Searching for the Higgs and other Exotic Objects

(A “How to” Guide from LEP to the LHC)

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Abstract

Methods and ideas to search for new phenomena at existing and future collider facilities like LEPII and the LHC are analysed. Emphasis is put on the experimental aspects of discovery strategies for the Higgs Boson of the Standard Model. This is followed by a critical analysis of search methods for the extended Higgs sector and the direct detection of Supersymmetric Particles within the Minimal Supersymmetric Standard Model. We also discuss methods and the potential mass reach of the LHC experiments to discover new Bosons and Fermions.

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1 Introduction

The search for new physics phenomena is often defined as the main motivation for new experiments at higher center of mass energies. This is especially true for the LHC project, with its two general purpose experiments ATLAS and CMS. The prime motivation of the LHC physics program is to discover the “mechanism of electroweak symmetry breaking” usually associated with a scalar particle, the Higgs boson. Theoretical ideas suggest that this hypothetical particle with a mass of less than roughly 1 TeV could explain the observed mass spectrum of bosons and fermions. The simplicity and mathematical elegance of this model leads however to its own problems, the so called hierarchy problem or fine tuning problem of the Standard Model.

These problems originate from theoretical ideas to extrapolate todays knowledge at mass scales of a few 100 GeV to energy scales which existed shortly after the Big Bang, e.g. to energies of about $10^{15}$ GeV and more. A purely theoretical approach to this extrapolation has lead theorist to SUPERSYMMETRY which could solve these conceptual problems by the introduction of supersymmetric partners to every known boson and fermion and at least an additional Higgs supermultiplet. Despite the largely unconstrained masses of these new partners, the potential to discover such new objects has become a central question for many design issues of future high energy particle physics experiments.

The search for the Higgs boson(s) and the search for the supersymmetric particles can be considered as “safe searches”, as they fit well into todays theoretical fashions. In addition to safe searches one might be tempted to search for less fashionable exotic new phenomena. Such new phenomena, like new forces leading to CP violation or lepton number violation, might simply exist because they are not forbidden by any fundamental reason. Such searches are often motivated by the possibility that the guidance from our theoretical methods has not yet reached a mature status. These exotic searches require certainly a “gambling mentality” as they lead to “all or nothing” results.

Having currently no clear experimental evidence for any exotic new phenomena or anomalies, our discussion on search strategies for new phenomena at future high energy colliders should be quite general. However, despite the few ideas discussed in section 4, we follow todays fashion and discuss mainly the ideas and detector requirements discussed for future succesfull searches for the Higgs and for Supersymmetry. The presented ideas and methods should nevertheless give a good guidance to other “all or nothing” searches. Consequently, todays simulation results of future LHC experimentation provide an important guidance on why one wants to participate in future LHC experiments and on how these experiments should look like.

This “how to guide” on searches is structured as follows. First we discuss some general , “how to”, experimental methods of searches and compare these with a few examples. The proposed methods to search for the Standard Model
Higgs boson at LEPII, at the LHC and at the TeV33 project are described in section 3. Search methods for additional heavy $W'$ and $Z'$ bosons are discussed in section 4. Finally in sections 5–8 we analyse SUSY discovery prospects in the extended Higgs sector or with direct SUSY particle searches at the LHC.

2 How to discover new physics?

Discovering new phenomena in high energy physics experiments means obviously to separate “new” from “known” phenomena. The used methods exploit the different kinematics of signals and backgrounds by looking directly for new mass peaks, or indirectly for measurable quantities like the $p_t$ spectra of leptons, photons and jets and their angular correlations. Other searches exploit the missing energy and momentum signature, which might either originate from unknown neutrino like objects, extra neutrino sources or simply from detector imperfections. Depending on the particular search project different aspects of the detector design become important. The search for mass peaks requires in general excellent energy and momentum resolution for individual particles with less stringent requirements on the angular acceptance. In contrast, searches based on the missing energy signature or the rate of events with special kinematic properties like events with inclusive leptons and multi–jets with high mass require robust detectors with almost perfect angular coverage.

Table 1 and Figure 1 combine required experimental observables with new physics possibilities.

| Type of measurements | indicates | required for |
|----------------------|-----------|--------------|
| isolated high $p_t\ e^{\pm}, \mu^{\pm}$ | $W^{(*)}, Z^{(*)}$ decays | Higgs search, top physics, “all” searches |
| isolated high $p_t\ \gamma$'s | electro-magnetic process | Higgs search |
| $\tau$ and $b$-quark tagging | “rare” processes | special Higgs like searches |
| large missing $p_t, E_t$ | $\nu$ like events, $W, Z$ decays | Higgs, Supersymmetry, exotic “exotica” |
| jets | quarks and gluons | QCD, understanding of backgrounds/efficiencies |

Table 1: New physics and some required detector capabilities.

Obviously, real experiments like the LEP or Tevatron experiments have to be a compromise between these different requirements. Nevertheless, the existing experiments have proven to work according or better than specified in their technical proposals. Especially astonishing results have been achieved with silicon micro vertex detectors, which allow to identify $b$–flavoured jets with high
Figure 1: Possible new physics signatures and the corresponding detector needs efficiencies and excellent purity. In addition, quite accurate calorimetric measurements allow to measure the missing transverse energy in complicated events. Such indirect identification of energetic neutrino like objects is now routinely used by essentially all large collider experiments.

The design objectives of the future ATLAS [1] and CMS [2] LHC experiments follow the above desired detector capabilities with emphasis on high precision measurements with electrons, muons and photons and large angular coverage for jets. According to their technical proposals both collaborations expect to identify isolated electrons and muons, with $p_t > 10$ GeV and small backgrounds up to a pseudorapidity ($\eta = -\ln \tan(\Theta/2))$ of $|\eta| \leq 2.5$ and efficiencies of $\approx 90\%$. Furthermore, both experiments expect to achieve b-jet tagging with up to 50% efficiency and light flavour jet rejection factors of up to 100. These expectations are used for essentially all simulations of LHC measurements. For justifications of these figures we refer to the various ATLAS and CMS technical design reports and internal technical notes [3].

2.1 New Physics from mass peaks and from tails?

Peaks in the invariant mass spectrum of assumed decay products are an unambiguous signature for new unknown particles. Narrow mass peaks do in principle not even require any theoretical background estimates as the signal significance can be estimated directly from the data and significance estimations for future experiments can be quite reliable. The reason becomes quite obvious from the
following example with an expected Signal of 1000 events above a background of 10000. Such a deviation from known sources could be claimed with a significance of about 10 standard deviations \( N(\sigma) = S/\sqrt{B} = 1000/\sqrt{10000} \). Assuming a relatively smooth flat background over many non signal bins, background extrapolations to the signal region can reach systematic accuracies of less than a percent. Under such ideal conditions, even large background uncertainties are acceptable. The significance of the above example would still correspond to about 5 standard deviations if the background would be increased by a factor of 4. Once a mass peak has been observed, one needs detailed signal Monte Carlos to determine cross sections and perhaps other quantities like spin and parity. Furthermore, signal and background Monte Carlos are usually required to eliminate obvious backgrounds with some kinematic selection criteria. Searchers should also remember that the advantages of optimised efficiencies, obtained with complicated selection methods, are easily destroyed by uncontrolled systematic errors. Other disadvantages of too much optimisation are model dependent phase space restrictions and the introduction of possible statistical fluctuations which increase with the number of studied cuts and mass bins.

In addition, it is not always an advantage to reduce signal and backgrounds to relatively small numbers when the significance has to be calculated from Poisson statistics! For example a simple \( \sqrt{B} \) estimate for 9 expected background events requires an observation of at least 24 events, e.g. an excess of 15 events above 9 background events, to claim a 5 \( \sigma \) excess above background. However, for small event numbers one finds that the \( \sigma = \sqrt{B} \) approximation is not good enough. A 5 \( \sigma \) excess requirement is equivalent to a background fluctuation probability of less than \( 6 \times 10^{-7} \). One finds, using Poisson statistics, that the required 5 \( \sigma \) excess corresponds to an observation of more than 27 events! Despite this reduced significance (roughly 1\( \sigma \)), systematic errors start to become important. For small background numbers the sideband method is limited by statistics and direct and clean background estimates from data might increase/decrease backgrounds and might be larger than Monte Carlo background estimates. The method to determine backgrounds, either from data or from Monte Carlo might thus hide or enhance a real signal and artificial good or bad limits can be obtained\(^\dagger\).

The possibility to observe fluctuations due to many mass bins appears nicely in a CMS simulation \( \Box \) of the two photons mass distribution for a SM Higgs with a mass of 130 GeV and backgrounds. Figure 2 shows a clear narrow peak at 130 GeV. The observed signal, assuming a simple straight line to estimate the background, corresponds to about 10 standard deviations. A more careful analysis of the mass distribution shows why at least five standard deviations are required to establish the existence of a new particle. Ignoring for example the simulated Higgs signal at 130 GeV, one might try to look for an excess of 1

\(^\dagger\)It is surprising that most searches appear to be “lucky”; e.g. the number of observed events is smaller than the number of expected background events.
events at an arbitrary mass. The largest excess of events appears at a mass of about 115 GeV. Taking the background from the sidebands one finds a statistical fluctuation with a significance of about three standard deviations. Thus, many possible mass bins combined with various event selection criteria are a remaining danger for mass peak hunters.

Despite the simplicity to discover new physics with mass peaks, most searches for new physics phenomena require an excess of events in special kinematic regions or tails of distributions. Some difficulties of such searches are indicated in Figure 3. The figure shows a random simulation of missing transverse energy events from $pp \to ZX \to \nu\bar{\nu}X$ and small statistics which is compared to a large statistic background simulation of the same process. Depending on the new physics signature, the small excess of tail events might coincide with a signal, expected for a certain range of missing transverse momentum $p_t$. For a missing $p_t$ between 600-720 GeV one could quote an excess of almost 3 sigma, e.g. 6 events are seen while a background of only 2 events are predicted. “Good arguments” might increase the significance for new physics further. For example one might argue that the Monte Carlo overestimates the backgrounds, as the sideband region between 400–500 GeV shows about 50% more events than found with the “pseudo data”. Some additional unexpected features of the 6 events might further be found to increase the significance further. Of course, in case one wants to exclude new physics, one would argue that the number of 7.63 predicted events with missing $p_t$ above 500 GeV is in perfect agreement with the observed 8 events. The above
example justifies the statement “never search in tails”. Unfortunately, most new physics scenarios, like SUPERSYMMETRY, would appear as rare events and in tails of distributions.

![Random Simulation LHC 14 TeV Jet Events with Missing $p_t$](image)

**Figure 3:** Simulation of a background fluctuation for events with missing transverse energy.

Thus, ingenuity is required to separate new physics from tails of known processes. Such searches require not only to have enough statistical significance but a method to determine backgrounds. The difficulty to establish a signal becomes clear from the following two examples. **Case a** is for a comfortable signal to background ratio of 1:1 while **case b** is for a ratio of 1:10. The required minimal statistics is easy to estimate. A 5 sigma excess needs a statistics of roughly 25 Signal events on top of a background of 25±5 for **case a** while **case b** needs about 250 signal events above a background of 2500±50. The statistical excess however is not enough as the expected background has some systematic errors like uncertainties from the efficiency, the luminosity and the theoretical background model. Assuming that all these uncertainties are known with an accuracy of ±5%, the significance of **case a** is essentially unchanged while the significance of **case b** is reduced to about 2 standard deviations.

It is worth noting that some studies claim to be “conservative” by multiplying backgrounds by arbitrary factors (method 1) or by using the error estimate from $\sqrt{S + B}$ (method 2).
Using case b and method 1 one sees no dramatic change of the estimated sensitivity. One finds that only the minimal luminosity requirement has to be increased. At the same time, the signal to background ratio became 1:20 and a ±5% systematic error would result in almost meaningless results!

The estimated sensitivity, using method 2, does essentially not change for a bad signal to background ratio. However, method 2 reduces a clear signal, like 10 observed events with one expected background event, to a modest 3 standard deviation signal.

We thus disagree with the claim that the above methods are conservative and reliable. In contrast, a correct approach to a possible significance figure should give the statistical sensitivity for new physics, estimated with $\sigma \approx \sqrt{B}$, and should describe how backgrounds can be estimated or at least how well they need to be known. Most sensitivity estimates do not provide answers to the latter requirements. Attention should thus be paid to the estimated signal to background ratio, which allows to estimate the required systematic accuracies.

### 2.2 Simulating the Future?

A growing fraction of the preparation time for a modern collider experiment deals with the simulation of case studies and especially the search sensitivity for new physics. Such studies are not only required in order to motivate the required effort, time and money but should also provide some guidance on “what is possible” and how a real detector should look like. Close to data taking, these studies can be considered as the last preparation step towards a fast data analysis and the resulting discoveries.

Furthermore, such early “theoretical” case studies, wanted or not, define very often new and original ideas and methods which are rarely quoted when used later in real experiments.

Among the many possible case studies, essentially all simulation studies concentrate on the SM Higgs search, “question number 1” and on SUSY particle searches. The investigated signatures provide thus not only “dream-land” possibilities for a future collider but, as will become clear in the following, cover a wide range of detector requirements which help to shape the final and real experiment.

#### 2.2.1 The Higgs Search at LEP

The possibility to search for the Higgs particle at LEP has been a central question for the LEP physics program. With the now finished LEP I phase, it is interesting to compare the results of early simulation studies with the actual searches used at LEP.

The first studies, performed well before the discovery of the $W^\pm$ and $Z^0$, are described in a DESY preprint from 1979 [5]. The studies concentrated, among other possible channels on the signature $e^+e^- \rightarrow Z^{0(*)}H^0$. Their conclusions on
the neutral Higgs were:

“The best production process seems to be \(e^+e^- \rightarrow Z^0(\ast)H^0\), which should give reasonable rates for \(M_H\) up to \(\sqrt{s} - M_Z\). Even if a clear signature from the \(H^0\) is not available, the decays of the \(Z^0 \rightarrow e^+e^-\) or \(\mu^+\mu^-\) should provide a clear signature for this reaction. The mass and width of the Higgs could be measured quite precisely from the threshold behaviour.”

The study concluded further that \(Z^0\) decays at LEPI should allow to detect a Higgs with a mass of about 50 GeV using the \(e^+e^-H^0\) or \(\mu^+\mu^-H^0\) channel.

This early study was followed by more detailed “LEP Yellow book” studies in 1985/86 [6] and in 1989 [7] which essentially confirmed the 1979 studies. The most promising signature was identified to be the dilepton channel, \(e^+e^-H^0\) or \(\mu^+\mu^-H^0\), resulting in a mass sensitivity of about 35 (55) GeV for \(10^6 (10^7)\) produced \(Z^0\)’s. The 6 times larger cross section of the neutrino channel, \(\nu\nuH^0\), was also discussed. However, it was believed that this channel could at best confirm the results from the dilepton channel. Following the discussion in the 1989 yellow report it appears that the superiority of the neutrino channel, at least for Higgs masses between 5-20 GeV, has first been realized in a study by Duchovni, Gross and Mikenberg [8].

The actual performed searches at LEPI [9] gave negative results. It was nevertheless somehow surprising that the most significant results where obtained from the neutrino channel with individual experimental limits as high as 60-62 GeV. In contrast, the “golden” dilepton channel gave roughly the expected sensitivity of up to about 50 GeV. The reasons for these essentially wrong sensitivity estimates are perhaps the unexpected performance of the LEP experiments with respect to the complete angular coverage and the resulting missing energy detection and the absence of \(t\bar{t}\) production in \(Z^0\) decays. Furthermore, one should keep in mind that the early studies were aiming for an unambiguous signal to measure the mass and width and not for the discovery signature. It was thus natural to concentrate on the simplest Higgs signature provided by the dilepton channel.

### 2.2.2 SM Higgs search at LEP II

The first detailed studies for the Higgs search at LEPII were performed for the 1986 LEPII workshop [10] in Aachen\(^2\). Besides the b-lifetime tagging, essentially all required techniques and channels were identified and studied in detail. Without the tagging of b-jets the conclusion was that all channels provide signals up to masses of about 80 GeV. The accuracy of the dilepton channel combined with high statistics was thought to give results up to masses of up to 90 GeV.

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\(^2\)These studies were much more detailed than the comparable 1985/86 and 1989 studies for the LEPI phase.
The 1996 LEP II studies [11] could benefit from the now well understood experiments, combined with excellent b-lifetime tagging results. Consequently, the obtained Higgs sensitivity results from the 1997 data taking at $\sqrt{s} = 183$ GeV agree well with the expectations, but do still not show any sign of excess as shown in Figure 4 [12].

![LEP candidates at 183GeV](image-url)

Figure 4: Observed mass distribution of Higgs candidates from the four LEP experiments and $\sqrt{s} = 183$ GeV (1997 data) [12].

In fact, one finds in general a reasonable agreement between the data and Monte Carlo expectations without any sizeable excess at a fixed mass. A more careful investigation shows however some remarkable effects. The observed mass distribution for Higgs candidates from the four LEP experiments and an early fraction of the 1998 data is shown in Figure 5 [12].

The total number of 32 seen events agrees with an expectation of about 31 events. This good agreement is somehow spoiled by the fact that about 11 candidates are expected for masses below 80 GeV while 19 events are found from the data. This excess is compensated by a deficit for masses above 80 GeV with 20 expected and 13 seen events. It appears to be tempting to use this mass distribution not only to exclude the SM Higgs production up to a mass of roughly 95 GeV, but also to put doubts on the Monte Carlo background expectations. The simple splitting might perhaps exclude the SM background estimation with a confidence level of about 95%.
While preparing this article, not even rumours of excess Higgs candidates are known. One might thus guess that this year’s combined LEP limit might be as high as 97 GeV, using a luminosity of about four times 180 pb$^{-1}$ at $\sqrt{s} = 189$ GeV. The possible final Higgs sensitivity from the 1999/2000 data taking at LEPII has been estimated to be about 105 GeV, using a luminosity of about $4 \times 200$ pb$^{-1}$ at $\sqrt{s} = 200$ GeV [13].

### 3 The future of the SM Higgs search

As discussed above, one hopes that the 4 LEP experiments should have a combined sensitivity to a SM Higgs with a mass close to 105 GeV. Assuming that nothing will be found at LEPII, SM calculations can be used as a guidance for the Higgs search at future colliders. We thus start this section with a discussion on calculations about the expected SM Higgs mass. We then describe Higgs search strategies at the LHC and discuss the question of a potential Higgs window at the Tevatron.
3.1 The Higgs Mass and Electroweak precision tests

Starting with the assumption that the SM is a good approximation of nature, the Higgs boson and its mass remains to be discovered. The mass of the Higgs can be constrained indirectly by the requirement that all measurements of electroweak observables, like the various asymmetry measurements at LEP and SLD, as well as the mass of the top quark and the $W^\pm$ are consistent. The accuracy of this procedure is however limited as there is only a soft logarithmic Higgs mass dependence. Nevertheless, a fit to all precision data constrains the SM Higgs mass to $76 \pm 85 \pm 10$ GeV and less than about 300 GeV. One should however mention that the same procedure leads to a prediction of the top mass of $161 \pm 8$ GeV, slightly below the measured value of $173.8 \pm 5$.[14]

![Figure 6: $\Delta \chi^2$ result of a SM fit to all electroweak observables assuming to have the Higgs mass as the only remaining free parameter.](image)

Furthermore, a recent analysis by J.H. Field[15] shows that $\sin^2 \Theta_W$ measured from lepton asymmetries differs by more than 3 sigma from the $\sin^2 \Theta_W$ measurements with $b$-quarks. It appears that the simplest explanation are unknown systematic errors for asymmetry measurements with $b$-quarks. It could thus be justified to exclude the $b$-asymmetry measurements from the precision data. Such an approach[15] reduces the 95% upper limit for the possible Higgs masses to values lower than 200 GeV. Alternatively, one could argue that the data indicate some new physics in the $b$-sector and do therefore not allow to draw strong conclusions for the SM Higgs sector.

Thus, ignoring the problems related to the $b$-sector, the 1998 electroweak
precision data result in upper limits for the SM Higgs mass somewhere between 200–300 GeV. This value, assuming that only the Higgs remains to be discovered, appears to be in nice agreement with consistency calculations of the SM \[16\], which leads to a Higgs mass prediction of roughly $160 \pm 20$ GeV as shown in Figure 7.

![Figure 7](image)

Figure 7: The area between the two black curves shows the allowed Higgs mass range assuming the validity of the Standard Model up to a scale $\Lambda$ \[16\].

Such calculations lead to interesting implications. For example, a Higgs discovery with a mass of 100 GeV at LEPII or with a mass of 300 GeV at the LHC would immediately imply to have other new physics perhaps within the reach of the LHC experiments. Furthermore, once new physics is introduced, the assumptions used to constrain the Higgs mass from SM precision measurements are not valid. Thus even today's excluded Higgs, with a mass of 500 GeV might be in perfect agreement with today's precision data and a "slightly" enlarged model. Without new ideas in sight, the expected small improvements of the electroweak parameters will neither result in a precise Higgs mass prediction nor will allow to show unambiguously an inconsistency with the SM.

One can thus conclude that a Higgs or other new particles have to be discovered directly.
3.2 SM Higgs Search at the LHC

Figure 8 shows the results of Higgs cross section calculations \[17\] at the LHC for various production processes as a function of the Higgs mass. By far the largest contribution comes from the gluon–gluon fusion process \[18\].

To study the different Higgs signatures, the total cross section has to be multiplied with the various branching ratios \[19\]. Figure 9 shows estimated $\sigma \times BR$ for promising Higgs search modes, $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)} \rightarrow 4\ell^{\pm}$, and $H \rightarrow WW^{(*)} \rightarrow \ell^+\ell^-\nu\bar{\nu}$. The first two signatures allow a precise and direct mass reconstruction, but require a high luminosity due to the small detectable cross section. The third signature was recently studied and found to be very sensitive especially for the Higgs mass range between 155–180 GeV \[20\]. It was found that the absence of a narrow mass peak can be compensated by the large event rate.

For Higgs masses above $\approx 500$ GeV several additional and promising signatures involving hadronic $W$ and $Z$ decays as well as invisible $Z$ decays like $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ have been discussed. The advantages of much larger branching ratios are compensated by serious backgrounds from events of the type $tt\bar{t}$, $WX$ and $ZX$. These high mass Higgs signatures involve missing transverse energy and jet–jet masses and require thus hermetic detectors with good jet energy reconstruction.

Figure 8: Recent NLO cross section estimate for the SM Higgs \[17\].
A few simulated promising Higgs signals for different masses and signatures are shown in Figures 2 and 10-14. Recent estimates from ATLAS [1] and CMS [2] indicate that a luminosity of about 10 fb$^{-1}$, about 1 year of running with the initial “low” luminosity of 10$^{33}$ sec$^{-1}$ cm$^{-2}$ is required to discover a SM Higgs with masses between 200–500 GeV with at least 5 standard deviation in the four charged lepton channel.

For example, the ATLAS study [21] shows that a Higgs ($M_H = 300$ GeV and $H \rightarrow ZZ \rightarrow 4\ell^\pm$) should be seen with 35 signal events above a continuum background of $\approx 13 \pm 4$ events and 10 fb$^{-1}$. The ATLAS study indicates also that the signal to background rate can be improved dramatically by requiring that one reconstructed $Z$ has a $p_t$ of more than $M_H/2$. The corresponding event numbers for a 300 GeV Higgs would be 13 above a very small background of 0.6 events.

The most promising signature for a SM Higgs with masses between the expected LEPII limit, $\approx 100$ GeV, and 130 GeV is the decay $H \rightarrow \gamma\gamma$ with a branching ratio of only $\approx 2 \times 10^{-3}$. As such a signal has to be found above a huge background of continuum $\gamma\gamma$ events, as shown in Figures 2 and 11, an excellent $\pi^0$ rejection and $\gamma\gamma$ mass resolution of $\approx 1\%$, e.g. 1 GeV for $M_H \approx 100$ GeV, is required for a 5 standard deviation signal.
Figure 10: CMS simulation results for $H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ and $M_H = 300$ GeV and $M_H = 500$ GeV.

Figure 11: ATLAS simulation for $H \to \gamma\gamma$ with $M_H = 120$ GeV and backgrounds.
For Higgs masses between 130 GeV and 200 GeV the $4\ell^{\pm}$ signature suffers from very low branching ratios and a 5 standard deviation signal requires high luminosities of at least 30–100 fb$^{-1}$.

![Graph](image)

**Figure 12:** CMS simulation for $H \rightarrow ZZ^* \rightarrow \ell^{+}\ell^{-}\ell^{+}\ell^{-}$ and $M_{H} = 130, 150$ and $170$ GeV.

A recent study has demonstrated that this Higgs mass region can be covered by the channel $H \rightarrow WW^{(*)} \rightarrow \ell^{+}\nu\ell^{-}\bar{\nu}$ [21], [22]. The performed analysis, described in section 3.3, shows that this channel should allow to discover a SM Higgs with 5 standard deviation for a Higgs mass between 140–200 GeV and luminosities below 5 fb$^{-1}$.

For Higgs masses above 500 GeV the natural width is already quite large and the mass resolution becomes less important. Therefore, additional signatures with neutrinos and jets from hadronic $W$ and $Z$ indicate very promising and competitive Higgs discovery channels as indicated in Figures 13 and 14.
Figure 13: CMS simulation results for $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-$. 

Figure 14: ATLAS simulation results for $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$. 

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3.3 SM Higgs search with $H \to W^+W^-$

A recent simulation analysis has demonstrated that the previously ignored signature $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ allows to close the “last” LHC Higgs detection gap. Furthermore, it has been shown that this signature should provide even the first sensitive Higgs results at the LHC.

The analysis exploits mainly two differences between a SM signal and the non resonant background from $pp \to W^+W^-X$. The two most important criteria from the analysis [20] were:

1. As shown in the left part of Figure 15, the signal events from gluon–gluon scattering are more central than the $W^+W^-$ background from $q\bar{q}$ scattering. This difference is exploited by the requirement that the polar angle $\theta$ of the reconstructed dilepton momentum vector, with respect to the beam direction, satisfies $|\cos \theta| < 0.8$. As a result, both leptons are found essentially within the barrel region of the experiments with $|\eta| < 1.5$.

2. The $W^+W^-$ spin correlations and the V–A structure of the $W$ decays result in a distinctive signature for $W^+W^-$ pairs produced in Higgs decays. As shown in Figure 15 (right side), for a Higgs mass close to $2 \times M_W$ the $W^\pm$ boost is small and the opening angle between the two charged leptons in the plane transverse to the beam direction is very small.

![Figure 15: Signal and background distributions for the $|\cos \theta|$ distribution of the dilepton system with respect to the beam direction (left) and for $\cos \phi$, where $\phi$ is the angle between the two leptons in the plane transverse to the beam, after central dilepton events are selected (right).](image-url)
The other proposed criteria enhance the signal to background ratio by using indirectly the slightly different lepton momentum spectra. Following the proposed strategy [22], statistical significant Higgs signals can be obtained with a good signal to background ratio and a mass range between roughly 130–200 GeV as shown in Figure 16. The studied distributions indicate also that backgrounds can be determined, with good accuracy, directly from the data.

![Graph](image)

**Figure 16:** SM Higgs signal over background ratio (a) and (b) the required luminosity to obtain a 5 standard deviation statistical significance signal with $pp \rightarrow H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ for $M_H$ between 120 GeV and 500 GeV.

The resulting lepton $p_t$ spectra are shown in Figure 17 for a Higgs mass of 170 GeV. One finds that the lepton $p_t$ spectra are very sensitive to the Higgs mass as indicated in Figure 18.
Figure 17: Expected lepton $p_t$ spectra for $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^\ `-\bar{\nu}$ and a mass of 170 GeV. The signal is superimposed to various SM backgrounds.

Figure 18: Expected lepton $p_t$ spectra for $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^\ `-\bar{\nu}$ and three different Higgs masses.
3.3.1 New ideas for LHC Higgs searches?

The search for a Higgs with a mass below $\approx 130$ GeV relies currently only on the ability to measure the rare decay $H \rightarrow \gamma\gamma$ with a branching ratio of about $1-2 \times 10^{-3}$ above a $\approx 10-20$ times larger $\gamma\gamma$ continuum background. This channel requires background free photon detection with high efficiency and excellent mass resolution of $\approx 1$ GeV. It is thus interesting to combine this channel with possible alternatives. Recent theoretical studies, presented at the 1998 CERN theory workshop [23], discuss the possibility to improve the signal to background ratio drastically using jet tagging.

For example, D. Zeppenfeld [24] discussed a parton level study of the vector boson fusion Higgs production $qq \rightarrow q\bar{q}H$ using double jet tagging and the decay $H \rightarrow \gamma\gamma$. Additional background suppression is obtained from the different rapidity distributions of the underlying event. Their study indicates that a signal to background ratio of about 1:1 is obtainable, paying however the price of very low signal rates of about 11 events for a luminosity of 10 fb$^{-1}$. Some experimental studies within ATLAS and CMS have tried a similar approach to exploit the forward jet tagging. Unfortunately the obtained backgrounds from the ATLAS study [25] are roughly a factor of four larger than the ones obtained with similar criteria performed by the CMS group [26].

Another approach tries to exploit the $H \rightarrow \gamma\gamma$ signature using the different $p_t$ spectra for a Higgs signal and backgrounds [27]. Furthermore, very different angular distributions between jets and photons from signal and background where shown. This study indicates an interesting potential for a considerable improved signal to background ratio to at least 1:3 for a $\pm 1$ GeV signal window. This ratio should be compared to the inclusive study which results in a ratio of about 1:20 for the same mass window. The price to be paid seems to be a factor of 10 smaller efficiency. Consequently, taking just a statistical error estimation, the numbers do not really imply an improvement. However it appears possible that the suggested kinematic differences between signal and backgrounds allow rather nice systematic studies of a potential signal and should encourage further investigations.

Other ideas suggest to exploit the $H \rightarrow \gamma\gamma$ channel in the associated Higgs production channels $WH$ and $ttH$ [28]. The performed studies indicate signal to background ratios of roughly 6:1. The signal rate is however reduced to cross sections of only 0.1-0.2 fb, resulting in 1-2 accepted events for 10 fb$^{-1}$. Assuming that a high photon detection efficiency combined with low misidentification can be obtained, this channel might provide important additional significance.

We conclude, that a possible discovery signal from the $H \rightarrow \gamma\gamma$ signature relies not only on an excellent electro-magnetic calorimeter, but perhaps also on unknown improved analysis strategies.

Having discussed the rare decay $H \rightarrow \gamma\gamma$ one is tempted to ask about the possibility to search for the dominant decays $H \rightarrow b\bar{b}$ and $H \rightarrow \tau\tau$. Early
estimates have studied the potential of the above decay modes using the inclusive production of $gg \rightarrow H$ and concluded that even the most optimistic signals would be much to small [28]. Nevertheless, the potential of the associated Higgs production $WH$ and $t\bar{t}H$ and $H \rightarrow b\bar{b}$ has been studied in quite some detail [29]. Assuming an almost perfect b-jet identification with efficiencies between 30-50% and background rejection factors of about 100 only small signal to background ratios of about 1/50 have been obtained. The claimed statistical significance for 30 fb$^{-1}$ and a 120 GeV mass Higgs reaches at most 2-3 standard deviations. A judgement of the proposed signal relies on the possible systematic uncertainties which unfortunately, are not discussed.

The search for the associated Higgs production $WH$ and $t\bar{t}H$ and the decay $H \rightarrow \tau\tau$ suffers from the difficulty to reconstruct a mass peak. Nevertheless, a detailed study might still show that some signal indications can be obtained. Thus, after Higgs indications have been seen with other channels, the $H \rightarrow \tau\tau$ might give additional information.

Recently, the topology of events $gg \rightarrow H \rightarrow b\bar{b}$ has been compared to the one from $gg(q\bar{q}) \rightarrow b\bar{b}$ continuum production. The study shows that the hadrons produced between the observable jets and between the jets and the beam direction should be quite different for signal and background [30]. Keeping the expected excellent b-tagging capabilities of ATLAS and CMS and the large Higgs rate, $\sigma \approx 50$ pb in mind, one might eventually reconsider the inclusive $H \rightarrow b\bar{b}$ signature. A possible strategy might combine the different hadron production between the jets with the ideas discussed for the selection of Higgs events with large $p_t$ as presented above for the $H \rightarrow \gamma\gamma$ channel [27].

### 3.4 A Higgs window at the Tevatron Run III?

While patient physicists are waiting and preparing for a Higgs discovery at the LHC, others are trying to find the Higgs at LEPII or to investigate Higgs possibilities with Run III at the Tevatron collider. The upgraded Tevatron machine and experiments expect to analyse proton-antiproton collisions at a center of mass energy of 2 TeV and a yearly luminosity of about 1 fb$^{-1}$/year, Run II, starting in the year 2000. Machine physicists are looking into possibilities to increase this luminosity further. It seems possible to increase the luminosity by another factor of 10, the so called RUN III or TeV33 phase which should lead to roughly 10 fb$^{-1}$/year. Such a luminosity matches the requirements from theoretical parton level studies which show some SM Higgs sensitivity in the channel $WH \rightarrow \ell\nu b\bar{b}$ [31]. As the search for the Higgs appears to be the main issue of future collider physics, it is important to study this TeV33 possibility in some detail. In the following we will discuss the results of the TeV2000 study group [32] and compare them with today's experimental facts.

The basics for the discussion about the Higgs sensitivity at the Tevatron Run III rely essentially on the demonstrated b–jet tagging capabilities of the modern
silicon micro vertex detectors with single hit resolutions of 10-20 µ with high efficiencies and the experimental results on b physics from the CDF experiment. A further very encouraging CDF result [33] shows a ≈ 3 sigma signal for the decay $Z^0 \rightarrow b \bar{b}$. Despite the low signal efficiency, roughly 100 events are extracted from a total estimated production rate of about $10^5$, the obtained signal demonstrates the possibility to select an object decaying to $b \bar{b}$ jets.

3.4.1 The Higgs sensitivity claim

A detailed experimental analysis [32], following the original parton level study [31] has been performed for the TeV2000 study. The investigated signature consists of events with one “isolated” electron or muon and a two-jet system with a mass window of roughly ± 20 GeV around the assumed Higgs mass. Both jets are tagged as b–flavoured jets assuming a tagging efficiency of 50% per jet while the efficiency for other jets is assumed to be roughly 0.5%. Combining all the criteria a signal efficiency of 10% is obtained for $WH \rightarrow l\nu b \bar{b}$ and Higgs masses between 100-120 GeV. The expected SM Higgs signal for 10 fb$^{-1}$ drops from 52 events above a background of 249 events for a mass of 100 GeV to a signal of 27 events above a background of 130 events. The corresponding expected invariant mass distributions are shown in Figure 19.

![Figure 19: Expected Higgs signal plus background mass distribution for 10 fb$^{-1}$ at the upgraded Tevatron](image)

As a result one finds a statistical significance (assuming $\pm \sqrt{N_{\text{back}}}$) of 3.3 sigma for a mass of 100 GeV decreasing to 2.4 sigma for a mass of 120 GeV.
No comments are made on possible systematic uncertainties. These somehow encouraging results might be slightly improved, if combined with other $W$ decay modes and with $ZH \rightarrow \ell\ell b\bar{b}$. Taking these estimates, one might indeed conclude that there is some Higgs sensitivity for the Run III program.

To investigate the claim a little more we have compared the Run III assumptions with a real analysis from the existing CDF experiment published in 1997 [34]. This analysis was based on a total luminosity of $109 \pm 7 \text{ pb}^{-1}$ collected during the RUN I. The used event selection criteria are quite similar to the ones from the TeV2000 study group. The main difference are the lepton acceptance window of $|\eta| < 1$ compared to an assumed window of $|\eta| < 2.5$. Figure 20 shows the observed jet–jet mass distribution for the selected candidates.

![Figure 20: Observed and expected two-jet mass distribution from CDF in $W \rightarrow \ell\nu + 2$ jet events from single (a) and double (b) tagged b-jets events and $109 \text{ pb}^{-1}$ [34].](image)

Using the achieved signal efficiency of $0.4 \pm 0.11\%$ a cross section limit of about 10 pb is obtained. This is about a factor of 100 larger than the expected SM Higgs cross section, as shown in Figure 21.

Furthermore, the observed candidates agree with the background expectation of roughly one event for a $\pm 20$ GeV mass window. One thus finds that today’s background, obtained for an efficiency of 0.4%, should give an expected background of about 100 events for a luminosity of 10 fb$^{-1}$. Such a background rate agrees with the theoretical estimates, which assume however a factor 20 higher signal efficiency. The expected detector improvements for RunII, as given in [34], are estimated to increase a signal efficiency to about 1%.
Figure 21: The 1997 CDF experimental 95% C. L. upper cross section limit, using a luminosity of 109 pb$^{-1}$, for the associated production of a resonance X in WX events (black squares). The dotted line shows the theoretical SM WH cross section [34].

We are thus tempted to conclude that some factors, summarised in table 2, are still missing before one could claim that a SM Higgs window exists at the Tevatron with 30 fb$^{-1}$. This is even more true for theoretical optimists which hope to have some sensitivity for supersymmetric Higgs particles with lower detectable cross sections [35].

| existing efficiency | expected | required |
|---------------------|----------|----------|
| 0.4 ± 0.11 %        | 1%       | ≈ 10%    |
| ∆M (b-b jet)        | 15 GeV   | 15 GeV (?)| 11 GeV |
| background events    | ≈ 100    | ??       | ≈ 100 |
| systematic error     | ± 25%    | ??       | << 10% |

Table 2: Comparison of the existing, expected and required detector capabilities for the Tevatron Higgs potential.
4 Aspects of Searches for non Mainstream Exotica

The combination of high energies and luminosity allows to dream even of a discovery of unfashionable and unpredicted new phenomena. The more conventional searches hope for fourth family quarks and leptons or additional bosons like a $Z'$ or $W^{\pm'}$ and compositeness. Other searches look for new objects with fancy names like axigluons, mirror fermions, color octet technirho, massive stable sextets and octets etc. The motivation to search for such objects is mostly a "why not" or "what is not forbidden might be allowed".

Figure 22: Existing and expected CDF sensitivity for massive exotica [36]. The maximum mass reach for LEP and HERA experiments is also indicated.

Many such negative searches have been performed and published by essentially all experiments at high energy collider experiments. The main simplified search method (should) proceeds along the following steps:

1. Find a particular attractive and unexplored window to search for new physics.
2. Identify a “clean” signature for the exotic object which separates the new from the old.
3. Compare data and Monte Carlo using common sense.
4. Publish the result and start again.
Having almost an infinite list of possibilities, we prefer not to describe any details of such exotic searches but refer to the latest particle data book [37] and the references therein. In most cases it appears to be relatively easy to extrapolate the existing null results to future experiments at higher energies and luminosities. In general one expects a factor of \( \approx 2 \) in mass reach from the upgraded Tevatron (RUN II) as shown in Figure 22. Assuming no additional magic backgrounds at the LHC, ATLAS and CMS should increase the sensitivity well into the TeV mass range, about a factor of \( \approx 7 \) larger than the Tevatron RUN II.

Following our believe that the search for additional vector bosons at higher masses is a particular interesting area we will describe such possibilities in some detail.

4.0.2 LHC signals for \( W' \) and \( Z' \)

The sensitivity of ATLAS [38] for heavy \( W' \) bosons, \( W' \rightarrow e^\pm \nu \) has been studied using events with isolated high \( p_t \) electron with large missing transverse momentum. A \( W' \) would show up like a “peak” in the transverse mass spectrum above the steeply falling \( W^* \) continuum background, as shown in Figure 23. The analysis shows good sensitivity for \( W' \) bosons with masses up to 6 TeV and an integrated luminosity of 100 fb\(^{-1}\).

![Figure 23](image)

Figure 23: ATLAS simulation of the transverse mass distribution for the Standard Model \( W \) production and an exotic \( W' \) scenario.
Heavy additional $Z'$ bosons with TeV masses might for example show up as a mass peak in the dilepton invariant mass spectrum. Such a $Z'$ might be discovered, depending slightly on its couplings to fermions, up to masses of about 4 TeV. Assuming that such a $Z'$ would couple to quark pairs and lepton pairs like the SM $Z^0$, its mass and width could be measured at the LHC. Furthermore, the different $x$ distribution of valence quarks and sea antiquarks allow to analyse the forward backward charge asymmetry and thus study the couplings to quarks and leptons and the interference with the $Z^0$ and $\gamma$ in quite some detail. The results of a simulation \[39\], including realistic experimental criteria, for the $M_{\ell^+\ell^-}$ mass distribution and the corresponding forward backward lepton charge asymmetry are shown in Figure 24 for the SM and two different $Z'$ models.

![Graph showing expected dilepton mass distributions and asymmetries](image)

Figure 24: a) Expected dilepton mass distributions (a) and asymmetries (b) for the Standard Model and for two exotic $Z'$ scenarios.
5 Mainstream MSSM SUSY Searches

Among the many possible extensions of the Standard Model the Minimal Supersymmetric Standard Model (MSSM) is usually considered to be the most serious theoretical frame. The attractive features of this approach are:

- It is quite close to the existing Standard Model.
- It explains the so called hierarchy problem of the Standard Model.
- It allows to calculate.
- Predicts many new particles and thus “Nobel Prizes” for the masses.

These attractive features of the MSSM are nicely described in a Physics Report from 1984 by H. P. Nilles [40]. We repeat here some of his arguments given in the introduction:

“Since its discovery some ten years ago, supersymmetry has fascinated many physicists. This has happened despite the absence of even the slightest phenomenological indication that it might be relevant for nature. .... Let us suppose that the standard model is valid up to a grand unification scale or even the Planck scale $10^{19}$ GeV. The weak interaction scale of 100 GeV is very tiny compared to these two scales. If these scales were input parameters of the theory the $(mass)^2$ of the scalar particles in the Higgs sector have to be chosen with an accuracy of $10^{-34}$ compared to the Planck Mass. Theories where such adjustments of incredible accuracy have to be made are sometimes called unnatural.... Supersymmetry might render the standard model natural... To render the standard model supersymmetric a price has to be paid. For every boson (fermion) in the standard model, a supersymmetric partner fermion (boson) has to be introduced and to construct phenomenological acceptable models an additional Higgs supermultiplett is needed.”

Figures 25 and 26 [11] compare the consistency of the various electroweak measurements with the SM and the MSSM.

The largest difference, shown in Figure 26, appears in the relation between the $W^\pm$ mass and the top mass. Unfortunately todays data, $M_W = 80.39 \pm 0.06$ GeV and $M_{top} = 174 \pm 5$ GeV, favour an area which is perfectly consistent with both models. One might thus conclude that it is not possible to decide between the SM and the MSSM without finding direct evidence for SUSY particles.

As mentioned above, SUSY predicts a doubling of the fundamental fermions and bosons and requires at least 5 Higgs bosons. Beside the lightest, possibly invisible SUSY particle, one knows from the absence of such new particles that their masses have to be heavier than $\approx 100$ GeV. SUSY searches can be divided into a) the MSSM Higgs sector and b) the direct SUSY particle search.
Figure 25: Comparison of $Z^0$ precision measurements with the Standard Model and the MSSM with $\tan\beta = 1.6$ and very heavy SUSY particles [41].

6 Searching for the MSSM Higgs sector

The MSSM Higgs sector is highly constraint. With the known mass of the top quark, all Higgs masses are strongly related. For a fixed mixing angle between the stop quark and the Higgs one usually expresses all other Higgs masses as a function of $\tan\beta$ and $M_A$. The relations become particular easy for masses of $M_A$ larger than $\approx 200$ GeV when the masses of $M_A$, $M_{H^0}$ and $M_{H^\pm}$ are essentially degenerate and the mass of the lightest scalar Higgs, $h^0$, depends only on $\tan\beta$ and the mixing angle, resulting in an upper mass limit of about 120-130 GeV for at least one Higgs boson [42]. Thus, the search for a fundamental scalar particle with a mass below 130 GeV is often considered to be the most important test of the MSSM [35]. However, recent theoretical calculations show that this upper mass limit can be increased to masses of up to 200 GeV if additional Higgs doublets are introduced into the model [43]. One might argue that at least the
Figure 26: Expected relation between \( M_W \) and \( M_{\text{top}} \) in the Standard Model and the MSSM, the bounds are from the non-observation of Higgs or SUSY particles at LEP II [41]. The 1998 experimental area, with \( M_W = 80.39 \pm 0.06 \text{ GeV} \) and \( M_{\text{top}} = 174 \pm 5 \text{ GeV} \) is also indicated.

"minimal" of the MSSM model remains testable \(^3\).

For studies of the MSSM Higgs sector one usually assumes that the Higgs bosons can decay only to SM particles, e.g. that all SUSY particles are heavy. Furthermore, once the Higgs masses are fixed, couplings and kinematically possible decay modes are constrained mainly from \( \tan \beta \) and the mixing angle. Detailed branching ratio calculations can be found in reference [44]. Qualitatively one finds that the lightest Higgs, \( h^0 \), looks in all respects like the SM Higgs if the mass of the \( A \) is large, \( M_A > 400 - 500 \text{ GeV} \). Consequently, the lightest MSSM Higgs \( h^0 \) should be discovered at LEP II if \( \tan \beta \) is smaller than about 4, e.g. \( m_h \) is smaller than \( \approx 100 \text{ GeV} \) or at the LHC with the channel \( h \to \gamma \gamma \). if \( \tan \beta \) is larger than about 4.

\(^3\)Instead of discussing the meaning of the word minimal we remind the reader about the (three) quark model which was destroyed and accepted with the observation of the charm (the fourth) quark.
For a smaller mass of $M_A$ the $h^0$ cross section and possible decay modes depend strongly on $\tan \beta$. Again, the lightest MSSM Higgs $h^0$ should be discovered at LEPII if $m_h$ is smaller than $\approx 100$ GeV and if $\tan \beta$ is smaller than about 4. For $m_h$ larger than 100 GeV and larger values of $\tan \beta$ the expected LHC rate for the signature $h \to \gamma \gamma$ appears to be strongly suppressed.

The possible signatures for the other Higgs bosons depend strongly on their masses, the kinematically allowed decay products and the choice of $\tan \beta$.

For small values of $\tan \beta$ and a mass smaller than twice the top quark mass, $m_{H^0} < 350$ GeV, and smaller than twice the mass of $h^0$, the $H^0$ appears to behave like the SM Higgs. Once kinematically allowed, the branching ratio $H^0 \to h^0h^0$ might become large. As the couplings to the third quark and lepton family are enhanced proportional to $(\tan \beta)^2$ one expects that roughly 90% of the $H^0$ and $A^0$ decay to $b\bar{b}$ jets and 10% to $\tau^+\tau^-$ if $\tan \beta$ is large.

The couplings of the charged Higgs $H^\pm$ are dominated by the third fermion family. Up to a $H^\pm$ mass of roughly $m_t + m_b$ the dominant decay mode is $H^\pm \to \tau \nu$. For larger masses only the decay mode $H^\pm \to t b$ appears to be relevant. Having large couplings to the $tb$ system, direct searches can be performed in $t$ decays $t \to bH^+$ with $H^+ \to \tau^+\nu$. Furthermore, $b$-decays, like $b \to s\gamma$, provide strong indirect constraints on the charged Higgs as discussed in section 8.

6.1 MSSM Higgs search at LEPII

Experiments at LEPII and $\sqrt{s} \approx 200$ GeV will have an excellent sensitivity to the SM Higgs with masses of about 100 GeV. One finds that this sensitivity translates to a Higgs sensitivity of the MSSM for values of $\tan \beta$ of about roughly 4 (3) with no (maximal) mixing using the process $e^+e^- \to Z^* \to Zh^0$. For larger $\tan \beta$ values the couplings of the $h$ to the weak bosons are reduced proportional to $\cos \beta$ and the predicted mass value of $m_{h^0}$ increases. However, the $h^0, A^0$ Higgs pair production $\to Z^* \to h^0A^0$, if kinematically allowed, appears to be detectable. This process results in a distinct signature of events with four $b$-jets. The search for such 4 $b$-jet events during the future LEPII running will thus give sensitivity to masses of $M_h, M_A < 90$ GeV and all $\tan \beta$ values.

Searches for Higgs bosons with masses beyond the kinematic LEPII limit have to wait, either for the LHC, as will be discussed below, or for a future high luminosity high energy linear $e^+e^-$ collider.

6.2 MSSM Higgs search at the LHC

Current LHC studies show that the sensitivity to the MSSM Higgs sector is somehow restricted. One finds that one either needs Higgs particles with essentially SM like couplings, e.g. $M_A > 500$ GeV or one needs large $\tan \beta$ values. This sensitivity is usually shown in a complicated two–dimensional multi–line contour
plot like the one in Figure 27.

Figure 27: CMS 5 sigma significance contour plot for the different MSSM Higgs sector in the $M_A$ - $\tan\beta$ plane. Each curve indicates the sensitivity for different Higgs search modes.

6.2.1 The lightest neutral Higgs $h^0$

For the lightest Higgs, with a mass below 120-130 GeV, the only established signature appears to be the decay $h^0 \rightarrow \gamma\gamma$. For masses of $M_A$, larger than 400 GeV one finds essentially the SM rates and its sensitivity. For smaller masses of $M_A$, the branching ratio $h \rightarrow \gamma\gamma$ becomes too small to observe 5 standard deviations signals. The combination of the $h^0 \rightarrow \gamma\gamma$ search with other $h^0$ decay modes, like $h^0 \rightarrow b\bar{b}$, $h^0 \rightarrow ZZ^*$ and $h^0 \rightarrow WW^*$ should help to enlarge the 5 sigma domain.

6.2.2 The heavy neutral Higgse $H^0, A^0$ and low $\tan\beta$

For values of $\tan\beta$ smaller than $\approx 4$ one expects that the lightest Higgs will soon be discovered at LEPII. For such a scenario one finds that the $H^0$ might be visible for some masses and decays. For example a $H^0$ with a mass close to 170 GeV appears to be detectable with the channel $H^0 \rightarrow WW^* \rightarrow \ell\nu\ell\nu$. Other studies\footnote{Also called spaghetti plot.}
indicate possible $H^0$ signals with $H^0 \to hh \to \gamma\gamma b\bar{b}$ and $A \to Zh \to \ell^+\ell^- b\bar{b}$ and $H^0$ masses between 200-350 GeV. We will not go into further details here as the relevance of such “utopic” studies for low values of $\tan\beta$ depends so strongly on the near future LEP II results.

6.2.3 The heavy neutral Higgs $H^0, A^0$ and large $\tan\beta$

For large values of $\tan\beta$ the Higgs production cross sections, especially the ones for $b\bar{b}H^0$ and $b\bar{b}A^0$ are much larger than the ones for the SM Higgs with similar masses. The only relevant Higgs decays are $H^0, A^0 \to \tau\tau$ and $H^0, A^0 \to b\bar{b}$. While it is generally assumed that the Higgs decays to $b\bar{b}$ jets can not be seen at the LHC, the decays to $\tau^+\tau^-$ are believed to give a detectable signature.

The analysis of the $\tau^+\tau^-$ final states proceeds along the following ideas. The decay products of $\tau^\pm$, can be separated from quark and gluon jets by the low mass, the low charged multiplicity and the missing transverse energy. Studies indicate that hadronic $\tau$ decays with a $p_t$ of the observable hadrons above 20 GeV can be separated with good efficiency and a quark/gluon jet rejection factor of more than 100. Leptonic $\tau$ decays to electrons, muons allow even stronger jet rejection factors and provide in addition a straightforward trigger signal.

The proposed analysis proceeds along the following lines:

- The event should contain two opposite charged isolated $\tau$ candidates with high $p_t$. At least one of the two $\tau$’s should be an electron or a muon.
- The usual $\tau$ signature is an isolated charged hadron with a minimum $p_t$ of 5 GeV or more, combined eventually with some associated $\pi^0$ activity in the calorimeter. The reconstructed $\tau$ energy and momentum vector is obtained from the sum of the associated track and calorimeter measurements plus the assigned missing neutrino energy.
- The two $\tau$ candidates should not be back to back in the plane transverse to the beam direction. This requirement results in a considerable efficiency reduction, but is required to allow a $\tau\tau$ mass reconstruction and to reduce the background from leptonic $Z^0$ decays and higher mass Drell-Yan lepton pair events.
- The event should contain at least one jet with a large transverse energy of at least $\geq$ 40-50 GeV, to balance the required $p_t$ of the $\tau\tau$ system.
- The invariant mass of the $\tau\tau$ system is reconstructed under the assumption that the reconstructed $\tau$ direction agrees with the true $\tau$ direction. The measured missing transverse energy, using all other measured particles in the event, is assumed to originate from the two $\tau$ decays. The missing transverse event energy is thus split and added to each reconstructed $\tau$ decay products. The mass is determined according to $m_{\tau\tau} =$
\( \sqrt{2 \times E_r^1 \times E_r^2 (1 - \cos \theta)} \). Simulations indicate mass resolutions of about 10-15\%, about \( \pm 20-30 \) GeV for masses of about 200 GeV, and about \( \pm 50 \) GeV for a mass of 300 GeV.

- For values of \( \tan \beta \) above 10, the cross section for the process \( gg \rightarrow b \bar{b} A(H) \) becomes large enough to improve the signal to background ratio by requiring the presence of additional b-jets.

Depending slightly on the Higgs mass, the efficiency and the signal to background ratio are quite small. For example, a recent CMS study \([14]\) of the MSSM (\( \tan \beta = 8(15) \)) Higgs search with \( \tau \tau \) final states and a luminosity of 30 fb\(^{-1} \), expects a signal of roughly 500 (300) events for masses of 140 (300) GeV above a background of 7500 (3000) events. About 50\% of the estimated background comes from high mass Drell-Yan \( \tau \tau \) pair production. Simulation studies indicate that the signal to background ratio can be strongly improved if one jet is identified as a b-jet as indicated in Figure 28 \([17]\). Unfortunately most of the associated b-jets are expected to have a very low \( p_t \). Therefore, the good signal to background ratio can be achieved only with a small signal efficiency. As a result, statistical significance with 5 sigma requires large signal cross sections expected for \( \tan \beta \) values larger than 15–20.

![Figure 28: CMS simulation of the MSSM Higgs search for \( H, A \rightarrow \tau \tau \) with and without b-tagging \([15]\) for \( M_A = 140GeV \) and \( \tan \beta = 14 \) and for \( M_A = 300GeV \) and \( \tan \beta = 34 \)](image-url)
Optimists prefer therefore to assume negligible systematics and search for an excess of $\tau\tau$ pairs without b-tagging. Following this procedure one finds statistically significant 5 sigma signals for $\tan\beta$ values larger than 8–10 as shown in Figure 27. The significance figures from similar studies with the ATLAS simulation appear to be almost identical. Unfortunately, a direct comparison of the obtained results is difficult as different backgrounds are considered for both studies. We thus hope that the search for the MSSM Higgs with $A^0(H^0) \rightarrow \tau\tau$ final states will not be spoiled by unforeseen backgrounds and that the more realistic Next-to-Leading-Order Monte Carlos will not result in systematic background uncertainties larger than 2-3%.

Assuming large $\tan\beta$ values, the rare decay $A, H \rightarrow \mu\mu$ might show up as a resonance peak above a large background. Assuming excellent mass resolutions in the $\mu\mu$ channel of about 0.01-0.02 times $m$(Higgs) [GeV], the performed studies indicate a Higgs discovery possibility in this channel for a luminosity of 30 fb$^{-1}$ and $\tan\beta$ larger than $\approx 20$.

6.2.4 The charged Higgs $H^\pm$

Depending only slightly on $\tan\beta$, the relevant MSSM charged Higgs decay modes are $H^+ \rightarrow \tau^+\nu$ for masses below the $t\bar{b}$ threshold, and $H^+ \rightarrow t\bar{b}$ above. Having large couplings to the $t\bar{b}$ system, $t\bar{t}X$ events are a large source of charged Higgs events. Inclusive $t\bar{t}$ events might thus provide a good experimental signature for $H^\pm$ with a mass below $m_{top} - 10$ GeV. One has to search for $t\bar{t}$ events with isolated $\tau$ candidates which originate from the decay chain $t\bar{t}X \rightarrow bW^\pm bH^\pm$ and $H^\pm \rightarrow \tau\nu$.

The studied signature requires events with:

- an isolated high $p_t$ electron or muon from a $W$ decay,
- the decay products from an isolated energetic $\tau$,
- two $b$-flavoured jets and perhaps some missing $p_t$.

The performed ATLAS/CMS simulations [48], using a luminosity of 10 fb$^{-1}$, indicate that signals of a few 100 events with a signal to background ratio of about 1/7 can be obtained. Assuming that the backgrounds are well known, a sensitivity for $H^\pm$ masses up to about 130-140 GeV is obtained for all values of $\tan\beta$.

Another interesting process might be the production of a heavy $H^\pm$ in association with a top quark, $gb \rightarrow tH^- \rightarrow ttb \rightarrow WWbb$. A parton level analysis of this channel [49]indicates the possibility to obtain $H^\pm$ mass peaks with reasonable signal to background ratios. The proposed analysis selects events with one

\footnote{The branching ratio is expected to be about a factor of 300 smaller than the one for the decay to $\tau\tau$ as it scales with $(m_\mu/m_\tau)^2$.}
leptonic and one hadronic $W$ decay and three identified b-jets. The used efficiencies for lepton tagging and b-jet identification are close to the ones assumed in simulations from ATLAS and CMS for other LHC processes.

The performed analysis obtains the mass peaks, shown in Figure 29, from the mass distribution of the reconstructed $tb$ jet system, where the top is reconstructed from the decay $t \rightarrow W b$. Furthermore, the resolution and the combinatorial background is reduced using the known mass of the top quark. The study indicates accepted signal cross sections of up to 1 fb above background cross section between 1-2 fb and a 60 GeV mass bins for an interesting MSSM parameter

Figure 29: Comparison of the reconstructed mass $H^\pm$ signals and backgrounds for $H^\pm$ masses of 200, 300, 400 and 500 GeV. The upper and lower plots are for $\tan \beta = 1$ and $\tan \beta = 50$ respectively [49].
range. It would certainly be interesting to see if this parton level result can be confirmed in a more detailed detector level study.

6.2.5 Are MSSM Higgses a proof of Supersymmetry?

The discovery of at least one of the MSSM Higgs particles is often believed to be the proof of SUPERSYMMETRY. Figure 27 and 30 indicate the estimated sensitivity of the CMS and ATLAS experiments to various Higgs decay channels and different luminosities. These two dimensional multi line 5 sigma (statistical) significance plots, especially in the logarithmic version, indicate sensitivity over almost the entire MSSM parameter space.

![Figure 30: Estimated ultimate ATLAS 5 sigma discovery sensitivity for the MSSM with a luminosity of 300 fb$^{-1}$](image)

The sensitivity of the different search signatures are shown in the $M_A - \tan \beta$ plane.
However, it is worth to remind the reader that the assumed sensitivity includes only statistical errors. As a consequence, the obtained curves, especially when extrapolated to larger integrated luminosities and combined for ATLAS and CMS are doubtful. This is especially the case, as discussed above, for channels like $W^+H \rightarrow \ell\nu b\bar{b}$ and for $H^0, A^0 \rightarrow \tau\tau$ where the proposed signatures suffers certainly from the very bad signal to background ratio.

Despite these “small” problems, the performed studies indicate a hole for $\tan\beta$ values between roughly 4–10 and a mass of $M_A$ between 100–300(400) GeV. Furthermore, the different Higgs bosons indicate only little overlap. For example, the remaining discovery potential of LEPII experiments for the lightest Higgs require $\tan\beta$ values between $\approx 2–4$. Today’s LHC studies for this parameter range show a rather limited possibility to discover any additional MSSM Higgs bosons at the LHC.

In contrast, one might assume that all Higgs bosons, beside $h^0$ are very heavy. Theoretical calculations show that such a scenario results in a light Higgs with the couplings of the SM Higgs. This means that such a light Higgs can not be distinguished from the SM Higgs and does not prove or disprove SUPERSYMMETRY!

The remaining MSSM scenario for LHC experiments is a large $\tan\beta$ value combined with a $A^0$ with a mass below 300–400 GeV. For this scenario, the sensitivity plots indicate that one should look for the signature $H^0, A^0 \rightarrow \tau\tau$, which suffers unfortunately from the estimated bad signal to background ratio. It appears doubtful that this channel will convince anybody of SUPERSYMMETRY.

We thus conclude this section with the remark that neither the full MSSM Higgs parameter space can be covered at the LHC nor that the discovery of a single MSSM Higgs boson will allow to prove SUPERSYMMETRY. Furthermore, “minor” additions to the MSSM Higgs sector, like the existence of (one) additional Higgs doublet(s), increases the expected upper Higgs mass limit to values of up to 200 GeV [13]. Thus, even the discovery of a SM like Higgs with a mass of 160 GeV will not allow to distinguish between the Standard Model, SUPERSYMMETRY and other new physics.

Consequently, the only way to prove SUPERSYMMETRY is the direct unambiguous detection of at least one SUSY particle.
7 Direct Searches for SUSY Particles

The discussion in the previous chapter leads to the result that SUPERSYMMETRY can not be discovered or excluded from the Higgs sector. The experimental high energy physics community is thus forced to either discover at least one supersymmetric particle, or to show without any doubt that supersymmetric particles are much heavier than all known SM particles with masses of at least a few TeV.

Not even a small indication for SUSY like particles has been found at LEP II, at the TEVATRON or at HERA. Thus, the statement that detectable SUSY particles have to be heavier than \( \approx 100 \text{ GeV} \) appears to be quite safe. The experimental obligation to search for SUSY requires thus (a) to reach higher center of mass energies combined with large luminosities and (b) to search for various SUSY signatures in a multi dimensional parameter space. Following this guideline we describe in the following the known most promising SUSY signatures discussed for the LHC and the upgraded TEVATRON.

Starting from the MSSM, the so called minimal model, theoretical counting results in more than hundred free parameters. So many free parameters do not offer a good guidance for experimentalists, which prefer to use additional assumptions to constrain the parameter space. The simplest approach is the so called MSUGRA (minimal supergravity model) model with only five parameters \((m_0, m_{1/2}, \tan \beta, A_0\) and \(\mu)\).

This SUSY model is used for most sensitivity estimates of future colliders and the obtained results for the LHC will be discussed below. The main reason for this model choice is the existence of very advanced Monte Carlo programs \cite{51}, \cite{52}, required for detailed simulation studies. This pragmatic choice of one approach to investigate the potential of a future experiment appears to be more than sufficient, as essentially all required detector features can be tested.

However, such a pragmatic approach should not be considered as a too strong guidance principle if one wants to discover SUPERSYMMETRY with real experiments. Two recent examples show that the absence of any MSUGRA indications, enlarges the acceptance for more radical SUSY models.

The first example is the famous lonely CDF event, which has large missing transverse energy, 2 high \( p_t \) isolated photons and 2 isolated high \( p_t \) electron candidates \cite{54}. The presence of high \( p_t \) photons does not match MSUGRA expectations but might fit into so called gauge mediated symmetry breaking models, GMSB \cite{55}. This event has certainly motivated many additional, so far negative searches.

The second example is related to the 1997 HERA excitement. The observed excess of a handful of events appeared to be consistent with either a lepton–quark resonance with a mass of roughly 200 GeV or with a signature predicted from R–parity violation SUSY models \cite{56}. While this excess was not confirmed with larger statistics, the R–parity violation models became certainly much more attractive.
These modified searches indicate the discovery potential of searches which are not guided by today's fashion. Having reminded the reader of potential shortcomings between a SUSY Nature and the studied SUGRA model, we now turn to future LHC (and Tevatron) search strategies for SUSY particles within SUGRA.

### 7.1 MSUGRA predictions

Essentially all signatures related to the MSSM and in particular to MSUGRA searches are based on the consequences of R-parity conservation. R-parity is a multiplicative quantum number like ordinary parity. The R-parity of the known SM particles is 1, while the one for the SUSY partners is -1. As a consequence, SUSY particles have to be produced in pairs. Unstable SUSY particles decay, either directly or via some cascades, to SM particles and the lightest supersymmetric particle, LSP, required by cosmological arguments to be neutral. Such a massive LSP’s, should have been abundantly produced after the Big Bang and is currently considered to be “the cold dark matter” candidate. This LSP, usually assumed to be the lightest neutralino $\tilde{\chi}_1^0$ has neutrino like interaction cross sections and can not be observed in collider experiments. Events with a large amount of missing energy and momentum are thus the prime SUSY signature in collider experiments.

Possible examples are the pair production of sleptons with their subsequent decays, $pp \rightarrow \tilde{\ell}^+\tilde{\ell}^-$ and $\tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$ which would appear as events with a pair of isolated electrons or muons with high $p_{\text{T}}$ and large missing transverse energy.

Within the MSUGRA model, the masses of SUSY particles are strongly related to the so called universal fermion and scalar masses $m_{1/2}$ and $m_0$. The masses of the spin 1/2 SUSY particles are directly related to $m_{1/2}$. One expects approximately the following mass hierarchy:

- $\tilde{\chi}_1^0 \approx 1/2m_{1/2}$
- $\tilde{\chi}_2^0 \approx \tilde{\chi}_1^\pm \approx m_{1/2}$
- $\tilde{g}$ (the gluino) $\approx 3m_{1/2}$

The masses of the spin 0 SUSY particles are related to $m_0$ and $m_{1/2}$ and allow, for some mass splitting between the “left” and “right” handed scalar partners of the degenerated left and right handed fermions. One finds the following simplified mass relations:

- $m(\tilde{q})$(with q=u,d,s,c and b) $\approx \sqrt{m_0^2 + 6m_{1/2}^2}$
- $m(\tilde{\nu}) \approx m(\tilde{\ell}^\pm)$ (left) $\approx \sqrt{m_0^2 + 0.52m_{1/2}^2}$
- $m(\tilde{\ell}^\pm)$ (right) $\approx \sqrt{m_0^2 + 0.15m_{1/2}^2}$
The masses of the left and right handed stop quarks ($\tilde{t}_{\ell,r}$) might show, depending on other SUGRA parameters, a large splitting. As a result, the right handed stop quark might be the lightest of all squarks.

Following the above mass relations and using the known SUSY couplings, possible SUSY decays and the related signatures can be defined. Already with the simplest MSUGRA frame one finds a variety of decay chains.

For example the $\tilde{\chi}_2^0$ could decay to $\tilde{\chi}_1^0 + X$ with $X$ being:

- $X = \gamma^* Z^* \rightarrow \ell^+ \ell^-$
- $X = h^0 \rightarrow b\bar{b}$
- $X = Z \rightarrow f\bar{f}$

Other possible $\tilde{\chi}_2^0$ decay chains are $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^\pm + \ell^\pm \nu$ and $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \ell^\pm \nu$ or $\tilde{\chi}_2^0 \rightarrow \ell^\pm \ell^\mp$.

Allowing for higher and higher masses, even more decay channels might open up. It is thus not possible to define all search strategies a priori. Furthermore, possible unconstrained mixing angles between neutralinos, lead to model dependent search strategy for squarks and gluinos as will be discussed below.

Today's negative SUSY searches [57] provide the following approximate lower mass limits:

- $m(\tilde{\chi}_1^\pm) > 90$ GeV (LEPII)
- $m(\tilde{g})(\text{gluino}) > 160-220$ GeV depending slightly on the assumed squark masses (TEVATRON).

One might argue, that the negative results of the chargino search at LEPII imply that future gluino searches at the upgraded TEVATRON should not start for masses below $\approx 270$ GeV. However, the continuing TEVATRON searches indicate that many searchers do not follow too strictly specific mass relations of a MSUGRA model. Current experimental results are usually shown as a function of the searched for SUSY masses.

In contrast, sensitivity estimates for future collider experiments are usually given in the $m_0-m_{1/2}$ parameter space. Despite the model dependence, such estimates allow to compare the possible significance of the different studied signatures. Having various proposed methods, the resulting sensitivity figures appear to be quite confusing and require some time for appreciation. A typical example is shown in Figure 31a-d [58], where the different curves indicate the LHC sensitivity for different signatures and different SUSY particles. It is usually assumed that the maximum information about SUSY can be extracted in regions, covered by many signatures. The meaning of the various curves and their potential significance should become clear from the following sections.
Figure 31: Expected sensitivity for various SUSY particles and signatures in the $m_0-m_{1/2}$ plane using an integrated luminosity of 10 fb$^{-1}$ at the LHC. Figures a and b are for $\tan\beta=2$ with negative and positive $\mu$; the corresponding results for $\tan\beta=10$ and negative and positive $\mu$ are shown in c and d. The different curves indicate the sensitivity for SUSY events with $n$ leptons ($\ell$) and for events with lepton pairs with same charge (SS) and opposite charge (OS).

7.2 Anatomy of a Slepton Signature at the LHC

Hadron colliders are certainly not a good source of sleptons. Nevertheless, we start our analysis of the various SUSY search strategies with an anatomy of the simplest possible SUSY signal. Our discussion starts with the cross section and the expected decay modes. This is followed by a qualitative description of a possible discovery signature at the LHC which is then compared to a detailed simulation of a search for sleptons at the LHC.

The pair production of sleptons at the LHC can easily be related to the production of Drell-Yan dilepton pairs with high mass. The expected total slepton pair production cross section as a function of the slepton mass is shown in Figure 32.

Figure 33 shows the expected mass (with $m>200$ GeV) distribution of the
virtual $\gamma^*$, $Z^*$ system leading to a lepton or slepton pair. The cross section for scalar charged sleptons has a simple relation to the production of the corresponding right and left handed lepton pair production $\sigma(\tilde{\ell}\tilde{\ell}) = 1/4\beta^3\sigma(\ell\ell)$. For our example the masses of the left handed and right handed slepton were fixed to 129 GeV and 113 GeV respectively. The expected mass spectra show the $\beta^3$ cross section suppression close to threshold. The larger rate for Drell-Yan pairs produced from the left handed virtual $\gamma^*$, $Z^*$ system results, despite the larger mass, into a bigger cross section for left handed sleptons. This simple relation between slepton mass and cross section allows precise cross section predictions for slepton pairs, once the corresponding mass spectrum of Drell-Yan lepton pairs has been measured.

As a next step one has to consider the possible slepton decay modes. While the right handed slepton can decay only to the lightest neutralino and the corresponding lepton $\tilde{\ell}^\pm \to \chi^0_1\ell^\pm$, several somehow model dependent decay modes, are possible for left handed sleptons:

- $\tilde{\ell}^\pm \to \chi^0_1\ell^\pm$ or $\tilde{\ell}^\pm \to \chi^0_2\ell^\pm$ or $\tilde{\ell}^\pm \to \chi^\pm_1\nu$
- $\tilde{\nu} \to \chi^0_1\nu$ or $\tilde{\nu} \to \chi^\pm_1\ell^\mp$

Figure 32: Slepton mass dependence of the total pair production cross section at the LHC for various slepton combinations \[59\].
Figure 33: Mass distribution of Drell–Yan electron pairs with a mass above 200 GeV and for left or right handed selectron pairs at the LHC with selectron masses of 129 GeV and 113 GeV respectively as obtained with PYTHIA \[53\] and SPYTHIA \[52\].

The best signature for slepton pair production appears to be the two–body decay $\tilde{\ell}^\pm \rightarrow \tilde{\chi}_1^0 \ell^\pm$. The resulting signature are events with a pair of two isolated same flavour leptons with opposite charged and some missing transverse momentum. To distinguish such signal events from various possible SM backgrounds several kinematic selection criteria have to be applied. To identify good selection criteria at the LHC it is useful to start with simplified kinematics in the center–of–mass frame. The observable leptons, originating from the decays of massive sleptons, should show: (1) a characteristic momentum spectrum; (2) should not balance their momenta and (3) should not be back to back. Furthermore, the measurable mass of the event should be much smaller than the original center–of–mass energy and the missing mass should be much larger than zero.

A possible selection requires thus the possibility to measure isolated leptons with good accuracy and to determine indirectly the missing energy and momentum from all detectable particles. An accurate missing energy determination requires an almost $4\pi$ acceptance for all visible particles. Unfortunately, a realistic experiment has to live with several detection gaps especially the ones around
the beam pipe. Consequently, missing momentum measurements along the beam direction are of limited use. In addition, the event kinematics at a Hadron Collider are very different from the center-of-mass frame. As a result, signal and background events have a large and unknown momentum component along the beam direction. However, variables which exploit the missing transverse energy and momentum remain very useful.

Furthermore, in contrast to a $e^+e^-$ collider with a fixed dilepton mass, hadron collider searches must consider the effects that sleptons pairs are not produced at a fixed $\sqrt{s}$ and show a wide longitudinal momentum range. As a result, good selection criteria exploit the differences between signal and background in the plane transverse to the beam. Such variables are (1) the transverse momenta of each lepton, (2) the opening angle between the two leptons in the plane transverse to the beam and (3) the missing transverse momentum. The specific choice of cuts depends strongly on the studied mass region and the relevant backgrounds.

The largest “irreducible” background for slepton pair production are events with leptonic $W^\pm$ decays from $W$–pair production $pp \rightarrow WWX$ with $(\sigma \times BR(WW \rightarrow e^+\nu e^-\bar{\nu})$ of about 0.8 pb. Another potentially very large background comes from $t\bar{t}$ production with a $\sigma \times BR(t\bar{t} \rightarrow WWbb \rightarrow e^+\nu e^-\bar{\nu}X)$ with a cross section of about 7 pb. This background can be strongly reduced by applying a jet veto. Other potential backgrounds are miss-measured Drell–Yan lepton pairs and electrons and muons from leptonic $\tau$ decays produced in the reaction $pp \rightarrow \tau\tau$. Additional backgrounds might come from events of the type $W^\pm X$ and $Z^0X$ with one leptonic boson decay and one high $p_t$ hadron misidentified as an electron or a muon. In addition, other unknown sources of new physics, like $pp \rightarrow \tilde{\chi}^+\tilde{\chi}^-$ might also result in events with two isolated leptons and missing transverse momentum. These large background cross sections should be compared with the much smaller signal cross sections between about 0.2 and 0.02 pb for the pair production of sleptons with masses between 100–200 GeV respectively as shown in Figure 32.

The qualitative ideas discussed above, can now be compared with a quantitative simulation of a slepton search with the CMS experiment.

The analysis selects first events which contain a pair of opposite charged electrons or muons and no additional jets. It is assumed that isolated electrons or muons with a minimum transverse momentum of 20 GeV and $|\eta| < 2.5$ can be identified with high efficiency ($\epsilon > 90\%$) and small backgrounds. One assumes also that jets with a transverse energy above 30 GeV and $|\eta| < 4.5$ can be identified and vetoed. In addition, events from $pp \rightarrow Z \rightarrow \ell^+\ell^-$ are rejected by demanding that the invariant mass of the lepton pair should be inconsistent with a $Z^0$. Additional mass dependent selection criteria, specified in table 3, are required to improve the potential signal significance.

The lepton pairs from $W^+W^-$ and $t\bar{t}$ events appear to be the dominant backgrounds. For a slepton mass of about 100 GeV one finds a statistical significant signal of $\approx 300$ events above a background of about 1000 events and a luminosity of 10 fb$^{-1}$. The expected signal and background distributions before the $\Delta\phi$ cut
Figure 34: Relative azimuthal angle $\phi$ between the two leptons for (a) sleptons and other SUSY signals and (b) for the main SM backgrounds [60]. The proposed cut is $\phi > 130^\circ$.

are shown in Figure 34a and b.

The analysis shows that sleptons with masses between 200-300 GeV can be selected with signal to background ratios of about 1:1. The low signal cross section requires however a large luminosity of at least 30 fb$^{-1}$. For larger masses the slepton cross section becomes very small and seems to limit the mass reach to about 400 GeV with expected signal rates of 24 events and a total expected background of about 50 events for a luminosity of about 100 fb$^{-1}$. In summary, pair production of charged sleptons at the LHC appears to be detectable from an excess of events above dominant backgrounds from leptonic decays of $W^+W^-$ and $t\bar{t}$ events. The expected mass reach starts from about 100 GeV, roughly the final LEPII reach, and is limited to masses of about 400 GeV. Particular problems are the small signal to background ratio for masses below 200 GeV an the small signal rate for masses above 300 GeV.
| $m(\ell^\pm)$ | $p_t^{\ell^\pm}$ | $E_t^{\text{miss}}$ | $\Delta \phi_{\ell^\pm, t^-}$ | S (100 fb$^{-1}$) | B (100 fb$^{-1}$) |
|------------|-----------------|----------------|------------------|----------------|----------------|
| 100 GeV    | > 20 GeV        | > 50 GeV       | > 130°           | ≈ 3200         | ≈ 10000        |
| 200 GeV    | > 50 GeV        | > 100 GeV      | < 130°           | ≈ 230          | ≈ 170          |
| 300 GeV    | > 60 GeV        | > 150 GeV      | < 130°           | ≈ 67           | ≈ 45           |
| 400 GeV    | > 60 GeV        | > 150 GeV      | < 140°           | ≈ 24           | ≈ 53           |

Table 3: CMS simulation of the charged slepton search at LHC [60]. The proposed selection criteria and signal (S) and background (B) rates are given for a luminosity of 100 fb$^{-1}$ and a few slepton masses.

Other slepton signals, like the one from the reaction $pp \rightarrow W^* \rightarrow \ell \tilde{\nu}$ have been studied and were found to be hopeless [59].

The investigated signature of a single high $p_t$ lepton with large missing $E_t$ was found to be at least two orders of magnitude smaller than the event rate from single $W$’s as shown in Figure 35.

They concluded further that a possible trilepton signal, from cascade decays of the sneutrino $\tilde{\nu} \rightarrow \tilde{\chi}_2^0 \nu \rightarrow \ell \ell \tilde{\chi}_1^0$ is much smaller than a possible signal from the simultaneous produced trilepton events of the type $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ as described in the next section.

Figure 35: Reconstructed transverse mass of single high $p_t$ lepton events for signal events of the type $pp \rightarrow W^* \rightarrow \ell^\pm \tilde{\nu} \rightarrow \ell^\pm \nu \tilde{\chi}_1^0 \tilde{\chi}_1^0$ and various backgrounds. The studied slepton masses were 100 GeV (case 3) and 200 GeV (case 4) [19].
7.3 Chargino-neutralino searches; the Trilepton signature

In analogy to the reaction $q\bar{q}_j \rightarrow Z^0W^{\pm}$, one might expect the production of $q\bar{q}_j \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^{\pm}$ events. Such events can be detected from an analysis of events with three isolated high $p_t$ leptons and large missing transverse energy. The potential of this trilepton signature at hadron colliders like the LHC has been described in several phenomenological studies [61]. It was found, that trilepton events with jets should be rejected to distinguish signal events from SM and SUSY backgrounds.

After the removal of jet events, the only remaining relevant background comes from leptonic decays of $WZ$ events. Potential backgrounds from dilepton events like $W^+W^- \rightarrow \ell^+\ell^-\nu\bar{\nu}$ and hadrons misidentified as electrons or muons are usually assumed to be negligible. Depending on the analysed SUSY mass range, the background from leptonic decays of $WZ$ events, in contrast to a potential signal, will show a $Z^0$ mass peak in the dilepton spectrum.

This signature is also used at the Tevatron. Estimates for RUN II (with a few fb$^{-1}$) hope for a $\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}$ mass sensitivity of up to 130 GeV, which might be improved further to about 210 GeV with RUN III (with 20–30 fb$^{-1}$) [62]. These estimates assume that a background cross section of less than 0.5 fb. This number can be compared to recent searches for trilepton events, optimised for masses of $\approx$ 80 GeV, from CDF [63]. Table 4, shows the current CDF background estimates for various applied cuts resulting in a final background cross section about 10 fb.

| Cut                          | observed Events | SM Background Expectation | MSSM MC $M(\tilde{\chi}_1^{\pm}) = M(\tilde{\chi}_2^0) = 70$ GeV |
|------------------------------|-----------------|---------------------------|---------------------------------------------------------------|
| Dilepton data                | 3270488         |                           |                                                               |
| Trilepton data               | 59              |                           |                                                               |
| Lepton Isolation             | 23              |                           |                                                               |
| $\Delta R_{\ell\ell} > 0.4$ | 9               |                           |                                                               |
| $\Delta \phi_{\ell\ell} < 170^o$ | 8         | $9.6 \pm 1.5$           | $6.2 \pm 0.6$                                                |
| $J/\Psi, \Upsilon, Z$ removal | 6            | $6.6 \pm 1.1$           | $5.5 \pm 0.5$                                                |
| missing $E_t^{\text{miss}} > 15$ | 0           | $1.0 \pm 0.2$           | $4.5 \pm 0.4$                                                |

Table 4: Results from a recent trilepton analysis from CDF with a dataset of $\approx 100$ pb$^{-1}$ [63]. The number of observed events shows good agreement with various SM background sources.

A recent CMS simulation [64] of the trilepton signal at the LHC proceeds as follows:

- Events should contain three isolated leptons, all with $p_t > 15$ GeV and $|\eta| < 2.5$ and no jets.
- The missing transverse energy should exceed 15 GeV.
• The possible same flavour dilepton mass combinations should be inconsistent with a $Z^0$ decay.

Depending on the studied mass range, additional or harder selection criteria are applied. Figure 36 shows the expected missing transverse energy distribution for trilepton signal events, with different choices of $m_0$ and $m_{1/2}$, and for background events. Table 5 gives a few numbers for signal and backgrounds from the CMS study and different SUSY masses.

| $M_{1/2} \approx M(\tilde{\chi}^\pm)$ | $\sigma \times BR$ (trileptons) | Signal (100 fb$^{-1}$) | SM Background (100 fb$^{-1}$) |
|------------------------------------------|---------------------------------|-------------------------|-------------------------------|
| 100                                      | 0.8 -1.3 pb                     | 4000–8000               | 900                           |
| 150                                      | 0.04-0.08 pb                    | 300-600                 | 1000                          |
| 200                                      | 0.01-0.02 pb                    | 80-120                  | 700                           |
| 300-400                                  | 0.01-0.02 pb                    | 50                      | 100                           |

Table 5: Expected signal and background numbers from a CMS trilepton study with different choices of $m_0$ and $m_{1/2}$ with $\tan \beta = 2$ and negative $\mu$.

In all cases one finds signal efficiencies of $\approx 5\%$. The best results are obtained for masses close to 100 GeV with expected signal rates of $\approx 40$ above a background of 10 events per 1 fb$^{-1}$ of luminosity. The signal rate drops quickly for higher masses and much higher luminosities are required to establish potential signals up to masses of at most 300-400 GeV. Furthermore, for some $m_0, m_{1/2}$ mass regions, the estimated leptonic branching ratios are very small and result in signal to background ratios smaller than 0.2. We conclude that the LHC experiments can measure excellent trileptons signals in mass and parameter regions where the discovery has most probably been made at the upgraded Tevatron. Such high statistics signals will allow some detailed SUSY studies as described in section 7.5. For chargino/neutralino masses above $\approx 200$ GeV significant signals require at least 30 fb$^{-1}$ and a very good understanding of possible backgrounds. However, as will become clear from the next section, cascade decays of squarks and gluinos should provide a much better sensitivity for charginos and neutralinos with higher masses.
Chargino-Neutralino Production
Events with 3 isolated leptons and no jets

Figure 36: Missing transverse energy distribution for trilepton events without jets from $pp \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^{\pm}_1$ signal events and background [64]. The numbers in brackets give the used $m_0$ and $m_{1/2}$ values.
7.4 Squark and Gluino searches; the showcase for a hadron collider

The discussion in the previous sections covered the potential to study non-hadronic interacting SUSY particles with relatively small cross section. We now turn the discussion to the search for squarks and gluinos with large couplings to quarks and gluons. The cross section for strongly interacting particles at hadron colliders like the LHC are quite large. For example the pair production cross section of squarks and gluinos with a mass of \( \approx 1 \) TeV has been estimated to be as large as 1 pb resulting in \( 10^4 \) produced SUSY events for one “low” luminosity LHC year. Such high rates, combined with the possibility to observe many different decay modes, is considered often as a “raison d’être” for the LHC.

Depending on the SUSY model parameters, a large variety of massive squark and gluino decay channels and signatures might exist. A complete search analysis for squarks and gluons at the LHC should consider the various signatures resulting from the following decay channels.

- \( \tilde{g} \to \tilde{q}q \) and perhaps \( \tilde{g} \to \tilde{t}t \)
- \( \tilde{q} \to \tilde{\chi}_1^0q \) or \( \tilde{\chi}_2^0 \) or \( \tilde{q} \to \tilde{\chi}_1^0q \)
- \( \tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell^+\ell^- \) or \( \tilde{\chi}_2^0 \to \tilde{\chi}_1^0Z^0 \) or \( \tilde{\chi}_2^0 \to \tilde{\chi}_1^0h^0 \)
- \( \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu \) or \( \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0W^\pm \).

The various decay channels can be separated into at least three distinct event signatures.

- Multi–jets plus missing transverse energy. These events should be spherical in the plane transverse to the beam.
- Multi–jets plus missing transverse energy plus \( n(=1,2,3,4) \) isolated high \( p_t \) leptons. These leptons originate from cascade decays of charginos and neutralinos.
- Multi–jets plus missing transverse energy plus same charge leptons pairs. Such events can be produced in events of the type \( \tilde{g}\tilde{g} \to \tilde{u}\bar{u}\tilde{d}\bar{d} \) with subsequent decays of the squarks to \( \tilde{u} \to \tilde{\chi}_1^+d \) and \( \tilde{d} \to \tilde{\chi}_1^-u \) followed by leptonic chargino decays \( \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu \).

It is easy to imagine that the observation and detailed analysis of the different types of squark and gluino signatures might allow to measure some of the many MSSM parameters.

The above signatures have already been investigated with the data from the Tevatron RUN I. The negative searches gave mass limits for squarks and gluinos as high as \( \approx 200 \) GeV. The estimated 5–sigma sensitivity for RUN II and RUN III
reaches values as high as 350–400 GeV. More details about the considered signal and backgrounds can be found from the TeV2000 studies [62] and the ongoing Tevatron workshop.

A simplified search strategy for squarks and gluinos at the LHC would study jet events with large visible transverse mass and some missing transverse energy. Such events can then be classified according to the number of isolated high $p_t$ leptons. Once an excess above SM backgrounds is observed for any possible combination of the transverse energy spectra, one would try to explain the observed types of exotic events and their cross section(s) for different SUSY $\tilde{g}, \tilde{q}$ masses and decay modes and models. An interesting approach to such a multi-parameter analysis uses some simplified selection variables. For example one could use the number of observed jets and leptons and their transverse energy, their mass and the missing transverse energy to separate signal and backgrounds. Such an approach has been used to perform a “complete” systematic study of $\tilde{g}$ and $\tilde{q}$ decays [65]. The proposed variable $E^c_T$ is the value of the smallest of $E_T^{(\text{miss})}, E_T^{(\text{jet1})}, E_T^{(\text{jet2})}$. The events are further separated into the number of isolated leptons. Events with lepton pairs are divided into same sign (charge) pairs (SS) and opposite charged pairs (OS). Signal and background distributions for various squark and gluinos masses, obtained with such an approach are shown in Figure 37.

According to this classification the number of expected signal events can be compared with the various SM background processes. The largest and most difficult backgrounds originate mainly from $W+\text{jet}(s), Z+\text{jet}(s)$ and $t\bar{t}$ events. Using this approach, very encouraging signal to background ratios, combined with quite large signal cross sections are obtainable for a large range of squark and gluino masses. The simulation results of such studies indicate, as shown in Figure 38, that the LHC experiments are sensitive to squark and gluinos masses up to masses of about 2 TeV and 100 fb$^{-1}$.

Figure 38 indicates further, that detailed studies of branching ratios are possible up to squark or gluino masses of about 1.5 TeV, where significant signals can be observed with many different channels. Another consequence of the expected large signal cross sections is the possibility that the “first day” LHC luminosity $\approx 100$ pb$^{-1}$ should be sufficient to discover squarks and gluinos up to masses of about 600–700 GeV, well beyond even the most optimistic Tevatron Run III mass range.

Having this exciting discovery potential for squarks and gluinos with many different channels, one might want to know the “discovery” or simply the “best” channel. Such a question is unfortunately not easy to answer. All potential signals depend strongly on a good understanding of various backgrounds and thus the detector systematics. Especially the requirements of high efficiency lepton identification and a good missing transverse energy measurement demand for a “perfect” working and understood detector. This requirement of a good understanding of complicated “monster” like experiments needs thus some time.
and is in contradiction with the “first day” discovery potential. We conclude that the best discovery signature is not yet known, but should be one which is extremely robust and simple and should not depend on too sophisticated detector elements and their resolutions.

7.5 SUSY discovered, what can be studied at the LHC?

Our discussion of the LHC SUSY discovery potential has demonstrated the sensitivity of the proposed ATLAS and CMS experiments. Being convinced of this discovery potential, one certainly wants to know if “the discovery” is consistent with SUPERSYMMETRY and if some of the many SUSY parameters can be measured.

To answer the above question one should try find many SUSY particles and
Figure 38: Expected ultimate (L=100 fb$^{-1}$) CMS sensitivity for squarks and gluinos, sleptons and for $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ in the $m_0 - m_{1/2}$ plane. The different full lines show the expected 5 sigma signal, estimated from $S/\sqrt{S+B_{SM}}$, coverage domain for the various signatures with isolated high $P_t$ leptons. The dashed lines indicate the corresponding squark and gluino masses.

measure their decay patterns as accurately as possible. The sensitivity of direct exclusive SUSY particle production at the LHC has demonstrated the various possibilities and cross section limitations for weakly produced SUSY particles.

Nevertheless, one finds that the production and decays of $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ provide good rates for masses below 200 GeV and should allow, as indicated in Figure 39, to measure accurately the dilepton mass distribution and their relative $p_t$ spectra. The mass distribution and especially the edges in the mass distribution are sensitive to the mass difference between the two neutralinos. Depending on the used MSUGRA parameters one finds that the $\tilde{\chi}_2^0$ can have two or three body decays. The relative $p_t$ spectra of the two leptons can be used to distinguish the two possibilities.

Figure 40 shows the distribution for the variable $A$, defined as $A = (p_t^{\text{max}} - p_t^{\text{min}})/(p_t^{\text{max}} + p_t^{\text{min}})$ in trilepton events and dilepton masses below and above 50 GeV. This asymmetry variable originates from early investigations of $\tau$ decays where it allowed to demonstrate that the leptonic $\tau$ decays $\tau \rightarrow \ell\nu\nu$ are three body decays.
In contrast to the rate limitations of weakly produced SUSY particles at the LHC, detailed studies of the clean squark and gluino events are expected to reveal much more information. In detail, one finds that the large rate for many distinct event channels allows to measure masses and mass ratios for several SUSY particles, which are possibly being produced in cascade decays of squarks and gluons. Many of these ideas have been discussed at a 1996 CERN Workshop [68].

Especially interesting appears to be the idea that the $h^0$ might be produced and detected in the decay chain $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 h^0$ and $h^0 \rightarrow b\bar{b}$. The simulated mass distribution for $b\bar{b}$ jets in events with large missing transverse energy is shown in Figure 41. Clear Higgs mass peaks above background are found for various choices of $\tan\beta$ and $m_0, m_{1/2}$.

An interesting approach to determine a SUSY mass scale has been suggested in a recent ATLAS study [69]. The idea is to define an effective transverse event mass, using the scalar $p_t$ sum of the jets with the largest transverse energy plus the missing transverse energy of the event. One finds that this effective mass shows a reasonable linear relation to an underlying SUSY mass, defined as the minimum of the squark or the gluino mass. While this idea appears to be very attractive within the MSUGRA model, the validity of the proposed relation in more general SUSY models is not known.

In addition to the above SUSY studies, one would like to to get answers to
questions like:

- What are the branching ratios of various SUSY particles?
- Is the accuracy of the various channels sufficient to determine the spin of the new particles?
- Do the data allow to differentiate between specific SUSY models?
- Can one find evidence for CP violation in SUSY decays?

At least some answer might be obtained from future detailed studies of the various decay chains. We thus conclude this section with the hope that some SUSY enthusiasts will try eventually to answer some of these questions using the expected performance of the LHC and its planned experiments.

8 Putting it all together..

We have discussed the various proposed search/discovery strategies for the Higgs, supersymmetry and other exotica at LEP II and future hadron colliders with a focus on the LHC. Knowing that the LHC experiments will not provide any new physics before the year 2005 some time for analysis preparation is left.
The most important aspect for the coming years is the confrontation of the assumed detector performance with reality. First of all, the two huge experiments have to be build according to the proposed designs. Any of todays physics case studies has thus to be kept realistic and should also reflect the expected experimental and theoretical knowledge at day 0.

For example, LHC studies which show a wonderful method on how to discover a SM Higgs boson with a mass of 50 GeV can be considered as a waste of time. A similar judgement could be applied to some “hard work” studies, which require unrealistic experiments with non existing systematics. We do not follow such simple judgement on “first studies” as these studies indicate very often the steps towards a realistic strategy.

Realistic and relevant LHC studies should thus in any case be aware of possible constraints from near future experiments. Examples of such possible constraints come from the LEPII Higgs search and the new CLEO result on the branching
ratio for $b \rightarrow s\gamma$, being $(3.15 \pm 0.35^{(\text{stat.})} \pm 0.32^{(\text{exp.syst.})} \pm 0.26^{(\text{th})}) \times 10^{-4}$ \cite{70}. The near future high luminosity b–factory experiments should allow to decrease the current error by at least a factor of 4. The current negative Higgs search results from LEP II exclude almost the Higgs sector of the MSSM model with no mixing and $\tan \beta < 2 - 3$. During the next two years the LEP II sensitivity should increase to $\tan \beta$ values of $\leq 4$.

![Figure 42: Expected branching ratio for $b \rightarrow s\gamma$ for the SM and its supersymmetric extension. The branching ratio is shown as a function of $\tan \beta$ and a negative or positive value of $\mu$ \cite{71}.](image)

Following some theoretical calculations \cite{71}, the new CLEO $b \rightarrow s\gamma$ result, as shown in Figure 42 appears to exclude a wide MSUGRA parameter range. In particular, one finds that the MSUGRA parameter $\mu$ has to be positive and that values of $\tan \beta > 10$ are essentially inconsistent with the existing data.

Following strictly the assumed theoretical implications of the $b \rightarrow s\gamma$ branching ratios and the LEPII Higgs searches one might find that either the MSUGRA
model is excluded, or in case a Higgs is found at LEPII that $\mu$ is positive and $\tan\beta$ is somewhere between 2 and 4.

If the Higgs will not be discovered at LEPII and the near future $b \to s\gamma$ branching ratio results might give values between $2 - 3 \times 10^{-4}$, the MSUGRA believers should focus on $\tan\beta$ values between 4 and 10. Unfortunately, this $\tan\beta$ range appears to be a difficult MSSM Higgs search area at the LHC as can be seen from Figure 27. In contrast, a branching ratio result between $3.5 - 4 \times 10^{-4}$ could exclude MSUGRA. We thus conclude this section with the remark that one should think twice before a too large effort is put into very detailed simulation studies as the possible results might be proven irrelevant even before such studies are completed!

9 Summaries

Past discoveries of new particles and phenomena have demonstrated undoubtfully that searches are the most exciting domain of new high energy colliders experiments. In contrast, the success of the Standard Model of electro–weak interactions has put the Searchers for the New into an esoteric corner group of experimentalists. Allowed exceptions are however the search for the SM Higgs and perhaps the tolerated searches for the MSSM Higgs bosons and for SUSY particles within the mSUGRA frame. Almost unavoidable our guide on “How to do Searches” follows todays theoretical guidance and fashions. This restriction is however not too dramatic as the discussed methods to isolate the various new signatures are general enough to cover even tomorrows fashions.

Assuming that the existing and planned LEP II, Tevatron and LHC experiments and colliders behave as expected, a large domain of unexploited physics territory will be investigated during the coming 10–20 years.

While the LEPII experiments have reached almost the kinematical limit, the future high luminosity running of the Tevatron might improve the existing sensitivity for the mass range of new particles by a factor of about 1.5–2 compared to todays mass limits. The LHC experiments should increase this mass window by another factor of about 6.

Starting with the SM Higgs, we find that the proposed search methods at LEPII and the LHC are robust and should lead to the discovery of the SM Higgs. We have also studied the question of a potential SM Higgs window at RUNIII of the Tevatron (TeV33). Our investigation shows that large factors are still missing before one could claim that there is a Higgs window at the upgraded TeV2000 experiments and a luminosity of 30 fb$^{-1}$. We thus disagrees with the optimistic scenarios discussed in the literature.

Our discussion of Supersymmetry searches is split into the search for the MSSM Higgs sector and for the direct search for SUSY particles. The proposed and published search methods demonstrate that an unambiguous prove of SU-
PERSYMMETRY can essentially only be obtained from the discovery of at least one of the many “sfermions” or “inos”. One finds that direct SUSY discovery chances depend mainly on the available center of mass energy. Only marginal improvements can be expected from the future LEPII running, which can increase todays chargino sensitivity by perhaps another 5 GeV. Nevertheless, even todays limit of ≈ 95 GeV provides strong constraints \( m(\tilde{g} > 270 \text{ GeV}) \) on the lowest possible gluino mass. Optimistic studies assume that the LEPII charginos range can be improved with a few \( fb^{-1} \) (the TeV Run II) to masses of about 130 GeV and slightly higher for the Tevatron RunIII. Thus, negative chargino searches at the RunII exclude essentially any mSUGRA possibility to detect gluinos with Run III (\( L > 10 \text{ fb}^{-1} \)) where optimistic studies expect to reach a sensitivity to masses between 300–400 GeV.

In contrast, the squark and gluino searches at the LHC are expected to be sensitive up to masses of about 2 TeV. The LHC experiments should thus be able to increase this potential mass window by another factor of about six. In addition, the detectable LHC squark and gluino cross sections, even for moderate masses well above any possible Tevatron limit, are huge. Consequently, LHC SUSY discoveries might be possible with a luminosity of a few 100 pb\(^{-1}\) only, obtainable almost immediately at the LHC switch on. Such excellent perspectives have to be matched however with an almost perfectly working full detector and the accurate knowledge of all SM background processes. In addition, a well prepared search should consider a large variety of models and the resulting possible signatures.

Figure 43: Observed correlation between the transverse mass of the \( \ell \nu \) system and the missing transverse momentum for the \( e - X \) and \( \mu - X \) events in the data and in the SM Monte Carlo from the H1 collaboration [72].
Run 1 dilepton data (109 pb$^{-1}$), CDF preliminary

![Graph showing correlation between missing transverse energy and angle](image)

Figure 44: Observed correlation between the missing transverse energy and the angle between the missing $p_t$ vector and the nearest lepton or jet for the CDF dilepton $t\bar{t}$ candidates in the data and the Monte Carlo [73].

Having focussed on today’s fashionable models we would like to finish our review with the remark that a successful search does not need to please a theoretical exotic model. As an example we would like to mention the existence of a few unconnected mysterious events at HERA and at the Tevatron. The H1 collaboration has recently published the observation of a few high $p_t$ events which contain isolated muons, jets and large missing transverse energy [72]. The observed 5 $\mu - X$ events are somehow high compared to the expected SM rates of about 1 event. In addition, as shown in Figure 43, at least three of the five $\mu - X$ events show some weird kinematics while the corresponding $e - X$ event is in agreement with expectations. Another anomaly involving isolated leptons and jets has been reported by the CDF collaboration [73]. The analysis compares events which contain a pair of isolated leptons ($ee$, $\mu\mu$ and $e\mu$) and at least two jets with expectations from a $t\bar{t}$ Monte Carlo. As can be seen from Figure 44, one finds that the majority of the observed events are well reproduced by the Monte Carlo. However, four events have a somehow unexpected large missing transverse energy.

In both cases, an excess of events is found in tails of a two-dimensional distri-
bution. The interest in these events is enlarged as they are found in an analysis of events with isolated leptons plus jets plus missing transverse energy. A trivial but correct statement is that the observed excess does currently not allow any discovery claim and that more data are needed. This statement probably satisfies especially the experimentalists which are not working at the Tevatron or at HERA. The trivial and correct reply is “don’t worry” many more data might be available soon. However, hoping for a real effect, experimentalists and theorists should feel encouraged to imagine some new and related signatures which might perhaps be tested even with today’s data.

To finish this “How to do Searches” guide we would like to quote a few authorities:

“What can be measured, results from theory” Einstein to Heisenberg

“Experiments within the next 5–10 years will enable us to decide whether supersymmetry, as a solution to the naturalness problem of the weak interaction is a myth or reality” H.! P. Nilles 1984

“One shouldn’t give up yet” .... “perhaps a correct statement is: it will always take 5-10 years to discover SUSY” H. P. Nilles 1998

“Superstring, Supersymmetry, Superstition” Unknown

“New truth of science begins as heresy, advances to orthodoxy and ends as superstition” T. H. Huxley (1825–1895).

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