Early physics results

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For the past year, experiments at the Large Hadron Collider (LHC) have started exploring physics at the high-energy frontier. Thanks to the superb turn-on of the LHC, a rich harvest of initial physics results have already been obtained by the two general-purpose experiments A Toroidal LHC Apparatus (ATLAS) and the Compact Muon Solenoid (CMS), which are the subject of this report. The initial data have allowed a test, at the highest collision energies ever reached in a laboratory, of the Standard Model (SM) of elementary particles, and to make early searches Beyond the Standard Model (BSM). Significant results have already been obtained in the search for the Higgs boson, which would establish the postulated electro-weak symmetry breaking mechanism in the SM, as well as for BSM physics such as Supersymmetry (SUSY), heavy new particles, quark compositeness and others. The important, and successful, SM physics measurements are giving confidence that the experiments are in good shape for their journey into the uncharted territory of new physics anticipated at the LHC.

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1. Introduction

The first high-energy proton–proton (pp) collisions (3.5 + 3.5 TeV) at the LHC were registered on 30 March 2010, and since then the machine has operated in a superb way, providing the two general-purpose experiments A Toroidal LHC Apparatus (ATLAS) and the Compact Muon Solenoid (CMS) with data samples corresponding to an integrated luminosity of close to 50 pb$^{-1}$ during the pp running period in 2010. The two experiments have recorded collision data in a very effective way, reaching data-taking efficiencies of up to 94 per cent for the luminosity delivered by the LHC in stable conditions. Owing to a very careful and rather complete commissioning of the experiments over several years with cosmic ray data, and with the lower energy LHC collision data accumulated at the end of 2009 during the initial LHC operation, ATLAS and CMS were able to quickly produce a rich harvest of early physics results, within a few months after this running period. In fact, together they have published more than 80 papers in scientific journals up to this Discussion Meeting.

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One contribution of 15 to a Discussion Meeting Issue ‘Physics at the high-energy frontier: the Large Hadron Collider project’.
It would be impossible to review all these results; necessarily a very restrictive selection had to be made, in the spirit of giving illustrative examples. In the same spirit, an arbitrary choice is often made between ATLAS and CMS results, in general representing achievements of both. It can certainly be noted that both experiments perform well within the expectations. The results will be presented roughly speaking following a pattern of decreasing cross sections. This will naturally first lead to measurements of the known Standard Model (SM) particles, of which the top quark is the heaviest known, with the smallest cross section. All SM measurements, already with considerable accuracies and details, agree so far with the most sophisticated theoretical expectations. The status of the search for the still missing element of the SM, the Higgs boson as the messenger of the electro-weak symmetry breaking mechanism will be discussed next. Finally, several examples of searches and resulting new limits on various physics processes Beyond the Standard Model (BSM) will be reported, mostly involving heavy new particles with small production cross sections. For the searches, the exploration at the LHC has only just begun, as much larger data samples are anticipated for the future, once the integrated luminosity will have reached the expected 100-fold increase at the end of 2012, and further on also with the full LHC collision energy of $7 + 7$ TeV for the years 2014 and beyond.

2. General event properties

The experiments have collected large samples of the so-called minimum bias events (ordinary collision events without, or at most very minimal, selection criteria) in order to study general event properties. These properties are interesting in their own right as the physics of soft hadronic interactions (soft quantum chromo dynamics (QCD)), and an understanding of them is a crucial input to the modelling of background events for any measurements and searches of SM and BSM physics processes. The minimum bias events allowed the experiments also to verify in great detail that the average detector responses are well described in the Monte Carlo (MC) simulations, and that the detector elements are well aligned and calibrated, most convincingly demonstrated by the reconstruction and measurement of many well-known resonances, yielding the expected mass values and resolutions.

Charged particle production properties measured by ATLAS [1] over the central region in 7 TeV centre-of-mass pp collisions are shown in figure 1. The central region is expressed as $|\eta| < 2.5$, where $\eta$ is the pseudorapidity defined in terms of the polar angle $\theta$ with respect to the beam axis as $\eta = -\ln \tan (\theta/2)$. Figure 1a shows the number of charged particles (multiplicities) per unit $\eta$, and figure 1b displays the transverse momentum $p_T$ distribution with regard to the beam axis. Both measurements are compared with various MC model simulations before tuning of the latter, and as can be seen, in particular from the MC over data ratio plots, the model descriptions require adjustments to better represent the measurement.

The total charged particle multiplicities and the average charged particle density for the central $\eta$ region is shown in figure 2a,b from the CMS measurements [2,3] at all three centre-of-mass energies for which the LHC has.
Early physics results

Figure 1. (a) Charged particle multiplicity per event and per unit $\eta$, (b) charged particle transverse momentum $p_T$ distribution. The data (circles) are compared with various MC model simulations before tuning of the latter. (Online version in colour.)

Figure 2. (a) Charged particle multiplicities at three different centre-of-mass energies, (b) average charged particle density for the central region as a function of the centre-of-mass energy (including data from other experiments). (Online version in colour.)

been operated so far. The mean multiplicities are observed to increase somewhat faster with the centre-of-mass energy compared with several predictions.

A study of two-particle correlations by CMS [4] has revealed a somewhat unexpected feature that is not reproduced by the present QCD MC simulations. When selecting with a special trigger, a sample of very high-multiplicity events,
an enhancement is observed for pairs of particles on the same azimuth (projected angle measured in the transverse plane to the beam axis), even if largely separated in $\eta$ (i.e. along the beam axis), if these particles fall within a $p_T$ range 1–3 GeV. This subtle effect, which has not yet found a satisfactory explanation, is called by CMS ‘the ridge effect in long-range near-side’ angular correlations.

### 3. Known Standard Model physics

Observing, and measuring accurately at the new collision energies, the known particles from the SM can be considered to be a necessary stepping stone towards exploring the full potential of the LHC with its many promises of possible new physics discoveries. The SM processes are often called ‘standard candles’ for the experiments. However, there is much more value to measure the SM processes than this: never before could the SM physics be studied at a hadron collider with such sophisticated and highly accurate detectors, allowing ultimately a test of detailed predictions of the SM with unprecedented precision and minimal instrumental systematic errors, as already published for some ATLAS and CMS QCD results.

A nice illustration of the global coverage for SM particle detection is given by the di-muon mass spectrum, shown in figure 3 for CMS, which covers the whole mass range from classical low mass resonances over the heavy quark bound states to the $Z$ boson. Dedicated analyses have been published for the $J/\Psi$ and $\Psi'$ signals, which both result from direct production and as decay products from B mesons [5,6], as well as for the differential cross-section measurements of the $Y$ family [7].

The charged and neutral intermediate vector bosons (IVBs) W and Z are the major benchmark measurements at the LHC for demonstrating the excellent detector performance, as well as for testing model predictions to a high degree of accuracy. The $Z$ decays into electrons and muon pairs can be extracted almost free of any backgrounds, as shown in figure 4 from CMS [8] for the invariant mass distribution in the electron channel.
The classical W decay signatures into an electron or a muon and the associated neutrino are an excellent test for the missing transverse energy ($E_T^{\text{miss}}$) performance of the detectors owing to the undetected neutrino. $E_T^{\text{miss}}$ is inferred from the measured energy imbalance in the transverse projection of all observed signals with regard to the beam axis [9]. The ATLAS $E_T^{\text{miss}}$ spectrum for events with a well-identified muon candidate [10] is shown in figure 5a, and shows a clear W signal over the expected background sources. After applying a selection of events with $E_T^{\text{miss}} > 25$ GeV, only a small residual background remains present under the W signal, as indicated in the transverse mass distribution (defined in [10]) given in figure 5b.

The good agreement between the measured and expected cross-section times leptonic decay branching ratios (which is the expected rate for W bosons to be produced and then decay to leptons) is illustrated in figure 6. With the present data samples, the experimental uncertainties still dominate, but with the addition of the 2011 data, the measurements will already constrain the theoretical model parameters. Figure 6a shows the ratio of measurements to predictions from CMS, whereas in figure 6b, the ATLAS W and Z cross-section results are displayed in a two-dimensional plot including their correlated error ellipse, and compared with predictions with various parton distribution functions (describing the quark and gluon momentum distributions inside the protons). Detailed measurements of properties for IVB production and decay at the LHC have been published already, including, for example, the lepton charge asymmetry measurements for W decays [11,12], which were an important signature of the electro-weak nature of the W at the time of their discovery some 30 years ago.

Hard collisions (characterized by having final state particles with significant transverse energy) at the LHC are dominated by the production of high transverse momentum jets, which are the collimated sprays of particles from the

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Figure 4. (a) The electron-pair mass distributions in the Z mass region on a linear and (b) logarithmic vertical scale. The estimated small background contributions are indicated, as well as the expected signal shape from MC simulations. (Online version in colour.)
Figure 5. (a) Missing transverse energy distribution for events with a muon candidate. (b) Transverse mass distribution for W events selected further with a cut on the $E_T^{\text{miss}}$ (see text). The expected background contributions are also indicated. (Online version in colour.)

Figure 6. (a) Ratio of measured cross-section times branching ratios to the theory expectation for the various processes indicated and (b) correlation of the measured (solid circle) leptonic W and Z cross section when compared with theoretical expectations with various choices for the parton distribution functions (open circles). (Online version in colour.)
hadronization of the initially scattered partons (quarks and gluons) in the colliding protons. At work is the strong interaction described by QCD. Most commonly, two jets emerge at opposite azimuth with balanced transverse momenta, from an initial lowest order parton–parton scattering process. However, higher order QCD corrections alter this picture significantly, and detailed measurements of multi-jet configurations are very important to constrain the QCD descriptions of hadronic processes.

The most impressive results at this stage are the inclusive jet and the di-jet cross-section measurements [13,14]; examples for these are shown in figure 7. These measurements cover unprecedented kinematical ranges spanning typically over jet transverse momenta from 20 GeV to 1.5 TeV, in many angular bins up to $|\eta| < 4.4$ (i.e. very close to the beam axis). The cross sections vary over these ranges by up to 12 orders of magnitude. In general, the agreement with perturbative QCD calculations including next to leading order (NLO) corrections is good within the systematic uncertainties. This cannot be seen in figure 7 directly, only in ratio plots of measurement/theory for a given $\eta$-interval. The systematic uncertainties in the ratios are typically only 30 per cent, which is a great achievement compared with previous such measurements. The systematic uncertainties on the measurements are dominated by the jet energy scale uncertainty (calibration of the detectors for the energy of jets) that, owing to a considerable effort, has been determined to typically better than 3 per cent [15].

Figure 7. (a) Inclusive jet and (b) di-jet cross-sections, compared with NLO perturbative QCD predictions. (Online version in colour.)
Jets can also be produced together with W and Z bosons, the so-called QCD corrections to the IVB production. First results of these processes have been published by both experiments [16,17]. A good understanding of them is particularly important as they are, in many cases, a dominant source of backgrounds to the search for new particles, as well as to the measurements of top quark production discussed next.

The heaviest known particle in the SM is the top quark with its roughly 175 GeV mass. It decays almost exclusively into a W and a bottom quark. The measurement of top quark pair production typically requests that at least one of the W decays leptonically (also needed to trigger the events), and therefore the final states require one or two leptons (electrons or muons), $E_{T}^{miss}$ and jets, some of which, coming from the b-quarks, can be tagged by the displaced secondary vertices due the finite lifetimes of b-hadrons. While it is beyond the scope of this report to describe the sophisticated analyses employed, the message is that there are clear top pair signals in ATLAS [18] and CMS [19,20], both in the single and two-lepton channels, when considering the correct jet topologies. The resulting cross sections are shown in figure 8, which also illustrates the expected large rise of the cross section with the collision energy increase from 2 TeV at the TeVatron to 7 TeV at the LHC. Good agreement with NLO QCD calculations is seen within the present 10 per cent measurement errors. It can be mentioned that both experiments have also reported first single top observations (events with just one top quark) at a rate in agreement with QCD expectations.

4. The hunt for the Higgs boson

The search for the Higgs boson $H$, as the decisive manifestation of the Brout, Englert and Higgs mechanism for electro-weak symmetry breaking, postulated in 1961, was one of the major motivations for initiating the LHC project more than...
Early physics results

Projected 95% CL limit on $\sigma/\sigma_{SM}$

Figure 9. Sensitivity for the H searches at the LHC for different running scenarios in 2011/2012 (see text). (Online version in colour.)

25 years ago. The ability to detect it unambiguously over the full possible mass range from its lower experimental limit of 114 GeV (set at the Large Electron Positron collider (LEP)) up to 1 TeV, with very different favoured final states (decay modes) at different masses, was the major benchmark in the conception of the ATLAS and CMS detector designs [9].

The most stringent limits at hadron colliders are set today by the combined Higgs search results from the TeVatron experiments Collider Detector at Fermilab (CDF) and D0, excluding at 95% confidence level (CL), the mass range 157–173 GeV. This is achieved by combining searches for an excess of events over the SM backgrounds in several Higgs decay channels, but dominated in this mass range by $H \rightarrow W^+W^-$ decays, with the Ws decaying in turn leptonically (electron, or muon plus neutrino channel). ATLAS and CMS have recently presented their searches in this channel where they reach highest sensitivity for the 2010 data [21,22]. The data do not yet allow exclusion of, and therefore even less to establish, an SM H signal. Both experiments reached, with the 2010 data, a sensitivity (at 95% CL) for cross sections of a factor 2.1 above the SM for an H with a mass of 160 GeV.

However, the prospects for significant results in the Higgs search in the near future are very promising, as the LHC performance is ramping up rapidly for the 2011/2012 running period. A summary of the expected sensitivities is given in figure 9 for both experiments. The figure shows, for different running scenarios, the sensitivities expressed as the anticipated experimental 95% CL upper cross-section limits normalized to the predicted theoretical SM cross section, as a function of the H mass. If this ratio is below unity, the SM H can be excluded with at least this CL.

Highest sensitivity would be achieved by combining the individual ATLAS and CMS search results. For example, using an integrated luminosity of 5 fb$^{-1}$ (well within the potential of the LHC for the current running period [23]) gives a 95% CL exclusion over the full mass range above the LEP limit from 114 to 600 GeV, and more excitingly a 5 s.d. discovery sensitivity from 128 to 482 GeV. It
should be noted that a discovery in the very low mass region just above 114 GeV, which is favoured by SM predictions taking into account a large variety of lower energy experimental precision measurements [24], may well require data samples in excess of 10 fb$^{-1}$ at the LHC.

5. Searches for physics beyond the Standard Model

In addition to the quest to elucidate the mechanism of the electro-weak symmetry breaking by searching for the Higgs boson, the major excitement for the LHC comes from the great potential to explore uncharted territory of physics BSM [25], owing to its highest collision energy available in the laboratory. Since the beginning of the project, the search for Supersymmetry (SUSY) was a strong motivation, and besides the H boson, it has been the other benchmark physics guiding the detector designs [9]. However, many other hypothetical new processes can be searched for, and indeed ATLAS and CMS have already reported in many publications a very broad spectrum of searches for signatures of such processes (mass peaks for new particles or kinematical distributions with deviations from the expectations of known physics) for BSM physics. No such effect has yet been found, but all of these searches result in new exclusion limits, often well beyond the 1 TeV scale already. Only a few examples are shown in the following.

The most popular searches concern SUSY, which predicts additional fundamental particles. The search for SUSY is motivated in part by the prospect that the lightest stable neutral SUSY particle (LSP) could be an excellent candidate for explaining the dark matter (DM) in the Universe [25]. The mysterious existence of DM was postulated by Zwicky, and rather convincingly evidenced by Rubin, both astronomers, in the 1930s and 1970s, respectively. The SUSY searches at the LHC are very complex as they must be sensitive to many (model-dependent) decay chains, implying a large variety of possible final-state topologies. A common feature for most of them is the existence of significant missing transverse energy, $E_{T}^{\text{miss}}$, owing to the escaping LSPs (an experimental signature similar to that of the neutrinos in the W decays). Furthermore, the SUSY signatures include high transverse momentum jets, some tagged as B-jets for third-generation squarks, and leptons. The expected topologies depend not only on the model parameters, but also on the mass relations between squarks and gluinos (the SUSY partners of the SM quarks and the gluons).

As an illustration of the typical data in the SUSY searches, figure 10 shows the $E_{T}^{\text{miss}}$ distributions from ATLAS [26] for a search for SUSY in events with at least two jets, $E_{T}^{\text{miss}}$ and no lepton. The distributions are shown in figure 10a for a background control region that is enhanced with QCD multi-jet events having only minimal contributions from a possible signal, and in figure 10b for a kinematical region where the signal would be strongest. In both distributions, an expected signal for certain SUSY parameters is indicated by the dashed histogram, over the various SM backgrounds. The figure shows that the data are perfectly described at this stage with the background distributions only.

The data can then be used to extract 95% CL upper limits for the number of observable events and cross sections independently of new physics models, in the background-only hypothesis. These cross-section limits in turn can be
translated into lower limits for SUSY particle masses in SUSY models for a given set of model parameters. It is customary to represent the limits in a parameter plane correlating scalar ($m_0$) masses versus gaugino ($m_{1/2}$) masses of SUSY representations. Such a plane is shown in figure 11 for the analysis combining zero and one lepton in the final state in ATLAS, and very similar results are available from CMS [27]. All mass values smaller than indicated by the experimental limit are excluded by the data at 95% CL. It can be noted that the LHC results already extend significantly the search range from previous experiments. In this particular example, and assuming equal squark and gluino masses, their lower mass bound is 815 GeV at 95% CL. In a simplified model with only first- and second-generation squarks, gluinos and massless neutralinos, the corresponding exclusion would be 870 GeV. It is expected that the 1 TeV range will be quickly reached within the current LHC running, and ultimately, the LHC will be able to discover such particles up to about 2.5 TeV mass.

Classical searches for BSM physics include the exploration of IVB-like signatures in the high-mass range made kinematically accessible by the high collision energy of the LHC. The searches for hypothetical heavy $W'$ and $Z'$ particles is rather straightforward in the lepton-pair and lepton-neutrino decay channels, extending in mass coverage the SM IVB analyses mentioned previously. Such heavy resonances arise in a variety of models mostly related to hypothetical new forces, either with the same properties as the SM IVBs, in this case called

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sequential (and labelled as SSM), or in other models as referenced in the ATLAS and CMS publications reporting their first result [28–31]. As examples of such searches, figure 12 shows the $Z'$ and $W'$ data distributions superimposed with the expected signals for various IVB' masses. The absence of a signal in the data can be translated into 95% CL cross-section limits that are confronted with the expected theoretical cross sections as a function of the mass of the new particles in order to establish lower mass limits. At this stage, this typically leads to 95% CL lower limits for $Z'$ and $W'$ of 1.1 and 1.6 TeV, respectively. Ultimately, with the LHC running for several years at 14 TeV collision energy, the experiments will explore masses up to the order of 5 TeV for such particles.

Excited heavy quarks ($q^*$), axigluons (massive gluons) or other objects are predicted in various models that would decay into a pair of partons, manifesting themselves as resonances in the final state di-jet mass distributions above the SM QCD spectrum. Searches for such di-jet resonances have been published by both ATLAS [32] and CMS [33], and figure 13 shows an example of how well

Figure 11. Example of an exclusion contour in a SUSY parameter plane of scalar ($m_0$) mass versus gaugino ($m_{1/2}$) mass. Lower mass values than indicated by the solid line are excluded at 95% CL for the choice of SUSY model indicated. Results from previous experiments are also indicated at lower masses. (Online version in colour.)
Figure 12. Examples of (a) the di-muon mass distribution and (b) the electron–neutrino transverse mass distribution for the searches of heavy $Z'$ and $W'$ particles. The data are compatible with the SM backgrounds, the expected signals from hypothetical SSM signals are also indicated (see text). (Online version in colour.)

Figure 13. Example of a search for a resonance mass peak over the smooth QCD di-jet mass spectrum. The expected signal contributions for several $q^*$ masses are also indicated. (Online version in colour.)
the data are actually described by the smooth QCD spectrum, allowing both experiments to exclude at 95% CL typically $q^*$ with masses below 2.6 TeV and axigluons below 2.1 TeV.

Of great interest at this new energy frontier are also searches for a possible substructure of the quarks related to a new super-strong interaction. Such a substructure, called compositeness at a scale $L$, could manifest itself by deviations from QCD in the angular distribution of high-momentum transfer, large-angle scatterings, in analogy to the famous Rutherford scattering experiment some 100 years ago. No deviations have been observed so far, neither by ATLAS [32] nor by CMS [34], setting 95% CL lower limits on $L$ around 7 TeV, significantly higher than in previous experiments. Another possibility would be the formation of new bound states containing both quark and lepton properties that would decay into quarks (resulting in jets) and leptons, the so-called lepto-quarks. New limits on their existence have been established in dedicated searches.

As a last example of exploring BSM physics, one can note various searches for effects predicted in models with extra dimensions of space (extra-dimension models). Signals of massive Kaluza–Klein Graviton excitations could occur in di-lepton, di-photon and di-jet final states [25]. ATLAS and CMS have searched in all these channels for resonances but so far found none; the data are fully compatible with the SM physics rates. It would be beyond the scope of this short summary to report a broad variety of limits that can be set for various models. Another prediction from specific models with large extra dimensions is the formation of microscopic black holes (BHs), which would undergo immediate

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Figure 14. Distribution of the scalar sum of the transverse energy for five or more objects in the search for microscopic BHs. The data are compatible with the background shape, excluding the indicated effects of hypothetical BH decays, as indicated for three different parameter choices. (Online version in colour.)
Hawking radiation into many ‘objects’ (jets, leptons and photons), yielding events with rather spectacular final states. Such a direct search for multi-object events is shown in figure 14 from CMS [35], where the data for $N = 5$ or more objects are plotted as a function of the scalar sum of the transverse energy for $N$ objects in the events. The data follow the shape of the SM background well, and none of the predicted enhancements for various BH masses is observed as indicated in the figure. This translates at this stage into lower limits for BHs of typically 4 TeV with model parameters specified in the CMS Collaboration [35].

6. Conclusions

After only 1 year of high-energy operation of the LHC, the general-purpose experiments of ATLAS and CMS, as well as A Large Ion Collider Experiment (ALICE) [36] and the Large Hadron Collider beauty experiment (LHCb) [37] reported in separate contributions to this meeting, have already produced a very rich harvest of physics results. This should, in the first instance, be seen as a success of the overall LHC project with its three major components having worked in an extraordinary coherent way so early on: the collider, the experiments and the novel computing grid structure, the worldwide LHC computing grid (wLCG) [38].

ATLAS and CMS have already amply demonstrated that they master the analyses of SM physics, and have brought many SM measurements into domains of details and a degree of sophistication unprecedented at lower energy machines, which are a challenge for accurate theoretical descriptions. The early SM results also demonstrate that the experiments are well understood and operate at full potential to attack the main goals of the LHC, namely to make the conclusive investigations of the electro-weak symmetry breaking mechanism, i.e. establish the existence, or otherwise, of the Higgs boson, and explore the physics BSM. The searches for BSM physics are already in full swing, thanks to the superb start-up of the collider. One should remain aware, however, that the full physics potential will only become available in future years with the machine reaching its full design luminosity and energy. But there is no doubt: particle physics has exciting times ahead with the LHC project now operational.

References


8 CMS Collaboration. 2010 Measurement of the inclusive W and Z production cross sections at $\sqrt{s} = 7$ TeV with the CMS experiment at the LHC. (http://arxiv.org/abs/1107.4789)


10 ATLAS Collaboration. 2011 A measurement of the total $W^\pm$ and $Z/\gamma^*$ cross sections in the $e$ and $\mu$ decay channels and of their ratios in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. ATLAS-CONF-2011-041, CERN, Geneva, Switzerland.


25 ATLAS Collaboration. 2011 Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector at $\sqrt{s} = 7$ TeV. ATLAS-CONF-2011-005, CERN, Geneva, Switzerland.


