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HIGHLIGHTS FROM ATLAS

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Summary
For the past two years, 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 already a rich harvest of initial physics results have been obtained by the general purpose experiment ATLAS, as well as its sister-experiment CMS. The initial data has 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 like Supersymmetry (SUSY), heavy new particles, quark compositeness, and others. The important, and successful, SM physics measurements are giving confidence that the experiment is in good shape for their journey into the uncharted territory of new physics anticipated at the LHC.

Key index words
LHC, ATLAS experiment, experimental Standard Model measurements, and experimental searches for physics Beyond the Standard Model.

1. INTRODUCTION

The first high-energy proton-proton collisions (3.5 + 3.5 TeV) at the LHC were registered on 30th March 2010, and since then the machine has operated in a superb way, providing the two general-purpose experiments ATLAS and CMS with data samples corresponding to an integrated luminosity of close to 5 fb^{-1} during the pp running periods in 2010 and 2011. ATLAS has recorded collision data in a very effective way, reaching a data taking efficiency of up about 94% for the luminosity delivered by LHC in stable conditions. Thanks to a very careful and rather complete commissioning of the experiment 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 was able to quickly produce a rich harvest of early physics results. In fact, ATLAS has published more than 80 papers in scientific journals up to this Symposium.

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. 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. Next will be discussed 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. 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 hundredfold 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.

ATLAS is the result of an enormous collaborative effort that already lasts almost two decades including all its phases from conception, design, prototyping, construction, pre-assembling, installation in the underground cavern and commissioning to finally starting up operation with recording the first collisions in November 2009. There is no way that any justice can be given here to this huge scientific, technological and human undertaking; the reader is referred to [1,2] and references therein. Just as an indication of the complexity and how well the apparatus is functioning, one may note that for all different detector layers, totaling about 100 Million electronic read-out channels, typically 98% of channels are working within design specification. The Fig. 1 shows as an example the detector status in February 2007 during the peak period of the installation work.

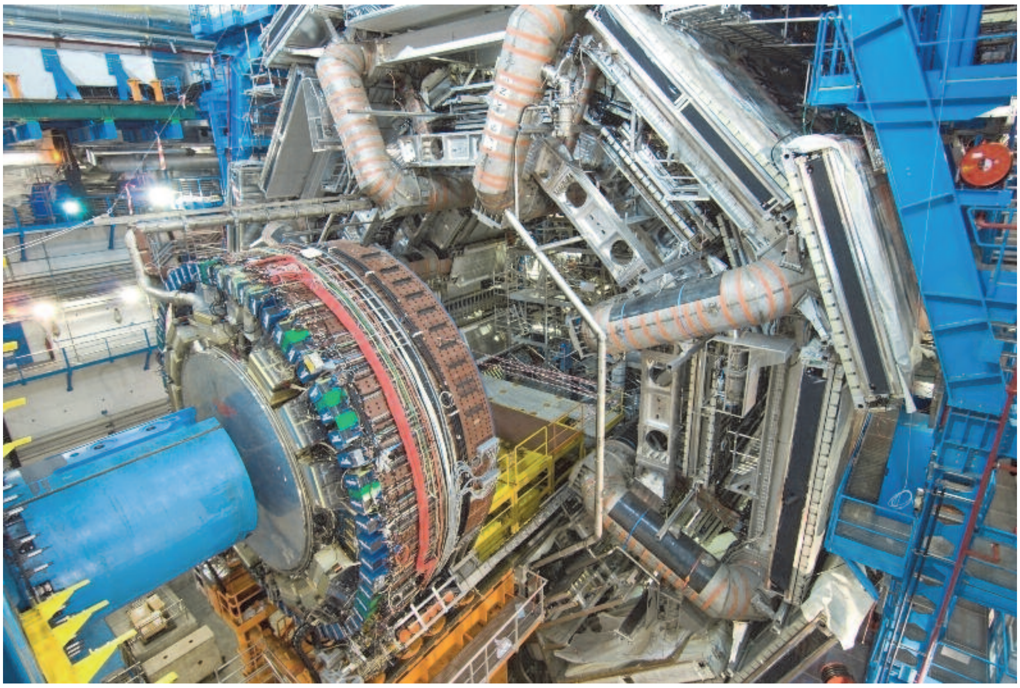

Figure 1. Photograph of one end of the ATLAS detector barrel with the calorimeter end-cap still retracted before its insertion into barrel toroid magnet structure (February 2007 during the installation phase).

The ATLAS Collaboration currently brings together about 3000 scientists in a world-wide common effort from almost 200 Universities and Laboratories located in 38 countries. About one-third of the scientists are students working on their PhD with data accumulated with the ATLAS experiment.

2. GENERAL EVENT PROPERTIES

The experiment has collected large samples of 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 QCD), and an understanding of them is a crucial input to the modeling of background events for any measurements and searches of SM and BSM physics processes. The minimum bias events also allowed the experiments 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 [3] over the central region in 7 TeV centre-of-mass proton-proton collisions are shown as an example in Fig. 2. The central region is expressed as $|\eta| < 2.5$ where η is the pseudorapidity defined in terms of the polar angle θ w.r.t. the beam axis as $\eta = -\ln\tan(\theta/2)$. Figure 2a shows the number of charged particles (multiplicities) per unit η, and Fig. 2b displays the transverse momentum p_T distribution w.r.t. the beam axis. Both measurements are compared with various Monte Carlo (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.

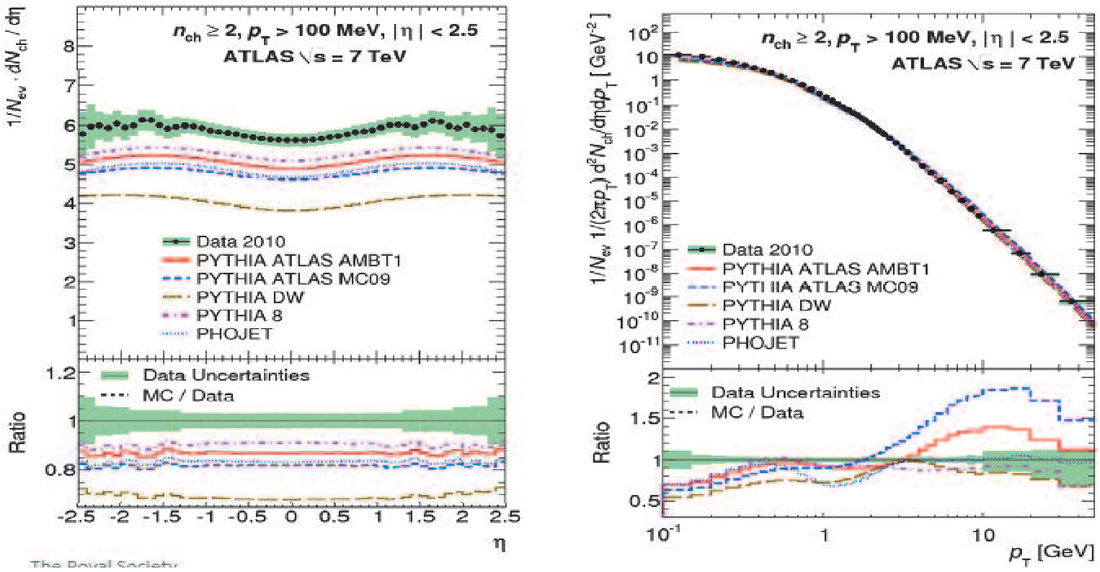

Figure 2. (a, left) Charged particle multiplicity per event and per unit η, (b, right) charged particle transverse momentum p_T distribution. The data (dots) are compared to various MC model simulations before tuning of the latter.

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 measuring the SM processes than this: never before could the SM physics be studied at a hadron collider with such sophisticated and highly accurate detectors, ultimately allowing a test of detailed predictions of the SM with unprecedented precision and minimal instrumental systematic errors, as already published for several ATLAS and CMS QCD results.

The charged and neutral Intermediate Vector Bosons (IVB) W and Z are the major benchmark measurements at the LHC [4] for demonstrating the excellent detector performance, as well as for testing model predictions to a high degree of accuracy. The Z decays into electron and muon pairs can be extracted almost free of any backgrounds, as shown in Fig. 3.

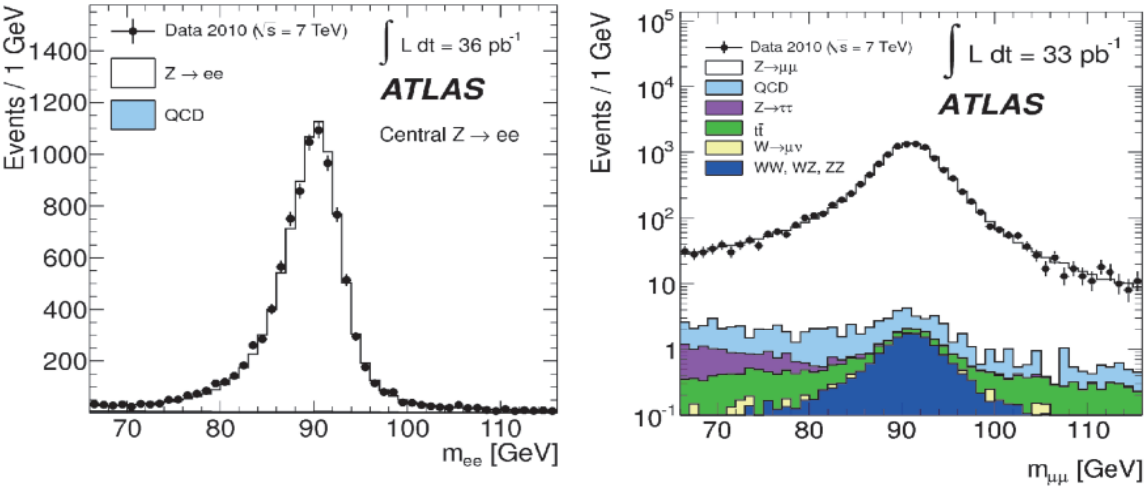

Figure 3. The electron-pair mass distribution on a linear (left) and the muon-pair mass distribution on a logarithmic (right) vertical scale, in the Z mass region. The estimated small background contributions are indicated, as well as the expected signal shape from MC simulations.

The classical W decay signatures into an electron or muon and the associated neutrino are an excellent test for the missing transverse energy (ETmiss) performance of the detector due to the undetected neutrino. ETmiss is inferred from the measured energy imbalance in the transverse projection of all observed signals w.r.t. the beam axis. The ETmiss spectrum for events with a well-identified muon candidate is shown in Fig. 4a, and shows a clear W signal over the expected background sources. After applying a selection of events with ETmiss > 25 GeV only a small residual background remains present under the W signal, as indicated in the transverse mass distribution (defined in [4]) given in Fig. 4b.

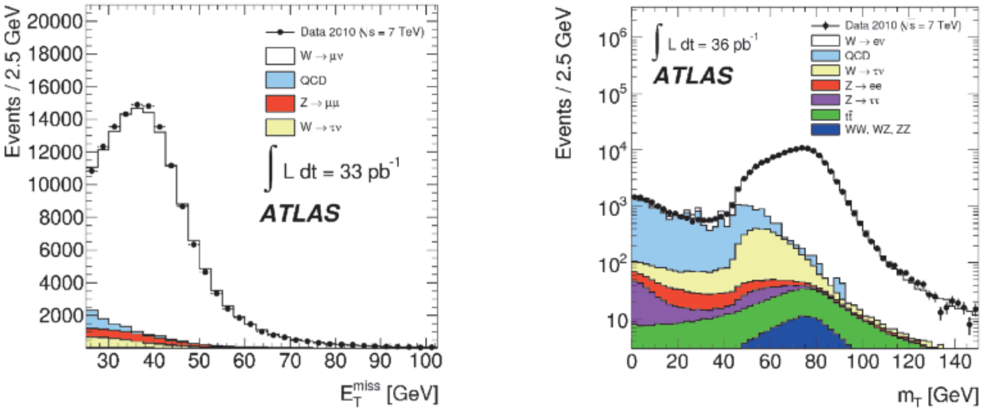

Figure 4. (a, left) Missing transverse energy distribution for events with a muon candidate. (b, right) Transverse mass distribution for W to electron decays before a cut on the transverse mass (see text). The expected background contributions are indicated as well.

The good agreement between the measured and expected cross-sections times the leptonic decay branching ratios (which is the expected rate for W bosons to be produced and then decay to leptons) is illustrated in Fig. 5. 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 5a shows the W cross-section measurements and predictions as a function of the collision energy, whereas in (b) the W and Z cross-section results are displayed in a 2-dimensional plot including their correlated error ellipse, and compared to 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 [4] which were an important signature of the electro-weak nature of the W at the time of their discovery some 30 years ago.

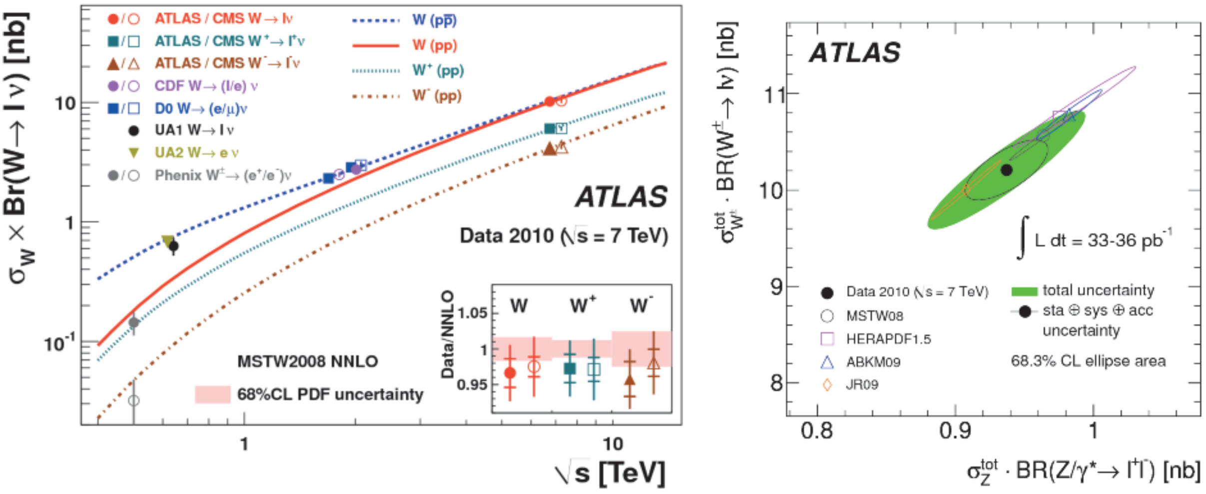

Figure 5. (a, left) W production cross-sections times leptonic branching ratio as a function of the collision energy, showing also previous measurements at lower energy colliders, (b, right) correlation of the measured (solid dot) leptonic W and Z cross-section as compared to theoretical expectations with various choices for the parton distribution functions (open dots).

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 hadronization of the initially scattered partons (quarks, gluons) in the colliding protons. At work is the strong interaction described by Quantum Chromo Dynamics (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 [5]; an example for them is shown in Fig.6a. 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 IηI < 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 well within the systematic uncertainties. This cannot be seen in Fig. 6a directly, only in ratio plots measurement/theory for a given η-interval. The systematic uncertainties in the ratios are typically only 30%, which is a great achievement compared to 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), which thanks to a considerable effort has been determined to typically better than 3% [6]. Another example of precise QCD results is displayed in Fig. 6b where the inclusive single isolated prompt photon cross-section [7] is compared to one of the most advanced QCD calculation.

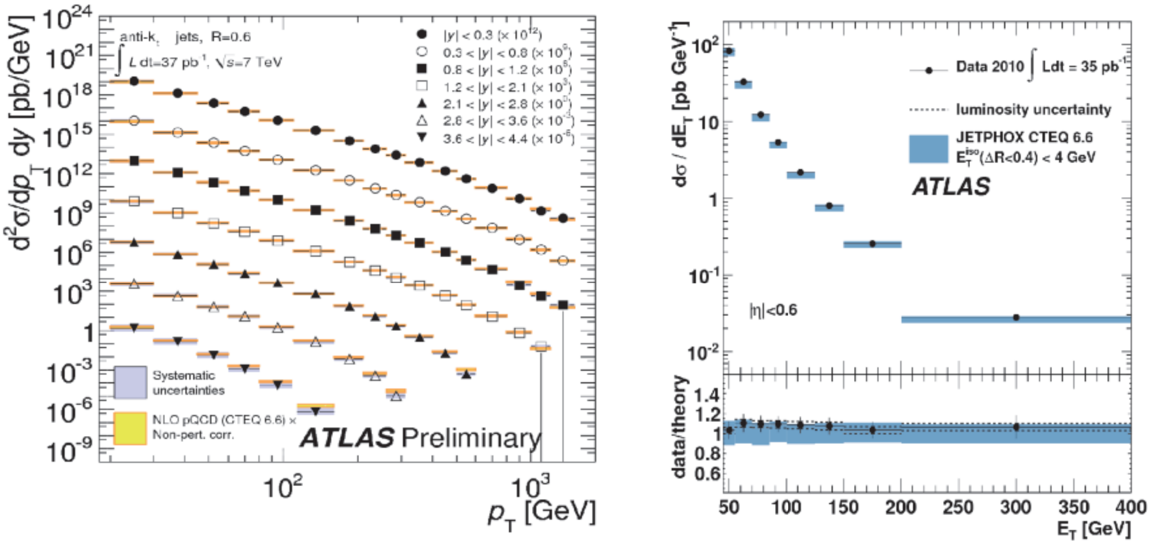

Figure 6. Inclusive jet (a, left) and single isolated prompt photon (b, right) cross-sections, compared to NLO perturbative QCD predictions.

Jets can also be produced together with W and Z bosons, so-called QCD corrections to the Intermediate Vector Boson production. First results of these processes have been published [8]. 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), ETmiss, and jets, some of which, coming from the b-quarks, can be tagged by the displaced secondary vertices due to the finite life times of b-hadrons. Whilst 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 [9], both in the single and two-lepton channels, when considering the correct jet topologies. The resulting cross-sections are shown in Fig. 7 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 7% measurement errors. It can be mentioned that ATLAS has also reported first single top observations (events with just one top quark) at a rate in good agreement with QCD expectations.

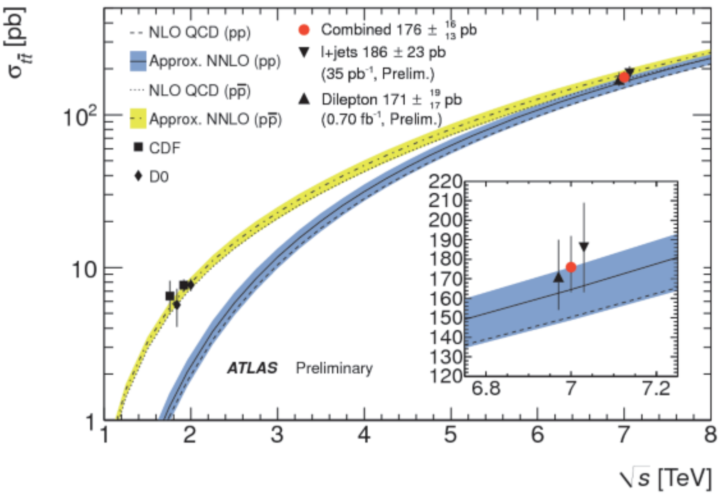

Figure 7. Top pair production cross-section as a function of the collision energy, showing the TeVatron and ATLAS LHC measurements.

A summary of many measurements of interesting Standard Model production cross-sections is given in Fig.8 which includes also the low cross-section processes of IVB pair productions.

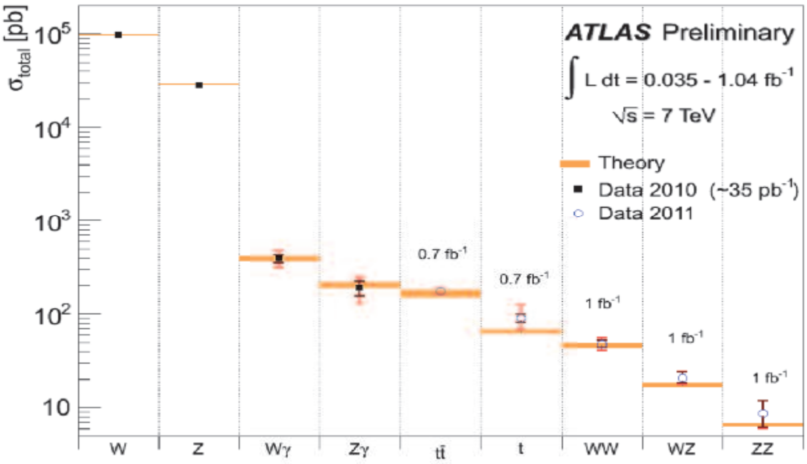

Figure 8. Summary of various Standard Model production cross-sections.

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 already more than 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 LEP collider) up to one 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.

The most stringent limits at hadron colliders were set until spring 2011 by the combined Higgs search results from the TeVatron experiments CDF and D0, excluding at 95% confidence level (CL) the mass range 157 to 173 GeV. This was 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 → W^+W^- decays, with the Ws decaying in turn leptonically (electron, or muon plus neutrino channel). ATLAS and CMS have updated their searches in many channels for the summer conferences, extending the H exclusion limits over a significantly larger mass range.

At the time of this Symposium the public ATLAS Higgs search status [10] corresponded to the results presented at the 2011 International Symposium for Photon Lepton Interactions at High Energies. Two examples are given in Fig. 9. The first (Fig. 9a) shows the relatively straight forward search for a mass peak from the process of the H decaying into two Z's (one might be virtual), which in turn decay into charged lepton pairs (electrons or muons in this figure). The second example (Fig. 9b) displays the search for the H decaying into WW, and each W decaying leptonically into an electron or muon and its associated neutrino. Because of the ETmiss from the neutrinos no mass peak can be reconstructed, only a broad enhancement in the transverse mass of the leptons and ETmiss can be expected. In both cases no excess is observed over the background distributions within the present data samples. The figures also illustrate the expected contributions from a Standard Model H boson.

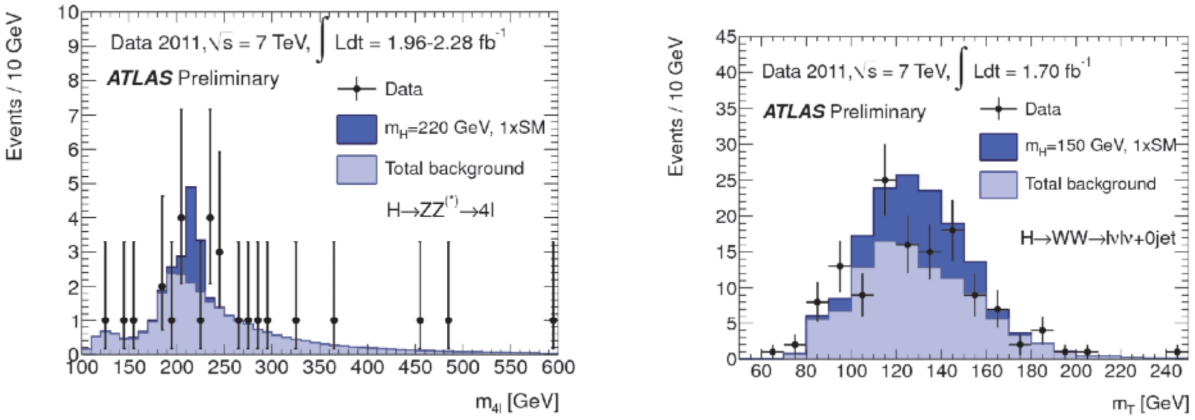

Figure 9. Examples of H search results, (a, left) in the four charged leptons channel and (b, right) in the two charged leptons plus two neutrinos channel (see text).

At this stage, the absence of any significant signal over the backgrounds in the analysis of many channels can be expressed in terms of 95% confidence level (CL) exclusion limits. For a graphical representation this is done in terms of a ratio between the limit cross-sections over the expected Standard Model H cross-sections, as shown in detail for several decay channels in Fig. 10. The mass range for which this ratio is smaller than one is then excluded at the 95% CL. Combining all analysis channels, and taking into account also possible correlations, leads to exclude at 95% CL the SM H boson in the mass ranges 146-232, 256-282 and 296-466 GeV [10].

Note, however, that much progress in the H search can be expected on the basis of already accumulated data, as well as the anticipated date from 2012. A definite statement about the existence or not of a SM H might well be in reach for the end of 2012.

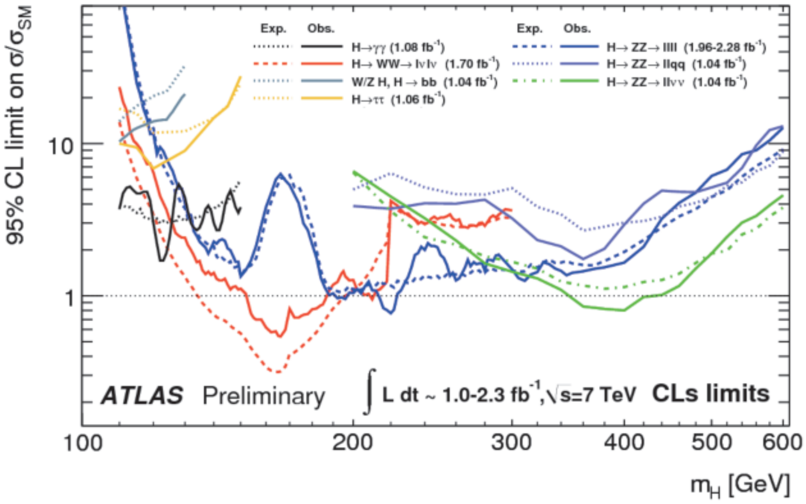

Figure 10. A summary of 95% CL limits, for various Standard Model Higgs search channels separately, as a function of the H mass (see text for explanations).

5. SEARCHES FOR PHYSICS BEYOND THE STANDARD MODEL

Besides the quest to elucidate the mechanism of the electro-weak symmetry breaking by searching for the Higgs boson, the major excitement for LHC comes from the great potential to explore uncharted territory of physics Beyond the Standard Model (BSM), thanks 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. 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 one 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. 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 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, ETmiss, due 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 [11], Fig. 11 shows the effective mass (meff) distributions, defined as scalar sum of ETmiss and all jet transverse momenta, for a search for SUSY in events with at least two jets, ETmiss and no lepton. The distributions are shown in (a) for a background control region which is enhanced with QCD multi-jet events having only minimal contributions from a possible signal, and in (b) 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.

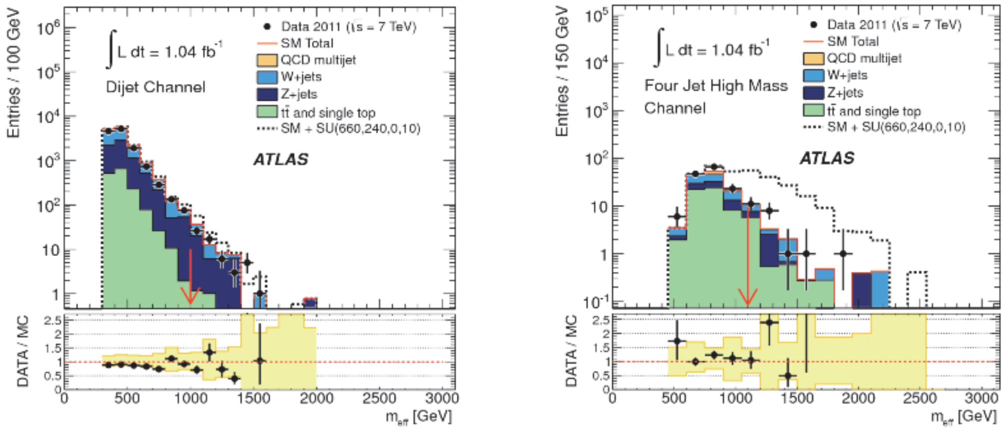

Figure 11. Typical meff distributions for (left) background enhanced and (right) signal enhanced SUSY search regions. A possible SUSY signal is indicated by the dashed histogramme (see text).

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 vs. gaugino ($m_{1/2}$) masses of SUSY representations [11]. The results for a simplified model are shown in Fig. 12 that assume only first- and second- generation squarks, gluinos, and massless neutralinos. 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 1.075 TeV at 95% CL. It is expected that the mass range will be quickly extended within more 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 before. 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 that case called sequential (and labeled as SSM), or in other models as referenced in the ATLAS publications [12].

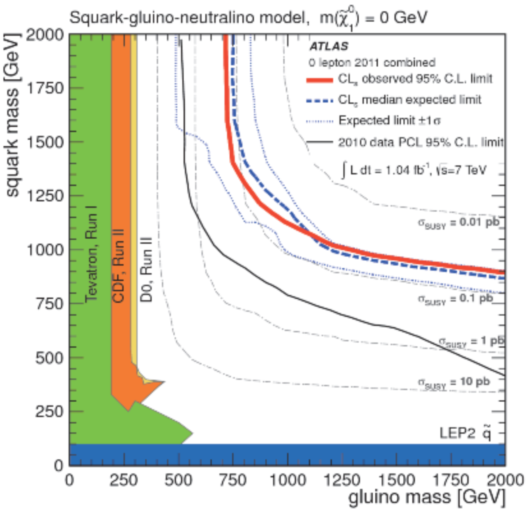

Figure 12. Example of an exclusion contour in a SUSY parameter plane of gluino mass vs. squark mass in the simplified SUSY model mentioned in the text. Lower mass values than indicated by the solid red line are excluded at 95% CL. Results from previous experiments are also indicated at lower masses.

As examples of such searches, Fig. 13 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 1.83 and 2.15 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.

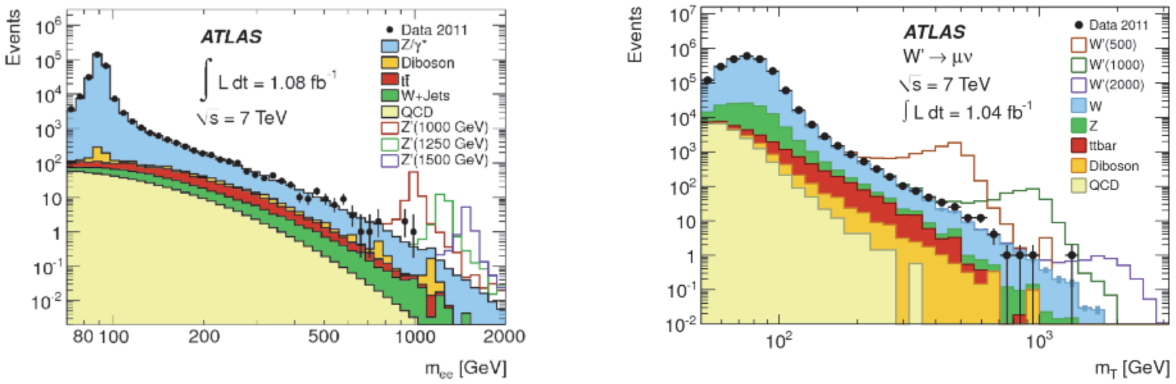

Figure 13. Examples of the di-electron mass distribution (left) and of the muon-neutrino transverse mass distribution (right) for the searches of heavy Z' and W' particles. The data are compatible with the SM backgrounds, the expected signals from hypothetical SSM signals are also indicated (see text).

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 in [13], and Fig. 14 shows an example of how well the data are actually described by the smooth QCD spectrum, allowing ATLAS to exclude at 95% CL typically q* with masses below 3 TeV and axigluons below 3.3 TeV.

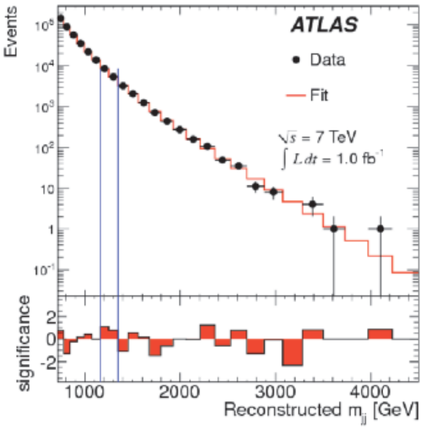

Figure 14. Example of a search for a resonance mass peak over the smooth QCD di-jet mass spectrum.

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 Λ, 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 [14], setting a 95% CL lower limits on Λ at 6.7 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, so-called lepto-quarks. New limits on their existence have been established in dedicated searches.

Many other searches aimed at exploring BSM physics have been conducted, all with finding any excess of event rates over the expected backgrounds from the SM. But in essentially all cases more stringent constraints could be established compared to previous experiments at lower collision energy. A non-exhaustive summary of such 95% CL limits is displayed in Fig. 15.

6. CONCLUSIONS

After only two years of high-energy operation of the LHC, ATLAS (as well as CMS, LHCb and ALICE) has already produced a very rich harvest of physics results. This should in first place 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 wLCG.

ATLAS (as well as CMS) has already amply demonstrated that it masters the analyses of Standard Model physics, and has brought many SM measurements into domains of details and a degree of sophistication unprecedented at lower energy machines, setting a challenge for accurate theoretical descriptions. The early SM results also demonstrate that the experiment is well understood and operates at full potential to attack the main goals of 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 Beyond the Standard Model. The searches for BSM physics are already exploring

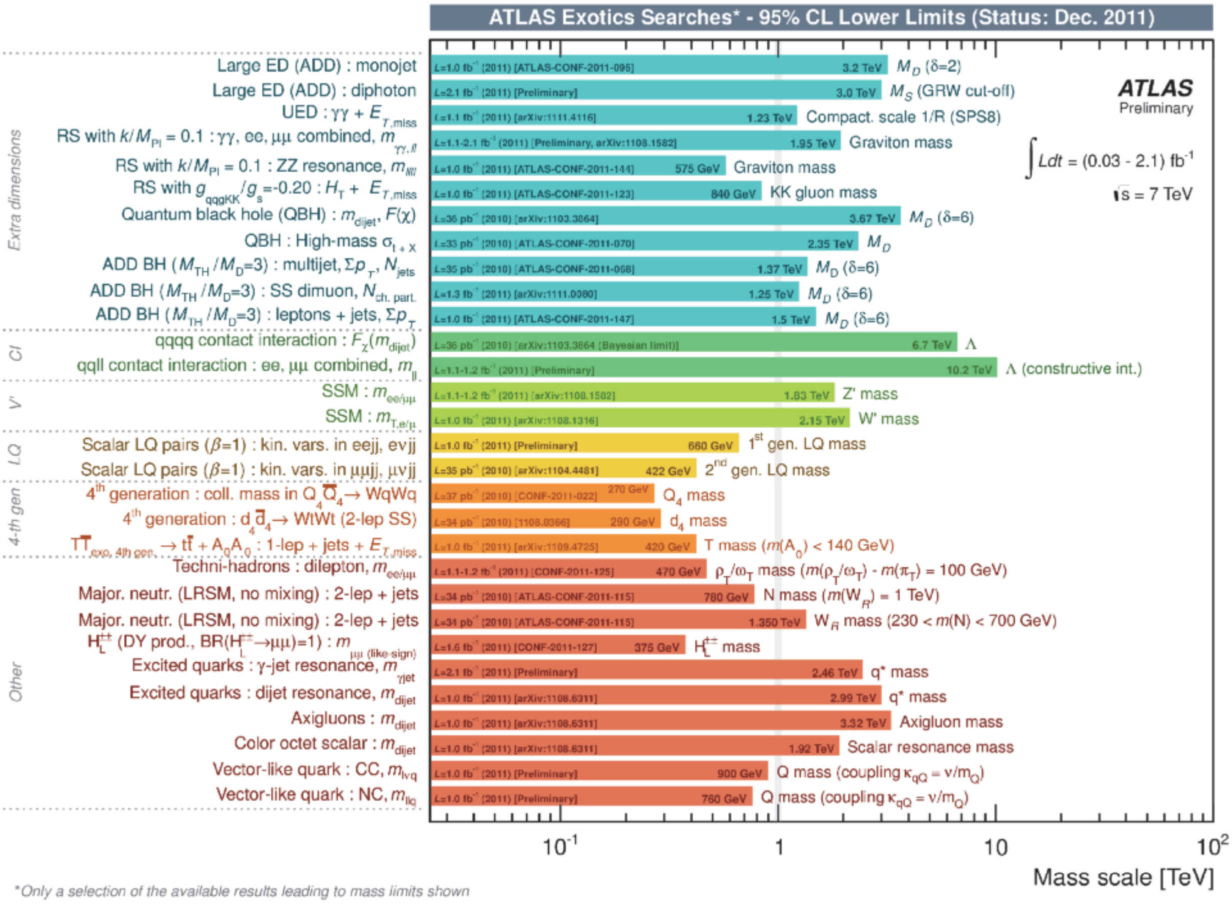

Figure 15. A non-exhaustive summary of 95% CL lower limits established so far on a variety of searches for BSM physics.

unchartered territory, 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.

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