LEPTON FLAVOUR UNIVERSALITY AT LHCb

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“I suppose I’ll be the one to mention the elephant in the room.”
Why flavour physics?

Most BSM physics models predict additional heavy particles:
- can enter in tree and internal loop diagrams
- can lead to sizeable modification of observables such as branching ratios

Comparison of precise measurements with precise predictions from SM can reveal the presence of BSM physics.
- Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed (A. Soni)

Indirect searches for BSM physics are sensitive to much higher mass scales $O(10 - 100\text{TeV})$ than direct searches for new particles

Theoretical uncertainties are under control for many observables
Standard Model features **Lepton Flavour Universality**: accidental symmetry of the SM

- Equal electroweak coupling to all charged leptons.
- Difference in dynamics driven solely by the difference in the masses $m_e < m_\mu \ll m_\tau$

In this presentation: intriguing hints of anomalies in B decays observed by different experiments in

**Flavour-changing CHARGED current** ($b \rightarrow c \ell \bar{\nu}$)

**Flavour-changing NEUTRAL current** ($b \rightarrow s(d)\ell^+\ell^-$)
Flavour physics at LHCb

• Single arm spectrometer designed for high precision flavour physics measurements
• Pseudorapidity range $\eta \in [2,5]$

  ◦ # of Primary Vertices $\sim 2$
  ◦ Decay time res: $\sim 45$ fs
  ◦ IP res: $\sim 20$ $\mu$m for high $p_T$
  ◦ Highly eff. PID
  ◦ Excellent primary and secondary vertex reconstruction [INT.J.MOD.PHYS A30 (2015) 1530022]

Large number of beauty hadrons:

  ◦ $\sigma_{b\bar{b}}(7$ TeV) $= 72.0 \pm 0.3 \pm 6.8 \mu$b
  ◦ $\sigma_{b\bar{b}}(13$ TeV) $= 154.3 \pm 1.5 \pm 14.3 \mu$b

[PRl 118 (2017) 052002]
Pre-HL-LHC → Post-HL-LHC
• End Run 3 → End Run 5: \( \text{LHCb}: 23/\text{fb} \rightarrow 300/\text{fb} \)
• NP scale probed by LHCb scales as \( \Lambda_{NP} \propto \sqrt[4]{\int \mathcal{L} \, dt} \), factor 1.9 gain from HL-LHC [LHCb Upgrade Physics Document]

Impact of Upgrade II comparable to moving from 14 TeV to 27 TeV for on-shell production!
RARE DECAYS
Rare decays as probe for NP

- Rare FCNC decays are loop-suppressed in the SM ($\mathcal{B} \sim 10^{-6} - 10^{-7}$)
- New heavy particles can significantly contribute, affecting decay rates and angular distributions
- Model independent description using effective, four-fermion point interactions

\[ \mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i \mathcal{O}_i + \frac{k}{\Lambda_{NP}^2} \mathcal{O}_{NP} \]

\[ \mathcal{O}_{NP} \]

- Local operator (effective vertex)
- NP coupling
- NP scale

\[ i = 1, 2 \quad \text{Tree} \quad i = 7 \quad \text{Photon penguin} \quad i = 9, 10 \quad \text{EW penguin} \]

\[ i = 3, 6, 8 \quad \text{Gluon Penguin} \]

\[ i = S, P \quad \text{(Pseudo)scalar penguin} \]
Experimental analysis and $q^2$ dependence

- B-hadron mass is reconstructed from final hadron decays and two energetic leptons.
- Background events suppressed by requiring displaced vertices.
- Study of the differential branching fraction in bins of $q^2 = m(\ell^+ \ell^-)^2$, invariant mass of di-lepton system.
- In order to remove long distance effects (i.e. $b \to (c\bar{c} \to \ell^+ \ell^-)s$) the narrow charmonium resonances are vetoed and used as control samples.
Branching fractions of rare $b \to s \mu^+ \mu^-$

- **Low $q^2$ region**: Data consistently below SM predictions
- But sizeable hadronic theory uncertainties
- Tensions at 1-3 $\sigma$

- **Future**: measurement of CP and Isospin asymmetries – percent level accuracy expected in Upgrade II
Angular analysis of $b \rightarrow s \mu^+ \mu^-$ decays

- $B^0 \rightarrow K^{*0}(\rightarrow K^+ \pi^-)\mu^+ \mu^-$ exhibits rich angular structure, e.g. the less form-factor dependent observable $P_5'$: proportional to asymmetry of red and blue

- In $q^2$ bins $[4,6]$ and $[6,8]$ GeV$^2$/c$^4$ local deviations of 2.8 $\sigma$ and 3.0 $\sigma$
- LHCb-only global $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ analysis corresponds to 3.4 $\sigma$
- Debate ongoing on SM calculations

LHCb, JHEP02 (2016) 104
Belle, PRL 118 (2017) 111801
ATLAS-CONF-2017-023
CMS, PLB 81 (2018) 517
Upgrade II sensitivity with $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Expect $\sim 440,000 B^0 \rightarrow K^{*0} \mu^+ \mu^-$ candidates in Upgrade II (roughly Run 1 statistics 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]
Global fit from $b \to s \mu^+ \mu^-$ decays

- Global fit to the real part of $C_9$ and $C_{10}$
- The best fit for several global analyses points towards a shift in $C_9$
- Discrepancy up to $5\sigma$
- Discussion is ongoing about our understanding of QCD effects in branching fractions and angular observables

[JHEP 06(2016)092]
[arXiv:1611.05060]
[EPJC 77 6(2017)377]
Lepton universality: $R(K^{(*)})$

$R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}\mu^+\mu^-)} / \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}\mu^+\mu^-)}$

- The double ratio reduces systematic uncertainties
- $R_{K^{(*)}}^{SM} = 1 \pm 0(10^{-3})$ (neglecting $m_\ell$), QED effects $O(10^{-2})$ [EPJC 76 (2016) 8,440]
- Selection between $\mu$ and $e$ channel as similar as possible
- Challenging due to the differences between $\mu$ and $e$

Bremsstrahlung correction to improve mass res.

- **Upstream brem**: photon emitted before the magnet, momentum underestimated

**Upgrade II**: higher backgrounds/combinatorics due to #pp collisions

- Higher calorimeter granularity
- Timing information
Current experimental status $R(K^{(*)})$

- LHCb results are consistently lower than 1
- Results from B-factories are compatible (with less precision)
- These results point to a shift in the muonic $C_9$ in accordance with the other anomalies detected in $b \to s \ell^+ \ell^-$ decays

PRL 113(2014)151601
JHEP 08(2017)055
Combination of $b \rightarrow s \ell^+ \ell^-$

- Many different global fits incorporating different measurements (up to 100 observables)
- Combine LFU obs. in effective theory framework to determine Wilson coeff. (here: $C^9$ and $C^{10}$)
- Combination of $R(K^{(*)})$ and angular analysis of $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ [arXiv:1612.05014] shows tension with SM prediction at $\sim 4\sigma$ [PRD 96 (2017) 055008]
- Remarkable consistency: BF, angular, $R(K^{(*)})$, $b \rightarrow s \gamma$ data all point to $\Delta C^9_\mu \sim -1$.
- Triggered models with $Z'$, leptoquarks (LQ), and composite Higgs
Upgrade II expectations for $R(K^{(*)})$

- Huge samples of rare electron modes available in Upgrade II \(N_{K^+e^+e^-} \sim 46 \, 000\), \(N_{K^{*0}e^+e^-} \sim 20 \, 000\)
- 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 possible!
- Projections don't include improved ECAL for Upgrade II
SEMI-LEPTONIC DECAYS
Lepton universality test in tree-level decays

Tests of LFU in semitauonic decays are obtained measuring the following ratios

\[ R_X = \frac{\Gamma(B \rightarrow X_c \tau^+ \nu_\tau)}{\Gamma(B \rightarrow X_c \mu^+ \nu_\mu)} \]  
with \( X_c = D^* \) or \( J/\psi \)

- SM predictions:
  - \( R(D^*) = 0.258 \pm 0.005 \) [HFLAV Summer 2018]
Current experimental status

LHCb has performed analysis of

- $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$ with $\tau^- \to \mu^- \nu \bar{\nu}_\mu$
  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 $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu \tau$
  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. $m_{miss}^2$, $q^2$, $E_\ell^*$ relying on
- its excellent vertexing to approximate the B-momentum
- powerful particle identification and tracking to suppress backgrounds

Combine LHCb $R_{D^*}$ with B-factory results. All measurements are above SM predictions.
Deviation of $R_{D^*}$ combination from SM $\sim 4.1\sigma$
Recent theory input reduces tension [JHEP 11 (2017) 061] to 3.8 $\sigma$
Upgrade II prospects

**Upgrade II: new observables beyond the BF ratio**
- Expect $O(10 \text{ M})\ \bar{B} \rightarrow D^{(*)}\tau \bar{\nu}$ candidates
- Sensitivity Upgr. II: $\sigma(R_{D^*})/R_{D^*} \sim 1\%$
- Angular analysis would allow to determine spin structure of potential NP contribution

- Kinematics of $\bar{B} \rightarrow D^{(*)}\tau \bar{\nu}$ fully described by dilepton mass, and three angles, $\chi, \theta_L$ and $\theta_d$ (better resolution)

**Upgrade II: exploit other b-hadron species**
- $\bar{B}_s^0 \rightarrow D_s^{(*)+}\tau^- \bar{\nu}$: 6% (2.5%) relat. unc. after Run 3 (Upgrade II)
- Semitauonic decays of $b$-baryons and of $B_c^+$ mesons
  - $R(\Lambda_c^+)$ 4% (2.5%) relat. unc. after Run 3 (Upgrade II)
Lepton flavour violation

- LFV branching fractions enhanced to $10^{-11}$ in certain models of leptoquarks, $Z'$ [Medeiros Varzielas, Hiller, JHEP 06 (2015) 072]
- LHCb was the first experiment to search for LFV $\tau$ decays in a hadron collider

<table>
<thead>
<tr>
<th>Translate BR limits into limits on leptoquark mass</th>
<th>$B(B^0_{(s)} \to e\mu)$</th>
<th>$B(B \to \tau\mu)$</th>
<th>$B(\tau \to \mu\mu\mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run I @ 90 C.L.</td>
<td>$&lt; 1.0 \ (5.4) \times 10^{-9}$</td>
<td>Soon</td>
<td>$&lt; 4.6 \times 10^{-8}$</td>
</tr>
<tr>
<td>HL-LHC @ 90 C.L.</td>
<td>$&lt; 3 \ (9) \times 10^{-10(11)}$</td>
<td>$&lt; 3 \times 10^{-6}$</td>
<td>$&lt; \mathcal{O}(10^{-9})$</td>
</tr>
</tbody>
</table>

Searches for $B \to K e\mu, B \to K^0 \tau(\rightarrow \pi\pi\nu)\mu, B \to K\tau(\rightarrow \pi\pi\nu)\mu$ and $\Lambda^0_b \to \Lambda^0 e\mu$ are ongoing
- Using Run1 + Run2 data expects limits $\mathcal{O}(10^{-9})$ and $\mathcal{O}(10^{-6})$ for $B \to K e\mu$ and $B \to K^0 \tau\mu$, respectively
- Complementary as charged lepton FV couplings among different families are expected to be different
- Multi-body final states: allow the measurement of more observables

Similar to what is expected from Belle II
Conclusions

◦ Intriguing hints of anomalies in B decays, powerful probes of the SM!
◦ Both Belle2 and LHCb experiments could individually confirm or rule out the current flavour anomaly by ~2025 [arXiv:1709.10308]
◦ If true, hugely important for the future development of high-energy particle physics, providing a clear target for future searches at energy frontier… exactly what’s missing right now!

Even if not confirmed, they serve as a good example of the potential of FP at Upgrade II to probe beyond the energy frontier.

NP should be around here (driven by $R_{D^*}$)

Neubert, Beauty 2018
Thanks for your attention!
what we have
here is a failure
to communicate

what?

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B-anomalies and neutrino interplay

- Impact of lepton flavour universality violation on CP violation sensitivity of long baseline neutrino oscillation experiments [https://arxiv.org/abs/1701.00327]
- Anomalies in (semi)-leptonic B decays and possible resolution with sterile neutrino [https://arxiv.org/abs/1702.04335]
- Leptoquarks in Flavour Physics and the anomalous magnetic moment of the muon [https://arxiv.org/abs/1801.03380]
- Synergy and complementarity between neutrino physics and low-energy intensity frontiers [https://arxiv.org/abs/1712.05947]
- And many more!
Prospects for selected flavour observables

Based on extrapolations from current measurements, and take no account of detector improvements apart from an approximate factor two increase in efficiency for hadronic modes, coming from the full software trigger that will be deployed from Run 3 onwards.
Similar challenges

Pileup in HL-LHC: ~200 for ATLAS/CMS, ~50 for LHCb
Common themes: timing, granularity and radiation hardness
FCNC transitions

- LFU will play a large role in Upgrade II physics case
- Improvements: Reduce the material (e.g. RF-foil), improve ECAL granularity, better Brem recovery algorithms
- Upgrade II: 440k fully reconstructed $B^0 \to K^{*0} \mu^+ \mu^-$ will allow a $q^2$-unbinned approach ⇒ probe the SM contributions, NP expected to have no $q^2$ dependence
- Compare angular distr. $B^0 \to K^{*0} e^+ e^- / B^0 \to K^{*0} \mu^+ \mu^-$
- Upgrade will provide thousands of $b \to d \ell^+ \ell^-$ decays (e.g. 4300 $B_s^0 \to K^{*0} \mu^+ \mu^-$), angular analysis possible
- 45k $B^+ \to K^+ e^+ e^-$ and 20k $B^0 \to K^{*0} e^+ e^-$ in the Upgrade II → Ultimate precision on $R_{K^{(*)}} < 1\%$
- $R_\varphi, R_{pK}, R_\pi, \ldots$ will be possible un Upgrade II

<table>
<thead>
<tr>
<th>scenario</th>
<th>$C_{NP}^9$</th>
<th>$C_{NP}^{10}$</th>
<th>$C'_9$</th>
<th>$C'_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>-1.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>II</td>
<td>-0.7</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>III</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>IV</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

All four NP scenarios could be distinguished at more than 5$\sigma$ in Upgrade II!
Where are we?

- After Higgs discovery, no more guarantees
- Situation may resemble around 1900 “... it seems probable that most of the grand underlying principles have been firmly established ...” (Michelson 1894)

- LHC confirms that the SM is robust, but:
  - Hierarchy problem
  - Dark part of the Universe
  - Matter/Antimatter asymmetry
  - ...

LHC at present is our most powerful accelerator to address these challenges