PROCEEDINGS OF SCIENCE

Highlights and searches from ATLAS

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Highlights from ATLAS are reported, focussing primarily on searches for new particles using proton-proton collision data. The data collected, its quality and the performance for physics are outlined. The initial part of the 2011 data sample has already provided a major extension in search sensitivity compared to the 2010 data, and examples are given. Rapid progress is being made in the search for the Higgs boson. Production of the Standard Model Higgs has been excluded at 95% CL over the ranges 155-190 GeV and 295-450 GeV.

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1. Introduction

These proceedings briefly summarise the status of ATLAS, and selected physics highlights, especially searches, as presented at the EPS-HEP conference in July 2011. A large number of parallel talks and posters from ATLAS presenters are also reported elsewhere in this volume, as are plenary talks which review ATLAS results in wider contexts, covering electroweak [1], top [2], QCD [3], heavy ions [4], and LHC Higgs searches [5]. Essentially all results included in these proceedings were preliminary at the time of the conference, and some are now published (see references).

2. Data Samples

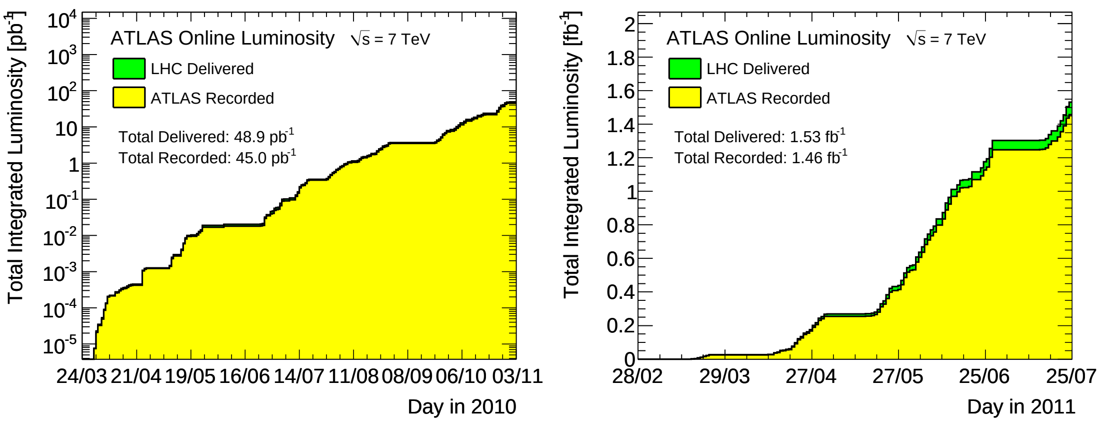

Figure 1: Integrated luminosity history in (left) 2010, and (right) 2011 to the date of the conference. Note log and linear vertical scales, respectively. The luminosity error is $\pm$3.4% and $\pm$3.7% respectively.

The LHC luminosity delivery in 2010 was characterised by a roughly exponential rise in peak luminosity, spanning five orders of magnitude over the year (Figure 1). A total of 45 pb^{-1} was collected by ATLAS. The year 2011 began with luminosities similar to those at the end of 2010, and has seen a roughly linear rise in instantaneous luminosity from fill to fill, by the end of July reaching 1.75×10^{33} cm^{-2}s^{-1}, and a "best day" with 63 pb^{-1}. The integrated luminosity collected is already, by the time of the conference, thirty times larger than in 2010, at close to 1.5 fb^{-1}. Analysis results presented use up to 1.2 fb^{-1} of 2011 data.

The most striking change in beam conditions between 2010 and 2011 data-taking has been the inexorable rise of multiple pp interactions ("pileup") in both the triggered beam-crossing ("in-time") and nearby ones in time ("out-of-time"). The latter affect the data taken primarily through the long integration times of the calorimeters. The level of pileup may be coarsely characterised by the mean number, μ, of interactions per bunch crossing at a given point in an LHC fill, together with the bunch spacing, which has been 50 ns in 2011. The distribution of μ in the early 2011 data is shown in Figure 2.

The absolute luminosity calibration is the result of several beam-separation ("van der Meer") scans, of excellent quality evidencing stable and very close-to-gaussian transverse beam profiles.

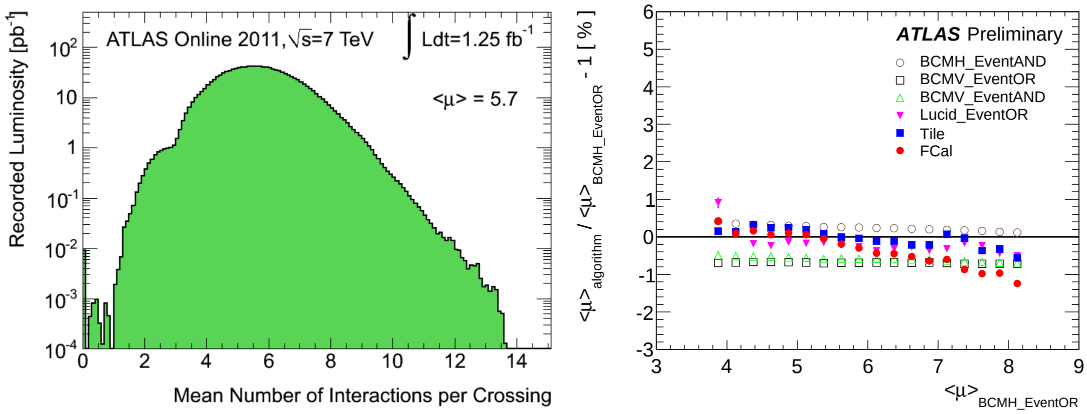

Figure 2: Left: mean number, μ, of interactions per bunch crossing for 2011 data; right: pileup dependence of luminosity estimators in 2011 data.

The luminosity calibration is transported to physics data-taking using a range of different relative luminosity measures and devices, illustrated in Figure 2. In 2010 data, a preliminary luminosity precision in physics of $\pm$3.4% is obtained [6]. The increased pile-up in 2011 results in only a small additional error in 2011, due to the multiple luminosity estimators available for cross-checks, so that a preliminary uncertainty of $\pm$3.7% [7] is used for 2011 analyses to date.

ATLAS' typical data-taking efficiency is at the $\sim$95% level, and the fraction of operational channels in different detector systems is at the $\sim$97% level or higher. The LHC experiments have precipitated a revolution in data handling and fast physics analysis compared to previous generations of large collider experiments. Data written to disk at the experiment are reconstructed at the CERN Tier-0 a couple of days later, after a delay to allow calibration and other conditions information to be updated based on the data themselves: these calibrations are sufficient for publication-quality physics analysis. Analysis typically can start around one week after the data are collected, when a full data quality assessment is complete. Thus results presented here are able to use data collected until around four weeks before the conference. This also reflects the superb performance of the Worldwide LHC Computing Grid, WLCG. Figure 3 (left) illustrates this excellent performance in terms of the numbers of ATLAS analysis and production jobs run each day across all Tier-1 and Tier-2 sites. Job totals of around two-thirds of a million a day are achieved.

To date, ATLAS has been able to operate with simple inclusive triggers which facilitate efficiency measurements from the data themselves: for electrons and muons transverse momentum thresholds $p_T > 20$ GeV and 18 GeV are deployed as the primary, stable, thresholds for the 2011 data collected until the conference. The very sharp efficiency turn-on available at the high-level trigger is illustrated in figure 3 (right). The trigger menu includes a host of trigger signatures, ranging from primary triggers through to supporting and monitoring triggers running at low rates. The reliable extrapolation of rates to higher luminosities indicates that the effects of pileup are sufficiently understood at the trigger level.

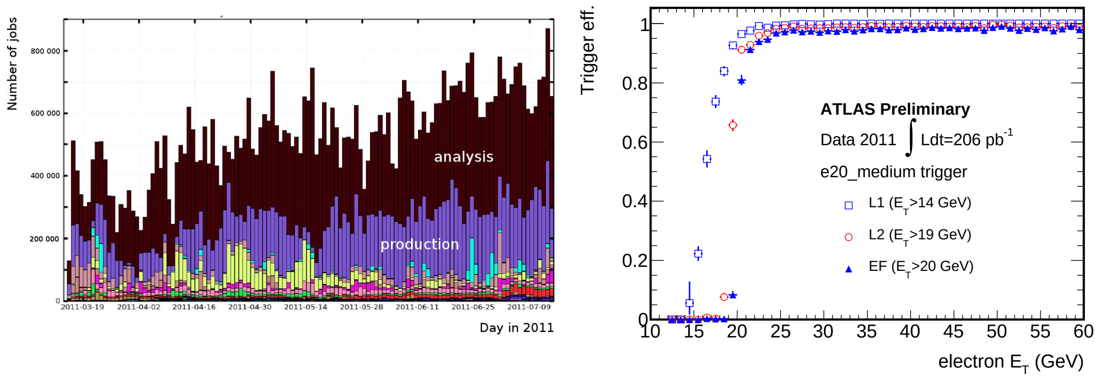

Figure 3: Left: total numbers of ATLAS jobs run on the grid, aggregated across all Tier-1 and Tier-2 sites, during the first part of the 2011 running; right: efficiency turn-on curves for 20 GeV p_T threshold electron trigger, at the first, second, and final (event filter) levels.

3. Dibosons and Top

There is no space in this article for a review of ATLAS' extensive Standard Model measurement programme. However, one highlight from 2011 data at this conference in this area has been the measurement of massive electroweak diboson production cross-sections. The most precise measurements are made in specific fiducial acceptances, which may be extrapolated to obtain inclusive WZ and ZZ cross-sections:

$$\begin{aligned} \sigma^{\rm tot}(WZ) &= 21.1 \pm^{3.1}_{2.8} (stat) \pm 1.2 (syst) \pm^{0.9}_{0.8} (lumi) \text{ pb [8]} \\ \sigma^{\rm tot}(ZZ) &= 8.4 \pm^{2.7}_{2.3} (stat) \pm^{0.4}_{0.7} (syst) \pm 0.3 (lumi) \text{ pb [9]} \end{aligned}$$

to be compared with Standard Model NLO expectations of 17 ± 1 and $6.5^{+0.3}_{-0.2}$ pb, respectively.

A highlight in the top sector is a measurement of the $t\bar{t}$ cross-section with dilepton events, using 0.7 fb^{-1} of 2011 data [10]. Combining this with earlier measurements results in a cross-section of:

$$\sigma(t\bar{t}) = 176 \pm 5 (stat) \pm^{13}_{10} (syst) \pm 7 (lumi) \text{ pb [11]}.$$

The precision of this measurement, $\pm 8\%$, challenges the current theoretical uncertainty which is at the level of 10% [12]. Another analysis [13] has measured the single-top production cross-section in the t-channel with an observed significance of 7.6σ (expected significance 5.4σ). The result is consistent with the Standard Model expectation.

4. Beyond the Standard Model

A wide range of searches for new phenomena beyond the Standard Model has been carried out by ATLAS. In this article, a subset of results on exotic physics searches are reported which use the 2011 data sample: for the most part these are in relatively simple topologies where a robust analysis could be done rapidly. Already by the time of the conference major improvements in sensitivity were possible over results based only on 2010 data. Furthermore, searches for supersymmetry in the 0-lepton and 1-lepton channels are reported, again using the early 2011 data sample.

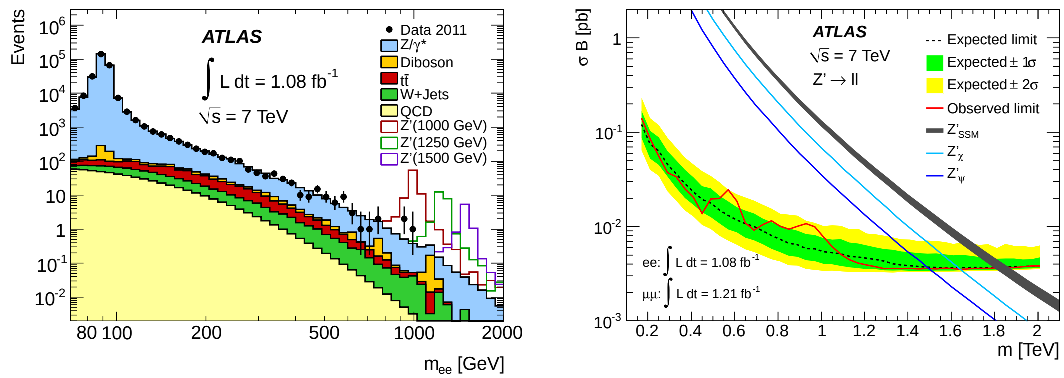

Figure 4: Left: Invariant mass spectrum of electron pairs in the Z′ →ee search; right: Limits obtained on Z′ production, combining the electron and muon channels [14].

4.1 Exotic Models

Updated results for dilepton searches are illustrated in figure 4: the electron-pair invariant mass distribution observed with more than 1 fb^{-1} is shown, together with cross-section limits on Z′-like (narrow) resonances as a function of mass. Production of a sequential standard model-like Z′ is excluded at 95% CL with mass below 1.83 TeV, 0.78 TeV above the limit derived from 2010 data. Further limits on other dilepton resonance models are also available [14]. In addition, an updated search for particles decaying to an electron and a muon has been performed, placing constraints, for example, on a straw-man R-parity violating SUSY model [15].

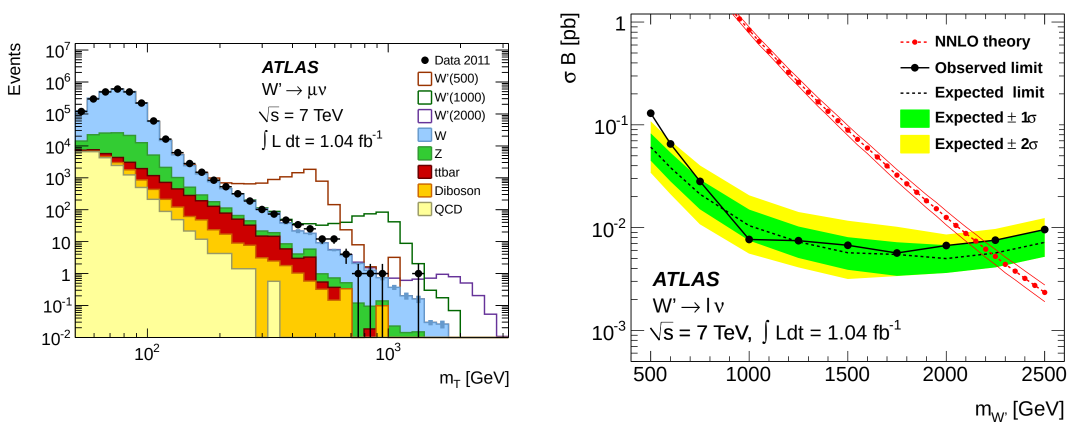

Figure 5: Left: Transverse mass spectrum of muon and missing transverse momentum in the W′ → $\mu\nu$ search. Right: Limits obtained on W′ production, combining the electron and muon channels [16].

The search for W′ production has similarly been extended with the early 2011 data [16], as shown in figure 5. Limits on a sequential standard model-like W′ now extend to 2.15 TeV at 95% CL, when the electron and muon channels are combined, 0.66 TeV higher than from 2010 data.

The search for peaks in the dijet invariant mass spectrum is also updated using 2011 data, as

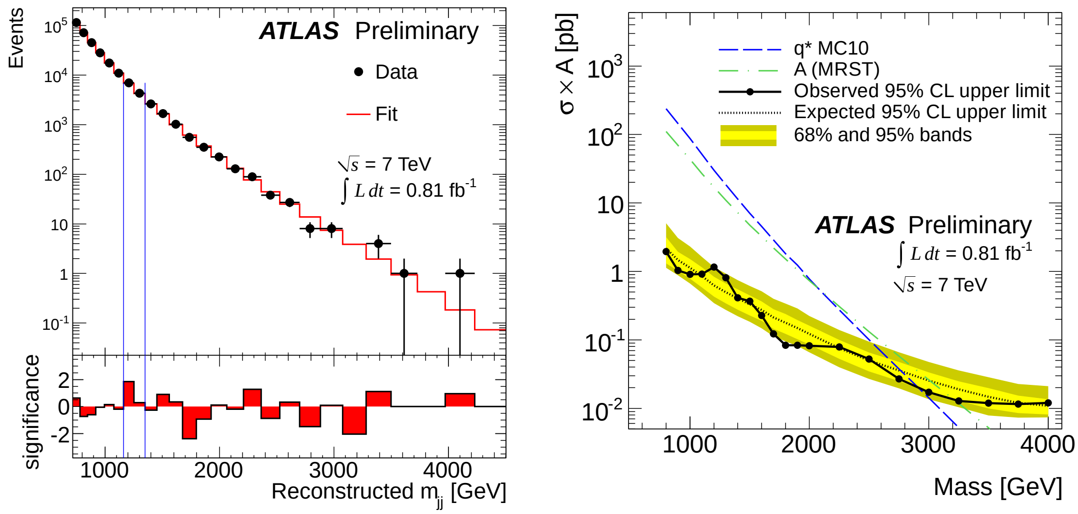

Figure 6: Left: Invariant mass spectrum of dijets; right: limits on cross-section times branching ratio for dijet resonance production, compared with the expectations for q^* and axigluon production [17].

depicted in figure 6. The 95% CL limit on the benchmark q^* model is increased by 0.76 TeV to 2.91 TeV, updated limits are also placed on axigluon and an S_8 colour-octet scalar model, and more generically on cross-sections for dijet resonances of different widths [17].

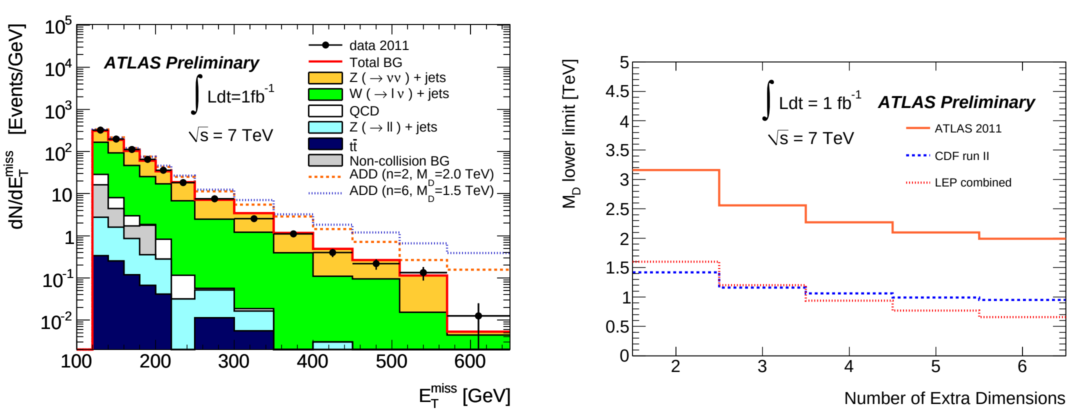

Figure 7: Left: Missing transverse momentum, $E_T^{\rm miss}$, observed in selected events with a jet $p_T > 120$ GeV and $|\eta| < 2$, and $E_T^{\rm miss} > 120$ GeV; right: The 95% CL lower limits on the $4+n$-dimensional Planck scale M_D for different numbers, n, of extra dimensions [18].

In a different combination of high-p_T objects, a search for "monojet"-type events has also been updated with 2011 data [18]. The event topology is that of a high-p_T jet recoiling against little observed activity in the detector, i.e. with missing transverse momentum opposite the jet. Constraints are placed on the Planck scale M_D in 4+n-dimensions in the ADD extra dimensions model [19], where an unobserved graviton gives rise to the missing transverse momentum. These lower limits on M_D are shown in figure 7.

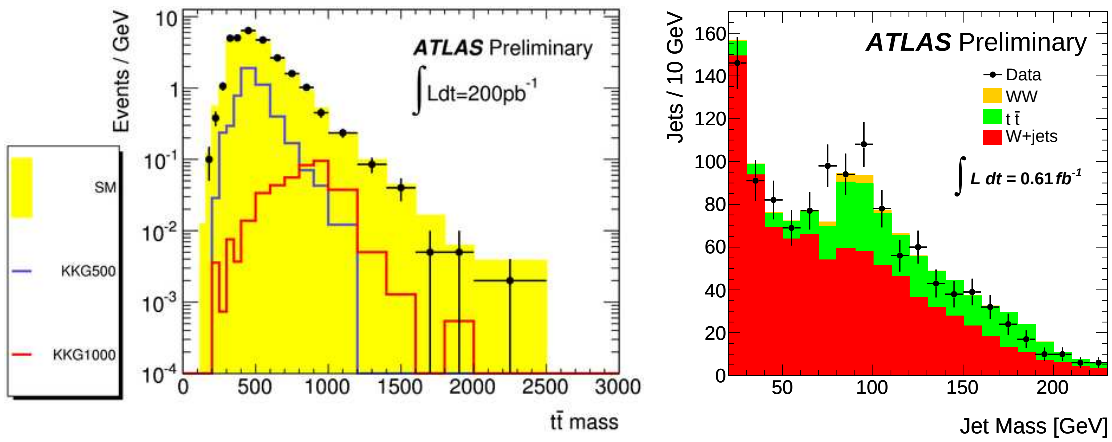

Figure 8: Left: Reconstructed $t\bar{t}$ invariant mass distribution in the lepton-plus-jets channel [20]; right: invariant mass of split and filtered subjets in events with a high-p_T $W \to \ell\nu$ candidate [21].

A more complex search relying on lepton, jets and missing transverse energy reconstruction is that for $t\bar{t}$ resonances. The reconstructed invariant mass distribution of single-lepton $t\bar{t}$ candidates is shown in figure 8. Events are observed, already in just 200 pb^{-1} of data, out to invariant masses of 2 TeV. Limits are placed on narrow and wide resonance production cross-sections [20]. This analysis uses standard top reconstruction techniques: looking to the future and more boosted tops, new techniques will be needed, which will also be important in other search topologies. As an example, figure 8 also shows the reconstructed mass distribution of split and filtered subjets in events with a high-p_T $W \to \ell\nu$ candidate ($p_T > 200$ GeV): a rather evident peak from hadronic W decays is seen [21].

4.2 Supersymmetry

At the time of the conference, ATLAS already had results over a wide spectrum of topologies for supersymmetric particle production and decay. The bulk of these searches look for signatures with R-parity conservation: missing transverse momentum being the common signature.

Selecting events with jets, missing transverse momentum and no leptons is sensitive to the simplest strong production of gluinos and squarks, with decays such as $\tilde{q} \to q\tilde{\chi}_1^0$ and $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$. The analysis is carried out in four kinematic regions, and the effective mass m_{eff} is used as the discriminating variable in all four cases. It is defined as the scalar sum of E_T^{miss} and the selected jet transverse momenta. The m_{eff} distributions obtained are shown in figure 9, together with the derived limits in the squark-gluino mass plane, and in the MSUGRA/CMSSM $m_{1/2}$ vs m_0 plane. A major improvement in sensitivity is evident from the addition of the 2011 data.

Selecting events with jets, E_T^{miss}, and at least one jet b-tagged by a lifetime algorithm allows searches to be more sensitive to models in which the $\tilde{b}_1$ or $\tilde{t}_1$ is the lightest squark [23]. This search is illustrated in figure 10.

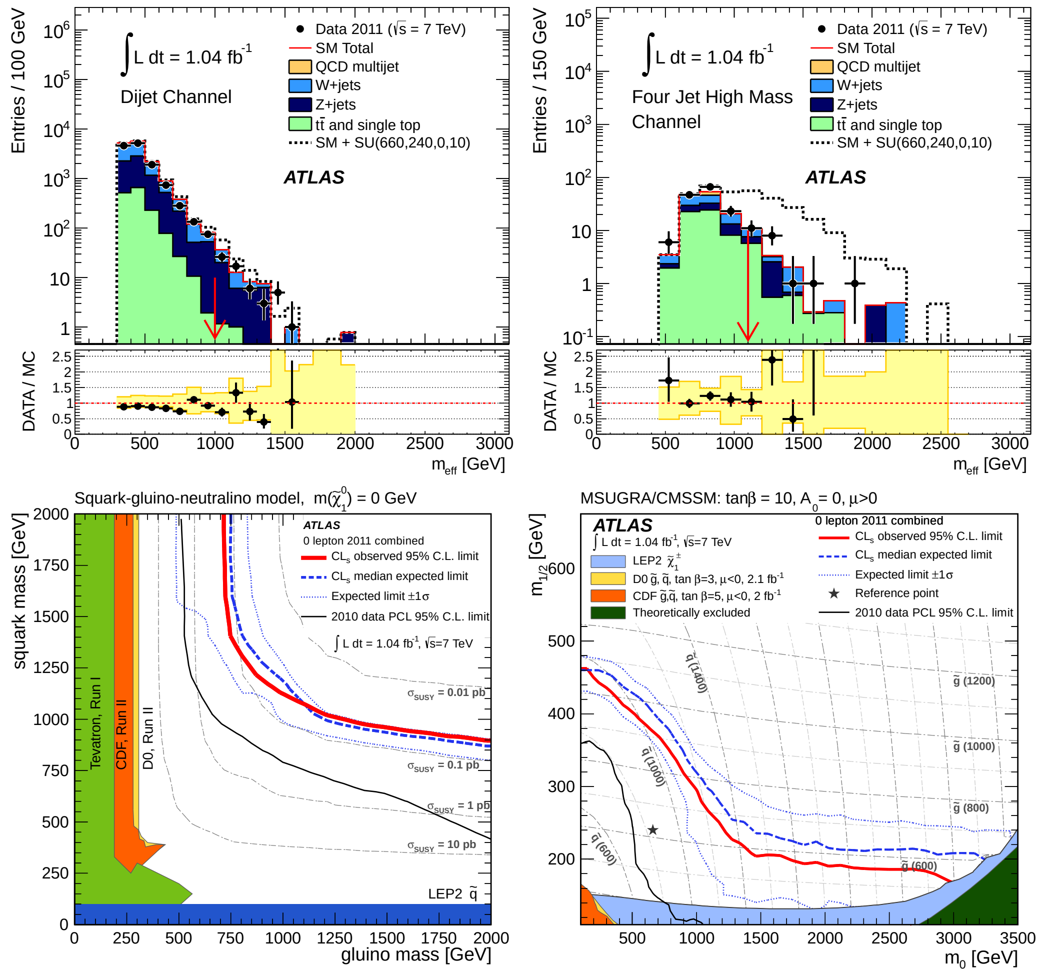

Figure 9: Top: Effective mass distribution, m_{eff}, for the dijet and four-jet high mass regions of the jets-plus-E_T^{miss} SUSY analysis; bottom: Limits obtained [22].

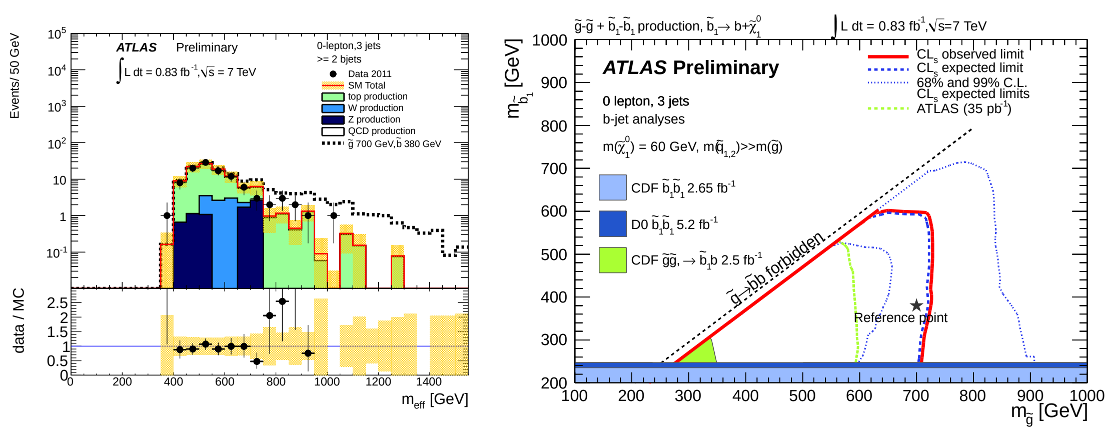

Figure 10: Left: Distribution of m_{eff} in the b-tagged SUSY search analysis, after requiring that two jets are b-tagged; right: limits obtained in a simplified model in the $\tilde{b}_1$ vs. $\tilde{g}$ mass plane [23].

5. The Latest on the Higgs Search

The current status of LHC Higgs searches is summarised elsewhere in these proceedings [5], and so here only the most sensitive channels are briefly reviewed. At this meeting, ATLAS reported updates with more than 1 fb^{-1} analysed on the channels $H \to \gamma\gamma$ [24], $H \to ZZ^{(*)} \to \ell\ell\ell\ell$ [25], $H \to ZZ \to \ell\ell\nu\nu$ [26], $H \to ZZ \to \ell\ell qq$ [27], $H \to WW^{(*)} \to \ell\nu\ell\nu$ [28], $H \to WW \to \ell\nu qq$ [29], $WH \to \ell\nu bb$ and $ZH \to \ell\ell bb$ [30]. Cut-based techniques have been used throughout at this early stage, to provide robust analyses.

Invariant mass distributions from the $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to \ell\ell\ell\ell$ analyses are shown in figure 11. Both channels allow the Higgs boson mass to be reconstructed with good experimental precision, but the sensitivities (expected 95% CL limits) at this point are not yet at the level of the Standard Model cross-section, due to the low branching ratios into these final states.

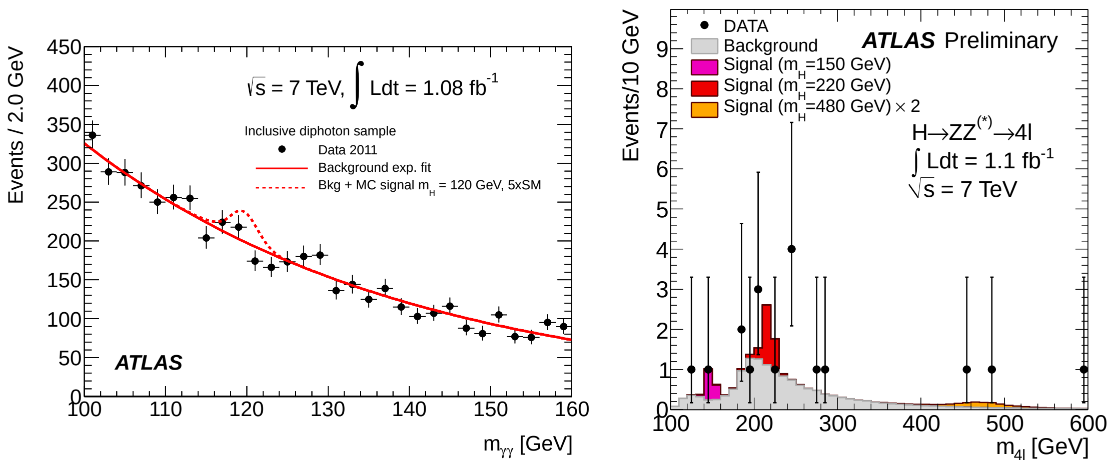

Figure 11: Left: Diphoton invariant mass in events selected in the $H \to \gamma\gamma$ analysis [24]; right: Four lepton invariant mass in events selected in the $H \to ZZ^{(*)} \to \ell\ell\ell\ell$ analysis [25].

The $H \to ZZ \to \ell\ell\nu\nu$ channel analysis is more powerful at high mass for Higgs exclusion, although it lacks such good mass resolution. As indicated in figure 12, this channel on its own provides a 95% CL exclusion for a range of high Higgs masses: the range $340 < m_H < 450$ GeV is excluded by this channel alone [26].

The $H \to WW^{(*)} \to \ell\nu\ell\nu$ channel is another powerful one for exclusion, also for low m_H, however it too does not allow event-by-event determinations of the Higgs mass, because of the two escaping neutrinos. In this channel the transverse mass distribution of the leptons and missing transverse momentum is formed (see figure 13), and a slice $0.75m_H < m_T < m_H$ is selected in order to derive cross-section constraints for specific m_H values [28]. This channel alone excludes production of the SM Higgs in the range $142 < m_H < 186$ GeV at 95% CL. It also shows a small $\sim 2\sigma$ surplus of events over the Higgs mass range 130-150 GeV: more data and analysis is required to understand whether this arises from a fluctuation, mis-estimated backgrounds, or something else.

Putting together all the channels analysed, constraints on the cross-section as a function of Higgs mass are obtained as shown in figure 14. ATLAS excludes at 95% CL SM Higgs production

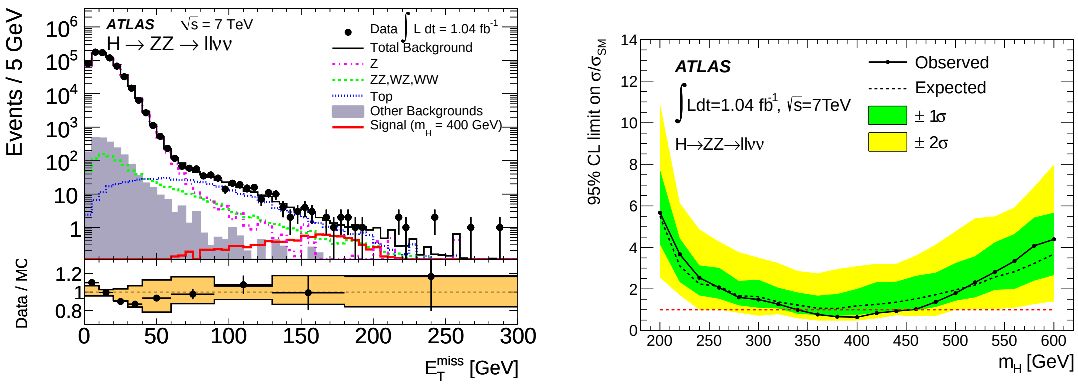

Figure 12: Left: Missing transverse momentum distribution for events selected in the $H \to ZZ \to \ell\ell\nu\nu$ analysis, before the E_T^{miss} requirement is applied ($E_T^{\text{miss}} > 66$ GeV for $m_H < 280$ GeV and $E_T^{\text{miss}} > 82$ GeV above); right: 95% CL upper limit on Higgs production cross-section vs. m_H from this analysis [26].

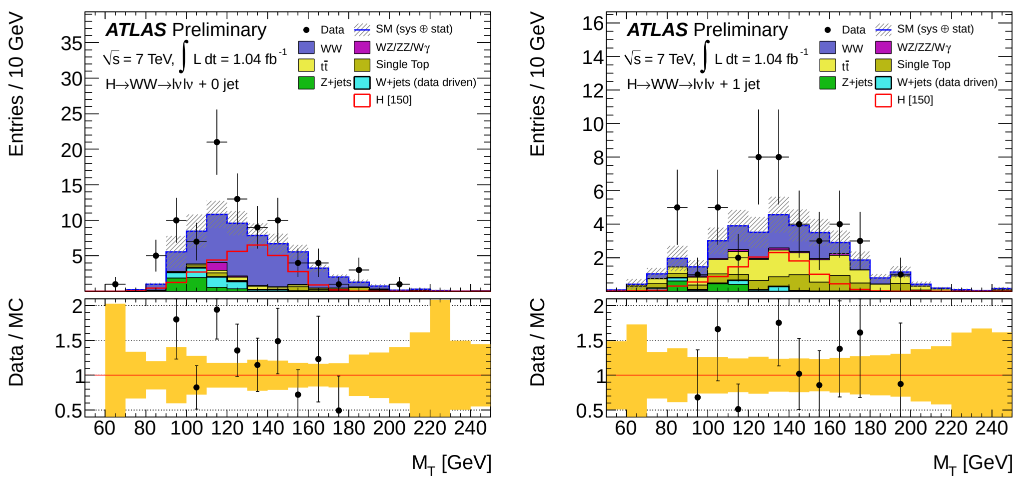

Figure 13: Transverse mass distributions for the low-mass selection in the $H \to WW^{(*)} \to \ell\nu\ell\nu$ analysis. Left: Zero-jet channel; right: one-jet channel [28].

in the two regions 155-190 GeV and 295-450 GeV [31].

6. Summary

The performance of the LHC in 2011 has been breathtaking, and the ATLAS detector is also performing very well indeed. A range of measurements and search results are available already from 2011 data, building on the wealth of physics from the 2010 data. In total, at the time of the conference, ATLAS had submitted 47 journal papers, and completed 212 conference notes. A total of thirty-five analyses were updated for this conference: ATLAS is pushing deep into unexplored regions of phase space with both simple and complex search topologies. The up-to-1.2 fb^{-1} of

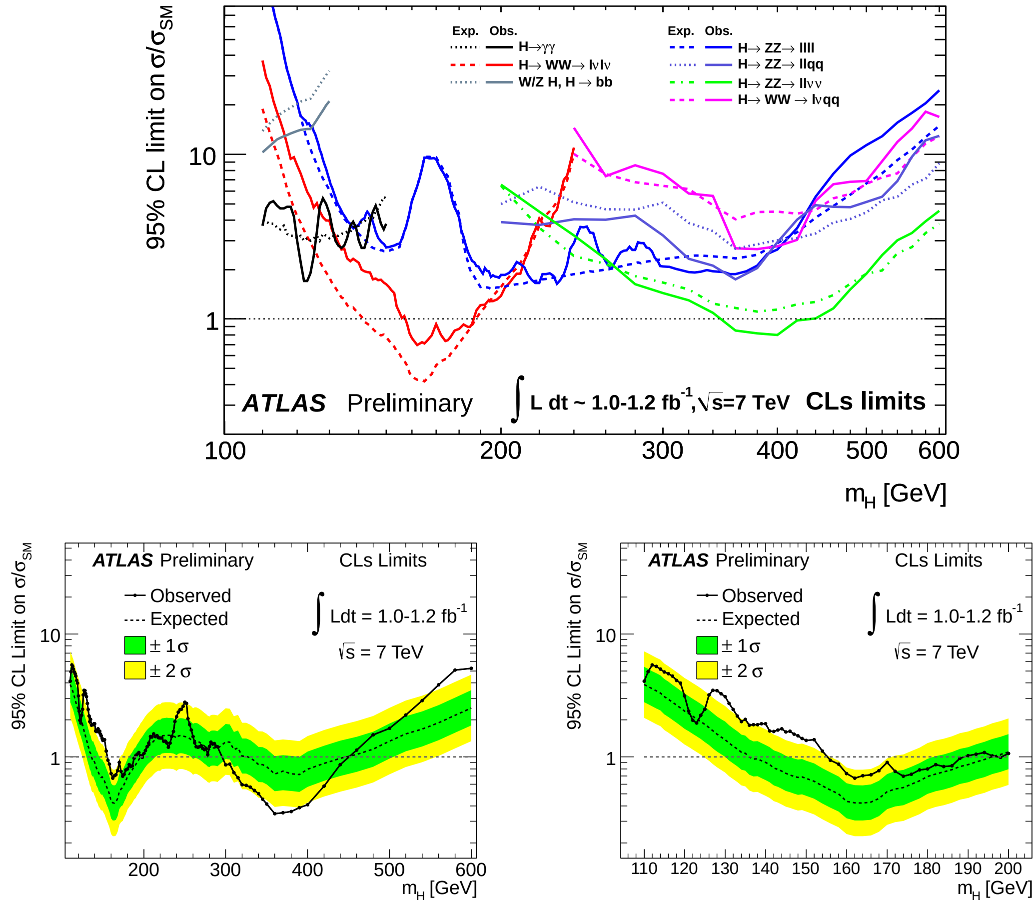

Figure 14: Constraints on Standard Model Higgs production cross-sections. Top: Comparison of the limits obtained from different channels; below: Combined limit (solid line) together with the expected limits, and the expected variation of them (green and yellow bands). The two plots cover different m_H ranges [31].

2011 data analysed by the time of the conference has brought a major increase in new physics sensitivity compared with 2010.

At this time early in the summer, there was no very significant evidence of Standard Model Higgs boson production, but thanks to the excellent LHC and ATLAS performance large swathes of mass were excluded at the 95% CL: specifically the regions 155-190 GeV and 295-450 GeV. The analysis of the full 2011 data sample promises much.

Acknowledgments

ATLAS is a huge collaboration and the results presented here provide only the briefest summary. It was a privilege to show just the tip of the iceberg of the combined work of many hundreds of people over, in many cases, many years. Although it is difficult to pick out specific names, I must mention Fabiola Gianotti, amongst several others, for her help with preparing the presentation, and to Klaus Mönig for proof-reading these proceedings (but any remaining errors, of course, are mine).

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