LOOKING BEYOND THE STANDARD MODEL

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Abstract

Within the framework of the Standard Model, the scale of electroweak symmetry breaking is unstable to radiative corrections. We discuss two broad classes of models of new physics (one with a strongly interacting and the other with a perturbatively coupled electroweak symmetry breaking sector) in which this stability is restored. After reviewing experimental constraints on these, we discuss the implications of these types of models for experiments, both at currently operating colliders as well as the next generation of colliders under consideration for construction. Other extensions of the Standard Model are briefly alluded to.

\footnote{Invited Talk, presented at the Physics in Collision Conference, Tallahassee, Florida, June, 1994}
1 The Status Of The Standard Model

1.1 Experimental Report Card.

It has become standard practice to begin such a review by showering praise upon the Standard Model (SM), which has indeed been spectacularly successful in accommodating a wide variety of experimental data. As discussed by Olchevski\[1\] at this meeting, the results from experiments at LEP shown in Table 1 appear to be in remarkable agreement with the SM.

Table 1: Summary of experimental electroweak measurements and corresponding SM fits from Ref. \[1\]. The last entry is from Ref. \[2\]. The entry in the last column represents the difference between the measured and fitted values, expressed as the number of standard deviations.

| Observable | Measurement | SM fit | Pull |
|------------|-------------|--------|------|
| **LEP**    |             |        |      |
| \(M_Z\) (GeV) | 91.1895 ± 0.0044 | 91.192 | 0.6 |
| \(\Gamma_Z\) (GeV) | 2.4969 ± 0.0038 | 2.4967 | 0.1 |
| \(\sigma_h^0 (nb)\) | 41.51 ± 0.12 | 41.44 | 0.6 |
| \(R_\ell\) | 20.789 ± 0.04 | 20.781 | 0.2 |
| \(A_{FB}^{0,\ell}\) | 0.0170 ± 0.0016 | 0.0152 | 1.1 |
| \(A_{\tau}(\tau \text{ pol.})\) | 0.150 ± 0.010 | 0.142 | 0.8 |
| \(A_{e}(\tau \text{ pol.})\) | 0.120 ± 0.012 | 0.142 | 1.8 |
| \(R_b\) | 0.2208 ± 0.0024 | 0.2158 | 2.0 |
| \(R_c\) | 0.170 ± 0.014 | 0.172 | 0.1 |
| \(A_{FB}^{0,b}\) | 0.0960 ± 0.0043 | 0.0997 | 0.8 |
| \(A_{FB}^{0,c}\) | 0.070 ± 0.011 | 0.071 | 0.1 |
| \(\sin^2 \theta_{\text{lept}}^\text{eff} \text{ from } q\bar{q} \text{ charge asymm.}\) | 0.2320 ± 0.0016 | 0.2321 | 0.1 |
| **pp and \(\nu N\)** |             |        |      |
| \(M_W\) (GeV) | 80.23 ± 0.18 | 80.31 | 0.4 |
| \(1 - \frac{M_W^2}{M^2} (\nu N)\) | 0.2256 ± 0.0047 | 0.2246 | 0.2 |
| **SLC** |             |        |      |
| \(\sin^2 \theta_{\text{eff}} \text{ pol. asymm.}\) | 0.2292 ± 0.0010 | 0.2321 | 2.7 |

Of the twelve quantities measured at LEP, only \(R_b = \frac{\Gamma(b\bar{b})}{\Gamma(\text{had})}\) deviates from the SM fit by 2\(\sigma\). Since there is a probability of about 5\% that any measurement will yield a 2\(\sigma\) deviation, the probability that the twelve independent LEP measurements will all agree to within 2\(\sigma\) is about 54\% (or slightly larger, depending on how one counts input parameters). The conservative would thus say that there is essentially a 50-50 chance that at least one of the LEP measurements would show such a deviation, and so, would conclude that there is no problem whatsoever at the present time, pointing also to the \(M_W\) and neutrino scattering measurements in Table 1 which are in agreement (within larger errors) with the SM.

The radical scientist\[2\] on the other hand, would point to the polarization asymmetry measurement\[3\] at the SLC and conclude that this, together with the measurement of \(R_b\) and \(A_e\) (from \(\tau\) polarization) at LEP, provide evidence for physics beyond the SM. To bolster these arguments, one could refer to the model-independent analysis of \[3\] where the (oblique)

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2The extremist would counter the conservative as follows: Any theory that agrees with all the experimental data has to be erroneous, since at any given time some of the experimental data are wrong. We will, of course, disregard such an extreme view.
corrections from any new physics, assuming that the new physics scale is well-separated from $M_Z$, are parametrized in terms of just three parameters S, T and U which are all zero in the SM. Indeed the radical would emphasize that $S < 0 \ (2\sigma)$. Are there other hints of deviation from the SM? We have heard from Kuhlmann that, generally speaking, perturbative QCD appears to be working well. The only aberration reported appears to be an excess of $p_T < 30$ GeV photons in direct photon production at CDF (which suggests a $k_T$ smearing of the initial state). The CDF measurement of the cross section for direct $\psi'$ production, which is 20-30 times the present theoretical estimates, may also be worth watching. Whether this measurement (if it holds up) signals an unthought-of production mechanism, or something deeper, only time will tell. On the neutrino front, the recent observations of the appearance of $\bar{\nu}_e$ in the LSND experiment, or the zenith angle dependence of the $\nu_\mu$ to $\nu_e$ ratio in the Kamiokande experiment both point to neutrino mixing, and hence, a mass for neutrinos. While this can be readily accommodated within the SM framework, the structure of the neutrino mass matrix may help further our understanding of fermion masses, or perhaps, provide clues about physics (new intermediate scales, see-saw neutrino masses, or something else) at higher scales. To my knowledge, the only other “clear discrepancy” is an old one; viz. the lifetime of orthopositronium is too short; if confirmed, this would be really revolutionary as it would signal a departure from QED!

1.2 Theoretical Report Card.

While it seems fair to say that the SM is in remarkable agreement with experiment, it leaves many items on the theorist’s wish-list unexplained.

- The replication of generations and the (perhaps, related issue of) patterns of fermion masses (strongly constrained by the absence of flavour-changing neutral currents(FCNC)) remains unexplained.

- The choice of the gauge group and the values of the three gauge couplings remain arbitrary.

- There is no explanation (although there is a beautiful parametrization) for the origin of CP violation.

- The dynamics of electroweak symmetry breaking (EWSB) is completely unknown.

- Finally, and most strikingly, gravitation is not incorporated.

There are no good answers to most of these issues. It is quite likely that an understanding of these will come from knowledge of physics at very high (and as yet unexplored) energy scales. The Grand Unification hypothesis is a beautiful idea which, by enlarging the gauge group and particle multiplets, leads to testable predictions for the relative strengths of the three gauge couplings, and also for certain ratios of fermion masses. The precise measurements of the gauge couplings at LEP, it is by now well known, are not compatible with the simplest Grand Unified model based on SU(5). This can be “fixed up”, for instance, by introducing new scalars with appropriate lepto-quark quantum numbers; this modifies the gauge coupling evolution so as to restore unification but is obviously completely ad hoc. It is, however, very interesting that the measured values of gauge couplings are compatible with Grand Unification.

\footnote{If the new physics scale is close to $M_Z$, the corrections can no longer be parametrized in terms of just S,T and U. Fits including additional parameters would then make the S-parameter consistent with zero, within the resulting larger error.}
within the context of the minimal model of low energy supersymmetry which, as we will discuss later, is introduced for very different reasons.

Despite the fact that the new physics of Grand Unified Theories (GUTs) is all at an energy scale \( > 10^{15} \) GeV, GUT models make striking predictions, the most generic of which is the instability of the proton. Also, in all but the simplest models \( B - L \) is not conserved, and \( n\bar{n} \) oscillations are possible. Finally, the multiplet structure of models with a gauge group larger than SU(5) includes singlet neutrinos, so that non-vanishing neutrino masses and non-trivial neutrino mixing patterns may be anticipated. We will not review the stringently constrained phenomenology of GUT baryon number violation here but refer the reader to the literature\[12\]. Implications of neutrino masses and mixing for the solar and atmospheric neutrino anomalies\[13\] as well as for neutrinoless \( \beta\beta \) decay\[14\] have been discussed at this meeting and will not be repeated. We will also not discuss the implications (or non-implications) of GUTs for the observed matter anti-matter asymmetry in the universe\[15\], but turn instead to EWSB in the SM.

Within the framework of the SM, EWSB is realized by introducing a doublet of spin zero fields which acquire a vacuum expectation value, resulting in the spontaneous breakdown of \( SU(2) \times U(1) \). The signature of this mechanism is an elementary spin zero particle, the Higgs boson, in the physical spectrum. Perturbative unitarity arguments dating back twenty years\[16\] suggest that the Higgs boson cannot be much heavier than 700-800 GeV, provided, of course, that perturbation theory is valid. An even stronger bound, \( m_H \sim 220 \) GeV can be obtained\[17\] by requiring that the running Higgs self-coupling remains perturbative all the way up to the GUT scale\[4\]. Unlike spin-\( \frac{1}{2} \) and spin-1 particles whose masses can be protected by chiral and gauge symmetries, respectively, there is no known symmetry that protects the mass of a spin-0 particle in a generic quantum field theory. Formally, this manifests itself as a quadratic divergence in one-loop quantum corrections to the Higgs boson mass, when these are computed using the SM framework. These loop integrals ought to be cut off at a scale \( \Lambda \) beyond which the SM is invalid, either because new degrees of freedom (\( e.g. \) additional fields in GUTs) not included in the SM manifest themselves, or due to form factor effects. We may thus expect, \( \delta m_H^2 \sim g^2 \Lambda^2 \), where the dimensionless coupling \( g \sim O(1) \). We see that if \( \Lambda \sim M_{GUT} \) (or \( M_{Planck} \)), a Higgs mass below \( \sim 800 \) GeV can only be obtained by adjusting the bare Higgs mass term, order by order in perturbation theory, with uncanny precision. Although there is nothing logically wrong with such a procedure, it is an ugly feature of the SM, often referred to as the fine-tuning problem. There are two broad ways out of this conundrum. Either

- the symmetry breaking interactions become strong at a scale \( \Lambda \lesssim 1 \) TeV, and that form factors cut off the loop integrals at the scale \( \Lambda \), or
- new elementary degrees of freedom not included in the SM manifest themselves at a scale \( \Lambda \lesssim 1 \) TeV, thereby vitiating the SM estimate of \( \delta m_H^2 \). In this case, the EWSB sector could be weakly coupled.

Assuming that we do not accept the possibility of fine-tuning, we infer that an exploration of the TeV energy scale must reveal new physics in some form. Our arguments do not fix what this new physics might be. If the EWSB sector is strongly coupled, the new physics may reveal itself as resonance states of new elementary quanta. Technicolour, to be discussed in the next section, is an illustration of such a scenario. The only known\[5\] realization of a weakly coupled

\[^{4}\text{This is also the origin of the upper bound of 140-150 GeV on the light Higgs boson in supersymmetric models\[18\].}\]

\[^{5}\text{Of course the possibility that some other mechanism will be discovered in the future remains open.}\]
EWSB sector without fine-tuning problems is weak scale supersymmetry (SUSY), discussed in Sec. 3. In this case, contributions to $\delta m_H^2$ from sparticles in loops cancel the offending SM contributions, thereby alleviating the fine-tuning issue.

There are many other extensions of the SM that have been considered in the literature. These include new quarks or leptons (sequential or otherwise), new gauge bosons, lepto-quarks, coloured exotics and doubly-charged scalars, to name a few. While there is no reason why these should not occur in nature, their existence does not shed light on any pressing theoretical issue. Also, unlike the case of Technicolour or low energy SUSY just discussed, the mass scale for these is essentially arbitrary. We will refer to such exotica as Optional New Physics. For reasons of space and time, we will not discuss these in any detail but will only touch on experimental constraints on these in Section 4.

2 Strongly Coupled Electroweak Symmetry Breaking

We first consider the case where the new physics implied by our analysis of the symmetry breaking sector of the SM consists of new strong interactions between the quanta of this sector. These are expected to manifest themselves as strong interactions in $V_L V_L$ scattering at high energy, since $V_L$, the longitudinal component of $W$ and $Z$ bosons is dominantly composed of quanta of the EWSB sector. These new strong interactions, if we are lucky, may also lead to formation of new resonance states which may be accessible at future colliders.

No one has been able to come up with a convincing and phenomenologically acceptable model in which electroweak symmetry is dynamically broken. One practical problem with all such scenarios is that the strong interactions make it difficult to perform dynamical calculations. Quite aside from this, the nature of the strong interactions that drive EWSB is unknown, except that they must respect a custodial symmetry in order to yield $\rho = \frac{M_W}{M_Z \cos \theta_W} \simeq 1$.

A conceptually beautiful idea goes under the name of Technicolour[10]. It is hypothesized that there are new (weak iso-doublet) fermions (dubbed Techni-fermions) that interact with one another via chirally symmetric Technicolour gauge interactions, in much the same way that ordinary quarks interact via QCD. Just as chiral symmetry between quarks is broken at a scale where QCD interactions become strong, it is assumed that the Technicolour interactions cause a condensate of Techni-fermions, but with a scale $\sim 3000\Lambda_{QCD}$, resulting in a (Techni-) chiral symmetry breakdown and the corresponding Goldstone boson, analogous to the pion in QCD. The self energy function of the electroweak vector bosons thus develops a dynamical pole at $k^2 = 0$, thereby giving non-zero masses to the $W$ and $Z$ bosons[20], together with the correct value of $\rho$.

Since ordinary fermions do not couple to Technicolour, their chiral symmetry prevents them from acquiring masses along with the vector bosons. In order to give masses to these, new extended Technicolour (ETC) gauge interactions that couple ordinary fermions ($f$) to Techni-fermions ($F$) need to be postulated[21]. The ETC gauge bosons convey the news of chiral symmetry breaking in the Techni-fermion sector to the ordinary fermions, which then develop masses as shown in Fig. 1. We find,

$$m_f \sim \frac{g^2_{ETC}}{M^2_{ETC}} \times <...>, \quad (1)$$

where $g_{ETC}$ is the ETC gauge coupling, $M_{ETC}$ the mass of the ETC gauge boson, and $<...>$ is the dynamics-dependent Technicolour condensate which is a measure of chiral symmetry

6Other resonances, with quantum numbers of the observed particles, but masses generically in the TeV range will also be present. A problem is that often complicated Technicolour models admit additional pseudo-Goldstone bosons with masses $O(10 GeV)$, and hence, are excluded by colliders searches.
Figure 1: A diagramatic representation of how ETC bosons ($V_{ETC}$) convey the information about chiral symmetry breakdown in the Techni-fermion ($F$) sector to the ordinary fermions ($f$), thereby inducing a mass ($m_f$) for these. The cross denotes the Technicolour condensate which is the order parameter for the chiral symmetry in the Techni-fermion sector.

breaking in the Techni-fermion sector. The ETC interactions must distinguish between ordinary fermion flavours in order to account for the wide range of quark masses observed in nature. This is dangerous\cite{22} because these ETC interactions can then induce interactions of the form,

$$\frac{g_{ETC}^2}{M_{ETC}^2} (\bar{s}\gamma^\mu d)^2,$$

which are strongly constrained by the $K_L-K_S$ mass difference. In the simplest case where Technicolour dynamics is assumed to be identical (except for scale) to QCD dynamics, a value of $\frac{g_{ETC}^2 M_{ETC}}{}$ large enough to produce masses of $O(10-100 \text{ MeV})$ for down and strange quarks is incompatible with FCNC constraints. The second strike against these models, is that they give\cite{3} (assuming QCD-like Technicolour dynamics) $S \simeq +1$ which is excluded, at the 4$\sigma$ level, by the data. It is also unclear whether it is possible to accommodate a large top-bottom mass splitting without inducing unacceptably large corrections to the $\rho$ parameter.

Walking Technicolour\cite{23} models were invented to alleviate the incompatibility between quark masses and FCNC constraints. In these models, the dynamics is arranged so that the renormalized condensate in Eq. (1) is enhanced relative to its naive value, thereby allowing for larger fermion masses for a fixed value of $\frac{g_{ETC}^2 M_{ETC}}{}$. It has been argued\cite{24} that these models may be able to accommodate smaller (or even negative) values of the Peskin-Takeuchi $S$-parameter. The real problem with all Technicolour models probably comes from the measured value of the $\bar{b}b$ branching fraction of the $Z$. The point is that the same ETC gauge boson that is responsible for the $t$-quark mass also contributes a correction\cite{25},

$$\frac{\delta \Gamma(\bar{b}b)}{\Gamma(\bar{b}b)} \simeq -3.7\% \frac{m_t}{100 \text{GeV}} \xi^2,$$

where $\xi$ is a Clebsch of order unity. We see that this correction tends to reduce $R_b$ from its SM value by about 5% if the top quark is heavy. Numerical estimates\cite{26} show that while the magnitude of these corrections can be made smaller in Walking Technicolour scenarios, they are generally large enough to impact on the LEP measurements. Since, as shown in Table 1, the measured value of $R_b$ is already higher than its SM expectation, this measurement, if it holds up, could create a serious problem for such scenarios.

We thus conclude that the Technicolour idea, where ETC interactions are responsible for fermion masses seems to be strongly disfavoured by experiment. It could, of course, be that while Technicolour is indeed responsible for EWSB and gauge boson masses, the origin of fermion masses lies elsewhere. Nevertheless, it is fair to say that no phenomenologically viable
model of dynamical EWSB has as yet emerged. On the other hand, because detailed dynamical consequences of strongly coupled theories are difficult to compute with present day techniques, it is impossible to absolutely exclude the Technicolour paradigm. Finally, it could, of course, be that there is indeed a strongly coupled EWSB sector, but that the specific realization of this provided by Technicolour is incorrect.

These inherent uncertainties have led many authors to adapt methods of chiral dynamics to explore the implications of a strongly coupled EWSB sector. It is conservatively assumed that the effects of any new physics, whether it is Technicolour resonances, a heavy scalar resonance, or something else, cannot be directly explored at energies that will be experimentally accessible, but may be indirectly observable in the scattering of longitudinal W and Z bosons. The starting point of this approach is the (non-renormalizable) momentum expansion of the effective Lagrangian that describes Goldstone boson scattering, the first term of which yields a model-independent contribution to the Goldstone boson scattering amplitude in agreement with low energy theorems. This amplitude is unitary only up to a scale Λ at which effects of other physics become significant; these effects are embodied in the (model-dependent) non-renormalizable terms in the effective Lagrangian. For values of s such that $M_W^2 \ll s \approx M_Z$, the equivalence theorem then tells us that the model-dependent, unitarized Goldstone boson amplitudes are a good approximation to longitudinal vector boson scattering amplitudes via which effects of a strongly coupled EWSB may be indirectly searched for.

How does one study vector boson scattering? In high energy hadron ($e^+e^-$) collisions, W and Z bosons can be radiated from the initial state quarks (leptons) in much the same way that these radiate photons. It is the elastic scattering of the vector bosons that is used to probe the EWSB sector. Bagger et. al.\cite{27} have studied the signal from $V_LV_L$ ($V = W, Z$) scattering at hadron supercolliders. They have focussed on the signal where the vector bosons decay leptonically to eliminate backgrounds from QCD jets. Then, the main backgrounds come from $V_TV_T$ and $V_LV_T$ production, which has the same kinematical characteristics as the signal, and in the case of $W_L^+W_L^-$ scattering, also from $tt$ production. As one might imagine, very stringent cuts discussed in Ref.\cite{27} are needed to sort out the signal from background. It is not our purpose here to address the details of these computations. We will content ourselves by presenting sample results together with a few remarks.

A sample of some results obtained in Ref.\cite{27} are illustrated in Table 2, where the background and signal rates at a 16 TeV $pp$ collider in various $VV$ scattering channels is shown after experimental cuts. The various columns refer to different unitarization schemes, so that the variation of the signal in the last five columns is indicative of theoretical uncertainties. We should mention that additional unitarization schemes (not shown here for brevity) have been considered in Ref.\cite{27} to which we refer the reader for further details. Yet another scheme has been discussed in Ref.\cite{28}. The unitarization models considered here are, the SM with $m_H = 1$ TeV, a model with an s-channel scalar isoscalar resonance with a mass of 1 TeV and width 350 GeV, an s-channel vector-isovector resonance (like the Techni-rho) with $M = 2$ TeV and $\Gamma = 700$ GeV, and finally, two non-resonant models where the amplitudes obtained from the low energy theorems are unitarized by cutting them off at the unitarity bound following Ref.\cite{29}(LET CG), or using the K-matrix method. It has been claimed that there is a statistically significant signal which should be visible above the background in at least one of the channels after two years of LHC running with a luminosity of 100 fb$^{-1}$ for all the models considered. We note, however, that the event rate is frequently very small — a few events per 100 fb$^{-1}$ at the LHC. Even if it can be argued that the physics backgrounds have been carefully analysed, the smallness of the

\footnote{In some models, amplitudes are really unitary. In other models, unitarity is only assured up to an energy scale of a few TeV, which is fine for practical purposes.}
Table 2: Signal event rates per 100 $fb^{-1}$ at a 16 TeV $pp$ collider for $m_t = 140$ GeV, with cuts given in Ref.[27] for several models discussed in the text. The Table is adapted from Ref.[27].

| Channel | Bkgd | SM | Scalar | Vec 2.0 | LET CG | LET K |
|---------|------|----|--------|---------|--------|-------|
| $ZZ$    |      |    |        |         |        |       |
| $M_{ZZ} > 0.5$ | 1.0  | 14 | 7.5    | 1.4     | 2.5    | 2.2   |
| $M_{ZZ} > 1.0$ | 0.1  | 3.9 | 2.7    | 0.4     | 1.1    | 0.9   |
| $W^+W^-$ |      |    |        |         |        |       |
| $M_{ll} > 0.25$ | 18   | 40 | 26     | 8       | 9.2    | 7.2   |
| $M_{ll} > 0.5$  | 15   | 32 | 21     | 7.4     | 8.3    | 6.3   |
| $W^+Z$   |      |    |        |         |        |       |
| $M_T > 0.5$  | 2.4  | 1.0 | 1.4    | 4.8     | 3.2    | 2.9   |
| $M_T > 1.0$  | 0.3  | 0.3 | 0.4    | 3.3     | 1.6    | 1.4   |
| $W^+W^+$  |      |    |        |         |        |       |
| $M_{ll} > 0.25$ | 6.2  | 9.6 | 12     | 12      | 27     | 24    |
| $M_{ll} > 0.5$  | 1.7  | 3.7 | 5.2    | 4.8     | 16     | 14    |

Signals should cause worry about reducible, detector-dependent backgrounds. Other significant concerns might be how long it would actually take the LHC experiments to accumulate 200 $fb^{-1}$ of data, and whether it will be possible to effectively implement the stringent cuts of Ref.[27] in the high luminosity LHC environment. It is worth mentioning that a study of these signals is the one area where the SSC had a clear advantage over the LHC. The design energy of the LHC has been reduced from 16 TeV in Table 2 to 14 TeV. Reducing it further would certainly make physics discovery in this channel extremely difficult. Indeed, untangling this signal, if nature has indeed chosen the strongly coupled EWSB sector option with no accessible new resonance states, will be a real challenge for our experimental colleagues.

The feasibility of detecting departures from a weakly coupled EWSB sector by studying $V_LV_L$ scattering at linear $e^+e^-$ colliders has also been investigated. We will not discuss this in detail but will refer the reader to the review in Ref.[30]. Here, the clean environment makes it possible to use the hadronic decay modes of the $W$ and $Z$ bosons, but has the disadvantage that $W^\pm_W^\pm_W^\mp$ scattering amplitudes, which could help sort out dynamical issues, are not accessible. Since only a small fraction of energy goes into $V_LV_L$ scattering, the signal rates are small, and frequently, comparable to background. A 1.5 TeV collider with an integrated luminosity of $\sim 200$ $fb^{-1}$ is the minimum that is required to be able to probe this physics. In addition, it is important to be able to distinguish hadronically decaying $W$ and $Z$ decays in order to be able to examine the underlying dynamics by separating $W^+W^-$ and $ZZ$ processes.

Finally, we briefly remark on the feasibility of studying strong $V_LV_L$ scattering at $\gamma\gamma$ colliders. It has been known for some time that the signal processes $\gamma\gamma \rightarrow W_LW_L, Z_LZ_L$ are swamped by backgrounds[31] from $\gamma\gamma \rightarrow W_TW_T, Z_TZ_T$ reactions. Very recently, it was pointed out[32] that in high energy collisions, photons may radiate $W_L$’s in the same way that they are radiated from electrons and positrons at Linear Colliders, except, of course, that the $W$ radiation from photons must occur in pairs. The idea then is to use the luminosity of $W_L$’s in resolved photon collisions to study the $W_L^+W_L^+ \rightarrow W_L^+W_L^+, W_L^+W_L^- \rightarrow W_L^+W_L^-, Z_LZ_L$ scattering amplitudes by tagging the two spectator $W$ bosons to eliminate backgrounds from $\gamma\gamma \rightarrow W_TW_T, Z_TZ_T$ processes. With an integrated luminosity of 100 $fb^{-1}$ and an overall efficiency of about 10%, a preliminary study[33] suggests that a signal should be observable in 1.5 TeV $\gamma\gamma$ collisions. Somewhat less optimistic conclusions have been obtained by Jikia[34] who has incorporated a realistic photon spectrum into the analysis.
3 Weakly Coupled Electroweak Symmetry Breaking: Low Energy SUSY

3.1 Motivation and Framework

If there are no strong interactions in the EWSB sector, then the unwanted large SM corrections to the Higgs boson mass discussed in Sec. 1 must be cancelled by other corrections from new physics that must enter by the TeV scale. This cancellation, between SM loop contributions and additive new physics contributions need not be exact, but must be good to many significant figures in order that two contributions, each of \(O(\Lambda^2)\) (recall that \(\Lambda\) could have been as large as \(M_{GUT}\) or even \(M_{Planck}\) without the intervention of new TeV scale physics), conspire to yield a result \(\sim (100 \text{ GeV})^2\). It is our prejudice that such a precise cancellation cannot be accidental, but must result from a symmetry between SM physics and the new physics in question. Since bosonic and fermionic loops contribute with opposite signs to \(\delta m^2_H\), such a cancellation is possible in a theory that contains bosons and fermions, with masses and couplings to the Higgs boson related in a way that provides this cancellation. Notice that a symmetry that accomplishes this differs from all known symmetries (e.g. gauge symmetries, Lorentz invariance, etc.) in that it relates properties of bosons and fermions. Such a symmetry is called a supersymmetry.

Low energy supersymmetry provides the only known way of incorporating elementary scalar bosons into the SM, without the need for fine-tuning order by order in perturbation theory. The idea is that for each “quadratically divergent” contribution from a SM boson (fermion) loop, there is a corresponding contribution from a loop with a new fermion (boson), the supersymmetric partner of the SM particle which cancels against it. One may wonder how this comes about when the loop integrals depend on the masses and the couplings of the various particles. The point is that supersymmetry implies the particles and their superpartners have exactly the same masses and couplings (aside from Clebsch-Gordan factors). This is, of course, unacceptable on phenomenological grounds since the SUSY partners of at least the charged particles would have long since been discovered. Fortunately, these cancellations need not be exact. Since it suffices to arrange matters so that

\[
\delta m^2_H \lesssim (1 \text{ TeV})^2,
\]

we need only to require,

\[
m^2_{\text{sparticle}} - m^2_{\text{particle}} \lesssim (1 \text{ TeV})^2. \tag{3}
\]

Eq. (3) provides the rationale for TeV scale supersymmetry. Within this framework, a weakly coupled EWSB sector can be stable to radiative corrections provided only that sparticle masses are smaller than about 1 TeV. These sparticles may be then be detectable at the next generation of high energy colliders.

The simplest supersymmetric extension of the SM, known as the Minimal Supersymmetric Model (MSSM), may be obtained by a direct supersymmetrization of the SM. For every chiral fermion \((f_i, i = L, R)\) in the SM, there is a spin zero particle \(\tilde{f}_i\) (the squarks and sleptons, collectively referred to as sfermions) with the same colour and electroweak quantum numbers. Any \(\tilde{f}_L - \tilde{f}_R\) mixing is proportional to the corresponding fermion mass, and hence, is negligible except for top squarks. We will also ignore any flavour mixing between squarks and, therefore, assume that the the sleptons (\(\tilde{\ell}_i\)) and squarks (\(\tilde{q}_i, q \neq t\)) are also mass eigenstates. Notice that gauge symmetry completely fixes the gauge interactions of these sfermions. Turning to the

\(^8\text{Since the particles and their superpartners have the same gauge quantum numbers, it is not possible to identify SM bosons and fermions as superpartners of one another.}\)
gauge sector, spin-\(\frac{1}{2}\) gauginos, in the adjoint representation of the gauge group, are the SUSY partners of the gauge bosons. These include the colour octet gluino (\(\tilde{g}\)), the charged winos, and the neutral photino and the zino. Because it is not possible to simultaneously couple fermions to both the Higgs field and its complex conjugate in a manner consistent with supersymmetry, even the simplest SUSY extension requires two doublets that acquire vacuum expectation values (vevs) in order to give masses to both up and down type quarks. After the Higgs mechanism, two neutral scalars \(H_\ell\) and \(H_h\), a pseudoscalar \(H_p\) and a pair of charged scalars \(H^\pm\) are left over in the physical spectrum. The spin \(\frac{1}{2}\) SUSY partners of the two Higgs boson doublets, the Higgsinos, mix with the gauginos of the same charge once electroweak symmetry is broken. The physical particles are two Dirac charginos (\(\tilde{W}^+_1\) and \(\tilde{W}^+_2\)) and four Majorana neutralinos (\(\tilde{Z}_i\), \(i = 1...4\)) labelled in order of increasing mass, along with gluinos which, being colour octets, cannot mix with anything else.

As we have seen, SUSY must be a broken symmetry. For phenomenological purposes, it is sufficient to parametrize SUSY-breaking by introducing all terms consistent with gauge and space-time symmetries that do not lead to the reappearance of quadratic divergences we have worked so hard to eliminate. All such terms, known as soft SUSY breaking terms, have been classified in Ref.[36]. They consist of sfermion (and also Higgs scalar) and gaugino (but not matter fermion or Higgsino) masses, along with the trilinear and bilinear SUSY breaking scalar couplings, which are generally unimportant for phenomenology except in the scalar top sector.

Without further assumptions, the number of soft-SUSY breaking parameters is very large, making phenomenological analyses intractable. For instance, each SU(3)×SU(2)×U(1) scalar multiplet has an independent SUSY-breaking mass, and also, the three gaugino masses are a priori unrelated. It is generally assumed that the gaugino masses all arise from a common GUT gaugino mass, and so, unify at some ultra-high scale. Within the GUT framework, scalars within a common GUT multiplet, of course, have the same mass\(^9\), since SUSY is assumed to be broken only at the TeV scale. This mass is defined at the unification scale and, of course, must be evolved\(^{[37]}\) down to the electroweak scale relevant for phenomenology. This leads to a splitting between the physical sparticle masses\(^{[9]}\). But even in a GUT, there are still a large number of free mass parameters. Motivated by supergravity models (which we will discuss in more detail later), it is frequently assumed that there is a single mass gap in the scalar matter sector, so that all the squarks and sleptons have a common mass at the unification scale. Evolution of these masses down to the weak scale removes this degeneracy. The dominant splitting comes from QCD interactions, resulting in a squark-slepton mass difference given by,

\[
\overline{m}_{\tilde{q}}^2 - \overline{m}_{\tilde{\ell}}^2 \simeq 0.77 m_{\tilde{g}}^2, \quad (4)
\]

where \(\overline{m}_{\tilde{q}}^2\) (\(\overline{m}_{\tilde{\ell}}^2\)) denotes the average squark (slepton) mass squared. The sfermions are also further split by electroweak interactions and by the so-called \(D\)-terms not shown here.

Finally, we mention that the gauge interactions of sparticles automatically conserve \(R\)-parity, which is a multiplicative quantum number defined to be +1 for ordinary particles, and -1 for their SUSY partners. In the MSSM framework, it is assumed that \(R\)-parity is conserved by all interactions. While the introduction of additional global or discrete symmetries is not particularly desirable, the introduction of \(R\)-parity conservation, or alternatively, the conservation of baryon or lepton number is absolutely essential to prevent proton decay at a catastrophic rate. Important consequences of \(R\)-parity conservation are that sparticles can only

\(^9\)For example, in SU(5) there would be two mass parameters for each generation but just one mass per generation in SO(10)

\(^{10}\)This splitting has often been ignored in many early MSSM analyses where squarks and sleptons are all taken to be degenerate.
be produced in pairs by collisions of ordinary particles, and that the lightest supersymmetric particle (LSP) is absolutely stable. Cosmological arguments then imply that it must be colour and electrically neutral. The LSP is a candidate for the dark matter content of the universe. Of the sneutrino and neutralino candidates for the LSP, the sneutrino is strongly disfavoured if we also assume that the LSP is also the galactic dark matter. R-parity violating models which lead to very interesting phenomenology can also be constructed. We will not have time to discuss these here.

With these assumptions, the model is completely determined by the parameters, $m_{\tilde q}$, $m_{\tilde g}$, $\tan \beta$, the ratio of the vevs of the two Higgs fields, $\mu$, the supersymmetric Higgsino mass, $m_{H_u}$, and $A_t$, the SUSY violating trilinear Higgs-stop scalar coupling which mainly affects only top squark phenomenology. We are now ready to study signals for sparticle production in high energy collisions and discuss how the non-observation of any signal to date serves to constrain the model parameters.

### 3.2 Constraints from Collider Experiments

The cleanest limits on sparticles come from the experiments at LEP. The agreement between the measured value of $\Gamma(Z)$ and its SM expectation implies an upper limit on the decays of the $Z$ boson into sparticles. This translates to a lower limit of $\sim 35-40$ GeV on the mass of the charged sparticles (and also sneutrinos if these decay visibly) which is independent of how the sparticles decay. Bounds from the invisible width of the $Z$ yield similar limits on $m_{\tilde g}$ if these decay invisibly via $\tilde{\nu} \to \nu \tilde{Z}_1$. The corresponding limits on neutralino masses are very sensitive to model parameters, since $\tilde{Z}_1$ and $\tilde{Z}_2$ couplings to the $Z$ become negligible when these are gaugino-like, as is the case for $\mu \gtrsim m_{\tilde g}$. Searches in exclusive channels, assuming that sfermions decay via $\tilde{f} \to f \tilde{Z}_1$, and $\tilde{W} \to f \bar{f} \tilde{Z}_1$ (which lead to spectacular $E_T$ events) yield lower mass bounds on sfermion and $\tilde{W}$ masses that are very close to $\frac{M_Z}{2}$. The non-observation of any signals from the decays $Z \to \tilde{Z}_1 \tilde{Z}_2$, $\tilde{Z}_2 \tilde{Z}_2$ also excludes some regions of the MSSM parameter space. In fact, the clean environment of $e^+e^-$ collisions should enable the discovery of charged sparticles all the way up to the kinematic limit, so that LEP II should be able to probe chargino, slepton and squark masses up to about 80-90 GeV.

Experiments at hadron colliders are best suited for the detections of squarks and gluinos. As is well known, gluinos and squarks in the mass range currently being probed at the Tevatron decay via a complicated cascade which terminates in the LSP. The various sparticle pair production mechanisms at hadron colliders together with the cascade decay patterns of all the sparticles as given by the MSSM, have been incorporated into ISAJET which can now be used to simulate SUSY signals in the CDF and D0 experiments currently operating at the Tevatron.

The classic signature of gluinos and squarks is $E_T$ from the undetected LSPs produced at the end of each cascade. The non-observation of an excess of $E_T$ events at the Tevatron has enabled the D0 collaboration to infer lower limits around 150 GeV on their masses, improving on the earlier limit of $\sim 100$ GeV obtained by CDF; if $m_{\tilde{g}} = m_{\tilde{q}}$, the mass bound improves to about 205 GeV, since then both squarks and gluinos can contribute to the signal. In this analysis, which is based on about $15 \text{ pb}^{-1}$ of data, it is assumed that all squarks other than $\tilde{t}$ have the same mass. The region of the $m_{\tilde{g}} - m_{\tilde{q}}$ plane excluded by the CDF and D0 analyses of their data is shown in Fig. 2. The Tevatron experiments are each expected to accumulate $50-100 \text{ pb}^{-1}$ of integrated luminosity by the end of the current run. This should enable them to probe gluino masses up to about 250-300 GeV, both via $E_T$ searches and by way of multi-lepton signals discussed below.

Before proceeding further, it is fair to ask what the measured value of $\Gamma(bb)$, which caused
Figure 2: The region of the $m_{\tilde{q}} - m_{\tilde{g}}$ plane excluded by the search for $E_T$ events at the Tevatron for ten degenerate squark flavours. This region is weakly dependent on $\mu$ and $\tan \beta$ which have been fixed at -250 GeV and 2, respectively. This figure is from the analysis by the D0 Collaboration[44].

so much problem for Technicolour models, implies in the SUSY framework. We note that SUSY, being a decoupling theory, cannot fair worse than the SM. The question, therefore, is whether sparticle loops can increase the prediction of $R_b$, bringing it closer to its measured value. This has recently been examined in Ref.[45]. Assuming that the top quark mass is within $1\sigma$ of the central value obtained by CDF[46], these authors find that within the MSSM framework, SUSY contributions from chargino-top squark loops can bring $R_b$ within $1\sigma$ of its measured value if at least one of the sparticles is lighter than 65 GeV[45]. We should view this in proper perspective. It is not too important at the present time to reduce the discrepancy to below $1\sigma$. What is important, of course, is that SUSY theories do not necessarily lead to a further reduction of $R_b$ as in the case of Technicolour.

3.3 SUSY Search in the 1990's

The Fermilab Tevatron and HERA are expected to remain the highest energy $\bar{p}p$ and $ep$ colliding facilities till well beyond the turn of the millenium, while LEP II, which should begin operation in just about a year, will be the energy frontier for $e^+e^-$ collisions. As already noted, the cleanliness of $e^+e^-$ collisions will enable experiments at LEP II to cleanly probe charged sparticle masses up to 80-90 GeV. LEP II will also be able to search for Higgs bosons with masses up

\[11\text{However, within the constrained framework that they advocate, they conclude that the 2} \sigma \text{ discrepancy cannot be significantly reduced.}\]
to about 90 GeV. As we have discussed, this is a substantial portion of the allowed parameter space, if we believe that Higgs boson interactions remain perturbative up to a very large energy scale. This is especially the case for the Higgs bosons in supersymmetry, as has been emphasized in Ref. [18].

At HERA, the most important SUSY processes are $q + e \rightarrow \tilde{q} + \tilde{\ell}$ and $q + e \rightarrow \tilde{q} + \nu$. Within the MSSM, Cashmore et. al. [47] have concluded that the range of sparticle masses that can be explored with an integrated luminosity of $200 \, pb^{-1}$ at HERA, is roughly given by $m_{\tilde{q}} + m_{\tilde{\nu}} \lesssim 180$ GeV, $m_{\tilde{q}} + m_{\tilde{\ell}} \lesssim 130$ GeV. The mass reach for other sparticles is even smaller. In view of the bounds on sparticle masses that have already been attained in experiments at the Tevatron and LEP, it appears extremely unlikely that HERA will be a discovery machine for supersymmetry. The situation may, however, be quite different if $R$-parity is not conserved. If $R$-parity is violated by electron lepton number violating interactions, it is quite possible that squarks can be singly produced (as resonances in $eq$ scattering) at HERA. We refer the reader to Ref. [48] for a study of the resulting signals.

The Tevatron experiments will collectively accumulate an integrated luminosity in excess of $\sim 100 \, pb^{-1}$ by the end of the current run, and are expected to improve on this by an order of magnitude after the Main Injector begins operations. In addition to extending the $E_T$ search region for gluinos and squarks, the large increase in the data sample should make it possible to search for supersymmetry in many other channels. The most promising of these are, ($i$) gluino and squark searches via multilepton events from their cascade decays, ($ii$) search for $\tilde{W}_1 \tilde{Z}_2$ production via isolated trilepton events free of jet activity, and ($iii$) search for the lighter $t$-squark, $\tilde{t}_1$. We note that Tevatron experiments will not be able to probe slepton masses significantly beyond the reach of LEP.

Multi-lepton Signals from Gluinos and Squarks. The conventional $E_T$ search for $\tilde{g}$ and $\tilde{q}$ is background limited. Even with an integrated luminosity of 1 $fb^{-1}$ that should be available with the Main Injector upgrade of the Tevatron, we anticipate a maximum reach of $\sim 270$ GeV ($\sim 350$ GeV) if $m_{\tilde{g}} >> m_{\tilde{q}}$ ($m_{\tilde{q}} \simeq m_{\tilde{g}}$) in this channel [19]. Heavy gluinos and squarks can also decay via the chargino and $\tilde{Z}_2$ modes which, unless suppressed by phase space, frequently dominate the decays of $\tilde{q}_L$ and $\tilde{g}$. The subsequent leptonic decays of the $\tilde{W}_1$ and $\tilde{Z}_2$ yield events with hard jets accompanied by 1-3 isolated, hard leptons and $E_T$. The cross sections for various multilepton topologies, after cuts [50] to simulate experimental conditions at the Tevatron, are shown in Fig. 3 for different choices of gluino and squark masses.

While there are substantial backgrounds to $\ell^+ \ell^- \ell^\pm$ event topologies, the *physics* backgrounds in the $\ell^+ \ell^- \ell^\pm$ and $3\ell$ channels mainly come from $tt$ production, where a secondary lepton from the decay of the daughter $b$ quark, which is usually inside a jet, is accidently isolated. These backgrounds have been evaluated in Ref. [14] and are essentially negligible, especially if $m_{\ell} > 160$ GeV; assuming detector dependent non-physics backgrounds can be controlled, the $3 \ell$ and $\ell^+ \ell^- \ell^\pm$ search channels are essentially rate limited. These channels, which at the Main Injector have a reach [51] of 230-300 GeV depending on $m_{\tilde{q}}$ and $m_{\tilde{g}}$, provide complementary ways of searching for gluinos and squarks at the Tevatron, and because they are free of SM backgrounds, may even prove superior to conventional $E_T$ searches if gluinos and squarks are very heavy. We remark that detection of these signals provides (indirect) evidence for charginos and neutralinos beyond the range of LEP.

Search for Isolated Trilepton Events. Associated $\tilde{W}_1 \tilde{Z}_2$ production which occurs by s-channel $W^*$ and $t$-channel $\tilde{q}$ exchanges, followed by the leptonic decays of $\tilde{W}_1$ and $\tilde{Z}_2$ results in isolated trilepton plus $E_T$ events, with hadronic activity only from QCD radiation. If $\tilde{W}_1$ and $\tilde{Z}_2$ are light enough, $\tilde{W}_1 \tilde{Z}_2$ production is dominated by the decay of on-shell $W$-bosons, so that the trilepton cross section is very large [21]. However, the region of parameter space where this is possible is now already excluded by the LEP bound on $m_{\tilde{W}_1}$. Nath and Arnowitt [52] had
Figure 3: Total cross sections for \( E_T, 1\ell, 2\ell, 3\ell, 4\ell \) and same-sign (SS) dilepton event topologies in 1.8 TeV \( p\bar{p} \) collisions. We have fixed \( \mu = -200 \) GeV, \( \tan \beta = 2 \), \( m_t = 140 \) GeV and \( m_{H_u} = 500 \) GeV. The experimental cuts as well as physics background levels are described in detail in Ref.[50] from which this figure is taken.

pointed that non-resonant \( \tilde{W}_1 \tilde{Z}_2 \) production will also lead to observable signals, once Tevatron experiments accumulate an integrated luminosity \( \sim 100 \text{ pb}^{-1} \). It was subsequently noted[52] that the leptonic decays of \( \tilde{Z}_2 \), and sometimes also of \( \tilde{W}_1 \), can be considerably enhanced if sleptons are substantially lighter than squarks and \( \mu \gtrsim m_{\tilde{g}} \), as is the case, e.g. in the no-scale limit of supergravity models[54].

SM physics backgrounds to the \( 3\ell + n_{\text{jet}} \leq 1 \) signal are negligible, assuming that \( WZ \) events can be vetoed with high efficiency by requiring \( m_{\ell\ell} \neq M_Z \) within experimental resolution; a conclusive observation of a handful of such events could, therefore, be a signal for new physics, depending on how well detectors can veto fake backgrounds from jet-lepton misidentification[52]. Preliminary analyses by the CDF and D0 experiments[55] (for large values of the Higgsino mass parameter, \( \mu \)) are already competitive with bounds from LEP. The experiments will soon explore[56, 57, 49] parameter ranges not accessible at LEP and, under favourable circumstances, may be competitive with LEP II. Within the MSSM framework, this reach translates to \( m_{\tilde{g}} = 250 - 400 \) GeV depending on \( m_{\tilde{g}}, \mu \) and \( \tan \beta \), the ratio of the two Higgs vacuum expectation values.

**Searching for Top Squarks at the Tevatron.** Third generation squarks differ from other squarks in that they have large Yukawa interactions. These interactions affect the mass of the squarks in two distinct ways. First, they reduce the diagonal masses of the \( \tilde{t}_R \) and the \( \tilde{t}_L \) (and by SU(2) invariance, also of \( \tilde{b}_L \)) squarks via their contributions to the running of squark masses. Second, they mix \( \tilde{t}_L \) and \( \tilde{t}_R \) further reducing the mass of \( \tilde{t}_1 \), the lighter of the two mass eigenstates. In fact, it is theoretically (but, of course, not phenomenologically) possible that \( \tilde{t}_1 \) is essentially massless with other squarks and gluinos all too heavy to be produced at

\[ \text{In fact, a recent detailed study[49] has concluded that Drell-Yan and } Z \rightarrow \ell\ell \text{ events where an additional jet fakes a lepton is the main background to this signal. It would be of interest to study whether this can be eliminated, without significant loss of signal by requiring } E_T \gtrsim 20 \text{ GeV.} \]
the Tevatron. The Tevatron lower limits on $m_{\tilde{t}}$ are derived assuming ten degenerate squark flavours, and thus, are not applicable to $m_{\tilde{t}_1}$. Currently, the best limit, $m_{\tilde{t}_1} \lesssim M_Z/2$, comes from LEP experiments; this bound can be evaded if the stop mixing angle and $m_{\tilde{t}_1} - m_{\tilde{W}_1}$ are both fine-tuned, a possibility we do not consider here.

The subsequent leptonic decay of one (or both) of the charginos lead to single lepton (dilepton) tree level decay $\tilde{\chi}^{-} \rightarrow \tilde{\chi}^{-} X$ in the range of interest at the Tevatron, $\tilde{\chi}^{-}$, fine-tuned, a possibility we do not consider here. About 100 GeV should be detectable in the 1-lepton channel by the end of the current Tevatron run, $T_1 \rightarrow \ell^- + \tilde{\chi}^{-}$ if the tree level decay $\tilde{t}_1 \rightarrow b \tilde{W}_1$ is kinematically forbidden. Stop pair production is then signalled by $\tilde{B}_T$, events from its direct decays to the LSP, and so, can be searched for via the canonical $\tilde{B}_T$ search for SUSY. A recent Monte Carlo analysis has shown that, with a data sample of 100 $pb^{-1}$, Tevatron experiments should be able to probe stop masses up to 80-100 GeV, even if $\tilde{Z}_1$ is relatively heavy.

The tree level mode $\tilde{t}_1 \rightarrow b \tilde{W}_1$ dominates stop decays whenever it is kinematically allowed. The subsequent leptonic decay of one (or both) of the charginos lead to single lepton (dilepton) $+ b$-jet(s)$+\tilde{B}_T$ events, very similar to those expected from $t\bar{t}$ pair production. Top production is thus a formidable background to the stop signal. For $m_t = 175$ GeV, $m_{\tilde{t}_1} = 100$ GeV and $m_{\tilde{W}_1} = 70$ GeV, we have estimated that stop events would contribute about 33% (20%) of the recently published CDF sample of top candidates in the 1-lepton (dilepton) channel. Thus $t$-squark production could be the culprit if Tevatron experiments conclusively measure a top cross section significantly above SM expectation. Special cuts need to be devised to separate the stop signal from top events. Since stops accessible at the Tevatron are considerably lighter than $m_t$, and because the chargino, unlike $W$, decays via three body modes into a massive LSP, stop events are generally softer than top events. It has been shown that by requiring $m_T(t\tilde{B}_T) < 45$ GeV, and $n_{jet} \leq 4$ in addition to other canonical cuts, stops with masses up to about 100 GeV should be detectable in the 1-lepton channel by the end of the current Tevatron run, assuming a $B$-tagging efficiency of 30% for $B$ hadrons with $p_T > 15$ GeV and $|\eta_B| \leq 1$. In the dilepton channel, the stop events can be selectively enhanced over those from top production by requiring $p_T(\ell^+) + p_T(\ell^-) + \tilde{B}_T < 100$ GeV. With an integrated luminosity of 100 $pb^{-1}$ Tevatron experiments should be able to detect stops up to about 80-100 GeV without the need for any $B$-tagging capability.

### 3.4 Supersymmetry Searches in the Next Millenium

Direct searches at the Main Injector and LEP II will probe sparticle masses between 80-300 GeV; even assuming MSSM mass patterns, the chargino search, by inference, will probe gluino masses up to about 400 GeV. Since the SUSY mass scale could be as high as $\sim 1$ TeV, it will, unless sparticles have already been discovered, be up to supercolliders such as the LHC at CERN or an $e^+e^-$ Linear Collider (*LC) to explore the remainder of the parameter space. There has also been some talk about possible upgrades of the Tevatron beyond the Main Injector. We will touch upon these only very briefly in our discussion.

In the $\tilde{B}_T$ channel, the LHC can search for gluinos and squarks with masses between 300 GeV to 1.3-2 TeV, depending on $m_{\tilde{g}}$ and $m_{\tilde{q}}$. It is instructive to note that several multilepton signals must simultaneously be present if any $\tilde{B}_T$ signal is to be attributed to squark and gluino production, though the various relative rates could be sensitive to the entire sparticle spectrum. The rate for like-sign dilepton plus $\tilde{B}_T$ events is enormous for $m_{\tilde{g}} \leq 300$ GeV; this ensures there is no window between the Tevatron and the LHC where gluino of the MSSM may escape detection. With 10 $fb^{-1}$ of luminosity, it should be possible to search for gluinos up

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\footnote{Even though the central value of $\sigma_{\tilde{t}}$ is larger than the SM expectation for $m_t = 174$ GeV (the CDF central value of mass measured from event characteristics), there is no statistically significant discrepancy at present.}
to about 1 TeV in this channel\cite{51,52}. Gluinos and squarks may also be a source of high $p_T$ $Z + \not{E}_T$ events at the LHC, but this signal is very sensitive to model parameters. The LHC can also search for “hadron-free” trilepton events from $\tilde{W}_1\tilde{Z}_2$ production. Backgrounds from top quark production can be very effectively suppressed\cite{24} by requiring that the two hardest leptons have the same sign of charge. The signal becomes unobservable when the two-body decays $\tilde{Z}_2 \to (Z$ or $H_\nu) + \tilde{Z}_1$ become accessible. The dilepton mass distribution in $\ell^+\ell^-\ell^\prime$ events can be used to reliably measure $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$. Selectrons and smuons with masses up to 250 GeV (300 GeV if it is possible to veto central jets with an efficiency of 99\%) should also be detectable\cite{53}. Finally, we note that with an integrated luminosity of 100 $fb^{-1}$ the $\gamma\gamma$ decays of scalar stoponium has been argued to allow for the detection of $\tilde{t}_1$ with a mass up to 250 GeV, assuming $\tilde{t}_1 \to b\tilde{W}_1$ (and, perhaps, also $\tilde{t}_1 \to bW\tilde{Z}_1$) is kinematically forbidden\cite{56}.

The SUSY reach of various hadron colliders is summarized in Table 3. In addition to the Main Injector and the LHC, we have also shown the reach for two possible upgrades of the Tevatron that have been much talked about recently. The results for these have been abstracted from Ref.\cite{19} to which we refer the reader for details.

Table 3: Discovery reach of various options of future hadron colliders. The numbers are subject to ±15\% ambiguity. Also, the clean isolated trilepton signals are sensitive to other model parameters; we show representative ranges from the supergravity analysis of Ref.\cite{12}, where $|\mu|$ is constrained to be large. If $|\mu| < 100 – 150$ GeV, the reach may be even smaller\cite{54}.

| Signal                          | Tevatron      | Main Injector | Tevatron* | DiTevatron | LHC        |
|--------------------------------|---------------|---------------|-----------|------------|------------|
|                                | 0.1 fb$^{-1}$ | 1 fb$^{-1}$   | 10 fb$^{-1}$ | 1 fb$^{-1}$ | 10 fb$^{-1}$ |
| $5\not{E}_T(q \gg \tilde{g})$   | $\tilde{g}(210)$ | $\tilde{g}(270)$ | $\tilde{g}(340)$ | $\tilde{g}(450)$ | $\tilde{g}(1300)$ |
| $6\not{E}_T(q \sim \tilde{g})$   | $\tilde{g}(300)$ | $\tilde{g}(350)$ | $\tilde{g}(400)$ | $\tilde{g}(580)$ | $\tilde{g}(2000)$ |
| $\tilde{t}^\pm l^\mp (\tilde{q} \sim \tilde{g})$ | $\tilde{g}(170)$ | $\tilde{g}(250)$ | $\tilde{g}(257)$ | $\tilde{g}(400)$ | $\tilde{g}(1000)$ |
| $\tilde{g} \tilde{q} \to 3l$ ($\tilde{q} \sim \tilde{g}$) | $\tilde{g}(200)$ | $\tilde{g}(270)$ | $\tilde{g}(300)$ | $\tilde{g}(500–550)$ | $\tilde{g}(\sim 1000)$ |
| $\tilde{W}_1\tilde{Z}_2 \to 3l$ | $\tilde{g}(200)$ | $\tilde{g}(250–450)$ | $\tilde{g}(300–500)$ | $\tilde{g}(250–470)$ | $\tilde{g}(400–700)$ |
| $\tilde{t}_1 \to c\tilde{Z}_1$ | $\tilde{t}_1(80–100)$ | $\tilde{t}_1(120)$ | $\tilde{t}_1(120)$ | $\tilde{t}_1(120)$ | $\tilde{t}_1(120)$ |
| $\tilde{t}_1 \to b\tilde{W}_1$ | $\tilde{t}_1(80–100)$ | $\tilde{t}_1(120)$ | $\tilde{t}_1(120)$ | $\tilde{t}_1(120)$ | $\tilde{t}_1(120)$ |
| $\tilde{\ell}^*$ | $\tilde{\ell}(45–50)$ | $\tilde{\ell}(50)$ | $\tilde{\ell}(50)$ | $\tilde{\ell}(50)$ | $\tilde{\ell}(250–300)$ |

We see that the Tevatron upgrades (especially the DiTevatron) mainly lead to a significant improvement in the reach for gluinos and squarks. The improvement over the Main Injector in the reach for the trilepton signal from $\tilde{W}_1\tilde{Z}_2$ production appears marginal, at best. This conclusion may be altered if it turns out to be possible to eliminate the reducible backgrounds (see Ref.\cite{49}) as discussed earlier. We also note that it is only at the LHC that the full range of sparticle masses, allowed by our general considerations of EWSB, can be explored.

Charged sparticles (and sneutrinos, if $m_{\tilde{\nu}} > m_{\tilde{\nu}_{\tilde{W}_1}}$) should be readily detectable at an $e^+e^-$ Linear Collider, essentially all the way up to the kinematic limit. Unfortunately, most detailed $e^+e^-$ studies to date do not incorporate cascade decays of sparticles\cite{25}. This is, of course, irrelevant for the production of the lightest of the charged sparticles, but could be important for the signals from the more massive ones. For SUSY models where the gaugino masses arise from a single unified gaugino mass so that $m_{\tilde{\nu}_{\tilde{W}_1}} \sim (0.3 – 0.4)m_{\tilde{g}}$, a linear collider with a reach of about 500 GeV for charginos would have the same discovery potential as the LHC.

\footnote{$e^+e^-$ to sparticle pair reactions are included in ISAJET 7.11.}
The real power of these machines, however, lies in the ability to do precision experiments which can then be used to measure sparticle masses with an accuracy of 1-3%\[67\], along with other MSSM parameters. These measurements can then be used to test various model assumptions. For instance, the analysis of Ref.\[68\] illustrates how a study of $\tilde{W}_1$-pair production even at LEP II can, in the favourable case of gaugino-like charginos, constrain the values of certain combinations of MSSM parameters. These authors find that if chargino pair production is kinematically accessible, measurements at LEP II could significantly constrain the ratio of the SU(2) and hypercharge gaugino masses, and thus directly test the gaugino mass unification hypothesis. The availability of beam polarization at future Linear Collider facilities is a definite advantage of these machines over hadron supercolliders. Polarized beams are useful for two reasons. First, they obviously increase the number of observables. Second, they can be used to reduce SM backgrounds; for instance $W$-pair production, which is a major background to the acollinear dilepton signal from slepton pair production, can be virtually eliminated\[67\] by using a beam of right-handed electrons. Precision measurements of masses and SUSY parameters will allow\[67\] direct tests of supergravity GUT models discussed in the next subsection. A related, and perhaps, even more basic, issue is whether such measurements allow us to test the supersymmetry between the couplings of any sparticles that may be discovered — for instance, SUSY relates the gaugino-fermion-sfermion coupling to the appropriate gauge coupling. Recent analyses\[69, 70\] suggest that the answer to this question is affirmative, at least if the model parameters happen to lie in favourable ranges.

Before closing this section, we remark that the *LC is also the optimal facility to study the Higgs sector of SUSY\[71\]. As is well known\[72\], even with optimistic detector assumptions, there are regions of MSSM parameter space where none of the MSSM Higgs bosons may be detectable either at LEP II or at the LHC.\[72\] Furthermore, over most of the MSSM parameter space, at most one Higgs boson would be detectable at the LHC or LEP. Since Higgs boson couplings cannot be measured with any precision at hadron colliders, it would be very difficult to distinguish the SUSY and SM Higgs sectors. In contrast, at a 500 GeV Linear Collider, the discovery of one of the MSSM Higgs bosons is guaranteed with just 1 $fb^{-1}$ of integrated luminosity. Furthermore, if $m_{H_p} \leq 400$ GeV, with an integrated luminosity of 50 $fb^{-1}$, it should be possible to distinguish\[73\] the MSSM and SM Higgs sectors, either by directly identifying more than one of the Higgs bosons, or by detecting a measurable deviation of the branching fraction for the decay $H \rightarrow b\bar{b}$ from its SM expectation.

### 3.5 Supergravity Phenomenology

Supergravity (SUGRA) GUT models, via specific assumptions about the symmetries of interactions responsible for SUSY breaking, provide an economical framework for phenomenology by relating the many SUSY breaking parameters of the MSSM. These relations hold at some ultra-high unification scale $M_X$ where these symmetries are manifest and the physics is simple. Complex sparticle mass and mixing patterns (recently incorporated into ISAJET 7.10), *along with the correct breaking of electroweak symmetry* emerge\[74\] when these parameters are renormalized down to the weak scale as required for phenomenology. The model is completely specified by just four SUSY parameters which may be taken to be the common values of SUSY-breaking gaugino ($m_{1/2}$) and scalar masses ($m_0$) and trilinear scalar couplings ($A_0$), all specified\[74\] at the scale $M_X$, together with the Higgs sector parameter $\tan \beta$. In particular,

\[\text{It has been proposed}\[73\] \text{that with sufficient } B\text{-tagging capability, it may be possible to fill up this “hole” in parameter space; whether this is realistic in the high luminosity environment of the LHC is still unclear.}\]

\[\text{The reason for the hierarchy between the values of the soft-breaking parameters, which must be be } O(1 \text{ TeV}), \text{ and the scale } M_X \text{ at which they are specified is not well understood. It, presumably, has to do with the unknown}\]
μ and the pseudoscalar Higgs boson mass are determined. Within this framework, the first two generations of squarks are approximately degenerate (consistent with FCNC constraints in the K-meson sector) while some third generation squarks may be significantly lighter. The splitting between squarks and sleptons is as in Eq. (4). The various flavours of left- (right-) type sleptons are almost exactly degenerate. In the gaugino-Higgsino sector, SUSY-breaking electroweak gaugino masses are typically considerably smaller than |μ|, so that the $\tilde{W}_1$, $\tilde{Z}_1$ and $\tilde{Z}_2$ are dominantly gaugino-like. This has important repercussions for the cascade decay patterns of heavy sparticles. It is remarkable that even the simplest SUGRA GUTs are consistent with experimental constraints as well as cosmology[73].

Since the phenomenology is determined in terms of just four SUSY parameters, various SUSY cross sections become correlated. Various analyses from LEP and Tevatron experiments can thus be consistently combined into a single framework[76], as illustrated in Fig. 4 for (a) μ < 0 and (b) μ > 0. Here, we have taken $A_0 = 0$ (this does not mean that the weak scale $A$-parameter vanishes) and tan β = 2, and performed the analysis in the $m_0 - m_{1/2}$ plane. The shaded region is excluded as it either does not lead to the correct EWSB pattern, or yields a sparticle other than $\tilde{Z}_1$ as the LSP. The region below the hatched line is excluded by experimental constraints. It comprises of the regions excluded by the non-observation of Higgs bosons, the chargino or sleptons at LEP, or, below the line labelled $E_T$, by the gluino and squark search at the Tevatron. For details, we refer the reader to Ref.[76] from which this figure is taken. The dot-dashed lines show the projected reach of LEP II, whereas the dashed line labelled 200 fb (20 fb) indicates the reach of the Tevatron to the trilepton signal for an integrated luminosity of 100 pb$^{-1}$ (1 fb$^{-1}$). Finally, the dotted lines indicate the boundaries of the region where the various two body decays of $\tilde{Z}_2$ become kinematically accessible. It is interesting to see that since the various searches frequently probe different parts of the parameter space they often complement one another. For large values of $A_0$, top squark signals also play a role in probing the parameter-plane in the Fig. 4. It should, however, be remembered that this framework depends on assumptions about physics at the unification scale. These assumptions, of course, need to be subjected to experimental tests. These unification hypotheses are directly falsifiable by precision measurements that will be possible at Linear Colliders. For current experimental analyses we suggest using SUGRA models to obtain default values of MSSM input parameters, and then, to test the sensitivity of the predictions on the assumed SUGRA relations.

The simplest SUGRA GUT models make several striking predictions. First, there is the unification of gaugino masses (this has to do with GUTs and not SUGRA) that we have already discussed. Second, the assumed unification of scalar masses together with our assumption regarding the minimality of the sparticle content, implies definite relations amongst the masses of the unmixed squarks and sleptons. These can be directly verified since it should be possible to precisely measure squark[78] and slepton[67] masses at the *LC. Somewhat more detailed tests that make use of the availability of polarized beams may also be possible. For example, if $\tilde{e}_R$ and the lighter chargino are both kinematically accessible, the measurement of $m_{\tilde{e}_R}$, $m_{\tilde{Z}_1}$, $m_{\tilde{W}_1}$, $\sigma_R(\tilde{e}_R)$ and $\sigma_R(\tilde{W}_1)$, would allow one to make a global fit and so determine the two electroweak gaugino masses, μ and tan β (with a precision depending on where we are in parameter space). This allows one to test the gaugino unification condition at the 5% level[67]. The determination of the other parameters would serve to restrict other SUSY reaction rates, and thus, provide further tests of this framework. Observation of sparticles would not only be a spectacular new discovery, but a measurement of their properties, particularly at linear dynamics of supersymmetry breaking. At present, this ratio has to be put in “by hand”, so that it would be premature to claim that supergravity models provide an understanding of the weak scale.

17This is especially important since an alternative proposal for a high energy symmetry to suppress FCNC does not require squarks to be degenerate[71].
colliders would test various SUGRA assumptions, and so, serve as a telescope to the unification scale.

4 Optional New Physics

As we discussed in Sec. 1, there are many other extensions of the SM than the ones that we have, motivated by our discussion of EWSB, chosen to focus on. For instance, it is possible to consider models with larger gauge groups, with the additional associated gauge bosons. Because these groups usually have large representations, such models frequently include additional matter fermions as well as additional spin zero bosons. The new physics spectrum depends on the essentially unknown scale at which the larger symmetry reduces to the SM gauge group. There already exist experimental limits on the masses of these exotic particles. The Tevatron experiments have searched for new, heavy $W$ and $Z$ bosons via their leptonic decays. Assum-
ing that these have the same couplings as the SM gauge bosons, they obtain direct bounds \[ M_{W'} \geq 620 \text{ GeV}, M_{Z'} \geq 500 \text{ GeV} \] on their masses. Lower limits of \( \sim 80-120 \text{ GeV} \) have also been obtained for leptoquarks and coloured stable (or long-lived) exotics. LEP experiments give lower limits \( \sim \frac{M_Z}{2} \) on new leptons, or excited lepton states that may exist in composite models. These experiments also constrain \[ \text{new } Z' \text{ bosons that mix with the SM } Z \]. We refer the reader to the literature for details on these and other issues.

5 Epilogue

Over the years, we have become used to hearing about the spectacular successes of the SM. As we have heard at this meeting, there is no glaring experimental discrepancy, though some measurements could possibly be taken as hints of a problem. Most theorists, however, regard the SM as an incomplete picture since it leaves many things unexplained. While there have been many ambitious attempts to write down “Theories of Everything” these frequently suffer from the fact that dynamical calculations are not possible with present techniques, so that it is difficult to test the underlying ideas. Quite possibly, progress on the various items on the theorist’s wish-list may occur one step at a time. The problem is that there is very little guidance from experiment as to the best strategy for extending the SM.

The one clue we have comes from the faith that the EWSB sector should not require uncanny fine-tuning, order by order in perturbation theory. It is possible that the fine-tuning issue may turn out to be an artifact of our theoretical techniques, but this is the only guidance that we have. If we take it seriously, general arguments suggest that there must be some new degrees of freedom not included in the SM, that will manifest themselves in elementary particle collisions at the TeV scale. These arguments, however, tell us nothing about the nature of the new physics.

We have examined collider signals from two broadly different extensions of the SM. In the first case, it is assumed that EWSB interactions become strong at the TeV scale, and that a fermion condensate is responsible for symmetry breaking. Extended Technicolour Models are an example. The observation of new bound states, the Techni-particles, would provide direct confirmation of the this idea. It could, however, be that these states are kinematically inaccessible at colliders. In this case, the detection of the signal will pose a formidable challenge, both at the LHC as well as at a 1.5-2 TeV \( e^+ e^- \) collider. The best hope of accessing the new physics is via a study of longitudinal \( W \) and \( Z \) boson scattering at high energy. The modification of the scattering amplitude due to the new strong interactions of gauge bosons which serves as the signal is somewhat sensitive to the details of the model. In many cases, the signal is rather marginal.\[18\] The LHC with an integrated luminosity of \( \sim 200 \text{ fb}^{-1} \) has roughly similar capability as a 1.5-2 TeV \( e^+ e^- \) super collider with a similar integrated luminosity.

The only known realization of the second case, where the EWSB sector is weakly coupled, is TeV scale supersymmetry. Unlike as in the case of Technicolour, it is possible to construct consistent and calculable models in agreement with phenomenology. Supergravity GUT models are particularly attractive in that they have relatively few additional parameters. Although this is not absolutely compulsory, the electroweak gauginos are typically only a third as heavy as gluinos in the simplest versions of SUSY GUT models. Thus an \( e^+ e^- \) collider operating at an energy \( \sim 1 \text{ TeV} \) would have a similar reach (via charginos) as the LHC in gluinos. But there

\[18\] Since the signal to background ratio improves dramatically with energy, a Large Super Giant New Accelerator (LSGNA) would be the optimal facility for an in depth study of such a scenario. Presumably, the type of machine and the design parameters will be decided after an assessment of what is found at the next generation of accelerators.
may be a much more significant sense in which the LHC and the LC may be complementary.

At the LHC, it is likely that it will be possible to detect gluinos in both the $E_T$ as well as multilepton channels, which will serve as indirect evidence for the existence of charginos and neutralinos. The detailed properties of charginos and neutralinos will, however, be measured only at Linear Colliders. Re-analysis of the LHC data in light of this new information, could then help sort out the complicated cascade decay patterns, which would otherwise be very difficult to disentangle. The complementarity of $e^+e^-$ and hadron colliders is also clear if we consider the search for Higgs bosons. An $e^+e^-$ collider operating at 500 GeV would be an ideal facility for detecting intermediate mass Higgs bosons which are generally difficult to detect at the LHC. Furthermore, at Linear Colliders, it is frequently possible to distinguish the SM Higgs sector from that of more complicated models.

We conclude by underscoring the necessity of experimentally exploring the TeV scale in order to obtain clues about some of the most pressing questions in particle physics. While no one knows what we will find, we are virtually guaranteed to find something, assuming of course that the detectors function as advertised. Hopefully, these discoveries will shed light on some of the items on the theorist’s wish list we introduced in Section 1. Perhaps, we will discover that the grand desert is populated with unexpected surprises; perhaps, we will find that the new physics directly probes the dynamics at ultra-high energy scales as, for instance, in SUGRA GUTs. One thing is certain: we will find nothing unless we look.

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References

[1] A. Olchevski, these proceedings.
[2] M. Fero, these proceedings.
[3] M. Peskin and T. Takeuchi, Phys. Rev. D46, 381 (1992).
[4] P. Langacker, these proceedings.
[5] C. P. Burgess et. al., Phys. Lett. B326, 276 (1994).
[6] S. Kuhlmann, these proceedings.
[7] M. Shochet, plenary talk at the Eighth DPF meeting, Albuquerque, NM, Aug. 1994.
[8] R. A. Reeder, presented at the Eighth DPF meeting, Albuquerque, NM, Aug. 1994.
[9] Y. Fukuda et. al., ICRR-preprint 321-94-16 (1994).

\footnote{For a more detailed discussion of the complementarity of these facilities, see Ref.\cite{69}.}
[10] J. Nico, D.W Gidley, A. Rich and P. W. Zitzewitz, *Phys. Rev. Lett.* **65**, 1344 (1990).

[11] U. Amaldi, W. de Boer and H. Fürstenau, *Phys. Lett.* **B260**, 447 (1991); J. Ellis, S. Kelley and D. Nanopoulos, *Phys. Lett.* **B260**, 131 (1991); P. Langacker and M. Luo, *Phys. Rev.* **D44**, 817 (1991).

[12] For textbook expositions, see G. G. Ross, *Grand Unified Theories*, Benjamin-Cummings Publishing Co. Inc. (1985); R. Mohapatra, *Unification and Supersymmetry*, Second Edition, Springer-Verlag (1992).

[13] A. Suzuki and J. Panman, *these proceedings*.

[14] L. Zanotti *these proceedings*.

[15] E. Kolb and M. Turner, *The Early Universe*, Addison-Wesley (1990).

[16] D. Dicus and V. Mathur, *Phys. Rev.* **D7**, 3111 (1973); B. Lee, C. Quigg and H. Thacker, *Phys. Rev.* **D16**, 1519 (1977).

[17] N. Cabibbo, L. Maiani, G. Parisi and R. Petronzio, *Nucl. Phys.* **B158**, 295 (1979); M. Lindner, *Z. Phys.* **C31**, 295 (1986).

[18] H. Haber and M. Sher, *Phys. Rev.* **D35**, 2206; M. Drees, *Int. J. Mod. Phys.* **A4**, 3635 (1989); G. L. Kane, C. Kolda and J. Wells, *Phys. Rev. Lett.* **70**, 2686 (1993). See also, M. Sher, William and Mary preprint, 94-07 (1994).

[19] S. Weinberg, *Phys. Rev.* **D19**, 1277 (1979); L. Susskind, *Phys. Rev.* **D20**, 2619 (1979).

[20] J. Schwinger, *Phys. Rev.* **125**, 397 (1962).

[21] S. Dimopoulos and L. Susskind, *Nucl. Phys.* **B155**, 237 (1979); E. Eichten and K. Lane, Phys. Lett. **B90**, 125 (1980).

[22] For a general review, see R. Kaul, *Rev. Mod. Phys.* **55**, 449 (1983).

[23] B. Holdom, *Phys. Lett.* **B105**, 301 (1985); K. Yamawaki, M. Bando and K. Matumoto, *Phys. Rev. Lett.* **56**, 1335 (1986); T. Appelquist, D. Karabali and L. Wijewardhana, *Phys. Rev. Lett.* **57**, 957 (1986).

[24] T. Appelquist and J. Terning, *Phys. Lett.* **B315**, 139 (1993); N. J. Evans, S. F. King and D. A. Ross, *Phys. Lett.* **B303**, 295 (1993); N. J. Evans and D. A. Ross, *Nucl. Phys.* **B417**, 151 (1994).

[25] R. S. Chivukula, S. Selipsky and E. Simmons, *Phys. Rev. Lett.* **69**, 575 (1992).

[26] R. S. Chivukula, E. Gates, E. Simmons and J. Terning, *Phys. Lett.* **B311**, 157 (1993).

[27] J. Bagger et. al., *Phys. Rev.* **D49**, 1246 (1994).

[28] K. Hikasa and K. Igi, *Phys. Lett.* **B261**, 285 (1991) and *Phys. Rev.* **D48**, 3055 (1993).

[29] M. Chanowitz and M. Gaillard, *Nucl. Phys.* **B261**, 379 (1985).

[30] T. Han, in *Proc. of Workshop on Physics and Experiments with Linear e+e- Colliders*, Waikaloa, Hawaii, April 1993, F. Harris, S. Pakvasa, S. Olsen and X. Tata, Editors, World Scientific (1993).
[31] E. Boos and G. Jikia, *Phys. Lett.* **B275**, 164 (1992); M. Herrero and E. Ruiz-Morales, *ibid.* **B296**, 397 (1992); A. Abbasabadi, D. Bowser-Chao, D. Dicus and W. Repko, *Phys. Rev.* **D49**, 1265 (1994); G. Jikia, *Phys. Lett.* **B298**, 224 (1993); M. Berger, *Phys. Rev.* **D48**, 5121 (1993); D. Dicus and C. Kao, *ibid.* **D49**, 1265 (1994).

[32] S. J. Brodsky, in *Proc. of Workshop on Physics and Experiments with Linear $e^+e^-$ Colliders*, Waikaloa, Hawaii, April 1993, F. Harris, S. Pakvasa, S. Olsen and X. Tata, Editors, World Scientific (1993).

[33] K. Cheung, *Phys. Lett.* **B323**, 85 (1994).

[34] G. Jikia, presented at the Workshop on Photon-Photon Colliders, Berkeley, March, 1994.

[35] For reviews of weak scale supersymmetry phenomenology, see H. P. Nilles, *Phys. Rep.* **110**, 1 (1984); H. Haber and G. Kane, *Phys. Rep.* **117**, 75 (1985); X. Tata, in *The Standard Model and Beyond*, p. 304, edited by J. E. Kim, World Scientific (1991); R. Arnowitt and P. Nath, *Lectures presented at the VII J. A. Swieca Summer School, Campos do Jordao, Brazil, 1993 CTP-TAMU-52/93; Properties of SUSY Particles*, L. Cifarelli and V. Khoze, Editors, World Scientific (1993).

[36] L. Girardello and M. Grisaru, *Nucl. Phys.* **B194**, 65 (1982).

[37] K. Inoue, A. Kakuto, H. Komatsu and H. Takeshita, *Prog. Theor. Phys.* **68**, 927 (1982) and 71, 413 (1984).

[38] See *e.g.* H. Baer, M. Drees and X. Tata, *Phys. Rev.* **D41**, 3414 (1990).

[39] For phenomenological reviews of signals in $R$-parity violating models, see *e.g.* D. P. Roy, *Proc. of the Tenth DAE Symposium on High Energy Physics*, S. Banerjee and P. Roy, Editors; H. Dreiner, in *Properties of SUSY Particles*, Ref. [35].

[40] J. Ellis, S. Ridolfi and F. Zwirner, *Phys. Lett.* **B237**, 423 (1990); M. Drees and X. Tata, *Phys. Rev.* **D43**, 2971 (1991).

[41] See *e.g.* G. Giacomelli and P. Giacomelli, *Riv.Nuovo Cim.* **16**, 1 (1993).

[42] H. Baer, J. Ellis, G. Gelmini, D. Nanopoulos and X. Tata, *Phys. Lett.* **B161**, 175 (1985); G. Gamberini, *Z. Phys.* **C30**, 605 (1983); H. Baer, V. Barger, D. Karatas and X. Tata, *Phys. Rev.* **D36**, 96 (1987).

[43] F. Paige and S. Protopopescu, in *Supercollider Physics*, p. 41, ed. D. Soper (World Scientific, 1986); H. Baer, F. Paige, S. Protopopescu and X. Tata, in *Proceedings of the Workshop on Physics at Current Accelerators and Supercolliders*, ed. J. Hewett, A. White and D. Zeppenfeld, (Argonne National Laboratory, 1993).

[44] M. Paterno, Ph.D. Thesis; D. Claes, presented at the Eighth DPF meeting, Albuquerque, NM, Aug. 1994. For the published CDF bound, see F. Abe et. al., *Phys. Rev. Lett.* **69** (1992) 3439.

[45] J. Wells, C. Kolda and G. Kane, University of Michigan preprint, UM-TH-94-23 (1994).

[46] F. Abe et. al., Fermilab preprint Fermilab-Pub-94/097-E (1994).

[47] R. Casmore et. al., *Phys. Rep.* **122**, 275 (1985).
[48] J. Butterworth and H. Dreiner, *Nucl. Phys.* **B397**, 3 (1993).

[49] T. Kamon, J. Lopez, P. McIntyre and J. White, Texas A and M preprint, CTP-TAMU-19/94 (1994).

[50] H. Baer, C. Kao and X. Tata, *Phys. Rev.* **D48**, R2978 (1993).

[51] D. Dicus, S. Nandi and X. Tata, *Phys. Lett.* **B129**, 451 (1983); H. Baer and X. Tata, *Phys. Lett.* **155B**, 278 (1985); H. Baer, K. Hagiwara and X. Tata, *Phys. Rev. Lett.* **57**, 294 (1986) and *Phys. Rev.* **D35**, 1598 (1987); R. Arnowitt, A. Chamesiddine and P. Nath, *Phys. Rev.* **D35**, 1085 (1987).

[52] P. Nath and R. Arnowitt, *Mod. Phys. Lett* **A2**, 1113 (1987).

[53] H. Baer and X. Tata, *Phys. Rev.* **D47**, 2739 (1993).

[54] A. Lahanas and D. Nanopoulos, *Phys. Rep.* **145**, 1 (1987).

[55] CDF Collaboration, submitted to *27 International Conference on High Energy Physics*, Glasgow, Scotland, Fermilab-Conf-94/149-E (1994); D0 Collaboration, presented at *9th Topical Workshop on pp Collider Physics*, Tsukuba, Japan, Fermilab-Conf-94-036-E (1994).

[56] H. Baer, C. Kao and X. Tata, *Phys. Rev.* **D48** (1993) 5175.

[57] J. Lopez, D. Nanopoulos, X. Wang and A. Zichichi, *Phys. Rev.* **D48**, 2062 (1993).

[58] K. Hikasa and M. Kobayashi, *Phys. Rev.* **D36** (1987) 724.

[59] H. Baer, J. Sender and X. Tata, Hawaii preprint UH-511-788-94 (1994), *Phys. Rev.* **D** (in press).

[60] H. Baer *et. al.*, *Phys. Rev.* **D44** (1991) 725.

[61] C. Albajar *et. al.*, *Proc. ECFA LHC Workshop*, Aachen (1990).

[62] ATLAS Collaboration, *Letter of Intent*, CERN LHCC/92-4 (1992).

[63] H. Baer, X. Tata and J. Woodside, *Phys. Rev.* **D45** (1992) 145.

[64] H. Baer, C-H. Chen, F. Paige and X. Tata, *Phys. Rev.* **D** (in press).

[65] H. Baer, C-H. Chen, F. Paige and X. Tata, *Phys. Rev.* **D49** (1994) 3283.

[66] M. Drees and M. Nojiri, *Phys.Rev.* **D49** (1994) 4595.

[67] T. Tsukamoto *et. al.*, KEK preprint 93-146 (1993).

[68] J. Feng and M. Strassler, SLAC preprint, SLAC-PUB-6497 (1994).

[69] M. Peskin, *Invited Talk, 22nd INS Symposium on Physics with High Energy Colliders, Tokyo, March, 1994*, SLAC-PUB-6582 (1994).

[70] J. Feng, *presented at the Eighth DPF meeting, Albuquerque, NM, Aug. 1994.*
[71] P. Janot in *Proc. of the Workshop on Physics and Experiments with Linear Colliders*, Waikaloa, Hawaii, F. Harris, S. Olsen, S. Pakvasa and X. Tata, Editors (World Scientific, 1993).

[72] V. Barger, M. Berger, A. Stange and R. Phillips, *Phys. Rev.* D45, 4128 (1992); H. Baer, M. Bisset, C. Kao and X.Tata, *Phys. Rev.* D46, 1067 (1992); J. Gunion and L. Orr, *Phys. Rev.* D46, 2052 (1992); Z. Kunszt and F. Zwirner, *Nucl. Phys.* B385, 3 (1992); for a recent review, see *e.g.* J. Gunion in *Properties of SUSY Particles*, Ref.[35].

[73] T. Garvaglia, W. Kwong and D-D. Wu, *Phys.Rev.* D48, 1899 (1993); J. Dai, J. Gunion and R. Vega, *Phys. Lett.* B315, 355 (1993).

[74] Some recent analyses of supergravity mass patterns include, G. Ross and R. G. Roberts, *Nucl. Phys.* B377, 571 (1992); R. Arnowitt and P. Nath, *Phys. Rev. Lett.* 69, 725 (1992); M. Drees and M. M. Nojiri, *Nucl. Phys.* B369, 54 (1993); S. Kelley et. al., J. Lopez, D. Nanopoulos, H. Pois and K. Yuan, *Nucl. Phys.* B398, 3 (1993); M. Olechowski and S. Pokorski, *Nucl. Phys.* B404, 590 (1993); V. Barger, M. Berger and P. Ohmann, *Phys. Rev.* D49, 4908 (1994); G. Kane, C. Kolda, L. Roszkowski and J. Wells, *Phys. Rev.* D49, 6173 (1994); D. J. Castaño, E. Piard and P. Ramond, *Phys. Rev.* D49, 4882 (1994); W. de Boer, R. Ehret and D. Kazakov, Karlsruhe preprint, IEKP-KA/94-05 (1994).

[75] R. Arnowitt and P. Nath, *Phys. Rev. Lett.* 69, 725 (1992); J. Hisano, H. Murayama and T. Yanagida, *Nucl. Phys.* B402, 46 (1993); J. Lopez, D. Nanopoulos and H. Pois, *Phys. Rev.* D47, 2468 (1993); H. Baer, M. Drees, C. Kao, M. Nojiri and X. Tata, *Phys. Rev.* D50, 2148 (1994); J. Lopez, D. Nanopoulos, G. Park, X. Wang and A. Zichichi, *Phys. Rev.* D50, 2164 (1994).

[76] H. Baer, C-H. Chen, R. Munroe, F. Paige and X. Tata, Hawaii preprint, UH-511-795-94 (1994).

[77] Y. Nir and N. Seiberg, *Phys. Lett.* B309, 337 (1993).

[78] J. Feng and D. Finnell *Phys. Rev.* D49, 2369 (1994).

[79] D. Wood, *these proceedings*.

[80] M. Pohl, *plenary talk at the International Conference on High Energy Physics, Glasgow, August 1994*. 
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