The ATLAS experiment: overview and main results

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Abstract

The status and recent performance of the ATLAS experiment at LHC is described. Selections of the most important recent results are presented together with the exclusion limits for a number of searches for new physics processes obtained using the ATLAS detector at LHC.

1. Introduction

The ATLAS experiment was designed to search for new physics phenomena that can manifest themselves at the high energies accessible at the Large Hadron Collider at CERN. The design of the detector [1] was optimized to search for the Higgs boson in the largest possible mass range, for possible heavy W- and Z-like objects, for new physics processes such as supersymmetry or compositeness of the fundamental fermions, and to maximize the discovery potential for new, unexpected physics. The construction of the detector was completed in 2008 and its final shape and performance are very close to the original design. The detector is illustrated in Fig. 1. The central (barrel) region has a cylindrical geometry. Particles emerging from the proton-proton collision point at the detector’s axis traverse a tracking system enclosed in a 2 Tesla solenoid magnetic field. Surrounding the magnet are the electromagnetic and hadronic calorimeter systems. Outside of the calorimeters a superconducting, torroidal spectrometer of integrated field \(\sim 4Tm\) is used to identify muons and to measure their momenta. The cylindrical barrel of the detector is complemented by a set of two end-cap assemblies of tracking, calorimeter.

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and muon detection systems providing an almost hermetic coverage for both primary and secondary collision products. A detailed description of the detector is collected in Ref [2]. L. Hervas has given a brief summary of its performance at the HEP-MAD09 conference [3].

![Cut away view of the ATLAS detector.](image)

The design performance [2] of the ATLAS detector is briefly characterized by the momentum resolution of reconstructed tracks in the inner tracking detector and the muon spectrometer, as well as the energy resolution of the electromagnetic and hadronic calorimeters:

- For the inner tracker, $\sigma/p_T \sim 3.8 \times 10^{-4} p_T \text{ (GeV)} \oplus 0.15$ in the central region;
- For the muon spectrometer, $\sigma/p \sim 10\%$ for muon tracks of up to 1 TeV;
- An electromagnetic energy resolution of $\sigma/E \sim 0.1/\sqrt{E}$ (E in GeV) and a hadronic energy resolution of $\sigma/E \sim 0.5/\sqrt{E} \oplus 0.03$ (E in GeV).

Performance studies based on both cosmic ray and collision data are in excellent agreement with Monte Carlo predictions based on the design parameters. To quote some examples:

- In the inner tracker, the precision of the track direction determination is $0.80 \pm 0.02$ mrad (polar angle) and $0.164 \pm 0.004$ mrad (azimuthal angle) [4]. The invariant mass resolution for reconstructed $\phi \rightarrow K^+ K^-$ decays is $2.5 \pm 0.5$ MeV [5].
The jet energy scale uncertainty (JES) depends on the jet energy and the detector region. For jets in the central barrel region with $60 \text{ GeV} < p_T^{\text{jet}} < 800 \text{ GeV}$ JES $\sim 2.5\%$, while for all jets of $p_T^{\text{jet}} > 20 \text{ GeV}$ measured in all detector regions, JES $\sim 4.6\%$ [6].

The scale factor $k$ associated with parametrizations of the mean missing transverse energy, $E_T^{\text{miss}} = k \sqrt{\Sigma E_T}$, is well predicted ($k=0.42$ for $Z \rightarrow l^+l^-$ decays and $k=0.51$ for jet events) [7].

There are about 90 million detector readout channels in the ATLAS detector. For each subdetector system, the fraction of live channels is greater than 97%. The electronics dead time effects, occasional calorimeter noise problems and other down time result in an overall operational efficiency of $\epsilon = 95.3\%$.

2. ATLAS observables

The event processing software is used to calibrate and transform the raw signals from individual detector elements into the measurements of the main observables used for data analyses.

- Electrons are identified as reconstructed, isolated tracks matched with electromagnetic clusters measured in the calorimeter. In most of the present data analyses, the direction is measured from the track information while the energy is measured from the calorimeter.

- Photons are identified by electromagnetic showers reconstructed as clusters in the calorimeter with no associated tracks. Those photons that convert into the $e^+e^-$ pairs in the beam pipe or in the inner silicon tracker and have two well-measured tracks are identified by their very low invariant mass and a vertex separated from the origin of the proton-proton collision event. Additional, often asymmetric in energy sharing, photon conversions with only one reconstructed track are recovered by selecting those tracks that do not have signals in the inner silicon microstrip tracking detector and have high ionization signature in Transition Radiation Tracker.

- Muons are selected as isolated tracks measured both in the inner tracker and in the outer muon spectrometer with matching momenta and directions.

- Jets are selected using the anti-$k_t$ algorithm [8] applied to the signals coming from the electromagnetic and hadronic calorimeters.

- b-jets are a special case of hadronic jets due to the relatively long lifetime of the parent particles containing b quarks. The decays of hadrons containing b quarks produce vertices that are spatially separated from the original point of collision. A selection requirement on the flight path is imposed that exceeds the number of standard deviations expected due to the multiple scattering of charged tracks in the material of the beam pipe and the tracker, $L/\sigma(L) > 5.7$.

- $E_T^{\text{miss}}$ - the energy imbalance in the transverse plane - is obtained by summing up all topological clusters in the calorimeters.

The examples of a b-jet and of a muon track taken from the detector display graphs are shown in Fig. 2.
3. Data collection

The number of collected events is related to the instantaneous luminosity $L$ reflecting the intensity of the beams and integrated luminosity $L_{\text{int}} = \int L \, dt$ by the relation

$$N_{\text{ev}} = \int dt \, \sigma \, A \, \epsilon,$$

where $\sigma$ is the cross section for a given process, $A$ represents the geometrical acceptance and $\epsilon$ is the data collection efficiency.

The LHC has performed beyond expectations since the first proton-proton collisions in November 2009 at a center of mass energy of $\sqrt{s} = 900$ GeV. During the initial 2010 run, ATLAS collected data at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity $L_{\text{int}} = 46$ pb$^{-1}$ with a peak instantaneous luminosity $L = 2.1 \times 10^{32}$ cm$^{-2}$s$^{-1}$. During 2011, ATLAS accumulated 2.5 fb$^{-1}$ of data until August, with a peak instantaneous luminosity $L = 2.5 \times 10^{33}$ cm$^{-2}$s$^{-1}$, an increase by over a factor of 50.

Additional data samples obtained with lead-lead ion collisions at $\sqrt{s} = 2.76$ TeV per nucleon will not be discussed here.

The high luminosity comes at a price of pileup, i.e., multiple proton-proton interactions occurring during each bunch crossing. ATLAS collects data with an average pileup of 6.2 events in each LHC bunch crossing. This puts a special strain on track finding, which so far copes well with the identification of separate interaction vertices. An example of the tracking software being able to find 7 vertices in one beam crossing is shown in Fig. 3.
During 2011, the LHC has operated with a beam configuration for which the proton bunches are spaced in time by 50 ns. In order to deal with about $10^8$ interaction per second, out of which only few hundred can be recorded by the data acquisition system, a set of special triggers has been installed to select events of interest for subsequent physics analysis. The main triggers select events compatible with: electrons of transverse momentum above 20 GeV; muons of transverse momentum above 18 GeV; jets above 180 GeV; and events with $E_T^{\text{miss}}$ greater than 60 GeV. Additional triggers are used for calibration and monitoring purposes. Minimum bias events with no high $p_T$ secondaries are collected at low beam intensity for verification studies and tuning of the Standard Model parameters used by Monte Carlo event simulation packages.

4. Physics results

It is not possible to discuss all recent ATLAS results in detail since in the last 18 months there have been over 60 journal publications and over 200 conference notes [9]. In the following, only a summary of the selected results will be presented.

A general method of a search for new physics in collider experiments is to look for deviations from the expectations based on known physics and to interpret the results within the framework of a specific model. The first step in such process is to verify that we can describe the “known” physics observables well.

4.1 Measurements of low-$p_T$ charged particle production

Quantum Chromodynamics (QCD) provides a good description of existing Standard Model processes involving strong interactions. For high-$p_T$ processes, perturbative QCD calculations are successful. At low-$p_T$, recent models are based on QCD but require tuning of the approximations needed to compare data and theory in the non-perturbative QCD region. This is a case for the low-$p_T$ charged particle properties measured in minimum bias events, or measured (with respect to the jet axis) in hadronic jets. The
agreement can be tested by measuring multiplicity and kinematic distributions of charged particles in minimum bias events \[10\] and hadronic jets \[11\] and comparing them to the Monte Carlo predictions. In each case, selected results are discussed in this paper. Data were collected at 900 GeV and 7 TeV using low proton beam intensity to minimize background from multiple interactions in the same bunch crossing. The effects of beam-induced backgrounds and cosmic rays have been estimated to be less than 1%. The measured distributions are corrected for the efficiency, trigger effects and geometrical acceptance.

In the case of minimum bias data, the charged particle multiplicity has been studied in different kinematic ranges of rapidity and transverse momentum, and compared with different PYTHIA tunes \[12, 13\]. An example for central production with \(|\eta| < 2.5\) is shown in Fig. 4. The distribution is well described by the Monte Carlo predictions over about 10 orders of magnitude.

Figure 4: Charged-particle multiplicities as a function of the transverse momentum for events with \(n_{ch} \geq 1, p_t > 500\) MeV and \(|\eta| < 2.5\) at \(\sqrt{s} = 7\) TeV \[10\]. The dots represent the data and the curves the predictions from different Monte Carlo models. The vertical bars represent the statistical uncertainties, while the shaded areas show statistical and systematic uncertainties added in quadrature. The bottom insert shows the ratio of the Monte Carlo expectations over the data. The values of the ratio histograms refer to the bin centroids.
The number of jets originating from the fragmentation of quark and gluons produced in the proton-proton collisions is also well described by QCD. However, the properties of particles within the jets must come from phenomenological models of parton showers and hadronization [14]. In a dedicated ATLAS study, collimated “jets” of charge particles have been identified. These jets are reconstructed from charged tracks using the anti-$k_t$ algorithm [8] and corrected for efficiency and kinematical effects. Jet 4-momenta are obtained by adding four-vectors of all selected particles. The distribution of jet transverse momentum is shown in Fig. 5.

![ATLAS](image)

Figure 5: The cross section for anti-$k_t$ charged particle jets as a function of $p_T$, with $|\eta| < 0.5$ and radius parameter $R = 0.4$ [11]. The shaded area is the total uncertainty for the corrected data distribution, excluding the overall 3.4% luminosity uncertainty. The data are compared to a range of theoretical results from Monte Carlo event generators, which are normalized to the data over the full momentum and rapidity range measured. The bottom inserts show the fractional difference between these distributions and the data.

The fragmentation variable $z$ measures the fraction of the longitudinal momentum of a jet carried by the charged particle within the jet. The corresponding distribution is shown in Fig. 6. Shown here are the distributions for a larger radius parameter, $R=0.6$. This data
selection has a higher efficiency for low momentum tracks that can deviate from the jet axis. Superimposed are the results of the Monte Carlo generation of events using Pythia 6.421 event generator [15] with several additional tunes. The description of the data appears to be good although none of the tunes agrees with the measurements in all kinematical ranges. Further improvements of the tunes are currently under study.

Figure 6: The distribution of the fragmentation variable $z$ for anti-$k_t$ jets with radius parameter $R = 0.6$, in the rapidity range $|\eta| < 1.9$ for five momentum ranges [11].

The production of the gauge bosons: $Z$, $W$ and $\gamma$ is less sensitive to the details of the fragmentation function and the phenomenology depends only on the parton distribution functions, pdf, describing a fraction of the parent proton momentum carried by quarks and gluons into the collisions. Simulations using the CTEQ5L pdf’s [16]– probability distributions for individual quarks and gluons to carry given fractions of parent proton momentum, describe the gauge bosons cross-sections and kinematic distributions very well [17].

4.2 Supersymmetry

Supersymmetry (SUSY) is a candidate theoretical extension of the Standard Model motivated by a need to protect the Higgs boson mass from divergent radiative corrections. It proposes an invariance under a symmetry that transforms fermions into bosons and bosons into fermions [18] thus allowing for cancellations of the divergent
terms. In an unbroken SUSY each Standard Model particle has a partner with the same mass and with spin that differs by ½. Since no such particles are observed, SUSY must be broken. Phenomenological extensions of the SUSY e.g., Minimal Supersymmetric Standard Model –MSSM - introduce a large number of free parameters. Addition assumptions are made that typically reduce that number to 5. An interesting feature introduced to the models to account for an apparent conservation of the baryonic and leptonic quantum numbers is the R parity that is equal to +1 for Standard Model particles and -1 for their SUSY partners. The consequence of R parity conservation is that SUSY particles must be produced in pairs and the lightest SUSY particle is stable. Popular models assume that the lowest mass supersymmetric particles are light, i.e., they can be produced at LHC and that they are neutral and escape detection. Such neutral particles carry the momentum leading to $E_T^{\text{miss}}$ – the transverse energy imbalance in the observed events and as a bonus they are candidates for Dark Matter. The specific selection and interpretation of parameters depends on the model. In mSUGRA, where SUSY breaking is mediated by the gravitational interactions, the lightest particle is the neutralino, while for GMSB, where the breaking is obtained via additional gauge field, the lightest particle is the gravitino.

The missing transverse energy, $E_T^{\text{miss}}$, is a powerful indicator of potential SUSY signal, but it can also arise from many known Standard Model process, e.g., neutrino production, as well as from the imperfection of the detector and from the inaccuracy of the measurements. Thus, a detailed understanding of all possible backgrounds is a necessary component of such studies.

The shape of the $E_T^{\text{miss}}$ distribution has been studied in detail in the context of measuring the W boson production cross-section. The distribution, shown in Fig.7, is very well described by the sum of the backgrounds and the expectation of the signal Monte Carlo. Since the overall normalization is arbitrary, the explicit search for supersymmetry effects has to be done within a context of a specific model.
Figure 7: Transverse momentum distribution for events with at least three tracks including an isolated muon with $p_T > 25$ GeV [19]. Only statistical errors are shown.

Several independent searches for the SUSY signal were made by studying events with at least one, two or three jets and either zero, one or two leptons. In Fig. 8 the $E_T^{\text{miss}}$ distribution is shown for selected events with at least three hadronic jets and an electron with $p_T$ greater than 25 GeV [20]. The spectrum is very well described by the sum of the expected backgrounds and is inconsistent with an existence of additional signal. The interpretation of such results can be done for an explicit model and the obtained limits are presented in Fig. 9 for specific values of fixed parameters and within the MSUGRA/CMSSM framework [21].
Figure 8: Missing transverse momentum in the electron channel, after requiring one electron with $p_t > 25$ GeV and at least three jets with $p_t > 60, 25, 25$ GeV [20]. The `Data/SM'' plots show the ratio between data and the summed Standard Model expectation. The uncertainty band on the Standard Model expectation combines the MC statistical uncertainty and systematic uncertainties on the jet energy scale and the lepton identification efficiencies. For illustration, the expected signal distribution of the MSUGRA/CMSSM model point for universal scalar mass $m_0 = 420$ GeV and gaugino mass $m_{1/2} = 300$ GeV is also shown.

Figure 9: Observed and expected 95% CL exclusion limits, as well as the ±1 sigma variation on the expected limit, in the combined electron and muon channels [20]. Results are obtained with the power constrained confidence level, PCL, technique. The plots also show the published limits from CDF, D0, and the results from the LEP experiments.
4.3 Bump Hunting

Another technique of searching for new physics consists of looking for resonant enhancements in the invariant mass distributions of pairs (or more) of particles or jets. A discovery may be claimed if an enhancement is inconsistent with the expected backgrounds from known processes. In the absence of an enhancement, the limits on the production cross-section times the expected branching fraction into the final state under study are obtained by simulating the signal and including the probabilities for the statistical fluctuations of the signal and each of the contributing backgrounds. This procedure has been applied to searches for heavy vector bosons as well as for excited quarks, supersymmetric squarks and gluinos, axigluons, color octet scalars and various exotic objects with multiple charges and even lepton number violation decay characteristics. An example of such a search is shown in Fig. 10, where the invariant mass distribution of muon pairs is compared to the sum of backgrounds coming from heavy boson and t-bar pair production [22]. Also shown are enhancements predicted for a sequential Z-like heavy boson Z’. None of these enhancements are confirmed by the data and a detailed study of the mass dependence, shown in Fig. 11 allows to set the limits for the Z’ production at $M(Z') > 1.83$ TeV at 95% confidence level. Similar limits can be obtained for other models predicting resonant peaks in the spectrum of lepton pairs.

![Figure 10: Dimuon invariant mass distribution after final selection, compared to the stacked sum of all expected backgrounds, with three example Z' SSM signals overlaid [22]. The bin width is constant in log $m(\mu\mu)$.](image-url)
Figure 11: Expected and observed 95% C.L. upper limits on $\sigma \cdot B$ as a function of mass for $Z'$ models for the combination of the electron and muon channels. The thickness of the $Z'$ SSM theory curve illustrates the theoretical uncertainties.

4.4 Higgs searches

The Higgs boson is the only particle of the Standard Model that has so far not been observed. The electroweak theory does not directly predict the Higgs mass. The major constraint comes from an assumption that gauge boson scattering satisfies s-wave unitarity leading to a constraint

$$m_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1 \text{ TeV},$$

where $G_F$ is the Fermi coupling constant [23]. If such bound is not satisfied, the weak interactions among $W$, $Z$ and $H$ become strong at the 1 TeV energy scale. Within the Standard Model Theory the Higgs has spin zero and mass dependent couplings.

The search for the Higgs boson was one of the main motivations for the construction of the LHC and remains as one of the most important activities for the ATLAS Collaboration. In the last few months data have allowed for searches in many Higgs decay final states, including di-bosons ($\gamma\gamma$, $ZZ$ and $WW$), $\tau$ pairs, associated production and various MSSM channels. A detailed description of those searches is given in the contribution by Craig Wiglesworth to this conference [24]. No signal has been detected so far. Fig. 12 illustrates the limit obtained from the combination of the results of searches for Standard Model Higgs completed by August 2011. The data exclude the possible mass ranges of $146 < m_H < 232$ GeV, $256 < m_H < 282$ GeV and $296 < m_H < 466$ GeV. A Higgs mass below 114.4 GeV is excluded by the LEP experiments. Searches for high mass Higgs are limited by the theoretical knowledge of its width.
Figure 12: The expected (dashed) and observed (solid) 95% C.L. upper limits on the cross-section, normalized to the SM cross-section, as a function of the Higgs boson mass [25].

4.5 Summary of the searches

No unexpected signal has been observed so far in the extensive studies of the ATLAS data summarized in over 200 conference notes and papers. A summary of the searches [26] illustrating the mass limits for the new phenomena is shown in Fig.13. An exploration for possible signatures of new physics awaits an increased data sample.
5. Conclusions

Searches for new physics done with $\sim 1$ fb$^{-1}$ of ATLAS data have not shown any evidence for new phenomena so far. Most of the studies provide a lower limit reaching and sometimes exceeding the 1 TeV mass range. No evidence for Supersymmetry has been seen to date. The mass range for a possible Higgs signal has been substantially narrowed. The ATLAS detector works very well and the LHC machine delivers ever increasing luminosity. Thus, a data sample exceeding $4$ fb$^{-1}$ may be realistically expected by the end of this calendar year. This should be sufficient to provide a more definite answer about the existence of the Higgs boson. These are exciting times.

References:


