ ratios extremely clean tests of the SM

$$R_X = \int \frac{d\Gamma(B \to X \mu^+ \mu^-)}{dq^2} \, dq^2 / \int \frac{d\Gamma(B \to X e^+ e^-)}{dq^2} \, dq^2$$

- $R_X^{SM} = 1 \pm \mathcal{O}(10^{-3})$ (neglecting $m_\ell$), QED effects $\mathcal{O}(10^{-2})$ [EPJC 76 (2016) 8,440]
- Hadronic uncertainties (form factors etc.) cancel in the ratio
- Different modes probe different operator combinations
Numerical result and compatibility with SM prediction(s):

\[ R_K(1 < q^2 < 6.0 \text{ GeV}^2) = 0.846^{+0.054+0.016}_{-0.054-0.014} \]  
\text{at central } q^2: \ 2.5 \sigma

\[ R_{K^*}(0.045 < q^2 < 1.1 \text{ GeV}^2) = 0.66^{+0.07}_{-0.07} \pm 0.03 \]  
\text{at low } q^2: \ 2.1-2.3 \sigma

\[ R_{K^*}(1.1 < q^2 < 6.0 \text{ GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05 \]  
\text{at central } q^2: \ 2.4-2.5 \sigma

Many further modes in preparation: \( R_\phi, R_{pK}, R_{K^{\pi\pi}}, \ldots \)
Lepton universality tests in Rare Decays

Experimental aspects: Bremsstrahlung and Trigger

- Perform Bremsstrahlung reconstruction to improve mass resolution
- Upgrade II: higher backgrounds/combinatorics due to \( #pp \) collisions
  - Higher calorimeter granularity
  - Timing information
- Improvement in trigger efficiency due to L0 removal (Upgrade I)
  Not taken into account for numbers in this presentation, conservative
Lepton universality tests in Rare Decays

Upgrade II expectations for $R_X$ ratios

- Huge samples of rare electron modes available in Upgrade II
  $N_{K^+e^+e^-} \sim 46\,000$, $N_{K^*0e^+e^-} \sim 20\,000$

- Ultimate precision on $R_{K,K^*}$ will be better than 1%

- Different $R_X$ allow to probe different combinations of Wilson coefficients, separation of NP scenarios with high significance

<table>
<thead>
<tr>
<th>Yield</th>
<th>Run 1 result</th>
<th>9 fb$^{-1}$</th>
<th>23 fb$^{-1}$</th>
<th>300 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^+e^+e^-$</td>
<td>254 ± 29</td>
<td>1120</td>
<td>3300</td>
<td>46000</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{*0}e^+e^-$</td>
<td>111 ± 14</td>
<td>490</td>
<td>1400</td>
<td>20000</td>
</tr>
<tr>
<td>$B^0 \rightarrow \phi e^+e^-$</td>
<td>–</td>
<td>80</td>
<td>230</td>
<td>3300</td>
</tr>
<tr>
<td>$B^0 \rightarrow pK^0e^+e^-$</td>
<td>–</td>
<td>120</td>
<td>360</td>
<td>5000</td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^+e^+e^-$</td>
<td>–</td>
<td>20</td>
<td>70</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>300 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_K$</td>
<td>0.745 ± 0.090 ± 0.036</td>
<td>0.043</td>
<td>0.025</td>
<td>0.007</td>
</tr>
<tr>
<td>$R_{K^*0}$</td>
<td>0.69 ± 0.11 ± 0.05</td>
<td>0.052</td>
<td>0.031</td>
<td>0.008</td>
</tr>
<tr>
<td>$R_{\phi}$</td>
<td>–</td>
<td>0.130</td>
<td>0.076</td>
<td>0.020</td>
</tr>
<tr>
<td>$R_{pK}$</td>
<td>–</td>
<td>0.105</td>
<td>0.061</td>
<td>0.016</td>
</tr>
<tr>
<td>$R_{\pi}$</td>
<td>–</td>
<td>0.302</td>
<td>0.176</td>
<td>0.047</td>
</tr>
</tbody>
</table>
Differences between angular observables in electrons and muons theoretically clean, simultaneous fit useful

Sensitivity to additional combinations of Wilson coefficients compared to $R_X$ measurements

Excellent NP sensitivity unaffected by hadronic contributions
Conclusions

- Rare decays are powerful probes for NP
- Reach of precision flavour measurements goes far beyond $\sqrt{s}$
- LHCb Upgrade II can extend the probed NP scales by a factor 1.9
- Expected Upgrade II performance for key RD measurements:
  - $B(B^0 \to \mu^+\mu^-)/B(B^0_s \to \mu^+\mu^-)$ at 10%
  - Precision measurements with 440 000 $B^0 \to K^{*0}\mu^+\mu^-$ candidates
  - $R_{K,K^*}$ at sub-1% level
- LHCb Upgrade II will allow access many new observables and analysis techniques
- LHCb Upgrade II will be able to probe many types of Physics beyond the SM and discriminate between them
Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb</th>
<th>LHCb 2025</th>
<th>Belle II</th>
<th>Upgrade II</th>
<th>ATLAS &amp; CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EW Penguins</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_K$ ($1 &lt; q^2 &lt; 6 \text{GeV}^2 c^4$)</td>
<td>0.1 [274]</td>
<td>0.025</td>
<td>0.036</td>
<td>0.007</td>
<td>–</td>
</tr>
<tr>
<td>$R_{K^*}$ ($1 &lt; q^2 &lt; 6 \text{GeV}^2 c^4$)</td>
<td>0.1 [275]</td>
<td>0.031</td>
<td>0.032</td>
<td>0.008</td>
<td>–</td>
</tr>
<tr>
<td>$R_\phi, R_{pK}, R_{\pi}$</td>
<td>–</td>
<td>0.08, 0.06, 0.18</td>
<td>–</td>
<td>0.02, 0.02, 0.05</td>
<td>–</td>
</tr>
<tr>
<td><strong>CKM tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma$, with $B^0 \rightarrow D^+_s K^-$</td>
<td>$(+^{0.0}_{-0.2})^\circ$ [136]</td>
<td>4$^\circ$</td>
<td>–</td>
<td>1$^\circ$</td>
<td>–</td>
</tr>
<tr>
<td>$\gamma$, all modes</td>
<td>$(+^{5.0}_{-5.8})^\circ$ [167]</td>
<td>1.5$^\circ$</td>
<td>1.5$^\circ$</td>
<td>0.35$^\circ$</td>
<td>–</td>
</tr>
<tr>
<td>$\sin 2\beta$, with $B^0 \rightarrow J/\psi K^0_S$</td>
<td>0.04 [609]</td>
<td>0.011</td>
<td>0.005</td>
<td>0.003</td>
<td>–</td>
</tr>
<tr>
<td>$\phi_s$, with $B^0_s \rightarrow J/\psi \phi$</td>
<td>49 mrad [44]</td>
<td>14 mrad</td>
<td>–</td>
<td>4 mrad</td>
<td>22 mrad [610]</td>
</tr>
<tr>
<td>$\phi_s$, with $B^0_s \rightarrow D^+ D^-$</td>
<td>170 mrad [49]</td>
<td>35 mrad</td>
<td>–</td>
<td>9 mrad</td>
<td>–</td>
</tr>
<tr>
<td>$\phi^{sss}_s$, with $B^0_s \rightarrow \phi \phi$</td>
<td>154 mrad [94]</td>
<td>39 mrad</td>
<td>–</td>
<td>11 mrad</td>
<td>Under study [611]</td>
</tr>
<tr>
<td>$\alpha^s_{3l}$</td>
<td>$3 \times 10^{-4}$ [211]</td>
<td>$10 \times 10^{-4}$</td>
<td>–</td>
<td>$3 \times 10^{-4}$</td>
<td>–</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>$</td>
<td>6% [201]</td>
</tr>
<tr>
<td>$B^0, B^0 \rightarrow \mu^+ \mu^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-)$</td>
<td>90% [264]</td>
<td>34%</td>
<td>–</td>
<td>10%</td>
<td>21% [612]</td>
</tr>
<tr>
<td>$\tau_{B^0 \rightarrow \mu^+ \mu^-}$</td>
<td>22% [264]</td>
<td>8%</td>
<td>–</td>
<td>2%</td>
<td>–</td>
</tr>
<tr>
<td>$S_{\mu\mu}$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.2</td>
<td>–</td>
</tr>
<tr>
<td><strong>$b \rightarrow c\ell^-\bar{\nu}_l$ LUV studies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(D^*)$</td>
<td>0.026 [215, 217]</td>
<td>0.0072</td>
<td>0.005</td>
<td>0.002</td>
<td>–</td>
</tr>
<tr>
<td>$R(J/\psi)$</td>
<td>0.24 [220]</td>
<td>0.071</td>
<td>–</td>
<td>0.02</td>
<td>–</td>
</tr>
<tr>
<td><strong>Charm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta A_{CP}(K K - \pi\pi)$</td>
<td>$8.5 \times 10^{-4}$ [613]</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$5.4 \times 10^{-4}$</td>
<td>$3.0 \times 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$A_\Gamma (\approx x \sin \phi)$</td>
<td>$2.8 \times 10^{-4}$ [240]</td>
<td>$4.3 \times 10^{-5}$</td>
<td>$3.5 \times 10^{-4}$</td>
<td>$1.0 \times 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$x \sin \phi$ from $D^0 \rightarrow K^+ \pi^-$</td>
<td>$13 \times 10^{-4}$ [228]</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$4.6 \times 10^{-4}$</td>
<td>$8.0 \times 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$x \sin \phi$ from multibody decays</td>
<td>–</td>
<td>$(K3\pi) 4.0 \times 10^{-5}$</td>
<td>$(K^0_s \pi\pi) 1.2 \times 10^{-4}$</td>
<td>$(K3\pi) 8.0 \times 10^{-6}$</td>
<td>–</td>
</tr>
</tbody>
</table>
Searches for Lepton Flavour Violation
Lepton non-universality generally implies lepton flavour violation

Many NP models predict sizeable $B$ for LFV $B$ decays

Upgrade II will allow to probe down to $\mathcal{B}(B_s^0 \to e^\pm \mu^\mp) < 3 \times 10^{-10}$ and $\mathcal{B}(B_s^0 \to \tau^\pm \mu^\mp) < 3 \times 10^{-6}$

Searches for $B \to K^{(*)} e\mu$ and $B \to K^{(*)} \tau\mu$ will set strong constraints
In the SM the LFV decay $\tau^{\pm} \to \mu^{\pm} \mu^+ \mu^-$ is forbidden.

Many BSM theories predict $\mathcal{O}(10^{-9} - 10^{-8})$, just below limit of $\mathcal{B}(\tau^{\pm} \to \mu^{\pm} \mu^+ \mu^-) < 2.1 \times 10^{-8}$ at 90% CL [Belle, PLB 687 (2010) 139]

Belle II will probe this interesting region with 50 ab$^{-1}$

LHCb Upgrade II expected to probe down to $\mathcal{O}(10^{-9})$

LHCb calorimetry improvements to suppress backgrounds, e.g. $D^+_s \to \eta(\rightarrow \mu^+ \mu^- \gamma) \mu^+ \nu_\mu$
Lepton Universality Tests in Tree-level Decays
Lepton universality can also be tested in \( b \to c \ell \nu \) tree-level decays

- Modified coupling in particular possible to third generation \( \tau \)
- Theoretically clean tests possible in \( B \) decays: \( R_{D^*} = \frac{\mathcal{B}(B \to D^{(*)\tau\nu})}{\mathcal{B}(B \to D^{(*)\mu\nu})} \)
- Nb. LHCb also allows for other modes using other \( b \)-hadron species: \( B_s^0, B_c^+, \Lambda_b^0, \ldots \)
Current experimental status

- LHCb has performed analyses of
  - $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$ with $\tau^{-} \rightarrow \mu^{-} \nu_{\tau} \bar{\nu}_{\mu}$ compatible with the SM at $2.1\,\sigma$ [PRL 115 (2015) 111803]
  - $R_{D^*} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$ with $\tau^{-} \rightarrow \pi^{-} \pi^{+} \pi^{-} (\pi^{0}) \nu_{\tau}$ compatible with the SM at $1\,\sigma$ [PRL 120 (2018) 171802]
  - $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ using $B^+_c$ decays compatible with the SM at $\sim 2\,\sigma$ [PRL 120 (2018) 121801]
- LHCb performs template fits to e.g. $m^2_{\text{miss}}$, $q^2$, $E^{\ast}_{\ell}$ relying on
  - its excellent vertexing to approximate the $B$-momentum
  - powerful particle identification and tracking to suppress backgrounds
Lepton universality tests in tree-level decays

\[ R_{D(*)} \] combination

- Combine LHCb \( R_{D^*} \) measurements with \( B \)-factory results
- All measurements are above SM predictions
- Deviation of \( R_D/R_{D^*} \) combination corresponding to \( \sim 4.1 \sigma \)
- Recent theory input reduces tension [JHEP 11 (2017) 061]
RF foil removal will drastically improve vertexing performance

- IP resolution at low $p_T$ nearly doubles, better bkg. suppression
- Fraction of wrong PV association reduced by 30%
- More precise determination of $m_{\text{miss}}^2$, $q^2$, $E_{\ell}^*$

- Expected trigger efficiency improvement of $\sim 1.5$
- Expect $\mathcal{O}(10 \text{M}) B \to D^* \tau \nu$ candidates in Upgrade II

- Sensitivity with Upgrade II: $\sigma(R_{D^*})/R_{D^*} \sim 1\%$

- Angular analysis would allow to determine spin structure of potential NP contribution

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![Graphs showing no $\tau$ decay and $\tau$ decay distributions for $\theta_\ell$, $\chi$, and $\theta_D$.](image-url)