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Colloquia: TOP2010

First results and status of the ATLAS detector at the LHC

P. Mättig for the ATLAS Collaboration
Bergische Universität Wuppertal - Wuppertal, Germany

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Summary. — The road with early ATLAS data towards top physics is discussed. This includes a detailed understanding of the detector performance for key components of top quark decays like jets, tracking and lepton identification as well as measurements on minimum bias and underlying event physics. The status of these studies based on the first tens of nb^{-1} is presented.

PACS 13.85.-t – Hadron-induced high- and super-high-energy interactions (energy > 10 GeV).
PACS 13.85.Ni – Inclusive production with identified hadrons.
PACS 13.85.Qk – Inclusive production with identified leptons, photons, or other nonhadronic particles.
PACS 13.87.-a – Jets in large-Q^2 scattering.

1. – The LHC environment

The LHC has collided its first proton bunches at $\sqrt{s}$ of 900 GeV in November 2009. Since then it has increased the energy to 7 TeV and the instantaneous luminosity by several orders of magnitude. At the time of TOP2010 some 15 nb^{-1} had been collected by ATLAS, at this time of writing a factor about 70 more data has been accumulated. Given the rapid progress in accumulated luminosity, only a snapshot of the fast-moving data analysis is possible.

Even though recent data open a wide spectrum of physics studies, still a substantial amount of work in ATLAS is devoted to understanding detector performance and to optimise algorithms to characterise physics objects. This will be addressed in this report. In addition measurements of soft QCD physics, *i.e.* minimum bias and underlying event studies, will be presented.

2. – The ATLAS detector and its performance goals

The ATLAS detector [1], being 44 m long and 25 m in diameter, is the largest detector at an accelerator ever built. It contains innermost precision tracking devices immersed in a 2 Tesla solenoidal magnetic field, electromagnetic and hadronic calorimetry, and on its

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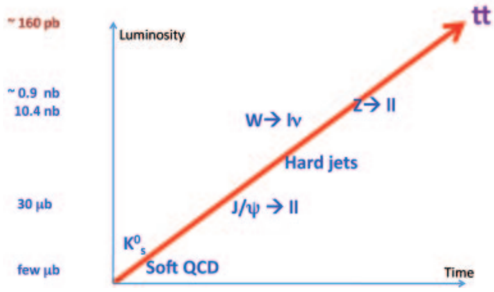

Fig. 1. – Major processes that lead to an understanding of the components of top quark decays. Also indicated are the typical cross sections at $\sqrt{s} = 7\,\mathrm{TeV}$.

outside a muon spectrometer in a toroidal magnetic field. The ATLAS detector covers almost the whole solid angle of up to pseudorapidities $|\eta| = 4.9$ for the calorimetric and $|\eta| = 2.5$ for tracking measurements.

From the beginning of LHC collisions, the detector operates with very high efficiency and all its components have 98–100% of the electronic channels functioning. More than 94% of the luminosity produced by LHC in stable beam conditions is recorded by ATLAS.

The prerequisite for getting the most physics out of the millions of top quarks that will eventually be produced at the LHC and the anticipated new physics is a thorough understanding of the detector performance. The ATLAS strategy is to derive the understanding of the physics objects as much as possible from data and therefore substantial effort is devoted to reach this objective. Even though an excellent foundation has been laid by test beams and several hundred millions of cosmic ray events, the ultimate precision can only be obtained from collisions, supported by a detailed simulation of the detector. The road to the top (and beyond) proceeds in the steps shown in fig. 1. Measurements of these physics processes will provide the confidence to identify and study top quark events which in turn eventually will be an efficient tool to calibrate the physics objects.

3. – Detector performance

Exploring top quark events requires all parts of the detector to be well understood. Tracking is needed for bottom tagging and lepton identification, electromagnetic calorimetry for electron, the outer muon system for muon identification, and both electromagnetic and hadronic calorimetry for jets. Finally all these measurements have to come together to determine the missing transverse energy (MET).

3˙1. *Tracking system.* – The ATLAS tracking detectors comprise an innermost pixel detector, a silicon strip detector and the transition radiation tracker. The quality of track reconstruction depends largely on alignment, material distribution and hit efficiency. Tracks in minimum bias data have been extensively studied —comparing data and simulation shows a remarkably good agreement.

Many hadron resonances have been observed that can be used to determine the quality of the tracking system. Especially the precisely known and highly abundant K^0_s meson decays are used by ATLAS to determine the momentum scale and resolution and to estimate the material before and inside the tracking detector. The reconstructed mass

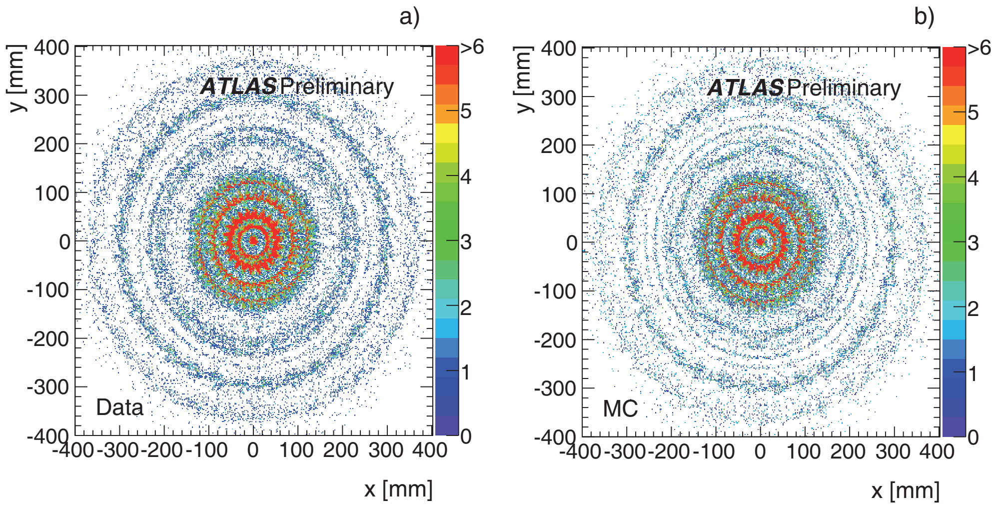

Fig. 2. – Distribution in the transverse plane of locations of photon conversions $\gamma + X \rightarrow e^+e^-$ in data (left, a) and simulation (right, b).

of $0.497 \pm 0.001\,\text{GeV}$ is in perfect agreement with the PDG value. By determining the mass as a function of radius, η and the azimuthal angle ϕ, the amount of material in the detector is mapped. These studies suggest that the material is largely simulated correctly in the inner detector, and is underestimated by at most 10% in some regions. The material distribution in terms of the radiation lenghts can also be measured using photon conversions (fig. 2). Although in general data and simulation agree very well, differences in detail are observed, which will be corrected in the future simulations.

The transverse impact parameter d_0 of tracks is particularly important for the identification of bottom, and to some extent for charm quarks and τ leptons. The simulation of d_0 agrees in general very well with data as a function of the transverse momentum approaching the goal of $\sigma(d_0) \sim 10\,\mu\text{m}$ for high-p_T tracks. The high precision in d_0 translates into an excellent measure of bottom decay vertices. As an example, the distribution of high decay length significances $L/\sigma(L)$ indicative of bottom quarks (fig. 3a) from a secondary vertex tagger shows the long tail expected for bottom decays. Zooming into the events with a large decay length significance, the invariant mass of the tracks associated to the secondary vertex shows nicely the cut-off from the charm mass and the power and quality of the data (fig. 3b).

3˙2. *Electrons and muons*. – Charged leptons can be tested in the decay of resonances like J/ψ and eventually the Z^0. In fig. 4, as an example, the J/ψ peak is depicted, its shape being in very good agreement with the expectation. The response of the calorimeter to electrons is checked using photon conversions and found to be in very good agreement.

3˙3. *Jets*. – A large number of di- and multiple jet events have been found in ATLAS, with invariant masses extending deep into the TeV range, already now providing probes of an as yet unchartered territory. The jet energy calibration in ATLAS proceeds in several steps. The first one is to exploit isolated charged particles and compare their energy E measured in the calorimeter and the momentum p determined with the tracking system.

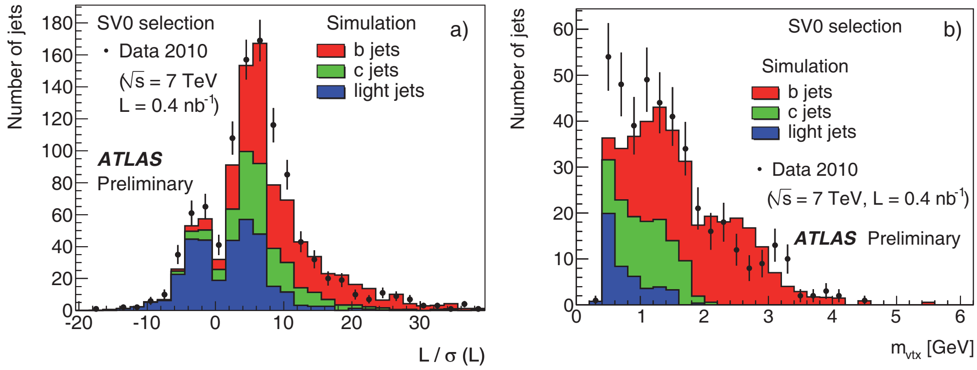

Fig. 3. – Distribution of the decay length significance $L/\sigma(L)$ in minimum bias events at 7 TeV (left, a). Invariant mass of tracks assigned to a secondary vertex with a decay length significance larger than 7 (right, b).

The E/p ratio rises with the momentum between 1 and 20 GeV and is described by the simulation to better than 5%, providing confidence in the quality of the detector description. In a next step the simulation is used to apply corrections for jet energies using global corrections for the electromagnetic and hadronic parts of the detector and dead material. The observed p_T^{jet} distribution agrees very well with the expected one (fig. 5a). In the future corrections will be used which are based on the local energy deposition.

3˙4. *Missing transverse energy*. – As already known from the discovery of the W boson, the measurement of the missing transverse energy is a powerful tool to identify (and measure) the existence of a neutrino and may eventually reveal the existence of a dark matter candidate. Its quality is largely determined by the understanding of "hot cells" of electronic noise in the calorimeter. Those can be identified by dedicated studies, only a small fraction of 10^{-5} of the jets is affected. The remaining jets show a remarkable agreement with the expectation (fig. 5b).

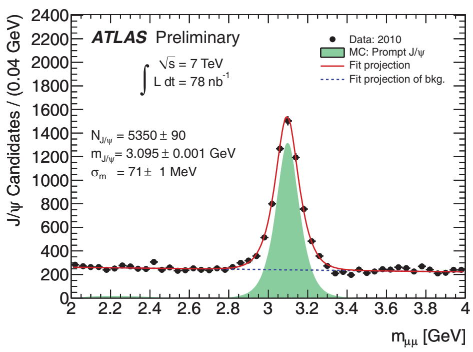

Fig. 4. – J/ψ signal in $\mu^+\mu^-$ final states.

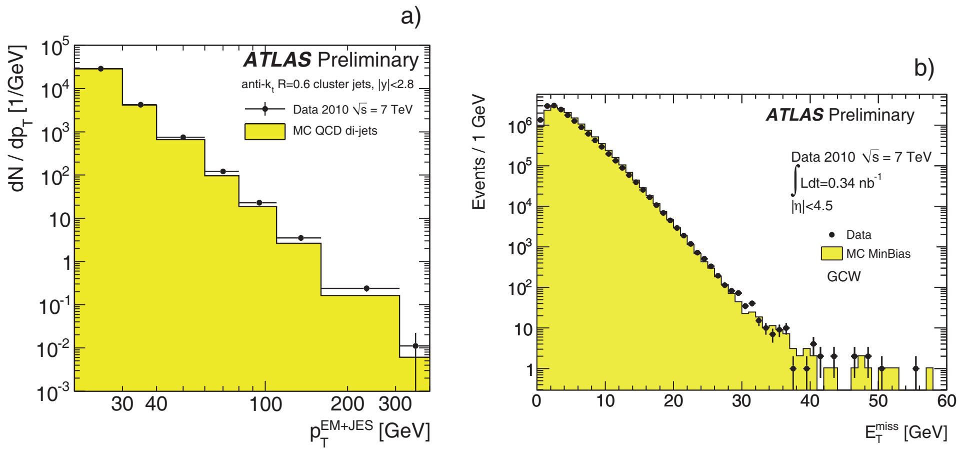

Fig. 5. – Distribution of jets as a function of transverse momentum p_T after calibration (left, a) and distribution of the transverse missing energy (right, b). Both distributions are compared to the PYTHIA model with MC09 tune.

4. – First electroweak physics

As these discussions on the detector performance underline, ATLAS is prepared for electroweak physics—all physics objects for the exploration of $W^{\pm}$ and Z^0 bosons and also top quarks are very well understood. Indeed with increasing luminosities candidate events for the vector bosons have been observed. At the time of the conference these were only a handful, meanwhile several hundred have been found in ATLAS. Top candidates have only appeared recently with luminosities exceeding $100\,\text{nb}^{-1}$. Candidate events for $W \to e\nu$ and $t\bar{t} \to e + \mu + jets + X$ are shown in fig. 6.

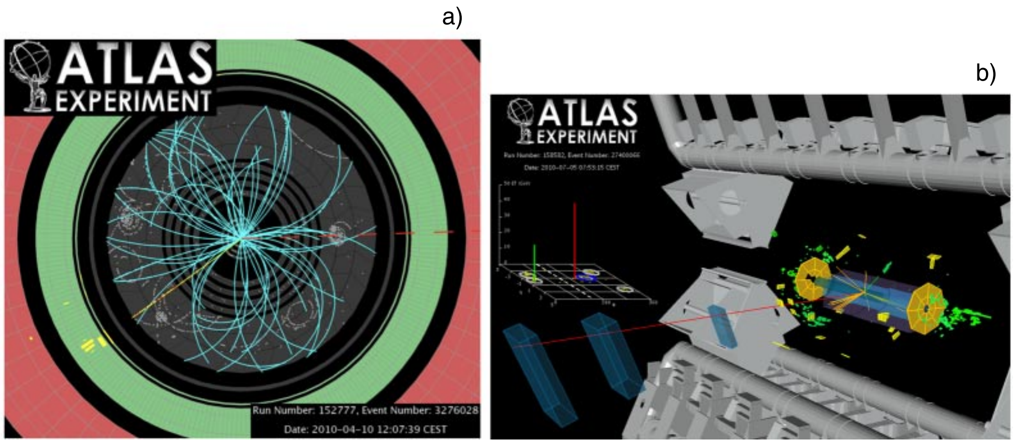

Fig. 6. – (Colour on-line) Candidate events for $W \to e\nu$ (left, a) and $t\bar{t}$ production (right, b). The electron in the W-decay is denoted by the yellow line, the MET by the dashed red line. In the case of the top quark pair, one top decays into an electron (green line), the other into a muon (red line).

5. – Minimum bias physics

With the increased bunch intensity also the number of concurrent proton-proton interactions rises, disturbing the measurements of the interesting hard interactions. The knowledge of these minimum bias events is therefore of importance to precisely study high-p_T physics. Furthermore, the theoretical predictions for these soft QCD events are rather uncertain and further constraints from different c.m. energies and phase space may illucidate this physics.

The ATLAS strategy to measure minimum bias events is somewhat different from the approach taken by other experiments. It is based on the principle to be as much as possible independent of the physics model. Therefore the data are unfolded to the hadron level and compared to the different models and parameter tunes without applying corrections for diffractive components.

ATLAS has measured particle densities and event properties for particles in a phase space region of $p_T > 500\,\text{MeV}$ and $|\eta| < 2.5$ [2]. Comparing the data to models, the main conclusions are

- The rapidity distributions show (fig. 7a,b) reasonable agreement for PYTHIA [3] with the ATLAS MC09 and MC09c tunes [4], whereas the DW [5] and Perugia0 [6] tunes significantly underestimate the particle yield. The same is true for PHOJET [7].
- All models and tunes have difficulties in describing the shape of the p_T spectrum.
- Both at 0.9 and, more significantly, at 7 TeV, high multiplicity events occur more often than predicted by all models. In particular PHOJET underestimates the high multiplicity events considerably. Note that diffractive events are expected to contribute strongest at low multiplicities.
- Models tend to overestimate the average p_T for high event multiplicities. This is particularly the case for 7 TeV (fig. 7c,d).

6. – Underlying events

Apart from the additional pp-interactions, the study of hard parton interactions is complicated by the "underlying events", *i.e.* residual contributions due to the colour flow among the proton remnants. A first ATLAS analysis at $\sqrt{s}$ 0.9 and 7 TeV [8] separates the plane transverse to the beam direction into four quadrants. The "toward" quadrant is defined by the highest p_T track. The opposite quadrant is the "away" region, the transverse quadrants "transverse regions". The idea of this method is that these transverse regions are largely unaffected by the hard process and therefore yield an unbiased picture of the underlying event.

The particle density as a function of ϕ, the angle with respect to the leading particle in the transverse plane is shown in fig. 8. The distributions show an accumulation of particles around the trigger particle which becomes more and more pronounced with the energy of the leading particle suggesting an evolving jet structure. The density in the transverse region also rises with the leading p_T. The measurements are compared to the PHYTHIA MC09 tune. Whereas the transverse region is fairly well described for a leading $p_T > 1\,\text{GeV}$, it significantly underestimates the density in the transverse region for higher p_T. The difference is more pronounced for 7 TeV than at 0.9 TeV.

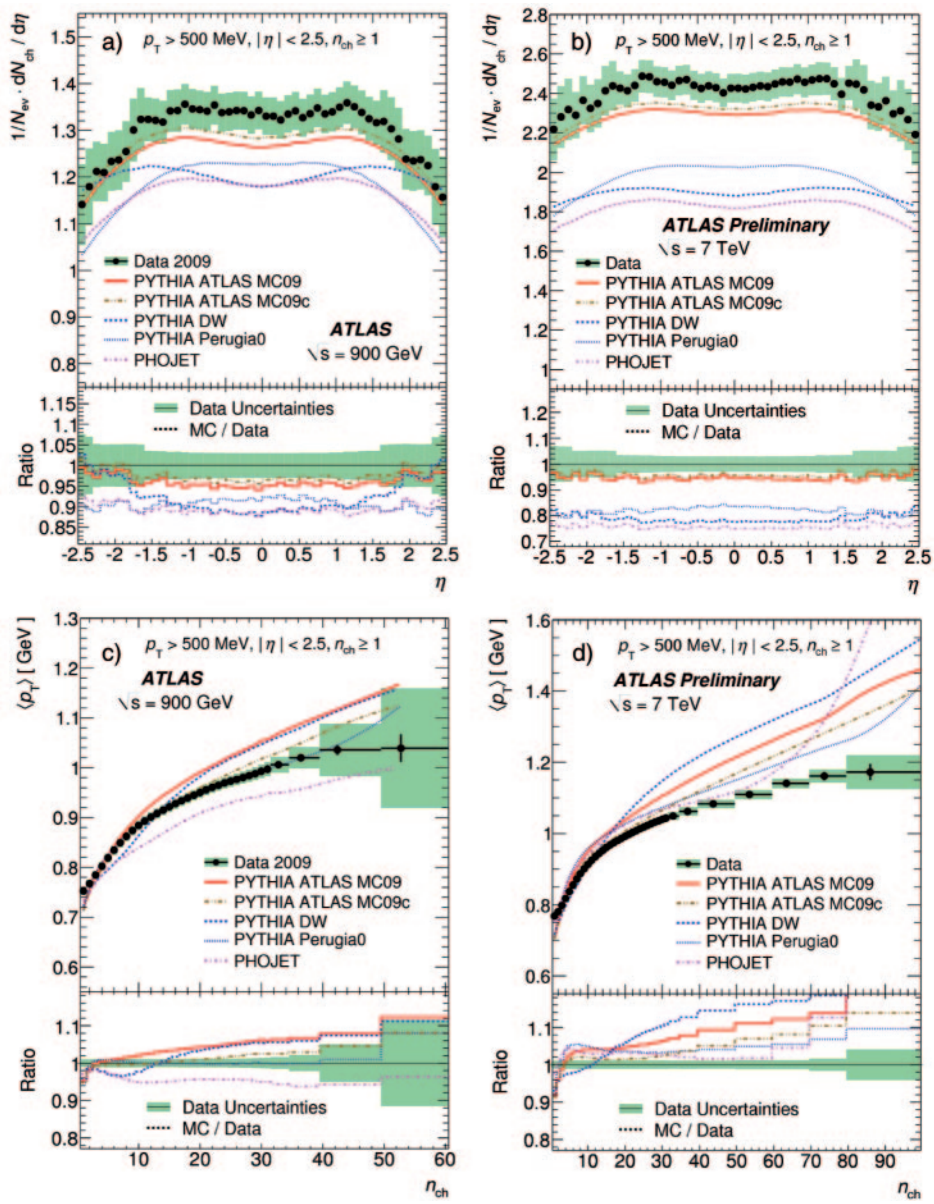

Fig. 7. – Particle density as a function of pseudorapidity η (a,b) and the average transverse momentum p_T as a function of charged particle multiplicity (c,d). The data are compared to the PYTHIA model with various tunes and the PHOJET model.

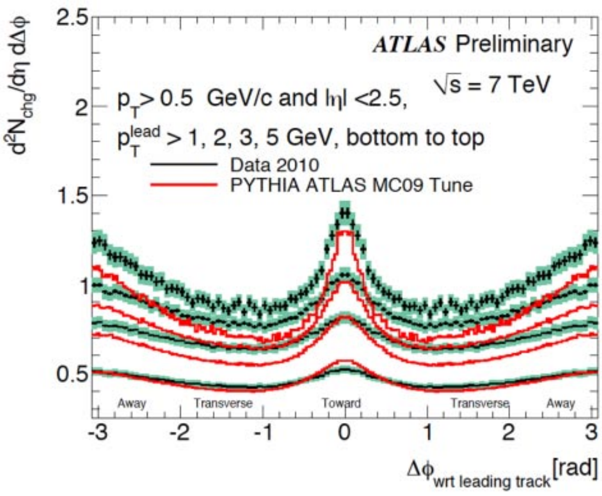

Fig. 8. – Particle density as a function of the angle in the transverse plane with respect to the leading particle. Note that the distributions are mirrored for the positive and negative ϕ ranges.

7. – Conclusions

The LHC is progressing fast and its luminosity is used by ATLAS to scrutinize the detector performance with collision data and to enter the physics of a new energy regime. All studies show that even after data worth a few months, the ATLAS detector is highly efficient, remarkably well understood and already now close to its design goals.

With the current more than $1\,\mathrm{pb}^{-1}$, ATLAS has entered the multi-TeV regime of jet physics and accumulated a data set of several hundreds of leptonically decaying $W^{\pm}$'s and Z^0's, opening the electroweak sector of LHC physics. Whereas at TOP2010 top quark events were eagerly expected, by now several candidates have been found. Top quark physics is on the verge of becoming reality at the LHC with several thousands of top-quark pairs expected until the end of this year, holding the promise for an exciting physics harvest at the top and beyond the Standard Model physics.

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