DISCOVERY PHYSICS FROM ATLAS AND CMS AT THE LHC

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For the past two 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 already a rich harvest of initial physics results have been obtained by the two general purpose experiments ATLAS and CMS, which are the subject of these lectures. 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 like Supersymmetry (SUSY), heavy new particles, extra space dimensions, 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 collisions (3.5 + 3.5 TeV) at the LHC were registered on 30th March 2010. 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 5 fb^{-1} during the pp running periods in 2010 and 2011. The two experiments have recorded collision data in a very effective way, reaching data taking efficiencies of up to 94% for the luminosity delivered by LHC in stable conditions. Thanks 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. In fact, together they have published almost 200 papers in scientific journals up to the end of 2011.

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 performed well within the expectations. The results reported in these lectures were presented roughly speaking following a pattern of decreasing cross-sections. This naturally first led 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 was 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. After this first lecture, several examples of searches for various physics processes Beyond the Standard Model (BSM) were covered in detail during the second lecture.

No New Physics has been discovered yet; however the searches all resulted in new limits on the production of postulated heavy particles with small production cross-sections. One has to be well aware that for these exciting BSM searches the exploration at the LHC has only just begun, as much larger data samples are anticipated for the future, and most importantly also after 2014 at the full LHC collision energy of 13-14 TeV.

2. GENERAL EVENT PROPERTIES

The experiments have 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 consist mostly of soft scattering collisions. 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 allowed the experiments also to verify in great detail that the 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.
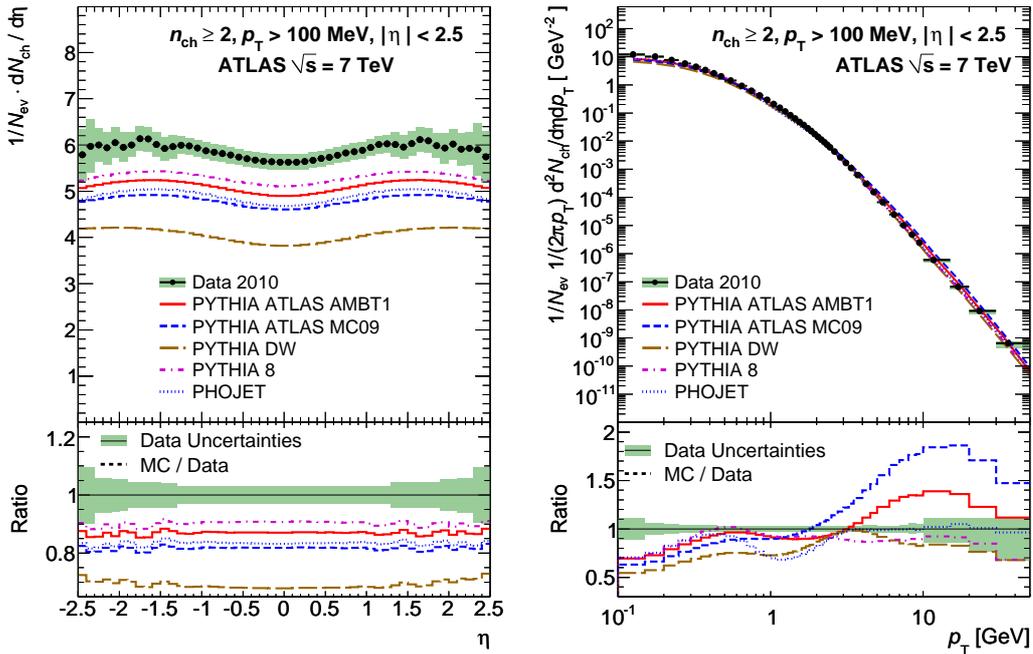
Figure 1: a) Charged particle multiplicity per event and per unit η, (b) charged particle transverse momentum p_T distribution. The data (dots) are compared to various MC model simulations before tuning of the latter.

Charged particle production properties measured by ATLAS[1] over the central region in 7 TeV centre-of-mass proton-proton collisions are shown in Fig. 1. The central region is characterized 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 1a shows the number of charged particles (multiplicities) per unit η, and Fig. 1b 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 required adjustments to better represent the measurement.

The total charged particle multiplicities and the average charged particle density for the central η region is shown in Figs. 2a and 2b from the CMS measurements [2, 3] at all three centre-of-mass energies for which the LHC has been operated so far. The mean multiplicities are observed to increase somewhat faster with the centre-of-mass energy compared to several predictions.

A study of two-particle correlations by CMS [4] has revealed a somewhat unexpected feature which 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 η (i.e. along the beam axis) if these particles fall within a p_T range of 1 to 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.
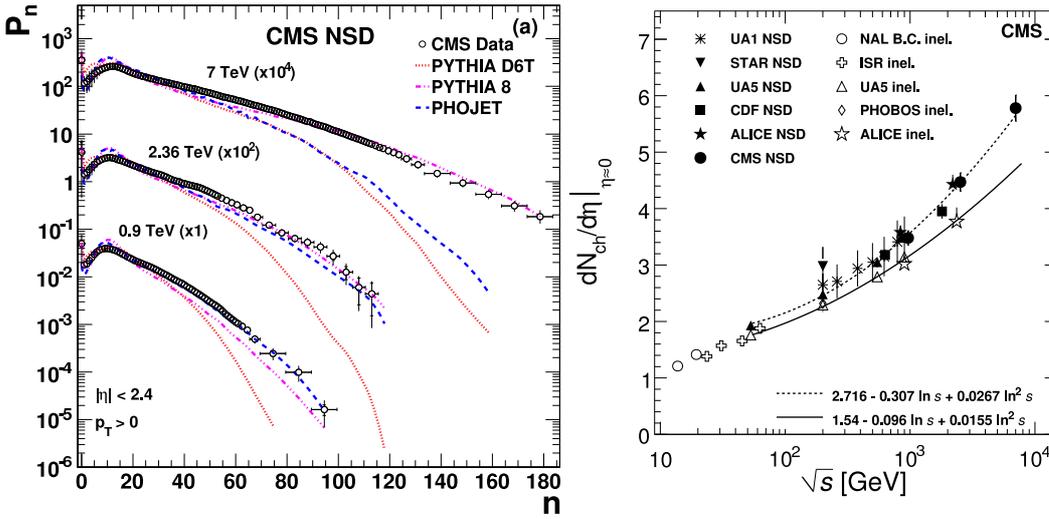
Figure 2: (a) Charged particle multiplicities at three different centre-of-mass energies, (b) average charged particle density for the central region as a function of the centre-of-mass energy (including data from other experiments).

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, 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 Fig. 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/ψ signals, which both result from direct production and as decay products from B mesons [5], as well as for the differential cross-section measurements of the Υ family [6].

The charged and neutral Intermediate Vector Bosons (IVB) 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 electron and muon pairs can be extracted almost free of any backgrounds, as shown in Fig. 4 from CMS [7] for the invariant mass distribution in the electron channel.

The classical W decay signatures into an electron or muon and the associated neutrino is an excellent test for the missing transverse energy (E_T^{miss}) performance of the detectors due to the undetected neutrino. E_T^{miss} is inferred from the measured energy imbalance in the transverse projection of all observed signals w.r.t. the beam axis. The ATLAS transverse mass distribution, defined in [8], for events with a well-identified muon candidate is shown in Fig. 5a, and shows a
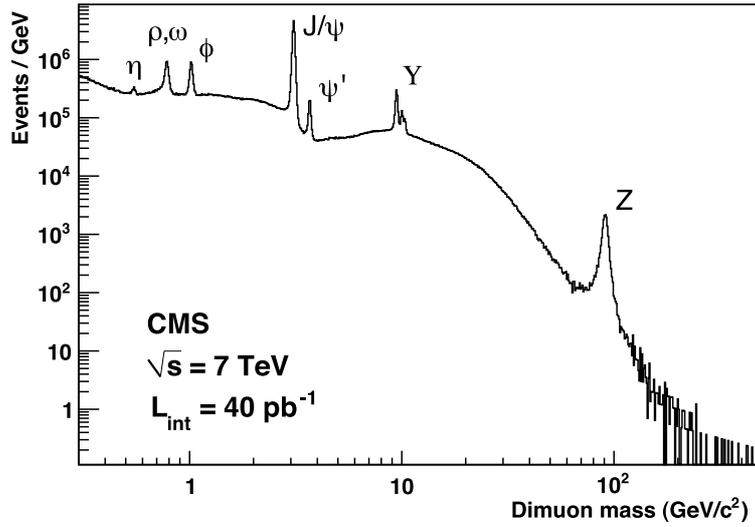
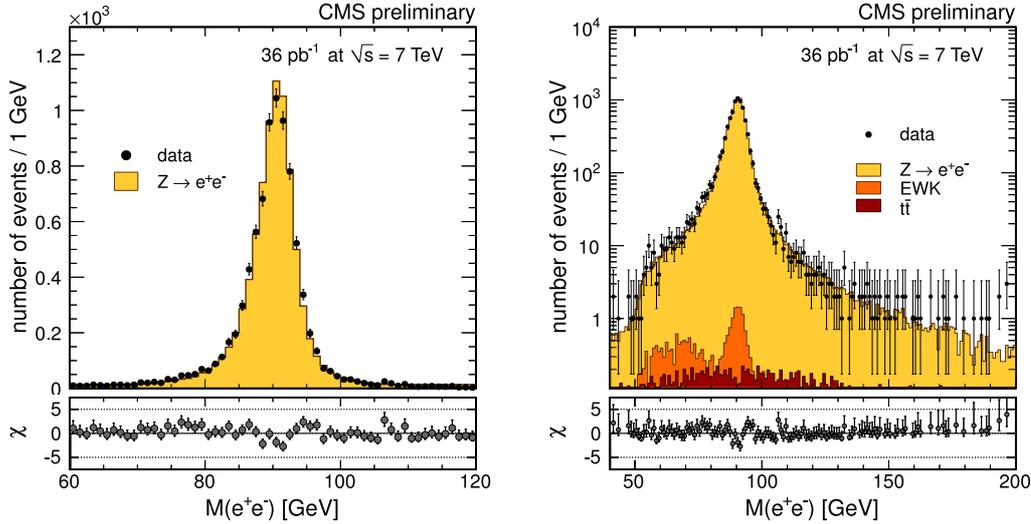**Figure 3:** Di-muon invariant mass spectrum from the full 2010 data set.

Figure 4: The electron-pair mass distributions in the Z mass region on a linear (left) and logarithmic (right) vertical scale. The estimated small background contributions are indicated, as well as the expected signal shape from MC simulations.

clear W signal over the expected background sources. After applying a selection of events with $E_T^{miss} > 25$ GeV only a small residual background remains present under the W signal, as indicated in the distribution given in Fig. 5b.

The good agreement between the measured and expected cross-sections times leptonic decay branching ratios (which is the expected rate for W bosons to be produced and then decay to leptons) is illustrated in Fig. 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 (b) the ATLAS W and Z cross-section results are displayed in a 2-dimensional plot in-
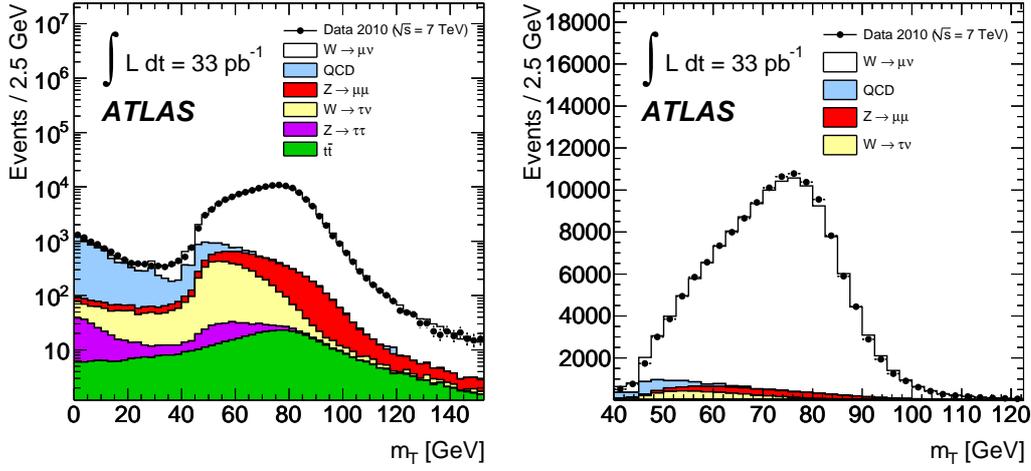
Figure 5: (a) Transverse mass distribution for events with a muon candidate. (b) Transverse mass distribution for W events selected further with a cut on the E_T^{miss} (see text). The expected background contributions are indicated as well.
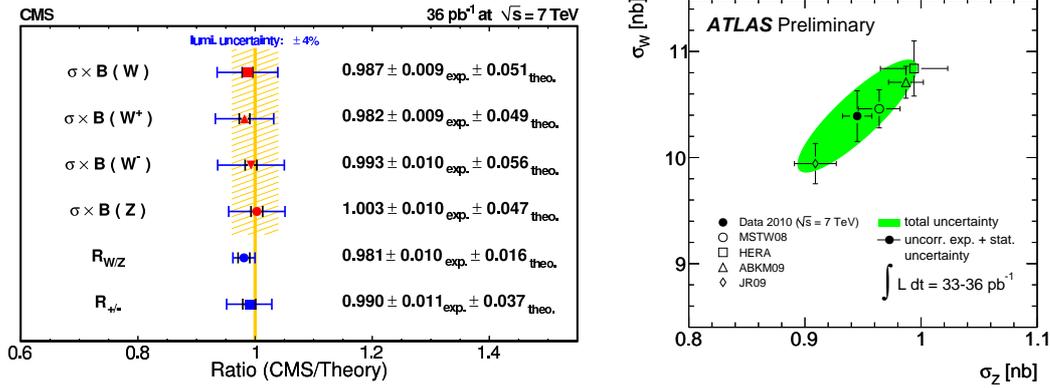

Figure 6: (a) Ratio of measured cross-sections times branching ratios to the theory expectation for the various processes indicated, (b) correlation of the measured (solid dot) leptonic W and Z cross-section as compared to theoretical expectations with various choices for the parton distribution functions (open dots).

cluding 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 [9] 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 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,
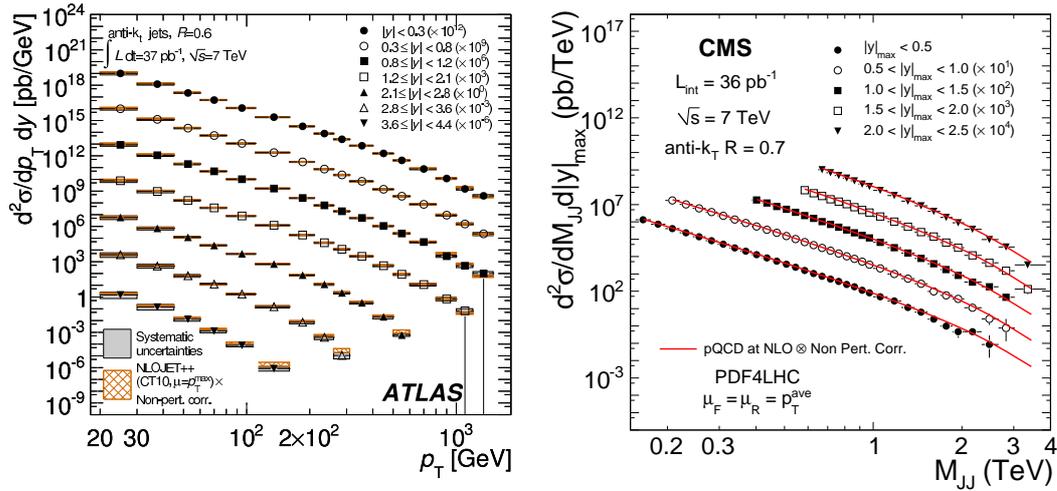
Figure 7: Inclusive jet (left) and di-jet (right) cross-sections, compared to NLO perturbative QCD predictions.

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 [10]; examples for them are shown in Fig.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 well within the systematic uncertainties. This cannot be seen in Fig. 7 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% [11].

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 by both experiments [12]. 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 life times of b-hadrons. Whilst it is beyond the scope of this report to describe the
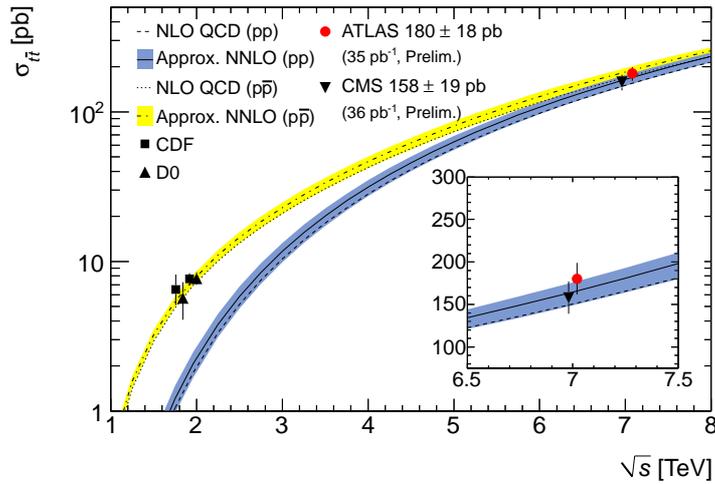
Figure 8: Top pair production cross-section as a function of the collision energy, showing the Tevatron and LHC measurements.

sophisticated analyses employed, the message is that there are clear top pair signals in ATLAS [13] and CMS [14], both in the single and two-lepton channels, when considering the correct jet topologies. The resulting cross-sections are shown in Fig. 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% 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 SM expectations.

Even lower cross-sections are expected for IVB pair productions (WW, WZ and ZZ). Deviations, not observed so far, from the SM cross-section values could reveal indirect hints for BSM physics. Both ATLAS and CMS have produced summary figures illustrating in a nice way the excellent agreement within the present measurement and theory errors of the experimental data with the SM. Figure 9 shows as an example the one from ATLAS. All these results give confidence that the experiments are well understood, and operating reliably to deal with known physics objects. They have demonstrated maturity to enter LHC's main objectives, search for the Higgs boson and for new physics beyond the Standard Model. The results are also of crucial importance in terms of understanding the SM processes as backgrounds to the various searches.

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 1964, 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 114.4 GeV (set at the LEP collider) up to one TeV, with very different favored final states (decay modes) at different masses, was the major benchmark in the conception of the ATLAS and CMS detector designs.
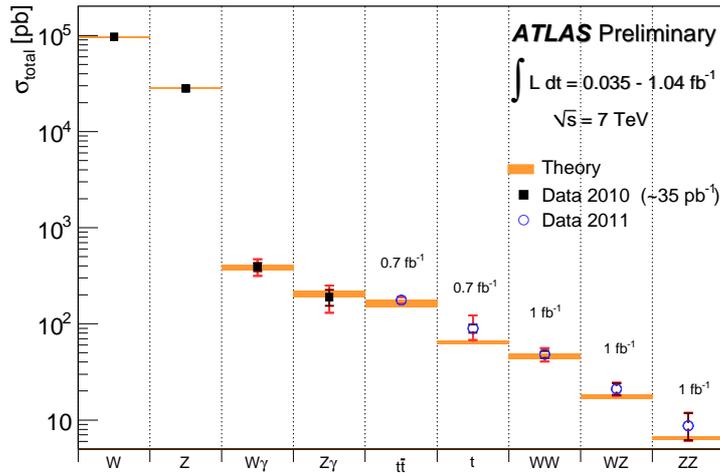
Figure 9: Summary plot showing the measured (points) and expected cross-sections (horizontal bands reflecting the theoretical uncertainties) for a variety of SM processes.
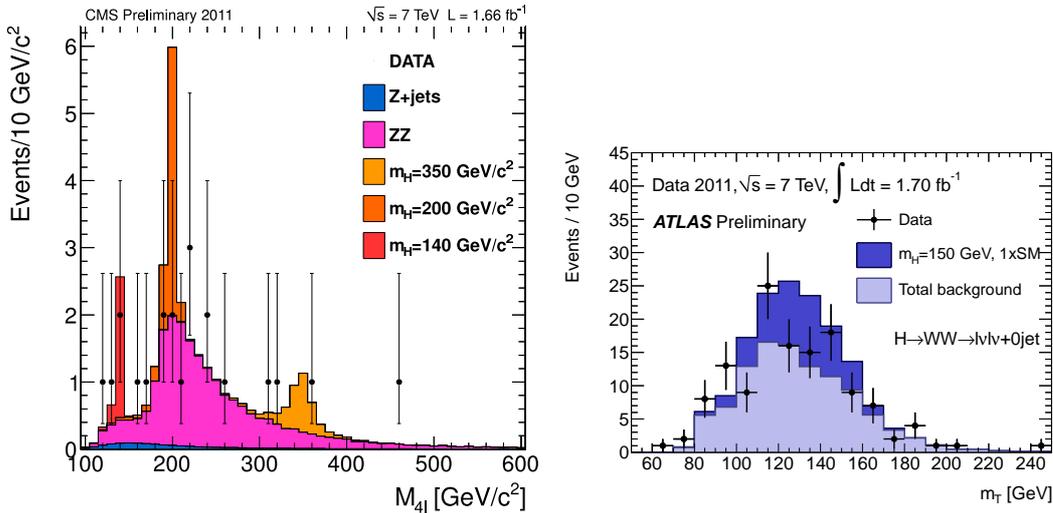

Figure 10: Examples of H search results, (a, left) in the four charged leptons channel and (b, right) in the two charged leptons plus two neutrinos channel (see text).

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 $H \to W^+W^-$ 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 2011 conferences, extending the H exclusion limits over a significantly larger mass range.

At the time of these lectures the public ATLAS and CMS Higgs search status [15, 16] corresponded to the results presented at the 2011 International Symposium for Photon Lepton Interactions at High Energies. Two examples are given in Fig. 10. The first (Fig. 10a) 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. 10b) 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 E_T^{miss} from the neutrinos no mass peak can be reconstructed, only a broad enhancement in the transverse mass of the leptons and E_T^{miss} 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.

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 Higgs cross-sections, as shown in detail for several decay channels in Fig. 11 from ATLAS. 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 Higgs boson in the mass ranges 146-232, 256-282 and 296-466 GeV [15]. Figure 12 shows from CMS their combined 95% CL exclusion limits, excluding in turn the mass ranges 145-216, 226-288 and 310-400 GeV [16].

Note that much progress in the Higgs search can be expected on the basis of already accumulated data, as well as the anticipated data from 2012. The reader is referred to the publications following this evolution, and details that would be reported today may well be obsolete tomorrow. A definite statement about the existence or not of a SM Higgs might likely be in reach for the end of 2012.
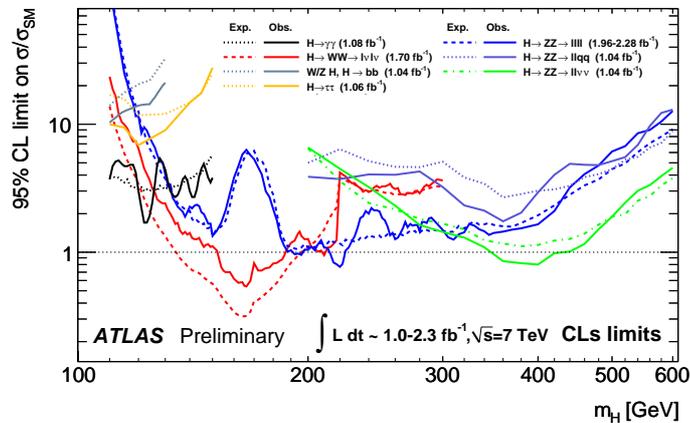
Figure 11: A summary of 95% CL limits, for various Standard Model Higgs search channels separately, as a function of the H mass (see text for explanations).

5. SEARCHES FOR NEW PHYSICS: SUPERSYMMETRY

Apart from finding, or excluding the existence of, the Higgs particle, the other important mission of the LHC is to search for physics beyond the Standard Model, also labelled BSM. Over the last 30 years a plethora of BSM models have been proposed but none of these is actually supported

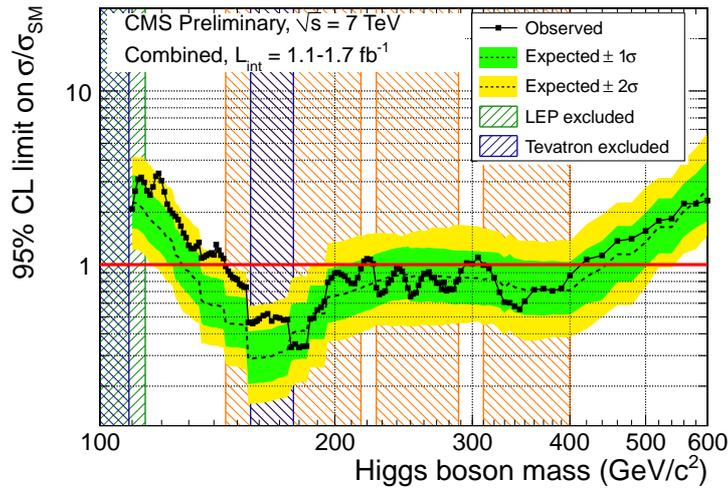**Figure 12:** The combined 95% CL upper limits as a function of the SM Higgs boson mass. The observed limits are shown by the solid symbols and the black line. The dashed line indicates the median expected limit on m_H for the background-only hypothesis, while the green/yellow bands indicate the ranges that are expected to contain 68%/95% of all observed limit excursions from the median. The mass ranges excluded by LEP, by Tevatron and by CMS are shown as hatched areas.

by data to date. We do know we have dark matter in the Universe, which could be our first sign for new physics, and is of strong interest to LHC searches if the dark matter consists of weakly interacting massive particles (WIMPs). As before, in these BSM sections we show illustrative examples from ATLAS and CMS; very similar results exist on most channels from both experiments.

Supersymmetry, in short SUSY[17], is probably the most popular extension of the Standard Model. SUSY has been a standard benchmark channel since many years for LHC studies so the experiments are generally ready for initial SUSY searches with the first significant set of data. There are a number of good reasons to consider SUSY as a relevant BSM model. It stabilizes the electro-weak scale: $|m_F - m_B| < $O(1 TeV); it predicts a light Higgs with $m_H < $130 GeV; it predicts/allows for gauge unification; it accommodates a heavy top quark mass; and it delivers a dark matter candidate in R_P conserving scenarios: eg via a neutralino, sneutrino, or gravitino. SUSY is consistent with electro-weak precision data. Discovering SUSY in the LHC data (or elsewhere) will lead to a true revolution in particle physics, and the need to re-write the text books.

In the experiments at the LHC SUSY particles will be dominantly strongly produced, leading to the pair production of squarks and gluinos. These particles decay in a cascade, leading to events with potentially many jets, leptons and E_T^{miss} due to the stable and escaping "dark matter" particle candidates. In all, SUSY particle production will generally lead very prominent signatures in CMS and ATLAS.

A key quantity for SUSY searches with so called R-paritiy conservation, ie where 'supersymmetry' is a conserved quantum number, is the measurements of missing transverse energy resulting from the escaping lightest SUSY particle (LSP), at the end of each sparticle decay cascade chain.
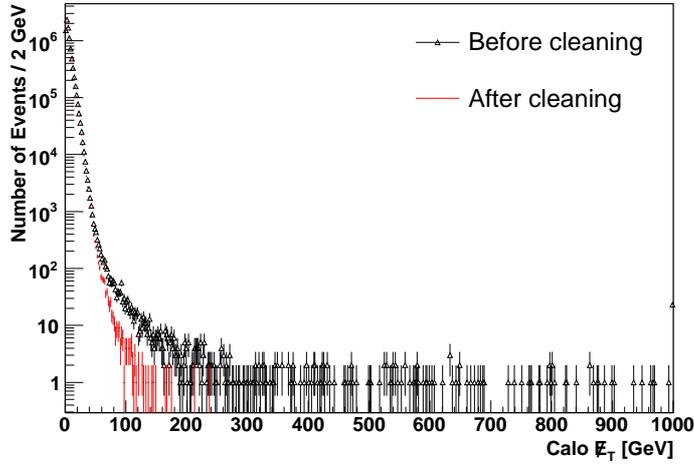
Figure 13: a) Calorimeter E_T^{miss} distributions in a minimum-bias data sample without (black dots) and with (open circles) cleaning and filters, compared to simulation. Overflows are included in the highest bin.

This quantity is generally appreciated to be a difficult one to measure. Experience from the Tevatron even predicted that this quantity would take a long time, perhaps more than a year, before it could be deployed in analyses. E_T^{miss} is very sensitive to e.g. fluctuations in jet measurements, miss-measurements, detector noise, backgrounds, etc. In practice, it turned out that E_T^{miss} was rather well under control from the start of the data taking, also thanks to the time the experiments had to prepare before first collisions in 2009. As an example the E_T^{miss} distribution for CMS [18] is shown for minimum bias events in Fig.13, before and after elementary cleaning for detector noise and other spurious effects. Of course when the machine will be operating with more pile-up in future, this will complicate the measurement of this quantity with sufficient quality.

The strategy for the present early searches for SUSY has been to scan the phase space for the most obvious SUSY channels, typically containing large E_T^{miss} and high p_T jets, possibly with one or more isolated leptons. Such signals are most easily to separate from Standard Model background, for which data-driven techniques have been developed and deployed to estimate this background from the data itself. Here is a typical work-flow for such searches. First one defines event selection criteria to tackle the data, typically tuned on background and signal Monte Carlo samples. Then one has to go through $\sim 2.000.000.000$ events triggered and stored on-line, collected eg in 2010, to select candidates (typically one has to go through less than 10% of that sample, due to pre-selected data sets which are based on trigger quantities, stored during the data recording). Next, clever kinematical cuts are deployed to suppress the dominant reducible backgrounds, such as QCD. Examples of these variables used in CMS to select the sample are α_T [19], missing H_T [20], and the razor[21] variable analyses for hadronic final state studies. Next one tries to "predict" the backgrounds in the signal region, using sidebands/disjunct regions or processes which can be measured to estimate those backgrounds (eg measuring photon+jets to predict the $Z(\nu\nu)$+jets background). Last, one determines the efficiencies and systematics of the signal and background estimates, and then one checks if there is an excess or not in data with respect to expectation in the signal box. An example for the agreement between data and three different background estimates

is given in Table 1, for the α_T analysis.

Table 1: Comparison of the measured yields in the different H_T bins for the hadronic, μ + jets and γ + jets samples with the SM expectations and combined statistical and systematic uncertainties given by the simultaneous fit.

| H_T bin (GeV)	275–325	325–375	375–475	475–575	575–675	675–775	775–875	>875
SM hadronic	787^{+32}_{-22}	310^{+8}_{-12}	202^{+9}_{-9}	$60.4^{+4.2}_{-3.0}$	$20.3^{+1.8}_{-1.1}$	$7.7^{+0.8}_{-0.5}$	$3.2^{+0.4}_{-0.2}$	$2.8^{+0.4}_{-0.2}$
Data hadronic	782	321	196	62	21	6	3	1
SM μ + jets	367^{+15}_{-15}	182^{+8}_{-9}	113^{+8}_{-7}	$36.5^{+3.8}_{-3.3}$	$13.4^{+2.2}_{-1.8}$	$4.0^{+1.4}_{-1.2}$	$0.8^{+0.9}_{-0.1}$	$0.7^{+0.9}_{-0.1}$
Data μ + jets	389	156	113	39	17	5	0	0
SM γ + jets	834^{+28}_{-30}	325^{+17}_{-17}	210^{+12}_{-12}	$64.7^{+6.9}_{-7.0}$	$21.1^{+3.9}_{-4.3}$	$10.5^{+2.5}_{-2.6}$	$6.1^{+0.9}_{-1.7}$	$5.5^{+0.9}_{-1.6}$
Data γ + jets	849	307	210	67	24	12	4	4
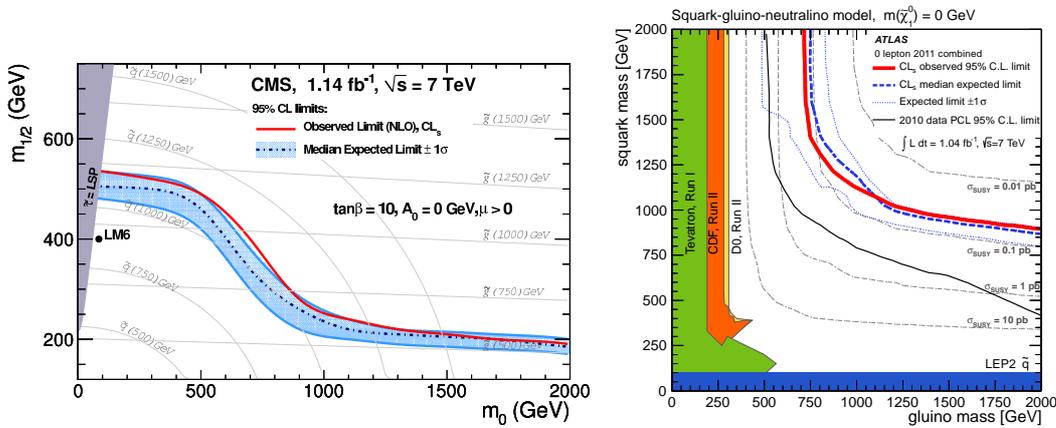
Figure 14: a) Observed and expected 95% CL exclusion contours for CMS in the CMSSM (m0,m1/2) plane ($\tan\beta = 10$, $A_0 = 0$, $\mu > 0$) using NLO signal cross sections with the CLs method, for the α_T analysis. The expected limit is shown with its 68% CL range. b) Combined exclusion limits for simplified SUSY models with the mass of the lightest SUSY particle set to zero from ATLAS. The combined limits are obtained by using the signal region which generates the best expected limit at each point in the parameter plane. The dashed-blue line corresponds to the median expected 95% C.L. limit and the red line corresponds to the observed limit at 95% C.L. The dotted blue lines correspond to the $\pm 1\sigma$ variation in the expected limits. Also shown for comparison purposes in the figures are limits from the Tevatron and LEP, although it should be noted that some of these limits were generated with different models or parameter choices (see legends). The previous published ATLAS limits from this analysis are also shown.

As it turns out, up to now no significant excess has been observed yet in these early SUSY studies. For definiteness these results are typically interpreted in SUSY scenarios and models. So far the Constrained Minimal Supersymmetric Standard Model (CMSSM) is often used as a benchmark model for presenting the search results. The CMSSM has 4 parameters, namely $m_{1/2}$: the universal gaugino mass at GUT scale; m_0: the universal scalar mass at GUT scale; $\tan\beta$: the vacuum expectation value ratio for the two Higgs doublets; A_0: the trilinear coupling and the sign of Higgs mixing parameter μ. The obtained exclusion limits for a data sample of 1 fb^{-1}, ie 1/5th of the total 2011 data sample, in the CMSSM is shown in Fig.14 for CMS and ATLAS[22]. Within this model squark and gluino masses up to 1 TeV are excluded by both ATLAS and CMS using searches exclusively based on the presence of high p_T jets. The new results extend the limits on
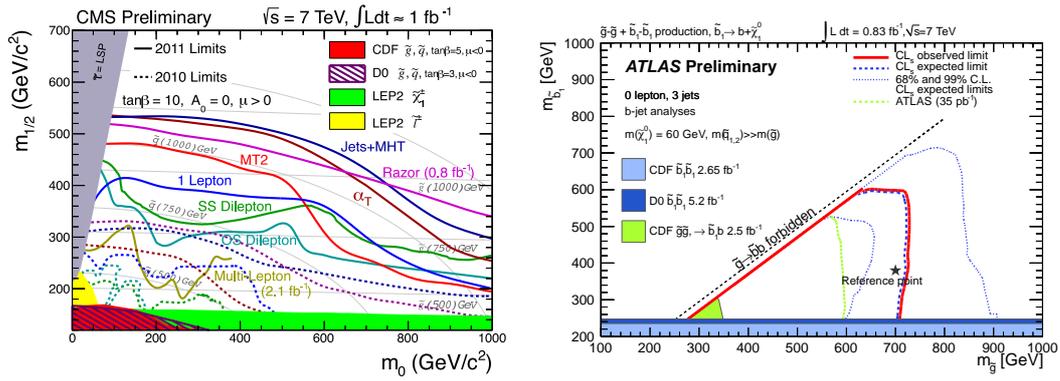
Figure 15: a) Observed limits from several 2011 CMS SUSY searches plotted in the CMSSM (m0,m1/2) plane. b) Observed and expected 95% C.L. exclusion limits in the gluino-sbottom mass plane. Also shown are the 68% and 99% C.L. expected exclusion curves. For each point in the plot, the signal region selection providing the best expected limit is chosen. The neutralino mass is set to 60 GeV. The result is compared to previous results from ATLAS and CDF searches which assume the same gluino-sbottom decays hypotheses. Exclusion limits from the CDF and D0 experiments on direct sbottom pair production are also shown.

the sparticle masses obtained with the 35 pb^{-1} 2010 data by ~250 GeV. Hence within the CMSSM model we are crossing now the border of excluding gluinos up to 1TeV and squarks up to 1.25 TeV. Note that for the squarks, these studies are essentially a test on the production of SUSY partners of the light quarks, which have the largest cross sections.

Figure 15(a) shows an overview of all different CMS searches in the CMSSM context. Together with similar ATLAS results no evidence for SUSY sparticles has been found so far in the region often called to be"just around the corner" of the searches prior to the LHC data. This may mean that either the SUSY particles are more heavy than anticipated, which may lead to unpleasant levels of fine-tunning, or the CMSSM, used as a guidance so far, is too constrained, and we have to start to think beyond the simplest or most constrained models and re-optimize searches. Examples are pMSSM, NMSSM, degenerate/compressed mass spectra, a light 3rd generation, Split SUSY, RPV SUSY, etc. How much of the "theory space" do we really cover with our present searches? We may have to revise our searches to study other, different scenarios. In particular if one looks at the basics of SUSY, and analyses what is really essential for it to stabelise electro-weak scale phenomena, one would require a low mass Higgs, ideally also a few low mass gauginos, a gluino with a mass below about 1.5 TeV, and in particular the masses of the stops (and left-bottom) to be preferably of order of 500-600 GeV well below 1 TeV to avoid large fine-tuning. The phase space for these searches is now becoming the focus of many studies, and by the end of 2012 the experiments will have explored this 'minimal scenario'. Until then at least, SUSY is as alive as ever, be it pushed more in the corner. Searches specific for the partners of the third generation quarks have started [23] and a study for sbottom production from ATLAS can be seen in Fig.15(b). No evidence has been found so far. Fig.16(a) also shows the search result for a study for a R_P-violating SUSY scenario[24], where the gluino can decay in 3 jets. The high mass excursion seen on the plot is less than 2σ taking into account look elsewhere effect.

In SUSY one expects a minimum of 5 Higgs bosons (and superpartners). In particular for a scenario with medium to high $\tan\beta$ we expect the decay of the Higgs to tau particles to be
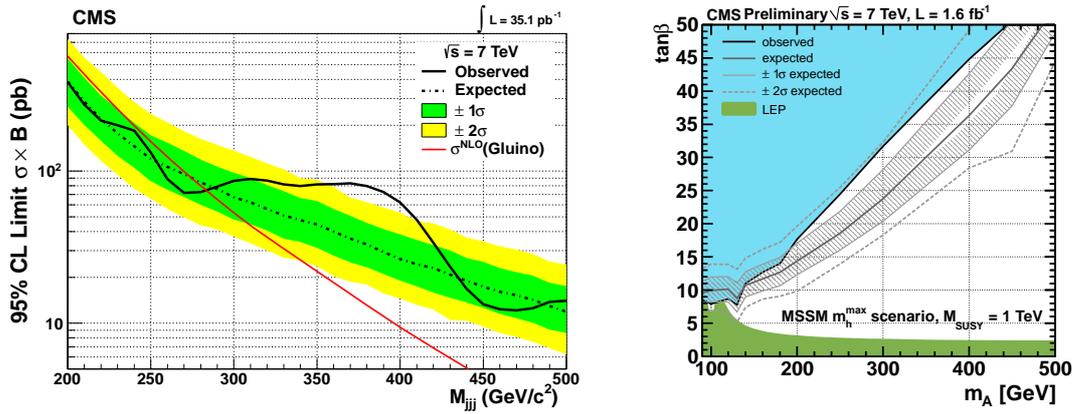
Figure 16: (a)Observed and expected 95% CL upper limits on the cross section for gluino pair production through RPV decays, where the branching ratio of the gluino to three jets is 100%. Also shown are the 1σ and 2σ bands on the expected limit, as well as the theoretical NLO cross section for gluino production. The most significant excess of 1.9σ standard deviations occurs at a mass of about 390 GeV. (b) Region in the parameter space of $\tan\beta$ versus m_A excluded at 95% CL in the context of the MSSM m_h^{max} scenario, with the effect of $\pm 1\sigma$ theoretical uncertainties shown. The other shaded regions show the 95% CL excluded regions from the LEP and Tevatron experiments.

an efficient and detectable signal. Fig. 16(b) shows the result of the search for a MSSM Higgs, excluding already a large part of the phase space at low mass of the CP-odd neutral Higgs [25].

6. Searches: Other exotica

About 15 years ago, a strong alternative to SUSY to deal with the hierarchy problem was proposed, in terms of possible small extra space dimensions. There are several versions of extra dimension models. In the so called large extra dimension models (ADD[26]) only gravity can access the extra dimensions– or said to go in the bulk– and consequently gravity becomes stronger more rapidly than projected from our present low energy knowledge. Hence the Planck scale could well be much closer to the electro-weak scale, i.e. in the TeV range. The signatures to study at the LHC for this scenario are either interference effects of graviton exchange in two fermion or two boson final states, or, more spectacularly, unbalanced events with a single hard photon or a single high p_T jet (so called monojet events). Other scenarios with extra dimensions include the so called Randal-Sundrum (RS)[27] models that assume that there are two branes with most SM particles living on one brane, and gravity on the other, with a warped space in between. This leads phenomenologically to the existence of heavy Kaluza-Klein (KK) graviton states, which can show up as resonances in the TeV range of e.g. di-leptons or di-top distributions. In universal extra dimension (UED) [28] scenarios all particles can move in the bulk, which leads to a phenomenology that all Standard Model particles have (multiple) KK partners, and will lead to new particle spectra which will look at face value similar to supersymmetry spectra. Hence, once experimental evidence for signatures from a SUSY-like spectrum of particles will be found, we will have to disentangle whether this is really a manifestation of SUSY our perhaps of UED. It will be therefor important to

determine the spin of these new particles: in case of the UED the partners of the Standard Model particles have the same spin, while in SUSY they differ by 1/2 unit.
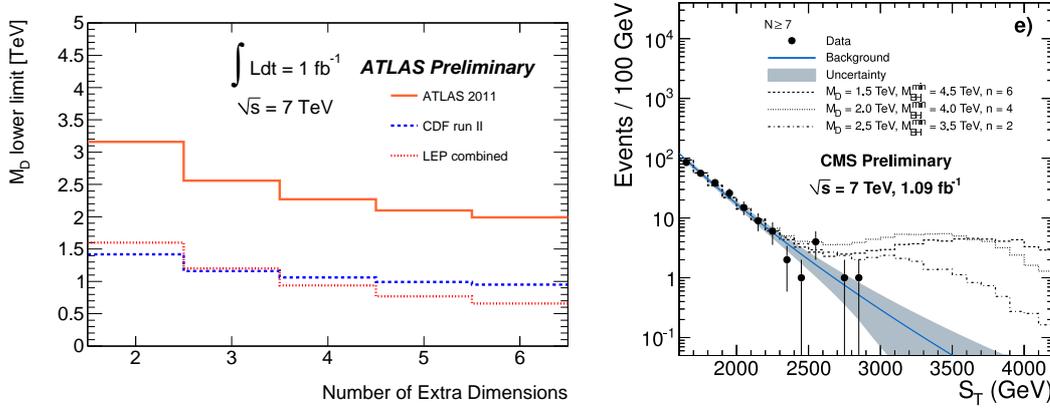

Figure 17: (a) The 95% CL observed lower limits on MD for different numbers of extra dimensions for ATLAS, compared with previous results. (b) Total transverse energy, S_T, for events with 7 or more photons, electrons, muons, or jets in the final state. Data are depicted as points with error bars; shaded band is the background prediction (solid line) with its uncertainty. Also shown are black hole signals for three different parameter sets.

Extra dimensions have been searched for in all the scenarios mentioned above. No evidence has been found so far. Figure 17(a)[29] shows the result of a mono-jet analysis based on 1 fb^{-1} of data. Selecting events which have a mono-jet with a $p_T > 250$ GeV and $E_T^{miss} > 220$ GeV, the comparison of the data with the background gives a lower limit on the Planck scale between 2 and 3 TeV depending on the number of extra dimensions.

In the presence of large extra dimensions, with the real Planck scale in the TeV region, there is a possibility of producing micro black holes, which would evaporate in the shortest of times, namely within 10^{-27} seconds, and lead to energetic jets and leptons in the detectors. While we have not detected extra dimensions yet, it remains interesting to search for these objects, as in some scenarios observing micro black holes could be the first detectable sign for the presence of extra dimensions. Searches have been conducted for an excess above background of events with a large total scalar sum of transverse momentum (including also the missing transverse momentum), called S_T. An example from this study is shown in Fig. 17(b)[30], for events with 7 high p_T photons, leptons or jets in the final state. No sign of micro black holes is found in the data so far for masses up to ~5 TeV, depending on assumptions.

A whole slew of other models for BSM physics has been studied by the experiments. These include the search for new gauge bosons, colored resonances, objects decaying into top quarks, strong EW symmetry breaking, 4th generation of quarks and leptons, quark substructure and contact interactions, technicolor, long lived particles, dark and hidden sector particles, and more... Fig.18(a) shows as an example the search for new Z' gauge bosons[31]. The data exclude (SSM) Z' bosons up to 1.94 TeV, as well as Kaluza Klein graviton production up to 1.7 TeV at 95% CL. Another example is the search for right handed currents and heavy neutrinos. Fig.18(b) shows the search result for a left-right symmetric extension of the Standard Model, with the production of a
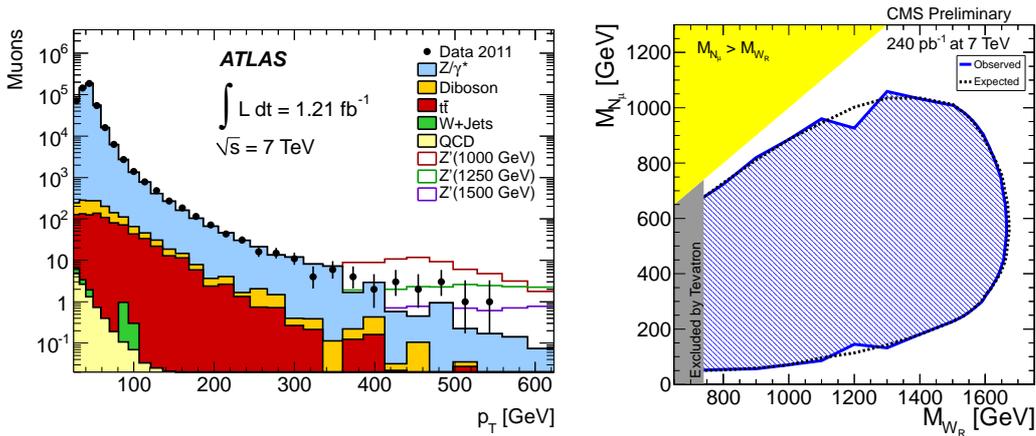
Figure 18: a) Muon transverse momentum after event selection. Both leading and sub-leading muon are shown in the distribution. The points represent ATLAS data and the filled histograms show the Monte Carlo stacked background except for the QCD, which is estimated from data. Three example SSM Z' signals are overlaid. The bin width is chosen to be constant in $\sqrt{(p_T)}$. The small excess in the tails of the distributions may be explained by the imperfect modeling of highly energetic jets in PYTHIA, since the agreement is much better with ALPGEN which generates more high energy jets which can boost the dilepton system in the Z+jets events. Of the ten highest p_T muons, only four belong to a dimuon pair with mass greater than 300 GeV. b) The 95% confidence level excluded $(M(W_R)$, $M(neutrino)$) region for the muon channels.

W_R and a heavy neutrino [32]. The search uses a selection of events that contain two leptons and two jets. No excess has been found. Hence the results lead to a large exclusion range in mass of the W_R and heavy neutrino of respectively 1.6 TeV and 1 TeV.

The searches at the LHC that probe deepest in the TeV region are those which involve colored objects. Typically the search for resonances in di-jet distributions is very sensitive to new colored objects. Fig.19(a)[33] shows the result of a high mass di-jet search, where events were selected with two jets with $p_T > 180$ GeV in an ATLAS study. A search was performed for a bump in the invariant di-jet mass mass distribution. No bump was found which leads to exclusion limits on colored objects in the range of 1-4 TeV. The CMS data exclude new particles predicted in the following models at the 95%CL: string resonances with mass M(S) <4.00TeV, E6 diquarks with M(D) <3.52 TeV, excited quarks with M(q*) <2.49TeV, axigluons and colorons with M(A,C)<2.47TeV, and W' bosons with M(W') < 1.51TeV.

Finally, during the last few years many theoretical models were proposed which involve new particles that are stable enough – at least for a few tens of nanoseconds, but maybe live as long as hours or days– so that they can traverse the detector and can be detected as unusual particles with e.g. large ionization loss or small velocities w.r.t the speed of light, and hence with a delayed arrival in the outer sub-detectors. Example scenarios that can produce these sort of particles are split supersymmetry, gravitino dark matter SUSY models and GMSB scenarios. In split supersymmetry type of scenarios one assumes Nature is fine tuned and SUSY is broken at some high scale. The only light particles are the Higgs, the gauginos and the gluino. The fermion partners have very high masses for example in the range of 10^{10} GeV. The gluino can therefor live long: seconds, minutes, even up to years. The gluino will dress up with a gluon or quark anti-quark pair to

become color neutral, and form a so called R-hadron, a particle with a mass larger than several hundred GeV. This R-hadron will exhibit unusual interactions with the material of the detectors, such as the calorimeters, and can be detected. In gravitino dark matter and GMSB models the NLSP (neutralino, stau lepton) can live long. In GMSB also decays of the neutralino into a photon and a gravitino with displaced vertices are a possibility, leading to non-pointing photons in the detector. Hence a lot of ingenuity was required in the last years to make sure that the experiments, a priori not designed for such new physics scenarios, would not miss these opportunities.
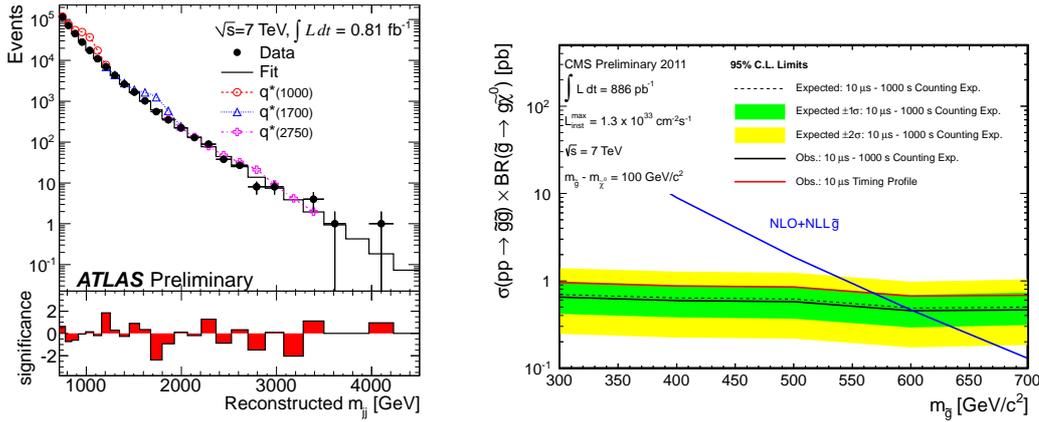

Figure 19: a) The observed (Data) di-jet mass distribution (filled points) fitted using a binned QCD background (Fit) distribution described by the smooth functional form (histogram). The bin-by-bin significance of the data-background difference is shown in the lower panel. For illustration, excited quark mass templates have been superimposed on the data. b)95% C.L. limits on gluino pair production cross-section as a function of m_g assuming the cloud model of R-hadron interactions. The gluino-neutralino mass difference is maintained at 100 GeV.

These and more scenarios are being studied by the experiments. A special example is the search for R-hadrons that may have stopped in the detector material, essentially the calorimeter, due to their energy loss in matter. These R-hadrons are stuck in the material and stay put until they decay. This decay, due to the significant gluino lifetime, is uncorrelated with the collision time of the event, and in general not correlated in time to a collision in the detector. Hence we search for these R-hadron decays, i.e. sudden burst of energy in the hadron calorimeter, at times when there are no collisions in the detector, when there is either no beam or during the empty abort gaps within a fill. No evidence for such new particle was found yet, and Fig.19(b) shows 95% CL limits from a CMS analysis for stopped gluinos, and puts limits on masses larger than 600 GeV and for stopped stop quarks to have a masses larger than 337 GeV[34].

7. Conclusion

The LHC has preformed magnificently in 2010 and 2011, and the experiments have collected a wealth of data. Several very important Standard Model measurements have been made, showing good agreement with the theoretical calculations, namely within 15-30% for QCD measurements, and down to 5 % or better for electro-weak measurements. ATLAS and CMS are already front-line

players in the studies of the top quark, with e.g. the top cross section being measured to a precision of about 8%.

These Standard Model measurements are indispensable for searches for the Higgs boson and new particles, in order to be able to tackle these with sufficient confidence.

These are exciting times in particular for the search of the Standard Model Higgs boson. The range where the Higgs particle can live has been substantially constrained already by the LHC experiments. Within that region some excess is perhaps building up. The luminosity of the 2011 data will likely not be enough to be conclusive, but increasing the data sample by a factor of a few should referee on the Standard Model Higgs existence question.

Searches for physics beyond the Standard Model are ongoing in both ATLAS and CMS. So far, at 7 TeV and with 1 fb^{-1} of data no significant signal of BSM physics as been observed. In particular SUSY has been scrutinized heavily in the last year, and the most naive, most constrained models are now being pushed back to very high masses for the sparticles. A paradigm shift towards more difficult scenarios, and with more attention to the partners of the third generation quarks, is now taking place with dedicated searches. A plethora of other possible new physics scenarios is also being explored, from extra dimensions to new gauge bosons, 4th family etc. Special attention is paid to unusual signatures like long lived particles and displaced vertices of decays of new particles.

This is only the beginning of the adventure of the exploration of the TeV-scale with the LHC. Right now the searches have reached a sensitivity for squarks and gluons up to 1 TeV (in constrained models), for new gauge bosons up to 2 TeV and for new colored objects such as axi-gluons and excited quarks up to 3 TeV. By the end of 2012 LHC will have delivered about 20 fb^{-1} of data to the experiments, the last 15 fb^{-1} will be at 8 TeV. It will likely clarify the situation of the Standard Model Higgs, but it is unclear if will be sufficient for observing BSM signals. The higher energy –13 or 14 TeV– that will be reached after a two year shutdown and upgrade of the machine, and data samples of 100 fb^{-1} will have an even better chance for that. Hence we have exciting years ahead of us.

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