$m_\nu \Rightarrow$ (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

(1412.xxxx,1207.4894,1001.0434, 1211.1248,1008.0280)

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2. SM external legs *exist* $\Rightarrow$ look for LFV interactions of SM particles?
with a *heavy* SM leg, so LHC complements lower energy searches

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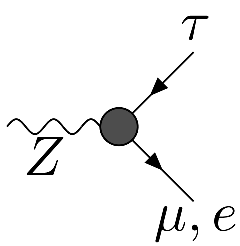
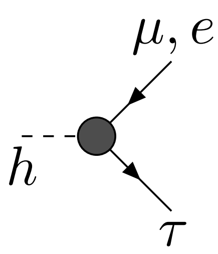
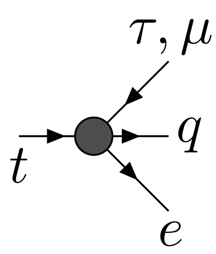
2. SM external legs $exist$ $\Rightarrow$ LHC look for LFV interactions of SM particles? with a $heavy$ leg, to complement lower energy searches







Parametrise LFV vertices as contact interactions
Bounds from low energy and LEP?
LHC sensitivity?

What about the Z?

LEP?
LHC?
low energy?

Dimension six operators for LFV Z decays

Mass dimension of Z and two lepton external legs $= 4$
$\Rightarrow Z \to \tau^{\pm}\mu^{\mp}$ operators contains two Higgs and/or Derivatives
Three options among gauge invariant operators at dimension 6:

$$\mathcal{O}(\partial^2) \quad : \quad \overline{\mu}\gamma_\beta D_\alpha \tau B^{\alpha\beta} \quad , \ldots$$

$$\mathcal{O}(H^2) \quad : \quad [H^\dagger D_\alpha H]\overline{\mu}\gamma^\alpha \tau \quad , \ldots$$

$$\mathcal{O}(yH\partial) \text{ dipole} \quad : \quad \overline{\ell}_\mu H \sigma_{\beta\alpha} \tau B^{\alpha\beta} \quad , \ldots$$

(where $B^{\alpha\beta} = \partial^\alpha B^\beta - \partial^\beta B^\alpha$, B hypercharge gauge boson).

Dimension six operators for LFV Z decays

Need two powers of a vev/momentum in operator.
Three options among gauge invariant operators at dimension 6.
Suppose operator coefficients such that:

Rossi+Brignole

$$\ldots,\quad \overline{\mu}\gamma_\beta D_\alpha \tau B^{\alpha\beta} \quad\to\quad g_Z C\frac{p_Z^2}{16\pi^2\Lambda^2}\overline{\mu}\gamma_\alpha\tau Z^\alpha$$

$$\ldots,\quad [H^\dagger D_\alpha H]\overline{\mu}\gamma^\alpha\tau \quad\to\quad g_Z A\frac{m_Z^2}{16\pi^2\Lambda^2}\overline{\mu}\gamma_\alpha Z^\alpha\tau$$

$$\ldots,\quad \overline{\ell}_\mu H\sigma_{\beta\alpha}\tau B^{\alpha\beta} \quad\to\quad g_Z D\frac{m_\tau}{16\pi^2\Lambda^2}[\overline{\mu}\sigma_{\alpha\beta}\tau]Z^{\alpha\beta}$$

NP of mass $\Lambda > m_Z$ in a loop, A, C, D dimless

LEP and the LHC

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

2. at LHC8, $\sigma(pp \to Z \to \mu\bar{\mu}) \sim$ nb, $\mathcal{L} \sim 20$ fb^{-1}, $BR(Z \to \mu\bar{\mu}) \simeq 0.0366$

$$\#Zs \simeq \frac{\sigma(pp \to Z \to \mu\bar{\mu}) \times \mathcal{L}}{BR(Z \to \mu\bar{\mu})} \sim 5 \times 10^7 Zs \sim 25 \times \text{ LEP}$$

ATLAS 1408.5774: $\boldsymbol{BR(Z \to e^\mp \mu^\pm) < 7.5 \times 10^{-7}}$ 95% C.L..

$\Rightarrow$ **LHC has more Zs than LEP, and better sensitivity**

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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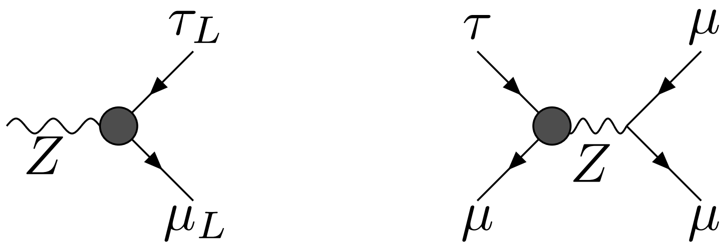


But gradient operators better constrained at high energy. Consider $(\partial^\alpha Z^\beta - \partial^\beta Z^\alpha = Z^{\alpha\beta})$

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

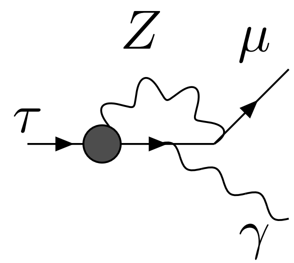
on the Z : vertex $= g_Z \frac{C m_Z^2}{16\pi^2\Lambda^2} \overline{\mu} \not{Z} \tau$

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

? But, am I allowed gradient operators? Yes, more later ...

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

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

Derivative Operators, Eqns of Motion and the Operator Basis

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

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

$$p^2 Z^\nu \; - \qquad m_Z^2 Z^\nu \qquad\qquad \simeq g' J^\nu$$

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.

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

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so the operator:

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

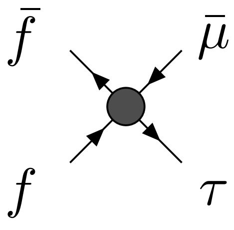
induces vertices

$$\overline{\tau}\gamma_\nu\mu\overline{f}\gamma^\nu f \ , \propto Q_Y^f$$

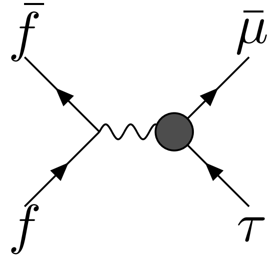
$$B^\nu \overline{\tau}\gamma_\nu \mu, \qquad \propto p_B^2 - m_B^2 \ (m_B = g'\langle H\rangle).$$

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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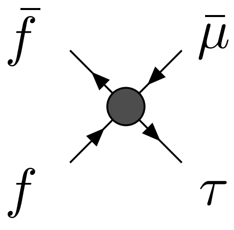
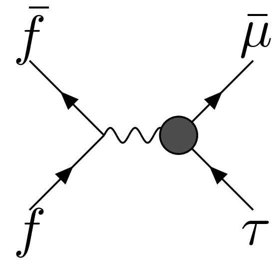


$$- \qquad Q_Y^f \frac{p^2 - m_B^2}{p^2 - m_B^2}$$



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

Getting the same constraints on NP in either basis?

1. four fermion operator and ∂^2 LFV Z operator:
   $(\overline{\tau}\gamma^\alpha\mu)(\overline{\mu}\gamma^\alpha\mu) \quad , \quad p_Z^2\overline{\tau}\not{Z}\,\mu$

   - on the Z, LFV Z coupling contributes, 4-f operator not.
   - in $\tau \to \mu\bar{\mu}\mu$, only 4-f operator contributes

2. four fermion operator and penguin$=H^\dagger D^\nu H$ LFV Z operator:
   $(\overline{\tau}\gamma^\alpha\mu)(\overline{\mu}\gamma^\alpha\mu) \quad , \quad m_Z^2\overline{\tau}\not{Z}\,\mu$

   - 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 $Z \to \mu^\pm \tau^\mp$, $Z \to e^\pm \tau^\mp$.

$$\boldsymbol{h \to \tau^\pm \ell^\mp}$$

low energy bounds

$h \to \tau \bar{\mu}$ selon CMS?

Operators and Models for LFV Higgs decays

LFV could appear in Higgs decays:

1. if have $Y_1 \bar{\ell} H \tau$, plus dim 6 operator $Y_2 H^\dagger H \bar{\ell} H \tau$

Giudice-Lebedev, Babu-Nandi

2. also two Higgs doublets of " type III" $=$ flavour changing couplings
   $+$ keep two neutral light scalars

...Davidson-Grenier

Aristizabal,Vicente

Low energy constraints

LFV could appear in Higgs decays:

1. due to effective dim 6 operator $H^\dagger H \bar{\ell} H \tau$ — Giudice-Lebedev, Babu-Nandi

2. also two Higgs doublets of " type III" $=$ flavour changing couplings ...
   $+$ keep two neutral light scalars — Aristizabal,Vicente

Diaz-Cruz,Toscana
Kanemura-Ota-Tsumura
Davidson-Grenier
...

allowed by low energy LFV searches:

Goudelis-Lebedev-Park
Harnik-Kopp-Zupan

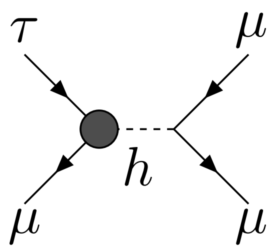
Blankenburg,Ellis,Isidori

- tree exchange of h : $\tau \to \eta\mu$, $\tau \to \mu\bar{\mu}\mu$
  : $y_{\tau\mu} \lesssim \mathcal{O}(1)$ ok

- loops : $\tau \to \mu\gamma$, EW precision, $b \to s\gamma$, etc
  : $y_{\tau\mu} \lesssim \mathcal{O}(y_\tau)$ ok

Tree level Higgs exchange (diff from Z! h is much narrower)

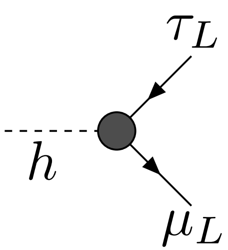
in low energy rare decays:



$$\frac{\Gamma(\tau \to 3\mu)}{\Gamma(\tau \to \mu\nu\bar{\nu})} \sim \frac{\frac{y_{\tau\mu}^2 y_\mu^2}{m_h^4}}{\frac{g^4}{m_W^4}} \sim \frac{y_{\tau\mu}^2 y_\mu^2}{g^4}$$

so feeble bounds on $y_{\tau\mu}$

on the *narrow* resonance ($\Gamma_h \sim 3y_b^2/16\pi$):



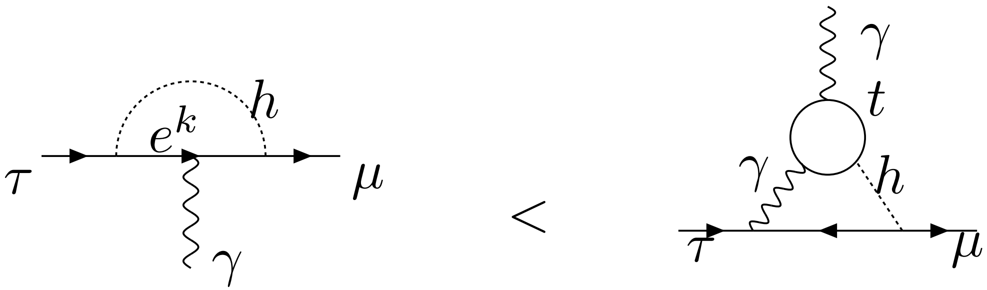
$$\frac{\Gamma(h \to \tau\mu)}{\Gamma(h \to b\bar{b})} \sim \frac{y_{\tau\mu}^2}{y_b^2}$$

right place to look for small couplings: $BR(h \to \tau\mu) \sim |y_{\tau\mu}|^2/y_b^2$

Bounds on LFV Higgs couplings from loops?

Recall perturbation theory expands in couplings and loops, and $m_\mu/m_t < 1/16\pi^2$

one-loop amplitudes $\propto (y_{LFV} y_\mu)/16\pi^2$ can be smaller than...



...two-loop amplitudes $\propto g^2(y_{LFV} y_t)/(16\pi^2)^2$

Most restrictive bound $y_{\tau\mu} \lesssim .1$ from 2-loop $\tau \to \mu\gamma$

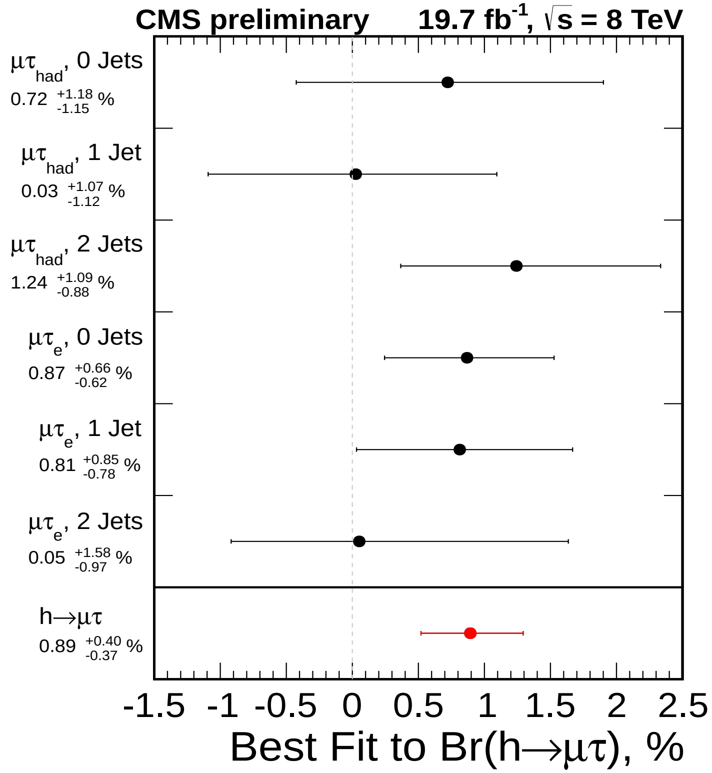
(model-dep; what else in loops?)

And not see $h \to e^\pm \mu^\mp$ at LHC because $BR(h \to e^\pm \mu^\mp) \lesssim 10^{-8}$ from $\mu \to e\gamma$...

CMS: $h \to \tau^\pm \mu^\mp$

$$BR(h \to \tau^\pm \mu^\mp) < 1.57\% \text{ (95\% C.L.)}$$
$$|y_{\tau\mu}| \leq 3.6 \times 10^{-3}$$

$$BR(h \to \tau^\pm \mu^\mp) = 0.89 \begin{matrix} +0.40 \\ -0.37 \end{matrix} \%(2.46\sigma)$$
$$|y_{\tau\mu}| \simeq 2.7 \times 10^{-3}$$
$$\sim \sqrt{y_\tau y_\mu} = 2.48 \times 10^{-3}$$



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

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

Low Energy?
LHC?

Contact interactions mediating LFV top decays

$$
\begin{aligned}
\mathcal{O}_{lq}^{(1)} &= (\bar{l}_i\gamma^\alpha l_j)(\overline{q}_r\gamma^\alpha q_t) \\
\mathcal{O}_{lq}^{(3)} &= (\bar{l}_i\gamma^\alpha \tau^a l_j)(\overline{q}_r\gamma^\alpha \tau^a q_t) \\
\mathcal{O}_{eq} &= (\overline{e}_i\gamma^\alpha e_j)(\overline{q}_r\gamma^\alpha q_t)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{O}_{lu} &= (\bar{l}_i\gamma^\alpha l_j)(\overline{u}_r\gamma^\alpha u_t) \\
\mathcal{O}_{eu} &= (\overline{e}_i\gamma^\alpha e_j)(\overline{u}_r\gamma^\alpha u_t) \\
\mathcal{O}_{lequ}^{(1)} &= (\bar{l}_i e_j)\epsilon(\overline{q}_r u_t) = -(\overline{\nu}_i e_j)(\overline{d}_r u_t) + (\overline{e}_i P_R e_j)(\overline{u}_r P_R u_t) \\
\mathcal{O}_{lequ}^{(3)} &= (\bar{l}_i\sigma^{\alpha\beta} e_j)(\overline{q}_r\sigma_{\alpha\beta} u_t)
\end{aligned}
$$

l, q are doublets, e, u are singlets
$i \neq j$ lepton flavour indices, $t =$ third generation quark index, $r =$ first or second generation quark index.

BRs for LFV top decays is small...

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

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

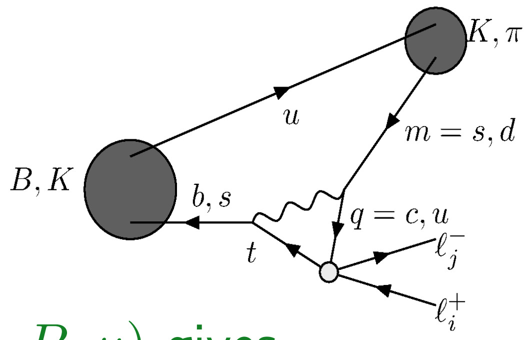
Three body decay, due to contact interaction $\frac{1}{\Lambda^2}(\bar{t}\gamma_\alpha P_R q)(\bar{\ell}_i \gamma_\alpha \ell_j)$
(guess from $\Gamma = G_F^2 m_\mu^5/(192\pi^3)$):

$$\Gamma(t \to \ell^+\ell^- + j)_{V\pm A} = \frac{m_t^5}{8 \times 192\pi^3 \Lambda^4}$$

So

$$BR(t \to \ell^+\ell^- + j) = \frac{m_t^4}{48\pi^2\Lambda^4} \lesssim 2 \times 10^{-3} \frac{m_t^4}{\Lambda^4}$$

Low energy: LFV B and K dec



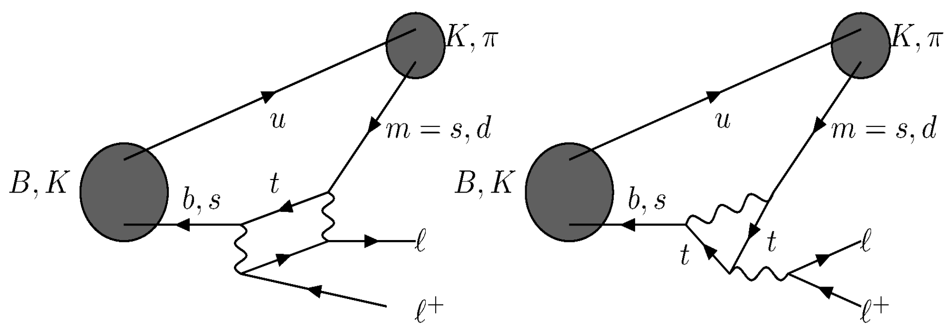
focus on t_R (because what t_L does, b_L does too...)

exchange a W between the quark legs of $\frac{1}{\Lambda^2}(\bar{c}\gamma^\alpha P_R t)(\bar{e}\gamma_\alpha P_L \mu)$ gives

$$\sim \frac{g^2 m_t m_c V_{ts} V_{cd}}{16\pi^2 \Lambda^2 (m_t^2 - m_W^2)} log \frac{m_t^2}{m_W^2} (\bar{d}\gamma^\alpha P_R s)(\bar{e}\gamma_\alpha P_L \mu)$$

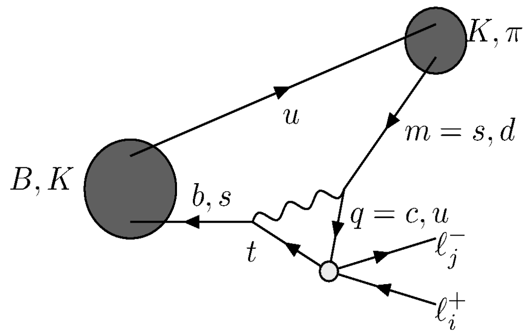
which contributes to $K^+ \to \pi^+ e^- \mu^+$.

compare to SM $K^+ \to \pi^+ \ell^- \ell^+$



$$\sim \frac{g^2}{32\pi^2 m_t^2} V_{ts}^* V_{td} (\bar{d}\gamma^\alpha P_R s)(\bar{\ell}\gamma_\alpha P_L \ell)$$

Low energy: LFV B and K dec



$B^+ \to K^+\ell^+\ell^-, e^+e^-, \mu^+\mu^-$	$4.5, 4.5, 5.5 \times 10^{-7}$
$K^+ \to \pi^+\mu^+\mu^-, e^+e^-$	$9.4, 3.0 \times 10^{-8}$
$B^+ \to \pi^+ e^\pm \mu^\mp$	$< 1.7 \times 10^{-7}$
$B^+ \to \pi^+ \ell^\pm \tau^\mp$	$< 7.2 \times 10^{-5}$
$B^+ \to K^+ e^\pm \mu^\mp$	$< 9.1 \times 10^{-8}$
$B^+ \to K^+ \ell^\pm \tau^\mp$	$< 3 - 4.8 \times 10^{-5}$
$K^+ \to \pi^+ e^- \mu^+$	$< 1.3 \times 10^{-11}$

constrain coefficient of LFV top operator by normalising with SM:

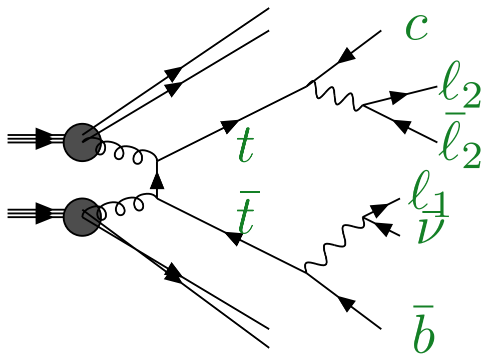
$$\frac{m_t^4}{\Lambda^4} \lesssim \frac{BR(K \to \pi e^+\mu^-)}{BR(K \to \pi \ell^+\ell^-)} \frac{m_t^2 |V_{td}|^2}{14.5 m_r^2 |V_{rd}|^2} \lesssim \begin{cases} 2 \times 10^{-4} & r = c \\ .12 & r = u \end{cases}$$

Also restrictive bounds from $K_L \to \mu\bar{e}$.

Summary: for one operator, $BR(t \to e\bar{\mu} + jet) \lesssim$ few $\times 10^{-4}$ (for other operators, $BR(t \to e\bar{\mu} + jet) \lesssim$ few $\times 10^{-7}$). $t \to \ell\bar{\tau} + jet$ unconstrained by B decays.

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 $BR(t \to \ell^+\ell^- + jet) \lesssim 4 \times 10^{-6}$.

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

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?