Guido Andreassi

LEPTON FLAVOUR VIOLATION SEARCHES AT LHCb
THE LHCb DETECTOR

- Single-arm forward spectrometer ($2<\eta<5$)
- Designed to study $b$ and $c$ quarks physics
- High resolution on decay vertex of flying $b$ hadrons and momenta
- Good particle identification
Lepton Flavour Violation (LFV): non-conservation of lepton flavour

- Conservation well established (e.g. $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$) ...
- ... but not supported by strong theoretical reasons
- Observation of neutrino oscillation implies LFV in loops ($BR < 10^{-40}$)
- LFV signatures: searches for forbidden decays in the SM (e.g. $e\mu/\mu\tau/e\tau$)

At LHCb:

- $b$ decays: $B \rightarrow e\mu$, $B \rightarrow K e\mu$, $B \rightarrow \tau\mu$, $B \rightarrow K^{(*)}\tau\mu$, $\Lambda_b \rightarrow \Lambda e\mu$
- $c$ decays: $D^0 \rightarrow e\mu$
- $\tau$ decays: $\tau \rightarrow \mu\mu\mu$
Guido Andreassi - LFV SEARCHES AT LHCb

METHOD

- Processes that are strongly suppressed (forbidden) in the SM might be enhanced by new mediating particles
- LFV predicted by a large variety of alternative models (Lepto-Quarks, new gauge Z’...)
- Such particles can enter SM diagrams as virtual particles ⇒ can indirectly observe mediators unaccessible to direct searches (> TeV)

![Diagram showing LFV processes](image)
Recent hints of LNU effects [1,2,3] open to new scenarios

Potential links between LNU and LFV in some models [4,5] entail a renewed interest on the subject

$$\mathcal{B}(B \to K \mu^± e^\mp) \sim 3 \cdot 10^{-8} \left( \frac{1 - R_K}{0.23} \right)^2,$$

$$\mathcal{B}(B \to K (e^\pm, \mu^\pm) \tau^\mp) \sim 2 \cdot 10^{-8} \left( \frac{1 - R_K}{0.23} \right)^2$$

$$\frac{\mathcal{B}(B_s \to \mu^± e^-)}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{SM}} \sim 0.01 \left( \frac{1 - R_K}{0.23} \right)^2,$$

$$\frac{\mathcal{B}(B_s \to \tau^+(e^-, \mu^-))}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{SM}} \sim 4 \left( \frac{1 - R_K}{0.23} \right)^2.$$
Forbidden decay from either $B_d$ or $B_s$

Primary background: $B^0 \rightarrow h^+ h'^-$ with both hadrons misidentified

Need to deal with bremsstrahlung:

- Brem improves electron ID → helps with background
- Split in categories

Selection efficiencies and mass shapes depend on whether or not a brem photon was added to the electron in the reconstruction (brem categories)

![Graphs showing mass shapes for no brem and brem cases](https://example.com/graphs.png)
$B_s \rightarrow e\mu$

- BDT against combinatorial. Response modelled to be flat on signal (MC) (and peaked on zero for bkg)
- Response on data evaluated on $B^0 \rightarrow K\pi$, as a proxy channel
  - Unbiased for trigger selection
  - Corrected for selection efficiency
  - Corrected for brem category
- Analysis binned in 8 BDT bins x 2 brem categories
Normalise simultaneously to two channels:

$B^+ \to J/\psi(\to \mu\mu)K^+$, chosen for the large yield, allowing a precise fit

$B^0 \to K^+\pi^-$, chosen for the similar topology to the signal (i.e. similar reco efficiencies)

Relative yield cross-checked:

$R^{PDG} = 0.321 \pm 0.013$

$$R_{\text{norm}} = \frac{N_{B^0 \to K^+\pi^-} \times \varepsilon_{B^+ \to J/\psi K^+}}{N_{B^+ \to J/\psi K^+} \times \varepsilon_{B^0 \to K^+\pi^-}} = 0.332 \pm 0.002 \text{ (stat)} \pm 0.020 \text{ (syst)},$$

[JHEP 1803 (2018) 078]
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**$B(s) \rightarrow e\mu$**

- $B \rightarrow e\mu$ on full Run I: 3fb$^{-1}$
- Fit to $m(e\mu)$: no excess $\rightarrow$ limits with CLs

\[ \mathcal{B}(B^0 \rightarrow e^\pm \mu^\mp) < 1.3 \ (1.0) \times 10^{-9} @90(95)\% \text{ CL} \]

---

**Two exclusive backgrounds surviving $B^0 \rightarrow \pi\mu\nu$ and $\Lambda^0 b \rightarrow p\mu\nu$**

- $\mathcal{B}(B^0_s \rightarrow e^\pm \mu^\mp) < 6.3 \ (5.4) \times 10^{-9}$ if $B_s$ light eigenstate dominates
- $\mathcal{B}(B^0_s \rightarrow e^\pm \mu^\mp) < 7.2 \ (6.0) \times 10^{-9}$ if $B_s$ heavy eigenstate dominates @90(95)% CL
$\Lambda_b \rightarrow \Lambda e\mu$ (ongoing)

- Baryons provide complementary information and independent confirmation of results obtained using B mesons. $\Lambda_b$ has:
  - non-zero spin
  - considerably different hadronic physics (form factors)
- Predictions comparable to those for B decays and new physics BR within reach in some models [arXiv:1607.04449v2].

<table>
<thead>
<tr>
<th>Decay process</th>
<th>Predicted branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b \rightarrow \Lambda\mu^-e^+$</td>
<td>$1.56 \times 10^{-9}$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda\tau^-e^+$</td>
<td>$3.2 \times 10^{-10}$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda\tau^-\mu^+$</td>
<td>$4.6 \times 10^{-9}$</td>
</tr>
</tbody>
</table>
\( \Lambda_b \rightarrow \Lambda e\mu \)

\( \Lambda^0 \rightarrow p\pi : 2 \) categories depending on reco of the child particles: LL/DD

- Both Run1 \((\sim 3 \text{ fb}^{-1})\) and Run2 \((\text{up to } 2017, \sim 3.6 \text{ fb}^{-1})\) data included
- Brem/NoBrem as in \( B(s) \rightarrow e\mu \)

8 categories

- MVA response cross-checked on \( \Lambda_b \rightarrow \Lambda J/\psi(\mu\mu) \) data
- Cuts optimised in each category
- Normalise to \( \Lambda_b \rightarrow \Lambda J/\psi(\mu\mu) \)
$\Lambda_b \rightarrow \Lambda \mu \nu$

- Preliminary blind fits in the 8 categories
- Exponential PDF for combinatorial
- Exclusive backgrounds on the left under study
- Signal mass PDF from MC, calibrated on resonant $\Lambda_b \rightarrow \Lambda J/\psi (ee/\mu\mu)$ data

LHCb simulation

LHCb UNOFFICIAL
Summary of LHCb LFV analyses and prospects:

### Published:

<table>
<thead>
<tr>
<th>Process</th>
<th>Journal</th>
<th>Year</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow e\mu$</td>
<td>JHEP 1803 078</td>
<td>2018</td>
<td>$\mathcal{O}(10^{-9})$</td>
</tr>
<tr>
<td>$D^0 \rightarrow e\mu$</td>
<td>PLB 754 167</td>
<td>2017</td>
<td>$\mathcal{O}(10^{-8})$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\mu\mu$</td>
<td>JHEP 02 121</td>
<td>2015</td>
<td>$\mathcal{O}(10^{-8})$</td>
</tr>
</tbody>
</table>

### Coming Soon:

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K e\mu$</td>
<td>no helicity suppression</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda e\mu$</td>
<td>baryon sector</td>
</tr>
<tr>
<td>$B \rightarrow K/K^* \tau\mu$</td>
<td>LFU suggests hierarchical couplings</td>
</tr>
<tr>
<td>$B \rightarrow \tau\mu$</td>
<td></td>
</tr>
</tbody>
</table>

+ analyses of previously published channels adding new data
LHCb is significantly contributing to constrain new physics.
Observation of LFV would be a clear sign of new physics

- Anomalies observed in LFU make LFV searches also interesting

- No LFV observed yet:
  - In many channels we are reaching the level of BSM predictions
  - Statistically limited: analysing Run 2!
  - New modes will be analysed
  - Particular emphasis put on \( \tau \) modes
  - Investigating BNV too: \( B \rightarrow \rho \mu \)
SUMMARY AND CONCLUSIONS

- Observation of LFV would be a clear sign of new physics
- Anomalies observed in LFU make LFV searches also interesting
- No LFV observed yet:
THE LHCB EXPERIMENT

- Single-arm forward spectrometer (2<\(\eta\)<5)
- Designed to study b and c quarks physics
- High resolution on decay vertex of flying b hadrons and momenta
- Good particle identification
LHCB UPGRADE
MASS FITS

LHCb

Data
Total
Combinatorial
$\Lambda_b^0 \rightarrow p \mu^- \nu$
$B^0 \rightarrow \pi^- \mu^+ \nu$
$B_s^0 \rightarrow e^\pm \mu^\mp$
$B^0 \rightarrow e^\pm \mu^\mp$
MASS FITS (2)

LHCb

- Data
- Total
- Combinatorial
- $\Lambda_b^0 \to p\mu^-\nu$
- $B^0 \to \pi^-\mu^+\nu$
- $B_s^0 \to e^\pm\mu^\mp$
- $B^0 \to e^\pm\mu^\mp$
EXCLUSIVE BACKGROUNDS

$B^0 \rightarrow \pi \mu \nu$

$\Lambda_b^0 \rightarrow p \mu \nu$

- Shapes shown are BDT bin 2 [0.25, 0.4], without brem recovery
TRIGGER STRATEGY AND EFFICIENCIES

\[
\begin{align*}
B_{d,s}^0 &\rightarrow e^\pm \mu^\mp \text{(HasBremAdded} = 0) & 0.726 \pm 0.002 \text{ (stat)} \pm 0.015 \text{ (syst)} \\
B_{d,s}^0 &\rightarrow e^\pm \mu^\mp \text{(HasBremAdded} = 1) & 0.621 \pm 0.002 \text{ (stat)} \pm 0.015 \text{ (syst)} \\
B^+ &\rightarrow J/\psi(\mu^+ \mu^-)K^+ & 0.758 \pm 0.006 \\
B^0 &\rightarrow K^+\pi^- & 0.212 \pm 0.002
\end{align*}
\]
PID STRATEGY AND EFFICIENCIES

- Optimisated with respect to $B^0(s) \rightarrow h^+ h^-$ double misID, with figure of merit (FOM):

\[
\text{FOM} = \sum_{B^0_d,s \rightarrow hh} \frac{f_d,s}{f_d} B(B^0_d,s \rightarrow hh) \epsilon_{hh \rightarrow e\mu}^{\text{PID}}
\]

- Same signal PID efficiency (~80%), but lower misID rate

PID efficiencies for $B_s \rightarrow e\mu$ without brems recovery in BDT bins for 2012

PID efficiencies for $B_s \rightarrow e\mu$ with brems recovery in BDT bins for 2012
PEAKING BACKGROUND - $B \rightarrow Hh$

Main method
- Estimation of expected amount of $B_{(s)}^0 \rightarrow h^+ h^-$ is determined using $B_{(s)}^0 \rightarrow h^+ h^-$ MC weighted with PIDCalib efficiencies.
- Normalise with respect to $B^+ \rightarrow J/\psi (\rightarrow \mu^+ \mu^-)K^+$.
- Expected result shown here in full mass, BDT and HasBremAdded range and is negligible.

Cross-check
- Single misID determined in $B_{(s)}^0 \rightarrow h^+ h^-$ data.
- Electron PID on one of the tracks and hadron PID on other.
- Additional misID efficiency with main method.
- Result compatible.
EFFICIENCIES - PID

- Determined using PIDCalib
- Reweighting to signal MC in bins of BDT and HasBremAdded with track $p_T$, $\eta$ (and nSPDHits for electron to data nSPDHits distribution)
- $B^0 \rightarrow K^+\pi^-$ uses $p$ and $\eta$ binnings

Run 1

$B^+ \rightarrow J/\psi (\rightarrow \mu^+\mu^-) K^+$ $0.9781 \pm 0.0002$ (stat)

$B^0 \rightarrow K^+\pi^-$ $0.3850 \pm 0.0001$ (stat)
EFFICIENCIES - TRIGGER

- TISTOS for L0xHlt1
- Using TIS sample of
- Reweight efficiencies to IP and $E_T$ (for electron) or $p_T$ (for muon) to account for biases
- $Hlt2$ efficiencies from MC
- Systematics from TISTOS binning and MC reweighted for $B \ p_T$ and nSPDHits

\[
\begin{align*}
B^0_{d,s} & \rightarrow e^\pm \mu^\mp \text{ (HasBremAdded == 0)} & 0.726 \pm 0.002 \text{ (stat)} \pm 0.015 \text{ (syst)} \\
B^0_{d,s} & \rightarrow e^\pm \mu^\mp \text{ (HasBremAdded == 1)} & 0.621 \pm 0.002 \text{ (stat)} \pm 0.015 \text{ (syst)} \\
B^+ & \rightarrow J/\psi(\mu^+ \mu^-)K^+ & 0.758 \pm 0.006 \\
B^0 & \rightarrow K^+ \pi^- & 0.212 \pm 0.002
\end{align*}
\]
Signal mass shape is taken from simulated emu and corrected using $\Lambda_b \to J/\psi(ll)\Lambda$

$$\sigma_{e\mu}^{data} = \sigma_{\mu\mu}^{data} + (\sigma_{e\mu}^{MC} - \sigma_{\mu\mu}^{MC}) \cdot \frac{\sigma_{ee}^{data} - \sigma_{\mu\mu}^{data}}{\sigma_{ee}^{MC} - \sigma_{\mu\mu}^{MC}}$$

### ee fits:

**LL NoBrem**

**LL Brem**

**DD NoBrem**

**DD Brem**
$M_{HOP} > 2900 + 170 \cdot \log(\chi_{FD}^2)$
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LB2LEMU BACKGROUNDS

Exclusive backgrounds to be considered:

- If misID taken into account ($\pi \rightarrow e^{-1,2\%}$ and $\pi \rightarrow \mu^{-0.5\%}$) the last two can be considered negligible, but fully hadronic decay can peak in our mass region.

- We checked with $\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda^0 \pi) \nu \pi$ MC already produced for Run1

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda^0 \nu \ell \nu)$</td>
<td>$2.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda^0 \pi \ell \nu)$</td>
<td>$0.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda^0 \ell \nu) \pi$</td>
<td>$1.7 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda^0 \nu) \pi \pi$</td>
<td>$0.7 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
• No misID and large BF ~ $10^{-3}$, populates the left sideband
• Recently produced MC, showing preliminary studies

• Selection efficiency
  ~ 88%
• PID efficiency
  ~ 95%
• BDT>0.6 efficiency
  ~ 29%

Each bkg component will be fully estimated once the normalisation is complete
**LB2LEMU BACKGROUNDS**

\[ \Lambda_b \rightarrow J/\psi(\mu^+\mu^-)\Lambda \]

- The resonant channel with a mu->e misID contributes in the signal region
- Removed via a veto on the J/Psi mass

\[ B_d \rightarrow J/\psi(\mu^+\mu^-)K_s \]

- Present in the normalisation mode
- One misidentified pion

\[ \Lambda_b \rightarrow \Lambda_c(\Lambda l\nu)l\nu \]

- This double semileptonic decay has the same final state of the signal and contributes in the left sideband -> interplay with combinatorial
- Under investigation
Optimal cut found by maximising the Punzi FOM separately in each category

\[
\frac{\epsilon(t)}{a/2 + \sqrt{B(t)}}
\]

- Signal from MC
- Background from sideband extrapolation to the signal region
Since we expect only one misID background component, we’re using the fairly loose PID included in the stripping*

<table>
<thead>
<tr>
<th></th>
<th>prior cuts</th>
<th>PID cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>mu</td>
<td>InMuonAcc</td>
<td>IsMuon</td>
</tr>
<tr>
<td>e</td>
<td>HasCalo</td>
<td>DLLe&gt;0</td>
</tr>
<tr>
<td>p</td>
<td>HasRich</td>
<td>DLLp&gt;-5</td>
</tr>
</tbody>
</table>

(p PID on LL only)

The efficiencies are evaluated with PIDCalib per year in bins of P and PT and then folded with the kinematics of the signal MC

- The folding procedure accounts for bin-by-bin error and correlations via toy
- The binning scheme has been chosen with the [binning optimiser tool](#)

* Run 2 HLT2 line also includes ProbNNmu
We are using Bu2LLK stripping line + some fiducial cuts including a HOP mass cut

- Blinded region of $\sim 2\sigma$
- We correct the signal MC kinematics to match the sWeighted data

+ a small correction to Lb vertex chi$^2$ and lifetime (and number of tracks in the event)
B2EMU - LQ Mass

LHCb

$B(B^0 \rightarrow e^+ \mu^-) < 2.8 \times 10^{-9}$ 90\%(95)\% C.L.

$M_{LQ}(B^0 \rightarrow e^+ \mu^-) > 135 \ (126)$ TeV/c²

$\text{LHCb}$

$B(B_s^0 \rightarrow e^+ \mu^-) < 1.1 \times 10^{-8}$ 90\%(95)\% C.L.

$M_{LQ}(B_s^0 \rightarrow e^+ \mu^-) > 107 \ (101)$ TeV/c²