

Lepton Flavour Violation with SM Particles @ LHC?

Sacha Davidson , (Sylvain Lacroix), Patrice Verdier
IPN de Lyon/CNRS

Looking for (contact) interaction with

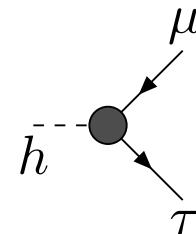
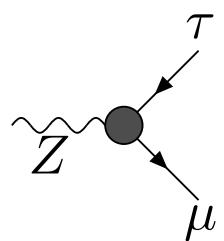
- (charged) lepton flavour change ($m_\nu \Rightarrow$ it exists)
- SM external legs (they exist)
- ? a heavy leg?
(= not excluded by precision obvservations...)

Lepton Flavour Violating h, Z Decays @ LHC?

Sacha Davidson , (Sylvain Lacroix), Patrice Verdier
IPN de Lyon/CNRS

Looking for (contact) interaction with

- (charged) lepton flavour change
- SM external legs
- ? a heavy leg?



1. $Z \rightarrow \tau^\pm \mu^\mp, (Z \rightarrow e^\pm \mu^\mp), Z \rightarrow \tau^\pm e^\mp$ (1207.4894, in JHEP)

2. $h \rightarrow \tau^\pm \mu^\mp, (h \rightarrow e^\pm \mu^\mp), h \rightarrow \tau^\pm e^\mp$ (1211.1248)

Outline

1. intro

- (theory stuff)
- channels for $h \rightarrow \tau^\pm \mu^\mp$

2. $gg \rightarrow h \rightarrow \tau^\pm \mu^\mp \rightarrow (e^\pm \nu \bar{\nu}) \mu^\mp$

- backgrounds + simulation
- cuts

3. results

- could exclude $BR(h \rightarrow \tau^\pm \mu^\mp) > 4.5 \times 10^{-3}$ at 95% C.L. with 20 fb^{-1} .
- for $h \simeq h_{SM}$, corresponds to $y_{\tau\mu} \sim \sqrt{y_\tau y_\mu}$ Cheng-Sher

4. (what about $Z \rightarrow \tau^\pm \mu^\mp$?)

- sensitivity about 4 times better than LEP, at 95% C.L. with 20 fb^{-1} .

$$BR(Z \rightarrow \tau^\pm \mu^\mp) < 3.5 \times 10^{-6} , \quad BR(Z \rightarrow e^\pm \mu^\mp) < 4.1 \times 10^{-7}$$

We know that ...

1. there are neutrino masses, therefore Lepton Flavour Violation(LFV)
2. there is a SM Higgs-like resonance at $\simeq 126$ GeV
3. LFV could appear in Higgs decays

LFV \equiv flavour changing point interaction of charged leptons \equiv FCNC in charged leptons : $\tau \rightarrow \mu\gamma, \dots$

We know that ...

1. there are neutrino masses, therefore Lepton Flavour Violation(LFV)
2. there is a SM Higgs-like resonance at $\simeq 126$ GeV
3. LFV could appear in Higgs decays
 - (a) models
 - one Higgs doublet + non-renom. operators e.g. $H^\dagger H \bar{\ell} H \tau$ Giudice-Lebedev, Babu-Nandi
 - two Higgs doublets of “ type III” = flavour changing couplings + keep two neutral light scalars ...Davidson-Grenier, ...
 - (b) pheno:
 - tree exchange of h : $\tau \rightarrow \eta\mu, \tau \rightarrow \mu\bar{\mu}\mu$
 : $y_{\tau\mu} \lesssim \mathcal{O}(1)$ ok
 - loops : $\tau \rightarrow \mu\gamma$, EW precision, $b \rightarrow s\gamma$, etc
 : $y_{\tau\mu} \lesssim \mathcal{O}(y_\tau)$ ok

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

Looking for $h \rightarrow \tau^\pm \mu^\mp$ at the LHC (in narrow width approx)

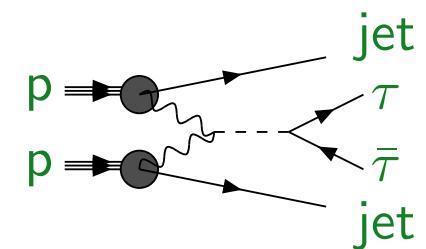
1. **production:** we suppose h from gluon fusion :

$$\sigma_{SM}(pp \rightarrow gg \rightarrow h) \simeq 20 \text{ pb}$$

Looking for $h \rightarrow \tau^\pm \mu^\mp$ at the LHC (in narrow width approx)

1. **production:** we suppose h from gluon fusion :

$$\sigma_{SM}(pp \rightarrow gg \rightarrow h) \simeq 20 \text{ pb}$$



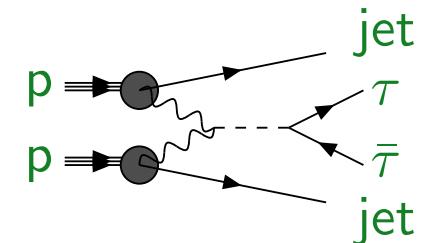
- (a) look for $h \rightarrow \tau^+ \tau^-$ in Vector Boson Fusion :
 - + dijets reduce background of $Z^* \rightarrow \tau \bar{\tau} \dots$ (we suppose no $Z \rightarrow \tau^\pm \mu^\mp$)
 - $(\sigma_{SM}(pp \rightarrow h) \simeq 1.6 \text{ pb})$
- (b) $h \rightarrow \tau^\pm \mu^\mp$ in Vector Boson Fusion studied by Harnik, Kopp, Zupan

2. **final state:** we look for $h \rightarrow \tau^\pm \mu^\mp \rightarrow (e^\pm \nu \bar{\nu}) \mu^\mp \rightarrow e^\pm \mu^\mp + E_T$

Looking for $h \rightarrow \tau^\pm \mu^\mp$ at the LHC (in narrow width approx)

1. **production:** we suppose h from gluon fusion :

$$\sigma_{SM}(pp \rightarrow gg \rightarrow h) \simeq 20 \text{ pb}$$



(a) look for $h \rightarrow \tau^+ \tau^-$ in Vector Boson Fusion :

+ dijets reduce background of $Z^* \rightarrow \tau \bar{\tau} \dots$ (we suppose no $Z \rightarrow \tau^\pm \mu^\mp$)

- $(\sigma_{SM}(pp \rightarrow h) \simeq 1.6 \text{ pb})$

(b) $h \rightarrow \tau^\pm \mu^\mp$ in Vector Boson Fusion studied by Harnik, Kopp, Zupan

2. **final state:** we look for $h \rightarrow \tau^\pm \mu^\mp \rightarrow (e^\pm \nu \bar{\nu}) \mu^\mp \rightarrow e^\pm \mu^\mp + E_T$

(a) can extrapolate our sensitivities to $h \rightarrow \tau^\pm e^\mp \rightarrow (\mu^\pm \nu \bar{\nu}) e^\mp \rightarrow \mu^\pm e^\mp + E_T$,
because soft μ easier to find than soft e .

(b) $BR(\tau \rightarrow e \nu \bar{\nu}) \sim 17.8\%$



(HKZ consider hadronic taus, with VBF)

Backgrounds and Simulations

Some processes which give $\mu^\pm e^\mp + \dots$, and expected # of events for 20 fb^{-1} data

1. $Z/\gamma^* \rightarrow \tau^\pm \tau^\mp \rightarrow \ell^\pm \nu \bar{\nu} \ell'^\mp \nu \bar{\nu}$ with $\ell, \ell' = e, \mu$ ($M_{Z/\gamma^*} > 20 \text{ GeV}$) **4 800 000**
2. $t\bar{t} \rightarrow b\ell^+ \nu \bar{b} \ell'^- \bar{\nu}$ with $\ell, \ell' = e, \mu, \tau$ **480 000**
3. $Wt \rightarrow \ell^\pm \nu b \ell'^\mp \nu$ with $\ell, \ell' = e, \mu, \tau$ **47 000**
4. $W^+ W^- \rightarrow \ell^+ \nu \ell'^- \bar{\nu}$ with $\ell, \ell' = e, \mu, \tau$ **120 000**
5. $Z/\gamma^* Z/\gamma^* \rightarrow f\bar{f} f'\bar{f}'$ **160 000**

Backgrounds and Simulations

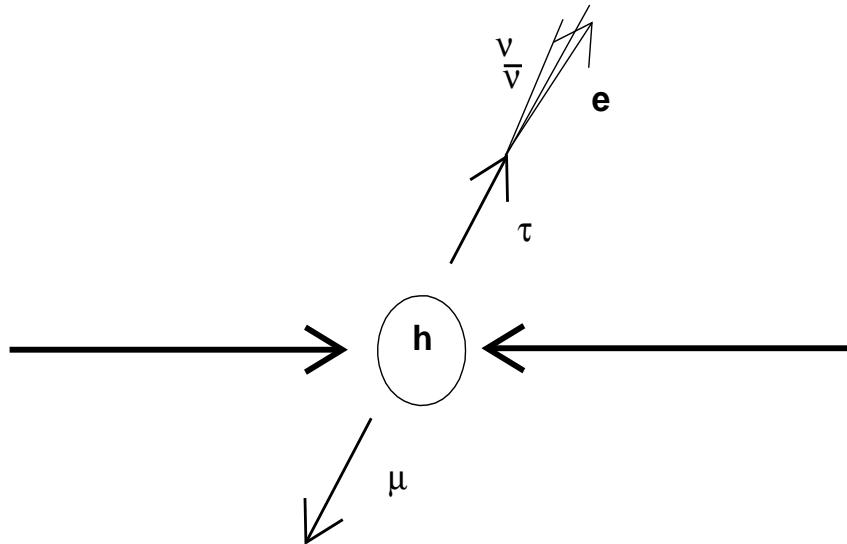
Some processes which give $\mu^\pm e^\mp + \dots$, and expected # of events for 20 fb^{-1} data

1. $Z/\gamma^* \rightarrow \tau^\pm \tau^\mp \rightarrow \ell^\pm \nu \bar{\nu} \ell'^\mp \nu \bar{\nu}$ with $\ell, \ell' = e, \mu$ ($M_{Z/\gamma^*} > 20 \text{ GeV}$) **4 800 000**
2. $t\bar{t} \rightarrow b\ell^+ \nu \bar{b} \ell'^- \bar{\nu}$ with $\ell, \ell' = e, \mu, \tau$ **480 000**
3. $Wt \rightarrow \ell^\pm \nu b \ell'^\mp \nu$ with $\ell, \ell' = e, \mu, \tau$ **47 000**
4. $W^+ W^- \rightarrow \ell^+ \nu \ell'^- \bar{\nu}$ with $\ell, \ell' = e, \mu, \tau$ **120 000**
5. $Z/\gamma^* Z/\gamma^* \rightarrow f\bar{f} f'\bar{f}'$ **160 000**
6. Higgs (assume produced with SM gluon fusion σ)
 - (a) $pp(gg) \rightarrow h \rightarrow \tau^\pm \tau^\mp \rightarrow \ell^\pm \nu \bar{\nu} \ell'^\mp \nu \bar{\nu}$ with $\ell, \ell' = e, \mu$ **3200**
 - (b) $pp(gg) \rightarrow h \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell'^- \bar{\nu}$ with $\ell, \ell' = e, \mu, \tau$ **9400**
 - (c) $pp(gg) \rightarrow h \rightarrow ZZ^* \rightarrow f\bar{f} f'\bar{f}'$ with $f = q, \nu, e, \mu, \tau$ **11000**

(N)NLO/(N)NLL cross-sections from various codes. LO simulation with Pythia8. CMS simulation of Delphes (anti- k_t of FastJet). Simulate $\sim 10 \times$ expected # events

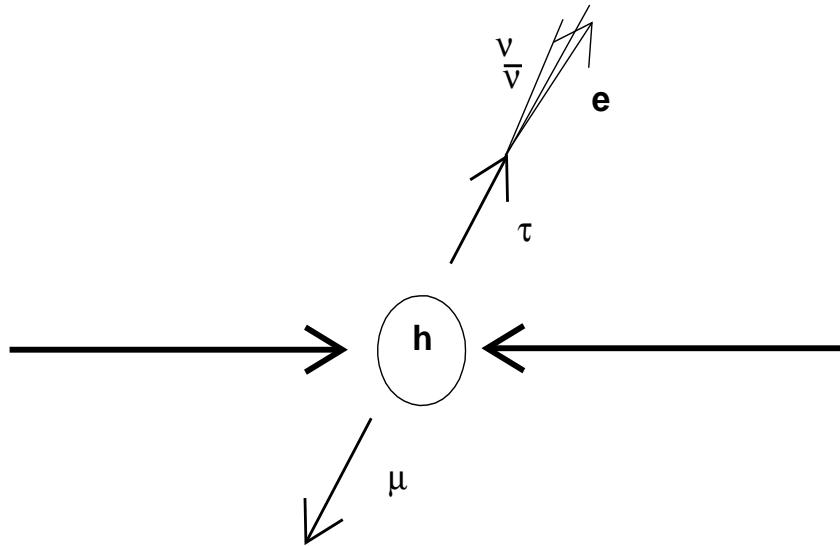
~ 280 $pp(gg) \rightarrow h \rightarrow \tau^\pm \mu^\mp \rightarrow e^\pm \nu \bar{\nu} \mu^\mp$ evts, for $BR(h \rightarrow \tau^\pm \mu^\mp) \sim \frac{m_\mu}{m_\tau} BR(h \rightarrow \tau \bar{\tau})$.

Looking for $h \rightarrow \tau^\pm \mu^\mp \dots$



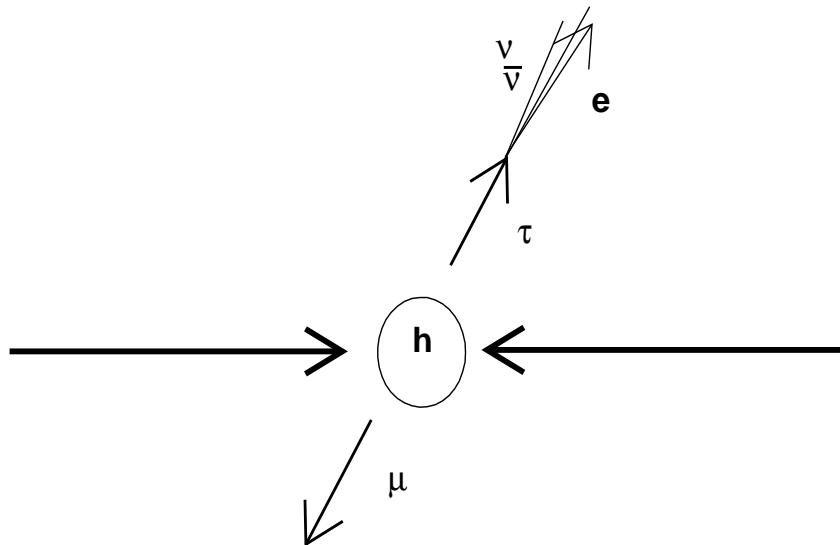
Selection criteria	$N_{bkgd.}$	$N_{h~bkgd}$	Signal efficiency (%)
muon, $p_T > 30$ GeV, $ \eta < 2.1$	59271	328	21.2
e, $p_T > 15$ GeV, $ \eta < 2.5$			
OS	58447	326	21.2

Looking for $h \rightarrow \tau^\pm \mu^\mp \dots$



Selection criteria	$N_{bkgd.}$	$N_{h\ bkgd}$	Signal efficiency (%)
muon, $p_T > 30$ GeV, $ \eta < 2.1$	59271	328	21.2
e , $p_T > 15$ GeV, $ \eta < 2.5$	58447	326	21.2
OS	19477	175	13.1

Looking for $h \rightarrow \tau^\pm \mu^\mp \dots$



Selection criteria	$N_{bkgd.}$	$N_{h\ bkgd}$	Signal efficiency (%)
muon, $p_T > 30$ GeV, $ \eta < 2.1$	59271	328	21.2
e, $p_T > 15$ GeV, $ \eta < 2.5$			
OS	58447	326	21.2
no $p_T > 30$ GeV jet at $ \eta < 2.5$	19477	175	13.1
$\Delta\phi(e, \mu) > 2.7$	13261	49	10.7
$\Delta\phi(e, \cancel{E}_T) < 0.3$	3885	18	7.85

If $BR(h \rightarrow \tau^\pm \mu^\mp) = 4.2 \times 10^{-3}$, have $\simeq 22$ signal events.

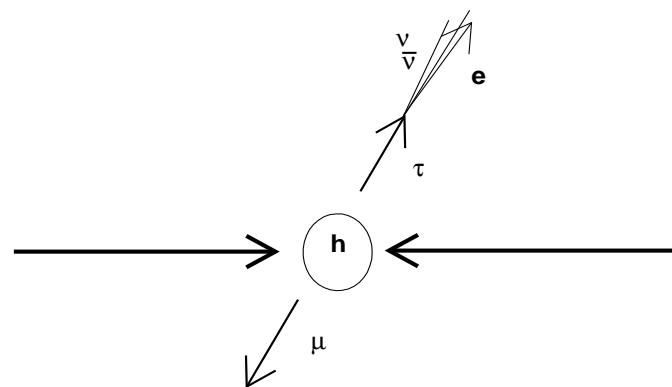
...use kinematics...

1. can calculate \cancel{E}_T in $h \rightarrow \tau^\pm \mu^\mp$ events, for collinear τ daughters ($e\nu\bar{\nu}$)

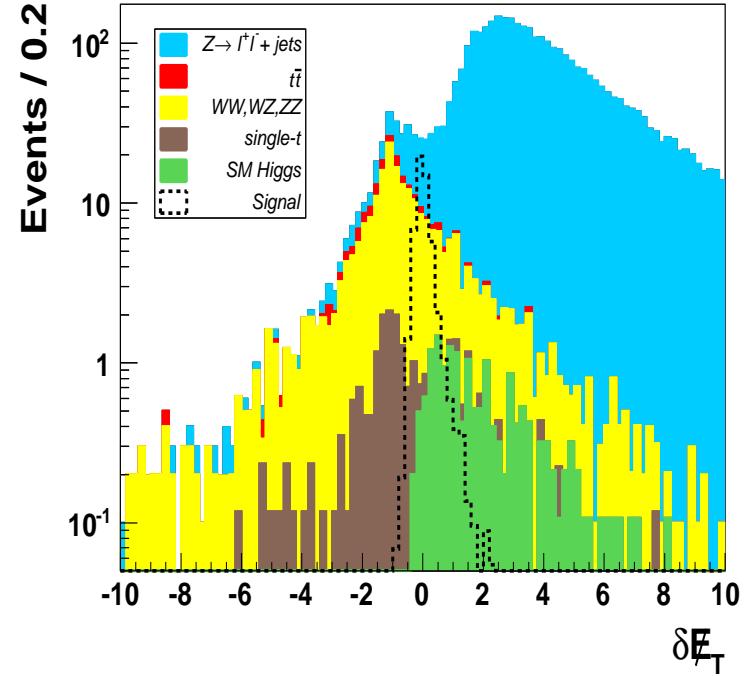
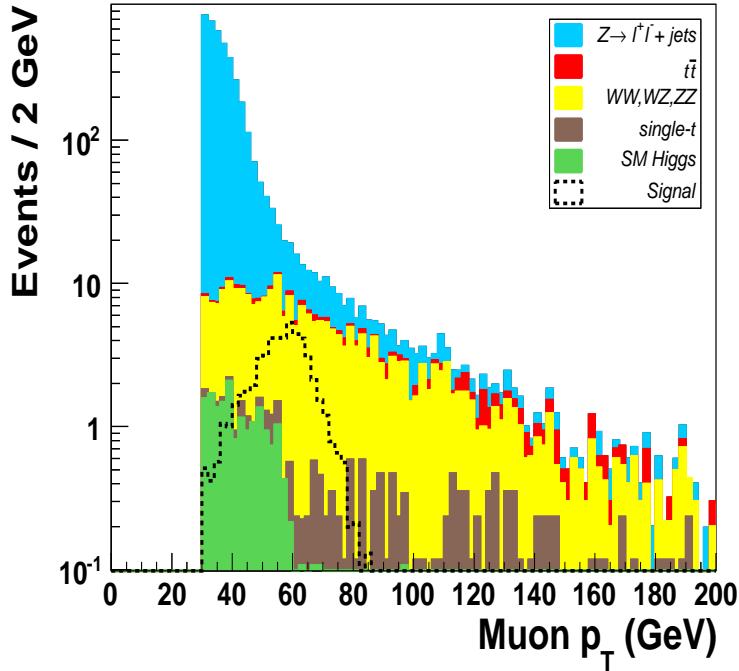
$$m_h^2 = (p_\mu + p_\tau)^2 = (p_\mu + \alpha p_e)^2 \quad (p_\tau = p_\nu + p_{\bar{\nu}} + p_e = \alpha p_e)$$

2. "measure" \cancel{E}_T (in total event, or in leptons)
3. compare:

$$\delta \cancel{E}_T = \frac{\cancel{E}_T^{calc} - \cancel{E}_T^{reco}}{\cancel{E}_T^{reco}}$$



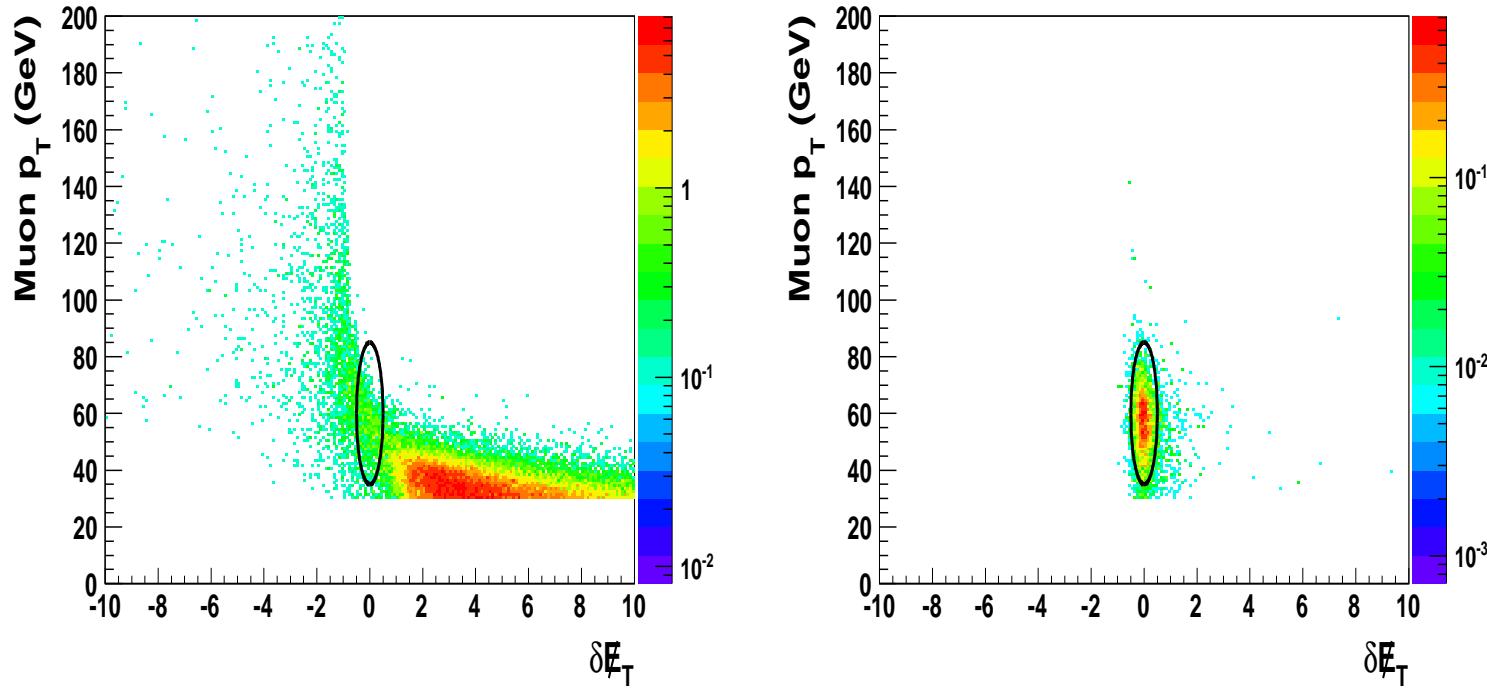
So where are we now? ...



$Z^* \rightarrow \tau\bar{\tau}$, diboson, SM Higgs. dashed = $BR(h \rightarrow \tau^\pm \mu^\mp) = 0.01$.

$$\delta E_T = \frac{E_T^{calc} - E_T^{reco}}{E_T^{reco}}$$

Plot backgrd (left) and signal (right) in p_T - δE_T plane...



Selection criteria	$N_{backgrd.}$	N_h background	Signal efficiency (%)
$\Delta\phi(e, \cancel{E}_T) < 0.3$	3885	18	7.85
2D cut in $(\delta \cancel{E}_T, p_T^\mu)$ plane	53	1	5.34

~ 15 $h \rightarrow \tau^\pm \mu^\mp$ evts, for $BR(h \rightarrow \tau^\pm \mu^\mp) \sim \frac{m_\mu}{m_\tau} BR(h \rightarrow \tau\bar{\tau})$.

Summary and Results

- Neutrinos have mass \Leftrightarrow there is New Physics dedicated to Lepton Flavour!
- But, no flavour-changing processes observed among charged leptons (yet).
 \Rightarrow look everywhere!
- @LHC
 - can look for New (s)Particles with LFV decays
 - can look for LFV with external legs that exist:
- 20 fb^{-1} data, systematic error reduction ($\rightarrow 3\%$), and Delphes \cancel{E}_T resolution:

$$\frac{\sigma(gg \rightarrow h)}{\sigma_{SM}(gg \rightarrow h)} BR(h \rightarrow \tau^\pm \mu^\mp) < 4.5 \times 10^{-3} \sim \frac{m_\mu}{m_\tau} BR(h \rightarrow \tau^\pm \tau^\mp)$$

at 95% CL_s .

(expect sensitivity $BR(\rightarrow \tau e)$ similar/better than $\rightarrow \tau \mu$).

Summary and Results

- Neutrinos have mass \Leftrightarrow there is New Physics dedicated to Lepton Flavour!
- But, no flavour-changing processes observed among charged leptons (yet).
 \Rightarrow look everywhere!
- @LHC : h or $Z \rightarrow \tau^\pm \mu^\mp, \tau^\pm e^\mp, \mu^\pm e^\mp$
- 20 fb^{-1} data, 3% systematic error(aggressive), and Delphes \cancel{E}_T resolution :

$$\frac{\sigma(gg \rightarrow h)}{\sigma_{SM}(gg \rightarrow h)} BR(h \rightarrow \tau^\pm \mu^\mp) < 4.5 \times 10^{-3} \sim \frac{m_\mu}{m_\tau} BR(h \rightarrow \tau^\pm \tau^\mp)$$

- 20 fb^{-1} data, 3% systematic error, \cancel{E}_T from e, μ (conservative) :

$$BR(Z \rightarrow \tau^\pm \mu^\mp) < 3.5 \times 10^{-6}, \quad BR(Z \rightarrow e^\pm \mu^\mp) < 4.1 \times 10^{-7}$$

factor 4 improvement over LEP1. $\tau\mu$ systematics limited.

And what about the Z?

the LHC is *not* the wrong place to do Z physics

1. vs LEP 1

- LEP1 was a clean Z machine, with 17×10^6 Z s
 $BR(Z \rightarrow e^\pm \mu^\mp) < 1.7 \times 10^{-6}$, $BR(Z \rightarrow e^\pm \tau^\mp) < 9.8 \times 10^{-6}$, $BR(Z \rightarrow \mu^\pm \tau^\mp) < 1.2 \times 10^{-5}$
- at the 7,8 TeV LHC, $\sigma(pp \rightarrow Z \rightarrow \mu\bar{\mu}) \sim \text{nb. } \mathcal{L} \sim 20 \text{ fb}^{-1} \Rightarrow 20 \times 10^6$ Z s ??

$$\#Zs \simeq \frac{\sigma(pp \rightarrow Z \rightarrow \mu\bar{\mu}) \times \mathcal{L}}{BR(Z \rightarrow \mu\bar{\mu})} \sim 10^8 Zs$$

$$BR(Z \rightarrow \mu\bar{\mu}) \simeq 0.0366$$

(compare *e.g.* $\sigma(pp \rightarrow t\bar{t}) \sim 160 \text{ pb} \dots \gtrsim 150 \text{ } Z$ s for each $t\bar{t}$ pair)

What about the Z ? We know well the Z ...

1. vs LEP 1

- LEP1 was a clean Z machine, with 17×10^6 Z s
 $BR(Z \rightarrow e^\pm \mu^\mp) < 1.7 \times 10^{-6}$, $BR(Z \rightarrow e^\pm \tau^\mp) < 9.8 \times 10^{-6}$, $BR(Z \rightarrow \mu^\pm \tau^\mp) < 1.2 \times 10^{-5}$
- at the 7,8 TeV LHC, $\#Zs \simeq \frac{\sigma(pp \rightarrow Z \rightarrow \mu\bar{\mu}) \times \mathcal{L}}{BR(Z \rightarrow \mu\bar{\mu})} \sim 10^8 Zs$

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



What about the Z ? We know well the Z ...

1. vs LEP 1

- LEP1 was a clean Z machine, with 17×10^6 Z s
 $BR(Z \rightarrow e^\pm \mu^\mp) < 1.7 \times 10^{-6}$, $BR(Z \rightarrow e^\pm \tau^\mp) < 9.8 \times 10^{-6}$, $BR(Z \rightarrow \mu^\pm \tau^\mp) < 1.2 \times 10^{-5}$
- at the 7,8 TeV LHC, $\#Zs \simeq \frac{\sigma(pp \rightarrow Z \rightarrow \mu\bar{\mu}) \times \mathcal{L}}{BR(Z \rightarrow \mu\bar{\mu})} \sim 10^8 Zs$

2. decades of rare decay/precision data?... $BR(\tau \rightarrow \mu\bar{\mu}\mu) < 2.1 \times 10^{-8}$ But gradient operators better constrained at high energy. Consider

$$g_Z C \frac{1}{16\pi^2 M^2} B^{\alpha\beta} \bar{\mu} \gamma^\alpha D^\beta \tau \rightarrow g_Z C \frac{p_Z^2}{16\pi^2 M^2} \bar{\mu} \gamma_\alpha Z^\alpha \tau$$

on the Z : vertex $= g_Z \frac{C m_Z^2}{16\pi^2 M^2} \bar{\mu} \not{Z} \tau$, $BR(Z \rightarrow \tau^\pm \mu^\mp) \sim 1.7 \times 10^{-5} \frac{m_Z^4}{M^4}$, ($C = 1$)

in $\tau \rightarrow \mu\bar{\mu}\mu$: vertex $< g_Z \frac{C m_\tau^2}{16\pi^2 M^2} \bar{\mu} \not{Z} \tau$

Backgrounds and Simulations...

Some processes which give $\mu^\pm e^\mp + \dots$, and expected number of events for 20 fb^{-1} data

1. $Z/\gamma^* \rightarrow \tau^\pm \tau^\mp \rightarrow \ell^\pm \nu \bar{\ell}'^\mp \nu \bar{\nu}$ with $\ell, \ell' = e, \mu$ ($M_{Z/\gamma^*} > 20 \text{ GeV}$) **4 800 000**
2. $t\bar{t} \rightarrow b\ell^+ \nu \bar{b}\ell'^- \bar{\nu}$ with $\ell, \ell' = e, \mu, \tau$ **480 000**
3. $Wt \rightarrow \ell^\pm \nu b \ell'^\mp \nu$ with $\ell, \ell' = e, \mu, \tau$ **47 000**
4. $W^+ W^- \rightarrow \ell^+ \nu \ell'^- \bar{\nu}$ with $\ell, \ell' = e, \mu, \tau$ **120 000**
5. $Z/\gamma^* Z/\gamma^* \rightarrow f\bar{f} f'\bar{f}'$ **160 000**

(N)NLO/(N)NLL cross-sections from various codes. LO simulation with Pythia8. Fast CMS simulation of Delphes (anti- k_t jets of FastJet).

Simulate $\sim 10 \times$ number of events expected by end 2012 (grid). And 10^5 signal evts.

Looking for $Z \rightarrow \tau^\pm \mu^\mp \dots$

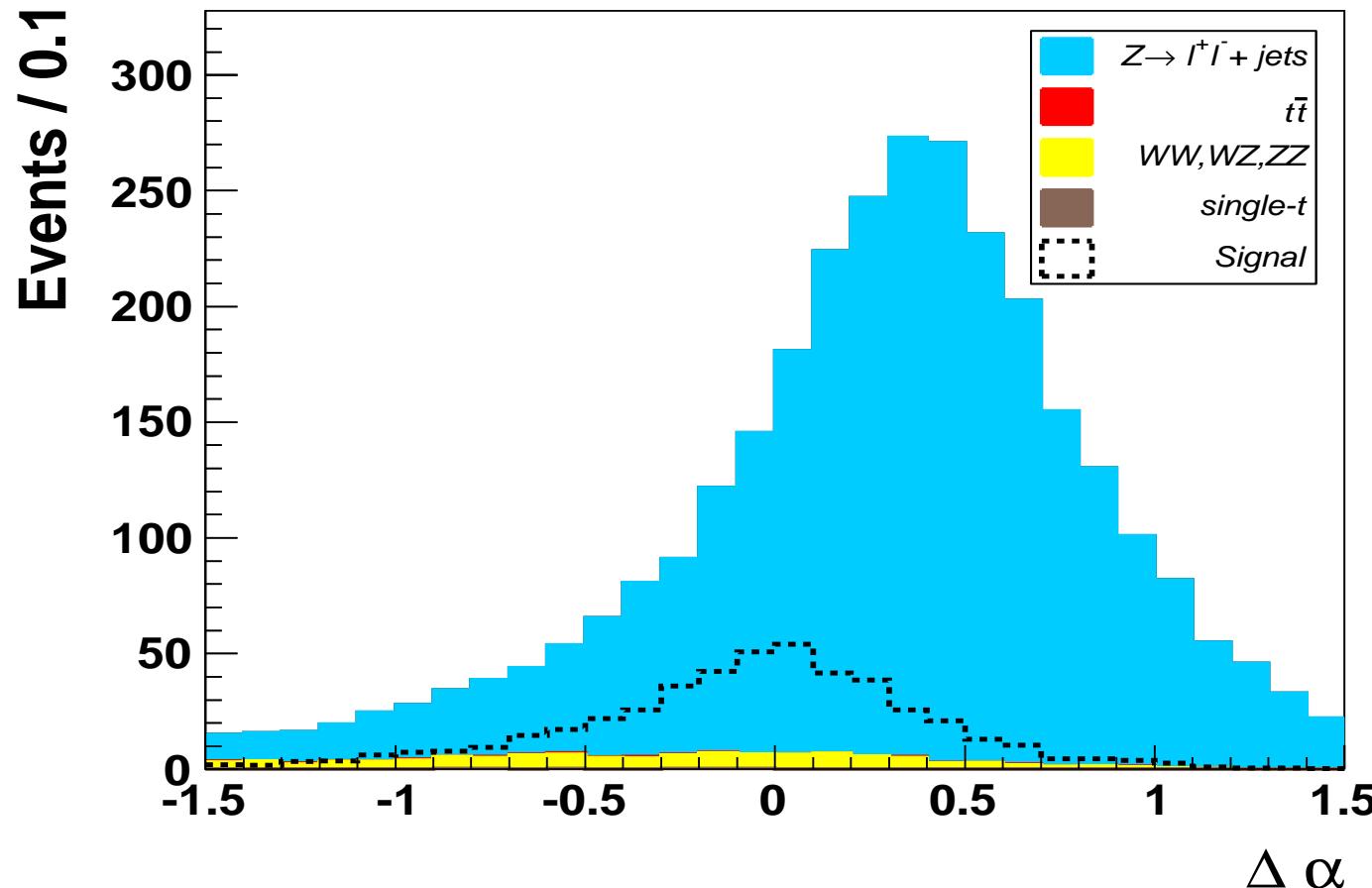
Selection criteria	$N_{backgrd.}$	Signal efficiency (%)
muon, $p_T > 30$ GeV	43,500	9.4
e, $p_T > 10$ GeV		
OS	42,652	9.4
no jet with $p_T > 30$ GeV	11,358	7.8
$\Delta\phi(e, \mu) > 2.7$	6,850	6.9
$\Delta\phi(e, \cancel{E}_T) < 0.7$	3,763	6.2
$38\,GeV < M_{e\mu} < 92\,GeV$	3,201	6.1

Originally 5.5 M SM background events, are left 3201. Of which, 95% are $Z/\gamma^* \rightarrow \tau^\pm \tau^\mp \rightarrow \mu^\pm e^\mp \nu \bar{\nu}$ (see next page).

signal efficiency : 6.1 %.

LEP limit ($BR(Z \rightarrow \tau^\pm \mu^\pm) < 1.2 \times 10^{-5}$) = 489 signal events.

So where are we now? ...



$\Delta\alpha \propto \cancel{E}_T(\text{calculated for } Z \rightarrow \tau^\pm \mu^\mp) - \cancel{E}_T(\text{reconstructed from leptons})$

(dashed line is $Z \rightarrow \tau^\pm \mu^\mp$ at the LEP1 limit: 489 evts. Backgrd = 3201)

Getting a bound on $BR(Z \rightarrow \tau^\pm \mu^\mp)$ from that plot... statistics

Want to quantify that the simulated background does not look like the signal (significance test)

Have expected background, and signal efficiency.

Assume 3% systematic uncertainty (!)

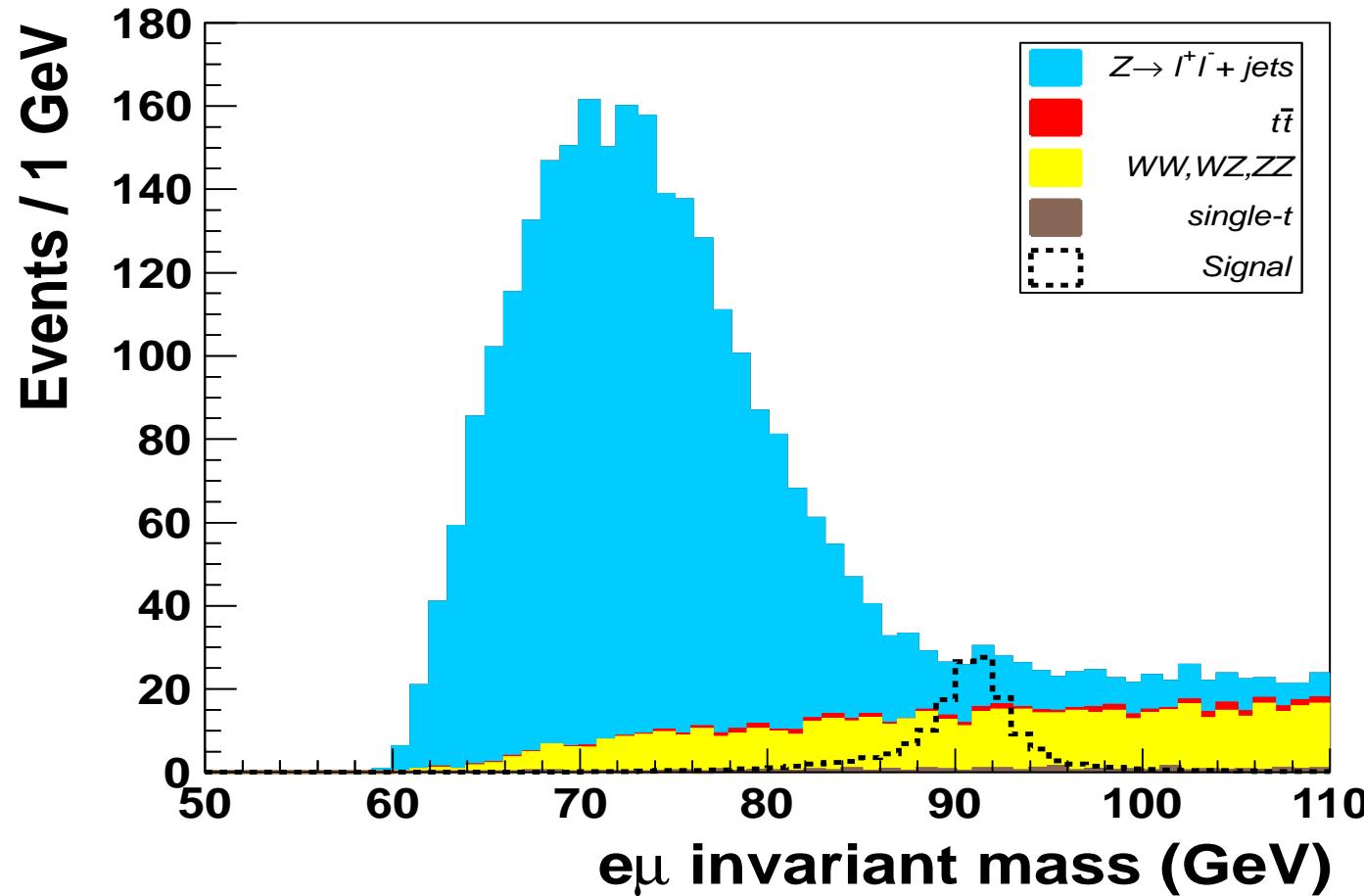
Compute 95% CL expected limit...using CL_s

(\simeq value of BR such that should see more events in 95% of cases):

$$BR(Z \rightarrow \tau^\pm \mu^\mp) < 3.5 \times 10^{-6}$$

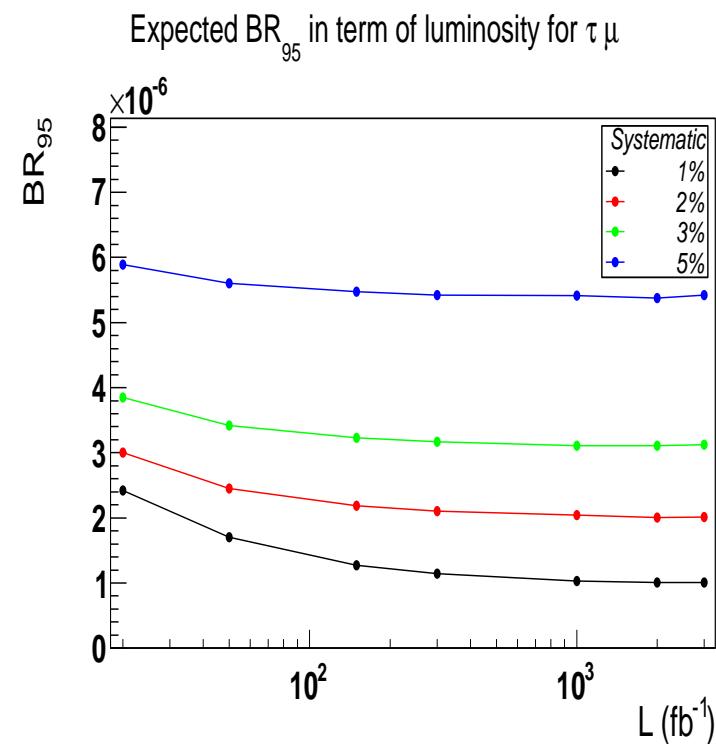
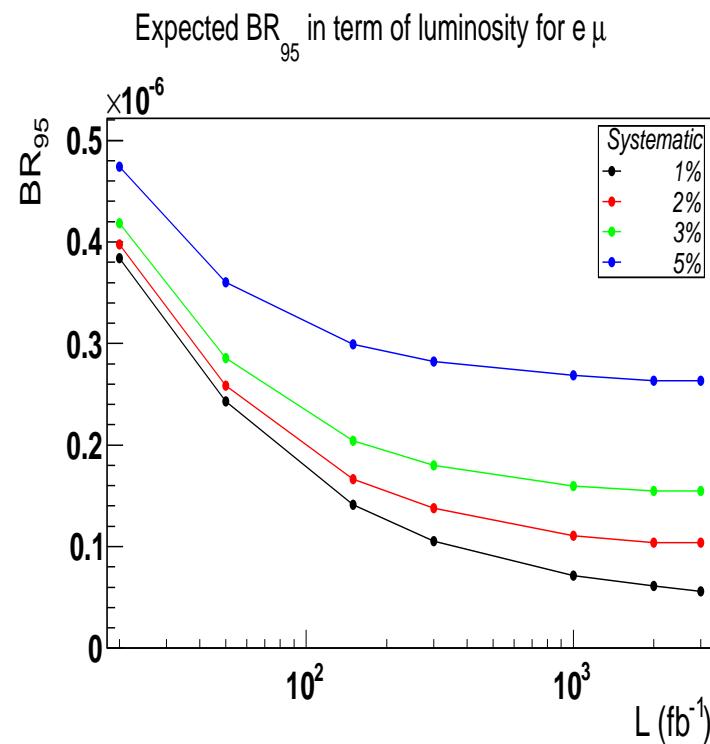
(4 times better than LEP1)

If look for $BR(Z \rightarrow e^\pm \mu^\mp)$ too...



$$BR(Z \rightarrow e^\pm \mu^\mp) < 4.1 \times 10^{-7}$$

Systematics...



BackUp

Interpreting what we know: bounds assuming dimension 6 operators

process	bound	scale, dim 6, loop
$BR(\mu \rightarrow e\gamma)$	$< 2.4 \times 10^{-12}$	48 TeV
$BR(\mu \rightarrow e\bar{e}e)$	$< 1.0 \times 10^{-12}$	174 TeV (tree) 14 TeV
$\frac{\sigma(\mu + Ti \rightarrow e + Ti)}{\sigma(\mu Ti \rightarrow \nu Ti')}$	$< 4.3 \times 10^{-13}$	40 TeV
$BR(\tau \rightarrow \ell\gamma)$	$< 3.3, 4.4 \times 10^{-8}$	2.8 TeV
$BR(\tau \rightarrow 3\ell)$	$< 1.5 - 2.7 \times 10^{-8}$	0.8 TeV
$BR(\tau \rightarrow e\pi)$	$< 8.1 \times 10^{-8}$	0.5 TeV
$BR(\overline{K_L^0} \rightarrow \mu\bar{e})$	$< 4.7 \times 10^{-12}$	25 TeV($V \pm A$) 140 TeV($S \pm P$)
$BR(Z \rightarrow e^\pm \mu^\mp)$	$< 1.7 \times 10^{-6}$	0.22 TeV
$BR(Z \rightarrow e^\pm \tau^\mp)$	$< 9.8 \times 10^{-6}$	0.14 TeV
$BR(Z \rightarrow \mu^\pm \tau^\mp)$	$< 1.2 \times 10^{-5}$	0.14 TeV

if all flavour-changing couplings are of the same order, then should look for LFV in $\mu \rightarrow e$

lepton decays probe higher M than Z decays—in EFT, given μ, τ bounds, can LFV Z decay be observed?

Is it worth looking for LFV Z decays: \mathcal{L}_{eff} for $Z \rightarrow \tau^\pm \mu^\mp$ dim 6

Mass dimension of Z and two lepton external legs = 4

\Rightarrow operator contains two Higgs and/or Derivatives

Three options among gauge invariant operators at dimension 6:

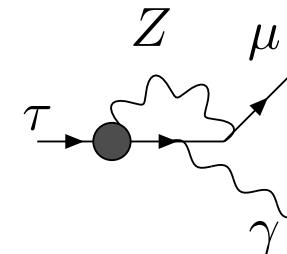
$$\mathcal{O}(\partial^2) : \bar{\mu}\gamma_\beta D_\alpha \tau B^{\alpha\beta}, \bar{\ell}_\mu \sigma^I \gamma_\beta D_\alpha \ell_\tau W^{I\alpha\beta}, \bar{\ell}_\mu \gamma_\beta D_\alpha \ell_\tau B^{\alpha\beta}$$

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

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

The gradient² $Z \rightarrow \tau^\pm \mu^\mp$ 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 $\tau \rightarrow \mu\gamma$), so “interaction”:

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

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

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

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

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



p_T of e and μ , for $Z \rightarrow \tau^\pm \mu^\mp \rightarrow (e^\pm \nu \bar{\nu}) \mu^\mp$

