NSI @ colliders?

S Davidson, V Sanz

if neutral current NSI are induced at dimension eight, $e.g.$ for f a first generation fermion

$$\frac{1}{\Lambda_8^4}(\overline{f}\gamma^\rho P_X f)(\overline{H\ell}_\alpha \gamma_r H \ell_\beta) \longrightarrow \varepsilon_{\alpha\beta}^{fX} \frac{4G_F}{\sqrt{2}}(\overline{f}\gamma^\rho P_X f)(\overline{\nu}_\alpha \gamma_r \nu_\beta)$$

then defining $v = 174$ GeV, this corresponds to $\frac{v^2}{\Lambda_8^4} \simeq \frac{\varepsilon}{v^2}$, so

$$\varepsilon = \frac{v^4}{\Lambda_8^4} \gtrsim 10^{-4} \Rightarrow \Lambda_8 \lesssim \left\{ \begin{array}{cc} 2 \text{ TeV} & \text{tree} \\ 500 \text{ GeV} & \text{loop} \end{array} \right.$$

$\Rightarrow$ colliders??

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... the LHC finds new particles, and νfact precisely measures their couplings via NSI?

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... if the LHC does not discover new physics... can νfact see NSI?

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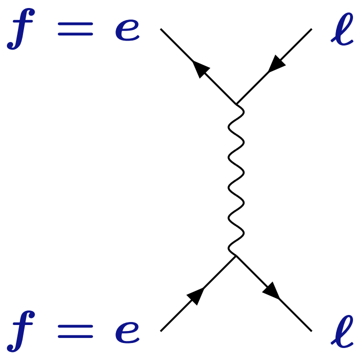
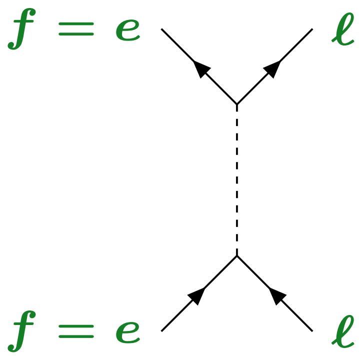
LEP2 $\Rightarrow$ not-really bounds on tree-level NSI
LHC — ???...wee numerical difficulties...

A little detour — what about dimension charged lepton operators?

- suppose NC NSI at dimension 8, due to *tree level* New Physics, and that coefficients of "dangerous" (charged lepton flavour changing) dimension 6 operators vanish due to a cancellation:





Gavela et al
Antusch etal

$$\frac{g^2}{m_V^2 - u}(\overline{e^c}\gamma^\mu \ell)(\overline{\ell}\gamma_\mu e^c) = -\frac{g^2}{m_V^2 - u}(\overline{e}\gamma^\mu e)(\overline{\ell}\gamma_\mu \ell)$$

$$-\frac{h^2}{m_S^2 - t}(\overline{e}\ell)(\overline{\ell}e) = \frac{h^2}{2(m_S^2 - t)}(\overline{\ell}\gamma^\mu \ell)(\overline{e}\gamma_\mu e)$$

- for $m_V^2, m_S^2 \gg s, t, u$, can take $g^2/m_V^2 = h^2/2m_S^2$ and sum gives

$$\frac{g^2(t/m_S^2 - u/m_V^2)}{m_V^2}(\overline{\ell}\gamma^\mu \ell)(\overline{e}\gamma_\mu e)$$

The cancellation only works at zero momentum transfer
$\Rightarrow$ 4-charged-lepton dimension 8 contact interaction, with coefficient $\sim s/\Lambda_8^4, (t-u)/\Lambda_8^4$

Not-really "bounds" from LEP2

LEP2 set bounds, from σ and A_{FB}, on dimension six contact interactions

$$\pm\frac{4\pi}{\Lambda^2_{6,\pm}}(\overline{e}\gamma^\mu P_X e)(\overline{f}_\alpha\gamma_\mu P_Y f_\alpha) \qquad \overline{f}_\alpha f_\alpha \in \{e^+e^-, \mu^+\mu^-, \tau^+\tau^-\}$$

with $\sqrt{s} \geq .85 \times (183 \to 209)$ GeV.

Translate to dimension 8 double-derivative operators, with same legs but coefficients

$$\frac{4\pi}{\Lambda_6^2} \to \frac{s}{\Lambda_8^4}, \frac{t-u}{\Lambda_8^4} \text{ by assuming } \frac{s}{\Lambda_8^4}, \frac{t-u}{\Lambda_8^4}\Big|_{LEP2} \simeq \frac{v^2}{\Lambda_8^4} \text{ and requiring} \frac{v^2}{\Lambda_8^4} \leq \frac{4\pi}{\Lambda_6^2}\Big|_{LEP2\ bound}$$

$(\overline{e}\gamma^\mu P_X e)(\overline{\ell}\gamma_\mu P_Y \ell)$	bound	ε
$e^+e^- \to e^+e^-$		
XY=LL	$\Lambda_{6+} \gtrsim 10.3$ TeV	$\lesssim 3.7 \times 10^{-3}$
LL	$\Lambda_{6-} \gtrsim 8.3$ TeV	$\lesssim 5.6 \times 10^{-3}$
RL	$\Lambda_{6+} \gtrsim 8.8$ TeV	$\lesssim 4.7 \times 10^{-3}$
RL	$\Lambda_{6-} \gtrsim 12.7$ TeV	$\lesssim 2.4 \times 10^{-3}$
$e^+e^- \to \mu^+\mu^-$		
XY=LL	$\Lambda_{6+} \gtrsim 8.1$ TeV	$\lesssim 5.9 \times 10^{-3}$
LL	$\Lambda_{6-} \gtrsim 9.5$ TeV	$\lesssim 4.3 \times 10^{-3}$
RL	$\Lambda_{6\pm} \gtrsim 6.3$ TeV	$\lesssim 9.1 \times 10^{-3}$
$e^+e^- \to \tau^+\tau^-$		
XY=LL	$\Lambda_{6+} \gtrsim 7.9$ TeV	$\lesssim 6.2 \times 10^{-3}$
LL	$\Lambda_{6-} \gtrsim 5.8$ TeV	$\lesssim 1.1 \times 10^{-2}$
RL	$\Lambda_{6+} \gtrsim 6.4$ TeV	$\lesssim 9.1 \times 10^{-3}$
RL	$\Lambda_{6-} \gtrsim 4.6$ TeV	$\lesssim 1.8 \times 10^{-2}$

$$\varepsilon = v^4/\Lambda^4$$

Many $\mathcal{O}(1)$ factors!!

$\varepsilon_{\alpha\alpha} \lesssim 10^{-2} - 10^{-3}$

OPAL — bounds on flavour-changing contact interactions at LEP2!

The OPAL experiment saw one $e^+e^- \to e^\pm\mu^\mp$ event at $\sqrt{s} = 189 - 209$ GeV, and published limits on $\sigma(e^+e^- \to e^\pm\mu^\mp, e^\pm\tau^\mp, \tau^\pm\mu^\mp)$.

Naively, "no point" in doing LFV at LEP2 because better bounds on dim 6 contact interactions from $\mu \to 3e$, $\tau \to 3\ell$.

Gives stronger bounds on double-derivative dimension 8 operators than LEP1 (not competing with the Z peak).

$\Rightarrow$ calculate σ for double-derivative dimension 8 operators... and get

$(\overline{e}\gamma^\mu P_X e)(\overline{\ell}\gamma_\mu P_Y \ell)$	ε
$e^+e^- \to e^\pm\mu^\mp$ $\forall\ XY$	$\lesssim 8.7 \times 10^{-3}$
$e^+e^- \to e^\pm\tau^\mp$ $\forall\ XY$	$\lesssim 1.6 \times 10^{-2}$
$e^+e^- \to \tau^\pm\mu^\mp$ $\forall\ XY$	$\lesssim 1.5 \times 10^{-2}$

Summary

- Neutral current NSI can arise as dimension 8 contact interactions

$$\varepsilon 2\sqrt{2}G_F(\overline{f}\gamma f)(\overline{\nu}_\alpha\gamma\nu_\beta) \sim \frac{1}{\Lambda^4}(\overline{f}\gamma f)(\overline{\ell}_\alpha H^\dagger \gamma H \ell_\beta) \qquad \Rightarrow \varepsilon = \frac{v^4}{\Lambda^4}$$

 for $f \in \{e, u, d\}$. Two ways to obtain these operators without dangerous dim 6 operators:
 - with tree level NP such that the dim 6 coefficients are absent/cancelled
 - in loops. (?use the quadratic GIM mechanism, suppresses FCNC by making them dim 8...?)

- suppose such NSI on electrons $(\overline{e}\gamma e)(\overline{\nu}_\alpha\gamma\nu_\beta)$ induced at tree level
  – if coefficients of dangerous dimension 6 operators vanish due to a cancellation, at dimension 8 could appear double derivative 4-charged-lepton operators (as well as NSI):

$$\frac{s}{\Lambda^4}(\overline{e}\gamma e)(\overline{L}_\alpha\gamma L_\beta) \qquad \frac{t-u}{\Lambda^4}(\overline{e}\gamma e)(\overline{L}_\alpha\gamma L_\beta)$$

  – Bounds from LEP2 on $e^+e^- \to L^+L^-$ translate to $\varepsilon \lesssim 10^{-2} \to 10^{-3}$.
  – But bounds are not very solid: if dim 6 vanishes due a symmetry (?GIM?), dim 8 $\left(\overline{f}_1\gamma P_X f_1\right)\left((\overline{\ell}_\alpha H^\dagger)\gamma(H\ell_\beta)\right)$ does not mix to $\left(\overline{f}_1\gamma P_X f_1\right)\left(\overline{\not{D}\,\ell}_\alpha\gamma \not{D}\,\ell_\beta\right)$.

prelim dim analysis

Neutral current NSI on quarks at the LHC

And the LHC??

- $(\overline{q}\gamma q)(\overline{\nu}_\alpha \gamma \nu_\beta)$ and the LHC?
  - if induced at loop, $\varepsilon \sim v^4/(16\pi^2\Lambda^4) \gtrsim 10^{-4} \Rightarrow$ LHC should produce the NP in the loop (squarks, etc).
  - if induced at tree level with dim 6 cancellation (Z', scalar $+$ vector leptoquarks, ...), have $\Lambda \lesssim 2$ TeV. LHC discovery prospects for such particles are model-dep... reach $\sim 3 - 5$ TeV??
  - Suppose that some of the new particles involved are beyond the reach of the LHC ($\Lambda^4 = M^2 m^2$, or some couplings $\gg 1$...) can we say anything?
    * Contact interactions at the LHC: appeal to the Equivalence Theorem, and replace $v\nu_\alpha \to W^+ e^-_\alpha$.

And the LHC??

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  - Suppose that some of the new particles involved are beyond the reach of the LHC ($\Lambda^4 = M^2 m^2$, or some couplings $\gg 1$...) can we say anything?
    * appeal to the Equivalence Theorem, and replace $v\nu_\alpha \to W^+ e^-_\alpha$.
      - The Equivalence Theorem relates matrix elements of the unbroken electroweak theory ($\langle H \rangle = 0$) to the broken theory
      - (...relativistic W, Z dominated by longitudinal components, who look like goldstones...)
      - In a gauge invariant dim 8 NSI operator

$$H\ell_\alpha = H_0 \nu_\alpha - H_+ e_\alpha$$

so... $\nu_\alpha v \to W^+ e_\alpha$.

And the LHC??

- $(\overline{q}\gamma q)(\overline{\nu}_\alpha \gamma \nu_\beta)$ and the LHC?
  - Suppose that some of the new particles involved are beyond the reach of the LHC ($\Lambda^4 = M^2 m^2$, or some couplings $\gg 1$...) can we say anything?
    - appeal to the Equivalence Theorem, and replace $v\nu_\alpha \to W^+ L^-_\alpha$.
    - dim analysis suggests

$$
\begin{aligned}
\sigma(pp \to W^+ W^- e^+_\alpha e^-_\beta) &\sim \int pdfs \times \frac{\hat{s}^3}{\Lambda_8^8} \times massless\ 4 - bdy\ phase\ space \\
&\sim 10 \text{ fb} \frac{\varepsilon^2}{(10^{-4})^2} \\
\sigma(pp \to L^+ \nu L^- \bar{\nu} \tau^+ e^-_\beta) &\lesssim 1 \text{ fb} \frac{\varepsilon^2}{(10^{-4})^2} \quad (L = e, \mu)
\end{aligned}
$$

    - Ack! backgrouunds...$\sigma(pp \to t\bar{t}) \sim$ nb $= 10^6$ fb.

And the LHC??

- $(\overline{q}\gamma q)(\overline{\nu}_\alpha \gamma \nu_\beta)$ and the LHC?
  - Suppose that some of the new particles involved are beyond the reach of the LHC ($\Lambda^4 = M^2 m^2$, or some couplings $\gg 1$...) can we say anything?
    * appeal to the Equivalence Theorem, and replace $v\nu_\alpha \to W^+ L_\alpha^-$.
    * dim analysis suggests

$$\sigma(pp \to W^+ W^- \tau^+ e_\beta^-) \quad \sim \quad 10 \text{ fb} \frac{\varepsilon^2}{(10^{-4})^2}$$

    * Small. Ack : backgrouunds...$\sigma(pp \to t\bar{t}) \sim$ nb $= 10^6$ fb.

$$(pp \to W^+ W^- b\overline{b}) \times \frac{1}{200} \longrightarrow (pp \to W^+ W^- b e_\beta^-)$$

Ack. τ vs b tagging? Event shapes?
$\Rightarrow$ maybe we can hope for sensitivity to $\varepsilon \gtrsim 10^{-3}$??

* But not ask if makes sense: $\varepsilon \sim 10^{-3} \leftrightarrow \Lambda \sim \text{TeV}$ ... even with non-perturbative couplings, new particles mass scale at $\pi\Lambda$ is accessible to the LHC?

Summary

- NSI are dimension 8 contact interactions

$$\varepsilon 2\sqrt{2}G_F(\overline{f}\gamma f)(\overline{\nu}_\alpha\gamma\nu_\beta) \sim \frac{1}{\Lambda^4}(\overline{f}\gamma f)(\overline{\ell}_\alpha H^\dagger\gamma H\ell_\beta) \qquad \Rightarrow \varepsilon = \frac{v^4}{\Lambda^4}$$

  for $f \in \{e, u, d\}$. Two ways to obtain these operators without dangerous dim 6 operators:
  -with tree level NP such that the dim 6 coefficients are absent/cancelled
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- suppose charged lepton NSI $(\overline{e}\gamma e)(\overline{\nu}_\alpha\gamma\nu_\beta)$ induced at tree level
  - if coefficients of dangerous dimension 6 operators vanish due to a cancellation, at dimension 8 could appear double derivative 4-charged-lepton operators (as well as NSI):

$$\frac{s}{\Lambda^4}(\overline{e}\gamma e)(\overline{L}_\alpha\gamma L_\beta) \qquad \frac{t-u}{\Lambda^4}(\overline{e}\gamma e)(\overline{L}_\alpha\gamma L_\beta)$$

  - Not-very-credible bounds from LEP2 on $e^+e^- \to L^+L^-$ translate to $\varepsilon \lesssim 10^{-2} \to 10^{-3}$.
- LHC could have some sensitivity to NSI.