R–Parity Violating SUSY or Leptoquarks: Virtual Effects in Dilepton Production

Gautam Bhattacharyya[*]**, Debajyoti Choudhury**[†] **and K. Sridhar**[‡]

Theory Division, CERN,
CH-1211, Geneva 23, Switzerland.

ABSTRACT

In the Standard Model (SM), dilepton production in hadron–hadron collisions proceeds through the conventional Drell–Yan mechanism $q\bar{q} \to l^+l^-$ with the exchange of a gauge boson. Some extensions of the SM contain a quark–lepton contact interaction *via* a $ql\phi$ Yukawa coupling, where ϕ is a scalar. Theories with scalar leptoquarks and *R*–parity violating SUSY models are the most important examples of such extensions. These Yukawa couplings induce a different dynamical configuration compared to the SM (t-channel vs. s-channel) in the $q\bar{q} \to l^+l^-$ process and thus offer the possibility of being identifiable upon imposition of suitable kinematic cuts. We discuss these effects in the context of the dilepton production in the CDF experiment, and explore consequences in the forthcoming Large Hadron Collider (LHC).

[*] gautam@cernvm.cern.ch
[†] debchou@surya11.cern.ch
[‡] sridhar@vxcern.cern.ch

In the quest of understanding physics at energy scales beyond that of the standard model (SM), many ideas have been discussed rather extensively in the literature. Two of the most popular, and in some sense intertwined, theories are those of grand unification and supersymmetry. In both theories, there arise new particles that connect the quark and lepton sectors. Such a particle can either be a scalar or a vector. In this letter, we shall restrict ourselves to scalars. As for weak $SU(2)$ properties, it can transform either as a singlet, a doublet or a triplet.

In grand unified theories [1], where quarks and leptons are part of the same multiplet, there naturally arise scalar leptoquarks leading to a contact interaction between a quark and a lepton. In the Minimal Supersymmetric Standard Model (MSSM) [2] too, the squarks may mediate interactions between quarks and leptons unless some extra symmetry (R–parity) is imposed on the theory. As there is no deep motivation for such a symmetry to actually exist, it is interesting to examine the possible consequences of such R–parity violating ($\not R_p$) interaction. Within the context of the MSSM, the part of the Lagrangian violating R–parity may be written in terms of the chiral superfields as

$$\mathcal{L}_{\not R} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c, \tag{1}$$

where L_i and Q_i are the $SU(2)$ doublet lepton and quark fields and E_i^c, U_i^c, D_i^c are the singlet superfields. Concentrating on the λ'_{ijk} piece above, it is obvious that the phenomenology due to such terms is very similar to that of certain scalar leptoquarks.

A generic scalar coupling between a lepton (l) and a quark (q) can be parametrized as

$$\mathcal{L} = g\bar{l}(h_L P_L + h_R P_R)q\phi + g\bar{l^c}(h'_L P_L + h'_R P_R)q\phi' + \text{h.c.}, \tag{2}$$

where g is the weak gauge coupling constant, l^c is the charge conjugate field and $P_{L,R} = (1 \mp \gamma_5)/2$ (ϕ and ϕ' are independent fields). Since diquark couplings violate baryon number, non-observation of proton decay forbids the simultaneous presence of diquark couplings as well.[1] Furthermore, to suppress flavour-changing neutral current processes [4], each such scalar is assumed to couple primarily to only one family of quarks (leptons). Finally, to survive stringent bounds coming from helicity suppressed $\pi \to e\nu$ and similar processes [3], the scalar coupling is assumed to be chiral (*i.e.* it is not allowed to simultaneously couple to the left- and right-handed quarks)[2]. There is a subtlety in the case of the MSSM as the squarks $\tilde f_L$ and $\tilde f_R$ will always mix. One may argue that such effects are proportional to m_f/m_{SUSY} and hence would be small in most cases including the one that we are about to discuss. Still, the existence of

---

[1]This implies that in the case of $\not R_p$ theories λ'' cannot simultaneously exist with either of λ or λ'. However, λ and λ'' are not relevant to the rest of our discussion.

[2]In principle, couplings of scalars with the left-handed quark doublets cannot be made fully flavour diagonal in the quark sector, since the presence of CKM mixings prevents its coupling to be diagonal in the up- and down-sectors simultaneously.

this mixing does affect some rare processes, and, as a result, the bounds [5] on $\rlap{/}{R}_p$ couplings are somewhat stronger than those for a chirally coupling leptoquark. With the above assumptions then, there are only five possible scalar couplings involving a charged lepton and these are listed in Table 1. We have grouped scalars with different $SU(2)_L \otimes U(1)_Y$ properties together as their gauge interactions are irrelevant for the processes that we intend to study.

Leptoquark couplings as well as $\rlap{/}{R}_p$ couplings are constrained by direct searches at various colliders [6]. The Fermilab CDF [7] and D0 [8] experiments rule out a 'first generation scalar' upto ~ 100 GeV, almost irrespective of the size of the Yukawa couplings. On the other hand, the HERA collaboration sets a limit of ~ 180 GeV [9] on the mass of a scalar coupling with electroweak strength to a first generation quark and electron. Similar bounds also hold for the $\rlap{/}{R}_p$ case. Due to the presence of other decay channels for the squarks, the exact constraints are somewhat different[10]. For example, the Tevatron dilepton [11] data have been used to set lower limits on squark/gluino masses for almost any value of the $\rlap{/}{R}_p$ coupling. For scalars coupling to the third generation, the bounds are understandably weaker. The strongest constraints to date can be inferred from the loop effects on the leptonic partial widths of the Z [12]. Stronger constraints on such scalars can be obtained in future colliders by looking either at τ–number violating processes [13] at LEP200 or at $t\bar{t}$ production [14] at the Next Linear Collider.

It is obvious that such experiments (other than those at HERA) have very little to say about the Yukawa couplings *per. se.* In this letter, we point out an experiment that would do so. To do this, we investigate the possibility of identifying the effects of a virtual scalar exchange in dilepton production in hadronic reactions. The signature we focus on is a lepton pair *without* any missing transverse momentum. The lowest order SM process leading to such a final state is the Drell–Yan mechanism *i.e.* $q\bar{q} \to (\gamma^*, Z^*) \to l^+l^-$. The presence of such a scalar would introduce an additional t–channel diagram, an obvious consequence being a modification of the total cross section [15]. A more sensitive probe, though, could be a comparison of the differential distributions. Owing to the extra diagram being a t–channel one in contrast to the s–channel SM contribution, it is conceivable that the effect of the former would be more pronounced for certain phase space configurations.

A particular distribution *viz.* the rapidity dependence suggests itself. In the sub-process centre-of-mass (c.m.) frame, one expects the t–channel contribution to be more central than the s–channel one. Another differential variable of interest could be the invariant mass of the lepton pair. Indeed, the CDF collaboration has studied the latter distribution for both dielectron and dimuon pairs [16]. In the first part of this letter, we show how this experiment can discriminate between the SM and a theory with an extra scalar interaction. We compare the theoretical predictions with the existing data

and point out the improvements necessary to make our conclusions more quantitative. In the second part, we examine the same effect for the LHC, and speculate on the sensitivity that can be achieved.

In principle, the contribution of a scalar of the type ϕ' (see eq. (2)) can be distinguished from that of type ϕ only if (i) the colliding beams are asymmetric and (ii) the individual lepton charges are distinguished. We shall not dwell upon this possibility here. We make the simplifying assumption that at best one of the scalars in Table 1 is present. As an example, we present here the differential cross section for the process $q\bar{q} \to l^+l^-$ for the case $h_R = 0$, $h_L \neq 0$. This corresponds to scalars of Types III, IV or V in Table 1. (The expressions for the other types of scalars can be obtained by simple modifications of the couplings.) Defining the left- and right-handed couplings of the Z to a fermion (f) by

$$a_L^f = (t_3^f - e_f \sin^2 \theta_W)/\sin \theta_W \cos \theta_W, \qquad a_R^f = -e_f \cot \theta_W \ , \tag{3}$$

where e_f and t_3^f are the corresponding charge and isospin respectively and θ_W is the weak mixing angle, we have, for a scalar of mass m_ϕ:

$$\frac{d\sigma}{dt} = \frac{d\sigma_{\text{SM}}}{dt} + \frac{\pi g^2 t^2}{3M^6} K_t \left[e_q e_l + a_L^q a_R^l \frac{M^2(M^2 - m_Z^2)}{(M^2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2} + \frac{1}{4} K_t M^2 \right], \tag{4}$$

where

$$K_t \equiv \frac{|h_L|^2}{t - m_\phi^2} \tag{5}$$

and M is the invariant mass of the l^+l^- pair. The QCD corrections to the Drell–Yan process have been calculated [17] to the next-to-leading order and is a function of the c.m. energy ($\sqrt{s}$) of the collider, the structure functions used and the subprocess scale M. For $M \gtrsim 20$ GeV, the dependence on M is marginal and one may approximate it by a scale–independent constant. In the absence of an explicit calculation of the higher-order effects, we assume that the QCD correction for the t-channel scalar exchange process is the same as that for the Drell–Yan process. One may argue that in the presence of scalars, these corrections are likely to be even larger.

To obtain the cross section for a hadronic collision $AB \to l^+l^-X$, we have to convolute the expression in eq. (4) with the parton distributions. For example, the invariant mass distribution is given by

$$\frac{d\sigma}{dM} = \frac{2M}{s} \sum_q \int dx dt \left[q_A(x) \bar{q}_B(M^2/sx) \frac{d\sigma}{dt} + (A \leftrightarrow B) \right], \tag{6}$$

where x is the fraction of the momentum of A carried by q_A. While the sum in eq.(6) runs over all species of quarks for the SM piece, for the scalar contribution it runs only

3

over those quarks with which the scalar couples. For the rest of this analysis, we shall concentrate only on those that couple to one or both of the first generation quarks. We use the MRSD-$'$ structure functions [18] evaluated at the scale $Q^2 = M^2$. For this choice, the QCD K-factor $\simeq 1.3(1.1)$ for $\sqrt{s} = 1.8(14)$ TeV.

The CDF collaboration at Fermilab measures the Drell–Yan cross section [16] $d\sigma/dM$ in the range $11 < M < 150$ GeV. They restrict their measurements to $|\eta_\pm| \leq 1$, where $\eta_\pm$ are the pseudorapidities of $e^\pm$ respectively. Furthermore, the numbers quoted are averaged over the rapidity of the lepton pair. For ease of comparison, we shall consider the same distribution (including the actual binning for M as used in the experiment). In Fig. 1, we compare the experimental data with the theoretical curves for the SM, and those for scalars of Type IVa (see Table 1)[3]. We have set here $h_L = 1$, *i.e.* the Yukawa coupling is of the electroweak strength. Though the effect of the scalar starts becoming visible at around $M \simeq 65$ GeV, it is immediately swamped by the Z–pole. At large M values though, the deviation is significant and information about scalars may be extracted. However, as even a cursory glance at the figure would reveal, the data at present are rather poor and any quantitative statement would be premature. We rather wish to point out that a refinement of measurement at the high invariant mass end ($M \gtrsim 150$ GeV) of the spectrum (along with an increase of luminosity at the possible Tevatron upgrade) would enhance considerably the ability to detect such scalar particles.

We now turn to the LHC. Due to the large operating energy (14 TeV) one would expect to see a more pronounced effect. In our analysis, we assume an integrated luminosity of 100 fb^{-1}. In Fig. 2, we first compare the invariant mass distribution for different masses of a Type IVa scalar ($h_L = 1$) with that for the SM. We use kinematic cuts of $|\eta_\pm| \leq 3$, numbers that have often been quoted. As is expected, the effect of the scalar exchange is more pronounced for large M. Due to the much larger energy available (and partly due to the wider angular coverage), the presence of much heavier scalars can be detected.

The information in Fig. 2 can be used to put bounds on the two-parameter space $(m_\phi,\ h)$ — here $h \equiv h_{L,R}$, as the case may be — that can be achieved at the LHC. It is obvious that imposing an acceptability cut on the invariant mass would enhance the effect of the scalar. In our analysis, we arbitrarily set $M_{\min} = 500$ GeV. Denoting the number of events expected in the SM, and in a theory with such a scalar by n_{SM} and n_ϕ respectively, we demand that

$$|n_\phi - n_{SM}| \geq 3\sqrt{n_{SM}} \tag{7}$$

for the effect to be considered visible. This allows us to draw contours in the m_ϕ–h

---

[3]It should be noted that the sharpness of the Z–resonance is somewhat reduced by the rather coarse binning adopted in the experiment.

plane (Fig. 3) for various types of scalars. The region of the parameter space above the respective curves can then be ruled out at the 3σ level. The difference in the sensitivity to the scalar type is a consequence of the difference in their coupling, as also of the relative abundance of various quarks in the proton. While it is true that a 2.5 TeV scalar may easily be pair produced at the LHC, such an event would afford us no handle on its couplings to the SM fermions. Indeed, the bounds presented here are the strongest that can be achieved on leptoquark couplings in the near future. For the $\not{R}_p$ case, this is illustrated even better. As we have pointed out right at the beginning, the low energy constraints on $\not{R}_p$ couplings are stronger than those for the usual leptoquarks. For our interaction, $\not{R}_p$ is phenomenologically identical to a case where both Type II a and Type III scalars are present, with the contributions adding incoherently. If we assume the two squarks ($\tilde{u}_L$ and $\tilde{d}_R$) to be mass–degenerate, the bound on the $\not{R}_p$ coupling lies in between the two above curves, and is somewhat weaker than those derived from low energy processes [5]. One should realise though that this experiment provides an independent constraint on the parameter space for the theory. Interestingly, in the extreme case of $m(\tilde{d}_R) \gg m(\tilde{u}_L)$, the low energy constraint becomes relatively unimportant and the experiment discussed here would provide the strongest constraints. Indeed, for all such scalars except that of Type III, dilepton data at the LHC would lead to bounds significantly stronger than those obtained from low energy processes such as π–decay, charge–current–universality $etc.$

As we had mentioned, our choice of $M_{\min}$ was rather arbitrary. The exact value that should be adopted to maximize the effect is dependent on the value of m_ϕ that one aims to probe. On the face of it, a larger value of $M_{\min}$ should serve to eliminate more of the SM contribution. This advantage can, however, be nullified by the consequent loss of statistics. In fact, a larger $M_{\min}$ is more useful for exploring larger m_ϕ. To illustrate our point, we superimpose the 3σ contours for two different values of $M_{\min}$ in Fig. 4.

Until now, we have neglected the other interesting dynamical variable in the process, namely the difference ($\Delta\eta = \eta_+ - \eta_-$) of the lepton rapidities. Since this is nothing but the scattering angle in the subprocess c.m. frame, one expects to see the difference between an s–channel and a t–channel process. This is borne out strikingly in Fig. 5. We would like to point out that instead of comparing the integrated cross section, much more information can be gleaned from a study of the differential distribution $d^2\sigma/dM\,d\Delta\eta$. This can be done, at a quantitative level, by performing a χ^2 test. We refrain from doing so, however, as such an analysis presumes some knowledge of the detector. We prefer instead, to only point out that once the detector parameters are well understood, such an analysis should be undertaken so as to improve the sensitivity of the experiment.

In summary, we have examined the virtual effect of a t-channel scalar exchange

in dielectron production at CDF and tried to foresee its possible impact at the LHC. In contrast to the pair production mechanism, the virtual effects are very sensitive to its Yukawa coupling. We point out that a few precise measurements of the dilepton distribution at CDF at higher invariant masses ($M \sim 150$ GeV) would allow us to probe the existence of a scalar of mass upto a few hundred GeV and coupling the electron and a first generation quark with electroweak strength. Similarly, at the LHC, we observe the possibility of probing scalar masses upto (1–3) TeV for a Yukawa coupling of electroweak strength. These estimates are significantly better than the bounds inferred from analyses of low–energy processes. We would also like to point out that such an analysis can as easily be done for a dimuon pair, and the bounds would be similar. For a $\tau^+\tau^-$ pair, the situation would be a bit more complicated as τ–identification efficiency is likely to be lower. If this efficiency could be raised, such an experiment would lead to a significant improvement in constraints on such scalars coupling a τ to a quark. Finally, one may also investigate possible couplings of leptons to the heavier quarks, although these bounds would be weaker on account of the lower densities within the proton.

References

[1] For reviews see P. Langacker, *Phys. Rep.* **72** (1981) 185;
J.L. Hewett and T.G. Rizzo, *Phys. Rep.* **183** (1989) 193 and references therein;
J.C. Pati and A. Salam, *Phys. Rev.* **D10** (1974) 275;
W. Buchmüller and D. Wyler, *Phys. Lett.* **B177** (1986) 377;
W. Buchmüller, R. Rückl and D. Wyler, *Phys. Lett.* **B191** (1987) 442.

[2] H.P. Nilles, *Phys. Rep.* **110** (1984) 1;
H.E. Haber and G.L. Kane, *Phys. Rep.* **117** (1985) 75;
L. J. Hall and M. Suzuki, Nucl. Phys. **B231** (1984) 419;
S. Dawson, Nucl. Phys. **B261** (1985) 297;
S. Dimopoulos and L. Hall, Phys. Lett. **B207** (1987) 210.

[3] O. Shanker, *Nucl. Phys.* **B204** (1982) 375; **B206** (1982) 253.

[4] M. Leurer, *Phys. Rev. Lett.* **71** (1993) 1324; *Phys. Rev* **D49** (1994) 333.
S. Davidson, D. Bailey and B.A. Campbell, *Z. Phys.* **C61** (1994) 613.

[5] V. Barger, G.F. Giudice and T. Han, *Phys. Rev.* **D40** (1989) 2987.

[6] J.L. Hewett and T.G. Rizzo, *Phys. Rev.* **D36** (1987) 3367;
J.L. Hewett and S. Pakvasa, *Phys. Rev.* **D37** (1988) 3165.

[7] CDF Collaboration, F. Abe *et al.* , *Phys. Rev.* **D48** (1993) 3939.

[8] D0 Collaboration, S. Abachi *et al.* , *Phys. Rev. Lett.* **72** (1994) 965.

[9] H1 Collaboration, I. Abt *et al.* , *Nucl. Phys.* **B396** (1993) 3;
ZEUS Collaboration, M. Derrick *et al.* , *Phys. Lett.* **B306** (1993) 173.

[10] J. Butterworth and H. Dreiner, *Nucl. Phys.* **B397** (1993) 3.

[11] D.P. Roy, *Phys. Lett.* **B283** (1992) 272;
H. Baer, C. Kuo and X. Tata, FSU preprint FSU-HEP-941001 (1994).

[12] G. Bhattacharyya, J. Ellis and K. Sridhar, *Phys. Lett.* **B336** (1994) 100; E **B338** (1994) 522, and references therein;
J.K. Mizukoshi, O.J.P. Eboli and M.C. Gonzalez–Garcia, CERN preprint CERN-TH.7508/94.

[13] R.M. Godbole, P. Roy and X. Tata, *Nucl. Phys.* **B401** (1993) 67.

[14] D. Choudhury, MPI preprint MPI-PhT/94–50. (1994) , hep-ph@xxx/9408250.

[15] R. Rückl and P. Zerwas, *Proc. Workshop at Future Accelerators*, La Thuille and CERN 1987, ed. by J.H. Mulvey, CERN Report 87-07, vol. II, p. 220;
H. Dreiner *et al.*, *Mod. Phys. Lett.* **A3** (1988) 443.

[16] CDF Collaboration, F. Abe *et al.*, *Phys. Rev.* **D49** (1994) R1.

[17] T. Matsuura, S.C. van der Marck and W.L. van Neerven, *Phys. Lett.* **B211** (1988) 171; *Nucl. Phys.* **B319** (1989) 570.

[18] A.D. Martin, R.G. Roberts and W.J. Stirling, *Phys. Rev.* **D47** (1993) 867.

Scalar Type	Coupling	$SU(2)_L \otimes U(1)_Y$ Transformation	Remarks
I a)	$\overline{l_L}u_R\phi$	$(2,\ -7/6)$	
b)	$\overline{e_R{}^c}u_R\phi$	$(1,\ 1/3)$	
II a)	$\overline{l_L}d_R\phi$	$(2,\ -1/6)$	Corresponds to $\tilde{u}_L$
b)	$\overline{e_R{}^c}d_R\phi$	$(1,\ 4/3)$	
III	$\overline{l_L{}^c}Q_L\phi$	$(1,\ 1/3)$	Corresponds to $\tilde{d}_R$
IV a)	$\overline{e_R}Q_L\phi$	$(2,-7/6)$	
b)	$\overline{l_L{}^c}Q_L\phi$	$(3,\ 1/3)$	
V a)	$\overline{e_R}Q_L\phi$	$(2,-7/6)$	$m(\phi^{5/3}) \gg m(\phi^{2/3})$
b)	$\overline{l_L{}^c}Q_L\phi$	$(3,\ 1/3)$	$m(\phi^{1/3}) \gg m(\phi^{4/3})$

Table 1: The possible scalar couplings between a charged lepton and a quark, grouped according to their chiral structures. For Type IV, we assume all the scalars to be mass degenerate. Type V corresponds to the (unlikely !) case where only the coupling to d_L is of importance.
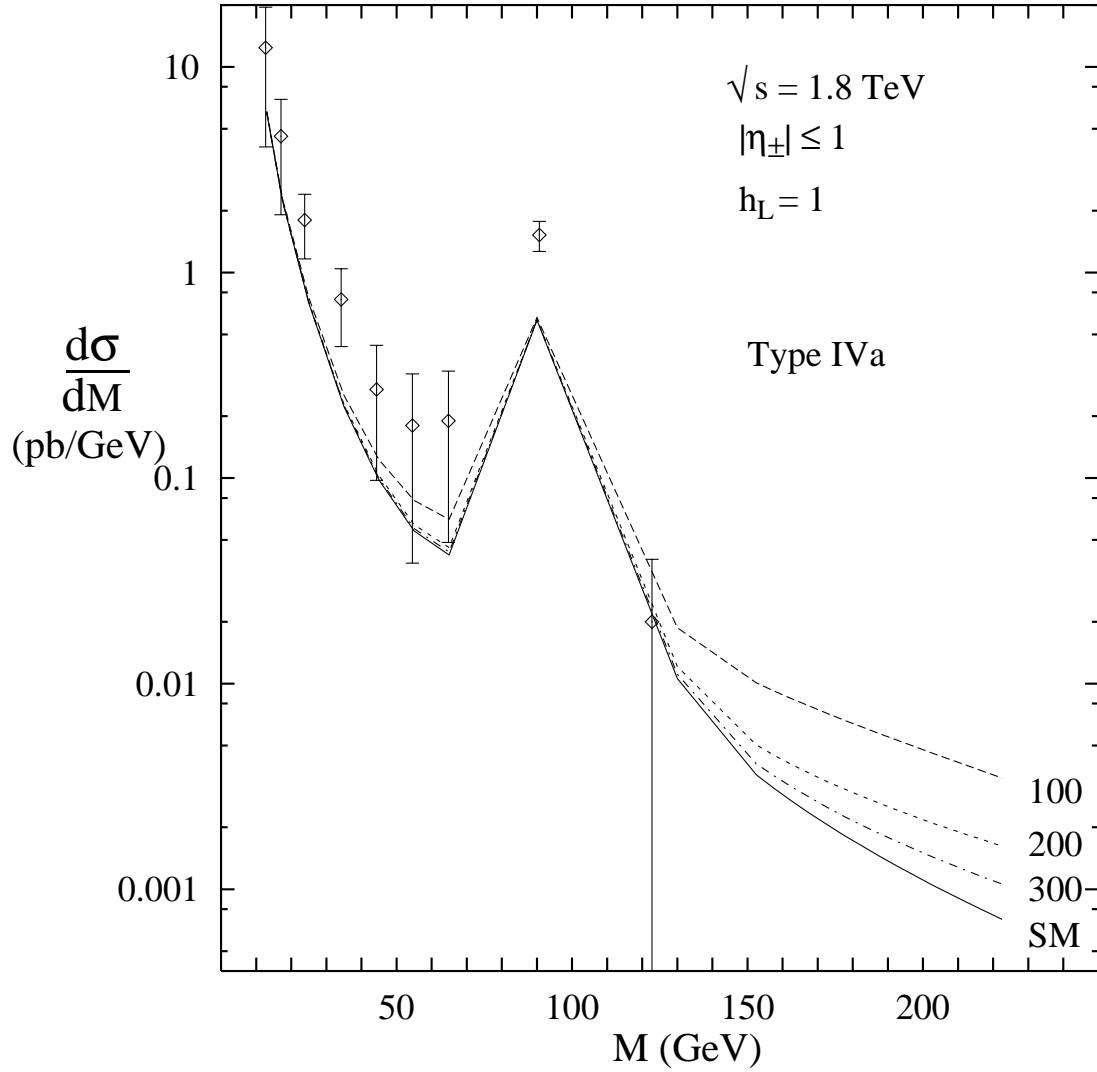
Figure 1: The dilepton invariant mass distribution at CDF. The curves correspond to the theoretical expectation for the SM and for leptoquarks (Type IVa) of masses $m_\phi = 100$, 200, 300 GeV respectively. For $M \leq 150$ GeV, the invariant mass binning is the same as that used in [16].
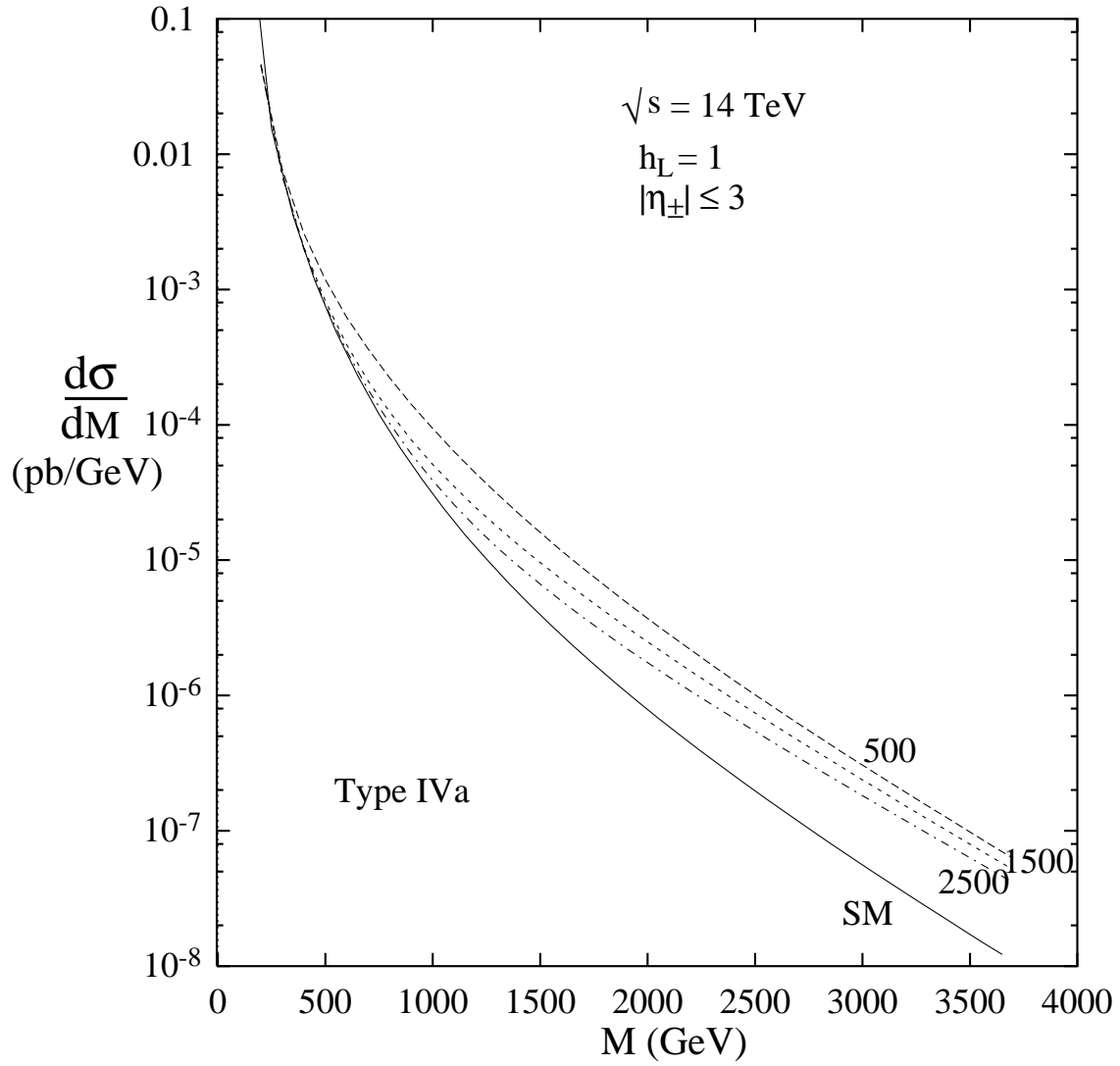
0.1

0.01

10^{-3}

$\dfrac{d\sigma}{dM}$ 10^{-4}

(pb/GeV)

10^{-5}

10^{-6}

10^{-7}

10^{-8}

$\sqrt{s} = 14$ TeV

$h_L = 1$

$|\eta_{\pm}| \le 3$

Type IVa

500

1500

2500

SM

0   500   1000 1500 2000 2500 3000 3500 4000

M (GeV)

Figure 2: The dilepton invariant mass distribution at the LHC. The curves correspond to the theoretical expectation for the SM and for Type IVa scalars of masses $m_\phi = 500, 1500, 2500$ GeV respectively.
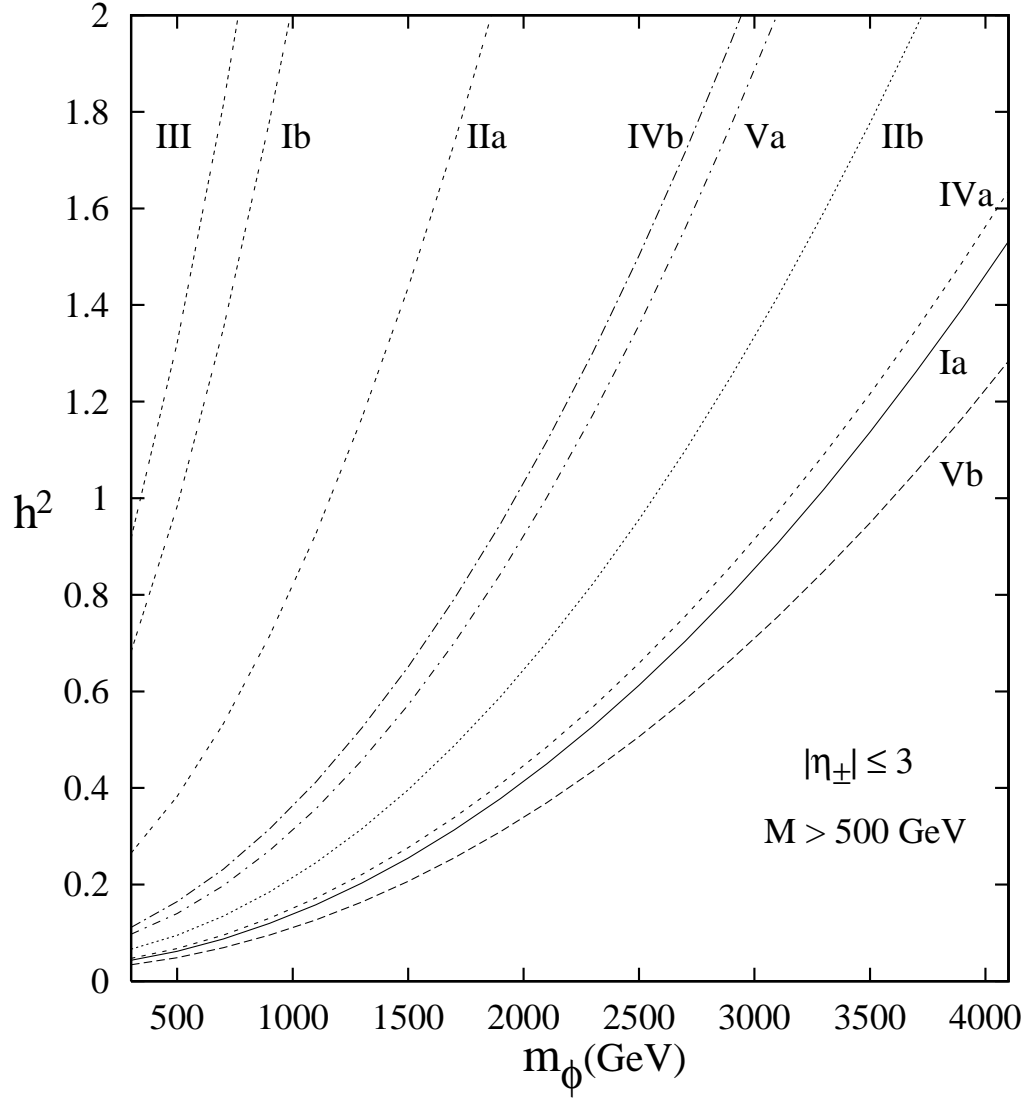
Figure 3: The parameter space that can be probed at the LHC. The different curves are for the various scalar types listed in Table 1, with the ordinate corresponding to the respective coupling. The part of the parameter space above the individual curves can be ruled out at the 3σ level.
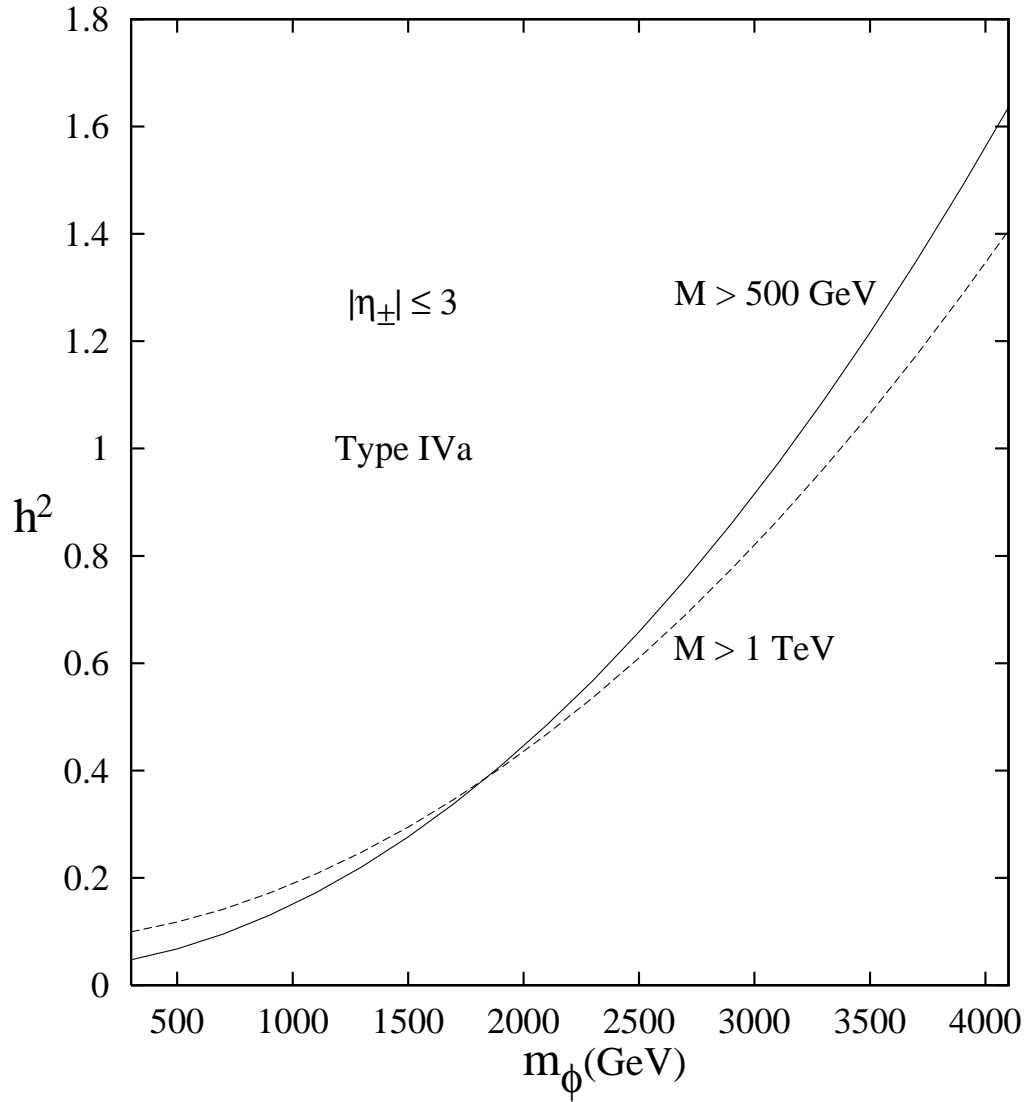
12

Figure 4: The dependence of the exploring ability on the invariant mass cut. The two curves (3σ) shown are for the Type IVa scalar (see Table 1) and for $M_{min} = 500$ GeV and 1 TeV respectively.
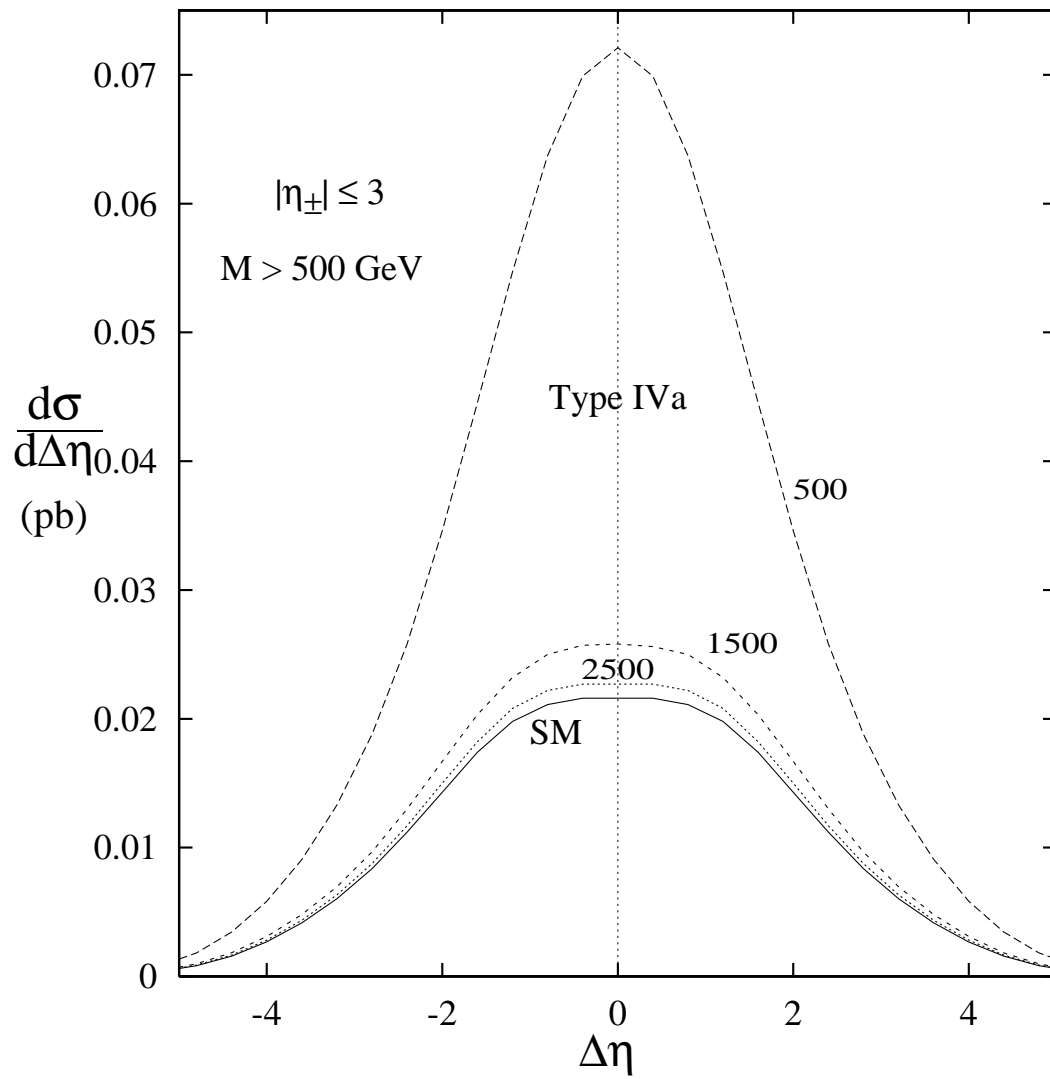
Figure 5: The differential cross section for various values of scalar masses (Type IVa) as a function of the difference of the lepton rapidities.