Lepton Number Violation in Higgs Decay

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We show that within the Left-Right symmetric model, lepton number violating decays of the Higgs boson can be discovered at the LHC. The process is due to the mixing of the Higgs with the triplet that breaks parity. As a result, the Higgs can act as a gateway to the origin of heavy Majorana neutrino mass. In order to assess the LHC reach, a detailed collider study of the same-sign di-leptons plus jets channel is provided. This process is complementary to the existing nuclear and collider searches for lepton number violation and can probe the scale of parity restoration even above other direct searches.

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The discovery of the Higgs boson [1, 2] allows to test the mechanism of elementary particle mass generation at the LHC [3]. Compared to this success, the problem of neutrino mass in the Standard Model (SM) appears acute. In contrast to charged fermions, neutrinos may be their own antiparticles [4], in which case lepton number is violated (LNV). One immediate phenomenological implication [5] is neutrino-less double beta decay (0ν2β), the canonical way of searching for LNV, induced either by light Majorana neutrinos or by new physics [6].

The latter, needed for neutrino mass, can be provided by the celebrated seesaw mechanism [7–11]. In particular, Left-Right symmetric models (LRSM) [12], designed to explain parity violation of weak interactions [13], embed naturally the seesaw [7,8] and also connect the Majorana and Dirac masses [14]. With the left-right (LR) scale in the TeV range, 0ν2β may be dominated by heavy neutrino (N) exchange [15, 16]. This may even be favored over light neutrino exchange in view of cosmology [17] in case a signal is found in the upcoming experiments [18].

A direct strategy for LNV searches at hadron colliders was suggested in [19] by Keung and Senjanović (KS) [20]. The KS production of heavy Majorana neutrinos would demonstrate LNV and also relate directly to the SM Higgs boson may not only test the origin of mass of known SM fermions but also that of heavy neutrinos. In this sense, the Higgs would act as a portal to LNV, complementary to 0ν2β and the KS reaction.

In order to estimate the LHC sensitivity to the signal, we implement the model [34], perform a simulation of both the signal and the expected SM background, and devise cuts to isolate the signal. To further enhance the search, we simulate the characteristic displaced vertices arising from N decay and highlight their importance. Given the current limits on the Higgs mixing [35], a discovery turns out to be possible even if the LR scale is beyond the reach of other direct searches.

We conclude with a discussion on alternative models with potential LNV Higgs decays and a short outlook on the related search at e+e− colliders.

Left-Right symmetry and Higgs mixing. Left-Right symmetric models [12], based on the gauge group SU(2)L × SU(2)R × U(1)−β−λ, contain a right-handed (RH) gauge boson WR and three RH Majorana neutrino masses. In particular, the Higgs boson can be discovered at the LHC [3]. Compared to this success, the problem of neutrino mass in the Standard Model (SM) appears acute. In contrast to charged fermions, neutrinos may be their own antiparticles [4], in which case lepton number is violated (LNV). One immediate phenomenological implication [5] is neutrino-less double beta decay (0ν2β), the canonical way of searching for LNV, induced either by light Majorana neutrinos or by new physics [6].

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In this Letter we show that within the LRSM a new channel arises, connecting Higgs physics to restoration of parity. We point out that the SM Higgs can have a sizeable mixing with the triplet that breaks LR symmetry spontaneously and provides a mass to heavy Majorana neutrinos. Through this mixing the Higgs decays to a pair of Ns, probing their Yukawa couplings and leading to a LNV final state with two same or opposite sign charged leptons and four jets, as shown on Fig. 1. The possibility of LNV from Higgs decay to RH neutrinos was suggested in [33] with effective operators. Here the LNV Higgs decay is directly connected with the origin of right-handed Majorana neutrino masses. As a result, the SM Higgs boson may not only test the origin of mass of known SM fermions but also that of heavy neutrinos. In this sense, the Higgs would act as a portal to LNV, complementary to 0ν2β and the KS reaction.

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nos. The scalar sector of the minimal LRSM [7, 8] features a complex bi-doublet $\Phi \in (2_L, 2_R, 0)$ and a pair of triplets $\Delta_L \in (3_L, 1_R, 2)$, $\Delta_R \in (1_L, 3_R, 2)$:

$$\Phi = \left( \begin{array}{cc} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^- \end{array} \right), \quad \Delta_{L,R} = \left( \begin{array}{cc} \delta^+ / \sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+ / \sqrt{2} \end{array} \right). \quad (1)$$

In the minimal LRSM, LR symmetry is restored at high energies. The scalar potential exhibits spontaneous breaking and since the original work [13] it has been the subject of several studies [27, 36–38]. Here we focus on the mixing between the triplet and the SM-like Higgs and display the relevant terms:

$$V = -\mu_1^2 (\Phi^\dagger \Phi) - \mu_2^2 (\Phi^\dagger \Phi^1 + \Phi^1 \Phi) - \mu_3^2 (\Delta_R^\dagger \Delta_R)$$

$$+ \lambda \Phi^\dagger \Phi^2 + \rho (\Delta_L^\dagger \Delta_R) + \alpha (\Phi^\dagger \Phi) (\Delta_L^\dagger \Delta_R). \quad (2)$$

The trace on the parenthesis is implied and $\Phi = \sigma_2 \Phi^* \sigma_2$. The results below hold for both generalized parity $P$ and charge-conjugation $C$ [28]; a detailed discussion will be presented in [39].

The parameters $\mu$ are fixed by spontaneous breaking in the usual way, $\mu_1^2 = 2 \lambda v^2 + \alpha v_R^2$, $\mu_2^2 = 0$, $\mu_3^2 = \alpha^2 v^2 + 2 \rho v_R^2$, and neutral scalars develop VEVs. The LR-breaking scale is set by $\langle \phi_0^0 \rangle = \nu_R$ and electroweak symmetry breaking is completed by $\langle \phi_1^0 \rangle = v$. For clarity we stick to the case where $\phi_0^0$ does not acquire VEV and we suppress higher $v/v_R$ terms. In what follows the neutral scalars $\phi$ and $\delta$ are the fluctuations of $\Re (\phi_1^0)$ and $\Re (\delta_R^0)$.

Expansion of the potential (2) around the minimum gives the following mass matrix for $\phi$ and $\delta$

$$M^2 = 2 \left( \begin{array}{cc} 2 \lambda v^2 & \alpha v v_R \\ \alpha v v_R & 2 \rho v_R^2 \end{array} \right). \quad (3)$$

Its diagonalization leads to the masses of the physical particles $m_N^2 = 4 \lambda v^2 - \alpha^2 v^2 / \rho$, $m_{\Delta_R}^2 = 4 \rho v_R^2$. Here $h = \phi \cos \theta - \delta \sin \theta$ is identified with the SM Higgs boson and $\Delta = \delta \cos \theta + \phi \sin \theta$ with the further neutral state. Their mixing angle is given by

$$\theta \simeq \left( \frac{\alpha}{2 \rho} \right) \left( \frac{v}{v_R} \right). \quad (4)$$

Since $\delta$ is a SM singlet, this mixing leads to a universal reduction of the SM-like Higgs couplings. Recent studies [35] allow for $\sin \theta < 0.44$ at $2\sigma$ CL, nearly independently of the singlet mass.

**Heavy Neutrino from Higgs decay.** In the LRSM the above mixing leads to a new type of Higgs decay, with the fascinating possibility of probing LNV and neutrino mass generation via Higgs physics.

After spontaneous breaking, the Yukawa term $L_{\Delta} = Y_N L_N^\dagger \Delta_{L,R} + \text{h.c.}$, which couples the RH leptonic doublet $L_R$ to the triplet Higgs, generates the heavy neutrino mass matrix. This is directly proportional to the LR scale

$$M_N = 2 Y_N v_R, \quad M_{WR} = g v_R, \quad (5)$$

where $g = g_{L_R}$ is the $SU(2)_{L,R}$ gauge coupling constant.

The number of $N$ pairs produced at the $13 \text{ TeV LHC}$ run with $100 \text{ fb}^{-1}$ luminosity is simple to estimate. Taking the Higgs gluon fusion cross-section [41] $\sigma(gg \rightarrow h) = 45 \text{ pb}$ and $\text{Br}(bb \rightarrow h) = 57\%$, one gets $500$ (2000) $h \rightarrow N N$ events for $m_N = 40 \text{ GeV}$ and $\theta = 10\% (20\%)$. This is sufficient motivation for an in-depth collider study.

**Lepton number violating Higgs decay at the LHC.** After pair-production from Higgs decay, each $N$ will decay further to a charged lepton and two jets via $W_R$, with a RH charged current quark flavour structure essentially identical to the left-handed one [42]. Due to the Majorana nature of $N$, $50\%$ of events will result in a final state of two same-sign leptons and four jets with no missing energy, explicitly signalling lepton number non-conservation.

In order to assess the LHC sensitivity, we extend [34] the FeynRules [43] implementation of the LRSM [44] to include the mixing (4) together with Higgs gluon fusion production. Parton level events are simulated with MadGraph 5 [45], hadronized with Pythia 6 [46] and passed to

![FIG. 2. Decay rate of the SM Higgs to a pair of heavy neutrinos $N$, normalized to the leading $h \rightarrow b \bar{b}$ channel.](image)
Delphes 3 [47] for detector simulation. We also use MadAnalysis 5 [48] for cuts and event counting. Dedicated software extensions were implemented in each module in order to study the displaced vertices.

Below we discuss the physical characteristics of the signal and background sources, and then describe a cut strategy at detector level to optimize the final sensitivity.

The channel $h \rightarrow \ell^+\ell^-4j$ carries plenty of physical information at parton level. The total invariant mass reconstructs the Higgs mass, while the $(\ell jj)$ invariant mass reconstructs the $N$ peak. Moreover, tagging the flavor of outgoing leptons identifies the RH analog of the PMNS mixing matrix and the related Majorana mass matrix [14]. Notice that with such low $N$ masses, LFV constraints are easily satisfied and one may expect LFV in Higgs decays.

Reconstruction at detector level is more delicate. The Higgs is produced with a boost $\gamma(h) \sim 3$ at $\sqrt{s} = 13$ TeV and the $N$ is further boosted if $m_N \ll m_h/2$. As a result the two jets from $N$ tend to merge. In addition, the jets get closer to the charged lepton and typical lepton isolation cuts may prevent its recognition. Furthermore, the distribution of transverse momentum of the lepton (and the jets) peaks at a fairly low value of $m_{jj}/6 \sim 20$ GeV. Typical detector simulation parameters forbid tight leptons with $p_T < 10$ GeV, causing a loss of the signal by a factor of 2. Still, the $N$ mass peak can be clearly observed in the $\mu_j$ invariant mass.

We add that the fairly long lifetime of $N$, characteristic for this portion of parameter space [21], can lead to a measurable displacement of the $N$ decay products. It ranges from sub-millimeter to a few meters, depending on $m_N$ and $M_{WR}$. This results in a striking LNV signature with two displaced vertices.

**Background estimation.** Since lepton number is conserved in the SM, there is no background at parton level for this final state. Nevertheless, there are three distinct ways in which background arises:

1. Electron charge mis-identification and secondary photo-production constitute a background that is hard to understand in absence of real data [49, 50]. Since at this stage one cannot reliably estimate this experimental effect, we study the muon channel free from such issues [49, 50].

2. The main prompt muon background comes from pair-production of electroweak gauge bosons, in particular $WZ$, $ZZ$ and $W^\pm W^\pm jj$, and $t\bar{t}$ production. These components also contain non-prompt muons from meson decays.

3. Significant background is due to non-prompt muons. This component, likely dominant and not easy to estimate, is due to QCD jets when some hadron is mis-identified as a muon. Even though the mis-identification probability is small, the huge QCD cross-section still gives a finite number [49, 50]. A realistic estimate will require a knowledge of hadron mis-id within the real detector in the next LHC run. Nevertheless, previous studies indicate this background behaves similarly to the $WZ + ZZ$ background (see supplement of [50]). From that sample, we estimate the QCD mis-id contribution by multiplying the $WZ + ZZ$ background by 2.5.

**Selection criteria and sensitivity.** We now turn to the event selection procedure. We adopt the default Delphes 3 ATLAS card with muon isolation parameters in agreement with [49] and the anti-$k_T$ jet algorithm with $\Delta R = 0.4$ and $p_{Tj_{min}} = 20$ GeV. We demand two same-sign isolated muons and no other leptons, together with $n_j$ jets, where $n_j = 1, 2, 3$. To increase the sensitivity, we require $E_T < 30$ GeV and leading muon transverse momentum $p_T < 55$ GeV. Moreover, we demand the transverse mass $m_{\mu p_T} < 30$ GeV and invariant masses $m_{\mu\mu} < 80$ GeV, $m_{\mu p_T} < 60$ GeV. The impact of these selection cuts on the event count is shown in Tab. I.

In addition, for both short and long lived $N$s the known decay length allows us to impose cuts on the muon vertex transverse displacement $d_T$, shown on Fig. 3. We simulate the displacement of signal and background, smearing the reconstructed vertex with the $p_T - \eta$ dependent resolution of 20–40 $\mu$m, as reported in [51]. Since the typical background contains one prompt and one secondary muon, it is very effective to cut on both short and long

| Process          | No cuts | Imposed cuts |
|------------------|---------|--------------|
| $WZ$             | $2 \ M$ | $544 \ 143 \ 78 \ 40 \ 20$ |
| $ZZ$             | $1 \ M$ | $55 \ 29 \ 16 \ 12 \ 8$ |
| $W^\pm W^\pm 2j$| $389$   | $115 \ 16 \ 5 \ 3 \ 1$ |
| $\ell\bar{\ell}$| $10 \ M$| $509 \ 97 \ 40 \ 22 \ 14$ |
| Signal (20)      | $254$   | $11 \ 11 \ 10 \ 9 \ 8$ |
| Signal (40)      | $543$   | $44 \ 43 \ 41 \ 38 \ 37$ |

**FIG. 3.** Reconstructed transverse muon displacement after $\mu^\pm \mu^\pm + n_j$ event selection and before other cuts.
Our analysis applies to those cases as well. Further extension with a singlet [60] or spontaneously broken $B - L$ models can generate an observable signal. Our analysis applies to those cases as well.

Models with supersymmetric R-parity violation provide an alternative to the seesaw mechanism [61], leading to the possibility of LNV (both at colliders and at low energy via $0\nu2\beta$ [62]). The same framework could feature a same-sign di-lepton decay of the Higgs boson, owing to a fairly large $h \rightarrow \chi^0\chi^0$ coupling. $\chi^0$ subsequently decays to $\ell jj$ through slepton exchange thanks to a non-zero $lqq'$ term. This scenario may deserve an updated study in light of recent limits. In case of slepton-neutrino mass degeneracy however, this LNV channel appears to be suppressed [63].

Finally, in the context of a sequential fourth generation, decays to a pair of fourth generation Majorana neutrinos $h \rightarrow \nu_4\nu_4$ was studied by [64]. After the first run of the LHC, this framework seems to be disfavored.

### Outlook.

In the SM, the Higgs mechanism provides masses to all charged fermions and leads to a distinct prediction of relative branching ratios. A completely analogous mechanism operates in the minimal LRSM for $N$ and $W_R$ [7, 8] where their masses determine the branching ratios of the 'right-handed' Higgs. In this Letter we point out that the mixing between these two bosons, derived in Eq. (4), leads to $h \rightarrow NN$ and to the interesting possibility of LNV in Higgs decay.

The main results are summarized on Fig. 4. For a large range of allowed $m_N$ and $\theta$ values, the $h \rightarrow \ell^+\ell^- + jets$ channel allows to identify the RH neutrino mass peak and can probe the LR scale even beyond the reach of $0\nu2\beta$ or direct collider searches.

Conceptually, this channel can be a starting point towards the determination of the neutrino mass origin. To fully realize such a program, i.e. to correlate the $m_N$ peaks with the Yukawa couplings, independent information on the LR scale and $\theta$ would be needed. This would be possible by direct observation of $W_R$ and $\Delta$, together with respective branching ratios. Also, for some pattern of $N$ masses RH neutrino cascade decays may open up, leading to peculiar equal-sign multilepton signatures. A comprehensive study will be presented in [39].

From the collider perspective, the present analysis leaves room for improvement once the detector knowledge will be available in the next LHC run. A number of potential improvements can be identified: i) it seems feasible to include reconstructed muons with $p_T < 10$ GeV, leading to a factor of two more signal events; ii) in the case of short lived $N$, tight cuts on displacement could reduce further the QCD multijet background; iii) on the other hand, for the boosted long lived $N$s, for which typically the muon tends to merge with the jet, the signal contains displaced jets. Although a clear challenge, it may be possible [65] to identify their displacement.

We conclude by pointing out that $e^+e^-$ colliders provide a particularly clean environment for heavy neutrino searches [66]. For the LNV Higgs decay, the relative decrease in production cross-section to $\sigma = 0.24\text{fb}$ at $\sqrt{s} \sim 240$ GeV may be compensated by lack of background (only $ZZ$ remains) and large luminosity $\sim 1 - 10\text{ab}^{-1}$ [67]. Conversely, a positive signal at LHC without the associated $W_R$ discovery would make a case at a future high energy hadron collider.
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[1] P.W. Higgs, Phys. Rev. Lett. 13 (1964) 508.
[2] S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264.
[3] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 716, 1 (2012) [arXiv:1207.7214 [hep-ex]]; S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 716, 30 (2012) [arXiv:1207.7235 [hep-ex]].
[4] E. Majorana, C. R. N. 14 (1937) 171.
[5] G. Racah, N. Cim. 14 (1937) 322; W.H. Furry, Phys. Rev. 56 (1939) 1184.
[6] G. Feinberg, M. Goldhaber, Proc. Nat. Ac. Sci. USA 45 (1959) 1301; B. Pontecorvo, Phys. Lett. B26 (1968) 630.
[7] P. Minkowski, Phys. Lett. B 67 (1977) 421.
[8] R.N. Mohapatra, G. Senjanović, Phys. Rev. Lett. 44 (1980) 912.
[9] T. Yanagida, Workshop on unified theories and baryon number in the universe, ed. A. Sawada, A. Sugamoto (KEK, Tsukuba, 1979).
[10] S. Glashow, Quarks and leptons, Cargèse 1979, ed. M. Levy (Plenum, NY, 1980).
[11] M. Gell-Mann et al., Supergravity Stony Brook workshop, New York, 1979, ed. P. Van Nieuwenhuizen, D. Freeman (North Holland, Amsterdam, 1980).
[12] J.C. Pati and A. Salam, Phys. Rev. D 10, 275 (1974) [Erratum-ibid. D 11, 703 (1975)]; R.N. Mohapatra and J.C. Pati, Phys. Rev. D 11, 566 (1975); R.N. Mohapatra and J.C. Pati, Phys. Rev. D 11, 2558 (1975).
[13] G. Senjanović and R.N. Mohapatra, Phys. Rev. D 12, 1502 (1975); G. Senjanović, Nucl. Phys. B 153, 334 (1979).
[14] M. Nemček, G. Senjanović and V. Tello, Phys. Rev. Lett. 110 (2013) 15, 151802 [arXiv:1211.2837 [hep-ph]].
[15] R.N. Mohapatra and G. Senjanović, Phys. Rev. D 23 (1981) 165.
[16] V. Tello, M. Nemček, F. Nesti, G. Senjanović and F. Vissani, Phys. Rev. Lett. 106 (2011) 151801 [arXiv:1011.3522 [hep-ph]].
[17] M. Nemček, F. Nesti, G. Senjanović and V. Tello, arXiv:1112.3061 [hep-ph].
[18] J.J. Gomez-Cadenas, J. Martin-Albo, M. Mezzetto, F. Monrabal and M. Sorel, Riv. Nuovo Cim. 35 (2012) 29 [arXiv:1109.5515 [hep-ex]]; W. Rodejohann, J. Phys. G 39 (2012) 124008 [arXiv:1206.2560 [hep-ph]].
[19] W.-Y. Keung, G. Senjanović, Phys. Rev. Lett. 50 (1983) 1427.
[20] For a review, see: G. Senjanović, Int. J. Mod. Phys. A 26 (2011) 1409 [arXiv:1012.4104 [hep-ph]]; G. Senjanović, Riv. Nuovo Cim. 34 (2011) 1.
[21] M. Nemček, F. Nesti, G. Senjanović and Y. Zhang, Phys. Rev. D 83 (2011) 115014 [arXiv:1103.1627 [hep-ph]].
[22] V. Cirigliano, A. Kurylov, M.J. Ramsey-Musolf and P. Vogel, Phys. Rev. D 70 (2004) 075007 [hep-ph/0404233].
[23] J.A. Aguilar-Saavedra, F. Deppisch, O. Kittel and J.W.F. Valle, Phys. Rev. D 85 (2012) 091301 [arXiv:1203.5998 [hep-ph]].
[24] J.F. Nieves, D. Chang and P.B. Pal, Phys. Rev. D 33 (1986) 3324.
[25] G. Beal, M. Bander and A. Soni, Phys. Rev. Lett. 48 (1982) 848.
[26] R.N. Mohapatra, G. Senjanović and M.D. Tran, Phys. Rev. D 28 (1983) 546; K. Kiers, J. Kolb, J. Lee, A. Soni and G.-H. Wu, Phys. Rev. D 66 (2002) 095002 [hep-ph/0205082].
[27] Y. Zhang, H. An, X. Ji and R.N. Mohapatra, Phys. Rev. D 76 (2007) 091301 [arXiv:0704.1662 [hep-ph]] and Nucl. Phys. B 802 (2008) 247 [arXiv:0712.4218 [hep-ph]].
[28] A. Maiezza, M. Nemček, F. Nesti and G. Senjanović, Phys. Rev. D 82, 055022 (2010) [arXiv:1005.5160 [hep-ph]].
[29] S. Bertolini, J.O. Eeg, A. Maiezza and F. Nesti, Phys. Rev. D 86 (2012) 095013 [arXiv:1206.0668 [hep-ph]]; S. Bertolini, A. Maiezza and F. Nesti, Phys. Rev. D 88 (2013) 3, 034014 [arXiv:1305.5739 [hep-ph]].
[30] S. Bertolini, A. Maiezza and F. Nesti, Phys. Rev. D 89 (2014) 9, 095028 [arXiv:1403.7112 [hep-ph]].
[31] A. Maiezza and M. Nemček, Phys. Rev. D 90 (2014) 9, 095002 [arXiv:1407.3678 [hep-ph]].
[32] A. Ferrari et al. Phys. Rev. D 62 (2000) 013001; S.N. Givens, C. Groth, L. Ryan and M. Zupan, Phys. Rev. D 81 (2010) 055003 [arXiv:1003.4331 [hep-ph]].
[33] M.L. Graesser, Phys. Rev. D 76 (2007) 075006 [arXiv:0704.0438 [hep-ph]]; M.L. Graesser, arXiv:0705.2190 [hep-ph].
[34] https://sites.google.com/site/leftrighthep
[35] G.M. Pruna and T. Robens, Phys. Rev. D 88 (2013) 11, 115012 [arXiv:1303.1150 [hep-ph]]; S. Profumo, M.J. Ramsey-Musolf, C.L. Wainwright and P. Winslow, Phys. Rev. D 91 (2015) 3, 035018 [arXiv:1407.5342 [hep-ph]]; C.Y. Chen, S. Dawson and I.M. Lewis, Phys. Rev. D 91 (2015) 3, 035015 [arXiv:1410.5488 [hep-ph]]; T. Robens and T. Steffaniak, Eur. Phys. J. C 75 (2015) 3, 104 [arXiv:1501.02234 [hep-ph]]; V. Martin-Lozano, J.M. Moreno and C.B. Park, arXiv:1503.03799 [hep-ph]; A. Falkowski, C. Gross and O. Lebedev, arXiv:1502.01361 [hep-ph]; S.I. Godunov, A.N. Rozanov, M.I. Vysotsky and E.V. Zhemchugov, arXiv:1503.01618 [hep-ph].
[36] J. Basecq, J. Liu, J. Milutinović and L. Wolfenstein, Nucl. Phys. B 272 (1986) 145; J. Basecq and D. Wyler, Phys. Rev. D 39 (1989) 870; J.F. Gunion, J. Grifols,
