Beyond the Standard Model in pp Collisions

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1 Introduction

Experimental data, collected up to now, strongly support the Standard Model (SM) as being the correct description of physics at currently available energies. In particular, the analysis of about 700,000 Z at LEP has resulted in a very good agreement with the SM, which is at present tested to the 1% level. In spite of this impressive success, the SM leaves many fundamental questions unanswered. There is a general consensus that the SM is not the ultimate theory, and that new phenomena should manifest themselves in the energy region of the order of 1 TeV. The next generation of high-energy hadron colliders, the LHC at $\sqrt{s} = 16$ TeV and the SSC at $\sqrt{s} = 40$ TeV, will be the first machines to probe parton-parton collisions directly at energies of the order of 1 TeV. Such energies may be essential for an understanding of the outstanding problems of the SM: the electroweak symmetry breaking (the Higgs sector), the origin of the particle mass scales, and the origin of the number of matter species.

In the ECFA LHC Workshop, we have addressed the question of Physics Beyond the Standard Model in three working groups:

- Supersymmetry [1],
- New Heavy Gauge Bosons [2],
- Alternative Symmetry Breaking [3].

Supersymmetric theories [4] are of interest because they provide an elegant solution to the problem of stabilizing the mass of the Higgs boson, as a consequence of which, supersymmetric particles should be found with masses below about 1 TeV—thus directly accessible to future hadron colliders. In Section 2 we present possible signatures of supersymmetry within the Minimal Supersymmetric Standard Model (MSSM) with an exact multiplicatively conserved R-parity. The R-parity could be broken [5], and as a consequence new signatures are expected, which will be discussed as well.

Extending the gauge group $[SU(3)_C \times SU(2)_L \times U(1)_Y]$ of the SM (with or without supersymmetry), results in predictions of new vector bosons and possible other new particles beyond the SM [6]. The search for new heavy gauge bosons will be discussed in Section 3.

One of the main physics goals of the LHC is the understanding of the nature of electroweak symmetry breaking [7]. The symmetry-breaking sector can be either a weakly interacting system with a Higgs particle below 1 TeV or a strongly interacting system with just the longitudinal components of the weak bosons W and Z. The strongly interacting symmetry-breaking sector has been studied in two different approaches [8, 9] and possible signatures at future hadron colliders have been established; these will be discussed in Section 4.

Before discussing the possibility of detecting the above-mentioned ‘predicted’ new physics at the LHC, let us recall the challenge for the experiments to observe a signal above the enormous background from SM processes. Figure 1 shows examples of the ratio of signal cross-sections to the total cross-section at the LHC (100 mb) as a function of mass for gluino pair production, for $Z' \rightarrow e^+e^-$ and $W^+_R \rightarrow \ell^+\nu\ell^+\ell^-$, and for longitudinal WZ scattering $W^+_LZ_L \rightarrow \ell^+\nu\ell^+\ell^-$ (BESS\(^1\) Model) together with some of the most important background cross-section ratios. For example, to observe a new vector resonance $Z'$ of 1 TeV mass decaying into electron pairs, the ratio of signal to total cross-section is about $10^{-12}$, i.e. three orders of magnitude smaller compared with

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1) BESS stands for Breaking Electroweak Symmetry Strongly.
Figure 1: Ratio of signal to total cross-section at the LHC as a function of mass, together with examples of background cross-sections ratios.

the discovery of the $Z \rightarrow e^+e^-$ at the CERN pp Collider where 1 out of $10^9$ interactions produced one Z into electron pairs.

2 Supersymmetry
2.1 The Minimal Supersymmetric Standard Model (MSSM)

Sparticle production in hadron colliders has been discussed extensively in the literature [4, 10, 11]. We will recall a few important features of the MSSM that are relevant to our discussion on sparticle detection at the LHC [12]. The conservation of a new multiplicative quantum number, known as R-parity, has the following phenomenological consequences: i) sparticles, defined as R-odd states and denoted by a tilde, must be pair-produced, e.g. $pp \rightarrow \tilde{g}\tilde{g} + X$; ii) each sparticle can decay only into a lighter sparticle, e.g. $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0_1$; iii) the lightest sparticle (LSP) must be stable.

At least two Higgs doublets are needed to give masses to all particles. The characteristics of the MSSM is the existence of five Higgs bosons with the following tree level mass relations: charged Higgs $H^\pm : m_{H^\pm} > m_W$; lightest neutral scalar $h^0 : m_{h^0} < m_{\tilde{g}}$; heavy neutral scalar $H^0 : m_{H^0} > m_{Z^0}$; and a pseudoscalar $A^0 : m_{A^0} > m_{h^0}$. However, new calculations of radiative corrections indicate that the lightest neutral Higgs ($h^0$) could be significantly heavier than $m_{Z^0}$, if the top-quark mass is much larger than the $W$ mass [13].

Electroweak symmetry breaking induces mixing between gauginos and Higgsinos of the same charge. Thus the photino, the Z-inos, and the neutral Higgsinos (the weak eigenstates) mix to produce (in order of increasing mass) the mass eigenstates $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, and $\tilde{\chi}_4^0$ (neutralinos). Similarly, the W-inos and charged Higgsinos mix to give mass eigenstates $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_3^\pm$ (charginos). It is generally assumed that the lightest neutralino, $\tilde{\chi}_1^0$, is the LSP. It has very small interaction cross-section and escapes detection, thus resulting in a missing transverse energy ($E_T^{miss}$) event signature. For gluino pair produc-
tion, for example, the amount of $E_T^{\text{miss}}$ expected depends on the assumed decay modes. For direct decay into the LSP (e.g. $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$) one expects large $E_T^{\text{miss}}$. Alternatively, heavy sparticles can decay into heavier charginos and neutralinos, which in turn decay into lighter charginos and neutralinos until the LSP is reached. In such cascade decays, where the LSP appears at the end of the decay chain, a softer $E_T^{\text{miss}}$ spectrum is expected. Cascade decays via charginos and neutralinos will produce final states that often contain $W$ and $Z$ bosons. In general, transitions from heavier to lighter neutralinos proceed via a $Z$ and/or $h^0$, and transitions from or to charginos occur via $W$'s. The decay chain can be rather complicated [14]. However, these cascade decays can also introduce interesting new signatures, which will be discussed later. A complete survey of all possible gluino and squark decay modes has been performed, including the loop decays $\tilde{g} \rightarrow g + \tilde{\chi}_i^0$ and taking into account the $t$-quark Yukawa coupling as well as all $t$-quark mass terms [15].

If one takes into account the unification constraints within the MSSM, in first approximation the masses of sparticles are related via five basic parameters: $m_{\tilde{g}}, m_{\tilde{q}}, \tan \beta \equiv v_2/v_1, \mu$, and $m_\phi$, where $\mu$ is the Higgsino mass parameter, $v_1$ and $v_2$ are the vacuum expectation values of the two Higgs doublets, and $m_\phi$ is (any) Higgs mass. Therefore, for example, fixing $m_{\tilde{g}}$ and assuming that $m_{\tilde{g}} < m_{\tilde{q}}$ and $m_{1\text{H}^0} = 500$ GeV leaves two free parameters: $\mu$ and $\tan \beta$. Thus for a given $\mu$ and $\tan \beta$, we can calculate all gluino branching ratios and all masses of $\tilde{\chi}_{j=1,2,3}^\pm$ and $\tilde{\chi}_1^0$. For example, for $m_{\tilde{g}} = 1000$ GeV (300 GeV), $\mu = -440$ GeV and $\tan \beta = 10$ one obtains for the neutralino masses 168.2 (51.1), 323.3 (101.4), 446.8 (449.3) and 464.1 (449.4) GeV and for the chargino masses 323.5 (101.5) and 466.0 (454.4) GeV. For these parameters the direct decay into the LSP amounts to 5.1% (16.6%).

The choice for $\mu$ and $\tan \beta$ is guided by the present limits from LEP and from future expectations, summarized in Fig. 2 [16]. The present limit on $\tan \beta$ is $> 1.6$, if one uses tree-level formulae. This limit is, however, weakened if radiative corrections are included [13]. With a foreseen sensitivity expected for 500 pb$^{-1}$ of integrated luminosity at $\sqrt{s} = 200$ GeV and using all the decay modes of the reaction $e^+e^- \rightarrow (H^0or h^0)Z$, LEP can exclude the minimal supersymmetric model. However, it is important to note that this exclusion of the MSSM is possible only if $\sqrt{s} \geq 190$ GeV [13]. If the radiative corrections push the mass of $h^0$ above the $Z^0$ mass, then $\sqrt{s}$ has to be raised accordingly.

2.2 Sparticle production at the LHC

A systematic survey of supersymmetric particle production mechanisms in high-energy hadron–hadron collisions has been carried out by EHLQ [17], and matrix elements for most processes of interest can be found in Ref. [18]. An example of $\tilde{g}\tilde{g}$, $\tilde{g}q$, and $\tilde{q}\tilde{q}$ production at the LHC is shown in Fig. 3. Gluino (squark) cross-sections depend on both gluino and squark masses. The cross-sections of Fig. 3 were computed [19] assuming that $m_{\tilde{q}} = 2m_{\tilde{g}}$, using EHLQ1 structure functions [20] and $\hat{s}$ for the $Q^2$-scale, leading to a conservative estimate of the cross-sections. For example, for a total integrated luminosity of $10^4$ pb$^{-1}$ (corresponding to one year of running at $L = 10^{33}$ cm$^{-2}$ s$^{-1}$), we expect about $0.5 \times 10^4$ gluino pairs to be produced at the LHC for $m_{\tilde{g}} = 1$ TeV. Strongly interacting sparticles such as gluinos and squarks are copiously produced and are therefore clearly a domain for hadron colliders.

2.3 Gluino signatures

Because of the large production cross-section, searches for gluino signals at future
Figure 2: Present limits from LEP, and future expectations in the \((\tan \beta, m_{\tilde{A}})\) plane. The expected cross-section sensitivity corresponds to an integrated luminosity of 500 pb\(^{-1}\) at \(\sqrt{s} = 200\) GeV.

Figure 3: Gluino–gluino, gluino–squark, and squark–squark production cross-section as a function of \(m_\tilde{g}\) for \(m_\tilde{A} = 2 m_\tilde{g}\) at the LHC.
hadron colliders have received a lot of attention. Detailed studies have been performed for direct decays into the LSP, leading to the `classical’ (\(E_T^{\text{miss}} + n \text{jet}) signature. As mentioned above, this signature should still remain valid if cascade decays are included. Details of gluino signatures depend on the chosen parameters: \(m_{\tilde{g}}, \mu, \) and \(\tan \beta\) (the squark is assumed to be heavier than the gluino). The branching ratios as a function of \(\mu\) for \(m_{\tilde{g}} = 1000\) GeV and \(\tan \beta = 10\) are plotted in Fig. 4 for two representative cases: i) direct decay into LSP: \(\tilde{g}\tilde{g} \rightarrow q\tilde{q}X_1^0 q\tilde{q}X_1^0\), and ii) cascade decays into ZZ: \(\tilde{g}\tilde{g} \rightarrow ZZ + X\), together with the \(\mu\) range covered by LEP 200 [15]. A large variation of the branching ratios as a function of \(\mu\) is observed.

To establish a gluino signal in the \((E_T^{\text{miss}} + n \text{jet}) channel, two different gluino masses have been chosen: \(m_{\tilde{g}} = 300\) GeV and \(m_{\tilde{g}} = 1000\) GeV, using \(\tan \beta = 2\) and \(\tan \beta = 10\) at \(\mu = -440\) GeV. This choice allows the sensitivity to the tan \(\beta\) parameter to be studied. Taking for \(\mu\) an asymptotic value rather than a \(\mu\) value which is more optimistic in terms of event rates, reflects the conservative assumption for the second parameter. The \(m_{\tilde{g}} = 300\) GeV value was chosen in order to study the capability of an LHC experiment to cover a mass spectrum down to gluino masses not yet excluded by previous experiments.

We have also studied a gluino signal in the \((ZZ \rightarrow 4 \text{ lepton}) channel for \(m_{\tilde{g}} = 750\) GeV, \(\tan \beta = 2,\) and \(\mu = -300\) GeV. Even though the branching ratio into ZZ increases with increasing gluino mass [15], the resulting event rate into four leptons is small owing to the \(Z \rightarrow \ell^+\ell^-\) branching ratio and the smaller cross-section at higher gluino masses. For example, as shown in Fig. 4, for \(m_{\tilde{g}} = 1000\) GeV and \(\text{BR}(\tilde{g}\tilde{g} \rightarrow ZZ + X) = 10\%\), one expects only about 25 events in the four-lepton channel for \(10^3\) pb\(^{-1}\).
2.3.1 Gluino: ($E_T^{\text{miss}} + n \text{ jet}$) channel

To study the ($E_T^{\text{miss}} + n \text{ jet}$) signature, cascade decays have been included in the simulation [21]. For $m_{\tilde{g}} = 300$ GeV, only decays into $\tilde{\chi}^0_i$, $\tilde{\chi}^0_a$, and $\tilde{\chi}^+_i$ are possible, owing to the low gluino mass. Neglecting loop decays for $\tan \beta = 10$ in the simulation [BR ($\tilde{g} \rightarrow g \tilde{\chi}^0_i$) $\approx$ 2%], we obtained for the two different $\tan \beta$ values: $\sigma \cdot \text{BR} = 640$ pb (tan $\beta = 2$) and $\sigma \cdot \text{BR} = 617.9$ pb (tan $\beta = 10$). For $m_{\tilde{g}} = 1000$ GeV, decays into all $\tilde{\chi}^0_i$ and $\tilde{\chi}^+_i$ are possible. For tan $\beta = 2$, we have included the largest branching ratios but have ignored loop decays, resulting in $\sigma \cdot \text{BR} = 0.235$ pb. For tan $\beta = 10$, loop decays become more important [e.g. BR($\tilde{g} \rightarrow g \tilde{\chi}^0_a$) = 32%], therefore they have been included in the simulation resulting in $\sigma \cdot \text{BR} = 0.424$ pb. For more details, see Refs. [15, 21].

We have used ISAJET [22] on the particle level for signal and background evaluation, and the UA2 SUSY [23] Monte Carlo to study the effect of smearing and pile-up. Figures 5a, b show the resulting $E_T^{\text{miss}}$ distributions for $m_{\tilde{g}} = 300$ GeV and 1000 GeV, together with the total background contribution from $t\bar{t}$ ($m_t = 150$ GeV), $W \rightarrow \ell \nu$ ($\ell = e, \mu, \tau$), and $Z \rightarrow \nu\bar{\nu}$. As expected, the $E_T^{\text{miss}}$ distribution is softer because of the addition of cascade decays, compared with the same distribution obtained for direct decays into LSP in Ref. [24]. The gluino signal always remains below the background.

The background contributions can be reduced by exploiting the difference in topology of signal and background events. Jet finding was carried out on the particle level, using a jet algorithm similar to that used by UA1. The highest track with $E_T > 10$ GeV was used to initiate a new jet, and all tracks within $\Delta R < 0.4$ of its initiator track were associated with the jet, where $(\Delta R)^2 = (\Delta \eta)^2 + (\Delta \phi)^2$. Only tracks with $E_T > 1$ GeV were considered. To study the topology of signal and background events, the following quantities were defined: i) jet multiplicity $N_{\text{jet}}$; ii) circularity $C$, computed from the transverse projection of the calorimeter jets ($E_T > 10$ GeV) and the $E_T^{\text{miss}}$ vector, defined as $C = \frac{1}{2} \min \left( \sum E_T, n \right)^2 / \left( \sum E_T^2 \right)$; and iii) $\Delta \phi_{12}$, the azimuthal angle between the two highest transverse-energy jets. A comparison of $N_{\text{jet}}$, circular-
Figure 6: Distribution of a) $N_{\text{jet}}$ for $E_{T}^{\text{jet}} > 200$ GeV, b) circularity $C$, and c) $\Delta \phi_{12}$ for gluino pair production of 1000 GeV mass and $\tan \beta = 2$ (solid histogram) and $\tan \beta = 10$ (dashed histogram), compared with Standard Model background (points with errors bars) for $E_{T}^{\text{miss}} > 100$ GeV. The distribution are normalized to 1.

ity, and $\Delta \phi_{12}$ distributions for gluino production of $m_{\tilde{g}} = 1000$ GeV with the total background is shown in Figs. 6a,b,c, for events with $E_{T}^{\text{miss}} > 100$ GeV. The expected differences in event topology for signal and background are clearly seen in each case. The $E_{T}^{\text{miss}}$ distributions for gluino pair production and for background are shown in Figs. 7a,b for one possible selection requiring $N_{\text{jet}} \geq 3$($E_{T}^{\text{jet}} = 200$ GeV), $\Delta \phi_{12} < 130^\circ$ and $C > 0.2$. This selection is aimed at finding isotropic multijet events—a signature expected from gluino decays. Because of the addition of cascade decays, the isotropic multijet topology is even more pronounced than in the case of the direct decay into the LSP.

The number of signal events that are expected for an integrated luminosity of $10^4$ pb$^{-1}$ with the above-mentioned cuts and $E_{T}^{\text{miss}} > 300$ GeV are: for $m_{\tilde{g}} = 300$ GeV: $414 \pm 299$ ($419 \pm 289$) events for $\tan \beta = 2$ (10); for $m_{\tilde{g}} = 1000$ GeV: $114 \pm 7$ (190 $\pm 12$) events for $\tan \beta = 2$ (10). The total background contribution is $31 \pm 12$ events, where the dominant contribution comes from $t\bar{t}$ (27 events). The quoted errors are the statistical errors arising from the Monte Carlo generation. The size of the error on the number of signal events after selection cuts, expected for $m_{\tilde{g}} = 300$ GeV, demonstrates that very few of the generated events survive the cuts. This analysis is therefore clearly sensitive to the tails of distributions for $E_{T}^{\text{miss}} > 300$ GeV because of the softer $E_{T}^{\text{miss}}$ spectrum, and a lower $E_{T}^{\text{miss}}$ cut would be desirable. We have also checked that the removal of isolated leptons with $p_T > 25$ GeV (isolation: $\text{d}p_T < 5$ GeV in $\Delta R < 0.2$) does not improve the signal-to-background ratio. This was expected, because isolated leptons from W and Z decays are present in the cascade decays of gluinos.

The proposed event selection should allow extrapolation to high-luminosity running, thus extending the expected gluino mass reach of about 1 TeV, for the assumed $10^4$ pb$^{-1}$ and a somewhat conservative choice of parameters. In order to make sure that in this case the conclusions are not altered, we have studied the effect of calorimeter smearing and pile-up. As expected, calorimeter smearing has little effect on the distributions employed in this analysis. Figure 8 shows the effect of pile-up on the highest-$E_T^{\text{jet}}$ jet in the event, simulated by superimposing $n$ minimum-bias events (generated using the PYTHIA [25] Monte Carlo program) on the signal, with $(n) = 2$ or $(n) = 15$ Poisson-
Figure 7: Missing transverse energy distribution after selection cuts for a) $m_{\tilde{g}} = 300$ and b) $m_{\tilde{g}} = 1000$ GeV. The solid (dashed) histogram corresponds to $\tan \beta = 2$ (10). The points with error bars show the total background contribution.

distributed. The difference between 15 and 2 superimposed minimum-bias events, displayed in Fig. 8, results in $\langle \Delta p_T \rangle = 1.6$ GeV, reflecting the fact that the jet definition used is not very sensitive to pile-up. We have also verified that the other distributions used in the selection are unaffected by pile-up.

So far, only physical backgrounds to the $E_T^{\text{miss}}$ signature have been considered. However, for an $E_T^{\text{miss}}$ requirement as low as $E_T^{\text{miss}} > 200$ or 300 GeV, it is necessary to get an estimate of $E_T^{\text{miss}}$ due to jet mismeasurements. This estimate has been made using the PAPAGENO [26] Monte Carlo at the parton level, which includes matrix elements for three, four, and five jets. A simulation at the particle level is not possible owing to the prohibitively large CPU-time required. To obtain a more realistic simulation [27], the parton jets have been ‘dressed up’ using a jet profile parametrization. ISAJET has been used to parametrize the $E_T$ flow of a jet as a function of $\Delta R$ and $E_T$. The resulting jets have been simulated in a calorimeter with pointing geometry (CDF geometry and granularity). The parts of the jet that fall into the calorimeter cells have been smeared, i.e. fluctuation of overall jet energy and fluctuation of jet direction via cell-to-cell fluctuations; the parts of the jet that fall into a crack were considered as lost. The resulting $E_T^{\text{miss}}$ distributions for three-jet events assuming three different jet resolutions are shown in Fig. 9. The effect of a fourth jet being lost in $|\eta| > 4.5$ results in a similar distribution. The $E_T^{\text{miss}}$ distribution thus obtained has a much steeper slope compared with those of the gluino signal and background displayed in Fig. 5 before selection cuts. Therefore, we can expect that, after selection cuts, the background from jet mismeasurement will be substantially reduced (as is the case for physics backgrounds), provided the calorimeter has a coverage of at least $|\eta| = 4.5$. Cracks clearly play an important role; however, their effect can only be studied in detail given a specific design for a detector at the LHC.
Figure 8: Effect of pile-up on the highest transverse energy jet in the event, simulated by superimposing an average of 15 or 2 minimum-bias events.

Figure 9: Missing transverse energy distribution for three jet events after calorimeter smearing, as explained in the text.
Figure 10: Mass distribution of the four hardest electrons from $\tilde{g}\tilde{g} \rightarrow ZZ + X \rightarrow 4e + X$ for $m_{\tilde{g}} = 750$ GeV and from ZZ and $t\bar{t}$ background. A t-quark of 150 GeV was assumed.

2.3.2 Gluino: ($ZZ \rightarrow 4$ lepton) channel

If a gluino signal is detected at the LHC, the possibility of detecting many different gluino decay modes allows this signal to be confirmed in possibly several different channels. It has already been pointed out that at larger gluino masses the $\tilde{g}\tilde{g} \rightarrow ZZ + X$ channel offers a very striking signature, but with a low rate. This signature was studied [21] for $m_{\tilde{g}} = 750$ GeV, and the dominant decay modes $\tilde{g} \rightarrow q\tilde{q}\tilde{q}$, $g\tilde{g}$, and $g\chi_0^0$, with the subsequent decay of $\tilde{\chi}_2^0 (\tilde{\chi}_4^0) \rightarrow Z\chi_1^0 \rightarrow \ell^+\ell^-\chi_1^0$, have been included in the simulation. Thus using a total branching ratio into Z of 20.1%, for $10^5$ pb$^{-1}$, results in a signal of 63 events with a signature of four leptons from the two Z's, two or more hard jets, and $E_T^{\text{miss}}$. The main background is expected from ZZ and $t\bar{t}$ production. Because of the low rate, $L \geq 10^{34}$ cm$^{-2}$ s$^{-1}$ is clearly desirable. For this reason, the four-electron channel was studied, including the effect of calorimeter smearing and pile-up. The electron resolution used was $\Delta E/E = 10\% / \sqrt{E} \oplus 1\%$, and the electron energy was deposited in one cell of a calorimeter of granularity $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$. In contrast to the SM Higgs $\ell^+\ell^-\ell^+\ell^-$ signature, no mass peak is expected for the gluino signature, as shown in Fig. 10, where the mass of the four hardest leptons in the event is plotted for signal and background. No sign requirement has been imposed for electrons. The $E_T^{\text{miss}}$ distribution, after demanding $m_{4e} > 250$ GeV, two Z (each pair of leptons defines a Z, if $81 < m_{\ell\ell} < 101$ GeV), and two hard jets ($> 200$ GeV and $> 100$ GeV, respectively), is shown in Fig. 11. A clear difference between signal and background is observed. The number of four-electron events expected for $10^5$ pb$^{-1}$ after these selection cuts is: 7.5 events for the signal and 2 (7.2) from ZZ ($t\bar{t}$) background, using a t-quark mass of 150 GeV. There is a very large statistical uncertainty attached to the background numbers for ZZ and $t\bar{t}$ owing to the cut-efficiency for the background,
Figure 11: Missing transverse energy distribution after selection cuts from $\tilde{g}\tilde{g} \to ZZ + X \to 4e + X$ for $m_{\tilde{g}} = 750$ GeV, and from ZZ and $t\bar{t}$ background.

of $10^{-3}$ and $10^{-4}$, respectively. The effect of pile-up of 15 minimum-bias events results in a small decrease in the number of events after cuts, which is due to the isolation requirement imposed for electron identification in the calorimeter simulation. Adding the $\mu$ channel will increase the statistics by about a factor of 4. Therefore, for a gluino mass of 750 GeV, one expects a signal of about 30 events with negligible background, which should, if necessary, allow a signal to be confirmed in the $(E_T^{\text{miss}} + n \text{ jet})$ channel.

Another possibility to search for a gluino signal makes use of the distinctive feature of gluinos being Majorana fermions, thus decaying with equal probability into fermions and antifermions. The $\tilde{g}\tilde{g}$ production will result in like-sign dileptons in the final state [11]. We have not investigated this signature in detail, but clearly it should be included in a more complete survey of interesting gluino signatures.

2.4 Squark signatures

For any given quark flavour in the MSSM, there are two spin-0 superpartners ($\tilde{q}_L, \tilde{q}_R$) corresponding to the two chiralities of the associated fermions. Left—right mixing can be neglected for the first five squark flavours, which are expected to be degenerate in mass. The special case of a stop-quark will be discussed later. Since the couplings of $\tilde{q}_L$ and, $\tilde{q}_R$ are different, one expects different signatures for the two cases. This difference has been studied [21] for one particular example: $m_{\tilde{q}} = 1000$ GeV, $\tan \beta = 10$, and $\mu = -440$ GeV; we further assumed that $m_{\tilde{g}} = 1500$ GeV and $m_{\tilde{d}_L} = m_{\tilde{d}_R}$.

2.4.1 $\tilde{q}_R$ decays

For the parameters mentioned, the right squark decays into $\tilde{\chi}_1^0$, with BR$(\tilde{q}_R \to q\tilde{\chi}_1^0) \approx 99\%$, except for $\tilde{t}_R$, if the t-quark mass and t-quark Yukawa coupling are fully
Figure 12: Missing transverse energy distribution after selection cuts for $\tilde{u}_L$ and $\tilde{d}_L$ pair production of 1000 GeV mass (histogram). The points with errors bars show the total background contribution.

taken into account [15]. For the first five squark flavours, we can therefore use the result from the analysis performed for the La Thuile Workshop [24], for $m_{\tilde{q}} = 1000$ GeV, where 100% branching ratio into the LSP was assumed, to obtain the number of events expected after analysis cuts. The La Thuile results have been re-scaled to account for the change in the production cross-section and for the fact that we only consider $\tilde{q}_R$. A signal-to-background ratio of order $8/1$ is still obtained for the proposed selection cuts [$E_T^{\text{miss}} > 800$ GeV, $N_{\text{jet}} \geq 3$ ($E_T^{\text{jet}} > 250$ GeV), and $C > 0.25$] for $10^4$ pb$^{-1}$. Scaling the results of the high-luminosity studies, 214 events from $\tilde{q}_R$ decays over a total background of 25 events are expected for $5 \times 10^5$ pb$^{-1}$ [24].

2.4.2 $\tilde{q}_L$ decays

For the assumed parameters the dominant decay modes for $\tilde{u}_L$ and $\tilde{d}_L$ are into $\tilde{\chi}_1^\pm$ : $\tilde{u}_L \rightarrow d\tilde{\chi}_1^+ (45\%)$ and $\tilde{d}_L \rightarrow u\tilde{\chi}_1^- (37\%)$, with the subsequent decay $\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_0^0 (m_{\tilde{\chi}_1^\pm} = 385.6$ GeV, $m_{\tilde{\chi}_0^0} = 209.8$ GeV). Again, $\tilde{L}_L$ and $\tilde{L}_R$ are different owing to the t-quark Yukawa coupling and the t-quark mass terms [15]. The $\tilde{u}_L$ and $\tilde{d}_L$ decays have been simulated using ISAJET for the above-quoted branching ratios, resulting in a total of $1.1 \times 10^3$ events in $10^4$ pb$^{-1}$ for a squark mass of 1 TeV. Figure 12 shows the $E_T^{\text{miss}}$ distribution, after possible selection cuts, for $m_{\tilde{q}_L} = 1000$ GeV [$N_{\text{jet}} \geq 3$ ($E_T^{\text{jet}} > 250$ GeV), $E_T^{\text{jet}} > 400$ GeV, and $C$ For $E_T^{\text{miss}} > 300$ GeV and an integrated luminosity of $10^5$ pb$^{-1}$, a signal of $348 \pm 198$ events and a total background of $185 \pm 41$ events (t$\bar{t}$ being again the dominant contribution) are expected. To obtain a mass-reach estimate for squarks ($\tilde{q}_L$, $\tilde{q}_R$), one can combine, as in the gluino case, all possible decay modes, which will allow us to set a discovery limit for squarks of about 1 TeV for $10^4$ pb$^{-1}$, i.e. one year of running at $L = 10^{33}$ cm$^{-2}$ s$^{-1}$. The effect of pile-up and calorimeter resolution and rapidity coverage, as investigated for the gluino case, applies to the squark case as well [21].
2.4.3 The possibility of a light stop

Squark signatures discussed in the previous sections were derived assuming five degenerate squark flavours. The scalar partner of the top quark is an exception, because the stop mass matrix contains a potentially large off-diagonal term, proportional to the top quark mass. It is therefore not excluded that the stop could be lighter than the top quark and \( m_t \ll m_q \).

Among the variety of possible stop scenarios the following cases have been studied [28]:

a) \( m_t = 110 \text{ GeV} \) and \( m_{\tilde{t}} = 200, 110, \) or 50 GeV. For the first two cases, where \( m_t \geq m_{\tilde{t}} \), stop can be produced only via stop pair production and \( \sigma(t\tilde{t}) \propto 1/10 \sigma(t\tilde{t}) \). In the third case, where the stop can also be produced in the t-quark decay \( t \rightarrow t\tilde{\chi}_1^0 \), large event rates are expected. The \( t \)-decay modes are different for all three \( t \) masses assumed, thus leading to different event signatures. For the signal evaluation, the following \( t \)-decays have been used: \( t \rightarrow t\tilde{\chi}_1^0 \), \( t \rightarrow \tilde{\chi}_1^+ b \), and \( t \rightarrow c\tilde{\chi}_1^0 \), for \( m_t = 200, 110, \) and 50 GeV, respectively.

b) \( m_t = 190 \text{ GeV} \) and \( m_{\tilde{t}} = 110 \text{ GeV} \): in this case the stop can also be produced in the t-quark decay, and the expected signature is similar to that of the SM t-decay, except that one expects more \( E_T^{\text{miss}} \) from the \( t \rightarrow t\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 b \tilde{\chi}_1^0 \) decay chain.

Signal and SM backgrounds have been evaluated using the ISAJET Monte Carlo program. Selection criteria are based on at least one isolated lepton with \( p_T > 50 \text{ GeV} \) and angular correlations between the lepton and \( E_T^{\text{miss}} \). Details of the event selection cuts can be found in Ref. [28]. A stop signal can be detected for the case where the top is heavier than the stop, allowing a \( t \rightarrow t\tilde{\chi}_1^0 \) decay with \( \text{BR} \geq 10\% \). In this case an increase of a factor of about 8 of the event rate for \( E_T^{\text{miss}} > 300 \text{ GeV} \) is expected for \( m_t = 50 \text{ GeV} \), which decreases to a factor of about 2 for \( m_t = 110 \text{ GeV} \), assuming a top mass of 110 GeV (190 GeV) respectively. The 'standard top' selection criteria used in Ref. [29] are not adequate to establish the existence of a light stop.

2.5 Chargino and neutralino production

Production cross-sections for electroweak sparticles such as \( \tilde{\chi}_\pm^\pm \) and \( \tilde{\chi}_1^0 \) are small in relation to those for squarks and gluinos of the same mass. As already mentioned, charginos and neutralinos can decay via (real or virtual) W's and Z's, resulting in multiparticle final states. One promising detection possibility for charginos and neutralinos involves three leptons in the final state [30]. The contour lines in Fig. 13 represent the cross-section in picobarns for \( pp \rightarrow \tilde{\chi}_\pm \rightarrow \ell\ell\ell + X \) for \( p_T^\ell > 15 \text{ GeV} \), \( p_T^\ell > 10 \text{ GeV} \), and \( |\eta_\ell| < 3, |\eta_\ell| < 2.5 \), and one more lepton with \( p_T > 10 \text{ GeV} \) in \( |\eta| < 3 \). Also shown in the \( M_{\tilde{\mu}-\mu} \) plane of Fig. 13 is the exclusion region from LEP 200 if no chargino with \( m_{\tilde{\chi}_\pm} < 80 \text{ GeV} \) is found. The main background contributions are expected from WZ and \( t\bar{t} \) production. The estimate of the background was done on the partonic level for the \( t\bar{t} \) case, resulting in a background cross-section of 0.25 to 0.67 pb for \( m_t = 150 \text{ GeV} \) and of 0.01 to 0.041 pb for \( m_t = 200 \text{ GeV} \), by cutting on the presence of a jet with \( p_T < 30 \text{ GeV} \) (50 GeV), respectively. For more details see Ref. [30]. The WZ background is believed to be negligible provided one removes events with \( m_{\tilde{q}/\tilde{g}} = m_2 \). It is difficult to establish a clear signal in the three-lepton channel, because the background is strongly \( t \)-mass dependent. A Monte Carlo simulation on the particle level is needed to confirm a three-lepton signal if \( m_t \leq 150 \text{ GeV} \).
2.6 Slepton pair production

Sleptons are expected to be the lightest charged sparticles in the MSSM. Already a relatively low bound on their mass translates into a rather stringent bound on the supersymmetric particle spectrum [31]. The dominant production mechanism for slepton pair production is via Drell–Yan, as shown in Fig. 14. Taking into account the small production cross-section for $\tilde{e}_L \tilde{e}_L \to e\nu \tilde{\chi}_1^0 \tilde{\chi}_1^0$ and the large background from $WW \to e\nu\nu$ (also shown in Fig. 14), and an additional background contribution from $t\bar{t}$ production does not leave us much hope of detecting a clear signal above background.

A more promising case for observing a signal could be $pp \to \tilde{\ell}^\pm \tilde{\nu} \to \ell^\pm \tilde{\chi}_1^0 \nu \tilde{\chi}_1^0$. Again, the background from SM is very large, and very likely it will not permit the observation of a signal. Clearly, for both the chargino–neutralino and the slepton pair production, the knowledge of the t-quark mass would be very helpful for establishing a criterion with which to detect electroweak sparticles at the LHC.

2.7 Broken R-parity

In the MSSM, a matter parity (equivalent to R-parity) is introduced to forbid $\Delta B \neq 0$ and $\Delta L \neq 0$ terms and to avoid fast proton decay. However, it is sufficient for proton stability to forbid either $\Delta B \neq 0$ or $\Delta L \neq 0$ terms, so that new models (with broken R-parity) may be constructed with the same minimal particle content as the MSSM. One of the motivations for broken R-parity [5,32] comes from the hypothesis that squarks and sleptons may transform differently under discrete symmetries as a possible consequence of ‘string’ compactification. If one allows R-parity to be broken, 45 additional terms coupling quarks and sleptons are possible and $\Delta B \neq 0$ or $\Delta L \neq 0$ is allowed. To study the effect of these additional terms [32], we make the following (plausible) simplifying assumptions: i) one term dominates, and ii) the LSP is neutral and a $(\tilde{\gamma}, \tilde{Z}, \tilde{H})$ mixture.

The experimental consequences of broken R-parity are: i) single-sparticle pro-
duction and ii) decay of the LSP. The latter can occur in many different ways, e.g. LSP $\to dd\nu$ or $e^+\mu^-\nu$ or three quarks, which again opens up a variety of different signatures, some of which look a priori very difficult to detect (e.g. $g \to q\bar{q}X_1^0$, $X_1^0 \to 3$ quarks), some that have a chance of being detected above background, and some that provide a rather spectacular signature (e.g. $g \to q\bar{q}X_1^0$, $X_1^0 \to e^+\mu^-\nu$). It should be noted that even in the case where the LSP decay does not offer a detectable event signature, cascade decays via W and Z may still provide a detection feasibility.

In the case of single-sparticle production the decay of the LSP is constrained by the particular mechanism chosen. Examples of single-sparticle production are: a) $q\bar{q} \to \nu X_1^0$ via squark exchange; for $m_{\tilde{g}} = 300$ GeV, the cross-section for this process is very small, making a detection unlikely; b) s-channel $\tilde{b}$ production: $d\bar{d} \to \tilde{b}$, with cross-section $O$(nb). For more details, see Ref. [32].

Conventional gluino pair production has been used to study one particular LSP decay signature, admittedly a very striking one. Taking $m_{\tilde{g}} = 300$ GeV and the same parameters and branching ratios as discussed in subsection 2.3 for the gluino decay modes, i.e. for $\tan\beta = 2$ and $\mu = -440$ GeV, BR($g \to q\bar{q}X_1^0$) = 17\%, and allowing the LSP ($m_{X_1} = 53.2$ GeV) to decay with BR($X_1^0 \to e^+\mu^-\nu$) = 30\%, leads to $1.6 \times 10^4$ events in one year of running at $L = 10^{33}$ cm$^{-2}$ s$^{-1}$ with an event signature of $2e^+, 2\mu^-, \geq 4$ hard jets, and softer $E_T^{miss}$. The main background is expected to come from $t\bar{t} \to e^+\mu^-e^+\mu^-+X$. The signal and background has been evaluated with ISAJET, using a t-quark mass of 200 GeV. In the signal case, one expects a correlation between the $e^+$ and $\mu^-$ coming from the LSP decay. This correlation is shown in Fig. 15a, where the difference in azimuthal angle between the highest transverse momentum $\mu^-$ and the nearest electron is plotted for the signal and for the $t\bar{t}$ background (no sign requirement was imposed for the electron). The angular distribution was plotted after requiring two electrons ($p_T > 20$ GeV), two $\mu^-$ ($p_T > 10$ GeV), and $N_{\text{jet}} \geq 3$ ($E_T^{miss} > 100$ GeV). A similar distribution is obtained for the $\mu^-$ and the other electron in the event as shown in Fig. 15b. For $\Delta \phi(\mu^- - e) < 80^\circ$, a signal of $884 \pm 11$ events over a background
of 23 ± 11 events was obtained for 10^4 pb^{-1}. No further requirement is necessary to establish a clear signal [32].

3 New Heavy Gauge Bosons

New heavy Abelian gauge bosons occur in a number of different attempts to extend the gauge group of the SM, because extra U(1) symmetries arise when larger groups are broken down to SU(3) × SU(2) × U(1) [33]. In superstring theories based on Calabi-Yau compactifications, the low-energy group is a subgroup of E_6 [34]. Being of rank 6, an extra U(1) gauge boson may be left light after breaking. In superstring-inspired E_6 models the Higgs sector is constrained and the breaking of E_6 is specified. The angle θ_2, which gives the direction of intermediate breaking, is fixed (θ_2 = 0 or ± arccos (5^1/2)), whereas in E_6 grand unified theories this angle appears as a free parameter.

Among the possible E_6 subgroups obtained at low energy, left-right (LR) models [35] are motivated by the attempt to understand the origin of parity violation and small neutrino masses. These LR models predict also a new charged boson W^±_R, which mixes with the ordinary W’s. In order to avoid a possible problem in the mixing sector, alternative left-right models (ALRM) [36] were introduced with the help of E_6 superstring-inspired theories. The production mechanism for these ALRM vector bosons involves quark-gluon scattering instead of the Drell-Yan mechanism.

A less model-dependent possibility of extending the gauge group of the SM is by retaining SM-like Z’ couplings as in the reference model (RM) and in the extended gauge model (EGM) [37]. These models differ only by the couplings of the Z’ to ordinary vector bosons. In both models the couplings to fermions are as in the SM. In the EGM, the Z’ coupling to ordinary W and Z are suppressed by a factor ≈ m_Z^2/m_{Z’}^2. This leads to a linear increase of the total Z’ width with mass. For the RM, the Z’ width increases
with $m_{Z'}^2$, resulting in a total width of about 10 TeV for a 1 TeV $Z'$, which is unrealistic and not detectable.

In the above models, owing to the existence of elementary Higgses, the problem of the Higgs mass—receiving quadratically divergent loop corrections—can be solved by introducing a supersymmetric scenario. An alternative approach is offered by the BESS [9] model, with the possibility of breaking electroweak symmetry strongly in a nonlinear way. In this scheme no Higgs is present, and the only physical states belonging to the symmetry-breaking sector below the TeV scale are the longitudinal components of the vector bosons. Within this model, a triplet of new vector resonances, $V^\pm$ and $V^0$, are predicted, which are similar to the $\rho$ of QCD, or to the techni-$\rho$ of technicolour theories. The parameters of the model are the mass of the $V$ triplet $m_V$, the new gauge coupling constant $g''$, and the parameter $b$ that describes the possibility of having a direct coupling of $V$ to fermions. Even for $b = 0$ there will be always a coupling of $V$ to fermions via mixing with $(W, Z, \gamma)$, the mixing angles being of order of $g/g''$.

The possibility that vector bosons are composite objects has been studied as well. Within the framework of an effective Lagrangian that satisfies local U(1)$_{\text{em}}$ invariance and is invariant under global SU(2) weak isospin symmetry, two kinds of isoscalar vector bosons have been considered [38]: those that couple to the weak hypercharge current (Y), and those that couple to left-handed currents only (Y$_L$). The parameters of these models are the mass of the isoscalar and the mixing parameter $\lambda^2_y$. For the first excited isotriplet $(W^*, Z^*)$ there is only one parameter $m_{W^*}$. The masses of $W^*$ and $Z^*$ are degenerate, and the coupling to gauge boson pairs is dominant, thus limiting the discovery potential in the lepton channel [39].

We will summarize the potential discovery limits for new heavy vector bosons at the LHC, and will address the question of whether it is possible to distinguish between different models. The search for a signal in $Z' \rightarrow W^+W^- + X$ is expected to be impeded by the large background from $t\bar{t}$ production; therefore only the decay of $Z'$ in lepton pairs is considered. The difficulty in observing a signal in the jet–jet mass spectrum is discussed in Ref. [40].

Before data-taking will start at the LHC, either mixing of the $Z^0$ with $Z'$ at LEP 1 will have been discovered, or a limit on a possible mixing of < 1% will have been set. With LEP 200, there will be a sensitivity to masses of new neutral vector bosons, and from precision measurements it will be possible to exclude certain models. For more details about present limits and future expectations from LEP, see Ref. [41].

### 3.1 $Z'$ discovery in the lepton channel

The total width of the $Z'$ as a function of the $Z'$ mass is shown in Fig. 16 for the models discussed above [33], except for the reference model (where for $m_{Z'} = 1$ TeV, $\Gamma_{Z'} = 10$ TeV) and the excited $Z^*$ (where for $m_{Z^*} = 1$ TeV, $\Gamma_{Z^*} = 260$ GeV). For $Y_L$ and $Y$, only two points are shown as examples owing to the strong dependence of the width on the parameter $\lambda_y^2$. For the BESS model a direct coupling of $b = -0.02$ was assumed. The branching ratios of $Z' \rightarrow e^+e^-$ for $m_{Z'} = 1$ TeV are displayed in Fig. 17. As can be seen, most of the models have a branching ratio into electron pairs between $\sim 1\%$ and $10\%$, except for the reference model and the BESS model for which the branching ratios are less than $10^{-3}$ if there is no direct coupling to fermions (i.e. if $b = 0$), thus limiting the discovery potential for $V^0$ in the lepton channel.

All the above-mentioned models have been simulated using the PYTHIA Monte
Figure 16: $\Gamma_{\text{tot}}(Z')$ as a function of $Z'$ mass for different models discussed in the text.

Figure 17: Branching ratios of $Z' \rightarrow e^+ e^-$ for a $Z'$ mass of 1 TeV.
Figure 18: Invariant $e^+e^-$ mass spectra after calorimeter smearing for a $Z'$ signal from the extended gauge model. Also shown are background contributions from Drell–Yan, $t\bar{t}$, and $b\bar{b}$.

Carlo [25] program, version 5.4, where the $Z'$ couplings to fermions have been modified accordingly. The background contributions to new vector bosons have also been evaluated with PYTHIA.

In order to establish a discovery limit, a simple detector simulation was performed, assuming a rapidity coverage up to $|y_{\text{max}}| = 2$ and an electron resolution of $\Delta E/E = 15%/\sqrt{E} \oplus 2\%$ [42]. Figure 18 shows the invariant $e^+e^-$ mass spectra for a $Z'$ signal from the extended gauge model, together with background contributions from Drell–Yan, $t\bar{t}$, and $b\bar{b}$. These distributions were obtained by including all electron pairs in a range of $\pm2\Gamma_{1\sigma}(Z')$ around the $Z'$ mass peak. For this analysis, the two highest-$p_T$ electrons (with a conservative $p_T$ cut of 15 GeV) have been taken irrespective of their charge. No significant difference has been found between the mass spectra thus obtained and those taking the charge of the electron into account. For an integrated luminosity of $10^5$ pb$^{-1}$ and requiring at least 20 $Z' \rightarrow e^+e^-$ events, the following discovery limits [42] are obtained: EGM: 4 TeV; $E_6$ ($\sin \theta_2 = 0$): 3.4 TeV; $E_8$ ($\sin \theta_2 = -\sqrt{5}/8$): 3.3 TeV; LRM: 3.7 TeV; ALRM: 4.2 TeV.

For the BESS model the discovery limit [43] is strongly dependent on the assumed direct coupling to fermions, as can be seen in Fig. 19. For $b = 0$, the production rate above 1 TeV is too small to observe a signal above SM background. The situation is, however, quite different if there is a small direct coupling to fermions. To evaluate the discovery limit, a detector simulation has been performed using a calorimeter coverage of $\pm3$ in rapidity and a segmentation of $\Delta \eta \times \Delta \phi = 0.06 \times 2\pi/100$. The energy of each particle entering the calorimeter is smeared according to $\Delta E/E = 15%/\sqrt{E} \oplus 2\%$ for electrons and photons, and $\Delta E/E = 50%/\sqrt{E} \oplus 4\%$ for hadrons. Figure 20a indicates
Figure 19: $d\sigma/dm$ as a function of ($e^+e^-$) mass for $m_{V^0} = 0.5, 1.0,$ and $1.5$ TeV (BESS model), assuming $g'' = 13$ and $b = 0 (-0.02)$ shown by the dashed (solid) lines.

that the discovery limit will reach 1.5 TeV only if $b = -0.02$. For a 1 TeV mass, no clear signal is visible after calorimeter simulation if $b = -0.01$ (see Fig. 20b). The electron-finding efficiency in this analysis was about 60%, as inferred from comparing the shaded area with the full one in Fig. 20. A value of $b = -0.02$ for $g'' = 13$ is allowed by present LEP and CDF/UA2 data, and also by future precision measurements at LEP, assuming that within the experimental errors no deviation from the SM is observed. The production and decay of $V^\pm$ in the WZ channel will be discussed in connection with alternative symmetry-breaking mechanisms (see Section 4). The discovery of $V^\pm$ in the leptonic channel looks hopeless because of the small branching ratio into a lepton + neutrino.

Two examples of $e^+e^-$ mass distributions for isoscalar vector bosons are shown in Fig. 21 [44]. The discovery limit for $Y_L$ ranges between 4.1 and 4.5 TeV, depending on $\lambda_y^2$. In the case of the $Y$ vector bosons the discovery limit is strongly $\lambda_y^2$-dependent. For example, for $0.1 < \lambda_y^2 < 0.4$, the limit ranges between 4.2 and 4.7 TeV; for $\lambda_y^2 = 0.68$ (the maximal value allowed) the limit is 3.2 TeV; and if $\lambda_y^2 = 0.03$, it will be very difficult to find a resonance for $m_Y = 2$ TeV with $\Gamma_Y = 800$ GeV. Finally, for the excited $Z^*$ of 1 TeV mass with a branching ratio into electron pairs of 1% and a width of 260 GeV (for $m_{Z^*} = 1.3$ TeV, $\Gamma_{Z^*} = 750$ GeV), the discovery limit will not exceed 1 TeV, as can be seen in Fig. 22 [44].

3.2 Forward–backward asymmetry $A_{FB}$

The rapidity dependence of the forward–backward asymmetry (where F, B of the leptons is defined with respect to the $Z^*$ direction) is expected to show a characteristic distribution for the different models. Provided there is enough statistics at larger rapidities, distinction between the models, or at least classes of models, should therefore be possible. Figure 23 shows the theoretical asymmetry values together with the expected experimental errors for one year of running ($10^8$ pb$^{-1}$) for a $Z^*$ mass of 1 TeV [45]. The $A_{FB}$ distribution for the excited $Z^*$ is very similar to the one obtained from the BESS
Figure 20: Invariant mass distribution of lepton pairs obtained with the BESS model for a) $m_{\nu_\ell} = 1$ TeV, $b = -0.02$, and b) $m_{\nu_\ell} = 1$ TeV, $b = -0.01$. The histogram is without detectors simulation, whereas the shaded area corresponds to the mass distributions obtained after detectors simulation.

Figure 21: Invariant mass distributions of lepton pairs for isoscalar vector bosons $Y$ and $Y_l$. The shaded area is the spectrum obtained after calorimeter simulation.
model, plotted in Fig. 23. In some cases such as B3 (a special $E_6$ model), one expects a clear difference in the $A_{FB}$ distribution compared with LR or BESS. However, making a distinction among $E_6$ models seems more difficult. In order to establish a certain model within $E_6$ it seems necessary to accumulate more than $10^5$ pb$^{-1}$ of integrated luminosity. The experimental requirements for $A_{FB}$ are evident: the sign of the leptons is necessary, and leptons should be measured at least up to $|\eta| = 2.5$.

3.3 Discovery of W' in the W' → ev and W' → WZ → eee channels

The W' discovery potential has been studied within the framework of the extended gauge model [46]. Again, the PYTHIA Monte Carlo program was used for simulation of signal and backgrounds. In Fig. 24a, $\sigma\cdot\text{BR}(W' \rightarrow ev)$ is plotted as a function of $m_{W'}$. For $m_{W'} = 3$ TeV, one expects about 2000 events in the $ev$ channel for $10^5$ pb$^{-1}$. Figure 24b shows the corresponding $\sigma\cdot\text{BR}(W' \rightarrow WZ \rightarrow eee)$ as a function of $m_{W'}$. For this channel the discovery potential is clearly limited by the low rate. The transverse mass is plotted in Fig. 25 for different $W'$ masses with a clearly visible Jacobian peak, expected from $W' \rightarrow ev$ decay, together with the background coming from $W \rightarrow ev$ and $t\bar{t}$ ($m_t = 120$ GeV). The $m_T$ distribution was obtained using the highest-$p_T$ electron in the event and assuming an electron resolution of $\Delta E/E = 15\% / \sqrt{E}$ and $2\%$ and an $E_T^{\text{miss}}$ resolution of $\Delta E_T^{\text{miss}} / E_T^{\text{miss}} = 70\% / \sqrt{E_T}$. A cut on $p_T^e$ and $E_T^{\text{miss}}$ of 180 GeV improves the signal-to-background ratio at low W' masses. However, at higher W' masses a clear signal above background is visible without applying additional selection requirements. The discovery limit for the $W' \rightarrow ev$ channel is 4 to 5 TeV for an integrated luminosity of $10^5$ pb$^{-1}$.
Figure 23: Forward–backward asymmetries as a function of rapidity for different models. Theoretical predictions are shown together with the expected statistical errors for an integrated luminosity of $10^3$pb$^{-1}$.

Figure 24: Cross-section times branching ratios as a function of $W'$ mass for a) $W' \rightarrow e\nu$ and b) $W' \rightarrow WZ \rightarrow e\nu e\nu$ for the extended gauge model.
Figure 25: Transverse mass distributions for a $W' \rightarrow e\nu$ signal of different $W'$ masses from the extended gauge model, and for $W \rightarrow e\nu$ and $t\bar{t}$ background after detector smearing.

The decay chain $W' \rightarrow WZ \rightarrow e\nu e\nu$ has been investigated as well [46]. As mentioned earlier, because of the low rate the discovery limit will not exceed 1 TeV. The background from WZ and $t\bar{t}$ can be kept small, provided that one requires $p_T^Z > 400$ GeV, $m_{ee} = m_Z \pm 3\sigma$, and all three leptons to be isolated. The latter cut is especially efficient in removing the $t\bar{t}$ background; this will be discussed in more detail in the next section.

For minimal left–right models, the discovery limit [47] depends on the mixing angle $\zeta$. For $\zeta = 10^{-3}$, the channel $W^\pm_R \rightarrow W^\pm Z \rightarrow \ell^\pm \nu \ell^\mp \ell^-$, which is well suited to obtaining discovery limits if $W^\pm_R \rightarrow \ell^\pm \nu_R$ is forbidden, allows us to reach a mass limit in the most favourable case of 2.8 TeV before detector simulation for $10^5$ pb$^{-1}$. The background contribution from WZ, investigated on the parton level, is small. The $t\bar{t}$ background is expected to be small also (see discussion in Section 4), and will not prevent a possible discovery of $W^\pm_R \rightarrow W^\pm Z \rightarrow \ell^\pm \nu \ell^\mp \ell^-$. 

4 Alternative Symmetry Breaking

Gauge boson pair production in the presence of a strongly interacting electroweak symmetry-breaking sector has been studied [48] using two different approaches: the BESS model and the DHT model (DHT stands for Dobado, Herrero and Terron).

4.1 The BESS model

In the BESS model [9] the electroweak symmetry breaking is described in a non-linear way, and the most relevant elements of a possible strong electroweak breaking are expected to be contained. In this scheme no Higgs particle is present. A triplet of
new vector resonances $V^\pm$ and $V^0$ are assumed, which are similar to the $\rho$ of QCD or to the techni-$\rho$ of technicolour theories. It is explicitly assumed that the bosons $V$ constitute effective dynamical degrees of freedom. Because of diagonalization of the boson mass matrix, the $V$ particles are expected to mix with $W$, $Z$, and $\gamma$, with a mixing angle of order $g/g''$ ($g''$ being a new gauge-coupling constant introduced in this model). In addition, a possible direct coupling to fermions can be present, specified by the parameter $b$. The detection of $V$ into lepton pairs has already been discussed (see Section 3). In this section the decay of $V$ into pairs of ordinary gauge bosons will be studied. The $ZZ$ mode has not been considered because it does not proceed via an s-channel contribution.

The $V$ bosons are produced through $q\bar{q}$ annihilation and IVB fusion. The process $q\bar{q} \rightarrow V$ depends on the assumed direct coupling of $V$ to fermions, but is still present even in the absence of this direct coupling. The decay of $V$ is dominated by $V \rightarrow WW$ or $WZ$ owing to the large couplings for $(V^0 W_L^+ W_L^-)$ and $(V^\pm Z_L^0 Z_L^-)$. The fusion process, where ordinary bosons are emitted from a quark or antiquark, is expected to be weak in the SM of electroweak interactions. In the BESS model this rescattering of two longitudinally polarized $W/Z$'s proceeds through the exchange of a $V$ boson.

The two production mechanisms have been evaluated for the process $pp \rightarrow W^\pm Z + X$. The observation of a signal in the $W^+W^-$ channel is expected to be impeded by the large background coming from $t\bar{t}$ production. Figure 26 shows an example of the expected signal [9, 49] in the invariant mass distribution for WZ pairs, assuming that $m_V = 1500$ GeV, $g'' = 13$, $b = 0$, and requiring $|\eta_{W,Z}| < 2.5$ and $p_T^Z > 480$ GeV. For the choice of the model parameters, present limits and future limitations from LEP data have been taken into account. Also shown in Fig. 26 are the SM background contributions from WZ production through $q\bar{q}$ annihilation and $\gamma W^\pm$ fusion. For $m_V = 1500$ GeV after optimized cuts ($|y_{W,Z}| < 2.5$, $p_T^Z > 480$ GeV, $m_{WZ} > 1250$ GeV) one
expects a signal of about 36 events over a total background of about 16 events in the \( W_L^\pm Z_L \rightarrow \ell^\pm \nu \ell^+ \ell^- \) channel for \( 10^5 \) pb\(^{-1}\) of integrated luminosity. At the LHC, the \( q\bar{q} \) annihilation contribution to the signal dominates for the mass range considered, and amounts to about 80% for the example shown in Fig. 26 [9, 49].

4.2 The DHT model

In the DHT model [8], the dynamics that governs the symmetry-breaking sector is studied through the scattering of the longitudinal components of the weak bosons based on chiral perturbation theory. This approach incorporates everything that is known about the symmetry-breaking sector. Three possible scenarios have been considered: i) a unitarized SM with a heavy Higgs to one-loop (Higgs-like scenario, \( m_H^2 \gg s \)); ii) a QCD-like scenario, where the longitudinal components of the weak bosons play the role of the pions in QCD; and iii) an underlying theory within the framework of technicolour [50]. The different scenarios can be simulated by choosing the parameters of the effective Lagrangian accordingly.

The most effective way to probe the Higgs-like dynamics is through the \( pp \rightarrow ZZ \) channel; however, signal-to-background ratios never exceed 1 in this case. As discussed above, the WZ channel is the best mode for searching for a signal of a strongly interacting symmetry-breaking sector in the case of a QCD-like or technicolour scenario. The WZ channel has been evaluated in the DHT model under the assumption that the underlying dynamics contains a vector resonance (QCD-like or technicolour scenario). The physical parameters that define this vector resonance (e.g. mass and width) are dependent on the SU(\( N \)) dynamics chosen. A systematic study of the above-mentioned scenarios has been performed, considering the WZ fusion mechanism. However, in SU(\( N_{TC} \)) scenarios it is important to incorporate also the process \( pp \rightarrow W^\pm \rightarrow \rho_{TC} \rightarrow W_L^\pm Z_L \). This annihilation process via \( \rho_{TC} \)–W mixing is described in terms of Vector Meson Dominance. The expected signal in the WZ invariant mass distribution for the technicolour scenario is shown in Fig. 27 for \( m_p = 1500 \) GeV and \( |g_{W,Z}| < 2.5 \). The background processes, also shown in Fig. 27 include WZ production via \( q\bar{q} \) annihilation (65%), \( \gamma W^\pm \) (15%), and \( W^\pm Z \) (20%), this last background being predominantly \( W^\pm Z_T \). For an integrated luminosity of \( 10^5 \) pb\(^{-1}\), one expects for \( m_p = 1500 \) GeV a signal in \( W_L^\pm Z_L \rightarrow \ell^\pm \nu \ell^+ \ell^- \) of about 49 events over a background of about 11 events, requiring \( |g_{W,Z}| < 2.5 \), \( p_T^Z > 300 \) GeV, and \( 1400 < m_{WZ} < 1550 \) GeV. The WZ fusion contributes about 24% to the signal for the example shown in Fig. 27 and the optimal cuts mentioned above. An increase in \( m_p \) results in a larger contribution from WZ fusion. Thus for large enough values of \( m_p \), this process will be the best mechanism for probing the strongly interacting symmetry-breaking sector in a technicolour scenario [50].

4.3 Monte Carlo simulation of signal and background for

\( pp \rightarrow W_L^\pm Z_L \rightarrow \ell^\pm \nu \ell^+ \ell^- \)

We have discussed possible signals of \( W_L Z_L \) pair production in the presence of a strongly interacting electroweak symmetry-breaking sector. In both approaches, the signal and backgrounds have been evaluated with a Monte Carlo simulation on the parton level. However, the potentially large background from \( t\bar{t} \) production has not been evaluated for the two models discussed above.

In order to understand the experimental requirements for observing a possible signal in the \( W_L Z_L \) channel, a Monte Carlo simulation on the particle level has been
Figure 27: WZ invariant mass distribution of the signal and background processes after cuts for the DHT model with $m_\rho = 1.5$ TeV, $N_{TC} = 5$, and $\Gamma_\rho = 185$ GeV. The number of events correspond to $5 \times 10^5$ pb$^{-1}$. The lower solid (dotted) histogram represents the signal from WZ fusion (q\bar{q} annihilation); the total background is the dashed histogram. The upper solid histogram represents the signal plus the total background contributions.

performed [51]. The signal has been evaluated using the PYTHIA program, where the q\bar{q} annihilation (using BESS) and the WZ fusion process (using DHT) have been included. The WZ and t\bar{t} backgrounds were simulated with ISAJET. A t-quark mass of 200 GeV was assumed. For the parameters of the models, the choice was such that for the same mass one obtains the same width for the BESS model and for the DHT model: $m_V = m_\rho = 1$ TeV, $\Gamma_V = 55$ GeV (corresponding to $N_{TC} = 12$, and $g'' = 5.9$) and $m_\nu = m_\rho = 2$ TeV, $\Gamma_V = 480$ GeV (corresponding to $N_{TC} = 3$, and $g'' = 11.7$). For the BESS model, no direct coupling to fermions has been assumed, i.e. $b = 0$, which leads to a more conservative rate estimate. Only the leptonic decays of W and Z have been considered. The dilepton mass spectrum for the signal and the background from WZ and t\bar{t} is shown in Fig. 28, requiring that $p_T^\ell > 20$ GeV, $|\eta_\ell| < 3$, and a lepton resolution of $\Delta p/p = 5\%$. For an integrated luminosity of $4 \times 10^5$ pb$^{-1}$, we can expect about 277 events for the signal, assuming that $m_V = 2$ TeV, 4829 events for $m_V = 1$ TeV, $3.1 \times 10^4$ events from WZ, and $2.9 \times 10^6$ events from t\bar{t} background. A clear mass peak at the Z mass is observed for the signals and for the WZ background in Fig. 28, where all mass combinations are plotted without imposing a sign requirement.

In order to reduce the background, the differences in the topology of signal and background events have been exploited. The signal is expected to have a much harder $p_T^\ell$ distribution compared with the background processes, as can be seen in Figs. 29a,b for $m_V = 1$ TeV and 2 TeV, respectively. These distributions were obtained by imposing a constraint on the lepton-pair mass, $m_{t\bar{t}} = m_Z \pm 3\sigma$, using a lepton resolution of $\Delta p/p = 5\%$ and requiring that $p_T^\ell > 20$ GeV for $|\eta_\ell| < 3$. For a 1 TeV mass, a clear signal is observed at high $p_T^\ell$, coming mostly from the q\bar{q} annihilation process. For a 2 TeV mass, no clear signal is visible, and in this case the fusion process amounts to about half the signal. The main background contribution comes from t\bar{t} production. Imposing
Figure 28: Dilepton mass spectra for $p_T > 20$ GeV and $|\eta_\ell| < 3$. From top to bottom, the histograms show the backgrounds from $t\bar{t}$ and WZ, and the signals from the decay chain $pp \rightarrow V / \rho_T \rightarrow W_L Z_L \rightarrow \ell \nu \ell \ell$, for masses of 1 TeV and 2 TeV.

Figure 29: The $p_T (Z)$ distribution for a signal from $pp \rightarrow V / \rho_T \rightarrow \ell \nu \ell \ell$ for a) $m = 1$ TeV and b) $m = 2$ TeV. The solid histogram represents the total signal, the dashed histogram shows the contribution for WZ fusion only. The stars show the total background from $t\bar{t}$ and WZ production.
a more stringent cut on the lepton-pair mass by requiring better lepton resolution, improves the signal-to-background ratio only slightly. A gain of a factor of about 4 in background reduction is expected if $\Delta p/p = 2\%$ is used instead of $\Delta p/p = 10\%$. However, the $t\bar{t}$ background can be further reduced by requiring $p_T^Z > 400$ GeV and imposing an isolation cut on all three leptons. The signal is expected to have three isolated leptons, whereas in the $t\bar{t}$ case the third lepton has to come from b- or c-quark decay and is therefore not expected to be isolated. The efficiency of reducing the $t\bar{t}$ background via isolation requirements increases with increasing $p_T$ cuts. However, an isolation cut of $\Sigma p_T < 5$ GeV in $\Delta R < 0.2$ around the lepton does not leave enough Monte Carlo statistics to obtain a reliable estimate for the $t\bar{t}$ background contribution—a well-known problem when dealing with cut efficiencies $\ll 1\%$. Therefore a conservative $t\bar{t}$ background reduction of a factor of 50 was used after requiring $p_T^Z > 400$ GeV. This reduction factor has been extrapolated from a study done in the Top Working Group [52].

The result, after imposing a cut of $p_T^Z > 400$ GeV and applying the reduction factor from lepton isolation for the $t\bar{t}$ background, is shown in Figs. 30a,b. For $4 \times 10^3$ pb$^{-1}$, one expects a signal of $2450 \pm 637$ (107 $\pm 27$) events for $m_V = 1$ TeV (2 TeV). The quoted errors are the statistical errors arising from the Monte Carlo generation. For the signal of 1 TeV mass, the fusion process contributes about 6%; for the signal of 2 TeV, 56% are contributed via the fusion mechanism after selection cuts. The total background amounts to $74 \pm 30$ events (64 events from WZ and 10 events from $t\bar{t}$). For $m_V = 2$ TeV, an improvement in signal-to-background ratio is obtained by applying a harder $p_T^Z$ cut. For $p_T^Z > 600$ GeV a signal of $67 \pm 17$ events is expected over a total background of $15 \pm 3$ events. Thus the background can be reduced sufficiently to observe a signal from vector resonances with masses up to 2 TeV, provided the integrated luminosity exceeds $10^8$ pb$^{-1}$ [51]. It should be noted that the stringent cuts on $p_T^Z$ are imposed to obtain the final signal-to-background ratios. However the full $p_T^Z$ range has to be measured experimentally, in order to see a clear Jacobian peak or an excess at
high $p_T^2$ over the SM background.

At the LHC, we can explore a possible strong electroweak symmetry-breaking sector if the underlying dynamics contains a vector resonance as predicted in the technicolour scenario or in the BESS model. A clear signal can be expected in the Jacobian peak of the $p_T^2$ distribution for $m_V = m_g = 1$ TeV. To reach a 2 TeV mass scale for these new resonances, a luminosity $L > 10^{34}$ cm$^{-2}$ s$^{-1}$ is required, in order to observe the expected enhancement at high transverse momentum of the $p_T^2$ spectrum.

5 Conclusions

Within the framework of the Minimal Supersymmetric Standard Model, gluino and squark signatures—clearly a domain for hadron colliders—have been studied including the complex decay chains via charginos and neutralinos. For the ($E_T^{\text{miss}} + n$ jet) signature, the SM background can be sufficiently reduced by using cuts on $E_T^{\text{miss}}$, on jet multiplicity, and on event topology. Given the uncertainties involved for signal and background, it is difficult to quote exact ‘discovery limits’. With the selection cuts applied for the ($E_T^{\text{miss}} + n$ jet) signature, acceptable event rates for gluino and squarks are obtained for masses up to about 1 TeV for one year of running at $L = 10^{33}$ cm$^{-2}$ s$^{-1}$. In the gluino case, the study was extended down to $m_g = 300$ GeV, resulting in a signal-to-background ratio of 13:1. To establish a signal for low gluino masses, contributions from jet mismeasurements to the $E_T^{\text{miss}}$ signature have to be taken into account owing to the softer $E_T^{\text{miss}}$ spectra for the signal. Preliminary studies indicate that this additional background can be kept small, provided there is a calorimeter rapidity coverage of $|\eta| > 4.5$. Pile-up seems to have only a small effect on the selection efficiencies; therefore, extrapolation to high-luminosity running is feasible. Cascade decays offer the possibility of many different signatures. In the case of gluino pair production, the $ZZ \to \ell\ell\ell\ell$ final state has been studied for large gluino masses. Small event rates are expected, but with negligible background.

Searches for electroweak sparticles are more difficult at hadron colliders owing to the low cross-section and large background from SM, in particular from t-quark production. However, the effort to find ways of extracting signals for electroweak sparticles should continue, because relatively low bounds on their masses translate into rather stringent bounds on the supersymmetric particle spectra. It should be also mentioned that, in the time available, it was not possible to fully optimize the event selections, and further improvements in signal-to-background ratios for sparticle searches are certainly possible in all cases.

Broken R-parity could be a possible extension of the MSSM. New signatures are expected in this case, arising from the possibility of single-sparticle production and from decays of the LSP. A variety of new signals emerge: some seem to be a priori very difficult to extract (e.g. LSP $\to$ 3 quarks); some have a fair detection possibility; some provide a rather spectacular signature (e.g. LSP $\to$ $e^+\mu^-\nu$), which makes it possible to establish a clear signal above background. This was demonstrated for the example of $gg \to \bar{q}q\chi_1^0, q\bar{q}\chi_1^0 \to q\bar{q}q\bar{q}e^+\mu^-\nu e^+\mu^-\nu$, assuming a gluino mass of 300 GeV. These initial results are promising, and more detailed signal and background evaluations would be desirable.

The observation of new heavy vector bosons ($Z', W'$) will be the necessary input for establishing higher symmetries. The discovery potential for new vector resonances decaying into lepton pairs is very high at hadron colliders. The discovery limit depends
on the assumed model parameters. Many different models have been studied, ranging from ‘simple’ extensions of the gauge group of the SM to the concept of a strongly interacting electroweak symmetry-breaking sector. For an integrated luminosity of $10^5$ pb$^{-1}$ and requiring at least 20 $Z' \rightarrow e^+e^-$ events, one obtains a discovery limit of 4 TeV for the extended gauge model and 4.2 TeV for the alternative left–right model. These are examples of the ‘maximal’ mass reach for a $Z'$ expected in the electron channel. Similar limits are obtained for the $W' \rightarrow e\nu$ decay using the extended gauge model. The $W_R$ mass reach is, in the most favourable case, about 2.8 TeV, obtained in the $W^+_R \rightarrow W^+Z \rightarrow \ell^+\nu\ell'^+\ell'^-$ channel and assuming that $W^+_R \rightarrow \ell^+\nu_R$ is forbidden.

The physics background to the new vector bosons is expected to be small for the lepton channel, even with the very conservative selection cuts used in establishing a signal. The rapidity dependence of the forward–backward asymmetry should allow us to distinguish between models, or at least classes of models, predicting a heavy neutral vector boson. For the $A_{FB}$ measurement, the sign of the leptons is necessary, and leptons should be detectable up to $|y| = 2.5$. To reduce the statistical errors for $A_{FB}$ at large $y$-values, high luminosity is desirable.

One of the main physics goals of the LHC is the understanding of the nature of electroweak symmetry breaking. The symmetry sector typically should be either a weakly interacting system with a Higgs particle below 1 TeV or a strongly interacting system with mostly the longitudinal components of the weak bosons $W$ and $Z$. Gauge boson pair production in the presence of a strongly interacting electroweak symmetry-breaking sector has been studied using two different approaches. In the BESS model, a triplet of new vector resonances is used, similar to the $\rho$ of QCD or the techni-$\rho$. No Higgs particle is present in this scenario. The second approach is based on chiral perturbation theory. Scenarios with scalar resonances (Higgs-like) or vector resonances (QCD-like, or technicolour-like) can be simulated by choosing the parameters of the effective Lagrangian accordingly. A signal above background can be established in the $W^+_R Z_L \rightarrow \ell^+\nu\ell'^+\ell'^-$ channel for masses up to 2 TeV if the underlying dynamics contains a vector resonance and if $L > 10^{24}$ cm$^{-2}$ s$^{-1}$. Lepton isolation requirements are necessary in order to reduce the $t\bar{t}$ background sufficiently in the case of a 2 TeV vector resonance.

With the high-luminosity option at the LHC we can therefore explore the symmetry-breaking sector: if it is a scalar resonance (Higgs particle of the SM) up to $\leq$ 1 TeV; if it is a strongly interacting system with a vector resonance (as predicted in technicolour scenarios or in the BESS model) up to 2 TeV. Therefore, an analysis of the $ZZ$ and $WZ$ channel at the LHC should help us to understand the nature of the symmetry-breaking sector.

Although the most exciting discoveries will be those of totally unexpected new particles, we can only prepare experiments for discovering anticipated new particles. However the experiments designed under these considerations should allow us to discover whatever nature will offer us.

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