PROBING LEPTON FLAVOUR UNIVERSALITY VIOLATION IN TOP DECAYS

DANIEL STOLARSKI

SM gauge interactions are flavour universal for leptons.
What breaks LFU in SM?
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- Masses (often easy to account for).
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- Masses (often easy to account for).
- Higgs interactions (often small).
LEPTON UNIVERSALITY

What breaks LFU in SM?

• Masses (often easy to account for).

• Higgs interactions (often small).

Most interactions are lepton flavour universal to very good approximation.
TESTS OF LFU

What are some tests of LFU?
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- **W decays**

| $\Gamma_2$ | $e^+\nu$ | $(10.71 \pm 0.16)$% |
| $\Gamma_3$ | $\mu^+\nu$ | $(10.63 \pm 0.15)$% |
| $\Gamma_4$ | $\tau^+\nu$ | $(11.38 \pm 0.21)$% |
What are some tests of LFU?

- **W decays**

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<thead>
<tr>
<th>Γ</th>
<th>Process</th>
<th>Percentage</th>
</tr>
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<tbody>
<tr>
<td>Γ₂</td>
<td>e⁺ν</td>
<td>(10.71 ± 0.16)%</td>
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- **Z decays**

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<tr>
<td>Γ₁</td>
<td>e⁺e⁻</td>
<td>(3.3632 ± 0.0042)%</td>
</tr>
<tr>
<td>Γ₂</td>
<td>μ⁺μ⁻</td>
<td>(3.3662 ± 0.0066)%</td>
</tr>
<tr>
<td>Γ₃</td>
<td>τ⁺τ⁻</td>
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What are some tests of LFU?

- **W decays**

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<tr>
<th>$\Gamma$</th>
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<tbody>
<tr>
<td>$\Gamma_2$</td>
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- **Z decays**

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<th>$\Gamma$</th>
<th>Decay Mode</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>$\Gamma_1$</td>
<td>$e^+e^-$</td>
<td>$(3.3632 \pm 0.0042)%$</td>
</tr>
<tr>
<td>$\Gamma_2$</td>
<td>$\mu^+\mu^-$</td>
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<td>$\Gamma_3$</td>
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</tbody>
</table>

- Less precise tests in pions, kaons, charm, and tau’s.
Hints of LFU violation in B decays:

• Charged current B decay to tau:

\[ R(D^{(*)}) = \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)} \]

• Neutral current B decay to e and mu:

\[ R(K^{(*)}) = \frac{\text{BR}(B \to K^{(*)}\mu^+\mu^-)}{\text{BR}(B \to K^{(*)}e^+e^-)} \]

More in the discussion on Friday.
Hints of LFU violation in B decays:

- **Charged current B decay to tau:**
  \[
  R(D^{(*)}) = \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)}
  \]

- **Neutral current B decay to e and mu:**
  \[
  R(K^{(*)}) = \frac{\text{BR}(B \to K^{(*)}\mu^+\mu^-)}{\text{BR}(B \to K^{(*)}e^+e^-)}
  \]

More in the discussion on Friday.
WHAT ABOUT TOP?

Does top decay to leptons?
WHAT ABOUT TOP?

Does top decay to leptons?

Of course it does, and it's been measured at LHC: 

\textbf{ATLAS 1506.05074.}

\[
\begin{align*}
\text{BR}(t \rightarrow b \, e \, \nu) &= 13.3\% \pm 0.4\% \pm 0.4 \% \\
\text{BR}(t \rightarrow b \, \mu \, \nu) &= 13.4\% \pm 0.3\% \pm 0.5 \% \\
\text{BR}(t \rightarrow b \, \tau_h \, \nu) &= 7.0\% \pm 0.3\% \pm 0.5 \%
\end{align*}
\]

Solving coupled equations gives \(~20\%\) precision on tau/lepton universality in top decays.
What about Top

Not competitive with W decays from LEP.

- W decays

| \(\Gamma_2\) | \(e^+\nu\) | \((10.71 \pm 0.16)\%\) |
| \(\Gamma_3\) | \(\mu^+\nu\) | \((10.63 \pm 0.15)\%\) |
| \(\Gamma_4\) | \(\tau^+\nu\) | \((11.38 \pm 0.21)\%\) |

Should we give up?
OTHER TOP DECAYS

What about other possible charged currents?
What about other possible charged currents?

- Additional vectors?

\[(W')^+ \to t^{-} \to b - \tau^+ - \nu_{\tau}\]
What about other possible charged currents?

• Additional vectors?

• Charged scalars?
What about other possible charged currents?

- Additional vectors?

- Charged scalars?

- Leptoquarks?
There are many tops at LHC, and there will be many more.

\[ \sigma(\bar{t}t) = 820 \text{ pb} \quad \sqrt{s} = 13 \text{ TeV} \]
\[ \sigma(\bar{t}t) = 970 \text{ pb} \quad \sqrt{s} = 14 \text{ TeV} \]
\[ \sigma(\bar{t}t) = 32 \text{ nb} \quad \sqrt{s} = 100 \text{ TeV} \]

Already have \(\sim 10^8\) tops analyzed, can expect \(\sim 10^{10}\) with HL LHC.

What can we do with such a huge data set?
Use anomaly central value to fix $g_{bc}g_\tau$.

Freytsis, Ligeti, Ruderman, 1506.08896.

Top decay only depends on $g_{tb}$, assume MFV structure.

$$\frac{g_{tb}}{g_{bc}} = \frac{V_{tb}}{V_{cb}} \approx 24$$
On-shell explanations to $R_D$ anomaly strongly constrained.
For off shell, can use EFT picture:

\[
\begin{align*}
(W')^+ & \rightarrow t^+ \nu_\tau \\
(\bar{t}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) & : \delta B_\tau = 1.8 \times 10^{-5} \bar{C}_{VL} + 2.0 \times 10^{-5} (\bar{C}_{VL})^2 \\
(\bar{t}P_{L/R} b)(\bar{\tau}P_L \nu_\tau) & : \delta B_\tau = 5.1 \times 10^{-6} \left[ (\bar{C}_{SL})^2 + (\bar{C}_{SR})^2 \right]
\end{align*}
\]
USE KINEMATICS
What is the difference between SM and BSM top decay?
What is the difference between SM and BSM top decay?

SM is effectively two body, b-quark is mono-chromatic in top rest frame.

\[ E^*_{b} = \frac{m_t^2 - m_W^2}{2m_t} \]
USE KINEMATICS

What happens in lab frame?
What happens in lab frame? Agashe, Franceschini, Kim, 1209.0772.

Peak is still at

$$E_b^* = \frac{m_t^2 - m_W^2}{2m_t}$$
What happens in lab frame?  

\[ E_b^* = \frac{m_t^2 - m_W^2}{2m_t} \]

Can use this to measure \( m_t \).

Measurement of the top-quark mass from the b jet energy spectrum

The CMS Collaboration

Abstract

The top-quark mass is measured using the peak position of the energy distribution of b jets produced from top-quark decays. The analysis is based on a recent theoretical proposal. The measurement is carried out selecting \( t\bar{t} \) events with one electron and one muon in the final state in proton-proton collision data at \( \sqrt{s} = 8 \) TeV, corresponding to an integrated luminosity of 19.7 \( fb^{-1} \). The fitted peak position of the observed energy distribution is calibrated using simulated events and translated to a top-quark mass measurement using relativistic kinematics, with the result \( m_t = 172.29 \pm 1.17 \) (stat.) \( \pm 2.66 \) (syst.) GeV.

CMS PAS TOP-15-002.
Take ratios of distributions.

\[ M_V = 200 \text{ GeV} \]
\[ g_{\tau g_{tb}} = 5 \]
\[ \delta B_\tau = 4 \% \]
\[ M_V = 333 \text{ GeV} \]
\[ g_{\tau g_{tb}} = 4 \]
\[ \delta B_\tau = 0.3 \% \]
\[ M_H = 333 \text{ GeV} \]
\[ y_\tau y_{tb}^L = -2.6 \]
\[ y_\tau y_{tb}^R = 3.1 \]
\[ \delta B_\tau = 0.1 \% \]
MORE REALISTIC STUDY

Where do we get a “denominator” sample?
MORE REALISTIC STUDY

Where do we get a “denominator” sample?

Assume new physics only couples to third generation (events with $\tau$).

Use $\mu/e$ as control sample (avoid same flavour to reduce Z background).
Put minimal cuts for realistic sample:

- 2 b-jets $p_T > 20$ GeV
- Lepton $p_T > 20$ GeV
- $\tau_h$ with $p_T > 30$ GeV

Get blue points, SM control sample appears very different from signal sample! Why?
$\tau^- \rightarrow \nu_\tau + h^- + \ldots$
$\tau^- \rightarrow \nu_\tau + h^- + \ldots$

Measured $\tau_h p_T$ is not the same as actual $\tau p_T$.

$\tau_h p_T$ is weakly correlated with b-jet energy.

Putting $p_T$ cut on $\tau_h$ sculpts b-jet energy distribution changing it relative to control sample.
Take $\mu/e$ event and replace one lepton with a $\tau$ in simulation, $\ell_h$.

Decay $\tau$ and apply same cuts as signal sample.

Now get red points, have a sensible control sample.
SM vs. NP, no backgrounds

\[ \frac{n[l\nu2j\bar{b}]}{n[l\nu2j\bar{b}]} \]

\[ E_b \text{ [GeV]} \]

- \( M_V = 200 \text{ GeV} \)
- \( g_\tau g_{tb} = 5 \)
- \( \delta B_\tau = 4 \% \)

- \( M_V = 333 \text{ GeV} \)
- \( g_\tau g_{tb} = 4 \)
- \( \delta B_\tau = 0.1 \% \)

Errors due to MC statistics corresponding to \( \sim 300 \text{ fb}^{-1} \).
Signal region is 2b, 1 lepton, 1 (hadronic) $\tau$.

What are the backgrounds?
Signal region is 2b, 1 lepton, 1 (hadronic) $\tau$.

What are the backgrounds?

- Semi-leptonic top with jet faking tau (large).
Signal region is 2b, 1 lepton, 1 (hadronic) $\tau$.

What are the backgrounds?

- Semi-leptonic top with jet faking tau (large).
- $Zb\bar{b}$, $Z \rightarrow \tau_h \tau_\ell$ (non-trivial shape).
STRATEGIES

Need fairly pure signal sample.

Combine three strategies to mitigate background.

1. Veto extra jets $p_T > 20$ GeV.

Can be applied equally to signal and control.
STRATEGIES

Need fairly pure signal sample.

Combine three strategies to mitigate background.

2. Use 1-prong $\tau$.

Tagging rate 70% and fake rate of 5%.

Modern taggers can probably do much better.

Majority of events in signal region are now signal.

Backgrounds are still important, have non-trivial shape.
Second control region which has same spectrum as semi-leptonic background.

- 2 b-jets $p_T > 20$ GeV
- Lepton $p_T > 20$ GeV
- 1 jet $p_T > 30$ GeV
- Veto $\tau_h$ and extra jets

Works well at low energy. High energy?
MORE CONTROL SAMPLES

Third control region which has same spectrum as Zbb.

- \( Z \rightarrow \mu\mu \) and replace both with \( \tau \).

- Apply same cuts as before.

Works well.
Mix together three control samples in same proportion as signal region.

\[
\frac{n[\ell \tau_h 2j_b](E_b)}{n[\ell'_h \ell 2j_b](E_b) + w_{j \rightarrow \tau_h} n[\ell j 2j_b](E_b) + w_{Z \rightarrow \ell \tau_h} n[(Z \rightarrow \ell_h \ell_h) 2j_b](E_b)}
\]

\[w_{j \rightarrow \tau_h} \approx 0.42\]

\[w_{Z \rightarrow \ell \tau_h} \approx 0.03\]

Determine \(w\) from Monte Carlo.
SM vs. NP, with backgrounds

$E_b$ [GeV]

$\frac{n[1\ell n2\ell b]}{n[1\ell h^*2\ell b]}$

- **SM**
- $M_Y = 333$ GeV
- $M_Y = 200$ GeV

Results Plot
Looks very similar to plot without backgrounds.

Can exclude green NP at \(~7\sigma\).

No sensitivity to red NP.
This is a first pass study showing feasibility.

Only generated MC for 300 fb$^{-1}$. LHC will eventually have much more.

Used simplistic $\tau$ tagging procedure, probably can be improved with smart experimentalists/machines.
WORK IN PROGRESS
(tγμP_Lb)(âγµP_Lν_ℓ)(tP_Lν_ℓ)(âP_Lb)

ℓ = e, µ  there are essentially no direct limits.

Two-heavy-two-lepton (8 + 3 CPV d.o.f. ×3 lepton flavours)

<table>
<thead>
<tr>
<th>Operator</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>3(ℓ)</td>
<td>C_ℓq</td>
</tr>
<tr>
<td>c_Qt(ℓ)</td>
<td>C_{1q}</td>
</tr>
<tr>
<td>c_{Q1}(ℓ)</td>
<td>C_{1q} - C_{3q}</td>
</tr>
<tr>
<td>c_{Q2}(ℓ)</td>
<td>C_{eq}</td>
</tr>
<tr>
<td>c_{Q3}(ℓ)</td>
<td>C_{1u}</td>
</tr>
<tr>
<td>c_{ct}(ℓ)</td>
<td>C_{cu}</td>
</tr>
<tr>
<td>S<a href="%E2%84%93">I</a></td>
<td>Re{C_{lequ}^{1(ℓ33)}}</td>
</tr>
<tr>
<td>T<a href="%E2%84%93">I</a></td>
<td>Re{C_{lequ}^{3(ℓ33)}}</td>
</tr>
<tr>
<td>C_b<a href="%E2%84%93">I</a></td>
<td>Re{C_{ledq}^{(ℓ33)}}</td>
</tr>
</tbody>
</table>

Aguilar Saavedra et. al, 1802.07237. See also Buckley et. al. 1506.08845, Jung and Straub 1801.01112, Greljo and Marzocca, 1704.09015.
OTHER EFT OPERATORS

\[(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell)\] \[(\bar{t}P_L \nu_\ell)(\bar{\ell}P_L b)\]

\[\ell = e, \mu\] , how can we probe them?
\[(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) \quad (\bar{t}P_L \nu_\ell)(\bar{\ell}P_L b)\]

\(\ell = e, \mu\), how can we probe them?

- Flavour physics (assuming MFV)
(\bar{t}\gamma_\mu P_L b)(\ell\gamma^\mu P_L \nu_\ell) \quad (\bar{t}P_L \nu_\ell)(\ell P_L b)

\ell = e, \mu \quad \text{, how can we probe them?}

- Flavour physics (assuming MFV)
- Ratios of distributions
(\bar{t}\gamma_\mu P_L b)(\ell\gamma_\mu P_L \nu_\ell)

(\bar{t}P_L \nu_\ell)(\ell P_L b)

\ell = e, \mu \quad \text{, how can we probe them?}

- Flavour physics (assuming MFV)
- Ratios of distributions
- Top + W production
(\bar{t}\gamma_\mu P_L b)(\ell\gamma_\mu P_L \nu_\ell) \quad (\bar{t}P_L \nu_\ell)(\ell P_L b)

\ell = e, \mu \ , \text{how can we probe them?}

- Flavour physics (assuming MFV)
- Ratios of distributions
- Top + W production
- ???
(\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell) \quad (\bar{t}P_L \nu_\ell)(\bar{\ell} P_L b)

\ell = e, \mu \text{, how can we probe them?}

- Flavour physics (assuming MFV)
- Ratios of distributions
- Top + W production
- ???
SHOULD WE CARE

\((\bar{t}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell)\) \hspace{1cm} (\bar{t}P_L \nu_\ell)(\bar{\ell}P_L b)

\(\ell = e, \mu\), why should we care?
SHOULD WE CARE

$$(\bar{t}\gamma_{\mu}P_Lb)(\bar{\ell}\gamma^{\mu}P_L\nu_{\ell})$$

$$(\bar{t}P_L\nu_{\ell})(\bar{\ell}P_Lb)$$

$\ell = e, \mu$, why should we care?

- General probes of SMEFT
SHOULD WE CARE

$$(\bar{t} \gamma_\mu P_L b)(\bar{\ell} \gamma^\mu P_L \nu_\ell) \quad (\bar{t} P_L \nu_\ell)(\bar{\ell} P_L b)$$

$\ell = e, \mu$, why should we care?

- General probes of SMEFT
- Does this somehow relate to anomalies?
SHOULD WE CARE

\[(\bar{t}\gamma_\mu P_L b)(\ell\gamma^\mu P_L \nu_\ell)\]  
\[(\bar{t}P_L \nu_\ell)(\ell P_L b)\]

\[\ell = e, \mu, \text{ why should we care?}\]

- General probes of SMEFT
- Does this somehow relate to anomalies?
- ???
Measurement of differential cross-sections of a single top quark produced in association with a $W$ boson at $\sqrt{s} = 13$ TeV with ATLAS

The ATLAS Collaboration

1712.01602

Figure 6: Normalised differential cross-sections unfolded from data, compared with selected MC models, with respect to $m_{T(\ell\nu\nu\ell)}$ and $m(\ell b)$. Data points are placed at the horizontal centre of each bin. See Section 1 for a description of the observables plotted.
Measurement of differential cross-sections of a single top quark produced in association with a $W$ boson at $\sqrt{s} = 13$ TeV with ATLAS

The ATLAS Collaboration

1712.01602

Normalised differential cross-sections unfolded from data, compared with selected MC models, with respect to $m(t\bar{t}+b)$ and $m(t\bar{b})$. Data points are placed at the horizontal centre of each bin. See Section 1 for a description of the observables plotted.
SINGLE TOP MEASUREMENT

Scalar operator, GeV^{-2} units.

Vector operator, GeV^{-2} units.

Get constraints from last bin.
Can bound scale at 430 (310) GeV for scalar (vector) operator.

Does better than total x-section measurement.

Probably not in regime of validity of EFT.
UV COMPLETIONS

Leptoquark

Cross section

$W'$

$m_T$ distribution
PROJECTIONS

Leptoquark

W'

Current bounds

Pessimistic

Optimistic
Can get EFT bounds at 980 (710) GeV for scalar (vector) operator.

Depends on how uncertainties are scaled to higher luminosities. Suggestions?

Could be other interesting variables to look at...
Lepton flavour universality is much less well established in top than in gauge sector.

Enormous top sample at LHC (and future hadron collider?) is an opportunity to do better, current measurements nearly systematics limited.

Ratios of distributions could provide very stringent tests of new physics models with sensitivity of ~few%.
NUMBERS

Table II: Eiciencies and

<table>
<thead>
<tr>
<th>Process</th>
<th>$N_{MC}$</th>
<th>$\sigma$ (pb)</th>
<th>$\epsilon_{inc}$ (%)</th>
<th>$\epsilon_{ex}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t} \to b\bar{b}\tau\ell\ell'$</td>
<td>6.3M</td>
<td>84.2</td>
<td>6.7</td>
<td>1.9</td>
</tr>
<tr>
<td>$t\bar{t} \to b\bar{b}\ell\nu2j$</td>
<td>40M</td>
<td>416</td>
<td>1.6</td>
<td>0.046</td>
</tr>
<tr>
<td>$Z(\to \tau\tau)b\bar{b}$</td>
<td>5.4M</td>
<td>4.79</td>
<td>1.2</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Table I: The production cross section, number of generated MC events, and the acceptance rates

<table>
<thead>
<tr>
<th>Process</th>
<th>$N_{MC}$</th>
<th>$\epsilon_{inc}$ (%)</th>
<th>$\epsilon_{ex}$ (%)</th>
<th>$w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR [$\ell_\ell \ell' 2j_b$]</td>
<td>6.6M</td>
<td>7.4</td>
<td>2.1</td>
<td>0.908</td>
</tr>
<tr>
<td>$t\bar{t} \to b\bar{b}\ell\nu2j$</td>
<td>7.6M</td>
<td>0.33</td>
<td>0.087</td>
<td>0.092</td>
</tr>
<tr>
<td>CR [$\ell_j 2j_b$]</td>
<td>40M</td>
<td>28</td>
<td>4.2</td>
<td>0.42</td>
</tr>
<tr>
<td>CR [$Z(\to \ell_\ell \ell_\ell') 2j_b$]</td>
<td>5M</td>
<td>1.2</td>
<td>0.32</td>
<td>0.033</td>
</tr>
</tbody>
</table>

NP vs. SM

<table>
<thead>
<tr>
<th>Model</th>
<th>$\epsilon_{inc}$ (%)</th>
<th>$\epsilon_{ex}$ (%)</th>
<th>$\chi^2$</th>
<th>$\chi_3^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM (unmatched)</td>
<td>6.82</td>
<td>1.71</td>
<td>41.3</td>
<td>4.1</td>
</tr>
<tr>
<td>$m_V = 333$ GeV</td>
<td>6.75</td>
<td>1.69</td>
<td>41.0</td>
<td>4.1</td>
</tr>
<tr>
<td>$m_V = 200$ GeV</td>
<td>7.69</td>
<td>1.93</td>
<td>147</td>
<td>61.6</td>
</tr>
</tbody>
</table>