NSI @ colliders?

S Davidson, V Sanz

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

\[
\frac{1}{\Lambda_8^4}(\bar{f}\gamma^\rho P_X f)(\bar{H}\ell_\alpha\gamma_\tau H\ell_\beta) \rightarrow \varepsilon f_X^\alpha \frac{4G_F}{\sqrt{2}} (\bar{f}\gamma^\rho P_X f)(\nu_\alpha\gamma_\tau \nu_\beta)
\]

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

\[
\varepsilon = \frac{v^4}{\Lambda_8^4} \gtrsim 10^{-4} \Rightarrow \Lambda_8 \lesssim \begin{cases} 
2 \text{ TeV} & \text{tree} \\
500 \text{ GeV} & \text{loop}
\end{cases}
\]

\[\Rightarrow \text{colliders??}\]
NSI @ colliders?

S Davidson, V Sanz

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

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

Then defining $v = 174 \text{ GeV}$, this corresponds to $\frac{v^2}{\Lambda_8^4} \sim \frac{\epsilon}{v^2}$, so

$$\epsilon = \frac{v^4}{\Lambda_8^4} \sim 10^{-4} \Rightarrow \Lambda_8 \lesssim \begin{cases} 2 \text{ TeV} & \text{tree} \\ 500 \text{ GeV} & \text{loop} \end{cases}$$

... The LHC finds new particles, and $\nu$ fact precisely measures their couplings via NSI?
NSI @ colliders?

S Davidson, V Sanz

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

$$\frac{1}{\Lambda_8^4} (\bar{f} \gamma^\rho P_X f) (\bar{H} \ell_\alpha \gamma_r H \ell_\beta) \rightarrow \varepsilon_{\alpha\beta} \frac{4G_F}{\sqrt{2}} (\bar{f} \gamma^\rho P_X f) (\nu_\alpha \gamma_r \nu_\beta)$$

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

$$\varepsilon = \frac{\nu^4}{\Lambda_8^4} \gtrsim 10^{-4} \Rightarrow \Lambda_8 \lesssim \begin{cases} 2 \text{ TeV} & \text{tree} \\ 500 \text{ GeV} & \text{loop} \end{cases}$$

... if the LHC does not discover new physics... can \nu fact see NSI?
if neutral current NSI are induced at dimension eight, \textit{e.g.} for \( f \) a first generation fermion

\[
\frac{1}{\Lambda_8^4} (\bar{f} \gamma^\rho P_X f) (H \ell_\alpha \gamma_r H \ell_\beta) \longrightarrow \varepsilon \frac{G_F}{\sqrt{2}} (\bar{f} \gamma^\rho P_X f) (\bar{\nu}_\alpha \gamma_r \nu_\beta)
\]

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

\[
\varepsilon = \frac{v^4}{\Lambda_8^4} \gtrsim 10^{-4} \Rightarrow \Lambda_8 \lesssim \begin{cases} 
2 \text{ TeV} & \text{tree} \\
500 \text{ GeV} & \text{loop}
\end{cases}
\]

LEP2 \( \Rightarrow \) not-really bounds on tree-level NSI
LHC \( \Rightarrow \) ???...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:

\[
\begin{align*}
\frac{g^2}{m_V^2 - u} (\overline{e}^c \gamma^\mu \ell)(\overline{\ell} \gamma_\mu e^c) &= -\frac{g^2}{m_V^2 - u} (\overline{e} \gamma^\mu e)(\overline{\ell} \gamma_\mu \ell) \\
- \frac{h^2}{m_S^2 - t} (\overline{e} \ell)(\overline{\ell} e) &= \frac{h^2}{2(m_S^2 - t)} (\overline{\ell} \gamma^\mu \ell)(\overline{e} \gamma_\mu e)
\end{align*}
\]

- 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
⇒ 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 \(\sigma\) and \(A_{FB}\), on dimension six contact interactions

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

with \(\sqrt{s} \geq 0.85 \times (183 \rightarrow 209)\) GeV.

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

\[
\frac{4\pi}{\Lambda^2_6} \rightarrow \frac{s}{\Lambda^4_8}, \frac{t-u}{\Lambda^4_8} \quad \text{by assuming} \quad \frac{s}{\Lambda^4_8}, \frac{t-u}{\Lambda^4_8} \mid_{\text{LEP2}} \simeq \frac{v^2}{\Lambda^4_8} \quad \text{and requiring} \quad \frac{v^2}{\Lambda^4_8} \leq \frac{4\pi}{\Lambda^2_6} \quad \text{LEP2 bound}
\]

<table>
<thead>
<tr>
<th>((\bar{e} \gamma^\mu P_X e)(\bar{e} \gamma^\mu P_Y e))</th>
<th>bound</th>
<th>(\varepsilon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e^+ e^- \rightarrow e^+ e^-)</td>
<td>(X Y = \text{LL})</td>
<td>(\Lambda^6_{6+} \geq 10.3) TeV</td>
</tr>
<tr>
<td>(\Lambda^6_{6-} \geq 8.3) TeV</td>
<td>(\lesssim 5.6 \times 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>(\Lambda^6_{6+} \geq 8.8) TeV</td>
<td>(\lesssim 4.7 \times 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>(\Lambda^6_{6-} \geq 12.7) TeV</td>
<td>(\lesssim 2.4 \times 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>(e^+ e^- \rightarrow \mu^+ \mu^-)</td>
<td>(X Y = \text{LL})</td>
<td>(\Lambda^6_{6+} \geq 8.1) TeV</td>
</tr>
<tr>
<td>(\Lambda^6_{6-} \geq 9.5) TeV</td>
<td>(\lesssim 4.3 \times 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>(\Lambda^6_{6+} \geq 6.3) TeV</td>
<td>(\lesssim 9.1 \times 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>(e^+ e^- \rightarrow \tau^+ \tau^-)</td>
<td>(X Y = \text{LL})</td>
<td>(\Lambda^6_{6+} \geq 7.9) TeV</td>
</tr>
<tr>
<td>(\Lambda^6_{6-} \geq 5.8) TeV</td>
<td>(\lesssim 1.1 \times 10^{-2})</td>
<td></td>
</tr>
<tr>
<td>(\Lambda^6_{6+} \geq 6.4) TeV</td>
<td>(\lesssim 9.1 \times 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>(\Lambda^6_{6-} \geq 4.6) TeV</td>
<td>(\lesssim 1.8 \times 10^{-2})</td>
<td></td>
</tr>
</tbody>
</table>

\[
\varepsilon = v^4/\Lambda^4
\]

Many \(O(1)\) factors!!

\[
\varepsilon_{\alpha \alpha} \lesssim 10^{-2} - 10^{-3}
\]
The OPAL experiment saw one $e^+e^- \rightarrow e^\pm\mu^\mp$ event at $\sqrt{s} = 189 - 209$ GeV, and published limits on $\sigma(e^+e^- \rightarrow e^\pm\mu^\mp, e^\pm\tau^\mp, \tau^\pm\mu^\mp)$.

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

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

⇒ calculate $\sigma$ for double-derivative dimension 8 operators... and get

<table>
<thead>
<tr>
<th>$(\bar{e}\gamma^\mu P_X e)(\ell\gamma_\mu P_Y \ell)$</th>
<th>$\varepsilon$</th>
</tr>
</thead>
</table>
| $e^+e^- \rightarrow e^\pm\mu^\mp$\ 
\ $\forall XY$ | $\lesssim 8.7 \times 10^{-3}$ |
| $e^+e^- \rightarrow e^\pm\tau^\mp$\ 
\ $\forall XY$ | $\lesssim 1.6 \times 10^{-2}$ |
| $e^+e^- \rightarrow \tau^\pm\mu^\mp$\ 
\ $\forall XY$ | $\lesssim 1.5 \times 10^{-2}$ |
Summary

- Neutral current NSI can arise as dimension 8 contact interactions

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

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 \((\bar{\epsilon}_\gamma e)(\bar{\nu}_\alpha \gamma \nu_\beta)\) 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):

\[ \frac{s}{\Lambda^4} (\bar{\epsilon}_\gamma e)(\bar{L}_\alpha \gamma L_\beta) \quad \frac{t - u}{\Lambda^4} (\bar{\epsilon}_\gamma e)(\bar{L}_\alpha \gamma L_\beta) \]

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

Neutral current NSI on quarks at the LHC
(\bar{q} \gamma q)(\bar{\nu}_\alpha \gamma \nu_\beta) and the LHC?

- if induced at loop, \( \varepsilon \sim \frac{v^4}{(16\pi^2 \Lambda^4)} \gtrsim 10^{-4} \Rightarrow \text{LHC should produce the NP in the loop (squarks, etc).} \)

- if induced at tree level with dim 6 cancellation (\( Z' \), scalar + vector leptoquarks, ...), have \( \Lambda \lesssim 2 \text{ TeV}. \) LHC discovery prospects for such particles are model-dep... reach \( \sim 3 - 5 \text{ TeV} \)??

- 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 \( \nu \nu_\alpha \rightarrow W^+ e^-_\alpha \).
And the LHC??

- \((\bar{q}\gamma q)(\nu_\alpha\gamma\nu_\beta)\) and the LHC?
  - if induced at loop, \(\varepsilon \sim v^4/(16\pi^2\Lambda^4) \gtrsim 10^{-4}\) ⇒ 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 are model-dep... reach \(\sim 3 - 5\) TeV??
  - Suppose that some of the new particles involved are beyond the reach of the LHC (\(\Lambda^4 = M^2m^2\), or some couplings \(\gg 1\)... can we say anything?

  ∗ appeal to the Equivalence Theorem, and replace \(v\nu_\alpha \rightarrow W^+e^-_\alpha\).
    - 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... \(\nu_\alpha v \rightarrow W^+e_\alpha\).
And the LHC??

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

\[
\sigma(pp \rightarrow W^+ W^- e_\alpha^+ e_\beta^-) \sim \int pdfs \times \frac{s^3}{\Lambda^8} \times \text{massless 4 - bdy phase space}
\]

\[
\sim 10 \text{ fb} \frac{\varepsilon^2}{(10^{-4})^2}
\]

\[
\sigma(pp \rightarrow L^+ \nu L^- \bar{\nu} \tau^+ e_\beta^-) \lesssim 1 \text{ fb} \frac{\varepsilon^2}{(10^{-4})^2} \quad (L = e, \mu)
\]

* Ack! backgrounds...\(\sigma(pp \rightarrow t\bar{t}) \sim nb = 10^6 \text{ fb.}\)
And the LHC??

- \((\bar{q}\gamma q)(\bar{\nu}_\alpha\gamma\nu_\beta)\) 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 \(\nu_\nu_\alpha \rightarrow W^+ L^-\).
  - dim analysis suggests
    \[
    \sigma(pp \rightarrow W^+ W^- \tau^+ e^-) \sim 10 \text{ fb} \frac{\varepsilon^2}{(10^{-4})^2}
    \]
  - Small. Ack: backgrounds...\(\sigma(pp \rightarrow t\bar{t}) \sim nb = 10^6\) fb.

\[
(pp \rightarrow W^+ W^- b\bar{b}) \times \frac{1}{200} \rightarrow (pp \rightarrow W^+ W^- b e^-)
\]

Ack. \(\tau\) 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

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

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 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):

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

  – Not-very-credible bounds from LEP2 on \( e^+ e^- \rightarrow L^+ L^- \) translate to \( \varepsilon \lesssim 10^{-2} \rightarrow 10^{-3} \).

• LHC could have some sensitivity to NSI.