$m_\nu \Rightarrow$ (charged) lepton flavour change happens, and the LHC exists ...so look for

Lepton Flavour Violation @ LHC?

Sacha Davidson , P Gambino, G Grenier, S Lacroix , ML Mangano, S Perries, V Sordini, P Verdier
IPN de Lyon/CNRS

(150y.xxxx,1207.4894,1001.0434, 1211.1248,1008.0280)

1. LHC is a discovery machine: look for LFV decays of theoretically motivated new particles (sleptons, N_R,...)

2. SM external legs $exist \Rightarrow$ look for LFV interactions of SM particles?
   $=$ stamping group of low energy precision expts (MEG,...)
   $\Rightarrow$ at LHC with a $heavy$ SM leg, so complements lower energy searches

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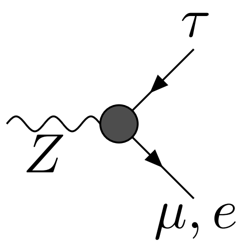

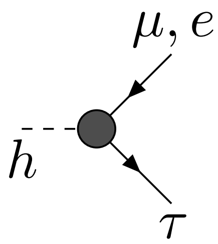

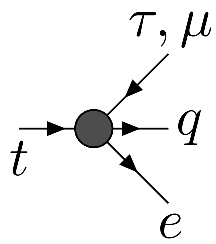

Parametrise LFV vertices as contact interactions
Existing bounds?
LHC sensitivity?

What about the Z?

LEP?
LHC?
low energy?

LHC has more Zs than LEP

1. 17×10^6 Zs at LEP1
   $BR(Z \to e^\pm \mu^\mp) < 1.7 \times 10^{-6}$, $BR(Z \to e^\pm \tau^\mp) < 9.8 \times 10^{-6}$, $BR(Z \to \mu^\pm \tau^\mp) < 1.2 \times 10^{-5}$

2. at LHC8, 5×10^8 Zs $\sim 25 \times$ LEP
   ATLAS 1408.5774: $BR(Z \to e^\mp \mu^\pm) < 7.5 \times 10^{-7}$ 95% C.L..

Low energy: the Z contributes too?

decades of rare decay/precision data?... $BR(\tau \to \mu\bar{\mu}\mu) < 2.1 \times 10^{-8}$

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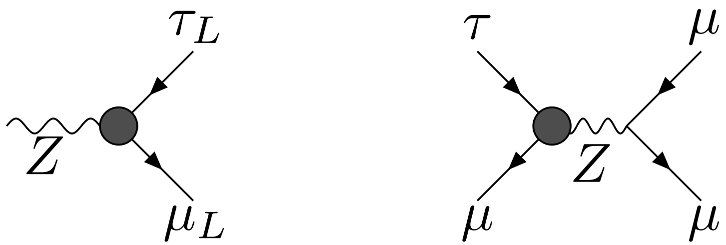


But gradient operators better constrained at high energy. Consider $(\partial^\alpha Z^\beta - \partial^\beta Z^\alpha = Z^{\alpha\beta})$

$$g_Z C \frac{1}{16\pi^2\Lambda^2} Z^{\alpha\beta}\overline{\mu}\gamma^\alpha\partial^\beta\tau \to g_Z C \frac{p_Z^2}{16\pi^2\Lambda^2}\overline{\mu}\gamma_\alpha Z^\alpha\tau$$

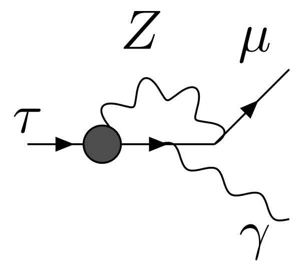
on the Z : vertex $= g_Z \frac{Cm_Z^2}{16\pi^2\Lambda^2}\overline{\mu}\not{Z}\tau$

in $\tau \to \mu\bar{\mu}\mu$:vertex $< g_Z \frac{Cm_\tau^2}{16\pi^2\Lambda^2}\overline{\mu}\not{Z}\tau$ (negligeable)

$\Rightarrow$ gradient operators negligeable in low energy *tree* processes

The gradient^2 $Z \to \tau^\pm \mu^\mp$ operators: are they important in loops?

and can I calculate that?



1. assume NP scale $\Lambda \gg m_Z$

2. assume NP generates only ∂^2 operator (no other LFV; not $\tau \to \mu\gamma$), so "interaction":

$$g_Z C_{\mu\tau} \frac{p_Z^2}{16\pi^2 \Lambda^2} \overline{\mu} \gamma_\alpha \tau Z^\alpha$$

3. in RG running between Λ and m_Z, $Z \to \tau^\pm \mu^\mp$ will mix to $\tau \to \mu\gamma$ operator (...estimate the coefficient of $1/\epsilon$ in dim reg...)

$$\widetilde{BR}(\tau \to \mu\gamma) \simeq \frac{3\alpha}{4\pi} \frac{g_Z^4}{G_F^2 \Lambda^4} \left(\frac{C_{\mu\tau} \log}{32\pi^2} \right)^2 \sim 4 \times 10^{-8} \frac{C_{\mu\tau}^2 v^4}{\Lambda^4}$$

$\Rightarrow$ no constraint on $C_{\mu\tau}$ from $\widetilde{BR}(\tau \to \ell\gamma) \lesssim 2 \times 10^{-7}$

but $\mu \to e\gamma$ constrains $C_{e\mu}$: $BR(Z \to e^\pm \mu^\mp) \lesssim 10^{-10}$.

$(BR(\mu \to e\gamma) < 5.7 \times 10^{-13})$

Am I allowed gradient operators?

1. Reduce operator basis using Eqns of Motion, eg for hypercharge boson B^μ:

$$\partial_\mu B^{\mu\nu} - \tfrac{g'}{2}(H^\dagger D^\nu H - [D^\nu H]^\dagger H) - g' \textstyle\sum_f Q_Y^f \overline{f}\gamma^\nu f = 0$$
$$p^2 Z^\nu \ - \qquad m_Z^2 Z^\nu \qquad\qquad \simeq g' J^\nu$$

so, eg, if four-fermion operators are in basis, include either

$$p^2 \overline{\tau} \not{Z} \mu \quad \text{or} \quad m_Z^2 \overline{\tau} \not{Z} \mu$$

other is redundant.

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$$p^2 \overline{\tau} \not{Z}\, \mu \quad \text{or} \quad m_Z^2 \overline{\tau} \not{Z}\, \mu$$
other is redundant.

2. same answer for either basis?
four fermion and ∂^2 Z operators: $(\overline{\tau}\gamma^\alpha \mu)(\overline{\mu}\gamma^\alpha \mu)$, $p_Z^2 \overline{\tau} \not{Z}\, \mu$
   - on the Z, LFV Z coupling contributes, 4-f operator not.
   - in $\tau \to \mu\bar{\mu}\mu$, only 4-f operator contributes

   four fermion and m_Z^2 Z operator: $(\overline{\tau}\gamma^\alpha \mu)(\overline{\mu}\gamma^\alpha \mu)$, $m_Z^2 \overline{\tau} \not{Z}\, \mu$
   - on the Z, LFV Z coupling contributes, 4-f operator not.
   - in $\tau \to \mu\bar{\mu}\mu$, both operators contribute in the amplitude, cancellations possible.

     (formally: below m_Z, must "match out" Z so the coeff of 4 ferm op changes)

Choose derivative operators to parametrise Z contact interactions, because these contribute at LHC (where Z is propagating particle), but not at low energy:

Summary about the Z: LHC has interesting sensitivity to $Z \to \mu^{\pm}\tau^{\mp}$, $Z \to e^{\pm}\tau^{\mp}$

$$\boldsymbol{t \to e^{\pm}\mu^{\mp}q}$$

$$\boldsymbol{(t \to \tau^{\pm}\ell^{\mp}q)}$$

Low Energy?

LHC?

(work in progress)

$SU(3) \times U(1)$ invar operators mediating LFV top decays

$$
\begin{aligned}
\mathcal{O}^{LL} &= (\overline{e}_i \gamma^\alpha P_L e_j)(\overline{u}_r \gamma^\alpha P_L t) \\
\mathcal{O}^{LR} &= (\overline{e}_i \gamma^\alpha P_L e_j)(\overline{u}_r \gamma^\alpha P_R t) \\
\mathcal{O}^{RL} &= (\overline{e}_i \gamma^\alpha P_R e_j)(\overline{u}_r \gamma^\alpha P_L t) \\
\mathcal{O}^{RR} &= (\overline{e}_i \gamma^\alpha P_R e_j)(\overline{u}_r \gamma^\alpha P_R t) \\
\mathcal{O}^{S+P,R} &= (\overline{e}_i P_R e_j)(\overline{u}_r P_R t) \\
\mathcal{O}^{S+P,L} &= (\overline{e}_i P_L e_j)(\overline{u}_r P_L t) \\
\mathcal{O}^{S-P,R} &= (\overline{e}_i P_L e_j)(\overline{u}_r P_R t) \\
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\mathcal{O}^{LQ,R} &= (\overline{u}_r P_R e_j)(\overline{e}_i P_R t) \\
\mathcal{O}^{LQ,L} &= (\overline{u}_r P_L e_j)(\overline{e}_j P_L u_t)
\end{aligned}
$$

e, u Dirac spinors. i, j are unequal lepton flavour indices, $r \in \{u, c\}$.

$SU(3) \times U(1)$ operators are almost S-matrix elements $\Leftrightarrow$ physical. Can inpose SU(2) later.

attribute coefficient $\boldsymbol{\epsilon}^{ijrt} 2\sqrt{2} G_F = \epsilon^{ijrt}/m_t^2$ to each operator (remember ϵ, it reappears...)

BRs for LFV top decays are small...

Standard model top decay is 2-body, enhanced by equivalence thm :

$$\Gamma(t \to bW) = \frac{g^2 m_t^3}{64\pi m_W^2} \simeq \frac{y_t^2 m_t}{32\pi}$$

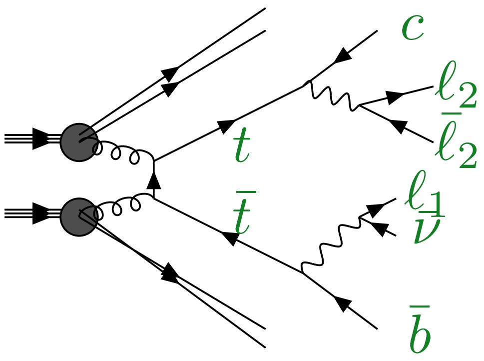
Three body decay due to LFV operators phase-space suppressed:

$$\Gamma(t \to \ell_i^+ \ell_j^- + q) = \frac{m_t}{(48\pi^2)(32\pi)} \left(|\epsilon_{V\pm A}^{ijrt}|^2 + \frac{1}{4} |\epsilon_{S\pm P}^{ijrt}|^2 + \ldots \right)$$

$$\Rightarrow \quad BR(t \to \ell_i^+ \ell_j^- + q) \le \frac{|\epsilon|^2}{48\pi^2} \lesssim 2 \times 10^{-3} |\epsilon|^2$$

LHC sensitivity to LFV top decays?

CMS and ATLAS search for $t \to Zc, Zu$:



Find $BR(t \to Z{+}jet) \lesssim 5{\times}10^{-4}$ (assuming $Z \to e\bar{e}, \mu\bar{\mu}$, $BR(Z \to \ell^+\ell^-) \sim .036$)).
Equivalently $BR(t \to \ell^+\ell^- + jet) \lesssim 4 \times 10^{-5}$.

?? $\Rightarrow$ sensitive to $BR(t \to e\overline{\mu} + jet) \lesssim$ few $\times 10^{-6}$??

($t \to \tau^{\pm}\ell^{\mp} + q$ more difficult)

$\Rightarrow$ is $\epsilon^{e\mu qt} \gtrsim .03$ allowed by existing data?

Existing bounds on tLFV operators (better/worse than .03?)

1. HERA ($\boldsymbol{e^+p}$ @ $\boldsymbol{\sqrt{s} = 320}$ **GeV**) looked for γut vertex:

$$\sigma(e^+p \to e^+t[\to \mu^+\nu b] + X) < .30 \text{ pb}$$

if assume this implies:

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then can use to constrain $(\overline{\mu}\Gamma e)(\bar{t}\Gamma u)$ contact interactions:

$$|\epsilon^{\mu etu}| \lesssim .3 \to .1$$

(NB: not constrain tc operators)

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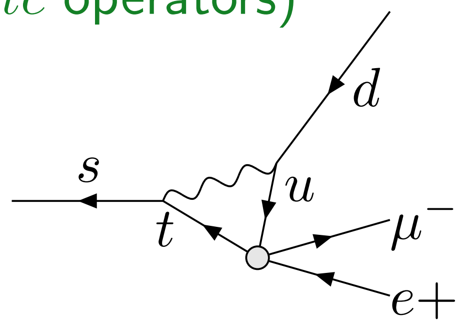
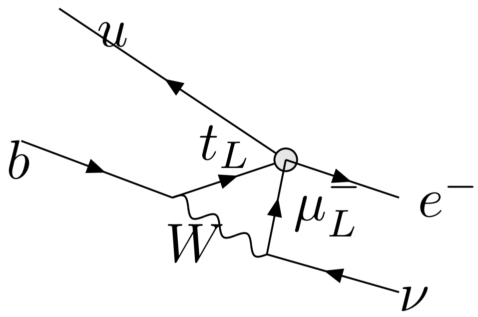
2. loops?





$K_L \to e\bar{\mu} \Rightarrow |\epsilon| < .01$ for $(\overline{e}\gamma^\rho P_X \mu)(\overline{u}\gamma_\rho P_L t)$

$\Rightarrow |\epsilon| < .1$ for $(\overline{e}\gamma^\rho P_X \mu)(\overline{c}\gamma_\rho P_L t)$

$\Rightarrow |\epsilon| < .3$ for $(\overline{e} P_X \mu)(\overline{c} P_R t)$

no bound on $(\overline{e}\gamma^\rho P_X \mu)(\overline{q}\gamma_\rho P_R t), (\overline{e} P_L \mu)(\overline{q} P_L t)$

$B^- \to e\bar{\nu} \Rightarrow |\epsilon| < .02$ for $(\overline{e} P_L \mu)(\overline{q} P_L t)$

$\Rightarrow$ many LFV top operators $\epsilon 2\sqrt{2} G_F (\overline{e}\Gamma\mu)(\overline{u}\Gamma t)$ can have coefficient $\epsilon \sim 1$

Summary

The LHC could $produce$ New particles with LFV decays.

If New particles are beyond the mass reach of the LHC, they could nonetheless have effects parametrised by contact interactions, involving kinematically accessible particles. The LHC is the only place where the t, h and Z are kinematically accessible, so it (?is the only place which ?) can probe their LFV contact interactions.

ATLAS : $BR(Z \to e\bar{\mu}) \leq 7.5 \times 10^{-7}$

CMS : $BR(h \to \tau\bar{\mu}) \leq 1.57 \times 10^{-2}$ (with $\sim 2\sigma$ excess:$BR \simeq .89 \times 10^{-2}$)

to do: the top?

Unlikely to see $h \to e^{\pm}\mu^{\mp}$, $Z \to e^{\pm}\mu^{\mp}$, due to $\mu \to e\gamma$ bound.
But maybe LFV top decays: $t \to e^{\pm}\mu^{\mp}+$ accessible to LHC?

Backup

Derivative Operators, Eqns of Motion and the Operator Basis

equations of motion (EoM) for the hypercharge boson ($B \simeq Z$)

$$\partial_\mu B^{\mu\nu} - \frac{g'}{2}(H^\dagger D^\nu H - [D^\nu H]^\dagger H) - g' \sum_f Q_Y^f \overline{f} \gamma^\nu f = 0$$

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Simma EJPC

Derivative Operators, Eqns of Motion and the Operator Basis

On-shell S-matrix elements induced by an operator containing EoM $vanish$. This is used to reduce the operator basis.

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so the operator:

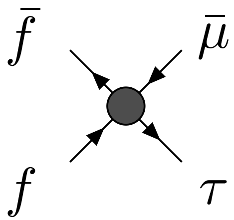
$$\mathcal{O} = \overline{\tau} \gamma_\nu \mu (\partial_\mu B^{\mu\nu} - i g'^2 H^\dagger H B^\nu - g' \sum_f Q_Y^f \overline{f} \gamma^\nu f)$$

induces vertices

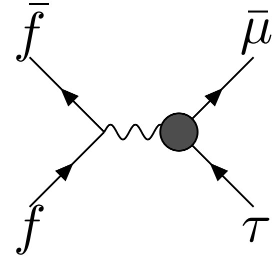
$$\begin{array}{ll} \overline{\tau}\gamma_\nu \mu \overline{f} \gamma^\nu f \ , & \propto Q_Y^f \\ B^\nu \overline{\tau} \gamma_\nu \mu, & \propto p_B^2 - m_B^2 \ {\scriptstyle (m_B = g' \langle H \rangle).} \end{array}$$

These vertices cancel in on-shell S-matrix elements :

$$\langle \bar{\mu} \tau | \mathcal{O} | f \bar{f} \rangle = \quad Q_Y^f$$



$$- \qquad Q_Y^f \frac{p^2 - m_B^2}{p^2 - m_B^2}$$



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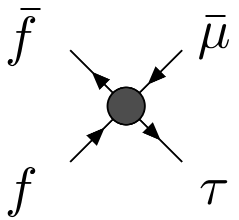
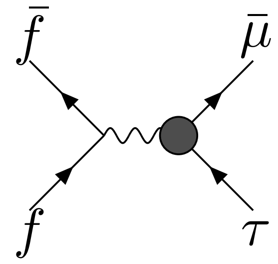


$$- \qquad Q_Y^f \frac{p^2 - m_B^2}{p^2 - m_B^2}$$



so only keep one dim 6 $Z \overline{\tau} \mu$ operator: $H D^\nu H$, or $\partial^2 Z^\nu \times \overline{\tau} \gamma_\nu \mu$