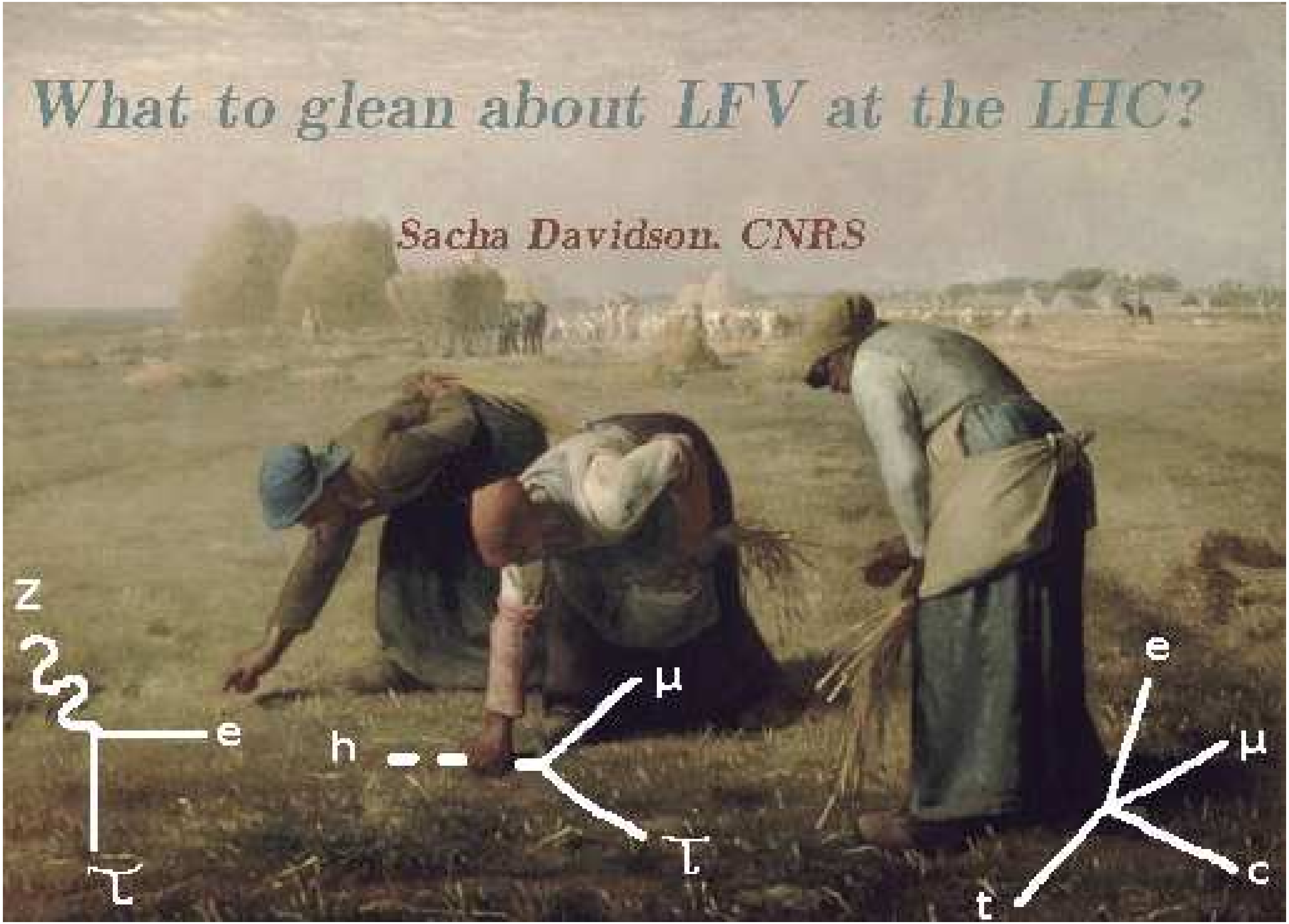
What to glean about LFV at the LHC?

Sacha Davidson, CNRS



Higgs and (Lepton) Flavour

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

1. Lepton Flavour Violation at CMS+ATLAS ("LHC")
   - complementary to low-energy : heavy external legs = t, h and Z

2. LFV decays of h (narrow) vs Z
   - LHC searches
   - Compared to tree processes at low energy
   - Parametrisations + models: does one expect LFV in Higgs decays?
   - Loop processes at low energy (perturbing in many parameters)

3. What about the top?
   - $t \to hq$
   - $t \to q\mu^{\pm}e^{\mp}$

$m_\nu, U_{\ell\nu} \Rightarrow$ (charged) lepton flavour change happens, and the LHC exists, so

Is it interesting to look for Lepton Flavour Violn at the LHC?

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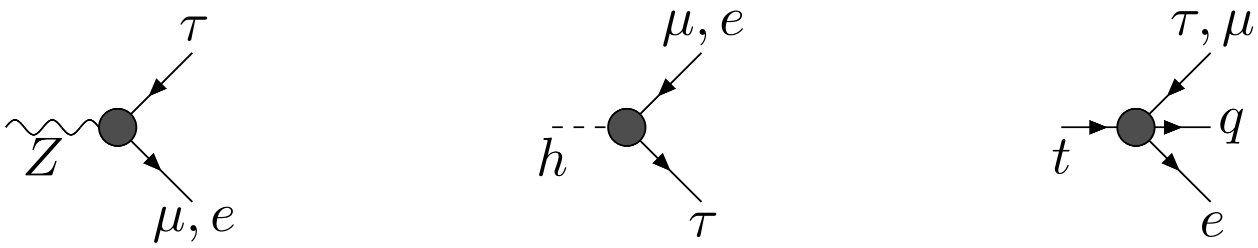
2. SM external legs *exist* $\Rightarrow$ look for LFV interactions of SM particles?
   = stamping group of low energy precision expts (MEG,...)
   $\Rightarrow$ maybe at LHC with a *heavy* leg, is complementary to lower energy searches?



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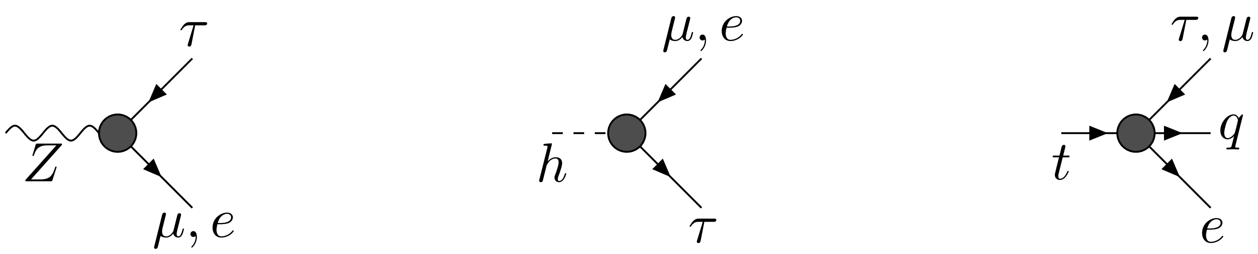

3. Parametrise LFV vertices as contact interactions
   NB: in EFT, only directly probe of effective cplings of heavy particles when they are on-shell (in loops, there are other contributions)
   $\Rightarrow$ Compare sensitivity of LHC and low energy processes ($\mu \to e\gamma$, $\tau \to \ell\gamma$, etc)

Yes! for $Z, h \to \tau^\pm \ell^\mp$ and $t \to q\mu^\pm e^\mp$.

LHC searches for LFV h and Z decays

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

at LHC8, 4×10^5 h s

CMS 1502.07400 : $BR(h \to \tau^\pm_{had,e}\mu^\mp) < 1.51\%$
$\simeq 0.84\%$ (2.4σ)

ATLAS @ EPS : $BR(h \to \tau^\pm_{had}\mu^\mp) < 1.85\%$
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introduce effective cpling $h(Y_{\tau\mu}\overline{\tau_L}\mu_R + Y_{\mu\tau}\overline{\mu_L}\tau_R + h.c.)$

NB: in SM (renormalisable, one Higgs doublet) there are no flavour-changing couplings

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Cheng-Sher ansatz : $Y_{ij} \simeq \mathcal{O}(1)\sqrt{\frac{m_i m_j}{v^2}} \Rightarrow Y_{\tau\mu} \sim 0.0025$

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$\boldsymbol{Z \to e^{\pm}\mu^{\mp}}$

at LHC8, 5×10^8 Z s $\sim 25\times$ LEP

ATLAS 1408.5774 $BR(Z \to e^{\pm}\mu^{\mp}) < 7.5 \times 10^{-7}$

(LEP: $BR(Z \to e^{\pm}\mu^{\mp}) < 1.7 \times 10^{-6}$, $BR(Z \to e^{\pm}\tau^{\mp}) < 9.8 \times 10^{-6}$, $BR(Z \to \mu^{\pm}\tau^{\mp}) < 1.2 \times 10^{-5}$)

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parametrise $\frac{g_2}{c_W}(g_{e\mu} \overline{e} \not{Z} \mu + h.c.)$ then $\boldsymbol{g_{e\mu} < 0.0017}$

NB: in SM, no (renormalisable) flavour-changing Z interactions.

LHC searches for LFV h and Z decays

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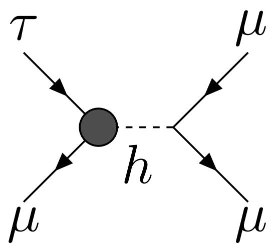
$\star$ $\Gamma_h \simeq 4$ MeV, $\Gamma_Z \simeq 2.5$ GeV, $\Rightarrow$ comparable sensitivity to new cplings of h and Z

...Kanemura-Ota-Tsumura
Davidson-Grenier...
Goudelis-Lebedev-Park
Harnik-Kopp-Zupan
...

The h: do tree-level low-E decays give competitive constraints?

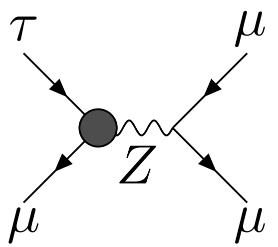


$$\frac{\Gamma(\tau\to 3\mu)}{\Gamma(\tau\to\mu\nu\bar{\nu})} \sim \frac{\frac{y_{\tau\mu}^2 y_\mu^2}{m_h^4}}{\frac{g^4}{m_W^4}} \sim \frac{y_{\tau\mu}^2 y_\mu^2}{g^4} \sim y_{\tau\mu}^2 10^{-7}$$

OK because $\frac{\Gamma(\tau\to 3\mu)}{\Gamma(\tau\to\mu\nu\bar{\nu})} \leq 1.2\times 10^{-7}$. $\tau \to \eta\mu$ ok too...

Not for h...h is narrow $\Rightarrow$ feebly coupled to light fermions

The Z: do tree-level low-E decays give competitive constraints?



$$\frac{\Gamma(\tau\to 3\mu)}{\Gamma(\tau\to\mu\nu\bar{\nu})} \sim \frac{\frac{g^4 g_{\mu\tau}^2}{c_W^4 m_Z^4}}{\frac{g^4}{m_W^4}} \sim g_{\mu\tau}^2 \leq 1.2\times 10^{-7}$$

$\tau \to 3\mu \Rightarrow g_{\mu\tau} \lesssim 3\times 10^{-4}$, LEP $\Rightarrow g_{\mu\tau} \lesssim 7\times 10^{-3}$

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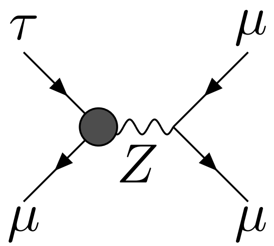

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Can avoid tree-level, low-energy bounds on Z by using $g_{\mu\tau}\propto p_Z^2/\Lambda^2$. Consider:

$$\frac{g}{c_W}\frac{p_Z^2}{\Lambda^2}\overline{\mu}\gamma_\alpha Z^\alpha\tau \qquad \leftrightarrow \qquad \left(g\frac{1}{\Lambda^2}[\partial^\beta B^\alpha - \partial^\alpha B^\beta]\overline{\mu}\gamma^\alpha D^\beta\tau\right)$$

$$\text{on the } Z: \ g_{\tau\mu} = \frac{m_Z^2}{\Lambda^2} \quad , \quad BR(Z\to\tau^\pm\mu^\mp)\sim 0.4\frac{m_Z^4}{\Lambda^4}$$

$$\text{in } \tau\to 3\mu: \ g_{\tau\mu} < \frac{m_\tau^2}{\Lambda^2}$$

(also suppresses $\bar{e}\,\not{Z}\,\mu$ sufficiently at tree, but not in loop contribution to $\mu\to e\gamma$)

Derivative cplings allow to avoid low-E tree bds on Z...

Am I allowed derivative couplings? Yes! See backup.

Need SU(2) invariant parametrisation to discuss LFV cplings in loops

To put LFV Higgs interactions in the SM Lagrangian

1. renormalisable (tree) LFV cplings for the 125 GeV Higgs— add a Higgs doublet:

   in the 2HiggsDoubletModel, with Lepton Flavour Changing Yukawas (type III), the lightest Higgs can have LFV couplings, if some other Higgs(es) below 300-400 GeV. (Inside loops, include both doublets. Also check ρ-parameter, etc.)

AristizabalVicente
+ B physics:Crivellin etal
+g-2:OmuraSenahaTobe
degenerate @125: DasKunchi
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2. Remain with SM particle content, and add effective operators:

$$\frac{C_{\mu\tau}}{\Lambda^2}H^\dagger H\overline{\ell}_2 H\tau_R + \frac{C_{\tau\mu}}{\Lambda^2}H^\dagger H\overline{\ell}_3 H\mu_R + h.c.$$

   Giudice-Lebedev, Babu-Nandi...
   Dorsner etal
   ...

   (LFV because diagonalising $Y_{\alpha\beta} + \frac{v^2}{\Lambda^2}(C_{\mu\tau} + C_{\tau\mu})$ and $Y_{\alpha\beta} + 3\frac{v^2}{\Lambda^2}(C_{\mu\tau} + C_{\tau\mu})$ is different)

   Can arise, eg, in Randall-Sundrum models

   $BR(h \to \tau^\pm\mu^\mp) \sim 1\% \Rightarrow \Lambda \lesssim 4$ TeV (for $C \lesssim 1$)

   $\Lambda \lesssim 300$ GeV (for $C \lesssim 1/(16\pi^2)$)

   $\Lambda \lesssim 14$ TeV (for $C \sim 4\pi$)

   Dorsner etal
   1502.07784

BjorkenWeinberg
loop caln by ChangHouKeung
LFV Higgs bds by...
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Harnik-Kopp-Zupan, GoudelisLebedevPark
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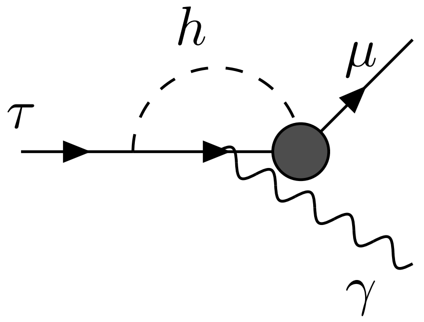
The higgs in loops...$1/(16\pi^2) \gg y_\tau^2$!

Perturbing in g, $\{y_i\}$,v^2/Λ_{NP}^2, loops,...



$$\sim e\frac{y_{\tau\mu}y_\tau^2}{16\pi^2}$$

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BjorkenWeinberg
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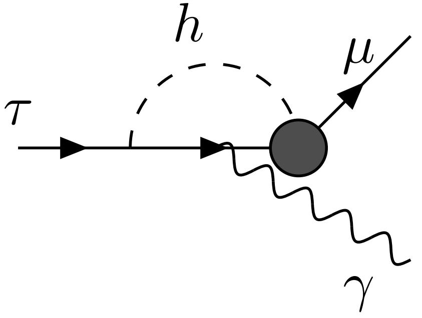
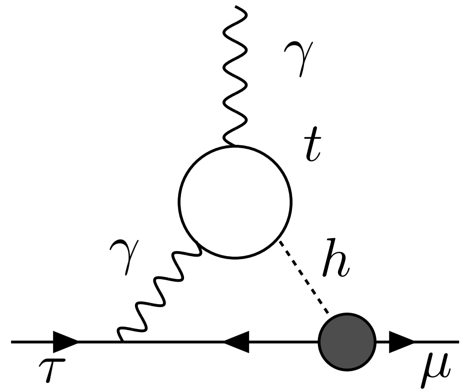
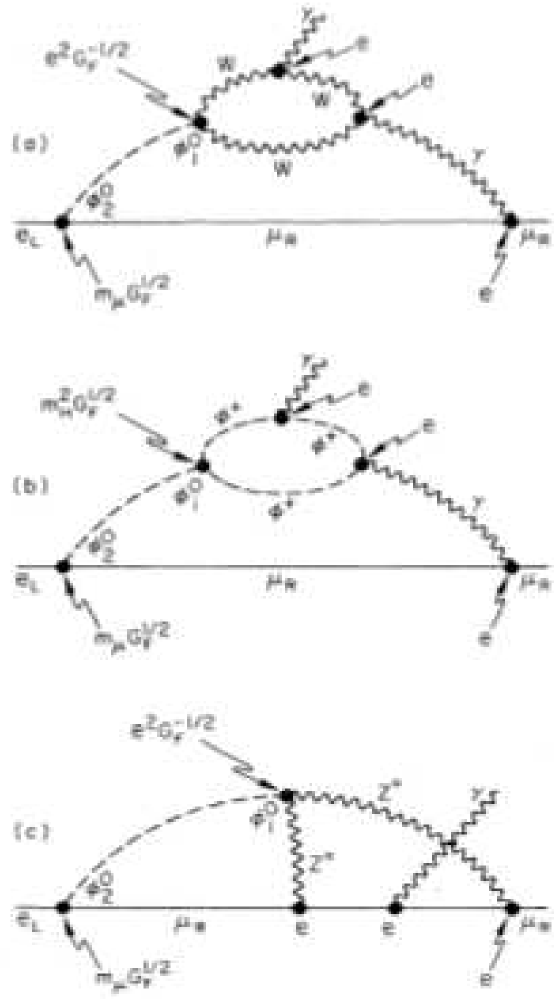


$\sim e\frac{y_{\tau\mu}y_\tau^2}{16\pi^2}$



$\sim e^3\frac{y_{\tau\mu}y_t}{(16\pi^2)^2}$



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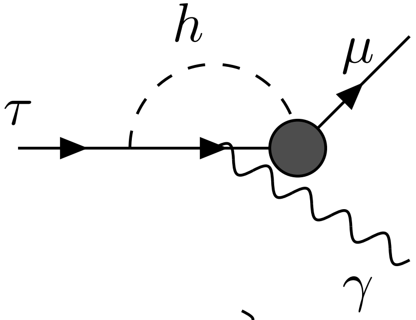
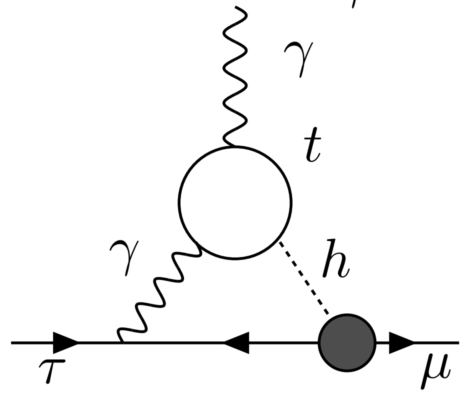


$$\sim e\frac{y_{\tau\mu}y_\tau^2}{16\pi^2}$$

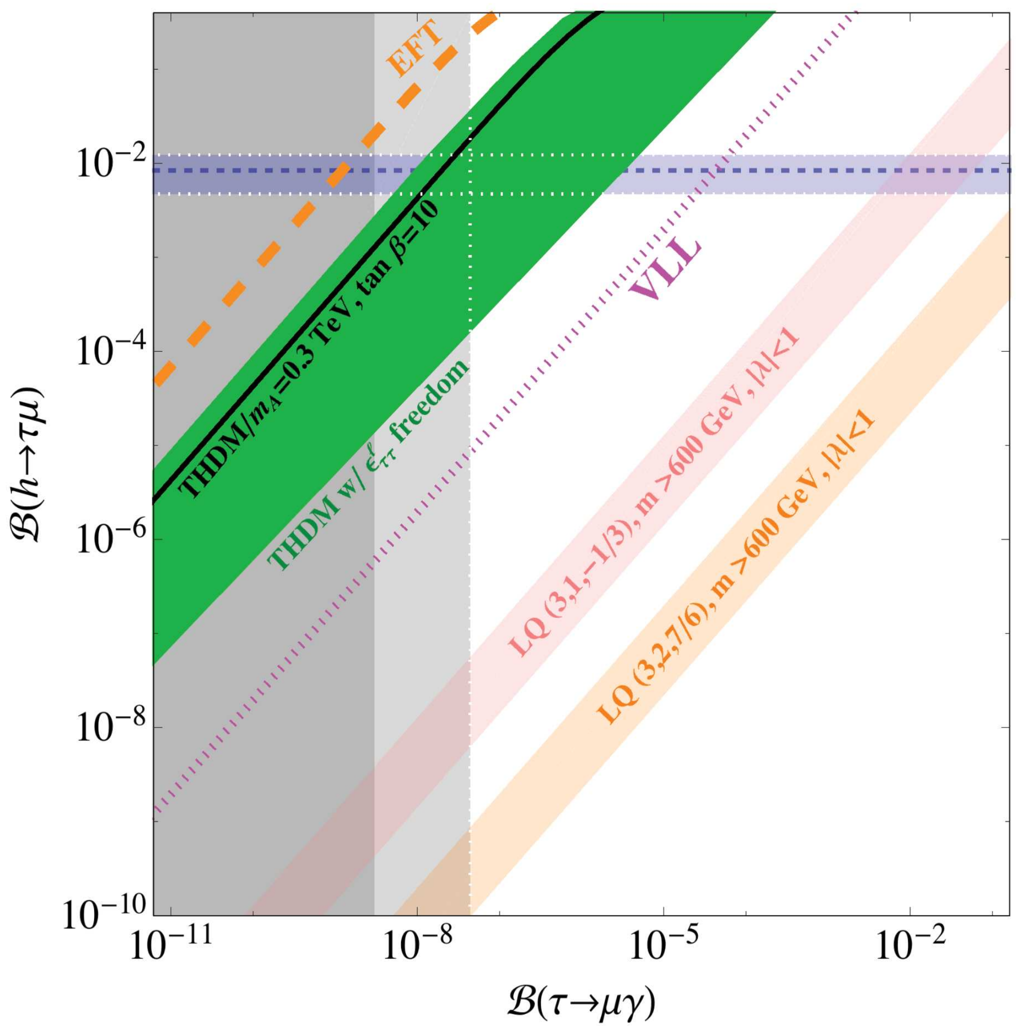


$$\sim e^3\frac{y_{\tau\mu}y_t}{(16\pi^2)^2} \sim A \lesssim \frac{y_\tau}{16\pi}\sqrt{\frac{BR(\tau\to\mu\gamma)}{BR(\tau\to\mu\bar{\nu}\nu)}} \sim y_\tau 10^{-5}$$

$\Rightarrow$ if $y_{\tau\mu} \lesssim y_\tau$, contribution of $y_{\tau\mu}$ to $\tau \to \mu\gamma$ ok
(but for $\mu \to e\gamma$: $y_{\mu e} \lesssim 0.003 y_\mu$)

NB: $BR(\tau \to \mu\gamma)$ depends on many New Physics parameters ($y_{\tau\mu}, m_H^2$, $m_A^2, \cos(\beta-\alpha)$, ..., or other operators in "EFT")
$\Rightarrow$ model-dep correlations with $h \to \tau^\pm\mu^\mp$, hard to set a "bound" on $h \to \tau^\pm\mu^\mp$

$h \to \tau^\pm \mu^\mp$ and $\tau \to \mu\gamma$ correlations in various models (Dorsner etal 1502.07784)



Does one expect LFV in Higgs decays?

Need a model...

1. Neutrino masses imply LFV, and the Higgs is related to fermion masses. So...?
   But to obtain m_ν, need Lepton Number Change, or ν_Rs (not more Higgses). Popular neutrino mass models contribute to $h \to \tau^\pm \mu^\mp$ at loop (eg inverse seesaw: $BR(h \to \tau\bar{\ell}) \lesssim 10^{-5}$)
   Arganda etal

2. ? A $BR(h \to \tau^\pm \mu^\mp) \sim 1\%$ suggests tree-level coupling?
   - eg 2HiggsDoubletModel of "type III" ?
     (seems to) require another neutral scalar at $200 \lesssim m \lesssim (?)\ 400$ GeV
   - if SM Higgs + non-renom. operators (e.g. $H^\dagger H \bar{\ell} H \tau$), then New Physics scale $M_{NP} \lesssim \sqrt{C}4$ TeV accessible at LHC? (provided $C_{NP} \ll 4\pi$)

Dunno ... ask Fabio :)

SD, Lacroix,Verdier

To put LFV Z interactions in the SM Lagrangian

1. ...small in many models... Goto,Kitano,Mori
   eg for Higgs LFV due to effective operators, $BR(Z \to \tau\bar{\mu}) \sim 10^{-14}\frac{y^2_{\tau\mu}}{10^{-5}}$
   with Dirac neutrino masses, lepton flavour-changing Z vertices $\propto \frac{m^2_\nu}{16\pi^2 m^2_W}$

2. can parametrise with effective operators
   gauge invariant, dimension 6 ops contains two Higgs and/or Derivatives:

$$\mathcal{O}(\partial^2) \quad : \quad \overline{\mu}\gamma_\beta D_\alpha \tau B^{\alpha\beta} \quad , \quad \overline{\ell}_\mu \sigma^I \gamma_\beta D_\alpha \ell_\tau W^{I\alpha\beta} \quad , \quad \overline{\ell}_\mu \gamma_\beta D_\alpha \ell_\tau B^{\alpha\beta}$$

$$\mathcal{O}(H^2) \quad : \quad [H^\dagger D_\alpha H]\overline{\mu}\gamma^\alpha \tau \quad , \quad [H^\dagger \sigma^I D_\alpha H][\overline{\ell}_\mu \sigma^I \gamma^\alpha \ell_\tau] \quad , \quad [H^\dagger D_\alpha H][\overline{\ell}_\mu \gamma^\alpha \ell_\tau]$$

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

3. LHC sensitivity to derivative operators, with τ, better than rare decays.
   But $\mu \to e\gamma \Rightarrow BR(Z \to e\bar{\mu}) =\lesssim 10^{-10}$.

more difficult than higgs :(

Am I allowed gradient operators? Yes, tis a basis choice. If instead I take the $\mathcal{O}(H^2)$ penguins, I can circumvent $\tau \to 3\mu$ with a cancellation between the Z and 4-fermion contributions

And what about the top?

$$\boldsymbol{t \to qh \quad , \quad t \to qZ}$$

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

$t \to hq$

1. CMS and ATLAS search for $BR(t \to h_{SM} q) \simeq .26(|Y_{tq}|^2 + |Y_{qt}|^2)$ with 20 fb^{-1}:

   $$BR(t \to qh) < 0.0056 \quad \Rightarrow \quad \sqrt{Y_{tq}^2 + Y_{qt}^2} < 0.14$$

   CMS-PAS-HIG-13-034

   (see also Greljo,Kamenik Kopp : $\sqrt{Y_{tu}^2 + Y_{ut}^2} < 0.13$)

   Sensitive to $BR(t \to qh) \sim 5 \times 10^{-4}$ with 300fb^{-1}.

   Cheng-Sher ansatz : $y_{ij} \simeq \mathcal{O}(1)\sqrt{\frac{m_i m_j}{v^2}} \Rightarrow Y_{tc}, Y_{ct} \sim 0.08$

$t \to hq$

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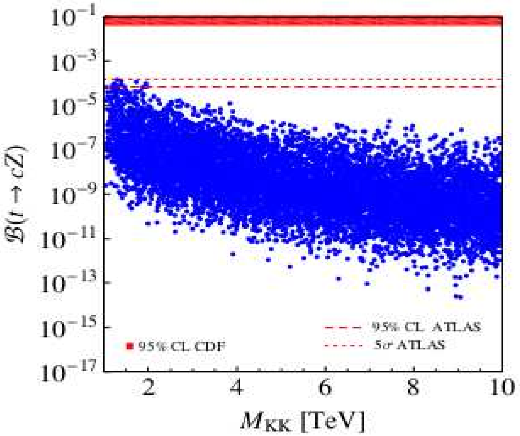
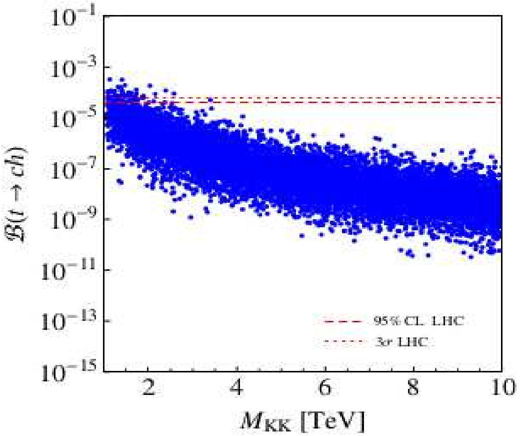
   Sensitive to $BR(t \to qh) \sim 5 \times 10^{-4}$ with 300fb^{-1}.

2. low energy bounds on real couplings are less restrictive, arise, from observables sensitive to a higgs-top loop. Harnik,Kopp,Zupan Crivellin etal Gorbahn Haisch
   But current edm bounds on phases :
   Im$(Y_{tc}Y_{ct}) \leq 4 \times 10^{-4}$, **Im**$(Y_{tu}Y_{ut}) \leq 5 \times 10^{-7}$.

3. obtain tree-level, renormalisable ($\Rightarrow \mathcal{O}(1)$) coupling in 2HDM ChiangFukadaTakeuchiYanagida
   or via effective operators in many models CasagrandeGoertzHaischNeubertPfoh





About LFV but not the Higgs: $t \to q\mu^{\pm}e^{\mp}$?

1. parametrise vertex as a four-fermion contact interaction, with coefficient ϵ/m_t^2

$$BR(t \to q\mu^{\pm}e^{\mp}) \simeq 3 \times 10^{-3}|\epsilon|^2$$

2. 20 fb^{-1} of data at 8 TeV sensitive to $BR(t \to q\mu^{\pm}e^{\mp}) \gtrsim 6 \times 10^{-5}$
   100 fb^{-1} of data at 13 TeV sensitive to $BR(t \to q\mu^{\pm}e^{\mp}) \gtrsim 10^{-5}$

3. Current bounds (from $\mu \to e\gamma$, rare B decays, HERA single top search) are more restrictive for some contact interactions, allow $\epsilon \gtrsim 1$ for others

4. a leptoquark could mediate $t \to q\mu^{\pm}e^{\mp}$. With cpling λ to fermions, lower bound from direct searches on m_{LQ} imposes $BR(t \to q\mu^{\pm}e^{\mp}) \lesssim \lambda^4 \times 10^{-6}$.

Summary

1. The higgs is narrow and heavy = low energy observables have limited sensitivity to flavoured interactions of the Higgs
   $\Leftrightarrow$ Higgs decays a unique window on the flavour sector

theory says that $\mu \to e\gamma$ says that the LHC should not see:

$$h, Z \to e\bar{\mu}, \text{ or, } h, Z \to e\bar{\tau} \textit{ and } h, Z \to \mu\bar{\tau}$$

(because would require cancellations in $\mu \to e\gamma$ that theorists do not know how to engineer).
$\Rightarrow$ *please LHC look for these too!*

2. In EFT, flavour-changing decays of heavy particles (h, Z, t) probe different operators from low-energy observables. So its interesting to look for flavour-changing decays of Zs and tops too

BackUp

What do we know (experimentally)

some processes	current sensitivities
$BR(\mu \to e\gamma)$	$< 5.7 \times 10^{-13}$
$BR(\mu 3e)$	$< 1.0 \times 10^{-12}$
$\frac{\sigma(\mu + Au \to e + Au)}{\sigma(\mu \text{ capture})}$	$< 7 \times 10^{-13}$
$BR(\tau \to \ell\gamma)$	$< 3.3, 4.4 \times 10^{-8}$
$BR(\tau \to 3\ell)$	$< 1.5 - 2.7 \times 10^{-8}$
$BR(\tau \to e\phi)$	$< 3.1 \times 10^{-8}$
$BR(\tau \to \ell + X_{m \lesssim m_\pi})$	$< 2.7 - 5 \times 10^{-3}$
$BR(\overline{K_L^0} \to \mu\bar{e})$	$< 4.7 \times 10^{-12}$
$BR(K^+ \to \pi^+\bar{\nu}\nu)$	$= 1.7 \pm 1.1 \times 10^{-10}$
$BR(\overline{K^+} \to \pi^+ X_{m\sim 0})$	$< 5.9 \times 10^{-11}$
$BR(B^+ \to K^+\tau\bar{\mu})$	$< 7.7 \times 10^{-5}$
$BR(Z \to \tau^\pm \ell^\mp)$	$< 1.2,\ 0.98 \times 10^{-5}$

See nothing. ... ... $\Rightarrow$ where is most promising place to look?

To interpret those numbers —what do theorists do?

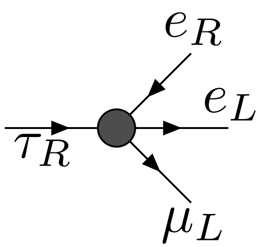
1. pick a scale

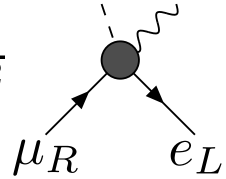
2. add new interactions

3. add new particles

4. calculate something

A first interpretation of current bounds using $\mathcal{L}_{eff}$:

$\Delta\mathcal{L}_{eff} = \ldots + \frac{1}{16\pi^2\Lambda^2}$ 

$+ \quad \frac{e m_\mu}{16\pi^2\Lambda^2}$ 

$+ \ldots +$ h.c.

For a given process with $BR < \ldots$, can obtain a lower bound on Λ:

1. find lowest dimension operator/diagram corresponding to a process, usually dim 6
2. set $C \simeq 1/16\pi^2$ — assume NP in loops!
3. compute rate. $BR(\Lambda) \quad \Rightarrow \Lambda > \ldots$

for afficionados: the dipole operator flips chirality, and has a Higgs leg. I assume this makes $C \propto m_\mu$, if not, the scale probed is increased by $\sqrt{v/m_\mu} \sim 40$.

Interpreting what we know: bounds assuming dimension 6 operators

process	bound	scale, dim 6, loop
$BR(\mu \to e\gamma)$	$< 5.7 \times 10^{-13}$	67 TeV
$BR(\mu 3e)$	$< 1.0 \times 10^{-12}$	14 TeV
$\frac{\sigma(\mu+Ti\to e+Ti)}{\sigma(\mu Ti\to \nu Ti')}$	$< 4.3 \times 10^{-13}$	40 TeV
$BR(\tau \to \ell\gamma)$	$< 3.3, 4.4 \times 10^{-8}$	2.8 TeV
$BR(\tau \to 3\ell)$	$< 1.5 - 2.7 \times 10^{-8}$	0.8 TeV
$BR(\tau \to e\pi)$	$< 8.1 \times 10^{-8}$	0.5 TeV
$BR(\overline{K_L^0} \to \mu\bar{e})$	$< 4.7 \times 10^{-12}$	25 TeV$(V \pm A)$ 140 TeV$(S \pm P)$
$BR(B^+ \to K^+\tau\bar{\mu})$	$< 7.7 \times 10^{-5}$	0.3 TeV
$BR(Z \to \tau\bar{\ell})$	$\lesssim 10^{-5}$	0.14 TeV

where to look?

? μ searches sensitive to higher scale than τ ??

LFV in kaons vs Bs?

But flavoured couplings we know are not 1?

Lets suppose

1. a mass scale for new particles $\sim$ TeV
2. tree diagrams (no factors of $1/(16\pi^2)$)
3. flavoured fermion couplings $\propto$ SM fermion masses:

$$\lambda_{ij} \simeq \sqrt{\frac{m_i m_j}{v^2}} \quad , \quad i,j \text{ any SM fermion}$$

Cheng Sher
extra dim ...

estimate rates assuming no additional suppression factors...
(except keep lepton mass and $1/16\pi^2$ in dipoles!)

Current bounds vs naive hierarchical expectations

process	bound	expectation
$BR(\mu \to e\gamma)$	$< 5.7 \times 10^{-13}$	$\sim 2.2 \times 10^{-14}$
$BR(\mu 3e)$	$< 1.0 \times 10^{-12}$	$\sim 1.3 \times 10^{-23}$
$\frac{\sigma(\mu + Ti \to e + Ti)}{\sigma(\mu \text{ capture})}$	$< 4.3 \times 10^{-12}$	$\sim 2.5 \times 10^{-19}$
$BR(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	$\sim 8 \times 10^{-11}$
$BR(\tau \to 3\ell)$	$< 1.5 - 2.7 \times 10^{-8}$	$\lesssim 3 \times 10^{-16}$
$BR(\tau \to \mu\pi)$	$< 8.0 \times 10^{-8}$	$\sim 10^{-17}$
$BR(\overline{K_L^0} \to \mu\bar{e})$	$< 4.7 \times 10^{-12}$	$\sim 1 \times 10^{-12}$
$BR(K^+ \to \pi^+\bar{\nu}\nu)$	$= 1.7 \pm 1.1 \times 10^{-10}$	$\sim 2 \times 10^{-10}$ (ν_τ)
$BR(B^+ \to K^+\tau\bar{\mu})$	$< 7.7 \times 10^{-5}$	$\sim 3 \times 10^{-10}$

1. tree level
2. a mass scale for new particles $\sim$ TeV
3. flavoured couplings $\propto$ SM masses:

$$\lambda_{ij} \simeq \sqrt{\frac{m_i m_j}{v^2}} \quad , \quad i,j \text{ any SM fermion}$$

Kinematics of distinguishing $Z^* \to \tau\bar{\tau}$ from $h \to \tau\bar{\mu}$

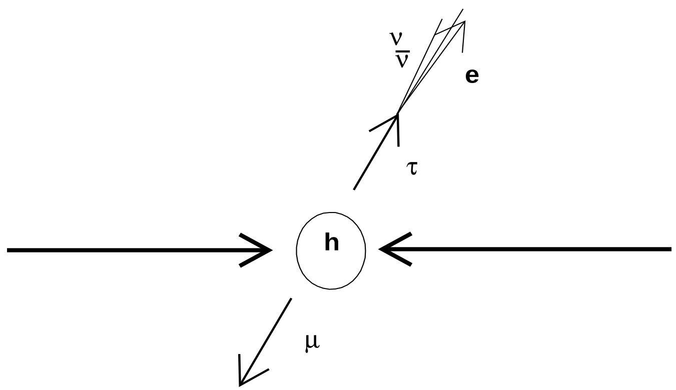
1. can *calculate* $\not{E}_T$ in $h \to \tau^\pm \mu^\mp$ events, for collinear τ daughters $(e\nu\bar{\nu})$

$$m_h^2 = (p_\mu + p_\tau)^2 = (p_\mu + \alpha p_e)^2 \qquad (p_\tau = p_\nu + p_{\bar{\nu}} + p_e = \alpha p_e)$$

2. "*measure*" $\not{E}_T$ (in total event, or in leptons)

3. compare:

$$\delta \not{E}_T = \frac{\not{E}_T^{calc} - \not{E}_T^{reco}}{\not{E}_T^{reco}}$$



Am I allowed gradient operators?

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

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

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.

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 $\tau \to 3\mu$, only 4-f operator contributes

four fermion and m_Z^2 Z operator: $(\overline{\tau}\gamma^\alpha \mu)(\overline{\mu}\gamma^\alpha \mu)$, $m_Z^2 \overline{\tau} \not{Z} \mu$

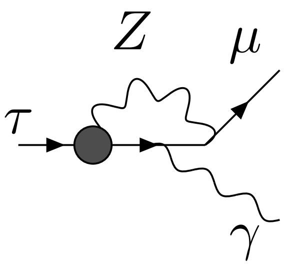
- on the Z, LFV Z coupling contributes, 4-f operator not.
- in $\tau \to 3\mu$, both operators contribute in the amplitude, cancellations possible.

(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:

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

and can I calculate that?



1. assume NP scale $M \gg m_Z$

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

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

3. in RG running between M 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...)

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

$\Rightarrow$ no constraint from $\tau \to \ell\gamma$

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