Lepton Flavor Violation Searches at the LHC
A path to new physics

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• Do charged leptons violate flavor conservation?
  ▸ Neutrino contribution is small:
  ▸ Clear signature for new physics:

Ex: \( \text{Br} \sim 10^{-50} \)
• Do charged leptons violate flavor conservation?
  ‣ Neutrino contribution is small:
  ‣ Clear signature for new physics:
  ‣ Example 1: 2 Higgs Doublet Models (2HDM)
    - SM + second Higgs doublet
    - Charged LFV Higgs couplings are possible.
    - Sensitive to off-diagonal terms in Yukawa matrix.

Ex: \( \text{Br} \sim 10^{-50} \)
• Do charged leptons violate flavor conservation?
  ‣ Neutrino contribution is small:
  ‣ Clear signature for new physics:
  ‣ Example 2: R Parity Violating (RPV) SUSY.
    - $R = (-1)^{3B+L+2S}$
    - R Parity conserved $\rightarrow$ stable proton, LSP
    - RPV, by lepton number only $\rightarrow$ stable proton
• Do charged leptons violate flavor conservation?
  ▸ Neutrino contribution is small:
  ▸ Clear signature for new physics:
  ▸ Many models of new physics (2HDM, SUSY, CHM, Heavy Neutrinos…) predict LFV decays of Higgs, Z, other massive resonances.
  ▸ Can be observed as SM decay, \((Z \rightarrow e\mu)\), BSM decay \((Z' \rightarrow e\mu)\), other \((QBG \rightarrow e\mu)\).
  ▸ Complimentary searches for LFV and FCNC at LHC.

Ex: \(\text{Br} \sim 10^{-50}\)
Collider, Detectors and Data
Collider, Detectors and Data

Delivered / Recorded Luminosity
- 2.21 / 2.08 (fb⁻¹), in 2012
- 1.22 / 1.11 (fb⁻¹), in 2011
- 0.04 / 0.04 (fb⁻¹), in 2010

2011: 3.5 TeV + 3.5 TeV
2012: 4 TeV + 4 TeV

CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:22 to 2016-10-27 14:12 UTC

ATLAS Online Luminosity
- 2011 pp \(\sqrt{s} = 7 \text{ TeV}\)
- 2012 pp \(\sqrt{s} = 8 \text{ TeV}\)
- 2015 pp \(\sqrt{s} = 13 \text{ TeV}\)
- 2016 pp \(\sqrt{s} = 13 \text{ TeV}\)
Rare Decays
• In SM $b \rightarrow sll$ occurs through FCNC.

![SM Diagram]

• New physics can enhance or suppress rate.
• Previous analyses of $B^+ \rightarrow K^+ ll$ has SM tension at 2.6 $\sigma$
• Test lepton flavor universality in $B^+ \rightarrow K^+ ll$, $B^0 \rightarrow K^{*0} ll$ with 3 fb$^{-1}$ collected at 7 and 8 TeV.

LHC Seminar 18 April 2017, https://indico.cern.ch/event/580620
• Measure double ratio:

\[ R_{K^*0} = \frac{\mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi (\to \mu^+ \mu^-))} \div \frac{\mathcal{B}(B^0 \to K^{*0} e^+ e^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi (\to e^+ e^-))} \]

- Cancelation of many systematic effects

• Selection of electrons and muons are as similar as possible.
  - Differences: triggers and bremsstrahlung.
  - Analysis split into 3 exclusive electron trigger categories.
• Analysis regions split in $q^2$:
  ‣ Low [0.045 - 1.1] GeV
  ‣ Central [1.1 - 6.0] GeV
  ‣ Fit $ee$, $\mu\mu$ separately.

• Yields:

<table>
<thead>
<tr>
<th>Analysis Region</th>
<th>$B^0 \to K^{*0} \ell^+\ell^-$</th>
<th>$B^0 \to K^{*0} J/\psi (\to \ell^+\ell^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>low-$q^2$</td>
<td>$\mu^+\mu^-$: $285 \pm 18_{18}$</td>
<td>$274416 \pm 602_{654}$</td>
</tr>
<tr>
<td></td>
<td>$e^+e^-$ (L0E): $55 \pm 9_{8}$</td>
<td>$43468 \pm 222_{221}$</td>
</tr>
<tr>
<td></td>
<td>$e^+e^-$ (L0H): $13 \pm 5_{5}$</td>
<td>$3388 \pm 62_{61}$</td>
</tr>
<tr>
<td></td>
<td>$e^+e^-$ (L0I): $21 \pm 5_{4}$</td>
<td>$11505 \pm 115_{114}$</td>
</tr>
<tr>
<td>central-$q^2$</td>
<td>$\mu^+\mu^-$: $353 \pm 21_{21}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$e^+e^-$ (L0E): $67 \pm 10_{10}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$e^+e^-$ (L0H): $19 \pm 6_{5}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$e^+e^-$ (L0I): $25 \pm 7_{6}$</td>
<td></td>
</tr>
</tbody>
</table>

• Limited by electron statistics.
• Many cross checks:

\[ r_{J/\psi} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))} \]

- Lacks cancellation of systematics in double ratio.
- Measure (expect unity):

\[ 1.043 \pm 0.006 \text{ (stat)} \pm 0.045 \text{ (syst)} \]

- Flat as function of kinematic variables.

• Also check other ratios, reconstruction of kinematic distributions, background models etc. All show agreement.
Results

- low-\(q^2\) compatibility with SM of 2.2-2.4 \(\sigma\)
- central-\(q^2\) compatibility with SM of 2.4-2.5 \(\sigma\)
- “Particularly interesting” behavior of ratio.
- Measurement will benefit significantly from Run 2 data.

<table>
<thead>
<tr>
<th>LHCb Preliminary</th>
<th>low-(q^2)</th>
<th>central-(q^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_{K^{*0}})</td>
<td>(0.660 \pm 0.110 \pm 0.024)</td>
<td>(0.685 \pm 0.113 \pm 0.047)</td>
</tr>
<tr>
<td>95% CL</td>
<td>([0.517–0.891])</td>
<td>([0.530–0.935])</td>
</tr>
<tr>
<td>99.7% CL</td>
<td>([0.454–1.042])</td>
<td>([0.462–1.100])</td>
</tr>
</tbody>
</table>

\[ q^2 \text{ [GeV}^2/c^4] \]

LHC Seminar 18 April 2017, https://indico.cern.ch/event/580620

- PRD 86 (2012) 032012
- PRL 103 (2009) 171801
• Forbidden LFV decay in SM.
• *Belle* $\text{Br}(D^0 \rightarrow e^{\pm} \mu^{\mp}) < 2.6 \times 10^{-7}$ (90% CL).
• Signature of
  ‣ RPV SUSY : $\sim 10^{-6}$
  ‣ Leptoquarks : $4 \times 10^{-8}$
• Analyze 3 fb$^{-1}$ collected at 7 and 8 TeV
• $D^0$ selected using $D^{*+} \rightarrow D^0 \pi^+$
  ‣ BR of $D^0 \rightarrow e^{\pm} \mu^{\mp}$
  ‣ normalized to $\text{Br} D^0 \rightarrow K^- \pi^+$

• Simultaneous fit in 3 BDT bins:
  ▸ Background-like

  ▸ Intermediate

  ▸ Signal-like

LHCb $D^0 \rightarrow e^\pm \mu^\mp$

\[ \mathcal{B}(D^0 \rightarrow e^\pm \mu^\mp) = \frac{N_{e\mu}/\epsilon_{e\mu}}{N_{K\pi}/\epsilon_{K\pi}} \times \mathcal{B}(D^0 \rightarrow K^-\pi^+) \]

- $\mathcal{B}(D^0 \rightarrow e^\pm \mu^\mp) < 1.3 \times 10^{-8} @ 90\%$ CL
  - 20x improvement over previous results

• Analyze 3 fb\(^{-1}\) collected at 7 and 8 TeV
  ‣ Muon trigger
  ‣ Secondary vertex
  ‣ Three tracks, compatible with tau decay (momentum pointing to PV, lifetime)
• Use \(D_s^- \rightarrow \phi(\mu\mu)\pi^-\) for calibration and normalization
• Multivariate analysis: Likelihoods based on PID, tau selection and 3-body decay kinematics
• BR normalized to \( D_s^- \rightarrow \phi(\mu\mu)\pi^- \)
  
  ‣ \( \mathcal{B}(\tau \rightarrow \mu\mu) < 4.6 \times 10^{-8} @ 90\% \text{ CL} \)
  ‣ Belle : \( 2.1 \times 10^{-8} @ 90\% \text{ CL} \)
  ‣ BaBar : \( 3.3 \times 10^{-8} @ 90\% \text{ CL} \)

  ‣ Complimentary search by ATLAS
    in \( pp \rightarrow W \rightarrow \tau\nu \rightarrow (\mu\mu\mu)\nu \)
    ○ BR < \( 3.8 \times 10^{-7} @ 95\% \text{ CL} \)

Higgs boson decays
• Two channels:
  ‣ $\tau$ decay to hadrons
  ‣ $\tau$ decay to electrons

• Three jet categories
  ‣ 0-jet $\rightarrow$ ggF production
  ‣ 1-jet $\rightarrow$ ggF production
  ‣ 2-jet $\rightarrow$ VBF production

• Collinear Mass used a discriminator.

• 8 TeV analysis showed 2.4 sigma excess
  ‣ 13 TeV change to analysis: $Z \rightarrow \tau\tau$ modeled from MC.
  ‣ lepton misID from data
  ‣ other ($t\bar{t}b\bar{t}$, $VV$, ...) backgrounds from MC
0-jet

1-jet

2-jet

\(\tau_h\)

\(\tau_e\)

\(\mu\tau\)

\(\tau\)

\(e\)

\(\mu\)

\(h\)

\(\text{Preliminary}\)

\(\text{Events / 15 GeV}\)

\(\text{collinear } M_{\mu\tau} \text{ (GeV)}\)

\(\text{Data-BG}\)

\(\text{BG}\)

\(\text{LFV GF Higgs (BR=1%)}\)

\(\text{Misidentified leptons}\)

\(\text{SM Higgs}\)

\(\text{Post-fit background unc.}\)

\(\text{Data}\)

\(\text{Events / 20 GeV}\)

\(\text{collinear } M_{\mu\tau} \text{ (GeV)}\)

\(\text{Data-BG}\)

\(\text{BG}\)

\(\text{LFV GF Higgs (BR=1%)}\)

\(\text{Misidentified leptons}\)

\(\text{SM Higgs}\)

\(\text{Post-fit background unc.}\)

\(\text{Data}\)

\(\text{Events / 50 GeV}\)

\(\text{collinear } M_{\mu\tau} \text{ (GeV)}\)

\(\text{Data-BG}\)

\(\text{BG}\)

\(\text{LFV GF Higgs (BR=1%)}\)

\(\text{Misidentified leptons}\)

\(\text{SM Higgs}\)

\(\text{Post-fit background unc.}\)

\(\text{Data}\)
**CMS 13 TeV**

\[ H \rightarrow \mu \tau \]

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### Expected limits

<table>
<thead>
<tr>
<th></th>
<th>0-jet (%)</th>
<th>1-jet (%)</th>
<th>2-jets (%)</th>
<th>Combined (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu \tau_h )</td>
<td>&lt;4.17</td>
<td>&lt;4.89</td>
<td>&lt;6.41</td>
<td>&lt;2.98</td>
</tr>
<tr>
<td>( \mu \tau_e )</td>
<td>&lt;2.24</td>
<td>&lt;4.36</td>
<td>&lt;7.31</td>
<td>&lt;1.96</td>
</tr>
<tr>
<td>( \mu \tau )</td>
<td>&lt;1.62</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Observed limits

<table>
<thead>
<tr>
<th></th>
<th>0-jet (%)</th>
<th>1-jet (%)</th>
<th>2-jets (%)</th>
<th>Combined (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu \tau_h )</td>
<td>&lt;4.24</td>
<td>&lt;6.35</td>
<td>&lt;7.71</td>
<td>&lt;3.81</td>
</tr>
<tr>
<td>( \mu \tau_e )</td>
<td>&lt;1.33</td>
<td>&lt;3.04</td>
<td>&lt;8.99</td>
<td>&lt;1.15</td>
</tr>
<tr>
<td>( \mu \tau )</td>
<td>&lt;1.20</td>
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</tr>
</tbody>
</table>

### Best-fit branching fractions

<table>
<thead>
<tr>
<th></th>
<th>0-jet (%)</th>
<th>1-jet (%)</th>
<th>2-jets (%)</th>
<th>Combined (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu \tau_h )</td>
<td>0.12(+2.02)(-1.91)</td>
<td>1.70(+2.41)(-2.52)</td>
<td>1.54(+3.12)(-2.71)</td>
<td>1.12(+1.45)(-1.40)</td>
</tr>
<tr>
<td>( \mu \tau_e )</td>
<td>(-2.11)(+1.30)(-1.89)</td>
<td>(-2.18)(+1.99)(-2.05)</td>
<td>2.04(+2.96)(-3.31)</td>
<td>(-1.81)(+1.07)</td>
</tr>
<tr>
<td>( \mu \tau )</td>
<td>(-0.76)(+0.81)(-0.84)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### ATLAS

- Expected: \(<1.01^{+0.4}_{-0.29}\) %
- Observed: \(<1.43\) %

### CMS Preliminary

- 2.3 fb\(^{-1}\) (13 TeV)

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- No excess observed.
- More data is needed to understand 8 TeV excess.
- ATLAS result includes leptonic \( \tau \) decays to muons and electrons.

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• Summery of limits on off-diagonal Yukawa couplings from Higgs decays.

Z boson decays
• LVF search in $H \rightarrow e\tau$, $\mu\tau$ and $Z \rightarrow \mu\tau$ decays with 20 fb$^{-1}$ dataset follow similar strategy.
  ‣ Missing Mass Calculator (MMC): Use $\tau$ kinematics and missing $E_T$ to correct for undetected neutrino. Similar to Collinear Mass.
  ‣ Two signal regions $M_T(e, \text{missing } E_T)$:
    ○ high $M_T$ dominated by $W+jets$
    ○ low $M_T$ dominated by $Z$ decays
  ‣ Two channels: high $P_T$ electron or high $P_T$ muon.
    ‣ Result: $\text{Br}(H \rightarrow e\tau) < 1.04 \%$
• Search for $Z \rightarrow \mu \tau$ decays:
  
  ‣ lower cut values to match $Z$ boson decay kinematics
  ‣ larger $W + jets$ contribution in both signal regions, estimate across three bins.

  
  
  – Result: $\text{Br}(Z \rightarrow \mu \tau) < 1.07 \times 10^{-5}$ (95% CL)

• High $P_T$ $e$ and $\mu$, low jet activity and missing $E_T$.

- ATLAS BR ($Z \to e\mu$) < $7.5 \times 10^{-7}$ (95% CL)

- CMS BR ($Z \to e\mu$) < $7.3 \times 10^{-7}$ (95% CL)

LFV in SUSY
• Search for L-RPV SUSY in 13.3 fb\(^{-1}\) dataset.

  ○ Four high \(P_T\) leptons (lepton = \(e\) or \(\mu\)) and missing \(E_T\) in signal events.
  ○ Veto events with leptonically decaying \(Z\) boson
  ○ Discriminant: \(m_{\text{eff}} = \) scalar sum of lepton \(P_T\), missing \(E_T\) and jet \(P_T\).

• Backgrounds: \(VV\), \(VVV\), \(ttV\) dominate irreducible background. Measure reducible background, 2-fake lepton rate.
• No excess observed.
• $M(\text{chargino}) > 1.14$ TeV for large LSP masses.
• Limits set on RPV decays via $\lambda_{12k}, k = 1, 2$
Majorana Neutrinos
• Search for heavy Majorana neutrinos ($N$) with 19.7 $fb^{-1}$ dataset.
• Type-1 seesaw model with $N$ - SM $\nu$ mixing.
• Same-sign di-lepton signatures ($ee$, $\mu\mu$, $e\mu$).
• High-mass and low-mass (relative to $M_W$) selections.

• No excess observed.
• First limits for $e\mu$ for $M(N) > 40$ GeV.

• **Low mass: LHCb** sets limit on $\text{Br}(B^- \rightarrow \pi^+ \mu^- \mu^-)$ in 250 MeV to 5000 MeV range, and as function of lifetime.
High Mass Resonances
• Search for LPV with $Z'$ (coupling to SM),
• $\tilde{\nu}_\tau$ in RPV SUSY
• QBH (ADD and RS models)

**CMS:** $X \rightarrow \mu e$  
$2.7 \text{ fb}^{-1}$ (13 TeV)

**ATLAS:** $X \rightarrow \tau \mu, \tau e, \mu e$

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• ATLAS: $\tilde{\nu}_\tau, \chi_3^{11} = 0.11$
• CMS: QBH
  ‣ RS $\rightarrow n = 1$
  ‣ ADD $\rightarrow n > 1$

<table>
<thead>
<tr>
<th>Model</th>
<th>Expected Limit [TeV]</th>
<th>Observed Limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e\mu$</td>
<td>$e\tau$</td>
</tr>
<tr>
<td>$Z'$</td>
<td>3.2</td>
<td>2.7</td>
</tr>
<tr>
<td>RPV SUSY $\tilde{\nu}_\tau$</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>QBH ADD $n = 6$</td>
<td>4.6</td>
<td>4.1</td>
</tr>
<tr>
<td>QBH RS $n = 1$</td>
<td>2.5</td>
<td>2.2</td>
</tr>
</tbody>
</table>
FCNC
FCNC in top decays forbidden at tree level, heavily suppressed in SM.

CMS and ATLAS searches cover various decay and production mechanisms.

Sensitivity is approaching an interesting region.
Looking forward

- LFV is one of the best opportunities to find physics beyond the SM.

- Analyses at LHCb, ATLAS and CMS cover a wide variety channels. Some are finding “interesting behavior” while others are setting strong limits.

- Updates with higher energy and full statistics of 2016 dataset are coming.

- 2017 and beyond will be exciting years at the LHC…
LHC has delivered ~4% of expected dataset. We are just taking the first steps on the path to new physics.
Thank you
Additional Material Follows
• Higgs boson decays
  ▶ CMS - Search for lepton flavor violating decays of the Higgs boson in the $\mu$-$\tau$ final state at 13 TeV
    ○ https://cds.cern.ch/record/2159682/files/HIG-16-005-pas.pdf
  ▶ CMS - Search for lepton flavour violating decays of the Higgs boson to e tau and e mu in proton-proton collisions at sqrt(s) = 8 TeV
  ▶ ATLAS - Search for lepton-flavour-violating $H \rightarrow \mu \tau$ decays of the Higgs boson with the ATLAS detector
  ▶ ATLAS - Search for lepton-flavour-violating decays of the Higgs and Z bosons with the ATLAS detector
• Z boson decays
  ▶ ATLAS - Search for lepton-flavour-violating decays of the Higgs and Z bosons with the ATLAS detector
  ▶ CMS - Search for Lepton Flavor Violation in Z decays in pp collisions at sqrt(s)=8 TeV
  ▶ ATLAS - Search for the lepton flavor violating decay $Z \rightarrow e\mu$ in pp collisions at $s\sqrt{ } = 8$ TeV with the ATLAS detector
• RPV SUSY
  ▶ ATLAS - Search for supersymmetry in events with four or more leptons in s$\sqrt{ }=13$s=13 TeV pp collisions using 13.3 fb$^{-1}$ of ATLAS data
  ▶ ATLAS - Search for a Heavy Neutral Particle Decaying to e$\mu$, e$\tau$, or $\mu\tau$ in pp Collisions at s$\sqrt{ }=8$ TeV with the ATLAS Detector
• Majorana nu
  ▶ CMS - Search for heavy Majorana neutrinos in e$\pm$e$\pm$ jets and e$\pm$$\mu$$\pm$ jets events in proton-proton collisions at $\sqrt{s} = 8$ TeV
• Z'/BH/X
  ▶ CMS - Search for high-mass resonances and quantum black holes in the $e\mu e\mu$ final state in proton-proton collisions at $s\sqrt{ }=s= 13$ TeV
• FCNC ATLAS and CMS
  ▶ https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG