II.5 WZ PAIR PRODUCTION IN THE LEFT-RIGHT MODELS

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In this report we will study the production at LHC of W_R, the charged, heavy gauge vector boson of the left-right (LR) extensions [1] of the standard model (SM). In LR models parity is an exact symmetry at the lagrangian level, spontaneously broken by the vacuum expectation value of some scalar field. At the same time the presence of the right-handed neutrino ν_R, which has no counterpart in the SM, and of a suitable Higgs structure, allows for the so called see-saw mechanism [2] to occur, naturally accounting for the smallness of the left-handed neutrino masses.

As we shall see, at the LHC energies one can produce and detect a W_R with a mass up to several TeV's. As soon as the $W_L - W_R$ mixing angle is different from zero, the W_R decays into a WZ pair [3]. The study of this signature is the main topic of the present note. WZ pair production comes about in a variety of physical situations relevant to the LHC phenomenology, such as the possible presence of anomalous trilinear gauge couplings [4] or the production of technirho-like resonances [5] . In the case of the LR models, the WZ channel could be of particular interest if the ν_R is so heavy to suppress completely or in part the $e\ \nu_R$ decay mode.

We consider here the model based on the gauge symmetry $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$, with the symmetry breaking induced by two Higgs triplets Δ_L and Δ_R, transforming as (1,0,2) and (0,1,2), respectively, and one multiplet $\Phi = (1/2, 1/2, 0)$. The following vacuum expectation values (VEVs) are assumed:

$$< \Delta_L^0 > = v_L \quad , \qquad < \Delta_R^0 > = v_R \quad , \qquad < \Phi > = \begin{pmatrix} v & 0 \\ 0 & v' \end{pmatrix} \quad , \tag{1}$$

where $\Delta_{L,R}^0$ stands for the neutral component of the corresponding triplet. We further assume the usual hierarchy among the VEV's: $v_R \gg v, v' \gg v_L \sim 0$, which reflects the expectation $M_{W_R}, M_{Z_R} \gg M_W, M_Z$ and the absence of large deviations from the SM relation $\rho = M_W^2/M_Z^2 \cos^2\theta = 1$. The relative size of v and v' is an important parameter of our analysis. By defining:

$$\tan\alpha = v'/v \quad , \tag{2}$$

the $W_L - W_R$ mixing angle ξ is given by:

$$|\xi| \sim |\sin 2\alpha| \left(\frac{M_W}{M_{W_R}}\right)^2 \quad . \tag{3}$$

In the following we choose to work with a positive $\sin 2\alpha$.

We first briefly discuss the limits of the model coming from the experiments. The present data require an upper bound on $|\xi|$ in the range $10^{-2} - 10^{-3}$ [6], even though the most stringent existing bounds are not free from theoretical uncertainties and/or model dependent assumptions (for a review see [7]). Fig. 1 shows the limitations coming from $|\xi| < 10^{-2}$ in the $(\sin 2\alpha, M_{W_R})$ plane. Another constraint shown in Fig. 1 comes from the measurements of M_Z at LEP and M_W/M_Z at UA2 and CDF [8], using the recent values $M_Z = 91.173 \pm 0.031\ GeV$ [9] and $M_W/M_Z = 0.8808 \pm 0.0036$ [10].

Other limitations on M_{W_R} are derived from the analysis of the $K_S - K_L$ mass difference [11]: $M_{W_R} > 1.6$ TeV, assuming the so-called manifest or pseudomanifest left-right symmetry, which implies a specific relation between the Kobayashi-Maskawa mixing matrices of the left and the right sectors. Finally, the direct search of W' at the Tevatron collider gives the bound $M_{W'} > 478$ GeV [12], looking at the conventional $e\nu$ decay channel and assuming W' couplings equal to the SM's ones.

In the present analysis we will consider the W_R in the mass range from 750 GeV up to several TeV's. The dominant production mechanism at LHC is the usual $q\bar{q}$ annihilation. If the ν_R were light, one could look for W_R decaying into $e\nu_R$. This channel, neglecting the ν_R mass, has a branching ratio (BR) of about 8%. A year (10^7 sec) run at $\sqrt{s} = 16$ TeV with a total integrated luminosity of 10^5 pb^{-1} would lead to 10 $e\nu_R$ events for $M_{W_R} = 6$ TeV*. In the following we will mainly investigate the discovery limits for a W_R through the WZ decay mode. We will also briefly comment about the W *higgs* (Wh) channel.

In the range of W_R masses we are considering the partial width of W_R into WZ can be well approximated by the limit of massless W and Z,

$$\Gamma(W_R \to WZ) = \frac{g^2}{192\pi} M_{W_R} \sin^2 2\alpha \quad : \tag{4}$$

it follows that a preliminary condition to be met in order to have a sizeable WZ signal is a non vanishing and possibly not too small value of $\sin 2\alpha$. On the other hand, this requirement should not contradict the experimentally established smallness of ξ, discussed above.

M_{W_R}	750 GeV	1000 GeV	1000 GeV	2000 GeV	2000 GeV	2500 GeV
$\sin 2\alpha$	0.25	1	0.25	1	0.25	1
ξ	0.003	0.006	0.0016	0.0016	0.0004	0.001
$\Gamma_T(W_R)$(GeV)	19.4	27	26	53	52	67
$BR(W_R \to WZ)$	0.0020	0.029	0.0019	0.027	0.0017	0.026
$BR(W_R \to Wh)$	0.0012	0.021	0.0014	0.025	0.0016	0.025
$\sigma(W_R^+)$	109 pb	37.2 pb	37.2 pb	1.9 pb	1.9 pb	0.59 pb

Table I - *For the indicated values of* M_{W_R} *and* $\sin 2\alpha$, *one reads the* $W_L - W_R$ *mixing angle* ξ, *the total* W_R *width* $\Gamma_T(W_R)$, *the branching ratios into* WZ *and* Wh *(for* $M_h < 200$ GeV*) and the total cross section for* W_R^+ *production via* $q\bar{q}$ *annihilation at a pp collider with* $\sqrt{s} = 16$ TeV. *The total cross section has been evaluated with DFLM parton densities (*$\Lambda_{QCD} = 260$ MeV*) and a K-factor of approximately 1.25 has been included* [14].

In Table I we list a number of illustrative cases realizing this compromise. From eq. (3) one sees that a large M_{W_R} already leads to acceptable ξ values,

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* This number should not be taken as a discovery limit, since the $e\nu_R$ channel deserves a separate study of the appropriate experimental distributions [13].

without requiring a small value for $\sin 2\alpha$. For instance, at $M_{W_R} = 1$ TeV and $\sin 2\alpha = 1$ one has $|\xi| = 0.006$, of the order of the present upper bound. Table I shows that the largest value for BR($W_R \to WZ$), obtained for $\sin 2\alpha = 1$, is essentially independent from M_{W_R} and amounts approximately to 3%, which is comparable to the BR of the fermionic channels (the BR's were computed assuming a heavy ν_R, but they are not much sensitive to this assumption). Table I also shows that the production cross section for W_R^+ at $\sqrt{s} = 16$ TeV is relatively large, ranging from $\sim$ 109 pb for $M_{W_R} = 750$ GeV, to about $\sim$ 0.6 pb at $M_{W_R} = 2500$ GeV. For the cases considered in Table I, we can conclude that LHC, assuming an integrated luminosity of 10^5 pb^{-1}, could produce a considerable number of WZ pairs.

To further analyze the potentiality of LHC we have selected the completely leptonic decay mode ($3l+\nu$, $l = e, \mu$) of the produced WZ pair and we have studied the corresponding background. This includes an irreducible part coming from the WZ continuum electroweak production. Different production mechanisms contribute to this continuum: $q\bar{q}$ annihilation, γW and WZ fusion. Of these, the first two have been fully included in our analysis. We find that the ratio of the $q\bar{q}$ contribution to the γW one is approximately 5 to 1. The WZ contribution is estimated [5] to be comparable to the γW one.

Another source of background is the production of a $t\bar{t}$ pair, which, through its decay chain, could lead to a final state containing 3 charged leptons plus missing energy, i.e. to the signature we are looking for. This background has been studied in detail in ref. [15] in relation to the WZ production from technirho-like resonances, in kinematical configurations similar to those considered here. The conclusion of ref. [15] is that this background can be rejected at an acceptable level by imposing the constraint coming from the Z mass reconstruction, a suitable cut on the Z transverse momentum p_T^Z and the requirement of lepton isolation.

The background coming from the electroweak $q\bar{q}$ and γW continuum were generated, together with the signal, by a Montecarlo program.

		$(p_T^Z)_{cut}$ $(M_{WZ})_{cut}$	S	B	$(S/\sqrt{B})$
$M_{W_R} = 750$ GeV	$\sin 2\alpha = 0.25$	300 (500,1000)	166	51	23
$M_{W_R} = 1000$ GeV	$\sin 2\alpha = 1$	240 (750,1250)	1145	89	121
$M_{W_R} = 1000$ GeV	$\sin 2\alpha = 0.25$	360 (750,1250)	65	29	12.1
$M_{W_R} = 2000$ GeV	$\sin 2\alpha = 1$	420 (1750,2250)	58	3	33.6
$M_{W_R} = 2000$ GeV	$\sin 2\alpha = 0.25$	720 (1750,2250)	3	.5	4.8
$M_{W_R} = 2500$ GeV	$\sin 2\alpha = 1$	540 (2200,2800)	19	1	19

Table II - *Number of $3l+\nu$ events ($l = e, \mu$) from W_R (signal S) and from the electroweak continuum $q\bar{q}$ and γW (background B) for LHC at $\sqrt{s} = 16$ TeV and $L = 10^5$ pb^{-1}, after cuts. Only W^+Z events have been considered. S and B include a branching ratio of 0.015 for the decay of WZ into leptons of the first two generations. A common cut $|y_{W,Z}| < 2.5$ has been applied. Cuts for (p_T^Z) and (M_{WZ}) are expressed in* GeV. *In the M_{WZ} distribution, the events outside the window indicated have been cut. No K-factor has been included.*

Table II compares the signal S and the background B for the cases listed in Table I, after imposing suitable kinematical cuts. A BR of 1.5%, corresponding to the decay of the WZ pair into leptons of the first two generations, has been included in the quoted numbers. For the cases considered in Table II we have also studied the distributions in the invariant mass M_{WZ} and in the Z transverse momentum p_T^Z. As an example in fig. 2 we show the M_{WZ} distribution for $M_{W_R} = 2$ TeV and $\sin 2\alpha = 1$. The signal appears as a very narrow peak above the electroweak continuum. This feature should be compared to the analogous distribution from a technirho-like resonance which, at least for masses larger than 1.5 TeV, usually exhibits a much broader resonant behaviour [5]. In the p_T^Z distribution, shown in fig. 3 for $M_{W_R} = 2$ TeV and $\sin 2\alpha = 1$, the signal is peaked at a very high Z transverse momentum where the background from the electroweak comtinuum is very small.

Taking into account the background mentioned above, discovery limits were studied in the plane $(\sin 2\alpha, M_{W_R})$, for both LHC and SSC. Fig. 4 shows the reaches of the two colliders for W_R^+, assuming for LHC(SSC) $\sqrt{s} = 16(40)$ TeV and an integrated luminosity of $L = 10^5(10^4)$ pb^{-1}. We have asked for more than 15 leptonic $(3l + \nu + X)$ events, explicitly checking that, by applying suitable cuts, a ratio $S/\sqrt{B} > 3$ can always be obtained. In the conditions simulated here, the reaches of the two machines are very similar. For $\sin 2\alpha = 1$ a discovery limit of 2.8 TeV on M_{W_R} could be obtained. This value drops down if lower values for $\sin 2\alpha$ are considered. For $\sin 2\alpha = 0.2$ a W_R mass of 1.5(1.2) TeV could still be tested at LHC(SSC).

Finally we add some comment about the Wh decay channel. The Φ multiplet of eq. (1) consists of two $SU(2)_L$ doublets. One linear combination of these doublets has vanishing VEV. The orthogonal one corresponds to the usual SM doublet and we identify h with the real part of its neutral component. From Table I one sees that, for a light higgs ($M_h < 200$ GeV) and a M_{W_R} in the TeV range, the BR($W_R \to Wh$) is similar to the BR($W_R \to WZ$).

Therefore a production rate comparable to the previous case is expected. However, the further identification of the Wh pair reveals much more problematic.

The signature Wjj has huge QCD and $t\bar{t}$ backgrounds. Even in the most optimistic case of $\sin 2\alpha = 1$, which maximizes also the Wh BR, we obtain a peak value for $d\sigma/dM_{Wjj}$ of approximately $2 \cdot 10^{-2}(5 \cdot 10^{-4})$ pb GeV^{-1} for $M_{W_R} = 1(2)$ TeV. Assuming $m_t = 150$ GeV, the $t\bar{t}$ production lea ds to $d\sigma/dM_{Wjj} = 2 \cdot 10^{-2}(3 \cdot 10^{-4})$ pb GeV^{-1} at $M_{Wjj} = 1(2)$ TeV [16] and is comparable to the signal. The decay $Wh \to l\nu\gamma\gamma$ could be used in the mass range 100 GeV $<$ M$_\mathrm{h}$ $<$ 150 GeV, but due to the very small BR of approximately $2 \cdot 10^{-4}$, it would be effective only in extreme cases (for $M_{W_R} = 1$ TeV and $\sin 2\alpha = 1$ we get 15 events at LHC with $L = 10^5$ pb^{-1}). The same consideration applies to $Wh \to WZZ \to 5l + \nu$ in the range $M_h > 2M_Z$, which has a BR of approximately 10^{-4}. Finally, for $M_h > 2M_W$, the decay $Wh \to 3W \to 3l + 3\nu$ has a BR of about 10^{-2}. However, as in the WZ case, the same signature can be attributed to a non negligible fraction of the $t\bar{t}$ produced at LHC, and a detailed study of the achievable level of rejection, which goes beyond the purpose of this report, would be required.

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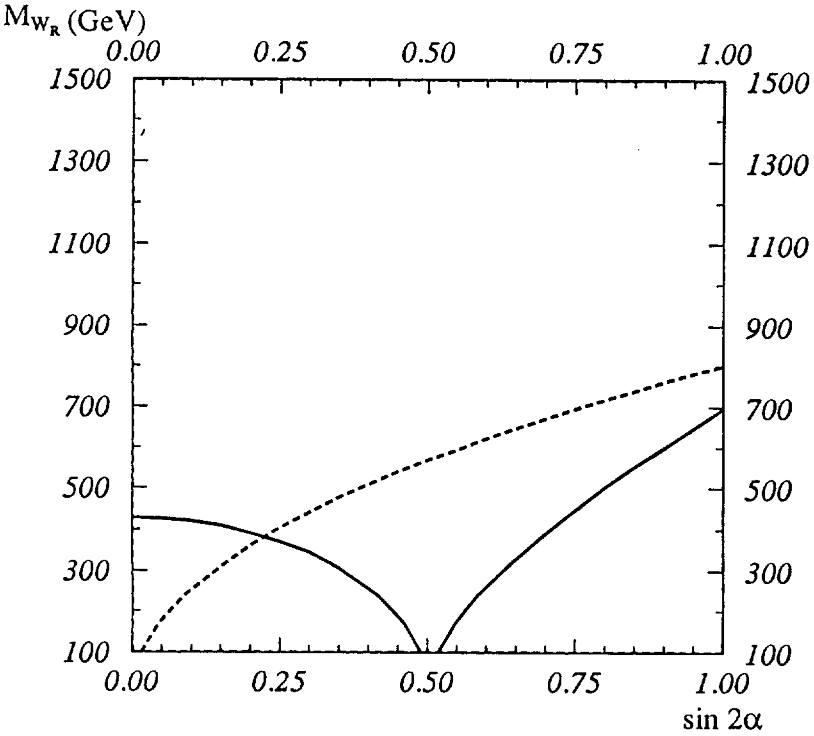

Fig 1 – Regions of the ($\sin 2\alpha, M_{W_R}$) plane allowed (above the corresponding line) from i) $|\xi| < 10^{-2}$, and ii) from the measurements of M_W/M_Z at $p\bar{p}$ colliders (UA2 and CDF experiments) and of M_Z at LEP, assuming m_t = 150 GeV. The two limits i) and ii) are represented by the dashed and the continuous line, respectively.

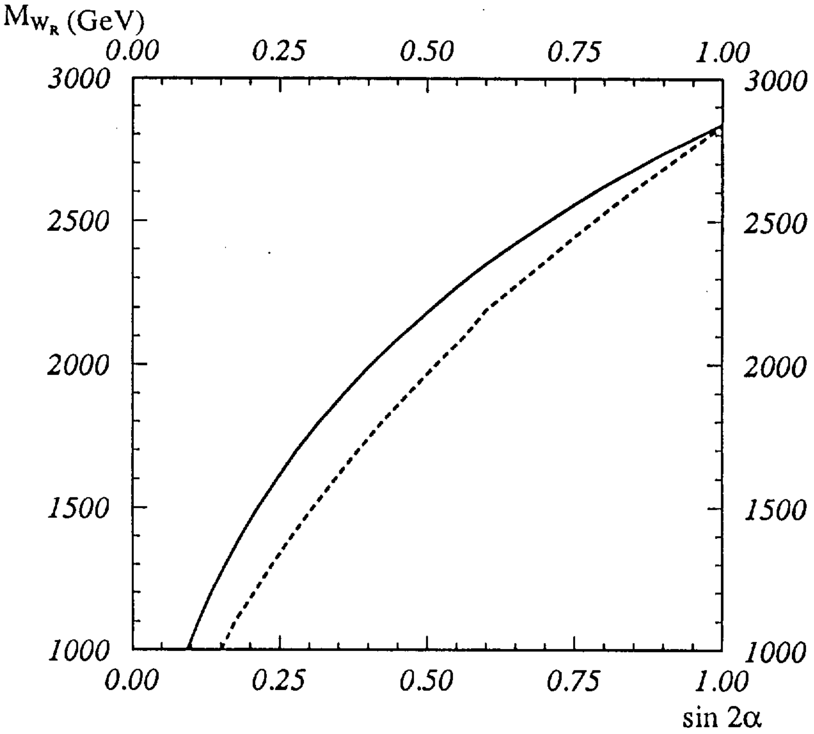

Fig 2 – Number of W^+Z pairs produced per year at LHC as a function of the WZ invariant mass $M_{W,Z}$, for M_{W_R} = 2 TeV, $\sin 2\alpha = 1$ and an integrated luminosity of 10^5 pb^{-1}. The lower continuous line represents the background from $q\bar{q}$ and γW and the upper one is the sum of signal and background. For the cuts applied see Table II.

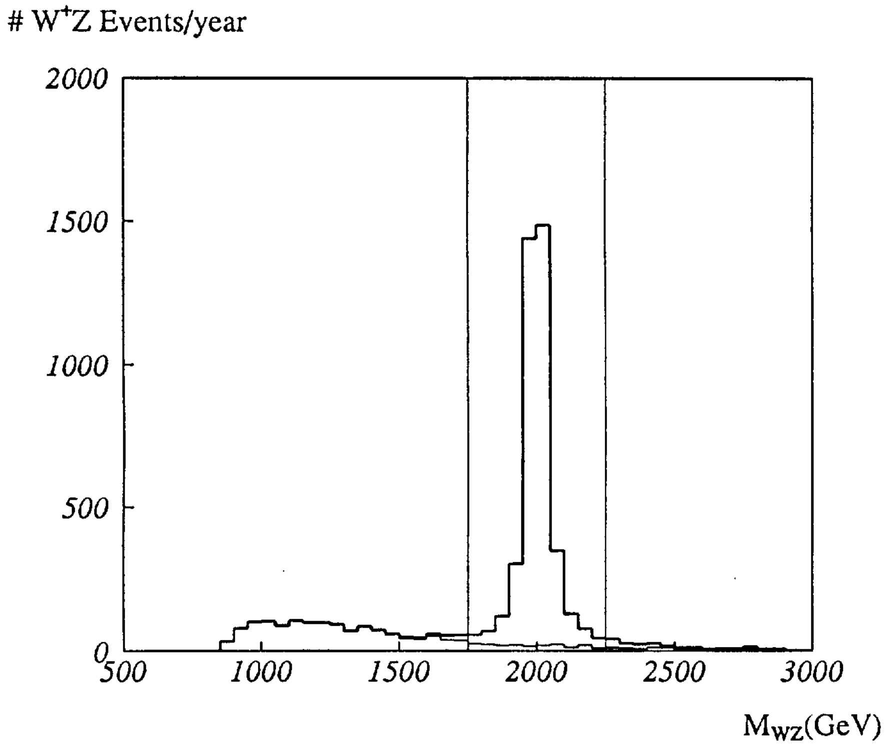

Fig 3 – Number of W^+Z pairs produced per year at LHC as a function of the Z transverse momentum p_T^Z, for $M_{W_R} = 2$ TeV, $\sin 2\alpha = 1$ and an integrated luminosity of 10^5 pb^{-1}. The lower continuous line represents the background from $q\bar{q}$ and γW and the upper one is the sum of signal and background. For the cuts applied see Table II.

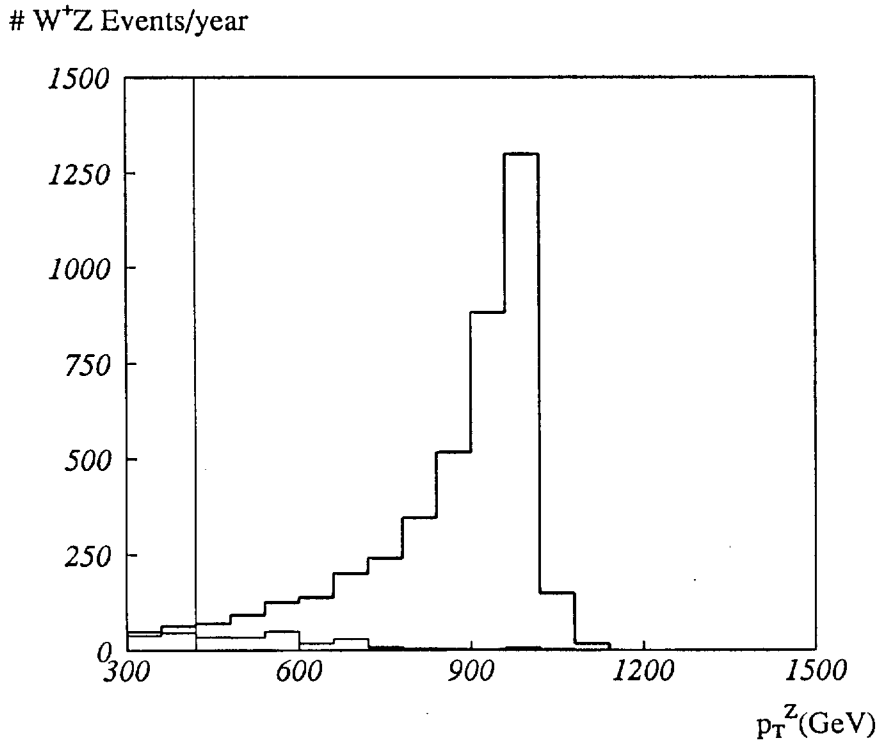

Fig 4 – Discovery limits of the W_R^+ in the WZ channel at LHC ($\sqrt{s} = 16$ TeV, L $= 10^5$ pb^{-1}) (continuous line) and SSC ($\sqrt{s} = 40$ TeV, L $= 10^4$ pb^{-1}) (dashed line). The region under the curves corresponds to more than 15 leptonic ($3l+\nu$, $l = e, \mu$) events with $S/\sqrt{B} > 3$.