SEARCHES FOR SUSY AT LHC*

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A short description is given of the perspectives for the detection of supersymmetric particles at the LHC. The first part of the lecture is on inclusive searches addressing the Minimal Supersymmetric Standard Model. Some results are then given of ongoing work on a model based on minimal supergravity (SUGRA).

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1. Introduction

The next step in elementary particle research employing high energy accelerators will be the LHC, a proton proton collider with energy $\sqrt{s} = 14$ TeV, to be built at CERN at the beginning of next century.

Experimentation at the LHC will open up a completely new energy domain, thus allowing a detailed study of the hitherto untested gauge symmetry breaking sector of the Standard Model (SM), and an exploration of its possible extensions.

Supersymmetry (SUSY) is probably the most interesting and phenomenologically best studied of these extensions. This paper is meant as an introduction to the analysis techniques which will be employed in the search for supersymmetry at the LHC. The scope of this lecture is limited to the SUSY partners of SM particles, as the SUSY Higgs sector is discussed in another lecture in these proceedings [1].

The first step in the investigation will be the search for the deviations from the Standard Model predicted by supersymmetric theories. Supersymmetry is not a single model, but a set of models with different assumptions, and each model is determined by a number of free parameters. In order to test if Supersymmetry exists, a very general model is chosen, which still

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gives definite predictions for experimental observables, the Minimal Supersymmetric Standard Model (MSSM). The simulation work based on the MSSM will be described in detail in the first half of this report.

Once supersymmetry is discovered, the next step is the measurement of the parameters of the model. The requirement of generality, essential in the discovery phase, implies a choice of global observables with little sensitivity to the details of the model. The simulation work is aimed at verifying if it is possible to elucidate the structure of the theory which produces the observed deviations from SM. To achieve this goal, studies based on specific model assumptions are needed. The present line of work concentrates on a supergravity–inspired model (SUGRA), which, albeit still very general, has a very limited number of free parameters, and a good predictive power. Work is in progress on this model, and some promising results are already available. This approach to SUSY studies will be the subject of the last section of this report.

2. Detector requirements

The basic detector requirements for the SUSY analyses presented in this report can be summarized as follows:

- Electron and muon identification and measurement with $\geq 90\%$ efficiency over a pseudorapidity range $|\eta| < 3$;
- Jet reconstruction and measurement inside $|\eta| < 3$ with a resolution $\Delta E/E = (50\%/\sqrt{E}) \oplus 3\%$;
- Hermetic calorimeter coverage inside $|\eta| < 5$ for $E_T^{\rm miss}$ measurement with control on non-Gaussian tails
- Capability for b–jet tagging with $\varepsilon_b = 60\%$ and a mistagging of $<1\%(<10\%)$ for light jets (c–jets) at a luminosity of 10^{33} cm^{-2}s^{-1}

Both general–purpose detectors being built for the LHC , ATLAS [2], and CMS [3] are designed to meet these specifications.

Many of the analyses described in this report assume an initial running of the LHC for a few years at a luminosity of 10^{33} cm^{-2}s^{-1}. Whenever appropriate the results for high luminosity running (10^{34} cm^{-2}s^{-1}) will be quoted.

3. MSSM searches

The Minimal Supersymmetric Standard Model (MSSM) [4] is a direct supersymmetrization of the SM, with R-parity conservation and the minimum number of new particles and interactions compatible with phenomenology.

In particular, 2 higgs doublets are needed to give masses to the up–type and the down–type fermions, giving rise to 5 physical higgs states, 2 scalars (h and H), 1 pseudoscalar (A), and 1 charged pair ($H^{\pm}$). The Lightest Supersymmetric Particle, assumed to be the lightest neutralino, is stable, and escapes detection, generating missing transverse energy ($E_T^{\rm miss}$) in the detector.

SUSY breaking is parametrized by incorporating all soft SUSY breaking terms. In order to further reduce the parameter space, 1) all gaugino masses are assumed to evolve as in SUSY GUTs, and parametrized in terms of the gluino mass; 2) the different generations of squarks and leptons are taken approximately degenerate.

Neglecting mixing in the third generation sector, the model has the following free parameters: the common mass of squarks ($m_{\tilde{\rm q}}$), the common mass of sleptons, the gluino mass ($m_{\tilde{\rm g}}$), the ratio of the vacuum expectation values of the two Higgs doublets of the model (tanβ), the pseudoscalar Higgs mass ($m_{\rm A}$), and the SUSY Higgs-Higgsino mass term (μ). The model is implemented in the ISAJET [7] generator which was used for the studies described in this section.

The most favorable channels for the search of SUSY at hadron colliders are the ones involving the productions of squarks and gluinos. Such particles are produced via strong interaction processes, and have therefore large productions cross-sections. They decay to the LSP through complex decay patterns involving the kinematically accessible charginos and neutralinos. These decays give rise to final states including $E_T^{\rm miss}$ from the LSP, high E_T jets, and leptons.

Two signatures, multijets+$E_T^{\rm miss}$and same–sign dileptons have been studied in detail by the two LHC collaborations. They give a sizeable signal over most of the parameter space, can easily be separated from background, and are basically independent from the model parameters except $m_{\tilde{\rm q}}$ and $m_{\tilde{\rm g}}$.

The studies performed by the ATLAS collaboration explore the $m_{\tilde{\rm q}}$–$m_{\tilde{\rm g}}$ plane fixing the remaining parameters to 'standard' values:

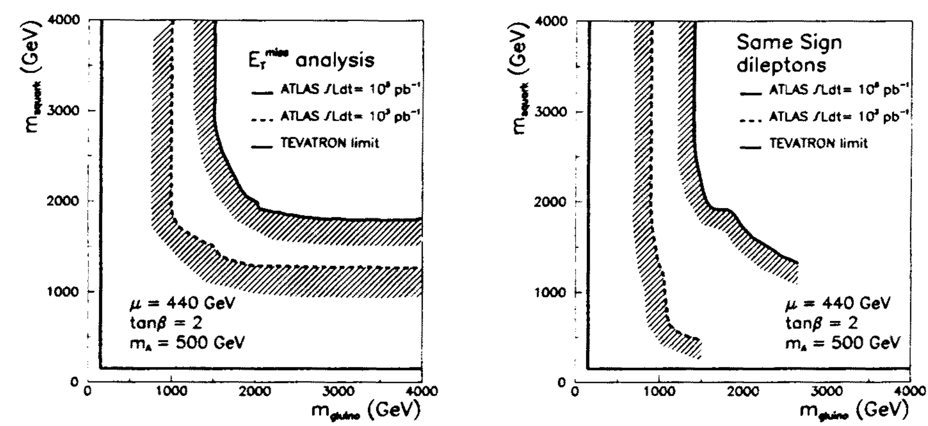
- values of $|\mu| < 100$ GeV will most likely be excluded by experiments at LEP2 or Tevatron. A large value of $|\mu|$ (usually μ =400 GeV) is therefore used;
- the choice of $m_{\rm A}$ is 500 GeV, so as to exclude Higgs bosons other than h in the decay chains of gluinos;
- most of the results shown are not affected by the choice for tanβ, and a low value tan$\beta = 2$ is used.

Other signatures cover a smaller region in parameter space, but allow a more direct insight into the parameters of the model. Among these, three lepton events from chargino–neutralino production will be described below.

3.1. $E_T^{\rm miss}$*+jets*

This is the classical signature, involving events with high jet multiplicity and large missing transverse energy ($E_T^{\rm miss}$). In order to evaluate the reach of the experiment in the $m_{\tilde{q}}$–$m_{\tilde{g}}$ plane, the ATLAS Collaboration has studied different combinations of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ for masses in the range 300–2000 GeV.

The irreducible background consists of events with high–p_T neutrinos in the final state: $t\bar{t}$, and W/Z + jets. The selection criteria applied in the ATLAS analysis require at least three jets with $p_T > 200$ GeV, a fourth jet with $p_T > 100$ GeV, a sphericity in the transverse plane $S_T > 0.2$, and $E_T^{\rm miss} > 300$ GeV. The accessible region in the $m_{\tilde{q}}$–$m_{\tilde{g}}$ plane was evaluated by requiring a significance of the signal after cuts of at least five standard deviations, defined according to the naive estimator $S/\sqrt{B}$. This is shown in Fig. 1.A for two different integrated luminosities: 10^3 pb^{-1} and 10^5 pb^{-1}.



A) B)

Fig. 1. ATLAS reach in $m_{\tilde{q}}$–$m_{\tilde{g}}$ plane: A) $E_T^{\rm miss}$ + jets analysis B) Same–sign lepton search

A large instrumental background may arise from multijet events where one (or more) jets are mismeasured in the detector. The ATLAS Collaboration has studied this background using samples of four–jet and five–jet events and a parametrization of the results of a full GEANT simulation of the critical region of the detector. The jet multiplicity cuts described above ensure that this background is smaller than the irreducible physics background for cuts on $E_T^{\rm miss}$ as low as 200 GeV.

3.2. Same–Sign dilepton searches

The cascade decays of squarks and gluinos can produce isolated leptons. The CMS Collaboration has studied signatures including 1-2-3 muons + jets + $E_T^{\rm miss}$. The ATLAS Collaboration has concentrated on a topology including a pair of isolated same–sign leptons, accompanied by a large number of jets and $E_T^{\rm miss}$. This topology is abundantly produced, as the gluinos are majorana particles, and decay with equal probability to charginos of either sign. The irreducible SM background mainly consists of $\rm t\bar{t}$ events where one of the leptons comes from the decay of a W boson, and the second from the semileptonic decay of a b quark. This background can be efficiently reduced by requiring that both leptons be isolated, and by jet multiplicity requirements. The ATLAS Collaboration has studied different combinations in the $m_{\tilde{\rm q}}$–$m_{\tilde{\rm g}}$ plane with masses ranging between 300 and 2000 GeV. Different reconstruction and selection cuts were used as a function of luminosity and $m_{\tilde{\rm g}}$. The following kinematic cuts were applied for $m_{\tilde{\rm g}} < 1$ TeV at 10^{34} cm^{-2}s^{-1}:

- Two isolated same-sign leptons with $p_T > 20$ GeV and $|\eta| < 2.5$;
- At least four jets with $p_T > 110$ GeV. The highest-p_T jet was required to have $p_T > 160$ GeV;
- $E_T^{\rm miss} > 150$ GeV.

The mass reach in the $m_{\tilde{\rm q}}$–$m_{\tilde{\rm g}}$ plane is shown in Fig. 1.B

The sensitive region is comparable to the one for $E_T^{\rm miss}$+ jets signature, and the sensitivity to model parameters is weak, making this channel a very good discovery channel for SUSY at the LHC.
There is a possible reducible background from $\rm t\bar{t}$ events, with two opposite–sign leptons, where one lepton charge is misidentified. This background was found to be negligible by the ATLAS Collaboration for the low p_T leptons considered in this analysis [2], and is essentially insensitive to the exact value of the charge misassignment probability.

This channel can also be used to extract information about the ratio of $m_{\tilde{\rm q}}$ and $m_{\tilde{\rm g}}$ through the measurement of the asymmetry between the dilepton signal cross-sections of positive and negative charge.

3.3. Charginos and neutralinos

Chargino and neutralino pairs, produced through the Drell–Yan mechanism or squark exchange, may be detected through their leptonic decays, $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to \ell\ell\ell + E_T^{\rm miss}$. The three-lepton signal is produced through the decay chain $\tilde{\chi}_1^{\pm} \to \ell\nu + \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to \ell\ell + \tilde{\chi}_1^0$, where the undetected neutrino and $\tilde{\chi}_1^0$ produce $E_T^{\rm miss}$.

Three-lepton final states were studied by the ATLAS Collaboration, for gluino masses in the range 200–600 GeV, for $m_{\tilde{q}} = m_{\tilde{g}} + 20$ GeV ,$m_{\tilde{q}} = 2m_{\tilde{g}}$ and $\mu = -m_{\tilde{g}}$.

The main backgrounds to this signal arise from WZ/ZZ and $t\bar{t}$ production, and can be suppressed by the following requirements, which were optimized for low luminosity:

- Three isolated leptons within $|\eta| < 2.5$ and with $p_T > 20$ GeV for the first two and $p_T > 10$ GeV for the third; no opposite-sign and same-flavour lepton pair with an invariant mass within $\pm$ 10 GeV of m_Z
- No jet with $p_T > 25$ GeV and $|\eta| < 3$.

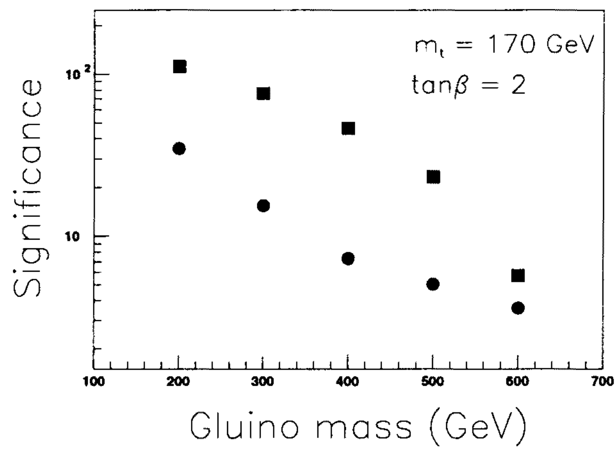


Fig. 2. For an integrated luminosity of 10^4 pb^{-1}, significance of SUSY three-lepton signal from chargino and neutralino decay as a function of $m_{\tilde{g}}$ for $\mu = -m_{\tilde{g}}$ and for $m_{\tilde{q}} = m_{\tilde{g}} + 20$ GeV (black squares) and $m_{\tilde{q}} = 2m_{\tilde{g}}$ (black circles)

For an integrated luminosity of 10^4 pb^{-1} and a lepton efficiency of 90%, the significance of the signal over the SM background is shown in Fig. 2 for $\tan\beta = 2$. If $\tan\beta$ is increased from 2 to 20, the statistical significance decreases, and the signal can only be extracted for $m_{\tilde{g}} < 400$ GeV.

It is important to note that $\tilde{q}$ and $\tilde{g}$ decays also produce a sizeable three-lepton signal, which, after cuts, is at the level of $\sim$ 20% of the chargino/neutralino signal. By applying more severe jet veto criteria, it is possible to extract a clean chargino/neutralino contribution to this signal, which allows to estimate $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ from the endpoint of the $m_{l^+l^-}$ spectrum [6].

3.4. Conclusions on MSSM

The studies described above show that, by using inclusive signatures, we will be able to measure deviations from the SM induced by the MSSM. Gluinos and squarks with masses starting from the maximum projected reach of the Tevatron collider ($\approx$ 200 GeV) up to 1–2 TeV will be easily discovered at the LHC.

Such analyses, however, can only be used to obtain a rough estimate of the mass scale of the superpartners. In the MSSM, the masses of the sfermions have no a priori relationship among them, and the higgs sector is essentially decoupled from the sparticle sector. This large freedom makes a complete exploration of the parameter space of the model well nigh impossible. More detailed studies therefore require the choice of specific SUSY models, with a smaller number of basic parameters, and hence a higher predictive power than the MSSM.

4. SUGRA searches

An interesting class of models is based on minimal supergravity (SUGRA) [5]. In these models, as in the MSSM as defined above, the coupling constants of the three gauge groups are assumed to unify at some large scale M_X. The breaking of supersymmetry in the effective theory defined at M_X takes place via gravitational interactions with a 'hidden' sector. Such interactions, being flavour blind, allow a limited number of independent SUSY breaking parameters. After performing the evolution via the Renormalization Group Equations to the electroweak scale, all the masses, couplings, and mixings of the model are fixed in term of four parameters plus a sign:

- the common gaugino mass ($m_{1/2}$)
- the common scalar mass (m_0)
- the common trilinear interaction (A)
- tanβ
- sign(μ)

The model described above has a high predictive power, as, for a given set of parameters, all different experimental signatures can be studied in a combined way, allowing to put strong experimental constraints on the underlying theory. This model is implemented in two event generators [7] [8], which show a very good agreement between them, and have been both used for the simulation studied performed in the ATLAS collaboration.

A pragmatic approach to the investigation the SUGRA model is the choice of some sample points in parameter space, which are studied in detail in order to identify exclusive signatures for specific decays. The aim, for each point, is to assess a number of channels which can be reliably isolated, and which yield information about the mass spectra of the model.

From the measured physical quantities, the position in the parameter space of SUGRA can be constrained, and, if the number of observables is high enough, the model can be uniquely identified. In the most optimistic case, an overconstrained fit on the model parameters can be envisaged, thus allowing to verify if the observed signatures are compatible with minimal SUGRA.

This work is being performed on 5 sample points by the ATLAS collaboration [9]. To clarify the procedure followed, and to give a flavour of the results obtained, we will describe in detail a few of the analyses performed on one of the sample points.

4.1. Analyses on example point

The chosen point is defined by the following parameters: $m_0 = 100$ Gev, $m_{1/2} = 300$ GeV, $A = 300$ GeV, $\tan\beta = 2.1$, $\mu > 0$. Squarks are lighter than gluinos in this point ($m_{\tilde{q}}$=660 GeV , $m_{\tilde{g}}$=760 GeV), and the total cross-section (20 pb) is dominated by $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{g}$ production. This point has been chosen in the region of parameter space favored by cosmology [10], and is characterized by the fact that the sleptons are relatively light. They can therefore be detected either by direct Drell–Yan production, either in the decay chain of other particles. Both the decays $\tilde{\chi}^0_2 \rightarrow \tilde{l}\, l$ and $\tilde{\chi}^0_2 \rightarrow$ h $\tilde{\chi}^0_1$ are kinematically open and compete with each other, giving rise to striking signatures which can be exploited to constrain the SUSY model.

Search for h → $b\bar{b}$ in squarks decays

In the considered points, the partners of left handed quarks, $\tilde{q}_L$, are abundantly produced, either directly or in gluinos decays, and have a sizeable branching fraction (BF) to the corresponding quark and $\tilde{\chi}^0_2$.

The decay chain $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1$ h, h $\rightarrow b\bar{b}$ has a BF of 50%. A high fraction of SUSY events therefore contains a h $\rightarrow b\bar{b}$ decay, making this channel a very good candidate for tagging SUSY events with a well identified decay chain. The final state is characterized by E_T^{miss}, hard jets from the $\tilde{q}$ decay, and 2 b-quarks. The main backgrounds are SUSY combinatorial, $t\bar{t}$, and IVB+jets. The signal can be isolated from backgrounds by requiring: $E_T^{miss} > 300$ GeV; at least 2 jets with $p_T > 100$ GeV; 2 and only 2 well separated b–jets with $p_T > 50$ GeV; no identified lepton with $p_T > 10$ GeV. The $m_{b\bar{b}}$ spectrum for the selected events is shown in Fig. 3. The Standard Model background is reduced to a negligible level, and the higgs mass peak clearly emerges

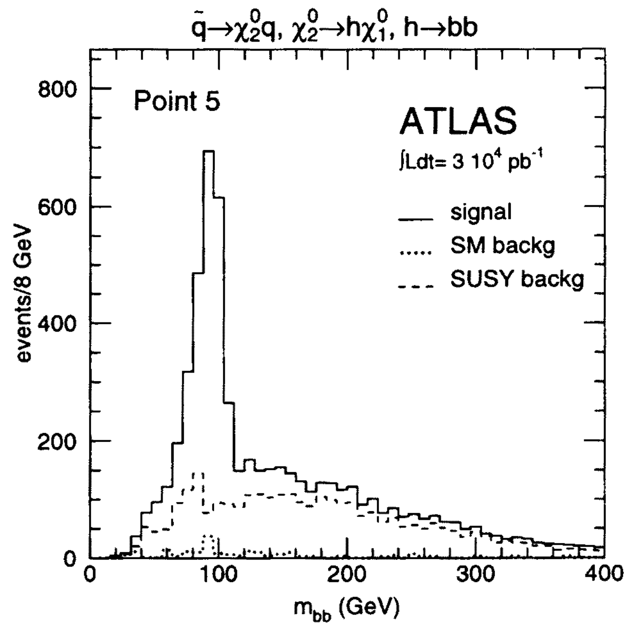


Fig. 3. $m_{b\bar{b}}$ spectrum after cuts for an integrated luminosity of $3{\cdot}10^4$ pb^{-1}

above the SUSY combinatorics. In a ±25 GeV window around m_h the sample includes ≈ 2600 events (for $3{\cdot}10^4$ pb^{-1}), with a 75% sample purity.

By selecting events requiring $m_{b\bar{b}}$ in the higgs mass window, and only two non-b jets in the event, the initial state $\tilde{q}_R\tilde{q}_L$ can be selected, where $\tilde{q}_L$ decays via the decay chain identified above, and $\tilde{q}_R$ via $\tilde{q}_R\to q\ \tilde{\chi}_1^0$. For this sample, variables sensitive to $m_{\tilde{q}}$ can be identified. A useful variable is the invariant mass of the $b\bar{b}$ pair with each of the two additional jets in the event. By choosing the minimum m_{jbb} combination, the distribution shown in Fig. 4 is obtained. This distribution sensitively depends on the masses of $\tilde{q}_L$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$, and can be used to evaluate the $\tilde{q}_L$ mass.

Two-lepton search

The branching fraction for the decay: $\tilde{\chi}_2^0\to\tilde{l}\ l$ is 17%, and the slepton decays in turn via $\tilde{l}\to l\ \tilde{\chi}_1^0$ with 100% BF. As for the previous channel studied, $\tilde{\chi}_2^0$ are produced in $\tilde{q}$ decays. The corresponding final-state signature includes E_T^{miss}, two hard opposite-sign, same-flavour leptons, one from $\tilde{\chi}_2^0$ decay, and one from $\tilde{l}$ decay, plus at least 2 jets from squarks decays.

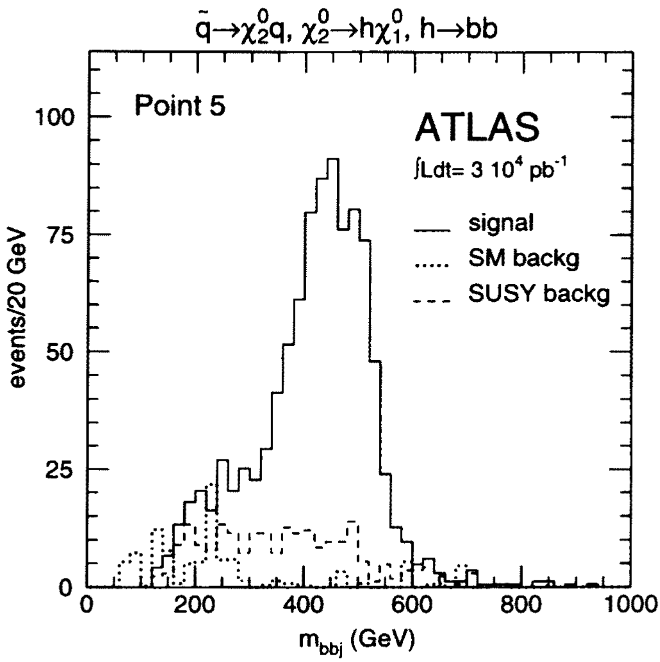


Fig. 4. $m_{\rm bbj}$ spectrum after cuts for an integrated luminosity of $3{\cdot}10^4$ pb^{-1}(veto additional jets with $p_T > 15$ GeV)

By selecting on these variables, the SM background can be reduced to a negligible level, retaining, for 3 years at 10^{33} cm^{-2}s^{-1}, a SUSY signal of $\approx$ 6000 events, of which $\approx$ 5000 come from the desired decay chain. The invariant mass of the two leptons, ($m_{\rm l^+l^-}$), shown in Fig. 5, shows a very sharp edge, which is related to the masses of the involved particles by the relationship:

$$m_{\rm l^+l^-}^{\rm max} = m_{\tilde\chi_2^0}\sqrt{1+\frac{m_{\tilde{\rm l}}^2}{m_{\tilde\chi_2^0}^2}}\sqrt{1+\frac{m_{\tilde\chi_1^0}^2}{m_{\tilde{\rm l}}^2}}\,.$$

The observation of such $\rm l^+l^-$ continuum with a rate comparable to $\rm h\to b\bar{b}$, and an edge at a mass higher than $m_{\rm Z}$, would suggest that the leptons come from a two-body decay of the $\tilde\chi_2^0$, and hence most probably from light sleptons. The precise measurement of the position of the edge would then provide a strong constraint on the sparticle masses.

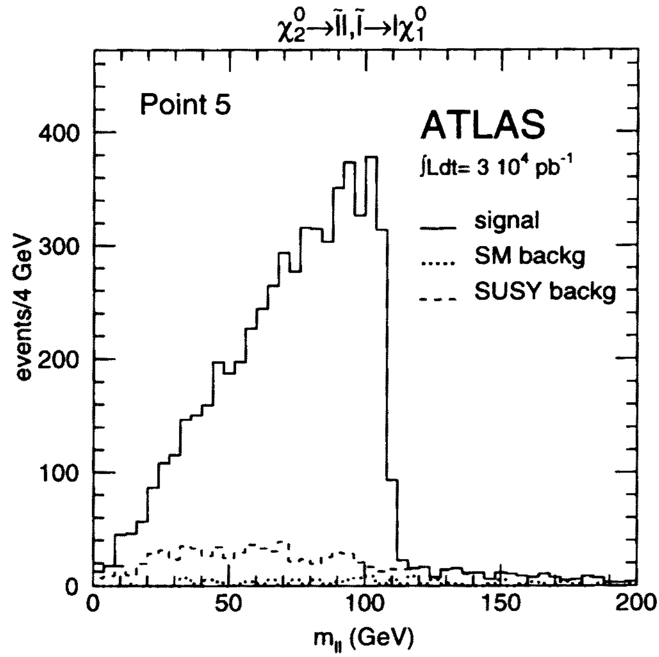


Fig. 5. $m_{l^+l^-}$ spectrum after cuts for an integrated luminosity of $3{\cdot}10^4$ pb^{-1}

A further constraint on the slepton masses can also be obtained by studying other kinematic variables such as the ratio of the p_T of the two leptons.

The analyses performed for this point, of which only a few examples have been shown, allow to constrain the masses of the light higgs, of the squarks, of the gluino and of the sleptons with a precision better than a few percent. With this information, it is possible to measure at the percent level the parameters of the SUGRA model.

4.2. Conclusions on SUGRA

For all the points being studied in ATLAS, exclusive signatures have been found which allow a direct and clean observation of SUSY sparticles, and, in most cases measurement of the masses [9]. With these results, a precise measurement of fundamental model parameters will be possible at the LHC. The study is being performed on a specific class of models, SUGRA, which can be severely overconstrained by the experimental analyses.

However, many of the measurements can be used to pose model–independent constraints on sparticle masses and their relationships, and the results of the ongoing studies suggest that:

- SUSY, if it exists, will be seen at the LHC;
- given a specific model, we will be able to test it, and to measure its fundamental parameters.

More work is ahead of us to complete the analysis of the SUGRA models, and to extend these analyses to wider classes of models, such as models with R-parity violation, or with the LSP decaying *e.g.* to $\tilde{G}\gamma$.

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