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# MASS BOUNDS FOR TRIPLET SCALARS OF THE LEFT-RIGHT SYMMETRIC MODEL AND THEIR FUTURE DETECTION PROSPECTS

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## ABSTRACT

*The standard formulation of the Left-Right symmetric model involves scalars transforming as a triplet under $SU(2)_L$. This multiplet contains particles which are uncharged, singly-charged, and doubly-charged. We derive a bound on the uncharged scalar mass of 55.4 GeV using results from LEP-II and find that a range upto 110 GeV may be explored at the NLC at the $5\sigma$ level. We also discuss search strategies for the singly- and doubly-charged scalars at the Tevatron and the LHC. Possible Standard Model backgrounds for the relevant modes are estimated and compared with the signal. At the LHC, the prospects of detecting the doubly-charged scalar are bright up to a mass of 850 GeV while the $5\sigma$ discovery limit of the singly-charged mode extends to 240 GeV for an integrated luminosity of 100 $fb^{-1}$. At the Tevatron, with an integrated luminosity of 25 $fb^{-1}$, the doubly-charged state can be detected if its mass is less than 275 GeV while the reach for the singly charged scalar is 140 GeV.*

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# 1 INTRODUCTION

The quest for the higgs boson is one of the urgent missions of the on-going and future particle physics experiments. It is the key missing ingredient of the Standard Model (SM) and is responsible for the spontaneous breaking of the $SU(2)_L \times U(1)_Y$ symmetry of electroweak interactions. So far, direct experimental searches for this scalar have proved fruitless and the absence of a higgs signal at LEP-I and II yield a lower limit, 87.9 GeV [1], on its mass.

Though the SM has met with spectacular success under experimental scrutiny, nonetheless, extensions beyond its gauge, scalar, or fermion sectors have received much attention. In particular, the Left-Right symmetric model (LRM), based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, has been put forward [2] as an equally viable alternative to the electroweak model with the added virtue that, unlike in the SM, the non-conservation of parity is a consequence of spontaneous symmetry breaking and not put in by hand. In the minimal version of this model, the spectrum is enriched through the introduction of right-handed partners of the observed gauge bosons and neutrinos. These are significantly heavy, typically of the scale $v_R \gtrsim 1$ TeV at which the LR symmetry is broken spontaneously. Detailed phenomenology of the LRM has been extensively examined and many constraints have been derived which restrict the character of this model [3]. In this work our attention will revolve, in the main, around the scalar sector of the model which consists of one bi-doublet, $\phi(1/2, 1/2, 0)$, one right-handed triplet, $\Delta_R(0, 1, 2)$, and one left-handed triplet, $\Delta_L(1, 0, 2)$. In the above, the $SU(2)_L$, $SU(2)_R$ and $U(1)_{B-L}$ quantum numbers of the fields are indicated in the parantheses. $\Delta_R$ breaks the $SU(2)_R$ symmetry and can also generate a majorana mass of the right-handed neutrino as required for the "see-saw" mechanism. Out of the 20 degrees of freedom, after spontaneous symmetry breaking to $U(1)_{EM}$, there remain 6 physical neutral scalars (4 CP-even and 2 CP-odd), 2 physical charged scalars (4 degrees of freedom), and 2 doubly-charged scalars (4 degrees of freedom). Except one CP-even neutral state, the others have masses at the $v_R$ scale if the couplings of the scalar potential bear no relation to each other. The former, originating from the bi-doublet, is the analogue of the higgs boson of the SM and has similar coupling to the gauge bosons, save the suppression by a mixing angle factor which

is typically very close to unity. A possible relationship among the couplings in the scalar potential discussed later, which can arise naturally from some larger symmetry, can keep the masses of some of the other scalars, specifically from the left triplet, in the scale of $m_W$, in which case they may be produced in the present and upcoming colliders. In this work we examine the mass limits for these particles and the prospect of their detection at the Tevatron and the LHC.

The plan of the article is as follows. In section 2, we discuss in detail the LRM lagrangian, couplings, and scalar mass matrices relevant to our analysis. In section 3, we begin with the pair production of the neutral triplet scalar at LEP-II. The triplet scalars can only have majorana-type coupling to the leptons and the neutral member couples only to neutrinos and decays invisibly. We utilize its production in association with a photon to set a bound on its mass using the measured LEP cross-section of the photon plus missing energy channel. In Section 4, we turn to hadron colliders and examine the feasibility of observation of the singly-charged scalars, which decay dominantly to leptons, along with an analysis of possible SM backgrounds at the Tevatron and the LHC. The production and detection of doubly-charged scalars are discussed in Section 5. The conclusions are in Section 6.

# 2 LAGRANGIAN AND THE RELEVANT COUPLINGS

We begin this section by reviewing the salient features of the minimal version of the LRM with an emphasis on the scalar sector. A convenient representation of the scalar fields is given in terms of $2 \times 2$ matrices:

$$\phi \equiv \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \Delta_L \equiv \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix}, \Delta_R \equiv \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix}$$

Under $SU(2)_{L,R}$ gauge transformations:

$$\phi \to U_L \phi U_R^\dagger, \;\; \Delta_L \to U_L \Delta_L U_L^\dagger, \;\; \Delta_R \to U_R \Delta_R U_R^\dagger \tag{1}$$

where $U_{L,R}$ are the appropriate $2 \times 2$ unitary matrices.

The gauge symmetry breaking proceeds in two stages. In the first stage, $\delta_R^0$, the electrically neutral component of $\Delta_R$, acquires a vacuum expectation value (*vev*) $v_R$ breaking the gauge symmetry down to $SU(2)_L \times U(1)_Y$. The masses of the $W_R$ and $Z'$ gauge bosons and that of the right-handed neutrino field are also driven by $v_R$. $k$ and $k'$, the *vev*s of the neutral members of the bi-doublet serve the dual purpose of breaking the $SU(2)_L \times U(1)_Y$ symmetry to $U(1)_{EM}$, thereby setting the mass scale of the observed $W_L$ and $Z$ bosons, and of providing the quark and lepton dirac masses. $v_R$ is significantly larger than $k, k'$ so that right-handed gauge bosons are heavier than the $W_L$ and $Z$. $\Delta_L$ is the LR symmetric counterpart of $\Delta_R$. $v_L$ must be much smaller than $k, k'$ in order that the deviation of $\rho$ $(= M_W^2/M_Z^2 \cos^2\theta_W)$ from unity be very small, as observed experimentally [4].

We now turn to the scalar potential. Under LR symmetry, $\phi \leftrightarrow \phi^\dagger$, $\Delta_R \leftrightarrow \Delta_L$ and also $\Psi_L \leftrightarrow \Psi_R$, where $\Psi_{L,R}$ are the column vectors containing the left-handed and right-handed fermionic fields of the theory. Moreover, the LR symmetry forbids any trilinear terms in the scalar potential. Because of the non-zero values of the $B-L$ quantum numbers of the triplet fields, they must appear in the quadratic combination $\Delta_i \Delta_j^\dagger$, where $i, j = L, R$. The scalar potential satisfying these requirements can be written as :

$$\mathcal{V} = \mathcal{V}_\phi + \mathcal{V}_\Delta + \mathcal{V}_{\phi\Delta} \tag{2}$$

where,

$$\begin{aligned} \mathcal{V}_\phi &= -\mu_1^2 Tr(\phi^\dagger\phi) - \mu_2^2[Tr(\tilde{\phi}\phi^\dagger) + Tr(\tilde{\phi}^\dagger\phi)] + \lambda_1[Tr(\phi^\dagger\phi)]^2 + \lambda_2[Tr(\phi^\dagger\tilde{\phi})^2 + \\ &\quad Tr(\tilde{\phi}^\dagger\phi)^2] + \lambda_3[Tr(\phi^\dagger\tilde{\phi})Tr(\tilde{\phi}^\dagger\phi)] + \lambda_4 Tr(\phi^\dagger\phi)[Tr(\tilde{\phi}\phi^\dagger) + Tr(\tilde{\phi}^\dagger\phi)] \end{aligned} \tag{3}$$

where $\tilde{\phi} = \sigma_2\phi^*\sigma_2$ and

$$\begin{aligned} \mathcal{V}_\Delta &= -\mu_3^2[Tr(\Delta_L\Delta_L^\dagger) + Tr(\Delta_R\Delta_R^\dagger)] + \rho_1[Tr(\Delta_L\Delta_L^\dagger)^2 + Tr(\Delta_R\Delta_R^\dagger)^2] + \\ &\quad \rho_2[Tr(\Delta_L\Delta_L)Tr(\Delta_L^\dagger\Delta_L^\dagger) + Tr(\Delta_R\Delta_R)Tr(\Delta_R^\dagger\Delta_R^\dagger)] + \\ &\quad \rho_3 Tr(\Delta_L\Delta_L^\dagger)Tr(\Delta_R^\dagger\Delta_R) \end{aligned} \tag{4}$$

$$
\begin{aligned}
\mathcal{V}_{\phi\Delta} &= \alpha_1 Tr(\phi^\dagger\phi)[Tr(\Delta_L\Delta_L^\dagger) + Tr(\Delta_R\Delta_R^\dagger)] \\
&+\alpha_2[Tr(\tilde{\phi}^\dagger\phi) + Tr(\tilde{\phi}\phi^\dagger)][Tr(\Delta_L\Delta_L^\dagger) + Tr(\Delta_R^\dagger\Delta_R)] \\
&+\alpha_3[Tr(\phi\phi^\dagger\Delta_L\Delta_L^\dagger) + Tr(\phi^\dagger\phi\Delta_R\Delta_R^\dagger)] \\
&+\alpha_4[Tr(\tilde{\phi}\tilde{\phi}^\dagger\Delta_L\Delta_L^\dagger) + Tr(\tilde{\phi}^\dagger\tilde{\phi}\Delta_R\Delta_R^\dagger)] \qquad (5)
\end{aligned}
$$

The discrete LR symmetry ensures that all the couplings are real and that the potential is CP conserving. The scalar potential may be simplified by imposing some more symmetry. Thus, requiring a $\phi \to i\phi$ symmetry, the $\mu_2^2$ as well as the $\lambda_4$ and $\alpha_2$ terms can be eliminated. In the above expression for the scalar potential, quartic terms of the form $\phi\Delta_R\phi^\dagger\Delta_L^\dagger + \phi^\dagger\Delta_L\phi\Delta_R^\dagger$ have been excluded. In the literature these terms are usually dropped by appealing to some suitable symmetry [5].
The conditions following from the minimization of the potential are:

$$k^{'}[\lambda_1(k^2 + k^{'2}) + 2(2\lambda_2 + \lambda_3)k^2 + (\alpha_1 + \alpha_3)(v_L^2 + v_R^2)/2 - \mu_1^2] = 0 \qquad (6)$$

$$k[\lambda_1(k^2 + k^{'2}) + 2(2\lambda_2 + \lambda_3)k^{'2} + (\alpha_1 + \alpha_4)(v_L^2 + v_R^2)/2 - \mu_1^2] = 0 \qquad (7)$$

$$v_L[\ \rho_1 v_L^2 + \rho_3 v_R^2/2 + \alpha_1(k^2 + k^{'2})/2 + (\alpha_3 k^{'2} + \alpha_4 k^2)/2 - \mu_3^2] = 0 \qquad (8)$$

$$v_R[\ \rho_1 v_R^2 + \rho_3 v_L^2/2 + \alpha_1(k^2 + k^{'2})/2 + (\alpha_3 k^{'2} + \alpha_4 k^2)/2 - \mu_3^2] = 0 \qquad (9)$$

An examination of the charged gauge boson mass matrix (not presented here) shows that the mixing between $W_L^\pm$ and $W_R^\pm$ is proportional to the product $kk^{'}$. The tight limits on any right-handed admixture in the observed weak interactions constrain this product to be very near zero [7] and in the remaining analysis we take $k^{'} = 0$, in consonance with eq. (6). From eq. (9), since $v_R \neq 0$ to break $SU(2)_R$, one gets in this limit:

$$\mu_3^2 = \rho_1 v_R^2 + \frac{\alpha_1 + \alpha_4}{2}k^2 + \rho_3 v_L^2/2 \qquad (10)$$

Using this relation and $k^{'} = 0$ in eq. (8) one obtains:

$$(2\rho_1 - \rho_3)v_L(v_R^2 - v_L^2) = 0 \qquad (11)$$

This relation can be satisfied by choosing either $v_L = 0$ or $2\rho_1 = \rho_3$. If $v_L$ is non-vanishing then a global symmetry of the theory – identified with lepton number if $\Delta_L$

has majorana couplings to leptons – is spontaneously broken resulting in a massless (goldstone) mode. Such a 'triplet majoron' is ruled out by the $Z$-decay data because the latter can decay to a pair of such massless states with full strength, enhancing its invisible decay width beyond the very stringent experimental constraints. Therefore we choose the other alternative, namely, $v_L = 0$ [8]. The minimization conditions now become:

$$\mu_1^2 = \lambda_1 k^2 + \frac{\alpha_1 + \alpha_4}{2} v_R^2, \quad \mu_3^2 = \rho_1 v_R^2 + \frac{\alpha_1 + \alpha_4}{2} k^2 \tag{12}$$

along with $v_L,\ k^{'} = 0$. Utilizing the above relations, the mass matrices for neutral and charged scalars in the $\phi_1,\ \phi_2,\ \Delta_L,\ \Delta_R$ basis can be simplified. Thus for real parts of the neutral scalars (CP even scalars):

$$\mathcal{M}_{0r}^2 = \begin{pmatrix} 4\lambda_1 k^2 & 0 & 0 & (\alpha_1+\alpha_4) k v_R \\ 0 & 4(\lambda_3+2\lambda_2)k^2 + (\alpha_3-\alpha_4)v_R^2 & 0 & 0 \\ 0 & 0 & (\rho_3 - 2\rho_1)v_R^2 & 0 \\ (\alpha_1+\alpha_4) k v_R & 0 & 0 & 4\rho_1 v_R^2 \end{pmatrix} \tag{13}$$

and for the imaginary parts (CP odd pseudoscalars):

$$\mathcal{M}_{0i}^2 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 4(\lambda_3-2\lambda_2)k^2 + (\alpha_3-\alpha_4)v_R^2 & 0 & 0 \\ 0 & 0 & (\rho_3 - 2\rho_1)v_R^2 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{14}$$

For the singly-charged scalars one has:

$$\mathcal{M}_{\pm}^2 = \begin{pmatrix} (\alpha_3-\alpha_4)v_R^2/2 & 0 & 0 & (\alpha_3-\alpha_4) k v_R/2\sqrt{2} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & (\rho_3-2\rho_1)v_R^2/2 + (\alpha_3-\alpha_4)k^2/4 & 0 \\ (\alpha_3-\alpha_4) k v_R/2\sqrt{2} & 0 & 0 & (\alpha_3-\alpha_4)k^2/4 \end{pmatrix} \tag{15}$$

while for the doubly-charged scalar mass matrix:

$$\mathcal{M}_{\pm\pm}^2 = \begin{pmatrix} (\alpha_3-\alpha_4)k^2/2 + (\rho_3-2\rho_1)v_R^2/2 & 0 \\ 0 & 2\rho_2 v_R^2 + (\alpha_3-\alpha_4)k^2/2 \end{pmatrix} \tag{16}$$

As expected, there are two massless states each in $\mathcal{M}_{0i}^2$ and $\mathcal{M}_{\pm}^2$, corresponding to the longitudinal modes of the gauge bosons $Z,\ Z^{'}$, $W_L$, and $W_R$. From $\mathcal{M}_{0r}^2$, it is

seen that $\phi_2^{0r}$ and $\delta_L^{0r}$ are mass eigenstates. The two other eigenstates of this matrix are superpositions of $\phi_1^{0r}$ and $\delta_R^{0r}$ with a mixing angle of the order of $\frac{k}{v_R}$. The lighter eigenstate, with a mass of the order of $k$ ($\sim m_W$), is the analogue of the SM higgs boson. Unless some combinations of couplings are small (see later), the mass of all the other scalars (including the singly-charged, doubly-charged and pseudoscalars) are controlled by $v_R$.

The particular feature of the mass matrices in eqs. (13 – 16) that we wish to stress in this work is that, in the chosen $v_L = 0, \quad k^{'} = 0$ limit, all the scalars originating from $\Delta_L$ are eigenstates of the corresponding mass matrices with the contributions proportional to $v_R^2$ in the eigenvalues multiplied by the factor $(\rho_3 - 2\rho_1)$. If this last factor is small then these states will be light. Now, $(\rho_3 - 2\rho_1)$ will be exactly vanishing if the gauge group is embedded in a simple grand unifying group – *e.g.,* $SO(10)$ Grand Unified Theory (GUT) – so long as *that* symmetry is unbroken since in the GUT $\Delta_L$ and $\Delta_R$ are members of the same irreducible representation of the symmetry group – **126** of $SO(10)$, for example. The deviation of the factor from zero can thus be considered as a result of the GUT symmetry breaking. We have examined the renormalisation group evolution of these $\rho$ couplings from the GUT scale to the TeV scale. When writing down the evolution equations, for simplicity, we have retained only the contributions from the gauge and $\rho$-type quartic couplings. We find that for a range of values of the paramters at the GUT scale, the magnitude of the combination $(\rho_3 - 2\rho_1)$ is in the appropriate ballpark [9]. Without confining ourselves to any particular GUT, we examine the phenomenology of the model assuming that the scalars originating from $\Delta_L$ are not beyond the reach of the present and future colliders.

A tree level relation among the masses of the scalars from the left-handed triplet is apparent from the matrices in eqs. (13 – 16), *viz.*:

$$2m_{++}^2 = 4m_+^2 - m_0^2 \tag{17}$$

Here $m_{++}$, $m_+$ and $m_0$ are respectively the masses of the doubly-charged, singly-charged, and the neutral scalars. In our subsequent analysis we vary the masses of the scalars over a phenomenologically interesting range, consistent with eq. (17), without delving into the details of the parameters of the scalar potential.

Here it might be mentioned that in our subsequent analysis the mass ordering $m^2_{++} > m^2_+ > m^2_0$ has been chosen. The opposite hierarchy of the scalar masses, *viz.*, $m^2_0 > m^2_+ > m^2_{++}$, can also be consistent with eq. (17). But it implies $(\alpha_3 - \alpha_4) < 0$ (see eqs. (15 – 16)) which in turn makes one of the charged scalar mass-squared negative (see eq. (15)). Therefore, we do not conisder this alternative.

Next we list the gauge boson - higgs boson interactions, relevant for our investigation, in the convention where all the momenta are incoming and each rule is to be multiplied by $i(p_1 - p_2)^\mu \cos\xi^0$ ($\xi^0$ is the mixing angle in the $Z - Z'$ sector [10]. $p_1$ is the momentum of the first scalar boson and $p_2$ is that of the second.):

$$\delta^{0i}\delta^{0r}Z : \frac{-ig}{\cos\theta_W}, \quad \delta^+\delta^-Z : \frac{-g\sin^2\theta_W}{\cos\theta_W}, \quad \delta^{++}\delta^{--}Z : \frac{g\cos 2\theta_W}{\cos\theta_W}$$

Finally, we note the majorana interaction of the triplet scalars $\Delta$ with the leptons:

$$\mathcal{L} = ih\Psi_i^T C\tau_2\Delta_i\Psi_i + h.c.; \quad \Psi_i \equiv \begin{pmatrix}\nu \\ l\end{pmatrix}_i ; \quad i = L, R \tag{18}$$

Here $C$ is the dirac charge conjugation matrix and $\tau_2$ the usual $SU(2)$ generator. It turns out to be important for our later analysis that the neutral member of the triplet couples only to neutrinos. In this work, we assume the above interaction to be diagonal and proportional to the identity in flavor space. This is the simplest choice but certainly not unique. Off-diagonal entries will drive lepton flavor violation and are constrained from processes like $\mu \to e\gamma$, $\mu \to eee$, $\tau \to \mu\gamma$, etc. In view of the tight experimental bounds on these [11], we take the liberty to drop the off-diagonal couplings. Even keeping the couplings flavor diagonal, one might admit non-universality. In the standard Yukawa sector, the couplings are proportional to the fermion mass which is not the case here. Rather, we stick to the simplest choice of universal, diagonal couplings [12]. We will illuminate this in some detail in the next section.

# 3 MASS BOUND ON $\delta^0$ FROM LEP-II AND PROSPECTS AT NLC

As discussed in the previous section, we are interested in the $v_L = 0$ scenario. In this limit, $\delta^0$ does not have any coupling to a pair of $Z$ bosons and cannot be searched for *via* a channel akin to the Bjorken process for the SM higgs $H$ (*viz.* $e^+e^- \to Z(Z^*) \to Z^*(Z)H$) at an electron-positron collider. Instead, one must look for the production of $\delta^{0r}$ in association with a $\delta^{0i}$. It is seen from eqs. (13 - 16) that $\delta^{0r}$ and $\delta^{0i}$ are degenerate and are the lightest among the members of the left-handed triplet. Consequently, they will decay to a pair of neutrinos with a 100% branching ratio. Thus, once produced in $e^+e^-$ collision, they will result in an invisible final state[1]. Therefore, we examine the production of $\delta^{0r}$ $\delta^{0i}$ pairs accompanied by a photon which gives rise to a single photon and missing energy signal. We have calculated the $e^+e^- \to \gamma\delta^{0r}\delta^{0i}$ cross-section at a center of mass energy of 182.7 GeV corresponding to LEP-II. The main background for this signal comes from the SM process $e^+e^- \to \nu\bar{\nu}\gamma$. As the photon can originate only from one of the initial electrons, a major part of the background will be a peak in the distribution at the photon energy around 90 GeV. This corresponds to $Z$ production exactly (or almost) on-shell. The distribution also shows the usual *bremsstrahlung* peak for the photon energy tending to zero. As regards the signal, since $m_0 < m_Z/2$ is disfavored by the constraint from the $Z$ invisible width, a bump in the photon energy is absent here. Thus if this energy is restricted to be inside a window that excludes the 'radiative return to Z' peak, the background cross-section is reduced significantly without affecting the signal very much. However, after imposing such cuts we find it hardly possible to get a signal with $5\sigma$ significance at LEP-II. We will return to this issue later in the context of the Next Linear Collider (NLC) which will have higher center of mass energy and more

[1]The degeneracy of $\delta^{0r}$ and $\delta^{0i}$ is a consequence of the $\phi \to i\phi$ symmetry that has been imposed, ruling out certain terms in the potential. In the absence of such a symmetry the degeneracy will be removed. In such an event, the heavier of the two will have an additional three body decay mode going to the lighter one and a fermion-anti-fermion pair via a $Z^*$ exchange. We have checked that for reasonable choices of the coupling $h$ (see eq. (18)) this three body mode has a branching ratio of less than 1%.

luminosity than LEP. As discovery of $\delta^0$ at LEP-II seems unlikely, it is of interest to look for the bound on $m_0$ that can be obtained from the data.

To obtain the prediction of the LRM for this process at LEP-II, in addition to the standard $Z$-exchange, the contribution from a t-channel $\delta^+$ exchange diagram involveing the $\delta^+ e^+ \nu_e$ vertex has to be included. Before proceeding further, let us spend a few words on the upper bounds of these flavor diagonal $\Delta$-lepton-lepton type couplings of majorana nature [6, 14]. The $\delta^+ e^+ \nu_e$ coupling is constrained from the Bhabha (*viz.* $e^+e^- \to e^+e^-$) scattering cross-section as follows. In the LRM there is an extra diagram contributing to Bhabha scattering *via* $\delta^{++}$ exchange which is quadratic in this coupling. The upper bound on it increases with $m_{++}$ and, in turn (by virtue of the mass relation, eq. (17)), with $m_+$. This yields an upper limit on the coupling of around 0.4 when $m_+$ is 200 GeV which increases to about 4 when the $\delta^+$ mass is of the order of 1 TeV. The upper bound for the diagonal $\mu\mu$ coupling can be as high as 10 derived from the measured $(g-2)$ of the muon. We found that in all cases, the $\delta^+$ exchange t-channel diagram only makes a very small contribution to the signal and does not affect our results significantly. As already noted, we exclude flavor non-diagonal couplings like $\delta^+ e^+ \nu_\mu$.

In Fig. 1 we present the number of $e^+e^- \to \gamma + \not{E}$ events in the LRM as a function of $m_0$. As mentioned earlier, the LEP collaborations have searched for the single photon and missing energy final state at LEP-II [15, 16]. We use the OPAL results as they are most conveniently adapted to our discussion. The following cuts have been used in line with ref. [15].

$$x_T^\gamma (\equiv E_T^\gamma / E_{beam}) > 0.05, \quad 165^0 > \theta_\gamma > 15^0$$

The OPAL collaboration has observed 191 $\gamma + \not{E}$ events in $e^+e^-$ collision at $\sqrt{s}$ = 182.7 GeV. The SM prediction for this process is equal to $201.3 \pm 0.7$ events at the same center of mass energy [15]. We use these numbers to set bounds on $m_0$ by requiring that the contribution from the LRM must not exceed the difference between the 95% C.L. *upper* limit of the measured value and the 95% C.L. *lower* limit of the SM prediction. This limit is indicated by the dashed horizontal line in Fig. 1. The lower bound on $m_0$ corresponds to the point of intersection of the cross-section curve with this line and is seen to be equal to about 55.4 GeV.

Now we turn to investigate the prospect of discovery of the $\delta^0$ at the Next Linear Collider with a center of mass energy 500 GeV. As earlier, we consider the $\gamma + \not{E}$ signal and use the following cuts to enhance the signal over background.

$$0.5 > x_T^\gamma > 0.05, \;\; 175^0 > \theta_\gamma > 5^0, \;\; \text{missing mass} > 100 \text{ GeV}.$$

The matrix element squared for the background $e^+e^- \to \gamma\nu\bar{\nu}$ process for this analysis and for the SM backgrounds in the following sections have been calculated using the package MADGRAPH [17] and the HELAS [18] subroutines. The cut on the photon energy and on the missing mass (invariant mass of the system recoiling against the photon) helps to remove the events coming from the production of an on-shell $Z$ and its subsequent decay to neutrinos, thus reducing the background to a large extent. But the signal itself is rather small at the NLC and, as evident from Fig. 2 where the significance has been shown as a function of $m_0$, a $5\sigma$ effect is possible upto about 110 GeV (and with $3\sigma$ upto 150 GeV) essentially due to the higher luminosity. For a neutral scalar mass larger than 200 GeV, the number of signal events falls rapidly so that the significance goes below 1. Therefore, it will be possible to exclude $m_0$ upto 160 – 165 GeV at 95% C.L. if no excess of $\gamma + \not{E}$ signal is seen at the NLC.

# 4 LOOKING FOR THE $\delta^+$ AT TEVATRON AND LHC

Now we turn to the pair-production and detection possibilities of the singly-charged scalar $\delta^+$ at hadron colliders. Since $v_L = 0$ has been chosen, $\delta^+ W^- Z$ couplings are absent and $\delta^\pm$ will decay only to a lepton and its neutrino. As already mentioned, we assume that the $\delta^\pm$ couples to the three lepton generations with equal strength and base this discussion on the supposition that the leptonic decay modes are dominant; *i.e.,* the $\delta^\pm$ will decay to a lepton and its anti-neutrino, branching ratio for each family being 33.33%. Thus, the pair produced charged scalars will give rise to two leptons plus missing energy in the final state.

Before proceeding with the analysis, it is important to consider what other decay modes might be possible for the $\delta^\pm$. Since the couplings of the scalars are chosen

diagonal in lepton flavor, decays of $\delta^{\pm}$ to a charged lepton and a neutrino of a different flavor are ruled out. An important allowed mode will be *via* the $\delta^{+}W_L^{-}\delta^{0}$ coupling. This decay may be a two-body or a three-body one depending on the kinematics. Leptonic decay of the $W$ (on-shell or off-shell) will result in the same lepton plus missing energy mode. But this channel is suppressed by phase space. Therefore the assumption that the $\delta^{\pm}$ decays to 3 families of charged leptons and their neutrinos with 100% branching ratio ($b^{+} = 1$, where $b^{+}$ is the total leptonic branching ratio), may be an overestimate to some extent for higher $m_{+}$ but not unrealistic. Some of these issues are discussed in greater detail in Ref. [6]. (For comparison, we make brief remarks about the results which obtain in the situation where the total leptonic branching ratio is reduced to half this value.)

The SM background to the process is greatly reduced by considering the case when the two final state leptons are of different flavor. Since the detection of $\tau$ at a hadron collider is not as efficient as that of the other leptons, our stress is on the $e^{\pm}\mu^{\mp}\not{p}_T$ signatures. For these cases, there are no contributions to the background from on-shell and off-shell $Z$ and photon Drell-Yan processes. Further, there is no background from $l^{+}l^{-}\gamma$ production where the photon evades detection giving rise to missing $p_T$. In the analysis presented below a parton level Monte-Carlo generator using CTEQ-3M set of parton distributions [19] has been used.

The potential source of background for the above signal is from on-shell and off-shell $W$ pair production. Another class of backgrounds arise from fake events where a quark jet is misidentified as an electron or muon. Missing energy in such events comes from two sources; 1) the mismeasurement of the jet energy, and 2) from a gluon or photon which is radiated from a quark and evades detection. The typical misidentification probablity of a jet as an electron is around 2%. The contribution from the $qqg$ background (where the gluon is outside the rapidity coverage and *both* quarks fake leptons) is found to be about 0.8 *fb* to be compared with the genuine $e\mu\not{p}_T$ background of the order of 0.1 *pb*. Therefore, in the following analysis fake backgrounds are not considered any further.

Another source of $e\mu$ background would be from the decay of Drell - Yan $\tau$ pairs. These $\tau$ pairs are back-to-back in the $p_T$ plane and are sufficiently energetic such that

the electron or muons coming from their decay are also moving in the same direction. So the $e$ and $\mu$ are also back-to-back in the $p_T$ plane. We applied a $\Delta\phi_{e\mu} < 160^o$ cut which hardly reduces the signal but removes this background completely.

We now turn to the detection possibilities. The kinematic distribution of the signal and background events are similar. We present in Fig. 3 the missing $p_T$ distribution of the signal and the background at the Tevatron. For the signal, a representative value of $m_+$ equal to 100 GeV has been chosen. One can see from Fig. 3 that for lower values of $p_T^{mis}$, the background is an order of magnitude larger than the signal but it falls rapidly and becomes less than the signal for $p_T^{mis} > 100$ GeV. The $p_T$ spectrum of the leptons for the signal and the background also show similar characteristics and are not presented.

The following cuts are imposed in line with the Tevatron detectors:

$$p_T^l > 35 \text{ GeV}, \;\; |\eta^l| < 3, \;\; \Delta R_{e\mu} > 0.5, \;\; p_T^{missing} > 80 \text{ GeV}$$

The cut on the missing $p_T$ is very effective in reducing the background. Still this does not give enough boost to the signal-to-background ratio with the present collected luminosity. But with an increased luminosity of 25 fb$^{-1}$ (at Tevatron II) the $5\sigma$ discovery limit extends upto a charged scalar mass of 140 GeV. This is shown in Fig. 4.

For LHC, the cross-section and luminosity being higher, more stringent cuts can be employed. For example, using

$$p_T^l > 50 \text{ GeV}, \;\; |\eta^l| < 3, \;\; \Delta R_{e\mu} > 0.5, \;\; p_T^{\text{missing}} > 100 \text{ GeV}$$

in Fig. 4 we plot the significance of the signal. It can be seen that the $5\sigma$ discovery limit of $m_+$ is 240 GeV for an integrated luminosity of 100 fb$^{-1}$.

In this discussion, the branching ratio of the $\delta^+$ decaying to leptons has been chosen to be 100% ($b^+ = 1$). We can be more conservative and assume the value of $b^+$ to be equal to 0.5 in which case the signal and hence also the significance will reduce to one fourth of their values above. It is straightforward to check from Fig. 4 that for both the Tevatron and the LHC a signal with $5\sigma$ significance can no longer be achieved. For LHC the $2.5\sigma$ discovery limit is $m_+ = 190$ GeV. It may be worth mentioning that

in the above analysis we always demand that the number of signal events be at least equal to 5.

# 5 PRODUCTION AND DETECTION OF $\delta^{++}$ AT LHC

We now turn to the production and detection of the doubly-charged scalars, the heaviest among the members of the left-handed triplet[2]. First consider the pair production of $\delta^{++}$. One might expect that this production cross-section is lower than that for the lighter $\delta^+$. But this kinematic suppression is more than compensated by the fact that the $\delta^{++}\delta^{--}$ coupling to $\gamma$ (and Z) is twice (almost) that of the $\delta^+\delta^-$. The $\delta^{++}$ will dominantly decay [21] to a pair of like sign leptons, thus giving rise to a spectacular four lepton signal. As in the case of $\delta^+$, here again there are some other decay modes of $\delta^{++}$ which may compete with the like-sign di-lepton channel but over a wide mass range the latter dominates [6]. When presenting the results for $\delta^{++}$ production and decay we set the $ll$ branching ratio to 100% ($b^{++} = 1$). Results for any other value of $b^{++}$, say $x$, can be readily obtained from these since the number of signal events is simply reduced by an appropriate factor, $x^2$, while the background is unaffected.

The main source of background for this process is from the hadronic four lepton production. Considering the case when one scalar decays to a pair of electrons ($e^-e^-$) while the other decays to a pair of muons ($\mu^+\mu^+$), one can easily see that this final state has no SM background at all since the detector can identify [22] the particle charge[3]

We apply the following set of acceptance cuts for the LHC:

$$p_T^l > 20 \text{ GeV}, \quad |\eta^l| < 3.0, \quad \Delta R_{ll} > 0.5$$

[2]To our knowledge, the detection possibilities of the $\delta^{++}$ of the LRM at hadron colliders has not been discussed in detail in the literature[20]. However, the production at colliders of doubly-charged scalars, in general, has been examined.

[3]If all the leptons are of the same flavor then the signal would be *e.g.,* $e^+e^+e^-e^-$. The SM background for this particular final state is small but non-zero. However, the requirement $M_{e^-e^-} = M_{e^+e^+}$ will remove these $4e$ SM events.

In Fig. 5 we plot the number of expected events as a function of $m_{++}$. As there is no background for this signal, 5 events may be considered as a benchmark for the discovery. From the figure we see that one can go upto a $\delta^{++}$ mass of 850 GeV with a proposed LHC integrated luminosity of 100 fb$^{-1}$. If $b^{++}$ equals 0.5, *i.e.,* the leptonic modes account for only half the total width, then $m_{++}$ upto about 640 GeV can be explored satisfying the '5 events' criterion.

One may be more conservative and ask about the significance of the signal if charge identification of the leptons is not very efficient [22]. For this purpose, we also calculated the SM cross-section for the process $pp \to e^+e^-\mu^+\mu^-$ using a parton level Monte-Carlo generator. We assume here the worst case scenario, namely, that one cannot identify the lepton charges at all. Thus the above background can mimic the signal. The main contribution to the background originates from the on-shell production of a pair of $Z$s. We also note that for signal events the invariant mass for the pair of electrons must be equal to that of the muon pair. Apart from the kinematic cuts given above we impose further cuts, $M_{ee} \simeq M_{\mu\mu} > 100$ GeV. This removes all events coming from the decay of two on-shell $Z$s. The presence of the background cannot reduce the prominence of the signal very much. The number of background events in the bins of invariant mass are orders of magnitude less than those from the signal. At $M_{ee} = 150$ GeV, the number of background events is around .01 compared to a signal of $6 \times 10^3$. The SM background falls to $10^{-6}$ at $M_{ee} = 600$ GeV where the signal from LRM is nearly equal to 20. This is mainly due to the kinematic cut used to remove the events coming from the decay of the $Z$s. For the remaining events, either from off-shell $Z$ or photon, it is highly unlikely that the invariant mass of the muon pair will be the same as that of the electron pair. Thus, non-observation of this spectacular $ee\mu\mu$ signal at the LHC will help to exclude the $\delta_L^{++}$ mass upto about 650 GeV.

We have also estimated the prospect of a search for the $\delta^{++}$ at the Tevatron. But with the lower center of mass energy compared to the LHC and with a luminosity of 25 fb $^{-1}$ (*i.e* at the upgraded Tevatron) one can reach $m_{++}$ upto only 275 GeV if 5 events are set as a benchmark for discovery (see Fig. 5).

# 6 CONCLUSIONS

We examined the minimal version of the Left-Right Symmetric model, specifically the phenomenology of the left-handed triplet scalars. In general, all the scalars barring one can be heavy (of the scale 1 TeV or more). But some choices of the scalar potential couplings, which are motivated by GUT ideas, can keep the masses of the scalars from the left-handed triplet in the scale of $m_W$. The neutral one of these scalars can only decay to neutrinos. So this decay is invisible. We have put a new bound on the mass of such a neutral scalar from the LEP-II measurement of the $e^+e^- \to \gamma + \not{E}$ cross-section and examined the reach of the NLC to explore $m_0$.

We have also investigated the production and detection of the singly-charged and doubly-charged scalars at the Tevatron and the LHC and compared the signal with the SM background. For the doubly-charged scalar signal there are basically no SM background events to compare with. The detection of such doubly-charged (as well as singly-charged) scalars at the LHC look quite promising. At the Tevatron with increased integrated luminosity, detection of a singly-charged scalar is possible upto a mass of 140 GeV while for the LHC the mass reach for $5\sigma$ discovery is around 240 GeV. The doubly-charged scalar can be probed at the LHC upto a mass of about 600 GeV.

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[5] See, for example, F.I. Olness and M.E. Ebel, *Phys. Rev.* **D32,** 1769 (1985). It needs to be mentioned, however, that the symmetry under consideration will also forbid *either* some majorana *or* dirac Yukawa couplings [6, 3].

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[8] Notice that one can no longer generate majorana masses for the left-handed neutrinos. However, in the usual see-saw formulation, this entry of the mass matrix is often neglected anyway.

[9] For example, if we choose $\rho_1 = .05,\ \rho_2 = .1,\ \rho_3 = .1$ at the GUT scale satisfying the $\rho_3 - 2\rho_1 = 0$ requirement, the magnitude of $\sqrt{\rho_3 - 2\rho_1}$ becomes 0.05 at the TeV scale, which is in the appropriate range. On the other hand the couplings become greater than unity at the TeV scale if they are assigned large values like $\rho_1 = .5,\ \rho_2 = 1,\ \rho_3 = 1$ at the GUT scale.

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generations while the third generation coupling is unconstrained. Some authors, *e.g.,* [13], choose the couplings taking this result into consideration.

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[21] The width of the decay $\delta^{++} \to l^+ l^+$ can be written as $\simeq h_{ll}^2 m_{++}/25$ (see, for example, the second paper in [20]). If $h$ is of the order of 0.1 then this width is of the order of 0.2 GeV for $m_{++} \sim 500$ GeV.

[22] CMS, Technical Proposal, CERN/LHCC 94-38, LHCC/P1; The charge assignment is correct at 99% C.L. upto a muon momentum of 7 TeV for full rapidity coverage.

## FIGURE CAPTION

Fig. 1. The number of $e^+e^- \to \gamma + \not{E}$ events as a function of the $\delta^0$ mass in the Left-Right symmetric model. The dashed horizontal line is the difference between the 95% C.L. upper limit of the observed number of events at LEP-II with $\sqrt{s} = 182.7$ GeV and the lower limit of the SM prediction at the same C.L. The lower limit on the $\delta^0$ mass is determined by the point of intersection of the solid curve with the dashed line.

Fig. 2. Significance ($\equiv$ Signal/$\sqrt{\text{Background}}$) for the process $e^+e^- \to \gamma + \not{E}$ as a function of $\delta^0$ mass in the Left-Right symmetric model at the NLC with 20 fb$^{-1}$ integrated luminosity and $\sqrt{s} = 500$ GeV.

Fig. 3. Missing $p_T$ distribution for the process $p\bar{p} \to e\mu + \not{p}_T$ from the Left-Right symmetric model signal (solid histogram) and the SM background (dashed line) at the Tevatron. For the signal, a representative value of the charged scalar mass equal to 100 GeV is chosen.

Fig. 4. Significance ($\equiv$ Signal/$\sqrt{\text{Background}}$) for the process $p\bar{p}$ or $pp \to e\mu + \not{p}_T$ in the Left-Right symmetric model as a function of $\delta^{\pm}$ mass for the Tevatron with an integrated luminosity of 25 fb$^{-1}$ (solid line) and for the LHC ($\sqrt{s} = 14$ TeV) with an integrated luminosity of 100 fb$^{-1}$ (dashed line).

Fig 5. Number of signal events for $pp \to e^-e^-\mu^+\mu^+$ from $\delta^{++}$ production as a function of $ee$ or $\mu\mu$ invariant mass for the Tevatron with an integrated luminosity of 25 fb$^{-1}$ (dashed line) and for the LHC ($\sqrt{s} = 14$ TeV) with an integrated luminosity of 100 fb$^{-1}$ (solid line).

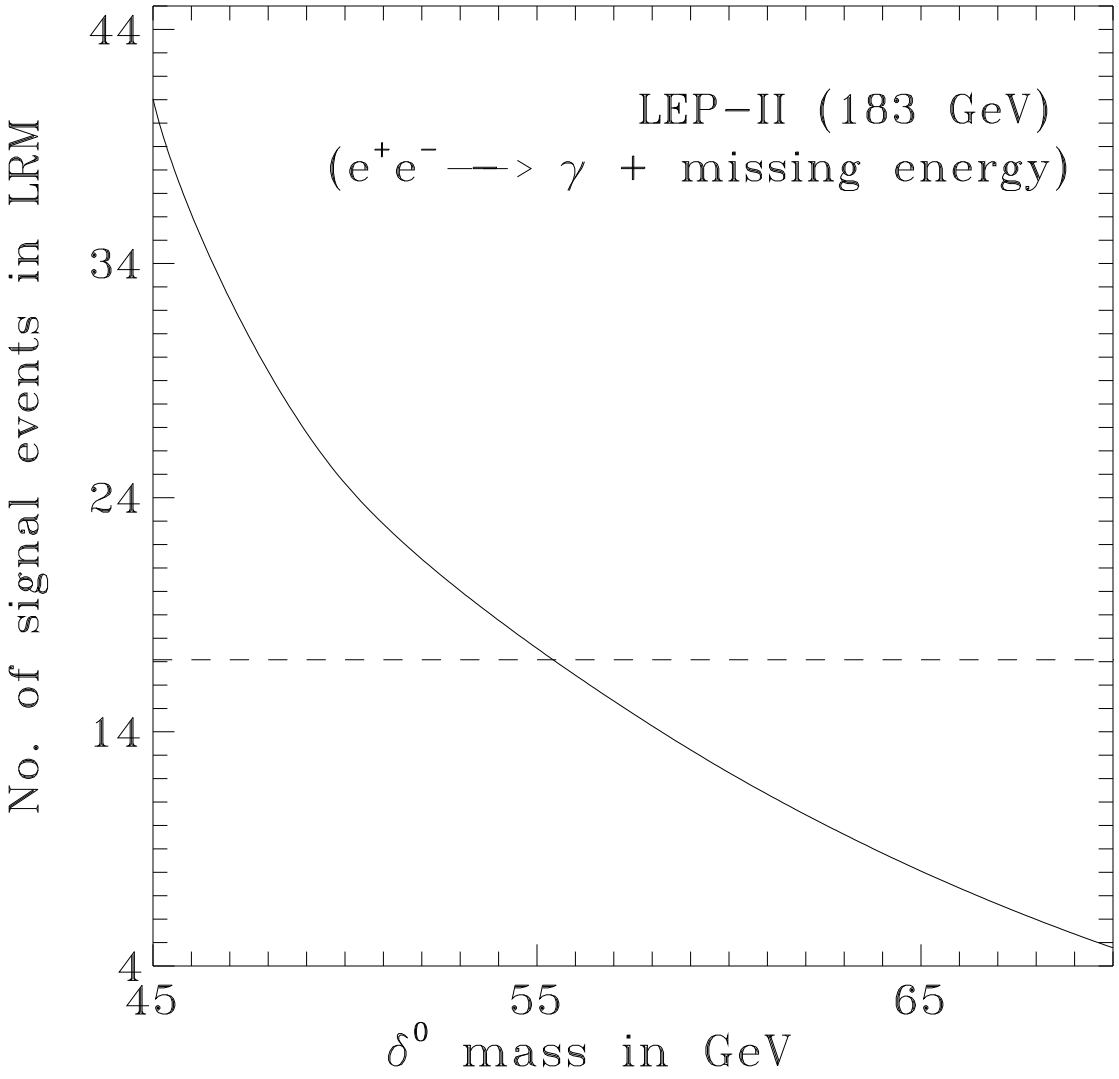
LEP−II (183 GeV)
(e+e− —> γ + missing energy)
No. of signal events in LRM
44
34
24
14
4
45
55
65
δ0 mass in GeV

Fig. 1

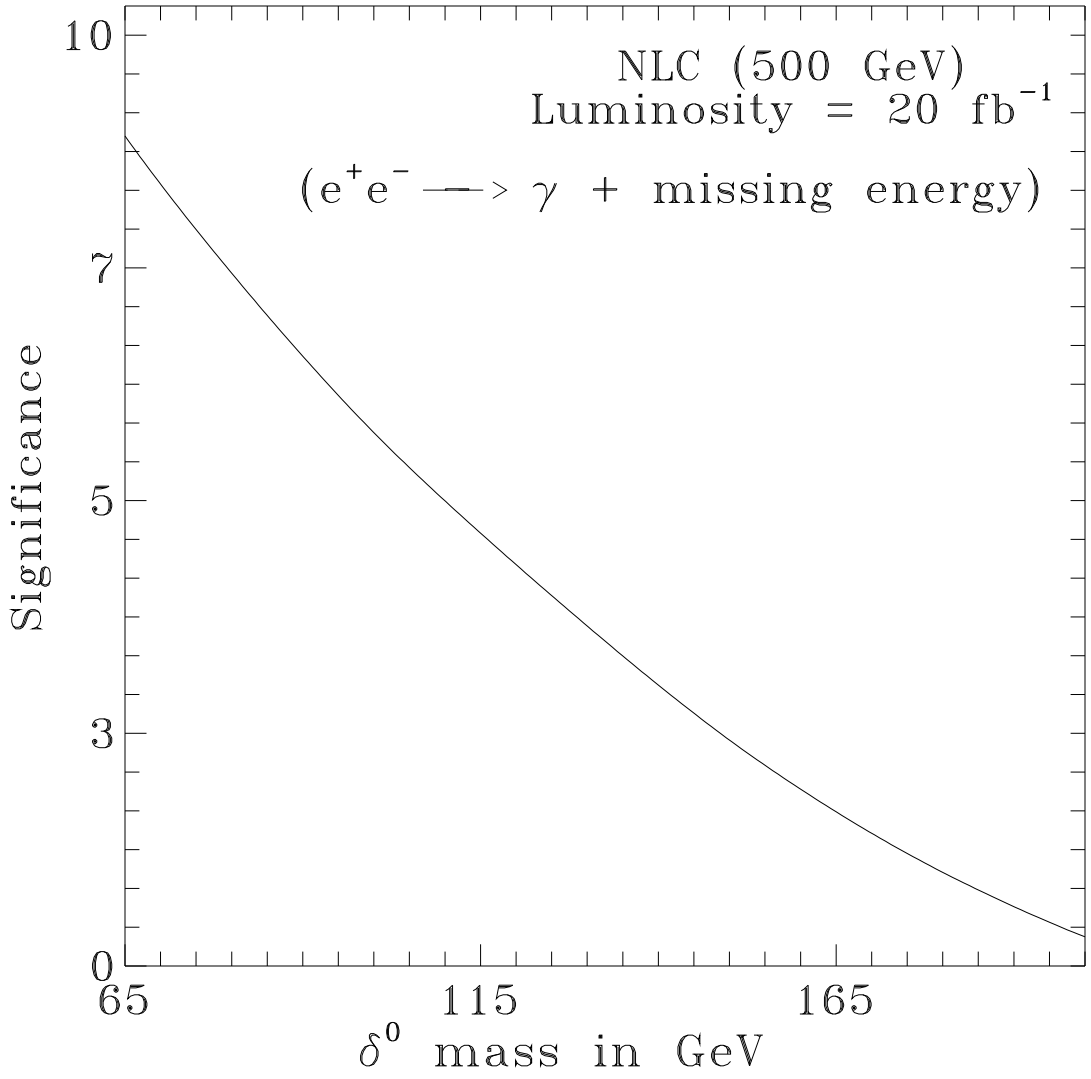
NLC (500 GeV)
Luminosity = 20 fb$^{-1}$
($e^+e^-$ —> $\gamma$ + missing energy)
Significance
10
7
5
3
0
65
115
165
$\delta^0$ mass in GeV

Fig. 2

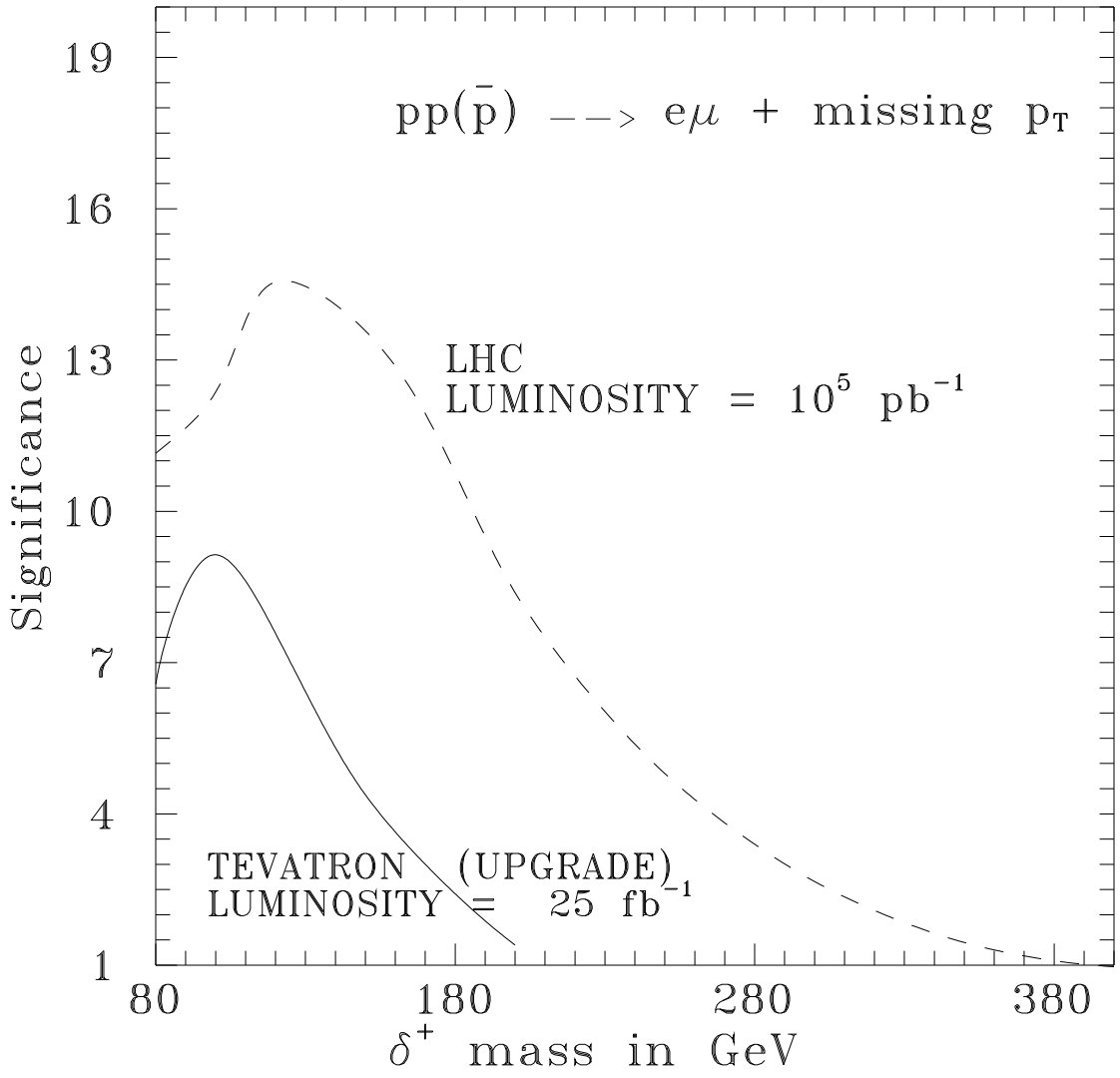
19
16
13
10
7
4
1
Significance
80
180
280
380
$\delta^+$ mass in GeV
$pp(\bar{p}) \longrightarrow e\mu$ + missing $p_T$
LHC
LUMINOSITY = $10^5$ $pb^{-1}$
TEVATRON (UPGRADE)
LUMINOSITY = 25 $fb^{-1}$

Fig. 4

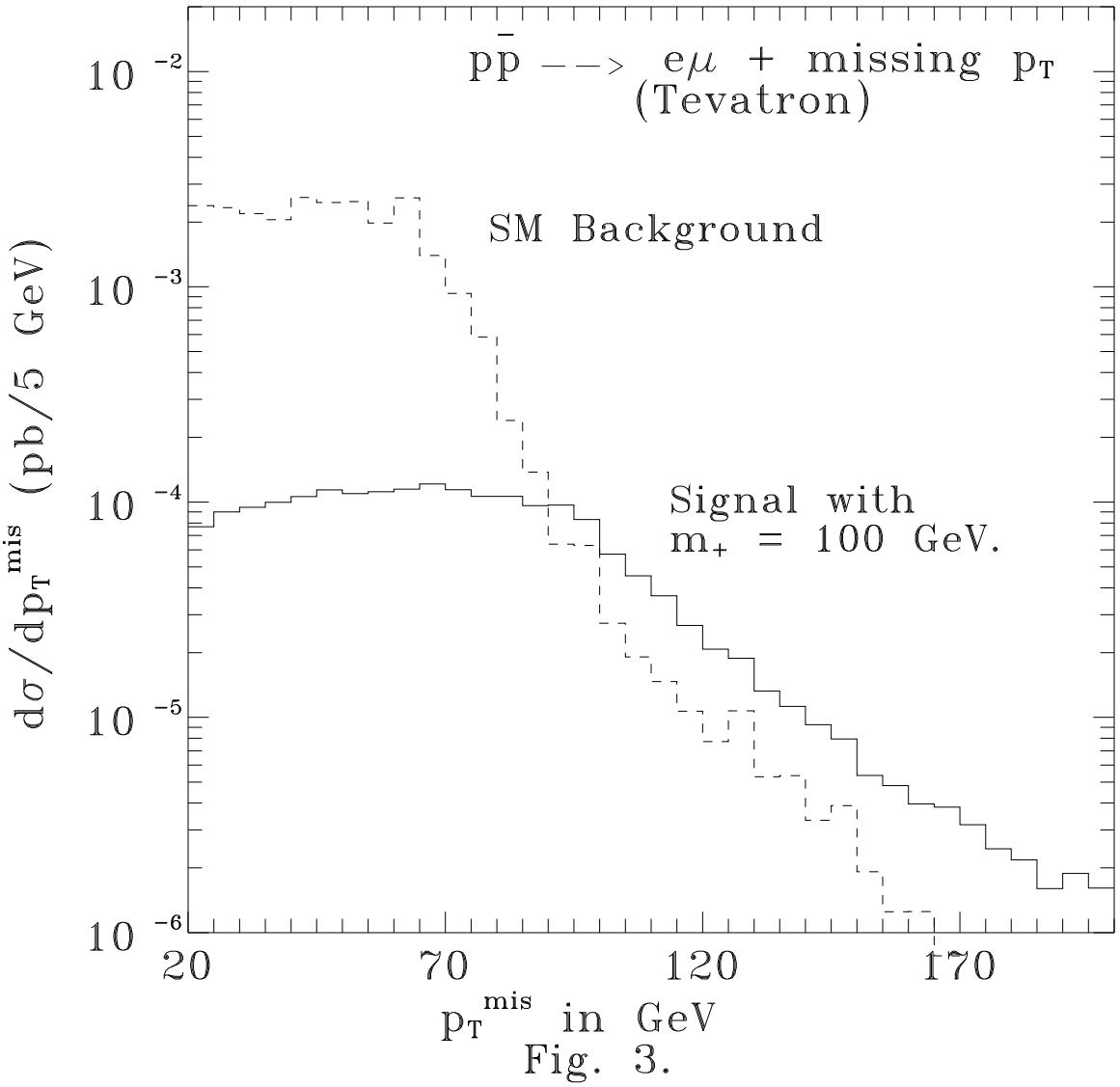
$p\bar{p}$ --> $e\mu$ + missing $p_T$
(Tevatron)
SM Background
Signal with
$m_+$ = 100 GeV.
$d\sigma/dp_T^{mis}$ (pb/5 GeV)
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
20
70
120
170
$p_T^{mis}$ in GeV

Fig. 3.

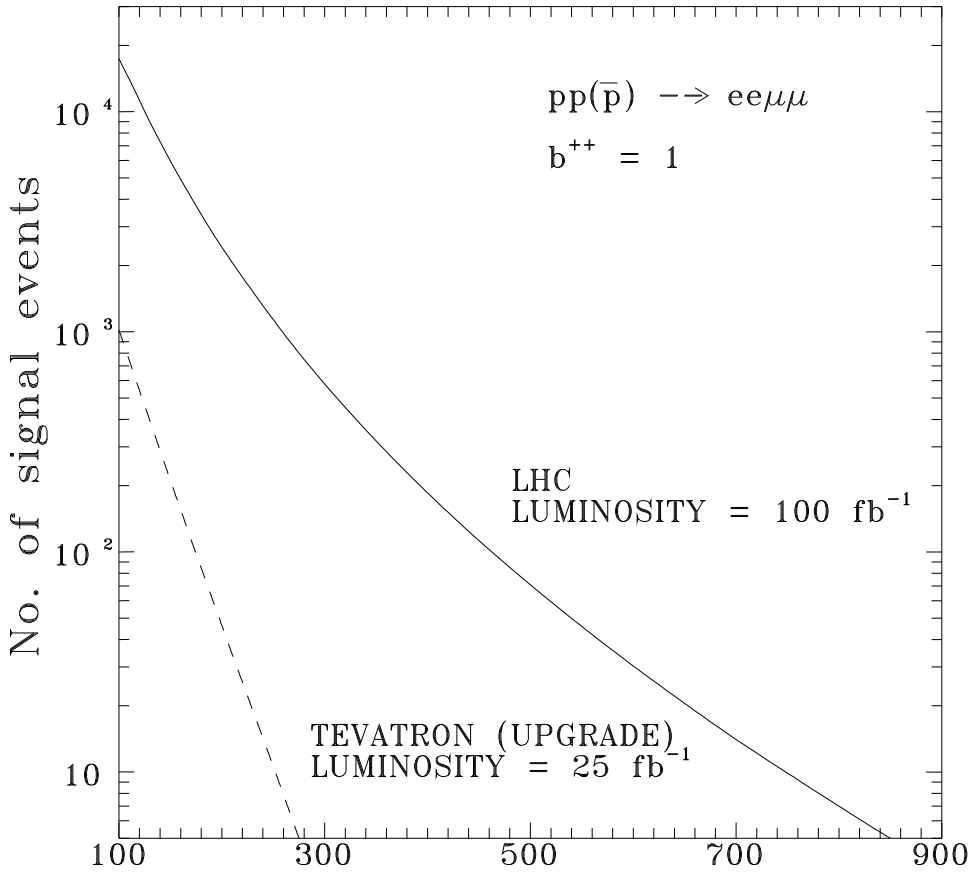
pp($\bar{p}$) −→ ee$\mu\mu$
$b^{++}$ = 1
LHC
LUMINOSITY = 100 $fb^{-1}$
TEVATRON (UPGRADE)
LUMINOSITY = 25 $fb^{-1}$
No. of signal events
$10^4$
$10^3$
$10^2$
10
100
300
500
700
900
$\delta^{++}$ mass in GeV

Fig. 5