# THE PHYSICS PROGRAMME WITH ATLAS*

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This article presents short overwiew of the physics programme which should be possible with the ATLAS detector, as documented in ATLAS Detector and Physics Performance Technical Design Report. The physics potential studied in previous documents (ATLAS Letter of Intent and ATLAS Technical Proposal) have been re-examined and many new strategies proposed. Here search for the Higgs boson is discussed in somewhat more details, while only highlights of the new results are given for each of the other important aspects in this very broad physics programme.

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## 1. Introduction

The Large Hadron Collider (LHC) is a proton-proton collider with 14 TeV centre of mass energy and a design luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The ATLAS experiment has now entered the construction phase for many of its detector components [5] with a strict schedule to meet the first collisions at LHC in summer 2005. The $30\mathrm{fb}^{-1}$ is expected to be collected with the low luminosity operation over first 3 years of running and $100\mathrm{fb}^{-1}$ per year with the high luminosity operation. The ultimate integrated luminosity will be $300\mathrm{fb}^{-1}$.

The ATLAS physics programme has been already discussed in several documents, the most comprehensive ones being the Letter of Intent [2] and the Technical Proposal [3] and recently completed Detector and Physics Performance Technical Design Reports [1]. The goals which have been defined there and which have guided the detector optimisation procedure remain

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essentially the same. The most important one being measurements that will lead to an understanding of the mechanism of electroweak symmetry breaking.

The high energy and luminosity of the LHC offers a large range of physics opportunities, from the precise measurement of the properties of known objects to the exploration of the high energy frontier. The need to accommodate the very large spectrum of possible physics signatures has guided the optimisation of the detector design. The desire to probe the origin of the electroweak scale leads to a major focus on the Higgs boson; ATLAS must be sensitive to it over the full range of allowed masses. Other important goals are searches for other phenomena possibly related to the symmetry breaking, such as particles predicted by supersymmetry or technicolour theories, as well as new gauge bosons and evidence for composite quarks and leptons. The investigation of CP violation in $B$ decays and the precision measurements of $W$ and top-quark masses and triple gauge boson couplings will also be important components of the ATLAS physics programme.

The excellent performance of the detector is needed to achieve these physics goals.

- The various Higgs boson searches, which resent some of the most challenging signatures, were used as benchmark processes for the setting of parameters that describe the detector performance. High-resolution measurements of electrons, photons and muons, excellent secondary vertex detection for $\tau$-leptons and $b$-quarks, high-resolution calorimetry for jets and missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) are essential to explore the full range of possible Higgs boson masses.

- Searches for SUSY set the benchmarks on the hermeticity and $E_{\mathrm{T}}^{\mathrm{miss}}$ capability of the detector, as well as on $b$-tagging at high luminosity.

- Searches for new heavy gauge bosons provided benchmark requirements for high-resolution lepton measurements and charge identification in the $p_{\mathrm{T}}$ range as large as a few TeV.

- Signatures characteristic for quark compositeness set the requirements for the measurement of very high-$p_{\mathrm{T}}$ jets.

- The precision measurements of the $W$ and top-quark masses, gauge boson couplings, CP violation and the determination of the Cabibbo–Kobayashi–Maskawa unitarity triangle yielded benchmarks that address the need to precisely control the energy scale for jets and leptons, determine precisely secondary vertices, reconstruct fully final states with relatively low-$p_{\mathrm{T}}$ particles and trigger on low-$p_{\mathrm{T}}$ leptons.

### *1.1. QCD processes, heavy flavour and gauge boson production*

In the initial phase at low luminosity, the experiment will function as a factory for QCD processes, heavy flavour and gauge bosons production. This will allow a large number of precision measurements in the early stages of the experiment. A large variety of QCD related processes will be studied. These measurements are of importance as studies of QCD 'per se' in a new energy regime with high statistics. Of particular interest will be jet and photon physics, open charm and beauty production and gauge bosons production. A study of diffractive processes will present significant experimental challenges itself, given the limited angular coverage of the ATLAS detector. Several aspects of diffractive production of jets, gauge bosons, heavy flavour partons will be nevertheless studied in detail. LHC will extend the exploration of the hard partonic processes to large energy scales (of few hundred $\mathrm{GeV}^2$), while reaching small fractional momentum of the proton being carried by a scattered partons (of $10^{-5}$). Precise constraints on the partonic distribution functions will be derived from measurements of Drell-Yan production, of $W$ and $Z$ bosons production, of production of direct photons and high-$p_{\mathrm{T}}$ jets, heavy flavours and gauge boson pairs. Deviation from the theoretical predictions for QCD processes themselves might indicate the onset of new physics, such as compositeness. Measurement and understanding of these QCD processes will be essential as they form the dominant background searches for new phenomena.

#### **1.1.1. B-physics**

Even at low luminosity, LHC is a beauty factory with $10^{12}$ $b\bar{b}$ expected per year. The available statistics will be limited only by the rate at which data can be recorded. The proposed B-physics programme is therefore very wide. Specific B-physics topics include the search for and measurement of CP violation, of $B_s^0$ mixing and of rare decays. ATLAS can perform competitive high-accuracy measurements of $B_s^0$ mixing, covering the statistically preferred range of the Standard Model predictions. Rare $B$ mesons such as $B_c$ will be copiously produced at LHC. The study of $B$-baryon decay dynamics and spectroscopy of rare $B$ hadrons will be also carried out.

Let us high-light thus two examples (see also Fig. 1):

The angle $\beta$ of the unitarity triangle is expected to be measured with a precision of $\delta(\sin 2\beta) = 0.012$ (stat) with an integrated luminosity of $30\mathrm{fb}^{-1}$, collected at low-luminosity data taking. Already after 1 year at low luminosity ($10\mathrm{fb}^{-1}$) around 14 400 signal events with lepton-tag and 11 600 events with $B\pi$-tag are expected from $B_d^0 \to \mathrm{J}/\Psi \to ee$ channel about the background of 900 events (in each cases).

For the $B_s^0$ oscillation the maximum value of $\Delta m_s$ which is expected to be measured with 30fb$^{-1}$ data is $38.5 ps^{-1}$ from samples of $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to D_s^- a_1^+$ with trigger muon-tag. The expected accuracy of the $\Delta m_s$ measurement is $0.16 ps^{-1}$ and this quantity can be measured over the whole range predicted in the Standard Model.

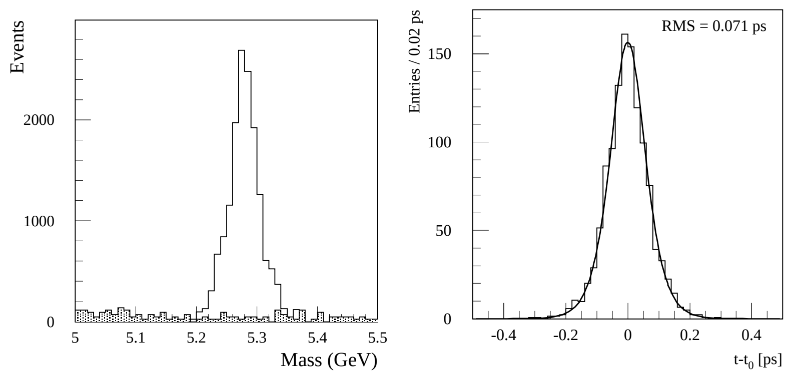



Fig. 1. On the left-side: Invariant mass distribution of the $B_d^0$ peak in the muon-tagged $J/\Psi \to ee$ channel (open histogram) with superimposed the estimated background contribution (shaded histogram). On the right side: Proper-time resolution for the decay channels $B_s^0 \to D_s^-(\phi\pi^-)a_1^+(\rho^0\pi^+)$. Plots are from [1].

#### 1.1.2. Top-quark physics

LHC has a great potential for performing high precision top physics measurements with about eight million $t\bar{t}$ pairs expected to be produced for an integrated luminosity of 10fb$^{-1}$. It would allow not only for the precise measurements of the top-quark mass (with a precision of  2 GeV) but also for the detailed study of properties of the top-quark itself. The single top production should be observable and the high statistics will allow searches for many rare top decays. The precise knowledge of the top-quark mass places strong constraints on the mass of the Standard Model Higgs boson, while a detailed study of its properties may reveal as well new physics.

A very large samples of top-quark events which will be accumulated at LHC will allow a precise measurement of the top-quark mass. More than 120 000 single lepton plus jet events would be selected, with a signal-to-background ratio of over 60, within a single year of running at low luminosity. Measuring $m_t$ by reconstructing the invariant mass of the $t \to jjb$ candidates in these events would yield a statistical error below 0.1 GeV (see Fig. 2). Studies on the systematics errors indicate a total error below 2 GeV should be

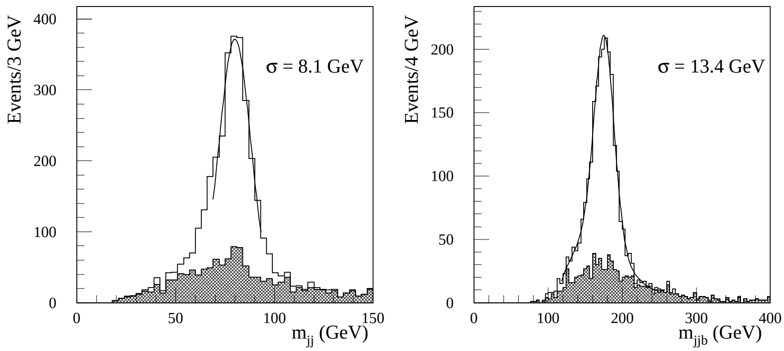



Fig. 2. On the left-side: Invariant mass distribution of the selected jj pairs for the inclusive $t\bar{t}$ sample, normalised to an integrated luminosity of $10\text{fb}^{-1}$. The shaded histogram shows the background, which is dominated by 'wrong combinations' from $t\bar{t}$ events. On the right side: The same but for accepted jjb combinations. Only the jjb combination with the highest $p_T$ is shown for each event. Plots are from [1].

obtainable, provided the energy scales for jets and $b$-jets can be understood at the 1% level.

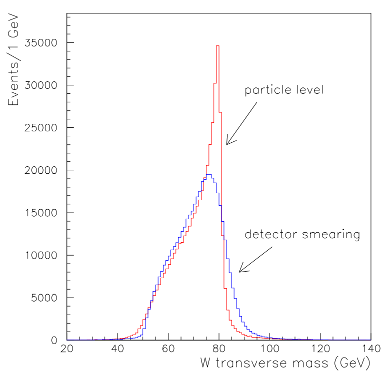
At LHC, the largest source of top-quarks is from $t\bar{t}$ production. The production cross-section will be determined with precision of 10%, dominated by the uncertainty on the absolute luminosity.

The large top-quark mass implies that the top quark would tend to couple strongly to other massive particles. Therefore determining whether the top quark has the couplings and decays predicted by the SM provides a sensitive probe of physics beyond SM. For example the measurement of the $V_{tb}$ will be possible with precision better than 10%. The BR$(t \to Wb)$ will be measured with relative statistical precision of 0.5% already after collecting $10\text{fb}^{-1}$. The upper limit which would be possible to derive on FCNC decay $t \to Zc$ will be of $5 \cdot 10^{-5}$ for an integrated luminosity of $100\text{fb}^{-1}$.

#### 1.1.3. Physics of electroweak gauge bosons

Gauge bosons and gauge-boson pairs will be abundantly produced at the LHC. The large statistics and the high centre-of-mass energy will allow several precision measurements to be performed, which should improve significantly the precision achieved as present machines.

One of the challenges to the LHC experiments will be whether the precision of the $W$-mass measurement can be improved. At the start of LHC $m_W$ will be known with precision of 30 MeV (Tevatron and LEP). Given the 300 million single $W$ events expected in one year of data taking almost 20 million events with reconstructed $W \to \ell\nu$ will have transverse mass in the range of 65-100 GeV, see Fig. 3. The expected statistical uncertainty on the end-point measurement of this distribution is about 2 MeV. The very ambitious goal for both theory and experiment is to reduce the individual sources of systematic errors to less than 10 MeV, which would allow for the measurement of the $W$ mass with precision better than 20 MeV. The most serious challenge in this measurement is the determination of the lepton absolute energy and momentum scale to 0.02%. The 20 MeV precision if achieved by ATLAS alone [6] should decrease to 15 MeV by combining ATLAS and CMS together. Such precision would ensure that the precision of the $W$ mass is not the dominant source of errors in testing radiative corrections in the SM prediction for the Higgs mass.



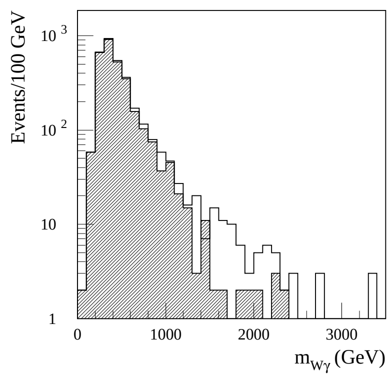




Fig. 3. On the left-side: Distribution of the $W$ transverse mass as obtained at particle level and by including the expected ATLAS detector resolution. On the right side: The distribution of the invariant mass of the $W\gamma$ system for the Standard Model (shaded histogram) and a non-standard value of 0.01 for $\lambda\gamma$ (white histogram). The number of events corresponds to integrated luminosity of $30\text{fb}^{-1}$. Plots are from [1].

The large rate of gauge boson pair production at the LHC enables ATLAS to provide critical tests of the triple gauge-boson couplings. The gauge cancellations predicted by the Standard Model will be studied and measurements of possible anomalous couplings made. The experimental sensitivity to Triple Gauge Couplings (TGCs) comes from the increase of the production cross-section and the alternation of differential distributions for non-standard TGCs. As a consequence an increase in the number of events with large di-boson invariant masses is a clear signature of non-standard TGCs as illustrated in Fig. 3, where the invariant mass of the hard scattering is shown for $W\gamma$ events simulated with Standard Model and non-standard TGCs; limits on TGCs can be obtained from event counting in the high-mass region. However the most sensitive variables to compare with Standard Model predictions are the transverse momentum spectra of high-$p_{\mathrm{T}}$ photons or reconstructed $Z$ bosons. It is also advantageous to combine it with information from angular distributions, including the boson decay angles.

A precision of (0.001) for the best constrained couplings, comparable to the world-limit at the time of the LHC start-up, can be achieved with only $10\mathrm{fb}^{-1}$.

## *1.2. Physics of Higgs boson*

If the Standard Model (SM) Higgs boson is not discovered before LHC begins operation, the searches for it and its possible supersymmetric extensions in the Minimal Supersymmetric Standard Model (MSSM) will be a main focus of activity. Search strategies presented here explore a variety of possible signatures, being accessible already at low luminosity or only at design luminosity. Although the cleanest one would lead to reconstruction of narrow mass peaks in the photonic or leptonic decay channels, very promising are the signatures which lead to multi-jet or multi-t final states. In several cases signal-to-background ratios much smaller than one are expected, and in most cases detection of the Higgs boson will provide an experimental challenge. Nevertheless, the ATLAS experiment alone will cover the full mass range up to 1 TeV for the SM Higgs and also the full parameter space for the MSSM Higgs scenarios. It has also a large potential for searches in alternative scenarios.

### 1.2.1. SM Higgs boson

The overall sensitivity for the discovery of a Standard Model Higgs boson over the mass range from $\sim$ 80 GeV to $\sim$ 1 TeV is shown in figure 4. The sensitivity is given in units of $S/\sqrt{B}$ for the individual channels as well as for the combination of various channels, assuming integrated luminosity of 30 and 100 $\mathrm{fb}^{-1}$. A $5\sigma$-discovery can be already achieved over the full mass range after a few years running at low luminosity. At least two discovery channels are available over most of the Higgs-boson mass range.

The most important channels in the intermediate mass region, for which a mass peak would be reconstructed, are the four-lepton channel, $H \to ZZ^* \to 4\ell$, the direct two-photon channel, $H \to \gamma\gamma$, as well as the associated production channels, where Higgs boson is produced in association with a vector boson or a $t\bar{t}$ pair and decays into $\gamma\gamma$ or $b\bar{b}$ pairs. For Higgs-boson masses around 170 GeV, for which the $ZZ^*$ branching ratio is suppressed, the discovery potential can be enhanced by searching for the $H \to WW^* \to \ell\nu\ell\nu$ decay. Most of these channels are challenging in terms of detector performance.

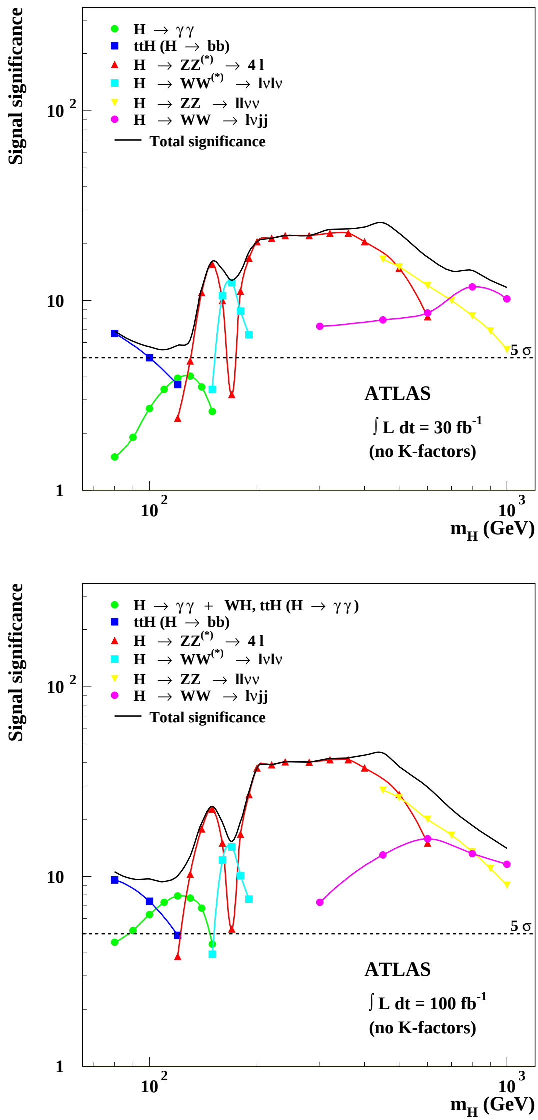



Fig. 4. ATLAS sensitivity for the discovery of a Standard Model Higgs boson. The statistical significances are plotted for individual channels, as well as for the combination of all channels, assuming integrated luminosities of 30fb$^{-1}$ (top) and 100fb$^{-1}$ (bottom). Depending on the numbers of signal and background events, the statistical significance has been computed as $S/\sqrt{B}$ or using Poisson statistics. Plots are from [1].

For $m_H > 2m_Z$, the dominant discovery channel is the four-lepton channel where the discovery can be achieved for Higgs boson masses up to 600 GeV over less than one year of data-taking at low luminosity. In the mass range between 400 GeV and about 1 TeV the best discovery potential is provided by $H \to WW \to \ell\nu jj$ mode complemented by $H \to ZZ \to \ell\ell jj, \ell\ell\nu\nu$ modes.

*$t\bar{t}H$ with $H \to b\bar{b}$*

If the mass of the Standard Model Higgs boson is lighter than 2 $m_W$, the $H \to b\bar{b}$ decay mode is dominant with branching ratio of 90%. The observation of such characteristic signature would be important for both the Higgs discovery and for the determination of the nature of any resonance observed in this mass region. Since the direct production $gg \to H$ with $H \to b\bar{b}$, cannot be efficiently triggered nor extracted as a signal above the huge QCD two-jet background, the associated production with a $W$ or $Z$ boson or a $t\bar{t}$ pair remains as the only possible process to observe a signal from $H \to b\bar{b}$ decay.

Of particular relevance turned out to be $t\bar{t}H$ production [7]. The considerably complex final state, consists of two $W$ bosons and four $b$-jets. Semileptonic decay of one of the $W$ bosons provides a trigger and reconstruction of both top-quarks in addition to asking for four $b$-tagged jets gives a handle against W+jet background and against combinatorial background from signal itself. The signal appears as a peak in the $m_{b\bar{b}}$ distribution above background dominated by $t\bar{t}b\bar{b}$ events, see Fig. 5.

The significance for the Higgs boson discovery in this channel exceeds $5\sigma$ for masses up to about 120 GeV (130 GeV) and for an integrated luminosity of 100fb$^{-1}$ (300fb$^{-1}$).

*$H \to WW^*$ with both $W \to \ell\nu$*

For Higgs-boson masses close to 170 GeV, the signal significance in the $H \to ZZ^* \to 4\ell$ channel is reduced, due to the suppression of the $ZZ^*$branching ratio as the $WW$ decay mode opens up. Based on the method suggested in [8], the discovery potential of this channel have been investigated with ATLAS. The signal signature consists of pair of opposite sign leptons and missing energy. It can be discriminate from the various backgrounds in the selection procedure which uses topological differences in the angular distributions of the di-lepton system due to the opposite spin orientation of the $W$ pair originating from the decay of the scalar Higgs boson, see Fig. 6.

A good signal-to-background ratio, of 0.7, can be obtained and the evidence for Higgs-boson signal is given by the excess of events in the transverse

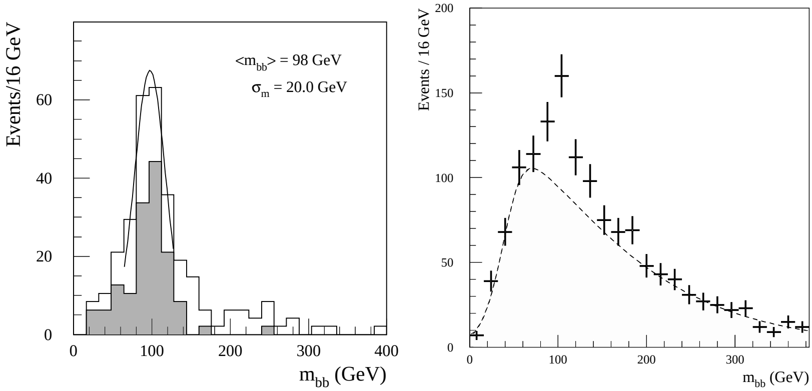



Fig. 5. On the left-side: For fully simulated events, the reconstructed $m_{b\bar{b}}$ distribution for $t\bar{t}H$ with $H \to b\bar{b}$ signal events with both top-quarks being reconstructed inside a mass window and for low luminosity performance. The shaded area denotes those events for which jet assignment in the Higgs boson reconstruction is correct. On the right side: Invariant mass distribution, $\mathrm{m_{b\bar{b}}}$, of tagged $b$-jet pairs in fully reconstructed $t\bar{t}H$ events with Higgs boson mass of 100 GeV above the summed background for an integrated luminosity of $100 fb^{-1}$ (30fb$^{-1}$ with low-luminosity performance and 70fb$^{-1}$ with high luminosity performance). Plots are from [1].

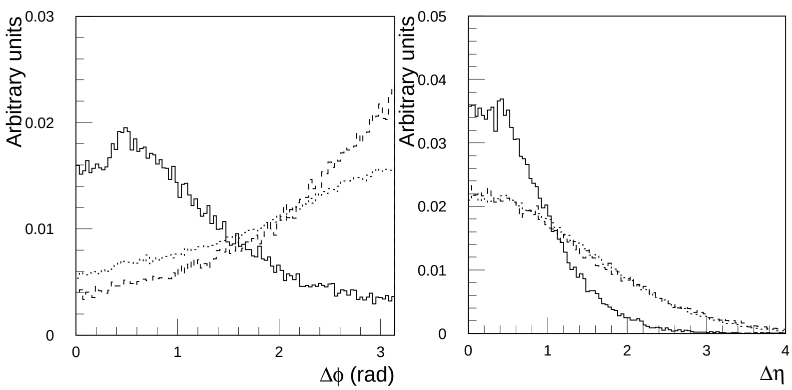



Fig. 6. On the left-side: Difference in the pseudorapidity between the two leptons for $H \to WW^* \to \ell\nu\ell\nu$ signal events with $m_H = 170$ GeV, and for the $WW^*$ and $t\bar{t}$ background events. All distributions are normalised to unity. On the right side:Difference in azimuth between the two leptons for $H \to WW^* \to \ell\nu\ell\nu$ signal events with $m_H = 170\ GeV$ and for the $WW^*$ and $t\bar{t}$ background events. All distributions are normalised to unity. Plots are from [1].

mass distribution of the di-lepton system. This distribution also shows the sensitivity to the Higgs boson mass which hopefully can be constrained in this channel to better than ± 5 GeV.

*Determination of the Higgs-boson mass and width*

Assuming that a Standard Model Higgs boson will have been discovered at the LHC, the precision measurements of its properties should give further insights into the electroweak symmetry-breaking mechanism and into the way the Higgs couples to fermions and bosons.

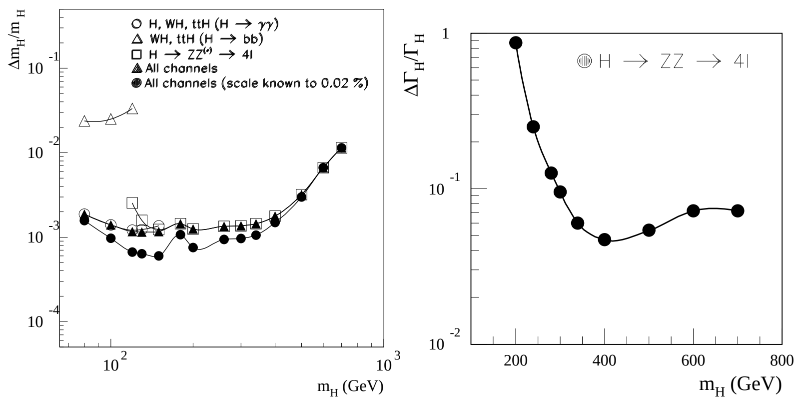



Fig. 7. On the left-side: Relative precision $\Delta m_H/m_H$ on the measured Higgs-boson mass as a function of $m_H$, assuming an integrated luminosity of $300\text{fb}^{-1}$. The black triangles (black circles) correspond to the combination of all channels for an overall uncertaintity of 0.1%(0.02%) on the absolute scale of EM Calorimeter. On the right side: Relative precision $\Delta\Gamma_H/\Gamma_H$ on the measured Higgs-boson width as a function of $m_H$, assuming an integrated luminosity of $300\text{fb}^{-1}$. Plots are from [1].

The ultimate experimental precision with which ATLAS should be able to measure the Higgs boson mass and width is shown in Fig. 7. It shows results expected for various channels as well as combination of all channels. The quoted precision includes the statistical error in determination of the peak position, coming from both the limited number of signal events, the error on the background subtraction, and the systematic error on the absolute energy scale. The latter is assumed to be 0.1% for decay channels which contain leptons or photons and 1% for decay channels containing jets. For comparison, the precision of the Higgs-boson mass measurement has also been determined assuming a systematic uncertainty of 0.02% for the electromagnetic scale.

The Higgs-boson width can be experimentally obtained from a measurement of the width of the reconstructed Higgs peak, after unfolding the contribution of the detector resolution. The direct measurements are only possible for masses larger than 200 GeV, above which the intrinsic width of the resonance becomes comparable to or larger than the experimental mass resolution. This mass region is covered mainly by $H \to ZZ \to 4\ell$ decays.

#### 1.2.2. MSSM Higgs bosons

Over the past years, prospects for the detection of MSSM Higgs bosons at LHC have been re-evaluated [9]. These studies have selected sets of parameters, for which supersymmetric (SUSY) particle masses are large, so that Higgs boson decays to SUSY particles are kinematically forbidden. The interest was focused on the discovery potential of various decay modes accessible also in the case of the SM Higgs boson: $h \to \gamma\gamma$, $h \to b\bar{b}$, $H \to ZZ \to 4\ell$, and of modes strongly enhanced at large $\tan\beta$: $H/A \to \tau\tau$, $H/A \to \mu\mu$. Much attention was given also to other potentially interesting channels such as:$H/A \to t\bar{t}$, $A \to Zh$ and $H \to hh$.

The conclusions which can be drawn from these studies and from Fig. 8 are that complete region of parameter space, $m_A = 50 - 500$ GeV and $\tan\beta = 1 - 50$, should be accessible for the Higgs boson discovery by the ATLAS experiment. The overall discovery potential relies heavily on the $H/A \to \tau\tau$ channel, on the $t\bar{t}h$ with $h \to b\bar{b}$ and on the direct and associated $h \to \gamma\gamma$ channels. Over large fraction of the parameter space more than one Higgs boson and/or more than one decay mode would be accessible. For almost all cases experiment will be able to distinguish between the SM and the MSSM models. This complete coverage can also be reached independent on the mixing scenario in the stop-sbottom sector.

Fig. 8 also display the present LEP2 limit and the ultimate limit expected by the end of LEP2 operation in 2000 assuming that no Higgs-boson discovery is made. The present experimental limit from LEP2 already excludes value of $\tan\beta$ below 2-3, and the expected ultimate limits will extend these excluded regions to $\tan\beta < 3$ (maximal mixing) or even $\tan\beta < 7$ (minimal mixing). It makes prospects for the discovery of several channels less promising as they do not have discovery potential at large $\tan\beta$. Studies of these channels are nevertheless considered valuable, since they provide model-independent probes of possible Higgs-boson signatures and since they contribute to the general process of quantifying and optimising the detector performance for the exploration of new physics signatures.

The interplay between SUSY particles and the Higgs sector has also been addressed. SUSY scenarios have an impact on discovery through the opening of Higgs boson decays to SUSY particles (mostly for H and A) and through presence of SUSY particles in loops (mostly for production via gg fusion and for $h \to \gamma\gamma$ decays). Scenarios in which SUSY particles are light and appear as Higgs decay products have been studied in the framework of

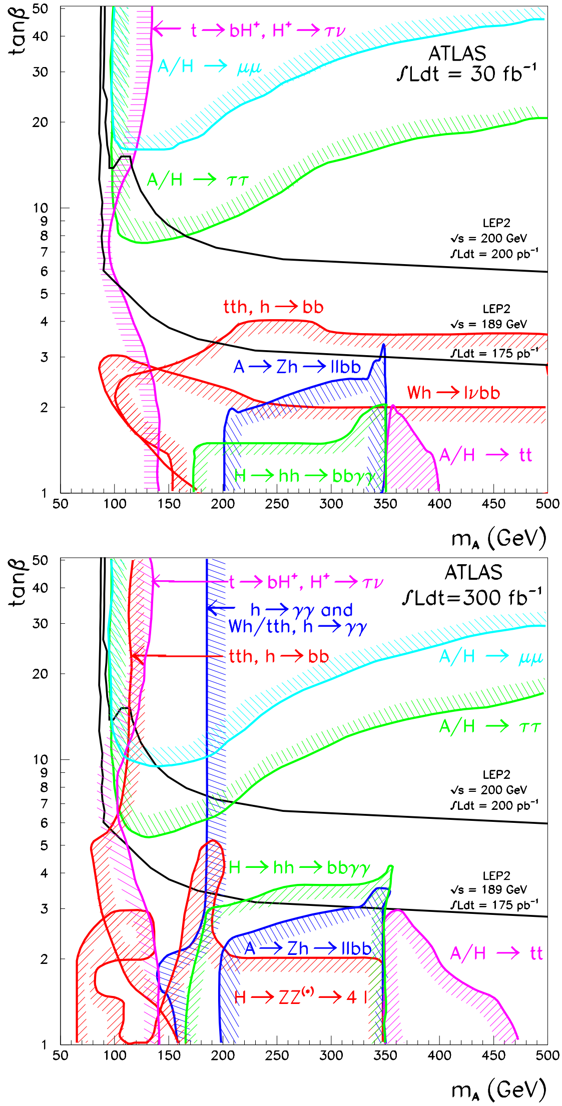



Fig. 8. ATLAS sensitivity for the discovery of MSSM Higgs bosons in the case of minimal mixing. The $5-\sigma$ discovery contour curves are shown in the $(m_A, \tan\beta)$ plane for individual channels discussed and for an integrated luminosities of 30fb$^{-1}$ (top) and 300fb$^{-1}$ (bottom). Also included are the present LEP2 limit (for an integrated luminosity of 175pb$^{-1}$ per experiment) and the expected ultimate LEP2 limit (for an integrated luminosity of 200pb$^{-1}$ per experiment at a centre-of-mass energy of 200 GeV). Plots are from [1].

SUGRA models. The discovery potential of the lightest neutral Higgs $h$ in the SM production processes would not be significantly different from what is obtained in the heavy SUSY scenario, since within the model, giving present experimental constraints, the decay of h to the lightest SUSY particles is kinematically forbidden. Moreover, over a large fraction of the SUGRA parameter space, the h-boson would appear at the end of the decay cascade of SUSY particles in the channel $\chi_0^2 \to \chi_0^1 h$ which will be observable with ATLAS detector. The neutral heavy Higgs bosons would be detected in some cases via their decays into neutralinos and charginos, using multilepton final states.

The evidence for MSSM Higgs-boson signal would not however constitute a direct proof of the existence of supersymmetry, unless supersymmetric particles are discovered themselves.

*The lightest Higgs boson*

The lightest Higgs boson will be seen in the Standard Model production processes, available as well for the SM Higgs boson in the mass range 100-150 GeV or in the decay of SUSY cascade. However there is a region of parameter space where it might be not accessible neither to LEP nor to LHC. As shown in Fig.8 it might happen for $\tan\beta > 10$ and $m_A \sim 120$ GeV

In the $(m_A, \tan\beta)$ parameter space relevant for the LHC searches, both the direct and associated production cross-sections and the branching ratios $h \to \gamma\gamma$ and $h \to b\bar{b}$ reach asymptotically the SM values as $m_A$ and/or $\tan\beta$ increases. In this decoupling limit the lightest MSSM Higgs boson behaves like a SM Higgs. The $5\sigma$-discovery contours are shown in Fig. 9. For an integrated luminosity of $30\mathrm{fb}^{-1}$ only low $\tan\beta$ region and only $h \to b\bar{b}$ is accessible while already for an integrated luminosity of $100\mathrm{fb}^{-1}$ almost full parameter space can be covered with importance of $h \to \gamma\gamma$ decay mode rising with increasing luminosity.

The lightest Higgs boson often appears at the bottom of the cascades. One copious production source is the decay of the second neutralino into the lightest SUSY particle; the former is produced with large rate in the decrease of squarks and gluinos. In the $R$-parity conserving SUSY models the light Higgs h is always accompanied by missing transverse energy; carried off by the lightest SUSY particle. The presence of missing transverse energy and several energetic jets can be used to obtain a sample that consists mainly of the decay products of SUSY particles. The discovery of the Higgs $h$ in its dominant decay mode $h \to b\bar{b}$ without a lepton being present then becomes possible (see Fig.10).

The SUGRA parameter was scanned in search for configuration where Higgs signal can be observable in the cascade decay. The projection on the $(m_A, \tan\beta)$ plane is shown in Fig. 10. Outside the marked region signal will

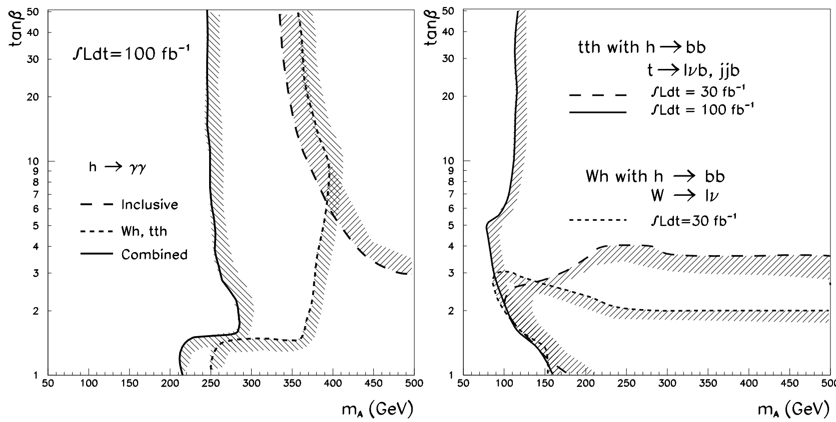



Fig. 9. For an integrated luminosities of $30\mathrm{fb}^{-1}$, $100\mathrm{fb}^{-1}$ and $300\mathrm{fb}^{-1}$, the $5\sigma$-discovery contour curves for the $h \to \gamma\gamma$ (left-side) and $h \to b\bar{b}$ channels (right-side) in the $(m_A, \tan\beta)$ plane. Plots are from [1].

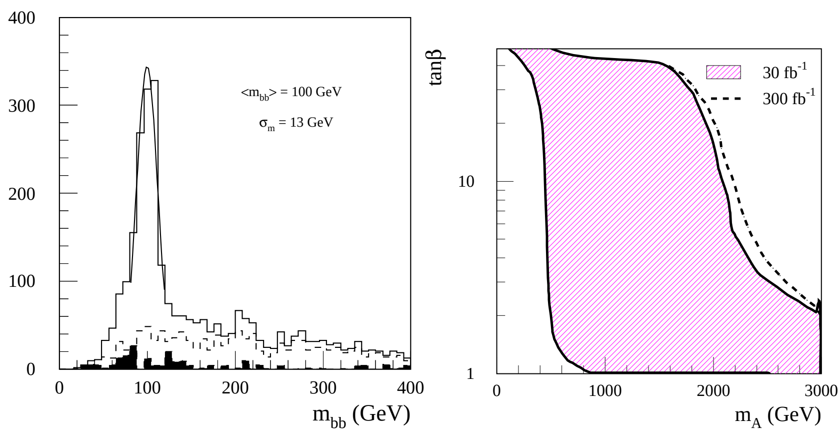



Fig. 10. On the left: The reconstructed $m_{b\bar{b}}$ distribution for $h \to b\bar{b}$ signal in SUSY cascade + total background (solid line), SUSY and SM background (dashed) and for SM background (black). for an integrated luminosity of $30\mathrm{fb}^{-1}$ and SUGRA point $(m_0, m_{1/2}) = (400, 400)$. On the righ: For integrated luminosities of 30 and 300 $\mathrm{fb}^{-1}$, $5\sigma$-discovery contour curves for the $h \to b\bar{b}$ from SUSY cascade in the $(m_A, \tan\beta)$ plane. Plots are from [1].

not be observable. Either the Higgs h is not produced in the SUSY cascade of heavy gaugino decays into lighter ones or a large $b\bar{b}$ reducible background overwhelms the signal. The observability region overlaps with the parameter space above $m_A = 500$ GeV where there is no or reduced sensitivity to the heavy boson in the MSSM model.

*The heavy Higgs boson*

The heavy Higgs bosons: H and A are almost degenerate in mass over most of the parameter space. Their accessibility relies on the predicted enhanced production in association with $b\bar{b}$ pairs for large $\tan\beta$ or on the direct production for low and moderate $\tan\beta$. The couplings ZZH and WWH are strongly suppressed with rising $\tan\beta$ and/or $m_A$ and as a consequence branching ratio to other decay modes like $\tau\tau, t\bar{t}, \mu\mu$ become enhanced. Thus discovery in these modes, not accessible for SM Higgs will become the evidence for the MSSM scenario of the Higgs sector.

The accessibility of the large $\tan\beta$ region was recently revisited for two decay channels $\tau\tau$ and $\mu\mu$. In the first case $\tau$-identification, the $E_T^{\rm miss}$ resolution and the reconstruction of the $\tau\tau$ invariant mass are crucial elements of the discovery potential. The second decay mode is less challenging experimentally requiring only high efficiency for muons identification and good mass resolution. New strategy for combined analyses with and without tagging on the spectator $b$-jet in the $b\bar{b}H$, $b\bar{b}A$ associated production was evaluated. This has resulted in the significant improvement of the overall sensitivity to these channels, presented in terms of $5\sigma$-discovery contours in Fig. 11.

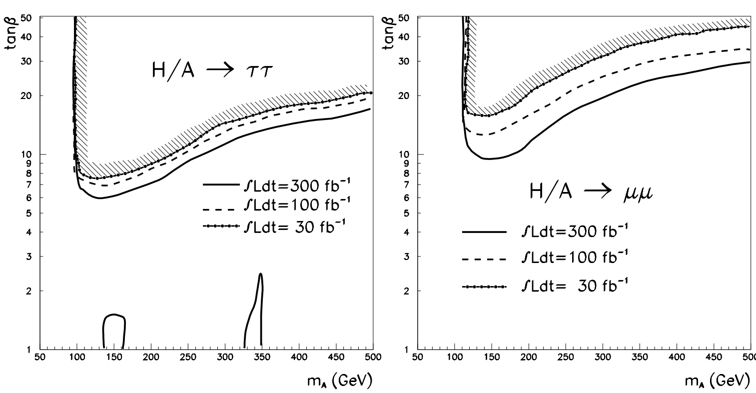



Fig. 11. For an integrated luminosities of $30\mathrm{fb}^{-1}$, $100\mathrm{fb}^{-1}$ and $300\mathrm{fb}^{-1}$, the $5\sigma$-discovery contour curves for the $H \to \tau\tau$ (left-side) and $H \to \mu\mu$ channels (right-side) in the $(m_A, \tan\beta)$ plane. Plots are from [1].

In some regions of SUSY parameters space is predicted large branching ratio for neutralino and chargino decays, $H \to \chi_i^0\chi_i^0$, or $H \to \chi_i^{\pm}\chi_i^{\pm}$, with further decay via cascades into multi-lepton final states. Such multi-lepton final states together with missing transverse energy provide a clean signature. In some regions of SUSY parameter space there would be possible to extract such signal from SM and SUSY background requiring presence of 2 pairs of same-sign and opposite-sign leptons, see Fig.12. The reconstructed invariant mass of the 4-lepton system will show sensitivity to the mass of the Higgs boson. In some cases, taking only events near the endpoint of the di-lepton mass distribution from $\chi_2^0 \to \chi_1^0 \ell\ell$ decays, would allow to reconstruct the four-momentum of the $\chi_2^0$ and, assuming its mass, even reconstruction of the mass of the Higgs boson in $H \to \chi_2^0\chi_2^0$ decay. The accessibility of this decay mode was studied within SUGRA and results of this scan are shown in $(m_A, \tan\beta)$ plane Fig. 13.

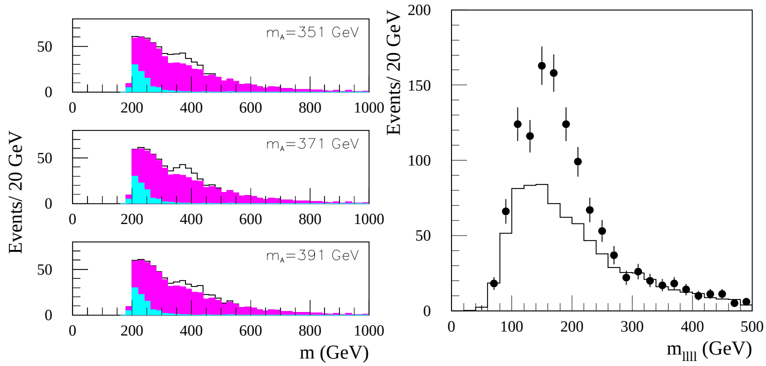



Fig. 12. On the left-side: For $H \to \chi\chi \to 4\ell$ decays with $m_A = 371$ GeV distribution of four-lepton invariant mass for the background (solid line) and the summed signal+background (points with error bars) for an integrated luminosity of 300fb$^{-1}$. On the right-side: Expected reconstructed Higgs mass for end-point OS-SF pairs (see text) and integrated luminosity of 300fb$^{-1}$. Plots are from [1].

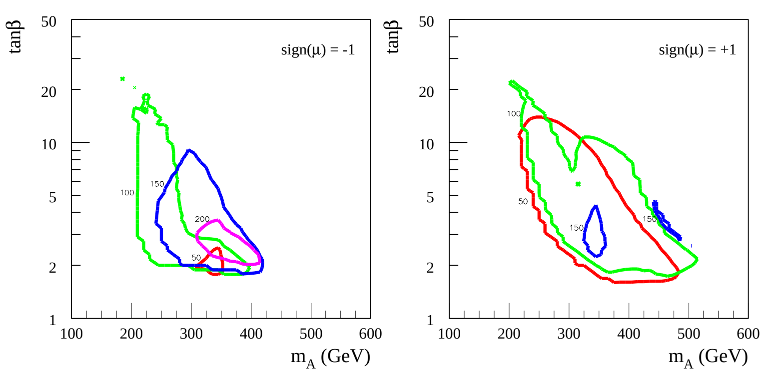



Fig. 13. For an integrated luminosity of 300fb$^{-1}$, the $5\sigma$-discovery contour curves for the $H \to \chi\chi \to 4\ell$ channel in the $(m_A, \tan\beta)$ plane for fixed ($m_0$ = 50, 100, 150 and 200 GeV). Plots are from [1].

*The charged Higgs boson*

The possibility for discovering the charged Higgs heavier than the top-quark produced by $gg \to H^{\pm}tb$ and $gb \to H^{\pm}t$ fusion have been investigated. With $H^{\pm} \to tb$ decay these processes lead to multi-top, multi-bjet final state. The accessibility of the $gb \to H^{\pm}t$ fusion was studied recently. Asking for 3 $b$-tagged jets, vetoing additional $b$-jet and reconstructing both top-quarks suppresses dominant $t\bar{t}$ background sufficiently for the Higgs signal observability in the small and large $\tan\beta$ ranges. The reconstructed mass peak is however rather broad, of 15-50 GeV for the Higgs mass varying from 200-500 GeV. Fig. 14 shows signal and background distributions for the 300 GeV Higgs (left) and $5\sigma$-discovery contour curves in the $(m_A, \tan\beta)$ plane (right).

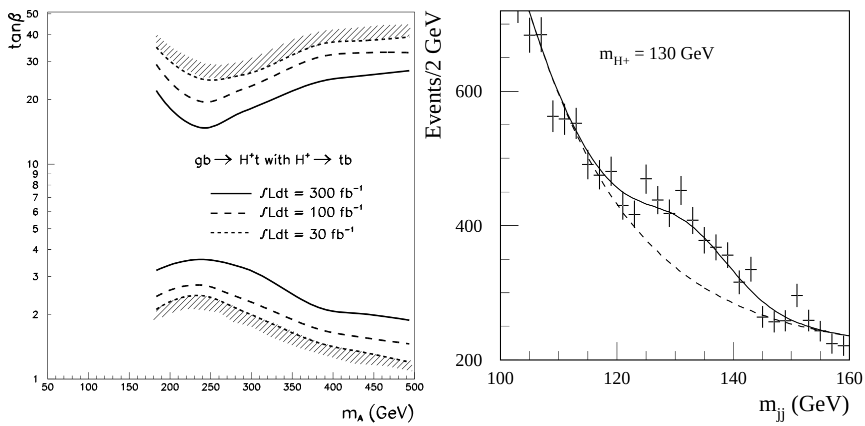



Fig. 14. On left-side: The signal and background distribution for reconstructed invariant mass $m_{tb}$ for Higgs mass of 200 GeV, $\tan\beta = 1.5$ and an integrated luminosity of 30fb$^{-1}$. Errors are statistical only. On right-side: For integrated luminosities of 30fb$^{-1}$, 100fb$^{-1}$ and 300fb$^{-1}$, $5\sigma$-discovery contour curves for the $H^{\pm} \to tb$ channel in the $(m_A, \tan\beta)$ plane. Plots are from [1].

*Determination of the Higgs-boson mass and* $\tan\beta$

The theoretical motivation for precision measurements in the MSSM is even stronger than in the Standard Model. In the SM, a precise knowledge of the profile of the Higgs boson (mass, width, branching ratios, couplings) would confirm correctness of the model itself. However, since the sensitivity of the precision electroweak measurements to the Higgs mass through radiative corrections is only logarithmic one, precise knowledge of the Higgs-boson mass would not substantially overconstrain the model.

In the MSSM, the Higgs sector constraints strongly the predicted relations between Higgs-boson masses, $\tan\beta$ and other parameters of SUSY model. Precise measurements of the Higgs(es)-boson parameters and of SUSY particle masses, if matched well by the precision of theoretical calculations, would allow to overconstrain the SUSY model itself.

Fig. 15 shows expected precision on the measurement of the Higgs boson mass and value of $\tan\beta$. Precision on the mass measurement vary from 0.1% to 12% depending on the final state of interest. For large $\tan\beta$ its value will be determined with precision to few percent as well from $H \to \tau\tau$ or $H \to \mu\mu$ channels.

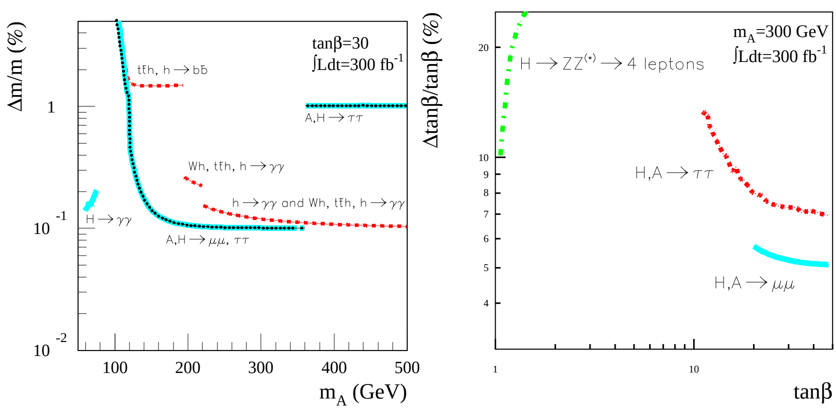



Fig. 15. Expectyed precision on the measurement of the Higgs boson masses (at $\tan\beta = 30$) and for $\tan\beta$ (at $m_A = 300$ GeV) for an integrated luminosity of $300\text{fb}^{-1}$. Plots are from [1].

### *1.3. Supersymmetry*

Discovering SUSY at the LHC will be straightforward if it exists at the electroweak scale. Copious production of squarks and gluinos can be expected, since the cross-section should be as large as a few pb for squarks and gluinos as heavy as 1 TeV. Their cascade decays would lead to a variety of signatures involving multi-jets, leptons, photons, heavy flavours, $W$ and $Z$ bosons, and missing energy. The combination of a large production cross-section and distinctive signatures makes it easy to separate SUSY from the Standard Model background.

In several models also the precision measurement of the masses of SUSY particles and the determination of the model parameters will be possible. The main challenge would be therefore not to discover SUSY itself, but to reveal its nature and determine the underlying SUSY model. For several specific SUSY scenarios: SUGRA, GMSB, and $R$-parity violating models, the characteristic signatures have been investigated in detail. Methods such as looking for kinematic endpoints for mass distributions and using these to determine combinations of masses have been proven generally useful.

*Inclusive discovery*

The starting point will be to look for characteristic deviations from Standard Model. In SUGRA and some other models, there could be events with multiple jets and/or leptons plus large $E_{\mathrm{T}}^{\mathrm{miss}}$. In GMSB models it would be events with prompt photons or quasi-stable leptons. In $R$-parity violating models, there would be events with high jets and/or leptons multiplicity. Any such signal would point to possible classes of models and would indicate the rough mass scale [10]. The next step would be to use partial reconstruction methods to try to constrain as many combinations of masses as possible.

*R-parity conserving scenarios*

In this scenarios several examples the decay products of SUSY particles always include and invisible $\chi_1^0$, so no mass peaks can be reconstructed directly. It is possible however to pick out particular multi-body decay modes and then to determine combinations of masses by measuring endpoints of the visible mass distributions [10]. For example, in the decay $\chi_2^0 \to \chi_1^0 \ell\ell$ the endpoint of the dilepton mass distributions measures $m_{\chi_2^0} - m_{\chi_1^0}$, see Fig.16. In the decay $\tilde{q} \to \chi_2^0 q$ with $\chi_2^0 \to \chi_1^0 h(\to b\bar{b})$ upper edge of the minimal combination of the $jjb$ system where $b$-jets reconstruct $h \to b\bar{b}$ decay is sensitive to the mass of the squark. Examples of such distributions are shown in Fig.16 In the favorable cases such measurement can be sufficient to fit the parameters of the model. If a long decay chain can be identified, it is even possible to determine the masses involved without relying on the model. The SUSY production cross section at the LHC is dominated by gluinos and squarks, which decay mainly through the lighter chargino and two neutralinos. For this reason many of the analyses involve decays of the second neutralino: $\chi_2^0 \to \chi_1^0 \ell\ell$, $\chi_2^0 \to \ell\ell$, $\chi_2^0 \to h\chi_1^0$.

*R-parity breaking scenarios*

In these scenarios were the LSP decay into quarks and/or leptons signatures (bayron or lepton number violation) are very different with respect to $R$-parity conserving models, for which the basic signature is the $E_{\mathrm{T}}^{\mathrm{miss}}$ from undetected $\chi_1^0$ in the final state. Depending on the value of the coupling the LSP will decay outside the detector, thus giving a phenomenology identical to $R$-parity conserving models or will decay inside the detector with a displaced vertex or at the interaction point. For this latter case, no additional information is available to disentangle the LSP decay products from the Standard Model background.

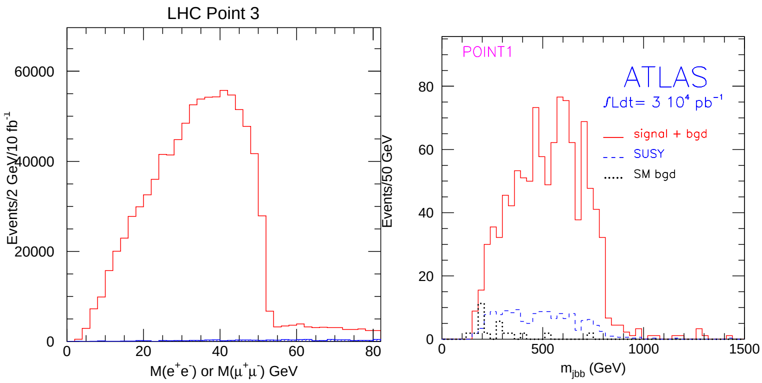



Fig. 16. On the left-side: Dilepton mass distribution for Point3 with cascade decay $\chi_2^0 \to \chi_1^0 \ell\ell$ (solid) and Standard Model background (shaded). On the right-side: The minimum mass combination in jbb mass distribution at Point1 with cascade decay $\chi_2^0 \to h(\to b\bar{b})\chi_1^0$. Plots are from [1].

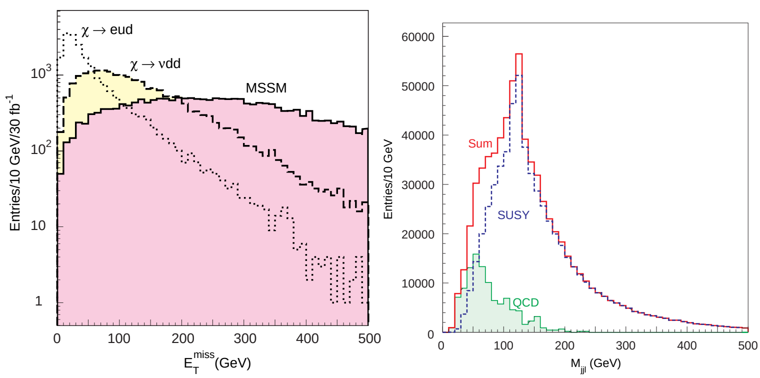



Fig. 17. On the left-side: The $E_{\mathrm{T}}^{\mathrm{miss}}$ spectra for the $R$-parity conserving case, and for the decay into two jets and respectively a charged lepton or a neutrino. On the right-side: The invariant mass spectrum of $jjl$ combination for SUSY (dashed), QCD (dashed), and both (full line). Plots are from [1].

Several such scenarios were studied in ATLAS. As as example Fig. 17 (left-side) shows the expected $E_{\mathrm{T}}^{\mathrm{miss}}$ spectra for the $R$-parity conserving case, and for decays into two jets and respectively a charged lepton ($\chi_1^0 \to q\bar{q}\ell$) or a neutrino ($\chi_1^0 \to q\bar{q}\nu$). In the first case there is available very distinct SUSY signature as the two additional leptons per event allow easy separation from SM background, and two leptons can be taken as a 'seeds' for the full reconstruction of the $\chi_1^0$. Example of such reconstruction is shown in Fig. 17 (right side).

*Gauge mediated SUSY breaking models (GMSB)*

In the GMSBmodels the lightest SUSY particle (LSP) is the gravitino with $m_G$ $<<$ 1 GeV. The next lightest SUSY particle (NLSP) is neutralino or slepton. The NLSP decay promptly to gravitinos $\chi_1^0 \to G\gamma$ or $\ell_R \to G\ell$ or decay outside the detector. There are four distinct cases of GMSB phenomenology, depending on whether the NLSP is neutralino or a slepton and whether is has a short or long lifetime: two hard photons + $E_{\rm T}^{\rm miss}$; multiple leptons; quasi-stable charged leptons; SUGRA like signature. Presence of extra photons plus the usual jets/leptons/$E_{\rm T}^{\rm miss}$ signatures renders the SM background negligible. Somewhat distinct signatures are non-pointing photons or long-lived charged leptons. ATLAS detector is particularly well suited to detect such event. Several studies on the capability of reconstructing such events were performed in ATLAS.

### *1.4. Physics beyond the Standard Model*

Other searches beyond the Standard Model have been also investigated with ATLAS, evaluating strategies for searching for technicolour signals, excited quarks, leptoquarks, new gauge bosons, right-handed neutrinos and monopoles have been evaluated [1]. Given the large number of detailed models published in this field, rather an exploratory point of view is taken, examples are used and in some cases a detailed study was performed.

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