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HADRON COLLIDER PHYSICS — FROM THE TEVATRON TO THE LHC —*

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Over the next decade hadron colliders will play an important role in the investigation of fundamental questions of particle physics. The high collision energy of the Fermilab *Tevatron* $p\bar{p}$ collider and the CERN *Large Hadron Collider* (LHC) will allow to probe physics in a new energy domain. In addition, important precision measurements in the area of electroweak physics can be carried out. In particular the experiments at the LHC have a large potential to explore physics beyond the Standard Model and to investigate the nature of electroweak symmetry breaking. In the present article the physics potential of the Tevatron and the LHC is summarized.

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1. Introduction

Present and future Hadron Colliders will open up the possibility to explore the TeV-energy scale, which plays a key role in the investigation of electroweak symmetry breaking and in the search for physics beyond the Standard Model.

The experiments ATLAS and CMS at the Large Hadron Collider have been designed and optimized to cover a large spectrum of possible physics signatures, accessible at the high luminosity and centre-of-mass energy of the LHC. In the main focus of the experiments will be the search for the Higgs boson as well as for particles predicted by supersymmetry or technicolor theories, new gauge bosons and searches for composite quarks and leptons. In addition, the exploration for additional space-time dimensions will play an important role. Besides the discovery potential for new physics

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the experiments have also a large potential to perform precision measurements of Standard Model parameters, like measurements of the W and top quark masses or triple gauge boson couplings.

At the Tevatron, a new data taking period has started in 2001 after the upgrade of both the accelerator and the CDF and D0 detectors. It is expected that until the start-up of the LHC the Fermilab experiments will collect data corresponding to an integrated luminosity of several fb^{-1}. With this dataset it will be possible already over the next years to address some of the aforementioned physics questions.

In the present article the physics potential of the Tevatron and the LHC experiments is briefly summarized. For the Tevatron also first results, based on data corresponding to an integrated luminosity of about $120\,\mathrm{pb}^{-1}$, which have been collected until summer 2003, are presented. For details on both the LHC and the Tevatron physics potential the reader is referred to Refs. [1–3] and [4], respectively. In these reports the reader will also find a discussion of those physics items which are not covered here, in particular, investigations in B-Physics.

2. Experimental issues

2.1. The Tevatron Run II

After a successful first period of data taking until 1996 (Run I), the Fermilab accelerator complex has been upgraded to provide collisions with an increased luminosity and a center-of-mass energy of 1.96 TeV. In 2001 the second phase (Run II) of the experimental programme started. After a long start-up phase, a peak luminosity of 3.6×10^{31} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ has been reached in Spring 2003. Despite the fact that the peak luminostiy exceeds the one achieved in Run I the design goals, in particular in terms of integrated luminosity per week, have not yet been reached. A number of performance issues in the machine have been identified and are being addressed [5]. These included injection aperture and lifetime, beam–beam effects, and instabilities. At present, it is anticipated to collect integrated luminosities in the range between 2 and 6 fb^{-1} until the end of 2006.

Both experiments CDF and D0 have undergone major upgrade programmes to accomodate the expected increase in luminosity. In the design, particular emphasis has been put to achieve an efficient identification of leptons and b-jets as well as to provide good jet and missing energy measurements.

In the CDF experiment the central tracking system from Run I has been replaced with a new tracking chamber and a multilayer silicon detector. New muon chambers with an increased η–ϕ coverage have also been installed. A new lead scintillator calorimeter in the forward region provides better electron identification, better coverage, and an improved jet energy resolution.

Also in the D0 experiment the tracking system has been substantially upgraded. The Run I system has been replaced by a silicon vertex detector and a central fibre tracker, situated in a 2 T magnetic field provided by a superconducting solenoid. The muon system surrounding the Liquid Argon calorimeter has been upgraded and extended.

In addition, the readout electronics as well as the trigger and data acquisition systems have been upgraded in both experiments to cope with the higher data rate. A new asset to the trigger system is a high-$P_{\rm T}$ track trigger at level-1.

After commissioning all subdetectors, a first pass of calibration and alignment has been completed successfully [6]. Trigger and reconstruction algorithms have been varified with physics signals and first physics results based on data corresponding to an integrated luminosity of about 120 pb^{-1} have been presented in Summer 2003.

2.2. LHC running scenarios and cross sections

Throughout the paper, it is assumed that at the LHC an initial luminosity of 10^{33} cm^{-2} s^{-1} (hereafter called *low luminosity*) can be achieved at the startup, which is expected for the year 2007. It is expected that this value should rise, during the first two to 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} and 100 fb^{-1} should therefore be collected at the LHC after about one and four years of data taking, respectively.

Due to the expected high machine luminosity the production rates of many relevant physics processes are large. The expected cross sections and the corresponding event rates at the LHC are shown in Table I.

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. The copious $t\bar{t}$ production will constitute a significant background for many searches of new physics signals since it may lead to characteristic final states with leptons, jets and missing transverse energy $E_{\rm T}^{\rm miss}$.

The LHC physics performance has been evaluated using the following assumptions:

(i) Despite the considerable progress in the calculation of higher order QCD corrections over the last years, these corrections (K-factors) are not known for all signal and background processes of interest. Therefore, the studies have consistently and conservatively refrained from using K-factors, resorting to Born-level predictions for both signals and backgrounds.

(ii) The non diffractive inelastic cross section has been assumed to be 70 mb. At low luminosity, this leads on average to a superposition of 2.3 minimum bias events on top of the hard collision. These so called pile-up contributions have been included for both low and high luminosity.

(iii) Physics processes have been simulated with the PYTHIA Monte Carlo [7] program, including initial- and final-state radiation, hadronisation and decays. Although many results have been obtained using a fast simulation, all key performance characteristics have been evaluated with a full GEANT simulation, both at low and high luminosity [1,2].

TABLE I

Cross sections and approximate numbers of expected events per second and per year at the LHC for some important physics processes at low luminosity (10^{33} cm^{-2} s^{-1}).

Process	σ (pb)	Events/sec.	Events/year
$W \to e\nu$	1.5×10^4	15	10^8
$Z \to e^+e^-$	1.5×10^3	1.5	10^7
$t\bar{t}$	800	0.8	10^7
$b\bar{b}$	$5{\times}10^8$	5×10^5	10^{12}
$\tilde{g}\tilde{g}$ ($m_{\tilde{g}} = 1$ TeV)	1	0.001	10^4
$H(m_H = 200$ GeV)	10	0.01	10^5
Inclusive jets $P_{\rm T} > 200$ GeV	10^5	100	10^9

3. Tests of QCD at the Tevatron

3.1. Jet production

As a result of parton parton scattering high $P_{\rm T}$ jets, *i.e.*, hadronic jets with large transverse momentum, are produced very copiously at hadron colliders. The increase in the center-of-mass energy and in luminosity compared to Run I will allow to extend the tests of perturbative QuantumChromoDynamics to yet higher $P_{\rm T}$ values.

In Fig. 1 the inclusive jet production cross section as measured in the D0 experiment, based on data corresponding to an integrated luminosity of 34 pb^{-1}, is shown as a function of the transverse momentum $P_{\rm T}$ of the jet. The slightly increased center-of-mass energy increases significantly the jet production cross section, *e.g.*, for $P_{\rm T}$ values around 400 GeV/c, the cross section increases by a factor of four. Superimposed on Fig. 1 is a theoretical NLO prediction using the CTEQ6M parametrization of the structure functions. There is an impressive agreement between data and theory over the full spectrum, which covers seven orders of magnitude. The ratio between the experimental data and the theoretical prediction is also shown in Fig. 1 together with a band that respresents the experimental uncertainties. Those are mainly dominated by uncertainties in the absolute value of the jet energy scale. Within the large uncertainties good agreement between data and theory is found. Also the CDF collaboration has carried out similar measurements and finds good agreement between data and theory in the new data.

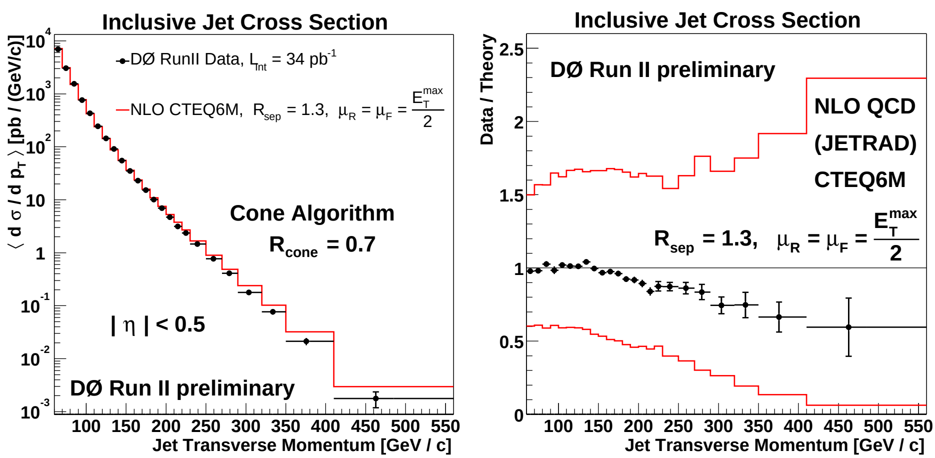

Fig. 1. (left): The inclusive jet production cross section as a function of P_T from data collected in the D0 experiment in Run II. The QCD prediction is superimposed. (right): Ratio between the experimental data and the theoretical predictions. The band indicates the systematic uncertainties in the data resulting from the uncertainties on the absolute jet energy scale.

3.2. W and Z production

W and Z bosons are produced at the Tevatron $p\overline{p}$ collider in leading order by the Drell–Yan process. There are significant contributions from higher order QCD corrections that increase the cross section by about 35%. These corrections have been calculated to NNLO. Hence a comparison between data and the theoretical prediction represents a qualitative test of QCD.

Using Run II data corresponding to 72 pb^{-1} the CDF experiment has selected about 39,000 $W \rightarrow e\nu$ candidate events with a small background by applying P_T and rapidity cuts on the electron and a cut on the missing transverse momentum. The transverse mass distribution for those events is shown in Fig.2.

The W and Z production cross section measurements extracted from data collected in Run II corresponding to an integrated luminosity of $\sim$100 pb^{-1} are shown in Fig. 2 together with the measurements of Run I at the slightly lower center-of-mass energy. Compared to the jet production the experimental systematic uncertainties are much smaller and therefore a more stringent test will be possible when the data samples increase. Also for the W and Z production good agreement between data and the QCD predictions is found.

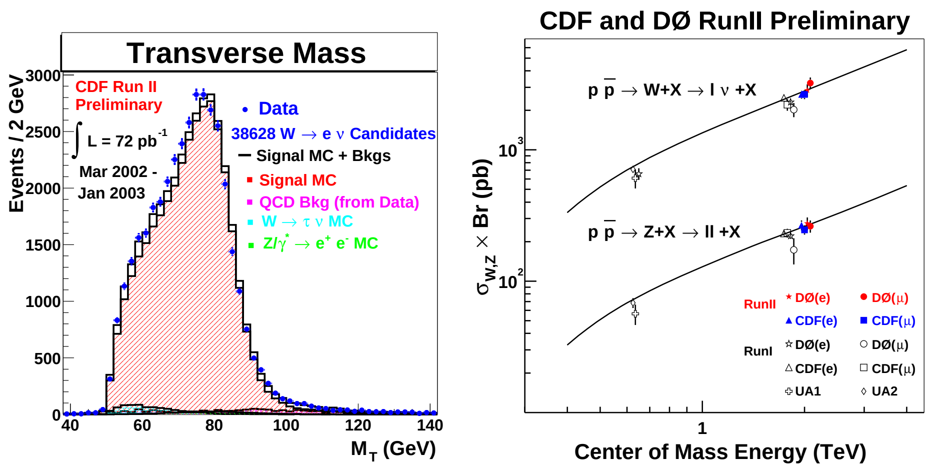

Fig. 2. (left): The transverse mass distribution of the $W \to e\nu$ candidates selected in the CDF Run II data based on an integrated luminosity of 72 pb^{-1}. (right): The W and Z boson production cross section as measured in the CDF and D0 in Run I and from first data collected in Run II. The NNLO QCD predictions are superimposed.

3.3. Top production

The data collected at the Tevatron in Run II until Summer 2003 have allowed to re-establish the signals from $t\bar{t}$ production. Both experiments have searched for the production of two leptons accompanied by jets and missing transverse momentum. This *di-lepton* final state should receive contributions from $t\bar{t}$ production with both top quarks decaying leptonically via the decay chain $t \to Wb \to \ell\nu b$. In addition, top quark pair production using the so called *lepton + jet* channel has been searched for. Contributions to this channel arise from events with one leptonic and one hadronic top decay via the decay chain $t \to Wb \to q\bar{q}b$. While the di-lepton channel has smaller background, it only amounts to 5% of the total $t\bar{t}$ sample. The *lepton + jets* channel represents about 30% of all $t\bar{t}$ decays. The remaining $t\bar{t}$ pairs decay fully hadronically into six jet final states or into final states with taus. Since these decay modes suffer from large backgrounds from QCD jet production, they have not yet been investigated at this early stage of the analysis.

In addition to $t\bar{t}$ production, Standard Model background processes such as Drell-Yan ($\gamma^*/Z \to \ell\ell$), $Z \to \tau\tau$, WW and WZ production contribute to the di-lepton sample. Another source of background results from events with one real lepton and a jet that fakes an electron. Both experiments have seen an excess of events above these background expectations: in data corresponding to an integrated luminosity of 72 pb^{-1} the CDF collaboration observes 5 di-lepton events, with an expected background of 0.3 events. The corresponding numbers for the D0 experiment are 7 events in the data and an expected background of 1.7 events for an integrated luminosity of 60 pb^{-1}.

In the *lepton + jet* channel different techniques are used to enhance the $t\bar{t}$ contribution with respect to Standard Model background processes. A CDF analysis relies on the identification of b-jets from a displaced secondary vertex resulting from the relatively long B-meson lifetime. In the D0 analyses either a topological selection of events with four high $P_{\rm T}$ jets is done or a b-jet is tagged using a soft muon in the event. In all three analyses a clear excess is seen in the data above the dominant background from W + *jet* production.

Based on these analyses first cross section measurements have been carried out. The results are shown for the various analyses in Fig. 3. Good agreement between the different measurements and between the data and the theoretical QCD prediction is found.

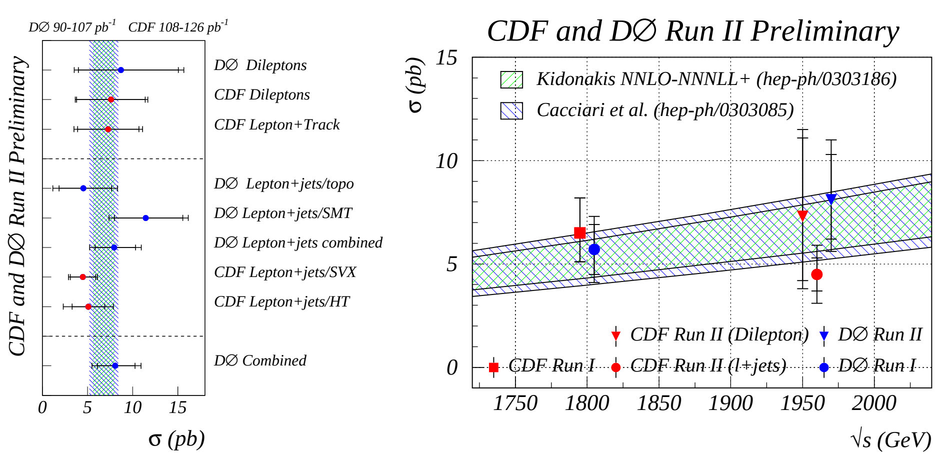

Fig. 3. (left): The measured $t\bar{t}$ production cross section from the first Tevatron Run II data using various analyses in the two experiments. (right): Comparison between the cross section measurements at the two Tevatron energies for both experiments and the theoretical QCD predictions.

At the LHC it should be possible to measure the $t\bar{t}$ production cross section with a precision of better than 10%. The dominant error is expected to result from uncertainties in the knowledge of the integrated luminosity.

4. Precision measurements of Standard Model parameters

4.1. Measurement of the W mass

At hadron colliders, the W mass is obtained from the distribution of the W transverse mass, defined as $M_{\mathrm{T}} = \sqrt{2P_{\mathrm{T}}(e)P_{\mathrm{T}}(\nu)(1-\cos\Delta\phi)}$, where $P_{\mathrm{T}}(e)$ and $P_{\mathrm{T}}(\nu)$ are the transverse momenta of the lepton and the neutrino, respectively, and $\Delta\phi$ is the angular separation between the momentum vectors in the transverse plane.

Once large statistics data samples will be collected, the CDF and D0 experiments will be able to make improved measurements of the W mass. Using the dataset collected in Run I, the combined result on the W mass measurement from the hadron collider experiments (CDF, D0 and UA2) is $m_W = 80.452 \pm 0.062\,\mathrm{GeV}/c^2$, assuming a common error of $25\,\mathrm{MeV}/c^2$, covering common uncertainties in parton density functions, W width and QED corrections. The dominant errors in this measurement results from the uncertainties on the absolute calibration of the lepton energy scale. It has been estimated that a precision of $40\,\mathrm{MeV}/c^2$ per experiment can be reached once data corresponding to an integrated luminostiy of $2\,\mathrm{fb}^{-1}$ have been collected in Run II.

If this result is combined with the final result from LEP-II, $m_W = 80.427 \pm 0.046\,\mathrm{GeV}/c^2$ [8], the W mass will be known with a precision of $\sim 30\,\mathrm{MeV}/c^2$ at the startup of the LHC. The motivation to further improve the precision on the W mass at the LHC is mainly that precise measurements of the W mass, of the top mass and of the Higgs mass will provide stringent tests of the consistency of the underlying theory. With a top mass measured with an accuracy of $\sim 1.5\,\mathrm{GeV}/c^2$, the W mass should be known with a matching precision of 15 MeV/c^2, in order not to become the dominant source of uncertainty in the test of the radiative corrections.

At the LHC, sixty million well-reconstructed $\mathrm{W} \to \ell\nu$ decays (where $\ell = e$ or μ) should be collected by each experiment in one year of data taking at low luminosity. The statistical error on the W mass measurement is therefore expected to be small ($< 2\,\mathrm{MeV}/c^2$). 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 result from the limited knowledge of the W P_{T} spectrum, structure functions, the W width and from W radiative decays. Uncertainties related to the detector result from the limited knowledge of the absolute lepton energy scale and the detector energy/momentum resolution and response. Many of these uncertainties (lepton scale, detector resolution and response and the W P_{T} spectrum) will be constrained in the experiment by using the high-statistics sample of leptonic Z decays.

Preliminary estimates of the expected uncertainties on the W mass measurement, based in part on extrapolating from Tevatron results, indicate, that like at the Tevatron [9], 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%, which represents the most serious challenge for this measurement.

All other systematic uncertainties are expected to be smaller than 10 MeV/c^2. By combining both ATLAS and CMS and both channels (electrons and muons), it should be possible to obtain a total error of 15 MeV/c^2 in the initial, low luminosity phase, provided the precison on the lepton energy scale can be reached. Improved theoretical calculations, in particular of the W P_{T} spectrum and of the impact of radiative corrections, will also be important to achieve this goal.

4.2. Measurement of the top quark mass

At the LHC, top quark measurements will benefit from the large $t\bar{t}$ event samples, so that not only the mass and the production cross section, but also branching ratios, couplings and rare decays can be studied in detail. In the year 2007, the top mass should be known with a precision of $\sim$2 GeV/c^2 or better from measurements at the Tevatron. At the LHC the best channel for the top mass measurement will most likely be $t\bar{t}$ 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 ($m_t = m_{jjb}$). The associated leptonic top decay will be used to trigger the events and to suppress backgrounds.

The statistical error is expected to be smaller than 100 MeV/c^2, the precision will be limited by the systematic error. An expected uncertainty of 1% on the absolute jet scale should translate into an uncertainty smaller than 1 GeV/c^2 on the top mass. The effect of final-state gluon radiation is estimated to lead to an uncertainty of $\sim$1 GeV/c^2. Other sources of systematic uncertainties such as those related to b-fragmentation, initial state radiation, and backgrounds are expected to be smaller. All together, a total uncertainty smaller than 1% should be achieved. This precision may be further improved by using $t\bar{t}$ pairs produced with very high P_{T}. It has also been proposed [10] to use events where a J/ψ originating from a b-decay and decaying to two leptons appears in the final state. The invariant mass of the J/ψ and an additional lepton from the decay of the associated W boson is correlated to the top quark mass. This method is interesting since it has different systematic uncertainties.

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

- Single top production via the weak interaction should allow the CKM matrix element $V_{\rm tb}$ to be measured with a precision of 10% or better.
- Upper limits at the level of 10^{-4}–10^{-5} on the FCNC couplings V_{tc} and V_{tu} with $V = Z$, γ, g should be set with 100 fb^{-1}, improving the Tevatron sensitivity by a factor of 10 at least.

5. Search for Higgs bosons

5.1. The LHC potential

The search for the Higgs boson is one of the key motivations for the construction of the LHC. The Standard Model Higgs boson is searched for at the LHC in various decay channels, the choice of which is given by the signal rates and the signal-to-background ratios in the various mass regions. The search strategies and background rejection methods have been established through many studies over the past years [1, 2, 11].

The overall sensitivity for the discovery of a Standard Model Higgs boson over the mass range from $80\,\mathrm{GeV}/c^2$ to $1\,\mathrm{TeV}/c^2$ in the ATLAS experiment is shown in Fig. 4. The sensitivity is given for individual channels as well as for the combination of the various channels, assuming an integrated luminosity of 100 fb^{-1}. A comparable significance can be achieved in the CMS experiment. A Standard Model Higgs boson can be discovered at the LHC over the full mass range from the LEP2 lower limit [12] up to the TeV range with high significance. Over a large fraction of the mass range the discovery of a Standard Model Higgs boson will be possible in two or more independent channels.

The search of the Standard Model Higgs boson is challenging in the intermediate mass region, $m_H < 2m_Z$. Even though the natural width of the Standard Model Higgs boson in this mass range is narrow, the backgrounds from $t\bar{t}$ and continuum ZZ or WW production are relatively large and thus, an excellent detector performance in terms of energy resolution and background rejection is required [1, 2]. For Higgs-boson masses in the range $180 < m_H <\sim 600\,\mathrm{GeV}/c^2$, the $H \to ZZ \to 4\ell$ decay mode is the most reliable channel for the discovery. The expected background, which is dominated by the continuum production of Z boson pairs, is smaller than the signal. In the mass range between $600\,\mathrm{GeV}/c^2$ and about $1\,\mathrm{TeV}/c^2$, a Higgs boson

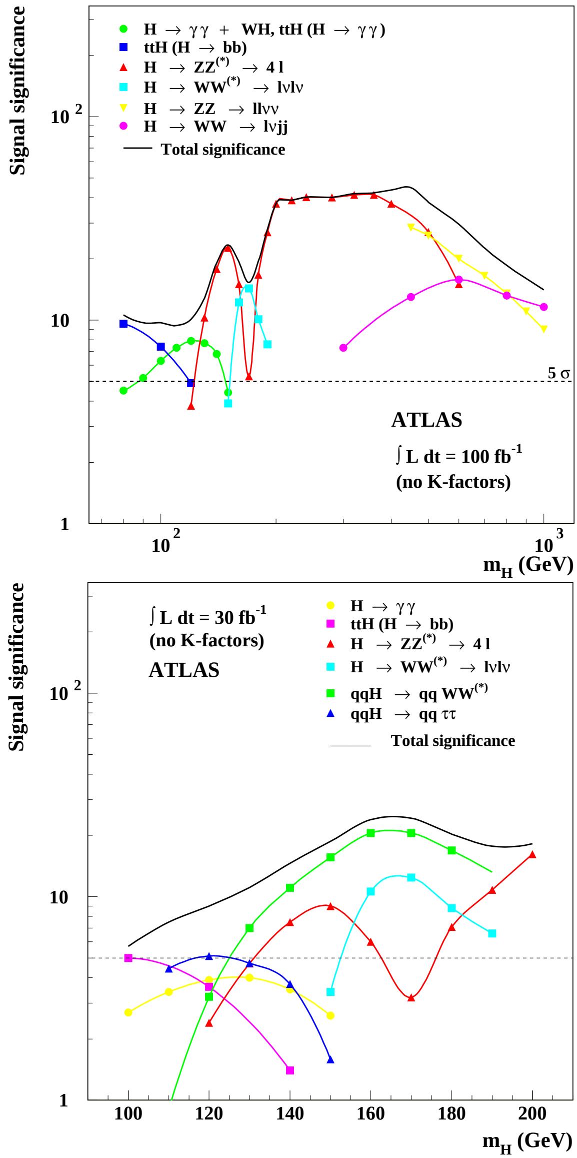

Fig. 4. Sensitivity for the discovery of a Standard Model Higgs boson as a function of the Higgs boson mass (upper plot): The statistical significance for the ATLAS experiment is plotted for individual channels as well as for the combination of all channels, assuming an integrated luminosity of 100 fb^{-1} (lower plot): The statistical significance in the intermediate mass region including the recently studied vector boson fusion channels for an integrated luminosity of 30 fb^{-1}.

would be discovered in the $H \to WW \to \ell\nu jj$ mode. The sensitivity in this channel can also be extended down to lower masses, where it provides independent and complementary information to the four-lepton channel. For $400 < m_H < 900\,\mathrm{GeV}/c^2$ the $H \to WW \to \ell\nu jj$ channel is complemented by the $H \to ZZ \to \ell\ell jj$ and $H \to ZZ \to \ell\ell\nu\nu$ channels, which will provide additional robustness to a Higgs boson discovery in this mass range.

In recent studies [13–15] it has been demonstrated that the discovery potential in the intermediate mass range can be significantly increased if a search for Higgs boson production in the fusion mode of two vector bosons is performed. The fusion of vector bosons radiated from initial state quarks represents the second most important contribution to the Higgs boson production cross-section at the LHC. Although in the intermediate mass range it amounts only to about 20% (at leading order) of the total production cross-section, additional event characteristics can be exploited to suppress the large backgrounds. In vector boson fusion events the Higgs boson is accompanied by two jets in the forward regions of the detector, originating from the initial quarks that emit the vector bosons. On the other hand, central jet activity is suppressed due to the lack of color exchange between the initial state quarks. This is in contrast to most background processes, where there is color flow in the t-channel. Jet tagging in the forward region of the detector together with a veto of jet activity in the central region are therefore useful tools to enhance the signal to background ratio. The performance of the detectors for jet tagging has been studied in detail [15]. According to the Monte Carlo studies the LHC experiments have a large discovery potential in the $H \to WW^{(*)} \to \ell^+\ell^- P_{\mathrm{T}}^{\mathrm{miss}}$ decay mode. The additional signatures of tag jets in the forward and of a low jet activity in the central regions of the detector allow for a significant background rejection, such that a better signal-to-background ratio than in the inclusive $H \to WW^{(*)}$ channel, which is dominated by the gluon gluon fusion process, is obtained. As a consequence, the signal sensitivity is less affected by systematic uncertainties in the predictions of the background levels. The experiments at the LHC would be sensitive to a Standard Model Higgs boson in this decay channel in the mass range between 135 and $190\,\mathrm{GeV}/c^2$ with data corresponding to an integrated luminosity of 10 fb^{-1} only.

It has also been shown that in the mass region $110 < m_H < 140\,\mathrm{GeV}/c^2$ the ATLAS and CMS experiments are also sensitive to the $\tau\tau$ decay mode of the Standard Model Higgs boson in the vector boson fusion channel. A discovery in this final state would require an integrated luminosity of about 30 fb^{-1}. The detection of the τ decay mode is particularly important for a measurement of the Higgs boson couplings to fermions, as discussed below. The discovery potential including those two vector boson fusion channels is also shown in Fig. 4 for an integrated luminosity of 30 fb^{-1} in one experiment alone. The inclusion of the vector boson fusion channels allows already for a full coverage of the difficult low mass region for relatively low integrated luminosities. With an integrated luminosity of only 10 fb^{-1}, the Higgs boson can be discovered in each experiment in the mass range above $\sim 120\,\mathrm{GeV}/c^2$ with a significance of more than 5 standard deviations.

Important Higgs boson parameters like the mass and the width as well as ratios of couplings can also be measured at the LHC with a reasonable precision. With an integrated luminosity of 300 fb^{-1} each experiment would measure the Higgs-boson mass with a precision of ~0.1% over the mass range 80–400 GeV/c^2, the Higgs-boson width with a precision of 6% over the mass range 300–700 GeV/c^2. By taking ratios of production cross sections times branching ratios for various final states, ratios of partial widths of the Higgs boson can be measured. By comparing the W and Z final states either in the gluon gluon fusion or in the vector boson fusion mode, Γ_W/Γ_Z can be measured in the mass range below 180 GeV/c^2 with a relative precison in the range between 10–20%. The vector boson fusion also opens up the possibility to measure the ratio Γ_τ/Γ_W over a limited mass range below 140 GeV/c^2, where the tau decay mode is detectable. The ratio Γ_b/Γ_W can be measured with a lower accuracy also in the low mass region. The relative errors of these measurements are presented in Fig. 5 for a combination of both experiments and assuming an integrated luminosity of 300 fb^{-1} per experiment.

The LHC experiments have also a large potential in the investigation of the MSSM Higgs sector. If the SUSY mass scale is large and supersymmetric particles do not appear in Higgs boson decays, the full parameter space in the conventional $(m_A, \tan\beta)$ plane can be covered. The regions covered with a significance of more than 5σ are shown in Fig. 6 for the combination of both experiments and for an integrated luminosities of 300 fb^{-1}. The maximal mixing scenario [1] has been assumed in this analysis. Other mixing scenarios are currently under investigation. In addition to the channels discussed for the Standard Model case, the MSSM Higgs search 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 a 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, the experiments would be able to distinguish between the Standard Model and the MSSM models.

The interplay between SUSY particles and the Higgs sector has also been addressed. SUSY scenarios have an impact on the discovery potential through the opening of Higgs-boson decays to SUSY particles (mostly for H and A) and through the 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

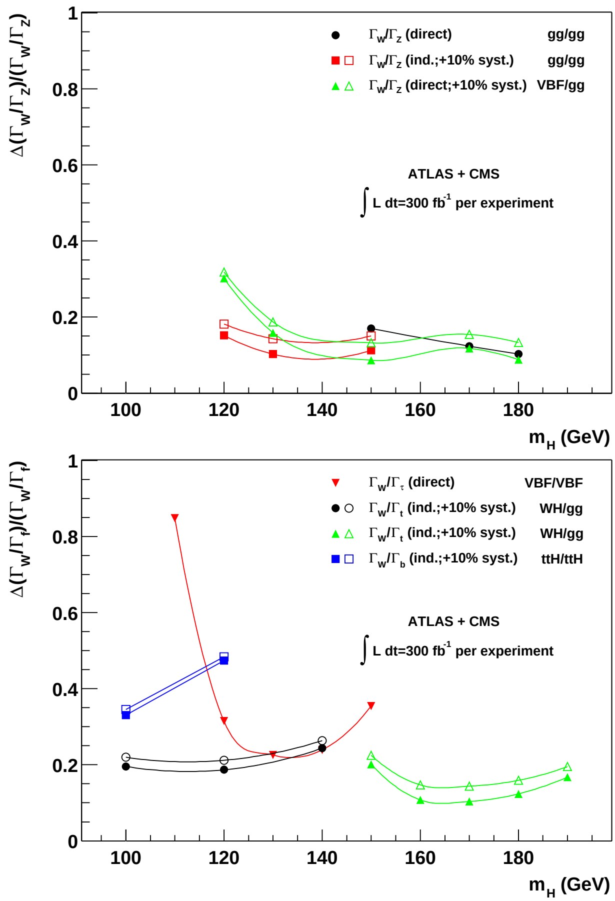

Fig. 5. The relative precision of the measurements of ratios of partial widths of a Standard Model Higgs boson for the combination of both experiments and an integrated luminosity of 300 fb^{-1} per experiment. The relative precision is shown for the measurement of Γ_W/Γ_Z (upper plot) and Γ_W/Γ_f, where f represents a fermion, as indicated in the lower plot.

the framework of SUGRA models. The discovery potential of the lightest neutral Higgs h would not be significantly different from what is obtained in the heavy SUSY scenario, since within the model, given 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 $\chi_2^0 \rightarrow \chi_1^0 h$ which will be observable with the ATLAS and CMS detectors (see below). The neutral heavy Higgs bosons would be detected in some cases via their decays into neutralinos and charginos, using multi-lepton final states.

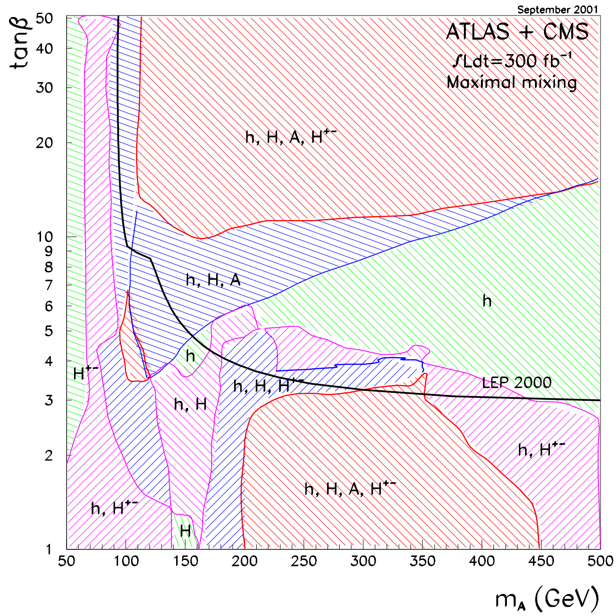

Fig. 6. The combined sensitivity of the ATLAS and CMS experiments for the discovery of MSSM Higgs bosons (in the case of maximal mixing). The excluded regions with a significance of 5σ in the $(m_A, \tan\beta)$ plane are shown. In the different regions the number of supersymmetric Higgs bosons that can be detected is indicated. Also included are the limits obtained from the LEP2 data.

In the absence of a scalar Higgs boson, the principal probe for the mechanism of electroweak symmetry breaking will be gauge boson scattering at high energies. It has been shown that the experiments will be sensitive to the presence of resonances, such as in the WZ system, up to masses around $1.5\,\mathrm{TeV}/c^2$. A study of nonresonant processes, such as the W^+W^+ production, will require a few years of high luminosity running and a good understanding of the underlying backgrounds.

5.2. The Tevatron potential

An interesting question is whether, and if yes over what mass range, a Standard Model Higgs boson can already be discovered in the ongoing Run II at the Tevatron. The potential has been evaluated first in fast detector simulations [4] and has been validated recently using more detailed simulations.

The situation is summarized in Fig. 7, where as a function of the Standard Model Higgs boson mass the integrated luminosity is given which is needed for a 95% exclusion, for a 3σ, and for a 5σ discovery. Due to the

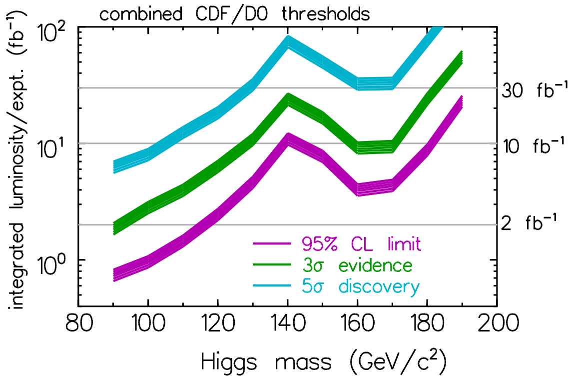

Fig. 7. The integrated luminosity needed per experiment for a 95% CL exclusion, a 3σ, and a 5σ discovery of a Standard Model Higgs boson at the Tevatron as a function of the Higgs boson mass [4]. The potential in the various search channels and of both experiments has been combined.

lower center-of-mass energy the Tevatron is only sensitive to light Higgs bosons in the mass range $m_H <\sim m_Z$. For Higgs boson masses around $120\,\mathrm{GeV}/c^2$, the associated production mode of the Higgs boson with a vector boson is used, with subsequent decays of the Higgs boson into $b\bar{b}$ and leptonic decays of the vector boson. It must be stressed that, even if large integrated luminosities in the order of 10 fb^{-1} per experiment can be collected, a Higgs boson discovery in a single channel will not be possible. To reach sensitivity all channels and the two experiments must be combined. For Higgs boson masses around $160\,\mathrm{GeV}/c^2$ where the WW branching ratio becomes large, the Higgs boson search can be performed in the decay modes $H \to WW \to \ell\nu\ell\nu$. In this case, the dominant gluon-gluon fusion process and the associated production mode with a vector boson can be used.

As shown in Fig. 7, the Tevatron experiments will be able to exclude with a confidence level of 95% a Standard Model Higgs boson over the mass range $m_H < m_Z$ if in each experiment an integrated luminosity of 10 fb^{-1} can be collected. Evidence for a Higgs boson signal at the 3σ level can be seen with the same integrated luminosity per experiment if the mass of the Higgs boson is below $130\,\mathrm{GeV}/c^2$ or in the range $160 < m_H < 170\,\mathrm{GeV}/c^2$.

5.3. First Higgs boson searches at the Tevatron

From the discussion presented above it is obvious that the data collected at the Tevatron so far do not provide sensitivity for a Standard Model Higgs boson search. However, there are exotic models where either the Higgs boson production cross section or the branching ratio in detectable final states are increased.

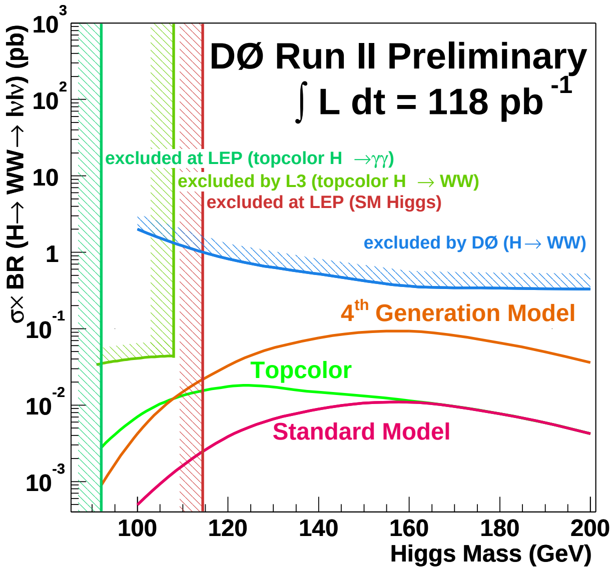

Fig. 8. Excluded cross section $\sigma \cdot \mathrm{BR}(H \to WW \to \ell\nu\ \ell\nu)$ (at 95% CL) together with expectations from Standard Model Higgs production and alternative models.

A first search has been performed by the D0 collaboration for ee, $e\mu$ and $\mu\mu$ final states with missing transverse momentum in data collected until July 2003, corresponding to an integrated luminosity of $\sim$110 pb^{-1}. The number of observed events has been found to be consistent with expectations from Standard Model backgrounds. An upper limit on the cross section times branching ratio $\sigma \cdot \mathrm{BR}(H \to WW \to \ell\nu\ \ell\nu)$ has been given. The excluded cross section is shown in Fig. 8 together with expectations from Standard Model Higgs boson production and alternative models. The alternative models considered are a fourth-generation model [16], where the Higgs boson production cross section is enhanced by about an order of magnitude due to heavy fourth-generation quarks, which contribute to quark loops in the gluon-fusion process. In fermiophobic (or bosonic) Higgs boson models [17] the coupling to fermions is suppressed leading to larger branching ratios for W or γ pairs.

6. Search for supersymmetry

6.1. Potential for SUSY searches at the LHC

If Supersymmetry (SUSY) [18] exists at the electroweak scale, its discovery at the LHC should be straightforward. The SUSY cross section is dominated by gluinos and squarks, which are strongly produced with cross sections comparable to the Standard Model backgrounds at the same Q^2. Gluinos and squarks then decay via a series of steps into the lightest supersymmetric particle (LSP), which may itself decay, if R-parity is violated. These decay chains lead to a variety of signatures involving multiple 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 a first step of SUSY searches at the LHC multijet events with large missing transverse momentum will be studied. An excess at large $E_{\mathrm{T}}^{\mathrm{miss}}$ would provide sensitivity to squarks and gluinos up to the TeV energy range. The discovery range for squarks and gluinos is shown in Fig. 9 in the $(m_0, m_{1/2})$ plane for the CMS experiment in the framework of the mini-

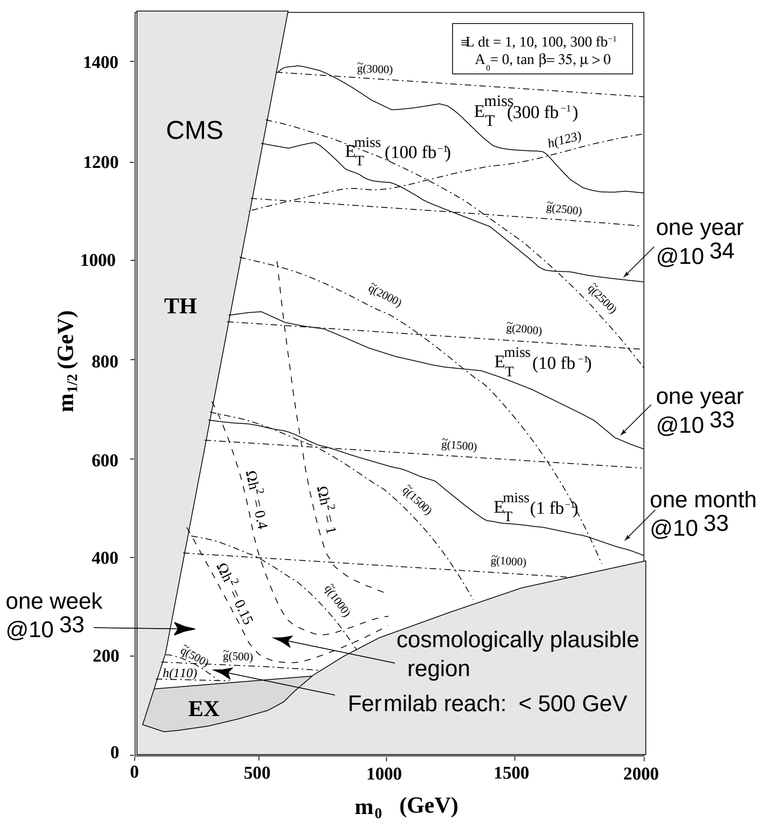

Fig. 9. The expected discovery reach for the CMS experiment for squarks and gluinos in the $(m_0/m_{1/2})$ parameter plane of mSUGRA. The excluded regions are shown for integrated luminosities of 1, 10, 100 and 300 fb^{-1}. The mSUGRA parameters are chosen to be $A_0 = 0$, $\tan\beta = 35$, and $\mu > 0$.

mal supergravity (SUGRA) model [19]. Already for an integrated luminosity of only 1 fb^{-1}, which can be collected in about one month, the reach in the jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ channel extends to squark and gluino masses in the order of 1.5 TeV. These mass limits can be extended up to about 2.5 TeV for an integrated luminosity of 100 fb^{-1}. SUSY cascade decays give also rise to lepton, b-jet and tau signatures. Selecting various multilepton final states similar regions in the $(m_0, m_{1/2})$ plane can be probed [3]. Therefore, the main challenge at the LHC is not to discover SUSY but to separate the many SUSY processes that occur and to measure the masses and other properties of the SUSY particles.

The approach followed by the collaborations has been to investigate in detail the signatures for particular points in the parameter spaces of the minimal supergravity (SUGRA) model, Gauge Mediated SUSY breaking (GMSB) models [20], and R-parity violating models [18]. Methods such as looking for kinematic endpoints for mass distributions and using these to determine combinations of masses have proven generally useful.

As an example, the production of $\tilde{q}_{\mathrm{L}}\tilde{q}_{\mathrm{R}}$, followed by the decays $\tilde{q}_{\mathrm{L}} \to q\chi_2^0$, $\chi_2^0 \to \tilde{\ell}_{\mathrm{R}}\ell$, $\tilde{\ell}_{\mathrm{R}} \to \ell\chi_1^0$, 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 Standard Model background). The resulting invariant mass distribution of the two leptons in the final state is shown in Fig. 10 (for a simulation of SUGRA study point 5, see Ref. [1]). 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 particles involved, 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.

Another example is the search for the $h \to b\bar{b}$ decay in SUSY events. If the two-body decay $\chi_2^0 \to \chi_1^0 h$ is kinematically allowed, it generally has a substantial branching ratio because the light neutralinos are dominantly gauginos. In many cases it is possible to reconstruct $H \to b\bar{b}$ as a resonance peak in the SUSY event sample, after applying simple kinematic cuts. An $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement usually suppresses the Standard Model background. An example of a reconstructed mass peak (for SUGRA study point 5, see Ref. [1]) is shown in Fig. 10. This signal may be easier to detect than $H \to \gamma\gamma$ and so it may provide the discovery mode for the light Higgs boson, although the $\gamma\gamma$ signal is still important to measure the mass precisely. The Higgs signal can also provide a good starting point for further analysis of SUSY particles.

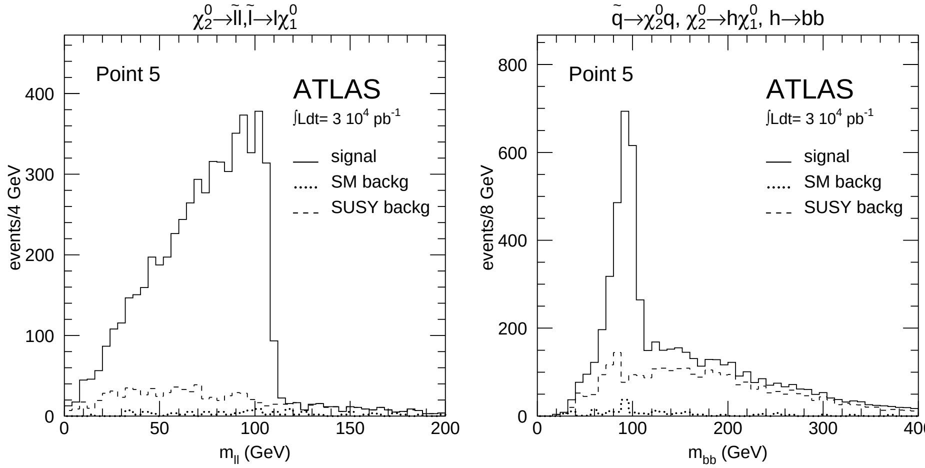

Fig. 10. (left): Invariant mass distribution of lepton pairs in the final state for SUSY events at SUGRA study point 5 selected as described in the text, as expected in ATLAS after three years of data taking at low luminosity. (right): Mass distribution of reconstructed $h \to b\bar{b}$ decays in SUGRA study point 5. Shown are in each case the signal (solid), the background from SUSY events (dashed) and the Standard Model background (dotted).

Given the success in extracting precise measurements for the points studied and the large number of SUSY events expected at the LHC, the experiments are likely not just to discover SUSY if it exists but to make many precise measurements. The starting point in this study will be to look for characteristic deviations from the Standard Model. In SUGRA and some other models, there would be events with multiple jets and leptons plus large $E_{\mathrm{T}}^{\mathrm{miss}}$. In GMSB models, there would be events with prompt photons or quasi-stable sleptons. In R-parity violating models, there would be events with very high jet multiplicity and/or leptons. Any such signal would point to possible classes of models and would indicate the rough mass scale. The next step would be to use partial reconstruction methods, like the ones shown above, to try to constrain as many combinations of masses as possible.

6.2. First SUSY searches at the Tevatron

The SUSY studies described above can already be started in the present Tevatron run, where the lower mass range can be explored.

In the D0 experiment, a search has been performed for the trilepton decay signature from the associated production of the lightest chargino and the next-to-lightest neutralino in leptonic channels with two electrons or electron and muon within the context of mSUGRA. The search uses data taken with the D0 detector corresponding to an integrated luminosity of 132 pb^{-1}. The selected events are in good agreement with the expected backgrounds from Standard Model processes and no evidence for supersymmetry has been found. The results for both selections can be translated into 95% CL upper limits on the cross section for associated production of charginos and neutralinos with decays into final states with three leptons. Since both analyses cover a couple of decay channels each, the results are given as limits on the cross section of the process $\chi^+\chi^0_2 \to 3\ell + X$, assuming equal branching fractions into the lepton flavours, which is common as long as the leptons are mass degenerate (for neglegible stau mixing). They are valid for parameter combinations with comparable chargino and neutralino masses, which is true for a large part of the mSUGRA parameter space.

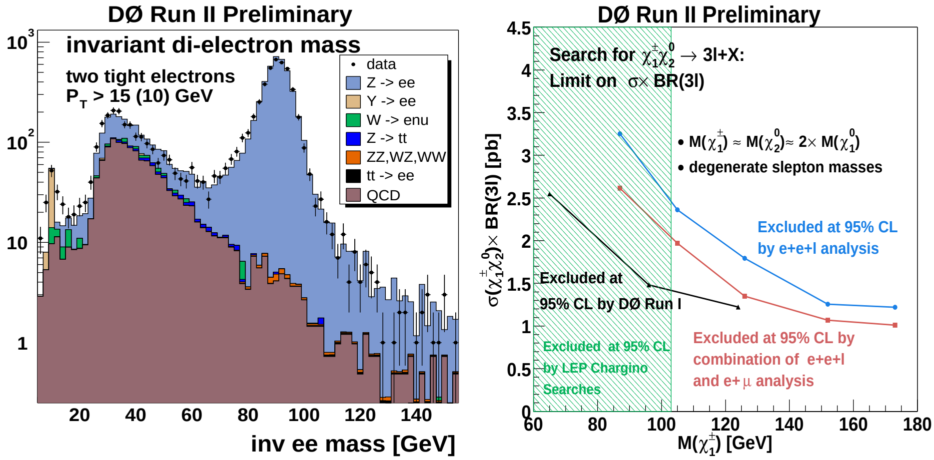

Fig. 11. (left): Distribution of the invariant mass of the two electrons in data (points with error bars) and background simulation (histograms, complemented with the QCD expectation) for events with two tight electron candidates, one electron candidate with $P_{\mathrm{T}} > 15\,\mathrm{GeV}/c$. (right): Limits on the cross section of associated neutralino-chargino production with decays into final states with three leptons depending on the chargino mass. Plotted are: the D0 Run I limit (triangles), the limit from the $ee\ell$ analysis (bullets) and the combined limit from the $e\mu$ and the $ee\ell$ analysis (squares). LEP is excluding chargino masses nearly up to the production limit of $103\,\mathrm{GeV}/c^2$.

7. Search for extra dimensions

There is much recent theoretical interest in models that have extra dimensions in addition to the 3+1 dimensions of normal space-time [21]. In these models, new physics can appear at a mass scale of order $1\,\mathrm{TeV}/c^2$ and can therefore be accessible at the LHC. The additional dimensions must be compactified on some scale R so that they are currently unobserved. Recently it has been suggested that R could be large, allowing the fundamental scale of gravity, here called M_D, to be at the TeV scale. If there are δ additional dimensions of size R, then the observed Newton constant is related to the fundamental scale M_D by [22] $G_N^{-1} = 8\pi R^\delta M_D^{2+\delta}$. When an extra dimension is compactified on a circle with size R, particles propagating exclusively in the extra dimensions appear from a four-dimensional viewpoint as a tower of massive states. In particular, gravitons G propagating in the extra dimensions will appear to be massive states and new physics is expected to appear at the scale M_D.

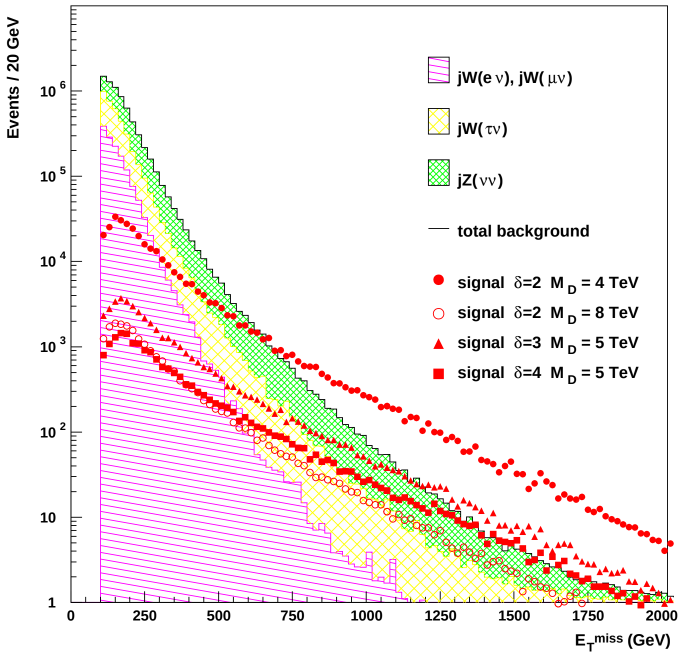

Fig. 12. Distribution of the missing transverse energy in background events and in signal events after the selection and for 100 fb^{-1}. The contribution of the three main kinds of backgrounds are shown as well as the distribution of the signal for several values of (δ, M_D).

The emission of gravitons in particle collisions, in processes like $gg \to gG$, $qg \to qG$, $q\bar{q} \to gG$, $q\bar{q} \to \gamma G$, is calculable in terms of the universal coupling of gravity to matter (see Ref. [22] for details). Since these emitted gravitons interact very weakly with ordinary matter, their emission gives rise to missing transverse energy signatures. Studies have shown [22] that the most promising signature is the one where a jet accompanies the missing transverse momentum. The distribution of the missing transverse energy in background events, which are dominated by $W + jet$ and $Z + jet$ production, and in signal events after the application of the selection criteria is shown in Fig. 12 for an integrated luminosity of 100 fb^{-1} [22]. For such a process and after one year of running at high luminosity, the LHC can probe the mass scale of the theory up to about 9, 7 and 6 TeV$/c^2$ if there are, respectively two, three or four extra dimensions.

In the proposed localized gravity model of Randall and Sundrum [23] a series of heavy narrow graviton excitations are predicted, which in some cases may be sufficiently well spaced to be detected as individual resonances at the LHC. In the scenario considered the massive graviton excitations are well separated from the other modes and couple with equal strength to the visible sector. This is in contrast to the study described above, in which many excitations, each with small coupling, contribute to the same scattering process. The discovery limit for the detection of the decay mode $G \rightarrow e^+e^-$ at the LHC has been derived [24]. It has been found that the resonances can be detected up to masses around 2.1 TeV$/c^2$. The limit is model independent as long as the graviton couplings are universal and give rise to narrow resonances, with widths less than the experimental resolution. The angular distribution of the lepton pair can be used to determine the spin of the state. In the model considered [24] a spin-2 hypothesis is favoured over a spin-1 hypothesis at 90% confidence for graviton masses up to about 1.7 TeV$/c^2$.

8. Other physics beyond the Standard Model

The ATLAS and CMS experiments will also be sensitive to a variety of other possible extensions of the Standard Model. Discovery limits for other phenomena are summarized below, assuming an integrated luminosity of 100 fb^{-1}. For more details the reader is referred to Refs. [1, 2].

- Technicolor resonances can be searched for in their decays to a pair of gauge bosons, or to a techi-pion and a gauge boson. The sensitivity for these resonances extends up to the TeV range. Although the technicolor parameter space is very large, there is a number of potential channels which allow for combinations of signatures to help in understanding the nature of the resonances.

- Excited quarks should be detected up to masses in the order of 5–6 TeV$/c^2$.

- The discovery potential for first generation leptoquarks extends up to $\sim$1.5 TeV$/c^2$ (assuming BR(LQ$\rightarrow eq = 0.5$)).

- New vector bosons (W' and Z') should be detectable up to masses in the order of 5–6 TeV/c^2.

- The high mass di-jet angular distribution has an excellent sensitivity to quark compositeness. One month of LHC operation at low luminosity allows discovering quark substructure if the constituent interaction constant is of the order of 14 TeV. An integrated luminosity of 300 fb^{-1} is needed to reach a 95% CL limit of 40 TeV.

9. Conclusions

The ATLAS and CMS experiments at the LHC in their final layout and optimization are well matched to search for physics beyond the Standard Model and to investigate the nature of electroweak symmetry breaking. The large event samples, which will be produced at the LHC for many physics processes, will allow in addition to perform precison measurements of important parameters of the Standard Model. Both the precision measurements and the searches can already be addressed in the ongoing Run II at the Tevatron.

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