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Physics Beyond the Standard Model †

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Abstract. I shall briefly summarize the prospects for extending our understanding of physics beyond the standard model within the next five years.

In this necessarily brief presentation, I shall attempt to outline how we may be able to discover physics beyond the standard model within the next five years. I shall interpret "beyond the standard model" to mean the physics of electroweak symmetry breaking, including the standard model Higgs boson. The nature of this TeV-scale new physics is perhaps the most crucial question facing high-energy physics, but we should recall (neutrino oscillations!) that there is ample evidence for interesting physics in the flavour sector too. In the next five years, before the LHC starts operations, the facilities available will be LEP2, HERA and the Fermilab Tevatron. I shall devote a bit more time to the Tevatron as it is a new initiative for United Kingdom institutions. The Tevatron schedule now calls for data taking in Run II, using two upgraded detectors, to begin on March 1, 2001, with 2 fb^{-1} accumulated in the first two years. A nine-month shutdown will follow, to allow new silicon detector layers to be installed, and then running will resume with a goal of accumulating 15 fb^{-1} (or more) by 2006.

Where does the standard model stand, circa 2000? We know that it works very well, indeed some precision observables test it at the 10^{-3} level[1]. All observations are consistent with a single, light standard model (SM) Higgs boson, though no such beast has yet been observed. As of Autumn 1999[2], Higgs masses less than 106 GeV are excluded by direct searches and greater than 245 GeV are excluded by fits to precision SM observables[3]. Despite this consistency with the SM, there are strong general arguments for the existence of new physics at the electroweak scale (250 GeV–1 TeV). The goodness of the SM fits may perhaps suggest that this new physics is weakly coupled. In addition there are indirect pointers that may suggest supersymmetry (SUSY) is a prime candidate for the new physics, though once again, all direct searches for supersymmetric particles have so far proved negative. Data from LEP2 have been used to rule out[3] squarks (stop and sbottom) below 80–90 GeV, sleptons (selectron, smuon and stau) below 70–90 GeV, charginos below 70–90 GeV, and the lightest neutralino below 36 GeV. Searches for squarks and gluinos, stop, sbottom, charginos

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and neutralinos at the Tevatron have also all proved negative and yield comparable limits[4].

Your mission, should you choose to accept it, is then clear. At your earliest convenience, please carry out one (or more!) of the following challenges:

- discover the standard model Higgs;
- discover or exclude the lightest Higgs of minimal SUSY (with masses up to $m_h \sim 130$ GeV);
- discover one or more superpartners;
- exclude (or at least disfavour) supersymmetry at the TeV scale by discovering some other new physics.

We know the LHC can address all of these questions given sufficient luminosity. But can any of this be done sooner, *i.e.* in the next five years?

1. The Standard Model Higgs

The search for the SM Higgs at LEP2 is well understood. The reach depends on the centre of mass energy which can be achieved, and the integrated luminosity obtained. For 150 pb^{-1} per experiment at $\sqrt{s} = 200$ GeV, Higgs masses $m_H < 109$ GeV will be ruled out[3]. The LEP energy may be pushed a few GeV higher, but to go much beyond this will require the use of the Tevatron. Much interest in the Tevatron's potential for Higgs searches was sparked by work carried out during the Run II SUSY/Higgs workshop in 1998[5].

The Higgs cross section at the Tevatron is large (1 pb for $m_H \sim 100$ GeV) but since the $gg \to H \to b\bar{b}$ process dominates, there is a huge QCD background. For Higgs masses below 130–140 GeV, the best potential seems to come from the processes where a W or Z is produced in association with the Higgs:

- $WH \to \ell\nu b\bar{b}$: Backgrounds from $Wb\bar{b}$, WZ, $t\bar{t}$, single top. A factor of 1.3 improvement in signal to background has been demonstrated in this channel by using a neural network compared to standard cuts. It is also possible that additional gains may be had if the angular distributions (WH, spin zero, vs. $Wb\bar{b}$, spin one) can be exploited. $WH \to q\bar{q}'b\bar{b}$ is overwhelmed by the QCD background.
- $ZH \to \ell\ell b\bar{b}$: backgrounds from $Zb\bar{b}$, ZZ, $t\bar{t}$.
- $ZH \to \nu\nu b\bar{b}$: backgrounds from QCD, $Zb\bar{b}$, ZZ, $t\bar{t}$. This requires a relatively soft missing E_T trigger (35 GeV) but is powerful because of the large $Z \to \nu\nu$ branching ratio.

For Higgs masses above 130–140 GeV:

- $gg \to H \to WW^*$: backgrounds from Drell-Yan, WW, WZ, ZZ, $t\bar{t}$, Wt. The initial signal to background ratio is 1:140, so many, rather finely tuned, selections are

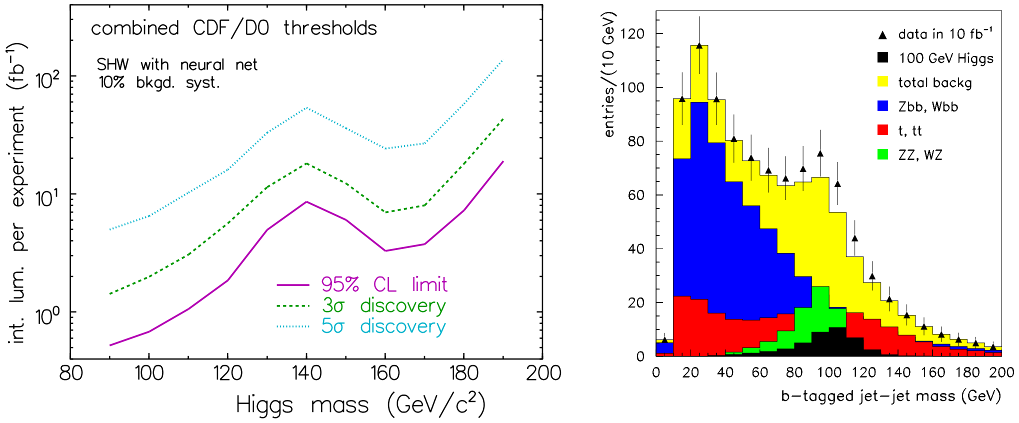

Figure 1. (left) Luminosity required at the Tevatron for Standard Model Higgs searches as a function of m_H. Background uncertainties of 10% have been included. (right) Higgs signal ($m_H = 100$ GeV) and background in the channel $p\bar{p} \to ZH \to \nu\bar{\nu}b\bar{b}$, for 10 fb^{-1}.

required, culminating in angular cuts to separate the signal from the "irreducible" WW background.

Combining all these search channels, and assuming a 10% systematic error on the backgrounds, one finds the sensitivity shown in Fig. 1. With 2 fb^{-1} of data, only a modest extension of the LEP reach is possible. With 15 fb^{-1}, on the other hand, it should be possible to either exclude, or observe at the 3–5σ level, a SM Higgs up to $m_H \sim 180$ GeV.

This is an exciting prospect. Is it credible? In my view, yes: it is an exercise similar in scale to the top discovery, with a similar number of backgrounds, and requiring a similar level of detector understanding. It will be harder — the irredicible signal to background ratio is worse — but it has caught the imagination of the experimenters. One problem with the studies so far (in my opinion) is the $b\bar{b}$ mass resolution. Can the assumed resolution really be attained in a high luminosity environment? The resolution not only affects the mass bins over which a Higgs signal would be smeared, but a detailed understanding of the shape of the $b\bar{b}$ mass spectrum will be needed to separate a putative Higgs signal from the nearby mass peak due to $Z \to b\bar{b}$ decays (see Fig. 1). For this reason, calibration samples of $Z \to b\bar{b}$ events will be very important. Tens of thousands of events (after cuts) are expected for 2 fb^{-1}, using a displaced vertex trigger, in both CDF and DØ.

2. Minimal Supersymmetry

Even the minimal spectrum of supersymmetry (the SM particles plus two Higgs doublets and their superpartners) can have many faces. Firstly, whether or not R parity is conserved determines whether the lightest supersymmetric particle (LSP) will or will not be stable. Secondly, how supersymmetry is broken determines the mass heirarchy of states and hence their decays. The typical benchmark, the supergravity-inspired or "minimal SUGRA" model, is determined by five parameters m_0, $m_{1/2}$, A_0, $\tan\beta$ and sign μ. In this picture, radiative electroweak symmetry breaking occurs naturally from the large top mass. The lightest neutralino is the LSP; the two lightest neutralinos, the lighest chargino and the lightest Higgs h are all "light", while the other charginos and neutralinos, squarks, gluinos and the other Higgs states are all "heavy" (above a few hundred GeV, perhaps). In gauge-mediated models, by contrast, the LSP is a gravitino, and there are signatures with photons and/or slow moving particles which may decay within or outside the detector. Recent anomaly-mediated models suggest that the lightest chargino and neutralino may be almost degenerate.

At LEP2, the increased centre of mass energy will allow the present SUSY limits to be raised by 5–10 GeV (my guess) with full use of data at and above 200 GeV.

At the Tevatron, the highest cross sections are for the pair production of colored particles like squarks and gluinos. As long as R-parity is conserved, the signature will be jets plus missing transverse energy ($\not\!\!E_T$). The Run I DØ analysis[7] required three jets (one with $E_T > 115$ GeV) and $\not\!\!E_T > 75$ GeV; it excludes squark masses below about 250 GeV and gluino masses below about 200 GeV[7]. This search may be combined with complementary channels where one or more leptons are required, together with jets and $\not\!\!E_T$ [8]. With 2 fb^{-1} of data the reach will approximately be doubled, to gluino masses of order 400 GeV[9]. For masses much larger than this, falling parton distributions kill the production rate very quickly. To extend the reach in parameter space, chargino/neutralino production will become increasingly important. Present searches in the "golden" trilepton mode do not really constrain models, but with 2 fb^{-1} of data, chargino masses up to 180 GeV should be probed (150 GeV if $\tan\beta$ is large)[9]. This places an emphasis on low-p_T lepton triggering, since one or more of the leptons tends to be soft. It would also help a lot if τ modes could be included.

In many models, the stop and sbottom squarks are significantly lighter than the others. It is therefore interesting to search for them separately. The decay channels involve b or c jets, and for stop there is also the possibility of $t \to \widetilde{t}$ decays or vice versa (depending on the masses). Present CDF limits[10] explore $m_{\widetilde{t}} \lesssim 120$ GeV and $m_{\widetilde{b}} \lesssim 145$ GeV; with 2 fb^{-1}, the sensitivity should improve to about 200 GeV[11].

Much interest in gauge-mediated supersymmetry was sparked a few years ago by the observation of a single $ee\gamma\gamma\not\!\!E_T$ event at CDF[12]. This final state is consistent with selectron production in a gauge mediated scenario. All we can now say is that searches for the expected related signatures have all proved negative: $\gamma\gamma\not\!\!E_T$ and $\gamma + \text{jets} + \not\!\!E_T$ at the Tevatron[4], and one or more photons plus missing energy at LEP[13].

This type of signature is just one example of what may be expected in gauge mediated models. Depending on the details of the model, the next-to-lightest superpartner or NLSP (which then decays into the gravitino LSP) may be a neutralino, a stau, or effectively more than one slepton state (if they are almost degenerate in mass). Prompt decays of the NLSP will then give final states containing photons+$\not\!\!E_T$, taus, and multileptons, respectively. Searching for such signatures is relatively straightforward. A more challenging possibility is that the NLSP has a finite decay length — since this is determined by the SUSY breaking interactions it is totally unknown. For neutralino NLSP's, decay lengths $c\tau$ more than a few metres will give standard $\not\!\!E_T$ signatures since the NLSP will escape the detector. Decay lengths of a few centimetres to a metre result in photons which do not point back to the primary vertex: searches at LEP[13] for such photons have excluded neutralino NLSP masses less than 85 GeV, for $c\tau < 1$ m. In Run II at the Tevatron, DØ will be able to make use of new preshower detectors upstream of the electromagnetic calorimeter to detect non-pointing photons. The resolution in the distance of closest approach to the vertex will be 2.2 cm along the beamline and 1.4 cm radially[14].

Charged NLSP's with long decay lengths appear as massive, slow-moving particles which exit the detector (so called "cannonballs"). LEP limits exclude stau NLSP masses less than 76 GeV, or slepton co-NLSP masses less than 85 GeV[3]. In Run II at the Tevatron, dE/dx and timing information will be available (using time of flight counters in CDF, and the muon system in DØ). CDF expect sensitivity up to stau masses of 180 GeV using the time of flight system[15]. Short decay lengths $c\tau \lesssim 1$ cm will give reconstructable impact parameters in the vertex detectors; 1 cm $\lesssim c\tau \lesssim$ 1 m is harder, especially to trigger. (With enough data, a combination of impact parameter and cannonball searches may be sensitive enough to exclude this intermediate region as well.) A general problem with understanding delayed decays is that event generators are not widely available, and the interface to the detector simulation is non-trivial.

Recently there has been considerable interest in anomaly-mediated SUSY models. The phenomenology of such models contains a light chargino which is almost degenerate with the LSP (a neutralino). Such small mass differences may result in delayed chargino decays, with cannonball type signatures, or decays inside the detector $\widetilde{\chi}^{\pm} \to \widetilde{\chi}^{0} + \text{soft } \pi$: very challenging indeed.

There is also considerable interest in scenarios with large extra dimensions. Gravitons may propagate into the higher dimensional space. Searches have been carried out[3] for $e^+e^- \to \gamma$+nothing, $p\overline{p} \to \gamma$+nothing, and $p\overline{p} \to$jet+nothing. Indirect effects have been searched for in $e^+e^- \to \gamma\gamma,\ \mu^+\mu^-,\ \tau^+\tau^-$.

Turning now to SUSY with R-parity violating decays, the usual assumption is that the R violating couplings are small compared with the R conserving ones. The production processes and subsequent decay chain then proceed as in minimal SUGRA, but the final LSP's decay via baryon or lepton number violating interactions. Hence there is no $\not\!\!E_T$ from the escaping LSP, but there are usually multi-leptons from cascade decays and $\not\!\!E_T$ from neutrinos. Both at LEP[3] and the Tevatron[16], it is found (perhaps surprisingly) that the excluded regions end up very comparable to those for mSUGRA with R conserved. R-violating couplings could also enter in the production of SUSY particles. At HERA, "leptoquark" searches have been interpreted in terms of $ep \to \widetilde{q}$[17], while at LEP, limits have been placed on processes like $e^+e^- \to \widetilde{\nu} \to \tau^+\tau^-$[18].

Both at LEP2 and the Tevatron, we therefore have a basic menu of supersymmetry searches which is well-defined and we should have no trouble in exploring:

- minimal SUGRA;
- gauge mediated supersymmetry with prompt photon signatures;
- some subset of R violation.

Our concerns are what we may have forgotten, especially at the Tevatron where triggering is a crucial issue. Can we cover:

- slow moving massive particles;
- gauge mediated supersymmetry with detached photons or taus;
- anomaly-mediated supersymmetry (*e.g.* $\widetilde{\chi}^{\pm} \to \widetilde{\chi}^0 + \text{soft } \pi$);
- general extra dimension signatures, *etc?*

A critical look at the proposed trigger lists is probably called for.

3. Supersymmetric Higgs

At LEP2, two complementary processes allow the neutral Higgs states of supersymmetric models to be explored: $e^+e^- \to (h/H)Z$ and $e^+e^- \to (h/H)A$. Combining these channels and the four experiments, one can exclude (Summer 1999[3]) $m_h < 81$ GeV and $m_A < 81$ GeV. Moreover, $0.9 < \tan\beta < 1.6$ ($0.6 < \tan\beta < 2.6$) is excluded for maximal (and for minimal) stop mixing. The $\tan\beta$ exclusion is very sensitive to the top mass, and it should be noted that there is no excluded range in $\tan\beta$ if $m_t = 180$ GeV. General scans of minimal SUSY parameter space find some points with strange decay patterns that can evade the limits, but these are rather few. Invisible Higgs decays have been included in the searches.

In Run II of the Tevatron, rather stringent limits will be set on the SUSY Higgs sector, given sufficient luminosity, since the whole allowed mass range for the lightest Higgs h ($m_h \lesssim 130$ GeV) is covered. One may also exploit the enhanced couplings between the Higgs states and b quarks at large $\tan\beta$ to search for $p\overline{p} \to b\overline{b}(h/A) \to 4b$. Using present data and requiring three b-tagged jets, CDF have been able to explore the region of $\tan\beta \sim 50$ and above[6]. With 10 fb^{-1} the sensitivity will extend to $\tan\beta = 30$ for m_A up to 150 GeV.

Supersymmetry also predicts the existence of charged Higgs states. Searches for pair production at LEP have excluded masses $m_{H^\pm} < 77$ GeV[3]. In minimal SUSY models, it is expected that $m_{H^\pm} > m_W$, and LEP is not really sensitive to this region. Searches at the Tevatron have concentrated on the production of $H^\pm$ in top decays[19] in competition with the standard $t \to W$ mode. This has been carried out both as an "appearance" experiment (looking for $H^{\pm} \to \tau$) and as a "disappearance" experiment (looking for fewer than expected $t \to e$ and μ). Present limits are sensitive only for $\tan\beta < 1$ and > 40, but with 2 fb^{-1} the sensitivity will extend to $\tan\beta \sim 2$ and 20.

4. Non-supersymmetric Electroweak Symmetry Breaking

There is no fully worked-out scenario for electroweak symmetry breaking through a new strong interaction, but this does not mean that it is not possible. Indeed, many schemes have been outlined in some detail, and a straw-man technicolor model is now implemented in PYTHIA[20]. In general, dynamical symmetry breaking schemes like technicolor and topcolor predict:

- new particles in the mass range 100 GeV – 1 TeV,
- with strong couplings and large cross sections,
- decaying to vector bosons and (preferentially third generation?) fermions.

Recently L3 has reported searches for technicolor resonances at LEP2[21], and several technicolor and topcolor searches have been made on present Fermilab data. All are negative so far. With Run II, the reach of the Tevatron will be greatly extended.

Besides all of the above scenarios, one should always be looking (at LEP, HERA and the Tevatron) for anything unexpected:

- leptoquarks
- fourth generation fermions, or isosinglet fermions
- W' and Z'
- contact interactions or compositeness, *etc.*

5. Conclusions

There are plenty of opportunities for us to find "something new" before the LHC starts operation. The standard scenarios have been explored in some detail, but different supersymmetry breaking schemes can produce radically different signatures. Theoretical fashion moves fast, and event generators are not always available. We need to keep an open mind in our searches. This is easy to say once one has the data in hand; the challenge right now is to ensure that we do our best to trigger on all possible interesting things, especially in the hadron collider environment.

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