LFV&LNV@LHC:
Lepton Flavour Violation and
Lepton Number Violation at the Large
Hadron Collider

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UK HEP Forum, *Quarks and Leptons*
15th November 2013
Outline

• The Lepton Sector: Definitions of Lepton Flavour and Lepton Number Violation and (brief) motivations for searches

• Possibilities for LFV and LNV at the LHC

• A (biased) selection of some recent searches at the LHC
  – LFV in tau lepton decays at LHCb
  – LFV in B and D meson decays at LHCb
  – LNV in B and D meson decays at LHCb
  – Heavy Majorana neutrinos in CMS
  – Narrow heavy resonances decaying to two different-flavour leptons at CMS
  – LFV in the $e^\pm \mu^\mp$ continuum at ATLAS

• Conclusions
# Some reminders (and to define nomenclature)

The **Standard Model picture** for leptons, adapted for neutrino oscillations

<table>
<thead>
<tr>
<th>Lepton Number, L</th>
<th>Lepton Flavour</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-$</td>
<td>+1</td>
<td>$L_e = +1$</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>+1</td>
<td>$L_e = +1$</td>
</tr>
<tr>
<td>$e^+$</td>
<td>−1</td>
<td>$L_e = −1$</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>−1</td>
<td>$L_e = −1$</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>+1</td>
<td>$L_\mu = +1$</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>+1</td>
<td>$L_\mu = +1$</td>
</tr>
<tr>
<td>$\tau^-$</td>
<td>+1</td>
<td>$L_\tau = +1$</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>+1</td>
<td>$L_\tau = +1$</td>
</tr>
</tbody>
</table>

Antiparticles have lepton number $L = −1$ and corresponding lepton flavour $−1$

- **Lepton Number Conservation:** Total lepton number $L$ is conserved
- **Lepton Flavour Conservation:** Total of each of $L_e$, $L_\mu$, $L_\tau$ are separately conserved
In the Standard Model

- The neutrinos are massless
  - Neutrino flavour is conserved
- Lepton Flavour is conserved by construction
  - But LF is now known to be violated by neutrino oscillations
  - But suppressed by terms of order \((\Delta m^2_{\nu}/M_W^2)^2\)
  - Charged LFV from neutrino oscillations is unobservable in any current or foreseeable experiment

- Charged LFV is expected in many New Physics (NP) extensions to the SM, with parameter spaces allowing rates up to current experimental limits

- Lepton Number is conserved by an “accidental” symmetry
  - LNV is needed for leptogenesis
  - May be violated along with baryon number (e.g. via sphalerons)
  - Would be violated if the neutrino is a Majorana particle (i.e. its own antiparticle)

- Note that LNV implies also LFV, but we can have LFV without LNV
A sample of various charged Lepton Flavour Violating reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Current bound</th>
<th>Expected</th>
<th>Possible</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B(\mu^+ \to e^+\gamma) )</td>
<td>(&lt;1.2 \times 10^{-11})</td>
<td>(2 \times 10^{-13})</td>
<td>(2 \times 10^{-14})</td>
</tr>
<tr>
<td>( B(\mu^\pm \to e^\pm e^\pm e^-) )</td>
<td>(&lt;1.0 \times 10^{-12})</td>
<td>–</td>
<td>(10^{-14})</td>
</tr>
<tr>
<td>( B(\mu^\pm \to e^\pm\gamma\gamma) )</td>
<td>(&lt;7.2 \times 10^{-11})</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( R(\mu^- Au \to e^- Au) )</td>
<td>(&lt;7 \times 10^{-13})</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( R(\mu^- Al \to e^- Al) )</td>
<td>–</td>
<td>(10^{-16})</td>
<td>(10^{-18})</td>
</tr>
<tr>
<td>( B(\tau^\pm \to \mu^\pm\gamma) )</td>
<td>(&lt;5.9 \times 10^{-8})</td>
<td>(\mathcal{O}(10^{-9}))</td>
<td>–</td>
</tr>
<tr>
<td>( B(\tau^\pm \to e^\pm\gamma) )</td>
<td>(&lt;8.5 \times 10^{-8})</td>
<td>(\mathcal{O}(10^{-9}))</td>
<td>–</td>
</tr>
<tr>
<td>( B(\tau^\pm \to \mu^-\mu^+\mu^-) )</td>
<td>(&lt;2.0 \times 10^{-8})</td>
<td>(\mathcal{O}(10^{-10}))</td>
<td>–</td>
</tr>
<tr>
<td>( B(\tau^\pm \to e^\pm e^+ e^-) )</td>
<td>(&lt;2.6 \times 10^{-8})</td>
<td>(\mathcal{O}(10^{-10}))</td>
<td>–</td>
</tr>
<tr>
<td>( Z^0 \to e^\pm\mu^\mp )</td>
<td>(&lt;1.7 \times 10^{-6})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Z^0 \to e^\pm\tau^\mp )</td>
<td>(&lt;9.8 \times 10^{-6})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Z^0 \to \mu^\pm\tau^\mp )</td>
<td>(&lt;1.2 \times 10^{-5})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( K^0_L \to e^\pm\mu^\mp )</td>
<td>(&lt;4.7 \times 10^{-12})</td>
<td></td>
<td>(10^{-13})</td>
</tr>
<tr>
<td>( D^0 \to e^\pm\mu^\mp )</td>
<td>(&lt;8.1 \times 10^{-7})</td>
<td></td>
<td>(10^{-8})</td>
</tr>
<tr>
<td>( B^0 \to e^\pm\mu^\mp )</td>
<td>(&lt;9.2 \times 10^{-8})</td>
<td></td>
<td>(10^{-9})</td>
</tr>
</tbody>
</table>

The “most interesting” Lepton Flavour Violating reactions have

- Clean experimental signatures
- Good prospects for experimental sensitivity
- Relatively clean theoretical predictions

\[ \mu^- \rightarrow e^- \gamma \]  
\[ \mu^- \rightarrow e^+ e^- e^- \]  
\[ \mu^- N \rightarrow e^- N \]  
\[ \tau^- \rightarrow \mu^- \gamma \]  
\[ \tau^- \rightarrow \mu^+ \mu^- \mu^- \]

Heavy SUSY/exotic particles

- BaBar, Belle, LHCb, Belle II

Majorana neutrinos

- BaBar, Belle, LHCb, ATLAS, CMS, Belle II, NDBD ...
What can be done in LFV and LNV at the LHC?

• Generic searches for new physics in final states with odd numbers of charged leptons
• Searches for new massive particles decaying into two different charged leptons
• Searches for doubly-charged Higgs bosons decaying to two same-sign leptons
• Direct searches for RPV+LFV SUSY particles
• Direct searches for LFV in tau lepton decays
• Direct searches for B and D meson decays containing two same-sign leptons (Majorana neutrinos)
A miscellany possibilities for LFV&LNV@LHC
Direct searches for Lepton Flavour Violation in tau lepton decays at LHCb
### Some (of many) New Physics predictions for LFV in tau decays

<table>
<thead>
<tr>
<th>Model</th>
<th>References</th>
<th>Limits ( \tau \to \mu\gamma )</th>
<th>Limits ( \tau \to 3\mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM + ( v ) mixing</td>
<td>Lee, Shrock, PRD 16,1444(1977)</td>
<td>(10^{-40})</td>
<td>(10^{-14})</td>
</tr>
<tr>
<td></td>
<td>Cheng, Li, PRD 45,1908(1980)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUSY Higgs</td>
<td>Dedes, Ellis, Raidal, PLB 549,159(2002)</td>
<td>(10^{-10})</td>
<td>(10^{-7})</td>
</tr>
<tr>
<td></td>
<td>Brignole, Rossi, PLB 566,517(2003)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM + heavy Majorana ( v )</td>
<td>Cvetic, Dib, Kim, Kim, PRD 66,034008(2002)</td>
<td>(10^{-9})</td>
<td>(10^{-10})</td>
</tr>
<tr>
<td>Non-universal ( Z' )</td>
<td>Yue, Zhang, Liu, PLB 547,252(2002)</td>
<td>(10^{-9})</td>
<td>(10^{-8})</td>
</tr>
<tr>
<td>SUSY SO(10)</td>
<td>Masiero, Vempati, Vives, NPB 649,189(2003)</td>
<td>(10^{-8})</td>
<td>(10^{-10})</td>
</tr>
<tr>
<td>MSUGRA + Seesaw</td>
<td>Ellis et al., EPJ C14, 319(2002)</td>
<td>(10^{-7})</td>
<td>(10^{-9})</td>
</tr>
</tbody>
</table>
Compilation by Heavy Flavor Averaging Group of LFV limits for tau decays

90% C.L. upper limits for LFV $\tau$ decays

<table>
<thead>
<tr>
<th>$h_\gamma$</th>
<th>$I^{0}_P$</th>
<th>$I^{0}_S$</th>
<th>$I^{0}_V$</th>
<th>$I^{0}_I$</th>
<th>$I^{0}_{hh}$</th>
<th>$\Lambda h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-5}$</td>
<td>$10^{-6}$</td>
<td>$10^{-7}$</td>
<td>$10^{-8}$</td>
<td>$10^{-9}$</td>
<td>$10^{-10}$</td>
<td>$10^{-11}$</td>
</tr>
</tbody>
</table>

CLEO
BaBar
Belle

HFAG-Tau
Winter 2012
Tau production at the LHC

- Tau production at the LHC is mainly from $D_s$ decays

<table>
<thead>
<tr>
<th>Decay chain</th>
<th>Probability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s \rightarrow \tau$</td>
<td>78.3</td>
</tr>
<tr>
<td>$D_s \rightarrow \tau$</td>
<td>68.9</td>
</tr>
<tr>
<td>$B_x \rightarrow D_s \rightarrow \tau$</td>
<td>9.4</td>
</tr>
<tr>
<td>$D^+ \rightarrow \tau$</td>
<td>4.9</td>
</tr>
<tr>
<td>$D^+ \rightarrow \tau$</td>
<td>4.7</td>
</tr>
<tr>
<td>$B_x \rightarrow D^+ \rightarrow \tau$</td>
<td>0.2</td>
</tr>
<tr>
<td>$B_x \rightarrow \tau$</td>
<td>16.8</td>
</tr>
</tbody>
</table>

- LHCb, with forward geometry, low-$p_T$ triggers, vertex locator and good mass resolution is well suited for these tau production channels
- But $\tau$s are produced in high-multiplicity hadronic environments
- Situation is much cleaner in exclusive $e^+e^- \rightarrow \tau^+\tau^-$ at B factories
LHCb searches for $\tau \rightarrow 3\mu$ and $\tau \rightarrow p\mu\mu$

- Inclusive $\sigma(pp \rightarrow \tau + X) = 80 \pm 8 \mu b$ at 7 TeV in the LHCb acceptance
  - So $8 \times 10^{10}$ produced $\tau$ in 1 fb$^{-1}$ in 2011
  - c.f. total of $3 \times 10^9 \tau$ produced in Belle+BaBar

- Search inclusively for $3\mu$ and $p\mu\mu$ from displaced vertex consistent with $\tau$ decay
- Loose cut-based selection followed by event classification according to
  - Decay topology and kinematics
  - Particle ID
  - Invariant mass
- Event classifiers trained on simulated signals and background Monte Carlo, and calibrated on control channels
- Relative normalisation of rates to $D^-_s \rightarrow \phi(\mu^+\mu^-)\pi^-$
- Limits on BF$s$ deduced using CL$_s$ method
• Two multivariate classifiers:

\[ M_{3body} \] includes vertex and track fit qualities, vertex displacement, momentum direction (vertex pointing), vertex isolation, \( p_T \) of candidate

• Boosted decision tree with adaptive boosting, trained on MC for signal and background

• Response calibrated on \( D_s^+ \rightarrow \phi(\mu^+\mu^-)\pi^- \) in data to account for data-MC differences

Vertex reconstruction relies on LHCb VELO
The VELO halves must be kept apart...
...until the LHC beam conditions stabilise:
- \( M_{\text{PID}} \) includes particle ID information from RICHs, ECAL, HCAL, MUON chambers

- Neural network trained on signal and background MC
- Calibrated on \( J/\psi \rightarrow \mu\mu \) in data
- For \( \tau \rightarrow p\mu\mu \) simple PID cuts applied, optimised on MC and data sidebands
LHCb upper limits on BFs for $\tau \rightarrow 3\mu$ and $\tau \rightarrow p\mu\mu$

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected (90% CL)</th>
<th>Observed (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow \mu^- \mu^+ \mu^-$</td>
<td>$8.3 \times 10^{-8}$</td>
<td>$8.0 \times 10^{-8}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \bar{p}\mu^+ \mu^-$</td>
<td>$4.6 \times 10^{-7}$</td>
<td>$3.3 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow p\mu^- \mu^-$</td>
<td>$5.4 \times 10^{-7}$</td>
<td>$4.4 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

• LHCb limits on $\tau \rightarrow p\mu\mu$ modes
  • No previous limits existed for these mode, which violate both Lepton and Baryon Number with $\Delta(B-L)=0$
  • But are we learning anything new here, or do limits on proton decay already rule this out (subject to CPT)?
Compilation by **Heavy Flavor Averaging Group** of LFV limits for tau decays (supplemented with **LHCb** results)

- Analysis now being updated using 3 fb⁻¹ 2011+12 dataset
- Search started also for $\tau \rightarrow \phi \mu$
For $\tau \rightarrow 3\mu$ LHCb may overtake Belle but will eventually be overtaken by Belle 2

In terms of sensitivity for $\tau \rightarrow 3\mu$, a rule of thumb is:

- 1 fb$^{-1}$ at LHCb is equivalent to 1 ab$^{-1}$ at an $e^+e^-$ B/charm/tau factory
Direct searches for Lepton Number Violation in B and D meson decays at LHCb
A range of LFV $B$-decays are allowed in BSM models with a Majorana neutrino or a doubly charged Higgs boson.

Search for the decays $B^+ \rightarrow h^- \mu^+\mu^+$, where $h^-$ is a $\pi^-$, $K^-$ or $D^-$ meson.

Different final states probe a range of Majorana neutrino masses.

Results obtained using $36 - 410 \text{ pb}^{-1}$ of LHCb data from 2010 + 2011.

Normalisation channels: $B^+ \rightarrow J/\psi K^+$ (3-body) and $B^+ \rightarrow \psi(2S)K^+$ (5-body).
LHCb searches for $B^- \rightarrow h^+ \mu^- \mu^-$

- No significant signals are observed
  → Set limits as a function of the Majorana neutrino mass
- All limits are new world’s bests
  → improved by as much as $\sim \times 100$

<table>
<thead>
<tr>
<th>Channel</th>
<th>Observed</th>
<th>95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \mu^- \mu^-$</td>
<td>$5.4 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$D^+ \mu^- \mu^-$</td>
<td>$6.9 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>$D^{*+} \mu^- \mu^-$</td>
<td>$2.4 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>$\pi^+ \mu^- \mu^-$</td>
<td>$1.3 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$D_s^+ \mu^- \mu^-$</td>
<td>$5.8 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>$D^0 \pi^+ \mu^- \mu^-$</td>
<td>$1.5 \times 10^{-6}$</td>
<td></td>
</tr>
</tbody>
</table>
Lepton Number Violating Charmless B Decays

HFAG
Jun 2013

LHCb

Branching Ratio x 10^6

LHCb

K^+ e^- μ^+
K^+ e^+ μ^-
K^{*+} e^- μ^+
K^{*+} e^+ μ^-
ρ^- e^+ μ^+
ρ^+ e^- μ^+
π^- e^+ μ^+
π^+ e^- μ^+
K^{*-} e^- μ^+
K^{*-} e^+ μ^+
K^- e^+ μ^-
K^- e^- μ^+
π^0 e^± μ^±
π^+ e^± μ^±
K^+ e^± μ^±
K^0 e^± μ^±
K^{*0} e^± μ^±
K^{*+} e^± μ^±
K^{*-} e^± μ^±
ρ e^± μ^±
π e^± μ^±
K e^± μ^±
K^{*} e^± μ^±

CLEO
Belle
BABAR
CDF
LHCb
New Avg.

LFV&LNV&LHC
George Lafferty (University of Manchester)
LHCb search for $D_{(s)}^{+} \rightarrow \pi^{-}\mu^{+}\mu^{+}$

- $D_{(s)}^{+} \rightarrow \pi^{-}\mu^{+}\mu^{+}$ decays can occur through leptonic mixing via a Majorana neutrino.
- World's best experimental limits from BaBar of $2 \times 10^{-6}$ and $1.4 \times 10^{-5}$ for $D^{+} \rightarrow \pi^{-}\mu^{+}\mu^{+}$ and $D_{s}^{+} \rightarrow \pi^{-}\mu^{+}\mu^{+}$ respectively.
LHCb search for $D_{(s)}^{+} \rightarrow \pi^{-}\mu^{+}\mu^{+}$

- Normalisation to $D_{(s)}^{+} \rightarrow \phi(\mu^{+}\mu^{-})\pi^{+}$
- Classification of signal and background from PID cuts and a BDT using kinematic and geometric variables, trained on 2010 data

- **Peaking background** from $D_{(s)}^{+} \rightarrow \pi^{+}\pi^{+}\pi^{-}$ decays with shape (grey) measured from data
- Fit in bins of $m(\pi^{-}\mu^{+})$ to improve statistical significance
- Limit of $2.2 \times 10^{-8}$ and $1.2 \times 10^{-7}$ for $D^{+}$ and $D_{s}^{+}$ decays respectively are a factor of fifty improvement

LHCb-PAPER-2012-051
Compilation by Heavy Flavor Averaging Group of LNV limits for $D^+$ decays (supplemented with LHCb result)
Compilation by **Heavy Flavor Averaging Group** of LNV limits for $D_s^+$ decays (supplemented with LHCb result)
Direct searches for Lepton Flavour Violation in B and D meson decays at LHCb
LHCb search for $B^{0}_{(s)} \rightarrow e^{\pm} \mu^{\mp}$

- These decays are allowed in several BSM models
  - Heavy singlet Dirac neutrinos
  - RPV and LNV SUSY models
  - Leptoquarks that couple leptons and quarks of different generations (Pati-Salam)

- Analysis uses 1 fb$^{-1}$ of 7 TeV data (2011 sample)

- Potential signal normalised to $B^{0} \rightarrow K^{+}\pi^{-}$ with $B^{0}(s) \rightarrow h^{+}h'^{-}$ as control channel

- Main backgrounds from semileptonic $b$ decays: $bb\rightarrow e^{\pm}\mu^{\mp}X$ and from particle misid

- Candidates classified by $e\mu$ mass and output of a geometrical BDT with 9 variables
LHCb search for $B^0_{(s)} \rightarrow e^\pm \mu^{\mp}$

- LHCb results give an order of magnitude improvement over previous limits (CDF)
- Limits also set on masses of Pati-Salam leptoquarks

\[
M_{LQ}(B^0_s \rightarrow e^\pm \mu^{\mp}) > 107 \text{ TeV} \\
M_{LQ}(B^0 \rightarrow e^\pm \mu^{\mp}) > 135 \text{ TeV}
\]
Lepton Number Violating Charmless B Decays

LFV&LNV&LHC
George Lafferty (University of Manchester)
LHCb search for $D^0 \rightarrow e^\pm \mu^\mp$

- LFV $D^0 \rightarrow e^\pm \mu^\mp$ decays would occur in R-parity violating SUSY, Higgs doublet models and models with extra fermions.

- Current best limit is from Belle: $\mathcal{B}(D^0 \rightarrow e^\pm \mu^\mp) < 2.7 \times 10^{-7}$

- Analysis now started in LHCb
  - using $D^0$ tagged by $D^{*+} \rightarrow D^0\pi^-$ decays
  - normalising to $D^0 \rightarrow \pi^+\pi^-$ which has a large yield

- LHCb 3 fb$^{-1}$ (2011+2012) data sample has potential to be competitive with the Belle result.
Compilation by Heavy Flavor Averaging Group of LNV limits for $D^0$ decays

LHCb projection with 2011+12 dataset
Search for heavy Majorana neutrinos in $\mu^+\mu^- + \text{jets}$ and $e^+e^- + \text{jets}$ at CMS

- Analysis uses 4.98 $fb^{-1}$ at $\sqrt{s} = 7$ TeV
- $N$ may decay to same-sign ($W^- l^+$) or opposite-sign ($W^+ l^-$) lepton
- Same-sign events have no SM background – search for events with two isolated leptons of same sign and same flavour, plus at least two jet
- Free parameters are heavy neutrino mass $m_N$ and mixing parameters $|V_{lN}|^2$ for $l=e,\mu$
CMS search for narrow heavy resonances decaying into two leptons

- An easily identifiable cLFV signature: a pair of different flavour, opposite sign leptons with large \( p_T \) could arise from e.g.
  - A sneutrino decaying into \( e^\pm \mu^\mp \) (in RPV+LFV SUSY)
  - A \( Z' \) boson with LFV couplings

- Analysis (CMS PAS EXO-12-061) used 20 fb\(^{-1}\) at 8 TeV
- Observed spectra consistent with SM
ATLAS search for LFV in the $e^\pm \mu^\mp$ continuum

- Exemplified/interpreted via t-channel exchange of a stop in LFV SUSY
- Analysis uses 2.1 fb$^{-1}$
- Puts limits on RPV couplings as function of stop mass
ATLAS search for LFV in the $e^\pm \mu^\mp$ continuum

- Analysis puts limits on RPV couplings as function of stop mass
Conclusions

• Already LHC has improved on previous limits for a number of LFV and LNV channels

• No signals have been seen

• But new Physics is out there somewhere

• So we will keep pushing back the frontiers ...