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WZ PAIR PRODUCTION AT LHC IN LEFT-RIGHT MODELS

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Abstract

The production of W_R and its identification through the WZ decay channel is studied at LHC. The signal is characterized by a very high Z transverse momentum. By considering the totally leptonic decay channel of the produced WZ pair and by taking into account the possible backgrounds, we estimate that LHC with an integrated luminosity of 10^5 pb^{-1} will be sensitive to W_R masses up to 2.8 TeV. A similar sensitivity is expected for SSC with 10^4 pb^{-1}.

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In this note we will study the production at LHC of the W_R, the charged, heavy gauge vector boson of the left-right (LR) extensions [1] of the standard model (SM). The interest in the LR models comes from the fact that they represent one of the simplest realizations of a gauge structure enriched with respect to the SM one, in which parity invariance is restored: in fact, 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, LR models require the presence of the right-handed neutrino ν_R, which has no counterpart in the SM. The problem of accounting for a very light ν_L and a heavy ν_R can be solved in a rather natural way by introducing the so-called see-saw mechanism [2], which makes use of the peculiar properties of the neutrinos. With a suitable Higgs structure, it is possible to justify the smallness of the mass of the left-handed neutrino whereas ν_R is generally shifted to a very high mass scale. It follows that, at least on phenomenological grounds, the first experimental indications in favour of a LR extension of the SM are mainly expected in the sector of the gauge bosons, even if the problem remains of the mass scale at which the restoration of parity takes place.

As we shall see, at LHC energies one can produce and detect a W_R with a mass up to several TeV. 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, taking into account that WZ pair production may come 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 LR models, the WZ channel could be of particular interest if, as discussed above, the ν_R is so heavy as to suppress completely or in part the $e\nu_R$ decay mode.

We consider here a model based on the gauge symmetry $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$, with 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 $\Phi = (\frac{1}{2}, \frac{1}{2}, 0)$. The following vacuum expectation values (VEV's) are assumed:

$$< \Delta_L^0 > = v_L \quad , \qquad < \Delta_R^0 > = v_R \quad , \tag{1}$$

$$< \Phi > = \begin{pmatrix} v & 0 \\ 0 & v' \end{pmatrix} \quad , \tag{2}$$

where $\Delta_{L,R}^0$ stands for the neutral component of the corresponding triplet and the components of Φ are specified according to:

$$\Phi = \begin{pmatrix} \varphi^0 & \psi^+ \\ \varphi_- & \psi_0 \end{pmatrix} \quad . \tag{3}$$

We further assume the usual hierarchy among the VEV's:

$$v_R \gg v, v' \gg v_L \sim 0 \tag{4}$$

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

$$\tan\alpha \equiv \frac{v'}{v} \quad , \tag{5}$$

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

$$|\xi| \sim |\sin 2\alpha| \left(\frac{M_W}{M_{W_R}} \right)^2 \quad . \tag{6}$$

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

We first briefly discuss the limits on the model coming from experiment. The present data impose 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 on the allowed region comes from the measurements of M_Z at LEP and M_W/M_Z at UA2 and CDF. Here we use the recent values $M_Z = 91.173 \pm 0.031\ GeV$ [8] and $M_W/M_Z = 0.8808 \pm 0.0036$ [9]. By combining them we can derive a determination of the ρ parameter:

$$\rho = 1.0066 \pm 0.0058 \quad , \tag{7}$$

to be compared with the theoretical expectation. In fact, quite generally, in any gauge extension of the SM, $\Delta\rho = \rho - 1$ can be decomposed into several terms [10]:

$$\Delta\rho = \Delta\rho_{top} + \Delta\rho_M + \dots \quad , \tag{8}$$

where, typically, $\Delta\rho_{top} \sim (3G_F m_t^2/8\pi^2\sqrt{2})$ represents the leading top contribution coming from radiative corrections and $\Delta\rho_M$ is the contribution coming from the mixing in the gauge vector boson sector. $\Delta\rho_M$ has the general asymptotic form [10]:

$$\Delta\rho_M = c_0^2 \left(\frac{M_Z}{M_{Z'}} \right)^2 - c^2 \left(\frac{M_W}{M_{W'}} \right)^2 \tag{9}$$

with c_0 and c constants depending on the VEV's of the scalar fields. In the case considered here we obtain:

$$\Delta\rho_M = [.254 - (\sin 2\alpha)^2] \left(\frac{M_W}{M_{W_R}} \right)^2 \quad . \tag{10}$$

Additional contributions to $\Delta\rho$ (dots in eq. (8)) could come from non–vanishing VEV's of scalars not in $SU(2)_L$ singlet or doublet representations, and from additional radiative corrections in case of large isospin splitting of matter multiplets. Neglecting these contributions, eqs. (7), (8) and (10) provide, for each given top mass, a limitation in the $(\sin 2\alpha, M_{W_R})$ plane. Fig. 1 shows the 90% CL allowed region for $m_t = 150$ GeV. Because of the structure of $\Delta\rho_M$ given in eq. (10), the constraint is not effective around $\sin 2\alpha \sim 0.5$. For $\sin 2\alpha < 0.5$, $\Delta\rho_M$ is positive and a lower bound on M_{W_R} is obtained from the upper limit of ρ in eq. (7). For instance, at $\sin 2\alpha = 0$, for $m_t = 150$ GeV one obtains $M_{W_R} > 424$ GeV at 90% CL. If $\sin 2\alpha > 0.5$, $\Delta\rho_M$ is essentially negative and the lower bound on M_{W_R} comes from the lower limit of ρ in eq. (7). At $\sin 2\alpha = 1$, for $m_t = 150$ GeV one obtains $M_{W_R} > 693$ GeV at 90% CL.

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 for a W' at the Tevatron collider gives the bound $M_{W'} > 478$ GeV [12], looking at the conventional $e\nu$ decay channel and assuming the W' couplings to be equal to the SM ones.

In the present analysis we will consider the W_R in the mass range from 750 GeV up to several TeV. The dominant production mechanism expected 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 particles:

$$\Gamma(W_R \to WZ) = \frac{g^2}{192\pi} M_{W_R} \sin^2 2\alpha \quad : \qquad (11)$$

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. In Table I we list a number of illustrative cases realizing this compromise. From eq. (6) one sees that a large M_{W_R} already leads to acceptable ξ values, without requiring a small value for $\sin 2\alpha$. For instance, at $M_{W_R} = 1$ TeV

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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].

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 of 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 very 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 ~ 109 pb for $M_{W_R} = 750$ GeV, to about ~ 0.6 pb at $M_{W_R} = 2500$ GeV (we have used the DFLM parton densities [14] with $\Lambda_{QCD} = 260$ MeV). For the cases considered in Table I, we can conclude that the LHC, assuming an integrated luminosity of 10^5 pb^{-1}, could produce a considerable number of WZ pairs.

To further analyze the potentiality of the 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 backgrounds coming from the electroweak $q\bar{q}$ and γW continuum were generated, together with the signal, by a Monte Carlo program. Table II compares the signal S and the total background B for the cases listed in Table I, after imposing suitable kinematical cuts. A cut on the rapidities of the W and Z, $|y_{W,Z}| < 2.5$, is common to all cases. A cut on the WZ invariant mass M_{WZ} has been applied below and above the resonant shape of the signal. Finally, a cut on p_T^Z has been obtained by optimizing the statistical significance of the signal. 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 continuum 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 the LHC and SSC. Fig. 4 shows the reach of the two colliders for W_R^+, assuming for the 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} was 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 the LHC(SSC).

Finally, we add some comments about the Wh decay channel. The Φ multiplet of eq. (3) 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 M_{W_R} in the TeV range, the BR$(W_R \rightarrow Wh)$ is similar to the BR$(W_R \rightarrow WZ)$. Therefore a production rate comparable to the previous case is expected. However, the further identification of the Wh pair appears to be much more problematic. Here we have considered the following possibilities:

i) The signature Wjj, which however has huge QCD and $t\bar{t}$ backgrounds. Even in the most optimistic case $\sin 2\alpha = 1$, 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 leads 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.

ii) The decay $Wh \rightarrow l\nu\gamma\gamma$. It could be used in the mass range 100 GeV $< \mathrm{M_h} <$ 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 the LHC with $L = 10^5$ pb^{-1}).

iii) The same consideration applies to $Wh \rightarrow WZZ \rightarrow 5l + \nu$ in the range $M_h > 2M_Z$, which has a BR of approximately 10^{-4}.

iv) Finally, for $M_h > 2M_W$, the decay $Wh \rightarrow 3W \rightarrow 3l + 3\nu$, which 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 the LHC, and a detailed study of the achievable level of rejection would be required.

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Table Captions

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.

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 the 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 I

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 II

		$(p_T^Z)_{cut}$ $(M_{WZ})_{cut}$	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

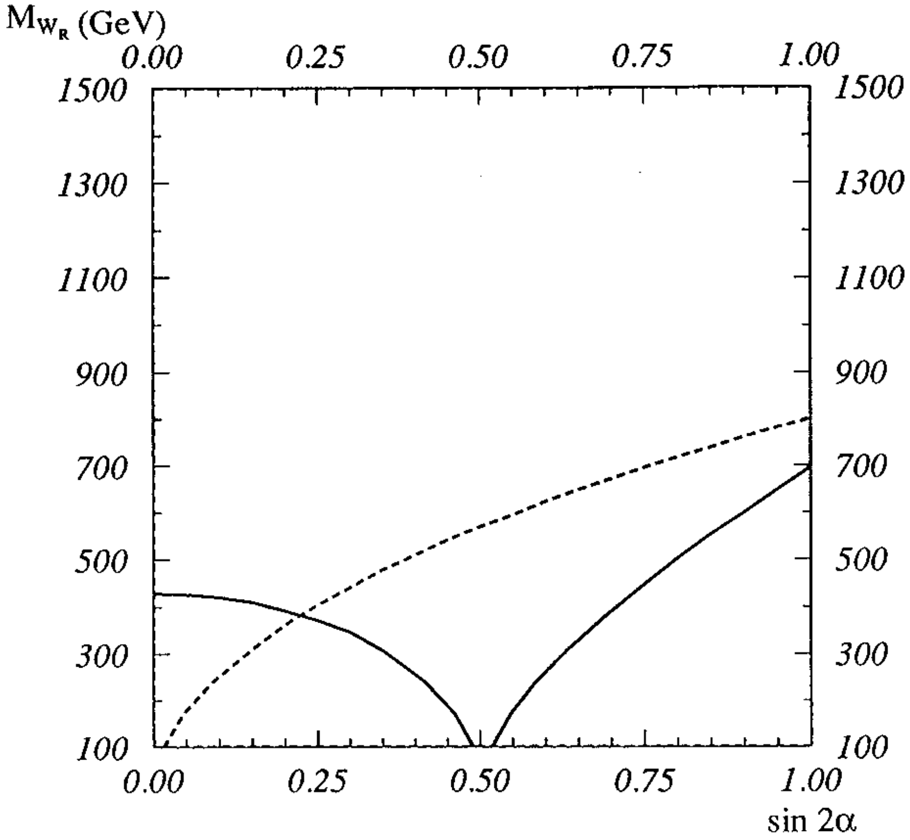
Figure Captions

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 the 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. The following cuts have been applied: $|y_{W,Z}| < 2.5$, $p_T^Z > 420$ GeV. The additional cut 1750 GeV $< \mathrm{M_{WZ}} <$ 2250 GeV leads to 204 events for the background and 3880 events for the signal.

Fig 3 – Number of W^+Z pairs produced per year at the 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. The following cuts have been applied: $|y_{W,Z}| < 2.5$ and 1750 GeV $< \mathrm{M_{WZ}} <$ 2250 GeV. The additional cut $p_T^Z > 420$ GeV leads to 204 events for the background and 3880 events for the signal.

Fig 4 – Discovery limits of the W_R^+ in the WZ channel at the LHC ($\sqrt{s} = 16$ TeV, L $= 10^5$ pb^{-1}) (continuous line) and the 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 $S/\sqrt{B} > 3$.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1.00
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1100
900
700
500
300
100
sin 2α

Fig. 1

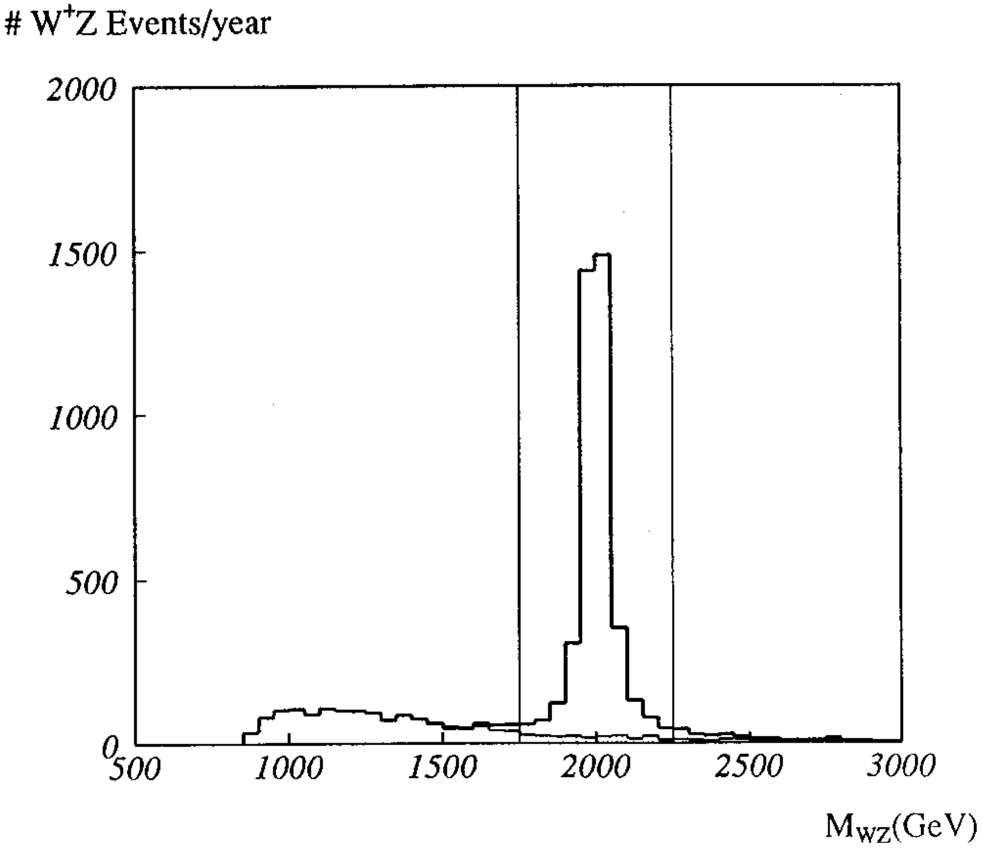
W^+Z Events/year
2000
1500
1000
500
0
500
1000
1500
2000
2500
3000
M_{WZ}(GeV)

Fig. 2

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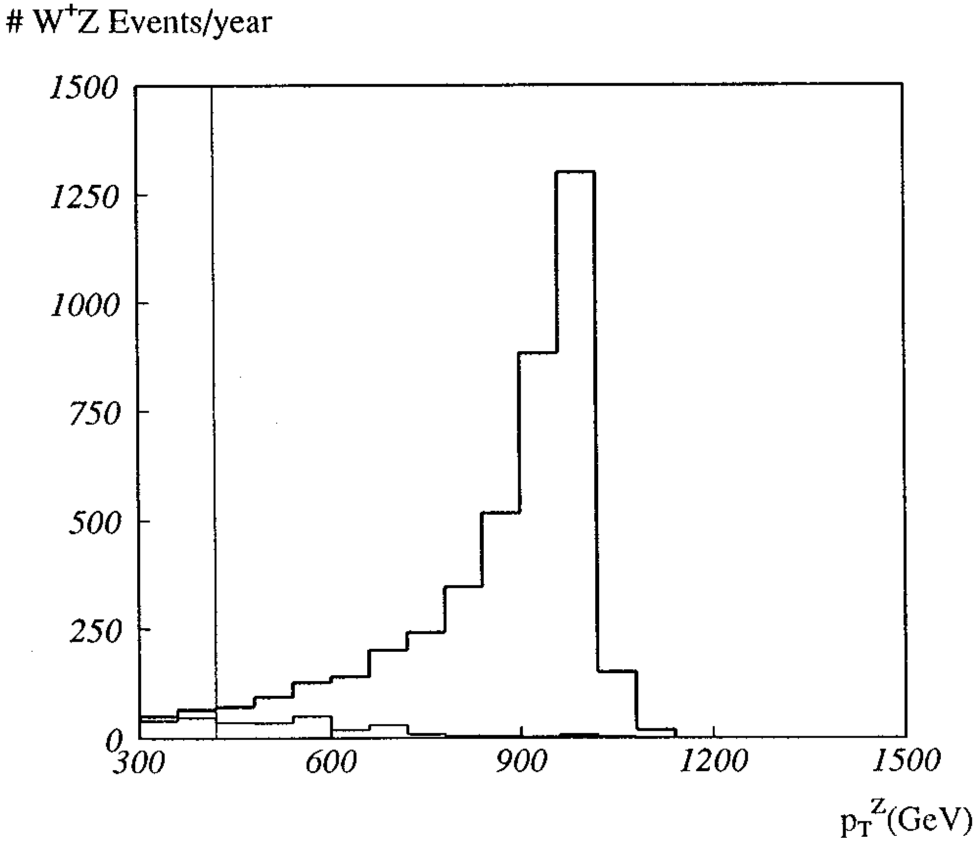

Fig. 3

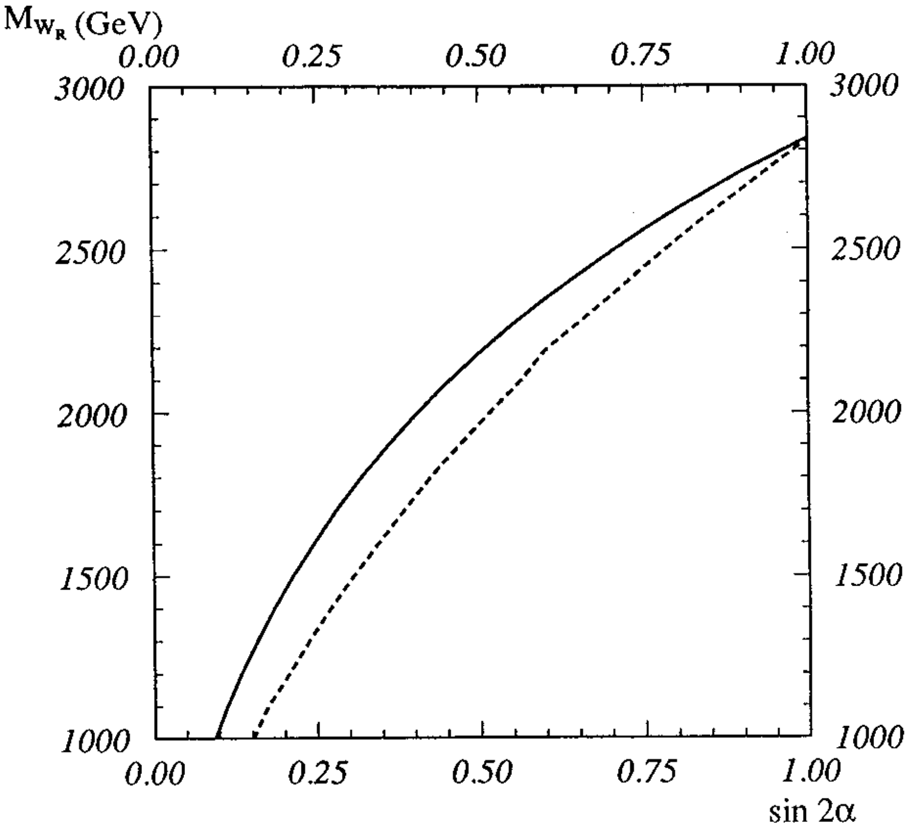

Fig.4