

# Non standard neutrino interactions at LEP2 and the LHC

Sacha Davidson and Veronica Sanz

<sup>1</sup> IPNL, Université de Lyon, Université Lyon 1, CNRS/IN2P3, 4 rue E. Fermi 69622 Villeurbanne cedex, France

<sup>2</sup> Department of Physics and Astronomy, York University, Toronto, ON, Canada

E-mail: s.davidson@ipnl.in2p3.fr, vsanz@yorku.ca

**Abstract.** We consider Non-Standard neutrino Interactions (NSI) connecting two neutrinos with two first-generation fermions ( $e, u$  or  $d$ ), which we assume to arise at dimension eight due to New Physics. The coefficient is normalised as  $4\varepsilon G_F/\sqrt{2}$ . We explore signatures of NSI-on-electrons at LEP2, and of NSI-on-quarks at the LHC, treating the NSI as contact interactions at both energies. In models where the coefficients of dangerous dimension six operators are suppressed by cancellations, LEP2 provides interesting bounds on NSI operators ( $\varepsilon \lesssim 10^{-2} - 10^{-3}$ ), which arise because  $\sqrt{s} \sim 200$  GeV, and the cancellation applied at zero momentum transfer. At the LHC, we use the Equivalence Theorem, which relates the longitudinal  $W$  to the Higgs, to estimate the rate for  $\bar{q}q \rightarrow W^+W^-e_\alpha^+e_\beta^-$  induced by NSI. We find that the cross-section is small, but that the outgoing particles have very high  $p_T > 400$  GeV, which reduces the issue of backgrounds. In a conservative scenario, we find that the LHC at 14 TeV and with  $100 \text{ fb}^{-1}$  of data would have a sensitivity to  $\varepsilon \gtrsim 3 \times 10^{-3}$ .

## 1. Introduction

Many extensions of the Standard Model, such as Supersymmetry or leptoquarks, naturally induce low energy contact interactions of the form:

$$\varepsilon_{\alpha\beta}^{fX} \frac{4G_F}{\sqrt{2}} (\bar{f}\gamma^\rho P_X f)(\bar{\nu}_\alpha\gamma_\rho\nu_\beta) \quad (1)$$

where  $f \in \{u, d, e\}$  is a first generation charged Standard Model fermion, and  $\alpha, \beta \in \{e, \mu, \tau\}$ . These are referred to as Non Standard neutrino Interactions (NSI) [1, 2], and can be generated by  $SU(3) \times SU(2) \times U(1)$  gauge invariant operators at dimension six or higher. Future neutrino facilities, such as a Neutrino Factory [1], could be sensitive to such interactions with  $\varepsilon \gtrsim 10^{-4}$ . Formalism and current bounds [3] on NSI are reviewed in the paper on which this proceedings is based [4].

This proceedings reports on a preliminary exploration [4] of the complementarity of current collider experiments and future neutrino facilities to these neutral current operators. We focus on neutral current NSI induced at dimension eight, from operators such as

$$\frac{1}{\Lambda_8^4} (\bar{q}\gamma^\rho P_L q)(\bar{H}\ell_\alpha\gamma_\rho H\ell_\beta) \quad (2)$$

where  $q$  and  $\ell$  are SM doublets, and  $H$  is the Higgs. Comparing with eqn (1) gives  $v^2/\Lambda_8^4 = \varepsilon/v^2$ , where  $v = \langle H \rangle = 174$  GeV. So  $\Lambda_8 \lesssim 2$  TeV, suggesting that new mediating particles, if weakly coupled or in loops, are kinematically accessible to the LHC. In this case, their discovery prospects are model-dependent, and have been widely studied[5]. Here, to retain some degree of model independence, we consider effective operators at colliders (LEP2, LHC). So we are assuming heavy New Physics with  $\gtrsim 1$  couplings. We also assume that the New Physics does not generate “dangerous” dimension six operators involving two charged leptons instead of two neutrinos, because these are strictly constrained [2, 6].

In section 2, we argue that in some models, such as those considered by Gavela *et.al.* [6], the dimension eight NSI interaction of the form (1) is accompanied by dimension eight contact interactions involving charged leptons rather than neutrinos, with coefficients  $\sim s/\Lambda_8^4, (t-u)/\Lambda_8^4$ , where  $s, t$  and  $u$  are the Mandelstam variables.

In section 3, we use the Equivalence Theorem to replace  $\langle H \rangle \nu_\alpha \rightarrow W^+ e_\alpha^-$ , and study the prospects for detecting  $q\bar{q} \rightarrow W^+ W^- \ell_\alpha^+ \ell_\beta^-$  at the LHC. Rough estimates suggest that couplings  $\gtrsim 1$  are required for NSI to function as dimension eight contact interactions at LHC energies (assuming  $\varepsilon \gtrsim 10^{-4}$ ). Such contact interactions would induce few events ( $\sigma(pp \rightarrow W^+ W^- \ell^+ \ell^-) \sim 10^{-3}$  fb  $\times (10^{-4}/\varepsilon)^2$ ), but at very high  $p_T$  where Standard Model backgrounds are negligible. We estimate that the LHC could be sensitive to  $\varepsilon \gtrsim 3 \times 10^{-3}$ .

## 2. LEP2 bounds on dimension 8 derivative operators

Some NSI models, which suppress dangerous dimension six operators via a cancellation [6], could give rise to four fermion contact interactions with coefficients  $\propto \{s, t, u\}/\Lambda_8^4$ . Such contact interactions are subject to LEP2 bounds. We present estimates of the translation of the LEP bounds to the  $\varepsilon$  coefficient of NSI.

As an example of a cancellation in the coefficient of a dangerous dimension six operator, consider a model containing an SU(2) doublet vector and scalar with large masses  $m_V, m_S$ , and couplings

$$h(\bar{e}\ell)\tilde{S}_2^\dagger + g(\bar{e}^c\gamma_\mu\ell)V_2^\mu \quad (3)$$

The exchange of these two bosons gives the operators

$$-\frac{h^2}{m_S^2 - t}(\bar{e}\ell)(\bar{\ell}e) + \frac{g^2}{m_V^2 - u}(\bar{e}^c\gamma^\mu\ell)(\bar{\ell}\gamma_\mu e^c) = \left( -\frac{g^2}{m_V^2 - u} + \frac{h^2}{2(m_S^2 - t)} \right) (\bar{\ell}\gamma^\mu\ell)(\bar{e}\gamma_\mu e) \quad (4)$$

where  $t, u$  are Mandelstam variables. At zero momentum transfer, the coefficient can be cancelled by choosing  $g^2/m_V^2 = h^2/(2m_S^2)$ . However, at dimension 8, operators arise such as

$$\frac{g^2(t/m_S^2 - u/m_V^2)}{m_V^2}(\bar{\ell}\gamma^\mu\ell)(\bar{e}\gamma_\mu e) \quad (5)$$

We consider two independent dimension eight operators, with coefficients  $\propto s/\Lambda_8^4$  and  $\propto (t-u)/\Lambda_8^4$ , and that have four visible fermion legs.

The LEP2 experiments searched for dimension six four fermion contact interactions in the channels  $e^+e^- \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}$  (where  $q \in \{u, d, s, c, b\}$  is a light quark. The published bounds [7, 8, 9] can be translated (to within factors of 2, see [4]) to bounds on dimension eight operators,  $\propto s/\Lambda_8^4$  or  $(t-u)/\Lambda_8^4$ , with the same external legs. If the NP inducing the derivative operators has  $\mathcal{O}(1)$  couplings to the Higgs, then bounds on the  $\varepsilon$  coefficient of the dimension eight NSI operator, can be obtained by taking  $s \sim v^2$ . See [4] for details.

The resulting limits are listed in figure 1. Although the bounds are quoted with two significant figures, they are merely order of magnitude estimates, as various constants could appear in the passage between four-charged-lepton-derivative operators and NSI operators.

The OPAL experiment saw one  $e^+e^- \rightarrow e^\pm\mu^\mp$  event at  $\sqrt{s} = 189 - 209$  GeV, and published limits [10] on  $\sigma(e^+e^- \rightarrow e^\pm\mu^\mp, e^\pm\tau^\mp, \tau^\pm\mu^\mp)$  at LEP2 energies. This analysis allows to set the bounds on  $\epsilon$  for flavour-changing NSI given in figure 1.

$(\bar{e}\gamma^\mu P_X e)(\bar{\ell}\gamma_\mu P_Y \ell)$	$\epsilon$
$e^+e^- \rightarrow e^+e^-$	
XY=LL	$\lesssim 3.7 \times 10^{-3}$
LL	$\lesssim 5.6 \times 10^{-3}$
RL	$\lesssim 4.7 \times 10^{-3}$
RL	$\lesssim 2.4 \times 10^{-3}$
$e^+e^- \rightarrow \mu^+\mu^-$	
XY=LL	$\lesssim 5.9 \times 10^{-3}$
LL	$\lesssim 4.3 \times 10^{-3}$
RL	$\lesssim 9.1 \times 10^{-3}$
$e^+e^- \rightarrow \tau^+\tau^-$	
XY=LL	$\lesssim 6.2 \times 10^{-3}$
LL	$\lesssim 1.1 \times 10^{-2}$
RL	$\lesssim 9.1 \times 10^{-3}$
RL	$\lesssim 1.8 \times 10^{-2}$

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

$(\bar{e}\gamma^\mu P_L e)(\bar{q}\gamma_\mu P_Y q)$	$\epsilon \lesssim$
Y=L	$\lesssim 4.8 \times 10^{-3}$
Y=R	$\lesssim 1.8 \times 10^{-2}$

**Figure 1.** Estimated bounds on  $\epsilon$ , from LEP2, obtained using the assumptions outlined in the text. These could apply to NSI models where the coefficient of dimension six operators is suppressed by a cancellation.

### 3. LHC discovery reach

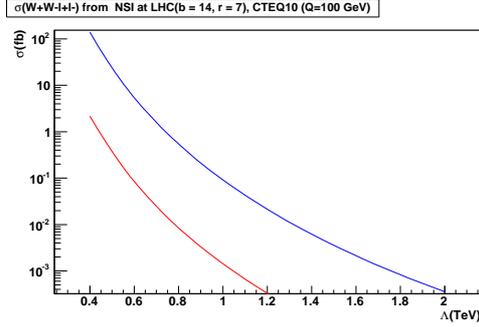
As mentioned before, the bound on  $\Lambda_8 \lesssim 2TeV$  suggests that the New Physics particles responsible of NSIs would show up as resonances at the LHC, provided the interactions are perturbative. We want to take a more pessimistic approach, and study the prospects at the LHC for NSI involving quarks, in the improbable, but comparatively model-independent, scenario that NSIs appear as contact interactions.

In a gauge invariant dimension eight NSI operator, the  $H_0^* H_0 \bar{\nu}_\alpha \nu_\beta$  interaction is accompanied by  $H^+ H^- \bar{e}_\alpha e_\beta$ , which could be expected to reincarnate, after electroweak symmetry breaking, as a vertex involving  $W^+ W^- \bar{e}_\alpha e_\beta$ . This expectation can be formalised, at energies  $\gg m_W$ , via the Equivalence Theorem[11], which identifies the Goldstone  $H^\pm$  with the longitudinal component of the  $W^\pm$ .

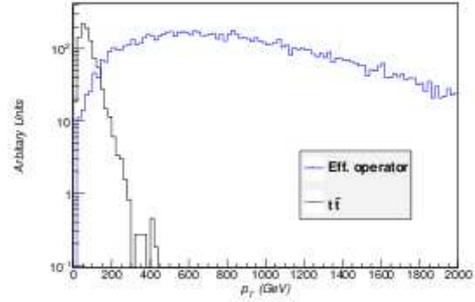
In the Equivalence Theorem limit, the partonic cross-section for  $\bar{q}q \rightarrow e_\alpha^+ e_\beta^- W^+ W^-$  is calculable, and small due to four body phase space. We obtain  $\sigma(pp \rightarrow H^+ H^- e_\alpha^+ e_\beta^-)$  plotted in figure 2.

To determine the reach of the LHC in  $\epsilon_{\alpha\beta}$ , we need to consider backgrounds, such as the  $t\bar{t}$  + jets, and signal selection. We simulated NSI events using FeynCalc [12] and MadGraph v5 [13], to obtain the  $p_T$  distribution of the signal leptons Fig. 3. We also plot the  $p_T$  of objects in a  $t\bar{t}$  sample. The signal and background distributions are well separated, so asking for a  $p_T$  cut of order 400 GeV would reduce the  $t\bar{t}$  backgrounds to less than  $10^{-5}$  fb and keeps 70% of our signal. In particular, this suggests sensitivity to NSI interactions producing taus. However, if such high- $p_T$  events were seen, boosted taus would be hard to tag, although they may show up as fat jets.

Summarizing, the cross-section is small, but the signal is characterized by well-separated, highly boosted objects in a pretty spherical event. Using these characteristics, especially a cut



**Figure 2.**  $\sigma(pp \rightarrow W^+W^-e_\alpha^+e_\beta^-)$  in fb, at the LHC with 14 TeV or 7 TeV, due to a contact interaction with coefficient  $1/\Lambda_8^4$ .



**Figure 3.**  $p_T$  of leptons at the 14 TeV LHC from NSI (flat) and  $t\bar{t}$  (peaked), normalised to fit both lines in the same scale.

on  $p_T$ , we showed that the largest background, from  $t\bar{t}$  can be reduced below the signal. The LHC reach depends on the value of  $\varepsilon$ , but if we assume the NSI signal is background-free, and ask for 100 events at a luminosity  $\mathcal{L}$  (in  $\text{fb}^{-1}$ ), then the reach in  $\varepsilon$  is

$$\varepsilon \sim 3 \times 10^{-2} / \sqrt{\mathcal{L}} \quad (6)$$

For example, for a luminosity of  $100 \text{ fb}^{-1}$ , the 14 TeV LHC could be sensitive to NSI-induced contact interactions corresponding to

$$\varepsilon \gtrsim 3 \times 10^{-3} \quad . \quad (7)$$

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