Precision Physics at the LHC

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A large number of precision measurements will be possible with the ATLAS and CMS experiments at the CERN Large Hadron Collider (LHC). Examples from W physics, Drell-Yan production of lepton pairs, Triple-Gauge Couplings, top physics, Higgs and Supersymmetry are discussed.

It is well known since many years that the LHC has a large discovery potential for new physics, e.g. Higgs and Supersymmetry (SUSY), owing to the large centre-of-mass energy ($\sqrt{s}$=14 TeV) and high design luminosity (10^{34} cm^{-2} s^{-1}).

In addition, the two general-purpose proton-proton experiments ATLAS [1] and CMS [2] will be able to perform precision measurements in a large number of physics channels [1]. In most cases, these measurements are expected to improve significantly on the results obtained at previous machines (LEP and TeVatron).

Precision physics with ATLAS and CMS is the subject of this paper. After a discussion of the most relevant issues for precision physics at LHC (Sect. 1), examples of measurements for some physics channels are presented: W-mass (Sect. 2), Drell-Yan production of lepton pairs (Sect. 3), Triple-Gauge Couplings (Sect. 4), top physics (Sect. 5), Higgs (Sect. 6) and SUSY (Sect. 7) (see Refs. [3–5] for extensive and recent reviews of these subjects).

The following assumptions on the instantaneous and integrated luminosities are made throughout this paper. The initial luminosity is expected to be 10^{33} cm^{-2} s^{-1} (hereafter called "low luminosity") and should rise, during the first three years of operation, to the design luminosity of 10^{34} cm^{-2} s^{-1} (hereafter called "high luminosity"). Integrated luminosities of 10 fb^{-1}, 30 fb^{-1}, 100 fb^{-1} and 300 fb^{-1} should be collected after one year, three years, four years and less than ten years of data taking, respectively.

1. Key issues

The main asset for precision physics at the LHC is statistics.

Table 1 shows the expected rates of some representative physics processes, both from Standard Model (SM) and new physics. In the initial phase at low luminosity, almost 50 W and five Z bosons decaying to lepton pairs will be produced every second, as well as one $t\bar{t}$ pair and 500,000 $b\bar{b}$ pairs. One SM Higgs boson of 700 GeV mass

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[1] LHCb, the dedicated B-physics experiment, is not discussed in this paper.

Table 1
For the physics channels listed in the first column, the cross section and the approximate expected number of events in each experiment in one second and in one year at low luminosity (10^{33} cm^{-2} s^{-1}).

Process	σ (pb)	Events/second	Events/year
W → eν	1.5×10^4	15	10^8
Z → e^+e^-	1.5×10^3	1.5	10^7
$t\bar{t}$	800	0.8	10^7
$b\bar{b}$	5×10^8	5×10^5	10^{12}
$\tilde{g}\tilde{g}$ ($m_{\tilde{g}}$=1 TeV)	1	10^{-3}	10^4
H (m_H=700 GeV)	1	10^{-3}	10^4
Inclusive jets $p_T > 200$ GeV	10^5	10^2	10^9

and one pair of 1 TeV gluinos would be produced every 15 minutes, while the rate of QCD jets with $p_T > 200$ GeV will be about 100 Hz. This last process is expected to be one of the dominant backgrounds to many interesting physics channels. Integrated over one year of data taking at low luminosity, these rates give rise to samples of millions of events in almost all channels. The LHC can therefore be considered as a factory of a large number of particles: W and Z bosons, top and b quarks, and possibly also Higgs boson(s) and supersymmetric particles.

As a consequence, for most measurements performed at the LHC the statistical error and the component of the systematic error which scales as $1/\sqrt{N}$ will be negligible (where N is the number of selected events). The uncertainty will instead be dominated by the component of the systematic error, arising from the knowledge of both detector and physics, which depends only weakly on the number of events. However, large statistics will allow hard cuts to be applied in order to select clean and well-understood events. Furthermore, high-statistics "control samples", e.g. $Z \to \ell\ell$ decays, will be available to study the detector response and the physics (background shapes, p_T distributions, etc.) in great detail.

Three main sources of uncertainty are expected to affect precision measurements at the LHC:

- The lepton energy and momentum scale, that is related to the calibration of the inner detector, of the electromagnetic calorimeter and of the muon spectrometer. This is the dominant source of uncertainty on the W mass measurement at the TeVatron, where the absolute lepton scale is known with a precision of ~0.1% [6,7]. At the LHC such a precision will be adequate for most measurements except for the W mass, for which a much better knowledge, i.e. ~0.02%, will be needed in order to improve on the accuracy expected at the end of the LEP2 and TeVatron programs, as described in Sect. 2. The lepton scale will be determined *in situ* by using, for instance, the large-statistics samples of $Z \to \ell\ell$ decays. The Z boson has the advantage of being a resonance very close in mass to the W and to the h boson of the Minimal Supersymmetric Standard Model (MSSM), so that the extrapolation error from the calibration region to the measurement region is considerably reduced. In contrast, TeVatron experiments do not have today enough Z events to calibrate the lepton scale with high accuracy, and other resonances like J/ψ or π^0 have to be used. Preliminary studies performed in ATLAS [3] indicate that a precision of 0.02% will be very difficult to achieve but not impossible.

- The jet energy scale, contributing for instance to the uncertainty on the top mass. Unlike the lepton scale, the precision on the jet absolute scale depends not only on the detector (calorimeter in this case) calibration, but also on the knowledge of the physics (fragmentation, gluon radiation, etc.). Today at the TeVatron the jet scale is determined with a precision of about 3% [8], by using mainly events with a γ or a Z decaying into leptons balanced by one high p_T jet. The LHC goal is to reach about 1%. In addition to the TeVatron methods, at the LHC the light quark jet calibration will be based on W→jj decays from $t \to bW$. Indeed, $t\bar{t}$ final states where one top decays to b$\ell\nu$ and the other one to bjj are relatively clean and their rate will be large at the LHC (~0.1 Hz at low luminosity). These same event samples will also be used to measure the top mass.

- The knowledge of the absolute luminosity, which will contribute to the uncertainty on all cross section measurements. Several methods are presently envisaged to determine the absolute luminosity at the LHC [1,2], one of them being the measurement of the rate of well-known processes such as W and Z production. For the time being, the expected precision from the various methods is about 10%. If this will be the case, then the luminosity uncertainty will be the dominant systematic error on most cross section measurements at the LHC. Improved theoretical understanding of the W and Z production mechanism will therefore be extremely useful to reduce the luminosity uncertainty to a more ambitious goal of $\leq 5\%$.

2. Measurement of the W mass

At the time of the LHC start-up, the W mass will be known with a precision of ~30 MeV from measurements at the TeVatron [9] and LEP2 [10]. The motivation to improve this result is mainly that precise measurements of the W mass, of the top mass and of the Higgs mass (SM Higgs boson or h boson in the MSSM) will provide stringent tests of the consistency of the underlying theory. With a top mass measured with an accuracy of ~1.5 GeV, as described in Sect. 5, the W mass should be known with a matching precision of 15 MeV, in order not to become the dominant source of uncertainty in the test of the radiative corrections. Such a precision, which is beyond the sensitivity of LEP2 and TeVatron, should constrain the Higgs mass to better than 30%.

At hadron colliders, the W mass is obtained from the distribution of the W transverse mass, that is the invariant mass of the W decay products evaluated in the plane transverse to the beam. This is because the longitudinal component of the neutrino momentum cannot be measured in a pp or p$\overline{\text{p}}$ collider. On the other hand, the transverse momentum of the neutrino can be deduced from the transverse momentum imbalance in the calorimeters. The transverse mass distribution, and in particular its trailing edge, is sensitive to the value of the W mass. Therefore, by fitting the experimental distribution to Monte Carlo spectra obtained for different values of $m_{\rm W}$, it is possible to deduce the mass value which is preferred by the data.

At the LHC, sixty million well-reconstructed W$\rightarrow \ell\nu$ decays (where $\ell = $ e or $\ell = \mu$) should be collected by each experiment in one year of data taking at low luminosity (a statistics fifty times larger than that expected at the TeVatron Run II). The statistical error on the W mass measurement is therefore expected to be small (< 2 MeV). The systematic error will arise mainly from the Monte Carlo reliability in reproducing the data, i.e., the physics and the detector performance. Uncertainties related to the physics are for instance the limited knowledge of the W $p_{\rm T}$ spectrum, of the structure functions, of the W width and of the W radiative decays. Uncertainties related to the detector are for instance the already-mentioned absolute lepton scale and the knowledge of the detector energy/momentum resolution and response to the recoil. Many of these uncertainties will be constrained *in situ* by using the high-statistics sample of leptonic Z decays. This sample will be used for instance to set the lepton scale, to determine the detector resolution and to model the detector response to the system recoiling against the W and the W $p_{\rm T}$ spectrum.

Preliminary estimates of the expected uncertainties on the W mass measurement in ATLAS, based in part on extrapolating from TeVatron results, are presented in Table 2. As it is today at the TeVatron [6,7], also at the LHC the dominant uncertainty will originate from the calibration of the absolute lepton energy scale. For the W mass to be measured to better than 20 MeV, the lepton scale has to be known with a precision of 0.02%, as already mentioned, which represents the most serious challenge for this measurement. It is interesting to note that a very high precision on the lepton scale (~0.04%) is also re-

Table 2
Expected contributions to the systematic uncertainty on the W mass measurement in ATLAS for each lepton family and for an integrated luminosity of 10 fb^{-1}. The corresponding uncertainties of the CDF measurement obtained in Run 1B [11] are also shown for comparison.

Source	Δm_W (CDF)	Δm_W (ATLAS)	Comments
Lepton E/p scale	75 MeV	15 MeV	TeVatron Run II: < 40 MeV
Lepton E/p resolution	25 MeV	5 MeV	Resolution known to < ±1.5%
Structure functions	15 MeV	< 10 MeV	Constrained with LHC data
$p_{\mathrm{T}}^{\mathrm{W}}$	20 MeV	5 MeV	Constrained with $p_{\mathrm{T}}^{\mathrm{Z}}$ spectrum
Recoil model	33 MeV	5 MeV	Constrained with Z data
W width	10 MeV	7 MeV	$\Delta\Gamma_{\mathrm{W}} = 30$ MeV from TeVatron Run II
Radiative decays W→ $\ell\nu\gamma$	20 MeV	< 10 MeV	Better theoretical calculations
Total	113 MeV	< 25 MeV	Per lepton species, per experiment

quired at the TeVatron Run II to reach the foreseen ∼40 MeV accuracy on m_{W}. The realization of such a stringent requirement will represent a good benchmark for the LHC experiments.

All other systematic uncertainties are expected to be smaller than 10 MeV. Therefore, by combining both ATLAS and CMS and both channels (electrons and muons), it should be possible to obtain a total error of 15 MeV in the initial, low luminosity phase. Improved theoretical calculations, in particular of the W p_{T} spectrum and of the impact of radiative corrections, will be needed to achieve this goal.

Another possible method for measuring the W mass is based on the p_{T} distribution of the charged lepton from the W leptonic decay, that is characterised by a Jacobian peak at $p_{\mathrm{T}}^{\ell} \sim m_{\mathrm{W}}/2$. This method is weakly affected by pile-up and can thus be used also in the high luminosity environement. However, it is strongly dependent on the W p_{T} spectrum and therefore requires a very precise theoretical knowledge of the W p_{T} distribution.

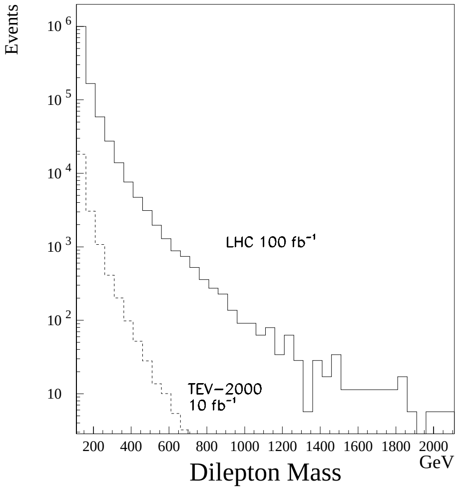

Figure 1. Expected number of Drell-Yan events for the TeVatron Run II and LHC per lepton channel and per experiment, as a function of the dilepton invariant mass.

3. Drell-Yan production of lepton pairs

The production of lepton pairs via s-channel exchange of photons or Z bosons is characterised by a very clean and distinctive experimental signature, a pair of well isolated leptons with opposite charge. At the LHC, the range of explored lepton invariant masses will be considerably extended, with respect to the presently accessible region. This is shown in Fig. 1, which displays the expected number of events per lepton channel after rapidity and p_{T} cuts for one experiment at the TeVatron Run II and at the LHC, as a function of the dilepton invariant mass. Deviations in the expected behaviour can reveal new physics (resonance formation, contact terms, etc.) or, if no signal of new physics is visible, one can take advantage of the large statistics to constrain parton densities and parton-parton luminosity functions [12]. A prerequisite for the success of this program is that the theoretical knowledge of the Drell-Yan process matches the expected experimental accuracy.

The main observables of interest are the total cross section and the forward-backward asymmetry which are both functions of precisely measurable quantities, the invariant mass and rapidity of the dilepton system. Figure 2 shows the relative statistical precision on the cross section measurement for one experiment at the TeVatron Run II and at the LHC as a function of the dilepton invariant mass. Also shown for comparison is the result of a complete one-loop parton cross section calculation [4,13] of the electroweak radiative corrections after folding with the probability density functions. The LHC will be able to probe such corrections up to approximately 2 TeV. However, only the statistical error was considered in this study. The uncertainty related to the luminosity measurement will deteriorate the experimental precision by a few %. This example shows the importance of devoting the necessary effort, both on the theoretical and experimental side, to achieve a precision of 5% or better on the knowledge of the absolute luminosity.

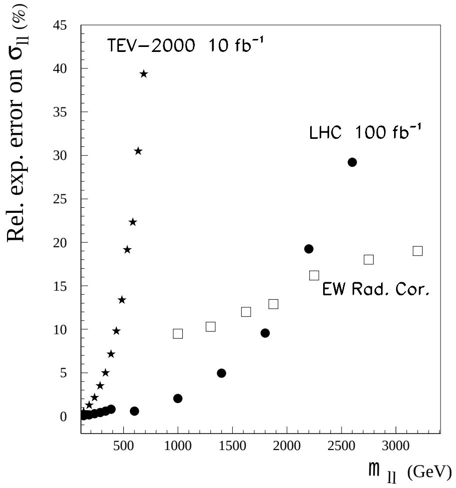

Figure 2. Relative statistical precision on the Drell-Yan cross section (in %) for an experiment at the TeVatron Run II and at the LHC as a function of the dilepton invariant mass. Also shown is a calculation of the electroweak radiative corrections based on [13].

A precise determination of the effective electroweak mixing angle $\sin^2\theta_{\text{eff}}^{\text{lept}}$ could be performed at the LHC by measuring the forward-backward asymmetry A_{FB} in dilepton production near the Z pole. The $Z\to \ell^+\ell^-$ cross section is ~1.5 nb for each lepton flavour, resulting in a very large number of $Z\to \ell^+\ell^-$ events which, in principle, could be used to measure $\sin^2\theta_{\text{eff}}^{\text{lept}}$ with a very small statistical error. The latest combination of several asymmetry measurements at LEP and SLD leads to an absolute uncertainty on $\sin^2\theta_{\text{eff}}^{\text{lept}}$ of 1.7×10^{-4} [14]. Can systematic effects be controlled with a comparable precision at the LHC?

The measurement of A_{FB} requires tagging of the original quark direction which is unknown in pp collisions and can only be extracted from the kinematic properties of the dilepton system. Events with a large rapidity of the lepton pair $y(\ell^+\ell^-)$ originate from collisions where at least one of the partons carries a large fraction x of the proton momentum. Since valence quarks carry on average a higher momentum than sea antiquarks, A_{FB} is signed according to the sign of $y(\ell^+\ell^-)$. Recent preliminary studies [4] indicate that a statistical precision on $\sin^2\theta_{\text{eff}}^{\text{lept}}$ better than 10^{-4} may be obtained by extending the detection of one of the two leptons (in the electron channel) to the rapidity range $2.5 < |y_\ell| < 4.9$ because A_{FB} is significantly larger in this region. Such a strategy is based on a moderate e/π separation capability (π rejection of 10–100) in the forward calorimeter, which however still needs to be proven. The main systematic effect on the measurement of $\sin^2\theta_{\text{eff}}^{\text{lept}}$ originates from the uncertainty on the parton distribution functions which affects the lepton acceptance as well as the results of the radiative correction calculations. It is far from obvious that this uncertainty can be brought down to the desired level of precision. However, new measurements from HERA, TeVatron and, ultimately, from the LHC itself, will certainly improve the uncertainty on the parton distribution functions and may render this measurement possible.

4. Measurement of the Triple-Gauge Couplings

The study of Triple-Gauge Couplings (TGCs), that is couplings of the type WWγ or WWZ, provides a direct test of the non-abelian structure of the SM gauge group and at the same time may yield hints for new physics, since many new processes are expected to give anomalous contributions to the triple-gauge vertices. This sector of the Standard Model is often described by five parameters: g_1^{Z}, κ_{Z}, κ_γ, λ_{Z}, λ_γ. New physics could show up as deviations of these parameters from their SM values (zero for the λ parameters and one for the κ and g parameters). The LHC has a large potential for testing the TGCs because the sensitivity to the anomalous contributions is enhanced at high centre-of-mass energies, particularly for λ-type TGCs.

Triple-Gauge couplings will give rise to gauge boson pair production, e.g., Wγ, WZ and WW production. The first two processes are characterised by relatively clean final states, containing one lepton and one photon or three leptons, respectively. The third process is less promising, since it suffers from the large $\mathrm{t\bar{t}}$ background.

Anomalous TGCs can affect both the total cross section and the shape of the differential distributions. This is illustrated in Fig. 3 that shows, as an example, the reconstructed p_{T} spectra of the Z boson in WZ events for the SM and in presence of non-standard couplings. An excess of events in the high-p_{T} tail is clearly visible in the case of anomalous couplings.

The expected statistical precision at 95% CL from single parameter fits to the total cross section and to distributions such as the one of Fig. 3 is summarised in Table 3, as obtained by ATLAS assuming an integrated luminosity of 30 fb^{-1}. These results based on a modest total integrated luminosity already improve on the final TeVatron and LEP2 precision expected to be in the range between ∼0.1 and ∼0.01 depending on the couplings. Systematic uncertainties due, for example, to higher order QCD corrections, structure functions, etc., are currently under study but are expected to be small.

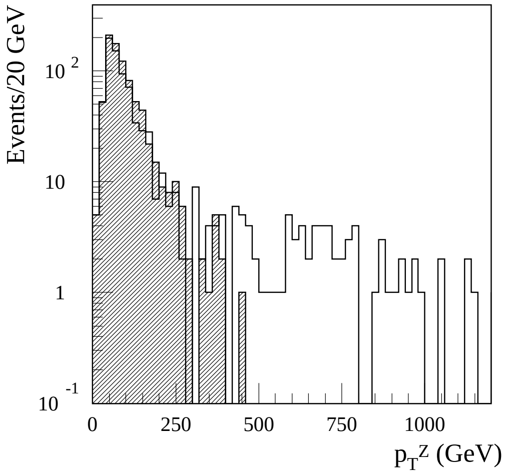

Figure 3. Reconstructed p_{T} of the Z boson in WZ events, as expected in ATLAS for an integrated luminosity of 30 fb^{-1}. The shaded and white histograms show, respectively, the SM expectation and the distribution obtained for $\Delta g_1^{\mathrm{Z}} = 0.05$.

5. Precision measurements in the top quark sector

Because of its large mass and width and of the special rôle it plays in radiative corrections, the top quark is a very peculiar fermion. Precision measurements in the top sector are therefore important to get more clues on the origin of the fermion mass hierarchy.

At the LHC, top quark measurements will benefit from very large statistics, so that not only the mass and the production cross section, but also branching ratios, couplings and exotic decays will be studied in detail. It should also be noticed that $\mathrm{t\bar{t}}$ production is expected to be the

Table 3
Sensitivity limits (95%CL) from single parameter fits to a given coupling for one LHC experiment assuming an integrated luminosity of 30 fb^{-1}. A form factor Λ=10 TeV has been assumed in deriving these results.

Coupling	95%CL
$\Delta\kappa_\gamma$	0.035
λ_γ	0.0025
Δg_1^{Z}	0.0078
$\Delta\kappa_{\mathrm{Z}}$	0.069
λ_{Z}	0.0058

main background to new physics processes, such as several possible channels arising from the production and decay of Higgs bosons and of supersymmetric particles. Furthermore, top events will be used to calibrate the calorimeter jet scale, as already mentioned in Sect. 1.

The $\mathrm{t\bar{t}}$ production cross section is expected to be ~800 pb at the LHC, to be compared with ~7 pb at the TeVatron. Taking into account also the higher luminosity, the LHC should be able to collect, in the initial phase at low luminosity, an event sample at least 1000 times larger than the one expected in the future at the TeVatron.

In the year 2005, the top mass should be known with a precision of 3 GeV or better from measurements at the TeVatron [9]. At the LHC the best channel for the top mass measurement will most likely be $\mathrm{t\bar{t}}$ production with one W decaying leptonically and the other one hadronically. The top mass will be determined from the hadronic part of the decay, as the invariant mass of the three jets originating from the same top ($m_{\mathrm{t}} = m_{\mathrm{jjb}}$). The leptonic top decay will be used to tag the event by exploiting the high p_{T} lepton and large $E_{\mathrm{T}}^{\mathrm{miss}}$.

The statistical error is expected to be negligible (smaller than 100 MeV), therefore the precision will be limited by the systematic error. The 1% uncertainty on the absolute jet scale should translate into an uncertainty smaller than 1 GeV on the top mass. The effect of final-state gluon radiation is estimated to lead to an uncertainty of ~1 GeV. Other sources of systematic uncertainties (such as, for example, those related to b-fragmentation, initial state radiation, background, etc.) are expected to be smaller.

All together, a total uncertainty smaller than 1% should be achieved. This precision may be further improved by using $\mathrm{t\bar{t}}$ pairs produced with very high p_{T}. In this case, the two top quark decay products are well separated in two opposite hemispheres, so that the mass measurement should be less sensitive to the details of the jet reconstruction method, to the choice of the fragmentation model and to the combinatorial background from gluon radiation.

Another interesting idea for measuring m_{t} proposed by CMS [16,17] is based on the decay $\mathrm{t} \rightarrow \mathrm{J}/\Psi + \mathrm{X}$ displayed in Fig. 4. In this case one takes advantage of the correlation between m_{t} and the invariant mass of the J/Ψ and lepton originating from the same top, that is enhanced by the presence of a heavy object, the J/Ψ, carrying a large fraction of the b momentum. The small branching fraction characterising this channel, of O(10^{-5}), is compensated by the clean final state which can be exploited also at the highest luminosities. The main systematic limitation of such a measurement originates from the uncertainty on the fragmentation function of the B hadrons contained in the b jet. Current preliminary studies suggest that such an analysis might lead to an error on m_{t} comparable or smaller than the one obtained from the single lepton plus jets channel.

In any case, the possibility of selecting different samples, each characterised by different systematic uncertainties, will allow useful cross-checks of the top mass determination.

Examples of other measurements which can be performed in the top sector are:

- The $\mathrm{t\bar{t}}$ production cross section should be determined with a precision $\leq$ 10%, dominated by the uncertainty on the absolute luminosity.
- Single top production via the weak interaction, a process not yet observed, should allow the CKM matrix element V_{tb} to be measured with a precision of 10% or better.

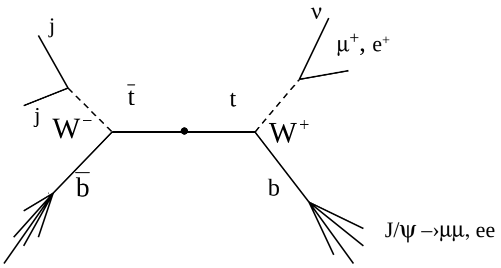

Figure 4. Diagram for top decaying into a J/Ψ+lepton final state.

- Upper limits at the level of $10^{-4} - 10^{-5}$ on the FCNC couplings tVc and tVu with V=Z, γ, g should be set with 100 fb^{-1}, improving by a factor of at least 10 the TeVatron sensitivity.
- A sensitivity of ∼3% on the branching ratio $\mathrm{BR}(\mathrm{t} \to \mathrm{bH}^{\pm})$ should be reached, by searching for an excess of τ production in $\mathrm{t\bar{t}}$ events, due to the decay $\mathrm{t} \to \mathrm{bH}^{\pm}$, followed by $\mathrm{H}^{\pm} \to \tau\nu$. This would allow H$^{\pm}$ masses below $m_{\mathrm{t}} - 20$ GeV to be probed for most of the tanβ range.

More details can be found elsewhere [3,5].

6. Precision measurements in the Higgs sector

The LHC discovery potential for a SM Higgs boson is well known since a long time [1,2]. After less than two years of data taking at low luminosity, a signal significance over the background larger than 5 σ is expected over the mass range between 115 GeV (approximate LEP2 lower bound) and 1 TeV (upper bound predicted by theory) by combining both experiments.

Assuming that a SM Higgs boson will be found at the LHC, the question of the precision with which the ATLAS and CMS experiments will be able to measure the Higgs parameters (e.g. mass, width, cross section, couplings) can be addressed.

Figure 5 shows the expected uncertainty on the measurement of the Higgs mass, as obtained by combining both experiments and for an integrated luminosity of 300 fb^{-1} per experiment. All expected experimental uncertainties are included in these results, i.e., the statistical error and the systematic error due to the uncertainty on the absolute energy scale and on the background subtraction. It can be seen that a precision of 0.1% can be obtained up to $m_{\mathrm{H}} \simeq 500$ GeV. For larger masses the precision deteriorates because the statistical error increases. Theoretical uncertainties are not taken into account in these results. Whereas the uncertainty arising from the knowledge of the structure functions is expected to be small, other effects may have a non-negligible impact. For instance, for large Higgs masses, when the Higgs width becomes broad, interference effects between the resonant and the non-resonant cross section are expected to produce a downward shift of the Higgs mass peak [18]. Accurate input from theory will therefore be needed in this case.

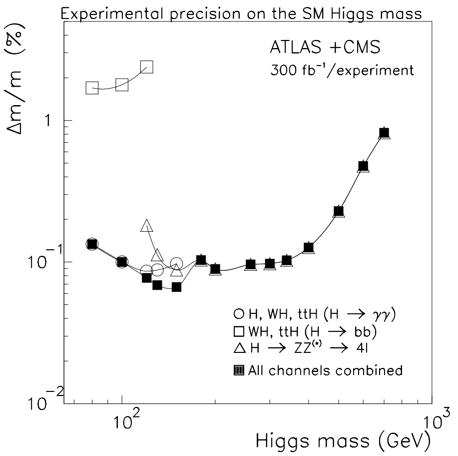

Figure 5. Expected fractional errors on the measured Higgs mass at the LHC, as a function of m_{H}. The different symbols indicate different production and decay channels.

The Higgs width can be directly extracted from a measurement of the width of the reconstructed Higgs peak after unfolding of the detector reso-

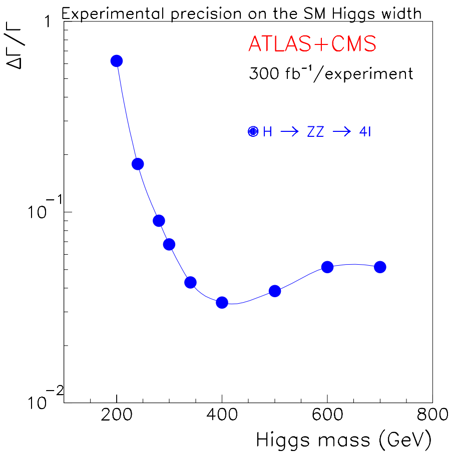

Figure 6. Expected fractional errors on the measured Higgs width at the LHC, as a function of m_{H}.

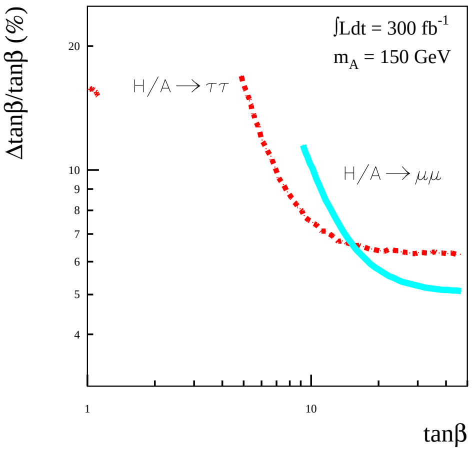

Figure 7. Expected fractional errors on tanβ in ATLAS assuming $m_{\mathrm{A}} = 150$ GeV and a total integrated luminosity of 300 pb^{-1}.

lution. This, however, will only be possible for Higgs masses larger than about 200 GeV, above which the intrinsic width of the resonance is comparable to or larger than the expected experimental resolution. For smaller masses the Higgs width is too narrow to be measured with the direct method. Figure 6 shows the expected uncertainty on the Higgs width, as a function of the Higgs mass, as obtained by combining both experiments and for an integrated luminosity of 300 fb^{-1} per experiment. The precision on Γ_{H} improves up to Higgs masses of approximately 300 GeV, after which the total resolution is dominated by the intrinsic width. In the mass range 300–700 GeV an approximately constant precision of $\sim$5% is obtained. This is the region where the best discovery channel is $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$. The measurement of the Higgs width to such an accuracy requires a very good knowledge of the detector energy and momentum resolution. The detector resolution is expected to be determined with a precision better than 1.5% from the measurement of the Z width. This error, which is dominated by the systematic uncertainty on the radiative decays of the Z, has been included in the results shown in Fig. 6.

A measurement of the Higgs production rate in a given channel provides a measurement of the production cross section multiplied by the branching ratio in that channel $\sigma \cdot$ BR. At the LHC the precision will be mainly limited by the uncertainty on the luminosity. For a luminosity uncertainty of 5%, $\sigma\cdot$BR should be measured with a typical accuracy of about 7% over the mass region $100 < m_{\mathrm{H}} < 700$ GeV, by combining both experiments and with an integrated luminosity of 300 fb^{-1} per experiment. This accuracy would degrade to $\sim$12% for a luminosity uncertainty of 10%.

The rates of the heavy Higgs bosons of the MSSM (H/A) provide good sensitivity to tanβ [3]. As shown in Fig. 7, from the measurements of the rate of H/A $\to \tau\tau$, tanβ can be determined with a $\pm$15% ($\pm$6%) precision for tanβ=5 (40), assuming $m_{\mathrm{A}} = 150$ GeV, a total integrated luminosity of 300 pb^{-1} and one experiment. A somewhat better precision is obtained at higher tanβ values by analysing the $\mu\mu$ final state.

From the measured $\sigma \cdot$ BR, one can deduce the Higgs branching ratio in a given channel if the Higgs production cross section is known from theory. Without theoretical assumptions, it is still possible to measure ratios of branching ratios, and therefore ratios of Higgs couplings to fermions and bosons. Work in this sector has just started, therefore only a few examples are given below. It is assumed that both experiments are combined and that the integrated luminosity is 300 fb^{-1} per experiment.

- By looking at the associated Higgs production ($\mathrm{t\bar{t}H + WH}$) and by measuring the rate of events where the Higgs decays to $\gamma\gamma$ divided by the rate of events where the Higgs decays to $\mathrm{b\bar{b}}$, it is possible to obtain the ratio between the branching ratio to $\gamma\gamma$ and the branching ratio to $\mathrm{b\bar{b}}$. This measurement can be performed over the mass range $80 \leq m_{\mathrm{H}} \leq 120$ GeV and the expected precision is about 15%.

- By comparing the rate of Higgs bosons produced in association with a $\mathrm{t\bar{t}}$ pair to the rate of Higgs bosons produced in association with a W (with the Higgs decaying to $\gamma\gamma$ or to $\mathrm{b\bar{b}}$), it is possible to measure the ratio of couplings $(\mathrm{t\bar{t}H/WWH})^2$. This measurement can be performed over the mass range $80 \leq m_{\mathrm{H}} \leq 120$ GeV and the expected precision is about 15%.

- By measuring the ratio between the $\mathrm{H} \rightarrow \gamma\gamma$ rate and the $\mathrm{H} \rightarrow 4\ell$ rate, it is possible to obtain the ratio between the branching ratio to $\gamma\gamma$ and the branching ratio to ZZ^*. This measurement can be performed over the mass range $120 \leq m_{\mathrm{H}} \leq 150$ GeV and the expected precision is about 7%.

In all the above cases, the error is dominated by the statistical uncertainty, since the systematic uncertainty on the absolute luminosity cancels out when ratios of rates are considered.

7. Precision measurements in the SUSY sector

It is well known that, if SUSY exists close to the electroweak scale, it will be easy to discover at the LHC for $\tilde{\mathrm{q}}$ and $\tilde{\mathrm{g}}$ masses up to about 3 TeV and almost irrespectively of the model parameters.

Assuming that SUSY will be discovered at the LHC, will the ATLAS and CMS experiments be able to perform precision measurements in SUSY final states, i.e., determine the particle masses and their couplings, and therefore extract the fundamental parameters of the theory ? The answer to this question is a priori not obvious: in R-parity conserving scenarios all SUSY events contain in the final state the two lightest neutralinos, which are stable and weakly interacting and hence escape detection. Therefore, in general there are not enough kinematic constraints to reconstruct mass peaks. In order to investigate this issue, five points in the parameter space of Minimal SuperGravity (SUGRA [19]) were studied.

SUGRA is a model with only five parameters: a common scalar mass at the GUT scale (m_0), a common gaugino mass at the GUT scale ($m_{1/2}$), the ratio of the vacuum expectation values of the two Higgs doublets (tanβ), a common trilinear term at the GUT scale (A_0) and the sign of the Higgsino mass parameter (μ).

The strategy adopted by ATLAS in the study of the five SUGRA points is the following. First, find an inclusive SUSY signal over the SM background. Second, try to isolate exclusive, therefore clean, channels where masses or combination of masses can be measured from kinematic distributions; this is possible because in most cases the expected event samples are large. Finally, perform a global fit of the model to all experimental measurements and extract the fundamental parameters of the theory, very much in the same way as the LEP experiments have done to test the SM predictions and to determine indirectly the top, W and Higgs masses.

As an illustration of the method and of the results which can be achieved, one of the five points ("Point 5") is discussed here in some detail. Point 5 is characterised by the following values of the SUGRA fundamental parameters: $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 300$ GeV, $\tan\beta = 2.1$, sign$\mu = +$. The masses of some of the corresponding SUSY particles are listed in Table 4.

The total cross section, which is mainly deter-

Table 4
Masses of some representative SUSY particles in Point 5.

Particle	Mass (GeV)
$\tilde{g}$	770
$\tilde{q}_L$	690
$\tilde{q}_R$	660
$\tilde{t}_1$	490
$\tilde{\ell}_L$	240
$\tilde{\ell}_R$	157
χ_1^0	121
χ_2^0	232
h	93
H	640

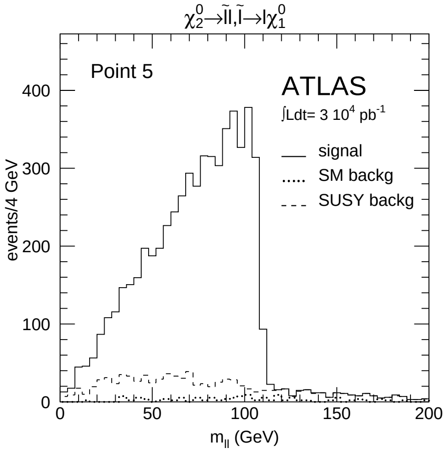

Figure 8. Invariant mass distribution of lepton pairs in the final state for SUSY events at Point 5 selected as described in the text, as expected in ATLAS after three years of data taking at low luminosity.

mined by the $\tilde{q}$ and $\tilde{g}$ masses since $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$ production dominates, is about 20 pb. The second lightest neutralino decays to the lightest Higgs boson and the lighest neutralino ($\chi_2^0 \to \mathrm{h}\chi_1^0$) with a branching ratio of almost 70%. It can also decay to slepton-lepton pairs ($\chi_2^0 \to \tilde{\ell}_R \ell$) with a branching ratio of about 10% per lepton species, since sleptons are relatively light for this choice of the SUGRA parameters.

As an example, the production of $\tilde{\mathrm{q}}_\mathrm{L}\tilde{\mathrm{q}}_\mathrm{R}$, followed by the decays $\tilde{\mathrm{q}}_\mathrm{L} \to \mathrm{q}\chi_2^0$, $\chi_2^0 \to \tilde{\ell}_R \ell$, $\tilde{\ell}_R \to \ell\chi_1^0$, can be selected in an inclusive way by requiring two leptons in the final state with the same flavour and opposite sign, large $E_\mathrm{T}^\mathrm{miss}$ and jet multiplicity (the last two cuts are needed to reject the SM background). The resulting invariant mass distribution of the two leptons in the final state is shown in Fig. 8. A clear signal is visible above the background. The mass distribution shows a very sharp end-point, which is due to the kinematic properties of the decay and depends on the masses of the involved particles (the two lightest neutralinos and the slepton) through a simple kinematic relation. The position of the end-point can be measured with a precision of 500 MeV (0.5%) with an integrated luminosity of 30 fb^{-1}, thus providing a combined constraint on the three masses mentioned above.

More details and further examples can be found elsewhere [3,20].

Table 5 summarises the various measurements of particle masses which can be performed in Point 5, together with the expected precisions in ATLAS for two integrated luminosities. In all cases, the ultimate precision is in the range between a few percent and a few permil. Furthermore, many SUSY particles (h, $\tilde{\mathrm{q}}_\mathrm{L}$, $\tilde{\mathrm{q}}_\mathrm{R}$, $\tilde{\mathrm{g}}$, $\tilde{\mathrm{t}}_1$, $\tilde{\mathrm{b}}_\mathrm{R}$, χ_2^0, $\tilde{\ell}_\mathrm{L}$, $\tilde{\ell}_\mathrm{R}$) will be directly observable at the LHC.

The above experimental measurements can then be used to constrain the model and its parameters. The results of the global fit in the case of Point 5 are presented in Table 6. The parameters $m_0, m_{1/2}$ and tanβ will be determined by ATLAS with a precision of a few percent after only three years of data taking at low luminosity. The sign of μ will also be unambiguously determined. The A_0 parameter will remain most likely unconstrained, because it has a very little influence on the phenomenology at the electroweak scale. Similar results were obtained for the four other SUGRA points [3].

In conclusion, precision SUSY measurements will be possible at the LHC: many SUSY particles should be discovered, and many of their masses

Table 5
Expected uncertainties on the measurements of SUSY particle masses at Point 5 in ATLAS for two different integrated luminosities.

Measurement	Expected value (GeV)	Error (%) 30 fb^{-1}	Error (%) 300 fb^{-1}
m_{h}	93	±1.0	±0.2
$m_{\ell^+\ell^-}$ end-point	109	±0.5	±0.2
$m_{\tilde{\ell}_{\text{R}}}$	157	±1.2	±0.3
$m_{\tilde{\ell}_{\text{L}}}$	240	±4	±1
$m_{\tilde{\text{q}}_{\text{L}}}$	690	±1.7	±1
$m_{\tilde{\text{q}}_{\text{R}}}$	660	±3	±1.5
$m_{\tilde{\text{g}}}$	770	±2.6	±1.5
$m_{\tilde{\text{t}}_1}$	490		±10

Table 6
Expected uncertainty on the measurement of the fundamental SUGRA parameters at Point 5 in ATLAS for two different integrated luminosities.

SUGRA parameter	Error for 30 fb^{-1}	Error for 300 fb^{-1}
$m_0 = 100$ GeV	±5 GeV	±3 GeV
$m_{1/2} = 300$ GeV	±8 GeV	±4 GeV
$\tan\beta = 2.1$	±0.11	±0.02

should be measured with precisions between a few permil and a few percent. Such a potential arises mainly from the large SUSY cross section and the variety of signatures which are produced by the cascade decays of $\tilde{\text{q}}$ and $\tilde{\text{g}}$. The fundamental parameters of minimal SUGRA should be measured with precisions of the order of 1%.

More generally, whatever the correct theory will be, the LHC experiments will be able to perform many model-independent observations and measurements, such as observations of excesses of events with top quarks, b quarks, Z bosons, observation of $\text{h} \to \text{b}\overline{\text{b}}$ peaks, measurements of end-points and shapes of several types of mass spectra. This will provide a large number of experimental results, which should constrain quite general SUSY models, models with R-parity breaking, and Gauge-mediated SUSY-breaking theories [3].

8. Conclusions

In addition to its huge potential for the discovery of new physics, the LHC will allow a wealth of precision measurements to be performed in many sectors: W/Z physics, Triple-Gauge Couplings, top physics, B physics, Higgs, Supersymmetry, etc. A few non-exhaustive examples have been presented.

In many cases, significant improvements on the future TeVatron and LEP results are expected after only one or two years of operation.

The statistical error will be negligible for most measurements, and the precision will be limited by systematic effects. Therefore, stringent requirements have been set on the design of the ATLAS and CMS experiments, and on their performance in terms of energy and momentum resolution, response uniformity, particle identification capability, etc. If the experiments will behave as expected, the precision of many measurements will be limited by the knowledge of the physics and not by the detector performance. Therefore, improved theoretical calculations will be necessary to match the expected experimental accuracies.

REFERENCES

1. ATLAS Collaboration, *Technical Proposal*, CERN/LHCC/94-43 (1994).
2. CMS Collaboration, *Technical Proposal*, CERN/LHCC/94-38 (1994).
3. ATLAS Collaboration, *Detector and Physics Performance, Technical Design Report*,

CERN/LHCC/99-15, ATLAS TDR 15.

4. *Electroweak Physics*, hep-ph/0003275, to appear in the Report of the *1999 CERN Workshop on SM physics (and more) at the LHC*, S. Haywood, P.R. Hobson, W. Hollik, Z. Kunszt (conveners).
5. *Top Quark Physics*, hep-ph/0003033, to appear in the Report of the *1999 CERN Workshop on SM physics (and more) at the LHC*, M. Beneke, I. Efthymiopoulos, M.L. Mangano, J. Womersley (conveners).
6. CDF Collaboration, *Phys. Rev.* D **52**, 4784 (1995).
7. D0 Collaboration, FERMILAB-PUB-97/328-E.
8. D.V. Elvira, in *Proceedings of the VII International Conference on Calorimetry in High-Energy Physics*, eds. E. Cheu *et al* (World Scientific Singapore, 1998).
9. D. Amidei and R. Brock, FERMILAB-PUB-96/082.
10. *Physics at LEP2*, CERN 96-01.
11. R. Wagner, presentation in Plenary Meeting of CERN Workshop on *Standard Model at the LHC*, 25 May 1999.
12. M. Dittmar, F. Pauss and D. Zürcher, *Phys. Rev.* D **56**, 7284 (1997), hep-ex/9705004.
13. U. Baur, O. Brein, W. Hollik, C. Schappacher, and D. Wackeroth, in preparation.
14. *A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model*, the LEP Collaborations ALEPH, DELPHI, L3 and OPAL, the LEP Electroweak Working Group and the SLD Heavy Flavour and Electroweak Groups, CERN-EP-2000-016, January 21, 2000.
15. P.C. Bhat, H.B. Prosper and D.D. Sneyder, FERMILAB PUB-98/236.
16. CMS Letter of Intent, CERN/LHCC 92-3 (1992) 90; I. Iashvili *et al*, CMS TN/92-34 (1992).
17. A. Kharchilava, Phys.Lett. B **476** (2000) 73 and hep-ph/9912320.
18. U. Baur and E.W.N. Glover, in *Proceedings of the Aachen LHC Workshop*, Vol. 2, eds. G. Jarlskog and D. Rein, CERN 90-10 (1990).
19. See for instance H. Baer *et al*, *Low Energy Supersymmetry Phenomenology*, FSU-HEP-950401 (1995), and references therein.
20. G. Polesello *et al*, *Precision SUSY measurements with ATLAS for SUGRA point 5*, ATLAS Internal Note PHYS-No-111, http://alice.cern.ch/ATLAS.