Lepton Flavour Violating Z decays @ LHC

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1. preliminaries: Zs at the LHC

2. introduction:

   - what is LFV? *and why is it interesting?*
   - some upper bounds

3. effective operators for $Z \to \ell\overline{\ell'}$...

   - an improbable place to find LFV

4. $Z \to \tau^{\pm}\mu^{\mp}$ @ LHC ... in the $Z \to \tau^{+}\tau^{-}$ background?

5. real work (thanks to S Lacroix)

6. expected limits

the LHC is not the wrong place to do Z physics

- LEP1 was a clean Z machine, with 17×10^6 Zs

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

- at the 7,8 TeV LHC, $\sigma(pp \to Z \to \mu\bar{\mu}) \sim$ nb. $\mathcal{L} \sim 20$ fb^{-1} $\Rightarrow 20 \times 10^6$ Zs ??

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

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

(compare $e.g.$ $\sigma(pp \to t\bar{t}) \sim 160$ pb... $\gtrsim 150$ Zs for each $t\bar{t}$ pair)

Lepton Flavour Violation: what is it? Why interesting?

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

1. we know $m_\nu \neq 0 \Rightarrow$ *Beyond the Standard Model in the leptons!* 

2. But not see LFV yet. 

3. But $\mathcal{A}(\mathrm{LFV}) \propto m_\nu^2/m_W^2 \sim 20^{-24}, \Rightarrow$ observable LFV requires dynamics other than m_ν

   entertainment for theorists: obtain log GIM in leptons...

What do we know (experimentally)

some processes	current sensitivities
$BR(\mu \to e\gamma)$	$< 2.4 \times 10^{-12}$
$BR(\mu \to e\bar{e}e)$	$< 1.0 \times 10^{-12}$
$\frac{\sigma(\mu+Au\to e+Au)}{\sigma(\mu \text{ capture})}$	$< 7 \times 10^{-13}$
$BR(\tau \to \ell\gamma)$	$< 3.3, 4.4 \times 10^{-8}$
$BR(\tau \to 3\ell)$	$< 1.5 - 2.7 \times 10^{-8}$
$BR(\tau \to e\phi)$	$< 3.1 \times 10^{-8}$
$BR(\overline{K_L^0} \to \mu\bar{e})$	$< 4.7 \times 10^{-12}$
$BR(K^+ \to \pi^+\bar{\nu}\nu)$	$= 1.7 \pm 1.1 \times 10^{-10}$
$BR(Z \to e^{\pm}\mu^{\mp})$	1.7×10^{-6}
$BR(Z \to e^{\pm}\tau^{\mp})$	9.8×10^{-6}
$BR(Z \to \mu^{\pm}\tau^{\mp})$	1.2×10^{-5}

How to interpret those numbers —two perspectives

1. m_ν arise in my favourite model — what do LFV bounds tell me about it?

2. I want to know what generates m_ν — how do I learn that from the data?

? maybe I learn something with the Effective Lagrangian?

(Organising and interpreting) what we know: the effective Lagrangian

Suppose that NP(articles) are above (fuzzy) mass scale $M > m_Z$. At $E \ll M$, describe their effects as "contact interactions" among light particles in an "effective Lagrangian":

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \Delta\mathcal{L}_{eff}^{LFV} + \Delta\mathcal{L}_{eff}^{other}$$

$$\Delta\mathcal{L}_{eff}^{LFV} = \sum_{d \geq 5} \sum_{n} \frac{C^n}{M^{d-4}} O_n(H, \{\psi\}, A_\mu, ...) + h.c.$$

The operators $\{O_n\}$:

- built with *kinematically accessible* SM fields (avec Z, at m_Z; sans Z à m_τ)
- respect SM gauge symmetries
- describe the legs of the LFV diagrams (including Higgs vevs)

The (dimless) coefficients C^n contain coupling constants, $1/16\pi^2$, ...

(SM = Standard Model, NP = New Physics, New Particles +...)

At dimension six in $\mathcal{L}_{eff}$, at scales $\lesssim m_Z$

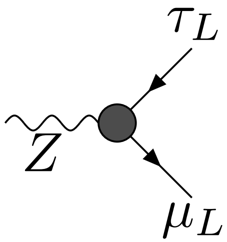
match in two steps:

1) @ M: EW + NP onto broken SM with particles $\{Z, W^{\pm}, \tau, \mu, e, \nu_\alpha, \gamma\}$ and $\mathcal{L}_{eff}$

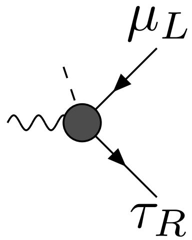
2) @ $m_Z(m_W)$: onto SM with particles $\{\tau, \mu, e, \nu_\alpha, \gamma\}$ and $\mathcal{L}'_{eff}$

After step 1):

$$\Delta\mathcal{L}_{eff}^{LFV,6} = +\frac{C^{\tau\mu} m_Z^2}{16\pi^2 M^2}$$

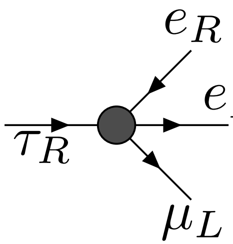


$$+ \quad \frac{e m_\tau C^{\tau\mu}}{16\pi^2 M^2}$$

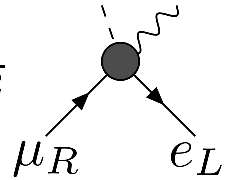


$+ \ldots +$ h.c.

$$+ \Big(\ldots + \frac{C^{e\tau\mu e}}{16\pi^2 M^2}$$



$$+ \quad \frac{e y_\mu C^{e\mu}}{16\pi^2 M^2}$$



$+ \ldots +$ h.c. $\Big)$

(NB I assume NP in loops; $\propto 1/(16\pi^2 M^2)$, for most LFV processes)

At dimension six in $\mathcal{L}_{eff}$, at scales $\lesssim m_Z$

match in two steps:
1) @ M: EW + NP onto broken SM with particles $\{Z, W^{\pm}, \tau, \mu, e, \nu_\alpha, \gamma\}$ and $\mathcal{L}_{eff}$
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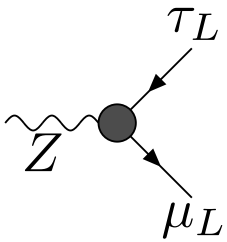
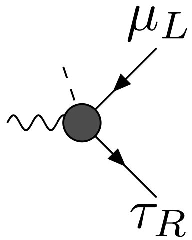
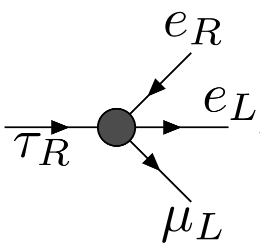


$$+ \quad \frac{e m_\tau C^{\tau\mu}}{16\pi^2 M^2}$$

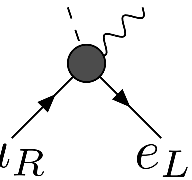


$$+ \ldots + \text{h.c.}$$

$$+ \left(\ldots + \frac{C^{e\tau\mu e}}{16\pi^2 M^2} \right.$$



$$+ \quad \frac{e y_\mu C^{e\mu}}{16\pi^2 M^2}$$



$$\left. + \ldots + \text{h.c.} \right)$$

For a given process with $BR <$ ..., can obtain a lower bound on M:

1. identify operators/diagrams corresponding to a process,

2. set $C \simeq 1$,

3. compute rate,...

Interpreting what we know: bounds assuming dimension 6 operators

process	bound	scale, dim 6, loop
$BR(\mu \to e\gamma)$	$< 2.4 \times 10^{-12}$	
$BR(\mu \to e\bar{e}e)$	$< 1.0 \times 10^{-12}$	
$\frac{\sigma(\mu + Ti \to e + Ti)}{\sigma(\mu Ti \to \nu Ti')}$	$< 4.3 \times 10^{-13}$	
$BR(\tau \to \ell\gamma)$	$< 3.3, 4.4 \times 10^{-8}$	
$BR(\tau \to 3\ell)$	$< 1.5 - 2.7 \times 10^{-8}$	
$BR(\tau \to e\pi)$	$< 8.1 \times 10^{-8}$	
$BR(\overline{K_L^0} \to \mu\bar{e})$	$< 4.7 \times 10^{-12}$	
$BR(Z \to e^{\pm}\mu^{\mp})$	$< 1.7 \times 10^{-6}$	0.22 TeV
$BR(Z \to e^{\pm}\tau^{\mp})$	$< 9.8 \times 10^{-6}$	0.14 TeV
$BR(Z \to \mu^{\pm}\tau^{\mp})$	$< 1.2 \times 10^{-5}$	0.14 TeV

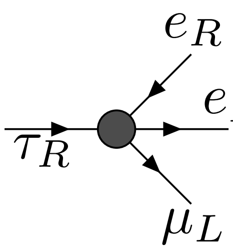
can produce such NP at LHC?

EFT marginally consistent?

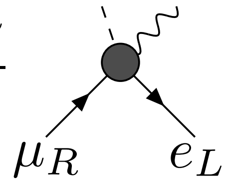
At dimension six in $\mathcal{L}_{eff}$, at scales $\lesssim 10$ GeV

operators $\mathcal{O}_n \Leftrightarrow$ diagrams, coefficients $\frac{C^{(n)}}{M^{d-4}} \approx$ coupling constant for the diagram,

$$\Delta\mathcal{L}_{eff}^{LFV,6} = ... + \frac{C^{e\tau\mu e}}{16\pi^2 M^2}$$



$$+ \frac{e m_\mu C^{e\mu}}{16\pi^2 M^2}$$



$$+ ... + \text{h.c.}$$

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3. compute rate,...

Interpreting what we know: bounds assuming dimension 6 operators

process	bound	scale, dim 6, loop
$BR(\mu \to e\gamma)$	$< 2.4 \times 10^{-12}$	48 TeV
$BR(\mu \to e\bar{e}e)$	$< 1.0 \times 10^{-12}$	174 TeV (tree)
		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$(S \pm P)$
$BR(Z \to e^{\pm}\mu^{\mp})$	$< 1.7 \times 10^{-6}$	0.22 TeV
$BR(Z \to e^{\pm}\tau^{\mp})$	$< 9.8 \times 10^{-6}$	0.14 TeV
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if all flavour-changing couplings are of the same order, then should look for LFV in $\mu \to e$

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

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   - **an improbable place to find LFV**

4. $Z \to \tau^\pm\mu^\mp$ @ LHC ... in the $Z \to \tau^+\tau^-$ background?

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6. expected limits

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

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:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

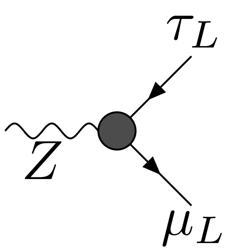
Rossi+Brignole

$$
\begin{aligned}
..., \quad \overline{\mu}\gamma_\beta D_\alpha \tau B^{\alpha\beta} \quad &\to \quad g_Z C \frac{p_Z^2}{16\pi^2 M^2} \overline{\mu}\gamma_\alpha \tau Z^\alpha \\
..., \quad [H^\dagger D_\alpha H]\overline{\mu}\gamma^\alpha \tau \quad &\to \quad g_Z A \frac{m_Z^2}{16\pi^2 M^2} \overline{\mu}\gamma_\alpha Z^\alpha \tau \\
..., \quad \overline{\ell}_\mu H \sigma_{\beta\alpha} \tau B^{\alpha\beta} \quad &\to \quad g_Z D \frac{m_\tau}{16\pi^2 M^2} [\overline{\mu}\sigma_{\alpha\beta}\tau] Z^{\alpha\beta}
\end{aligned}
$$

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

Operators with gradients better constrained at higher energies:

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



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

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

Rossi+Brignole

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

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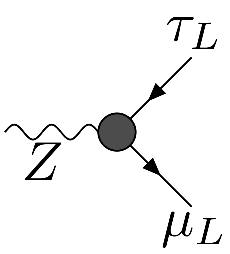
$$\ldots, \quad \overline{\ell}_\mu H \sigma_{\beta\alpha} \tau B^{\alpha\beta} \quad \to \quad g_Z D \frac{m_\tau}{16\pi^2 M^2} [\overline{\mu}\sigma_{\alpha\beta}\tau] Z^{\alpha\beta}$$

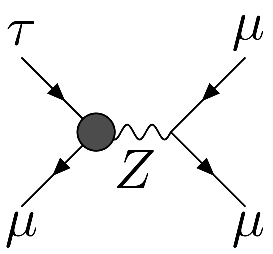
NP of mass $M > m_Z$ in a loop, A, C, D dimless

Operators with gradients better constrained at higher energies:

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

in $\tau^\pm \to \mu^\mp \mu^\pm \mu^\pm$: vertex $< g_Z \frac{C m_\tau^2}{16\pi^2 M^2} \overline{\mu} \not{Z} \tau$



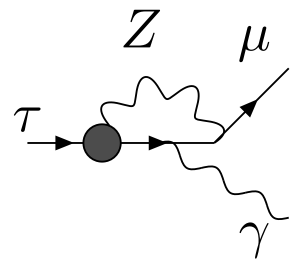


YES $\mathcal{O}(\partial^2)$ operators interesting

despite that I don't know
a model that gives C big and A, D small

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

(parenthèse: H^2 and dipole operators can be neglected for $Z \to \tau^\pm \mu^\mp$)

neglect $\mathcal{O}(H^2)$ and $\mathcal{O}(yH\partial)$ operators, because more strictly constrained elsewhere:

- for $[H^\dagger D_\alpha H]\overline{\mu}\gamma^\alpha \tau \to g_Z A \frac{m_Z^2}{16\pi^2 M^2} \overline{\mu}\gamma_\alpha Z^\alpha \tau$

$$\frac{BR(Z \to \tau^\pm \mu^\mp)}{BR(Z \to \mu^+ \mu^-)} \simeq \frac{m_Z^4}{s_W^4 M^4}|A|^2 \lesssim 1 \ , \ \frac{BR(\tau \to 3\mu)}{BR(\tau \to \mu\nu\bar{\nu})} = \frac{m_Z^4}{M^4}|A|^2 \lesssim 10^{-2}$$

- for $\overline{\ell}_\mu H \sigma_{\beta\alpha} \tau B^{\alpha\beta} \to g_Z D \frac{m_\tau}{16\pi^2 M^2}[\overline{\mu}\sigma_{\alpha\beta}\tau] Z^{\alpha\beta}$

  probably (?), SM gauge invariant operators contribute also to photon dipole...not pay m_τ factor in $\tau \to \mu\gamma$, so better bounds there.

$\Rightarrow$ better bounds on coefficients of H^2 and dipole operators from lepton precision than Z decay.

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5. real work (thanks to S Lacroix)
6. expected limits

$Z \to \tau^\pm \mu^\mp$ — how to find at the LHC?

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

- $\mu \to e\gamma \Rightarrow BR(Z \to e^\pm \mu^\mp) \lesssim 10^{-10}$

- end 2012, a few $\times 10^8$ Zs at the LHC

- reconstruct μ, e with $.5 \to$ few % accuracy (...hadronic τs are "difficult"...)

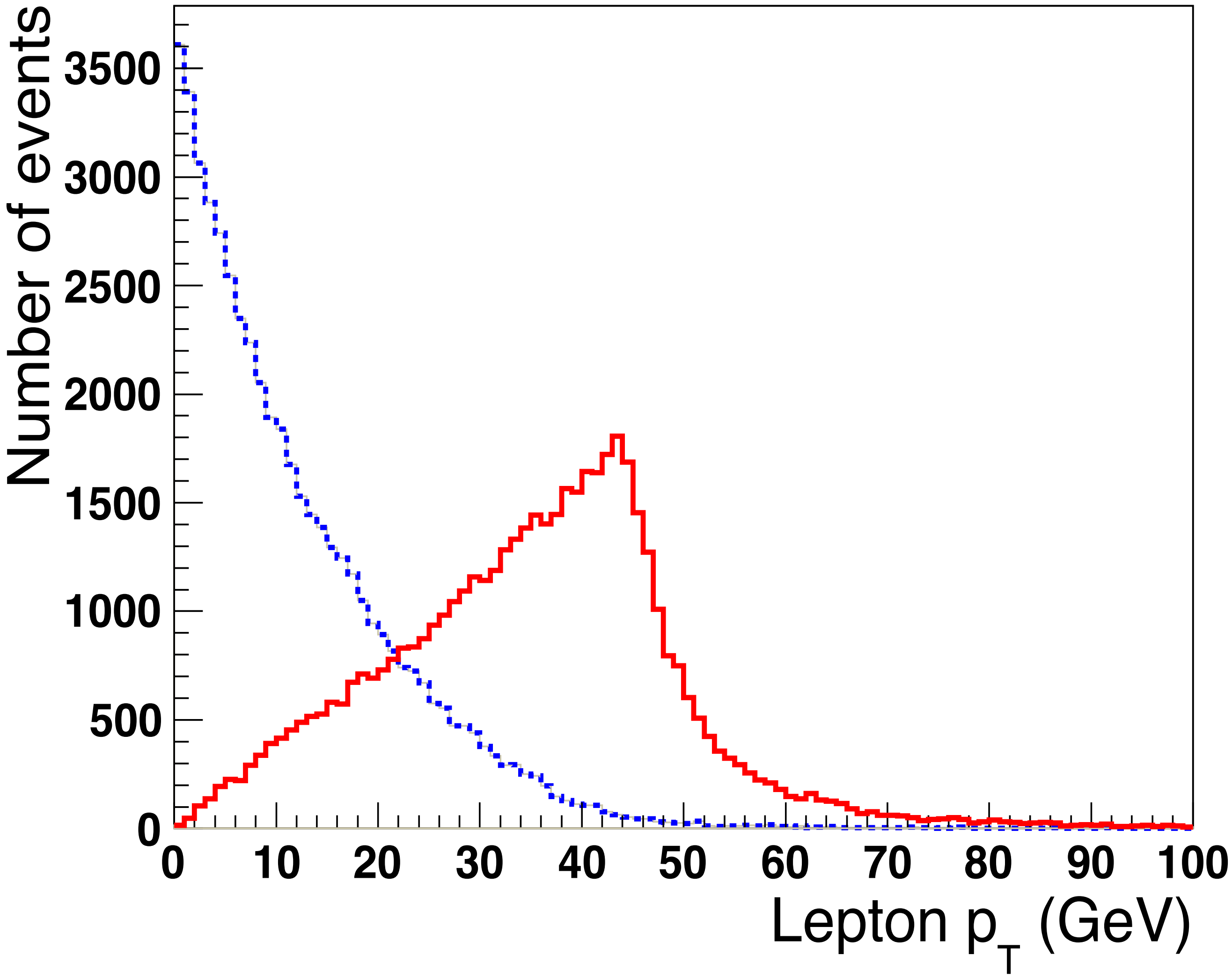
$$\Rightarrow \text{study } Z \to \tau^\pm \mu^\mp \to (e^\pm \nu \bar{\nu})\mu^\mp$$

(recall $BR(\tau \to \ell \nu \bar{\nu}) \simeq 0.176$)

- can extrapolate to $Z \to \tau^\pm e^\mp$, because soft μ easier to find that soft e (see next page)

- ?? how to find in $Z \to \tau^\pm \tau^\mp \to (e^\pm \nu \bar{\nu})(\mu^\mp \nu \bar{\nu})$?? $(BR(Z \to e\mu + 4\nu) \sim 10^{-3})$

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



Kinematics

- Want to distinguish $pp \to Z \to \tau^+\mu^- \to (e^+\nu\bar{\nu})\mu^-$
from background $pp \to Z \to \tau^+\tau^- \to (e^+\nu\bar{\nu})(\mu^-\nu\bar{\nu})$ ...
- variable that differs for $\not{p}_T$ with e (signal) from $\not{p}_T$ with e and μ:

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from background $pp \to Z \to \tau^+\tau^- \to (e^+\nu\bar{\nu})(\mu^-\nu\bar{\nu})$ ...
• variable that differs for $\not{p}_T$ with e (signal) from $\not{p}_T$ with e and μ:

1. *collinear approx* for τ decay products
   τ boosted : $\gamma \sim m_Z/(2m_\tau)$, $\Rightarrow$ all τ daughters aligned on τ:

$$p_{\tau^+} = p_{e^+} + p_\nu + p_{\bar{\nu}} \equiv \alpha p_{e^+}$$

   for backgrd, $Z \to \tau^+\tau^- \to (e^+\nu\bar{\nu})(\mu^-\nu\bar{\nu})$ also $p_{\tau^-} = \beta p_{\mu^-}$.
   $\text{signal} : p_Z^2 - m_\tau^2 = 2\alpha p_{e^+} \cdot p_{\mu^-} \quad , \quad \text{background} : m_Z^2 - 2m_\tau^2 = 2\alpha\beta p_{e^+} \cdot p_{\mu^-}$

2. Neglect p_T of Z :
   $\text{signal} : \alpha|p_{T,e^+}| = |p_{T,\mu^-}| \quad , \quad \text{background} : \alpha|p_{T,e^+}| = \beta|p_{T,\mu^-}|$

$\Rightarrow$ two determinations of $\not{p}_T = p_{T,\nu} + p_{T,\bar{\nu}}$ (α), assuming its aligned on $p_{T,e}$.
Difference is 0 for signal...and not for background.

Lepton Flavour Violating Z decays @ LHC

1. preliminaries: Zs at the LHC

2. introduction:

3. effective operators for $Z \to \tau\overline{\mu}$...

    - an improbable place to find LFV

4. Z $\to \tau^{\pm}\mu^{\mp}$ @ LHC ... in the $Z \to \tau^{+}\tau^{-}$ background?

5. **real work (thanks to S Lacroix, and P Verdier)**

6. expected limits

Backgrounds and Simulations...

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

1. $Z/\gamma^* \to \tau^\pm\tau^\mp \to \ell^\pm\nu\bar{\nu}\ell'^\mp\nu\bar{\nu}$ with $\ell,\ell' = e,\mu$ ($M_{Z/\gamma^*} > 20$ GeV) 4 800 000

2. $t\bar{t} \to b\ell^+\nu\bar{b}\ell'^-\bar{\nu}$ with $\ell,\ell' = e,\mu,\tau$ 480 000

3. $Wt \to \ell^\pm\nu b\ell'^\mp\nu$ with $\ell,\ell' = e,\mu,\tau$ 47 000

4. $W^+W^- \to \ell^+\nu\ell'^-\bar{\nu}$ with $\ell,\ell' = e,\mu,\tau$ 120 000

5. $Z/\gamma^* Z/\gamma^* \to f\bar{f}f'\bar{f}'$ 160 000

(N)NLO/(N)NLL cross-sections from various codes. LO simulation with Pythia. 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 $Z \to \tau^{\pm}\mu^{\mp}$...

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

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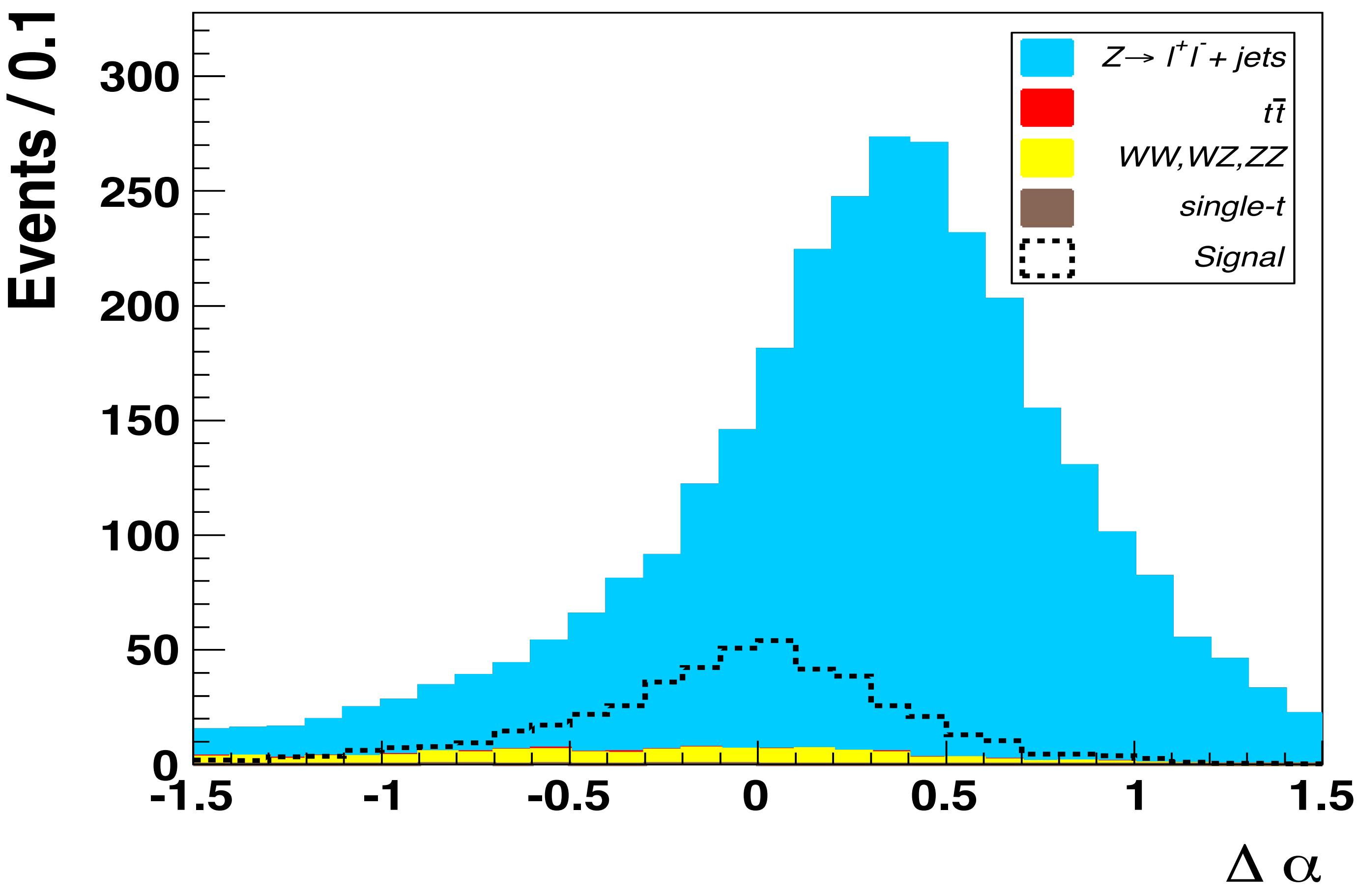
$\Delta\phi(e,\mu) > 2.7$	6,850	6.9
$\Delta\phi(e,\not{E}_T) < 0.7$	3,763	6.2
$38\,GeV < M_{e\mu} < 92$ GeV	3,201	6.1

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

signal efficiency : 6.1 %.
LEP limit ($BR(Z \to \tau^{\pm}\mu^{\pm}) < 1.2 \times 10^{-5}$) = 489 signal events.

So where are we now? ...



$\Delta\alpha \to 0$ for neutrino 4-p aligned on e

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

Getting a bound on $BR(Z \to \tau^{\pm}\mu^{\mp})$ 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 (!)

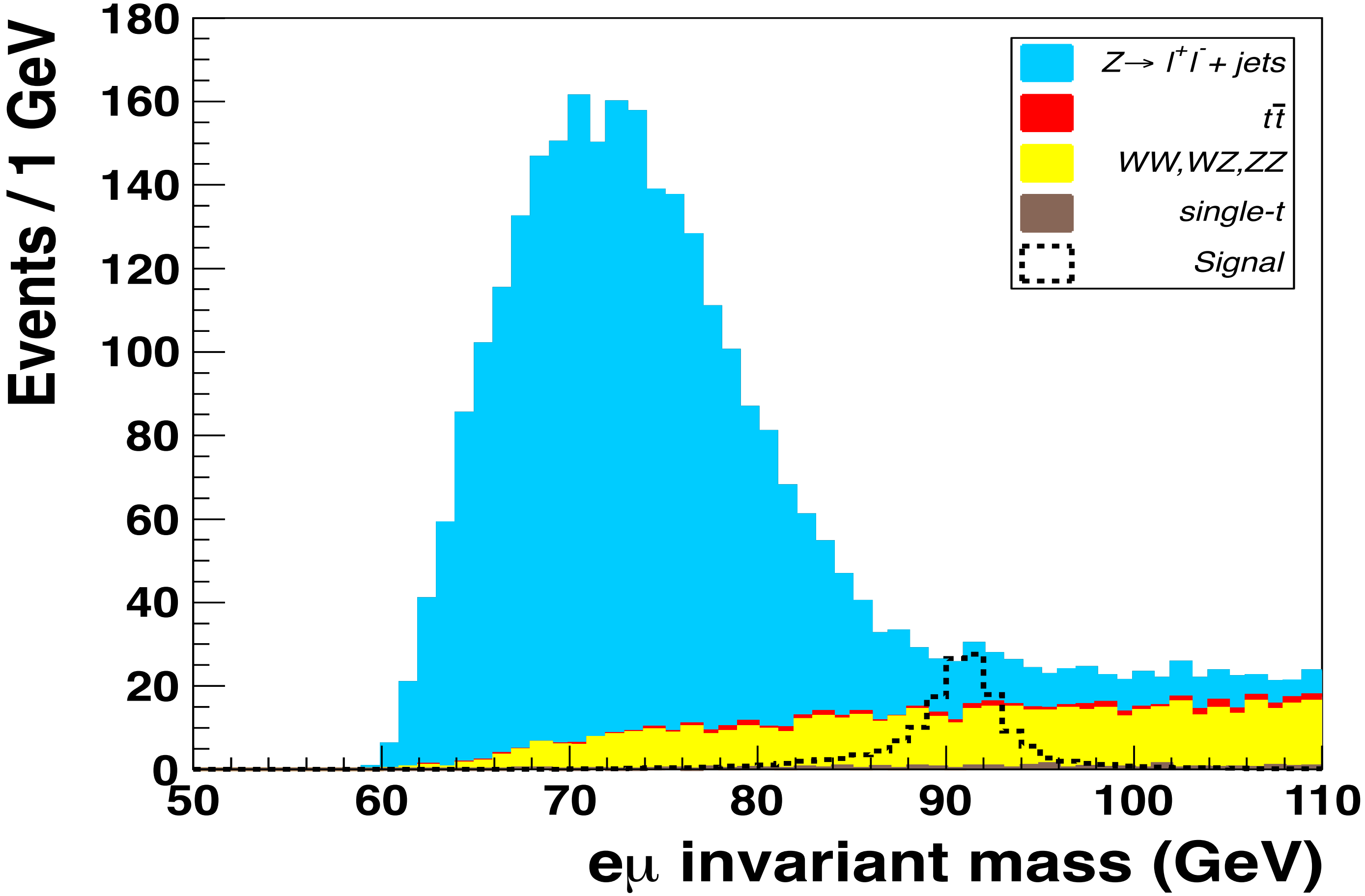
Compute 95% CL expected limit...using CL_s

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

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

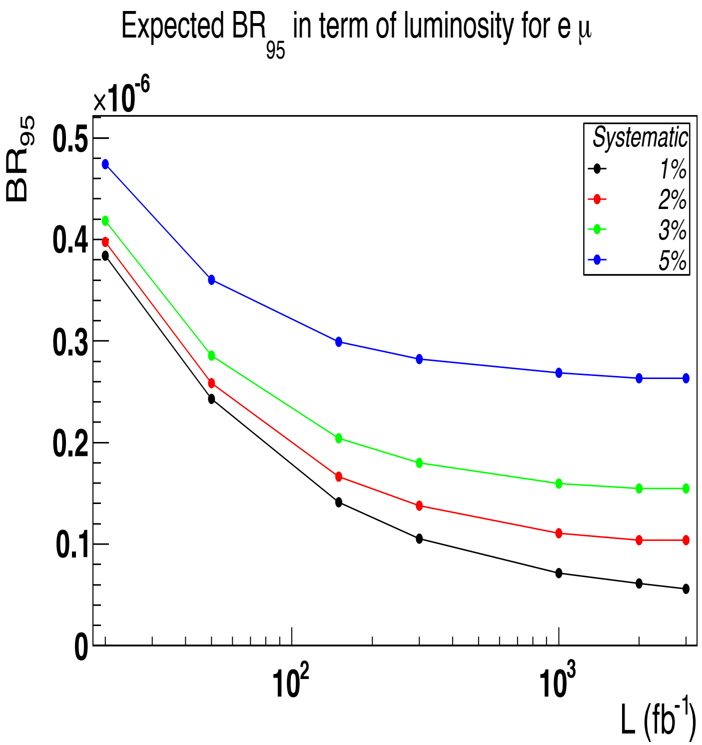
(4 times better than LEP1)

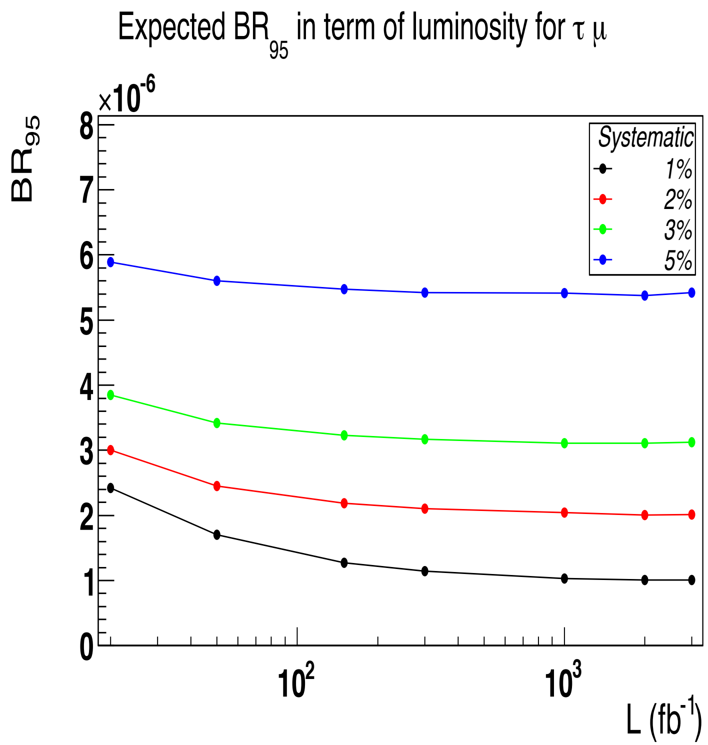
If look for $BR(Z \to e^{\pm}\mu^{\mp})$ too...



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

Systematics...





Summary

- 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:

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

- with data up to 2013, and aggressive systematic error improvement ($\to 3\%$), can improve LEP bounds by factor ~ 4:

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

(expect sensitivity $BR(Z \to \tau^\pm e^\mp)$ similar/better than $Z \to \tau^\pm \mu^\mp$. And $BR(Z \to e^\pm \mu^\mp) < 10^{-10}$ from $\mu \to e\gamma$).