SELECTED RESULTS FROM THE ATLAS EXPERIMENT ON ITS 25th ANNIVERSARY

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Abstract. The Lomonosov Conference and the ATLAS Collaboration celebrated their 25th anniversaries at a few weeks interval. This gave us the opportunity to present a brief history of ATLAS and to discuss some of its more important results.

1 The ATLAS History

The Letter of Intent (LoI) of the ATLAS Collaboration was submitted to the LHCC committee on the 1st of October 1992 [1]. This date has been retained as the date of birth of the ATLAS Collaboration. The 18th Lomonosov Conference was held few weeks before the 25th anniversary of ATLAS, giving us the opportunity to look backward to the ATLAS history and recall a selection of its most important results, while ATLAS is still collecting data during the LHC Run 2. In 1992, the landscape of particle physics was very different from the one of today. Two fermions were still to be observed (top quark and τ -neutrino), CP violation in B mesons and oscillations of neutrinos were not discovered yet, and the Higgs boson was still an hypothesis.

After the LoI acceptance, the ATLAS Technical Proposal was presented in 1994 [2]. ATLAS Experiment was approved in 1996 and the construction of its subdetectors started in 1999. Subdetectors R&D efforts started even before 1992, by testing new ideas and validating them in dedicated collaborations, before adapting them to ATLAS.

The installation in the ATLAS cavern started in 2004 and lasted until 2008. ATLAS recorded its first LHC collision in 2009. During the Run 1 of the LHC, ATLAS recorded 50 pb⁻¹ in 2010 and 5 fb⁻¹ in 2011, at a centre of mass energy of $\sqrt{s} = 7$ TeV and 21 fb⁻¹ in 2012 at $\sqrt{s} = 8$ TeV. The main improvement to ATLAS during the first long LHC shutdown (LS1) in 2013-2014 was the upgrade of its pixel detector with a fourth innermost layer. During Run 2, ATLAS collected 87 fb⁻¹ in 2015, 2016 and 2017 at $\sqrt{s} = 13$ TeV.

2 The ATLAS Detector

The ATLAS Detector [3] is made of three main systems: The Inner Tracker called Inner Detector (ID), the calorimetry system and the muon spectrometer.

The innermost components of the ID, made of silicon detectors (four pixel layers followed by eight microstrip layers) deliver high resolution hits for precise tracking and reconstruction of vertices. The outer part is made of thin gaseous straws which provides continuous tracking. The ID is immersed in a

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Figure 1: Transverse impact parameter resolution as a function of transverse momentum in 2012 (three pixel layers) and 2015 (four pixel layers) and ratio between the two periods [4].

Figure 2: Fractional jet energy systematic uncertainty as a function of transverse momentum for jets at $\eta = 0$ [6].

2 T uniform magnetic field created by a superconductor solenoid magnet for momentum measurements. Precise tracking covers pseudorapidities up to $|\eta| = 2.5$. Figure 1 [4] shows the resolution on transverse impact parameter as a function of the transverse momentum, for Run 1 and Run 2 after the insertion of the fourth innermost layer during LS1 [5].

Electrons and photons are measured by the liquid argon/lead electromagnetic calorimeter. It uses accordion-shaped absorbers and electrodes, allowing an excellent hermeticity and an easy implementation of fine granularity and longitudinal samplings. It is housed in three cryostats (one barrel and two endcaps, the barrel one containing also the solenoid magnet). π^0 mesons can be discriminated from photons thanks to the very fine granularity of the first sampling up to $|\eta| = 2.4$, while the acceptance goes up to $|\eta| = 3.2$.

Jets are reconstructed using the ID and the whole calorimeter system, including the hadronic component (scintillators/iron in the barrel, liquid argon/copper in the endcaps, and liquid argon/copper or tungstene in the forward). Forward calorimetry covers pseudorapidities between 3.2 and 4.9, while the two first techniques cover lower values of $|\eta|$. Jet energy is calibrated using both simulation and data-driven methods. Systematic error on the jet energy scale is one of the most important for various measurements and searches. It is shown in Figure 2 [6] as a function of the jet transverse momentum.

Missing transverse energy is computed by assuming transverse energy conservation using all reconstructed objects without double-counting between ID, calorimeters and muon spectrometer.

The muon spectrometer is based on three air-core toroid superconductor magnets (one in the barrel and two in the endcaps, each having 8 toroids housed in

cryostats). Toroids are instrumented with various kinds of muon chambers, for triggering and tracking, up to $|\eta| = 2.7$. Momentum measurement of muons benefits from both ID and muon spectrometer.

Identification of b-jets (b tagging) is used in a large fraction of physics analysis (top physics, SUSY searches...). b-jets are tagged by exploiting the long lifetime of B hadrons, which gives large impact parameters and secondary vertices. Thus it relies on the performance of the silicon pixel detector. After the insertion of the fourth innermost layer, the light jet rejection has been improved by a factor 4 for the same b-jet efficiency.

3 Selected Results

The discovery of the Higgs boson has been the main goal for LHC physics program. The general purpose detectors at LHC (ATLAS and CMS) were optimised to achieve this goal over all the theoretically allowed mass region, using different channels and reconstructed objects. Simulations of the discovery potential of the Higgs boson were done at each step of ATLAS before the start of LHC. ATLAS (and CMS) discovered the Higgs boson in 2012, using 2011 data at $\sqrt{s} = 7$ TeV and part of 2012 data at $\sqrt{s} = 8$ TeV, resulting in a total integrated luminosity of 10.7 fb^{-1} [7]. The discovery channels were the Higgs boson decay into bosons $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ where $4l$ stands for two electron pairs, two muon pairs or a pair of each. It is worth noticing that the obtained local significance (5.9 standard deviations at $m_H = 125$ GeV) was not far from the result of the last simulation campaign in 2008 [8], for a Higgs boson mass of 120 GeV and 10 fb^{-1} at $\sqrt{s} = 14$ TeV. Since then, results on two fermionic decays have been published: The observation of $H \rightarrow \tau^+\tau^-$ in 2015 [9] and an evidence for $H \rightarrow b\bar{b}$ in 2017 [10]. Figure 3 shows the $b\bar{b}$ invariant mass, where the Higgs boson contribution can be clearly seen besides the Z peak.

Since its discovery, measurements of the Higgs boson properties became one of the main LHC topics. ATLAS demonstrated the scalar nature of the discovered particle using the angular distributions of its four lepton decays [11]. The Higgs boson mass has been measured with a 0.2 % precision. More details are given in these proceedings [12].

Studying the top quark is the other important topic at LHC. LHC proton-proton collisions are a copious source of top quarks. It is the heaviest known elementary particle, and it decays before hadronisation, transmitting its properties to its daughter particles, making the properties measurable. The weak production of single top has been measured by ATLAS at all delivered centre of mass energies. Such measurements are sensitive to specific electroweak and QCD observables. In 2017, ATLAS observed the first production of single top associated with a Z boson [13], as it is shown on Figure 4. This channel fea-

Figure 3: Distribution of bb invariant mass after subtraction of all backgrounds except WZ and ZZ processes [10].

Figure 4: Neural network output after the fit of components contributions. The contribution of tZ production is visible [13].

tures the tZ coupling and is a background for the search for tH production. Details can be found in these proceedings [14].

The recent measurement of the W boson mass m_W by ATLAS [15] is a nice example of electroweak measurements at LHC. A competitive value of m_W has been obtained using $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays, by fitting the charged lepton transverse momentum and W boson transverse mass. Figure 5 shows the ATLAS measurement together with LEP and Tevatron measurements. Combined with Higgs boson and quark top masses, no deviation from Standard Model predictions is found, as shown in Figure 6.

Production of W and Z bosons is used to investigate QCD (e.g. multijets production [16]) and electroweak physics (e.g. triboson production [17] [18]). More can be found in [19] in these proceedings. Here we show the cross section of $Z + 1$ jet as a function of the jet transverse momentum (Figure 7) and the cross section of $Z +$ jets production as a function of exclusive jet multiplicity (Figure 8) [16]. We can see that NLO generators reproduce the jet transverse momentum distribution within uncertainties, providing a test for QCD scaling, while the number of jets produced with a Z boson is well reproduced up to 3 jets, beyond which the fraction of jets produced by parton shower becomes non negligible.

The high energy provided by LHC enables to look for new particles at unprecedented high masses. These searches concern not only particles predicted by the most popular theory beyond the Standard Model, namely SUSY ([20] in these proceedings), but all kind of heavy objects, like illustrated in Figure 9 which shows two photons invariant mass up to 2.5 TeV, and the absence of

Figure 5: ATLAS m_W measurements compared to LEP and Tevatron results [15].

Figure 6: Comparison between m_W and m_t measurements by ATLAS and a global electroweak fit of both masses using the LHC measurement of the Higgs boson mass [15].

Figure 7: Cross section of $Z + 1$ jet production as a function of the jet transverse momentum, and predictions/data ratio [16].

Figure 8: Cross section of $Z + N$ jets production as a function of N , and predictions/data ratio [16].

Figure 9: Diphoton invariant mass for the spin-0 hypothesis, with the background-only fit [21].

Figure 10: Diphoton invariant mass after applying the acoplanarity $A_{co} < 0.01$ cut [24].

any peak [21]. ATLAS searches for dark matter [22] and exotic Higgs boson decays [23] are also summarized in these proceedings. No supersymmetric nor any other new particle has been observed so far.

ATLAS pursues also a program of heavy ions physics (lead-lead collisions at $\sqrt{s_{NN}}$ up to 8.2 TeV) where the strong interaction is scrutinized in its quark-gluon plasma regime and its collective sector. Measurement of light by light scattering $\gamma\gamma \rightarrow \gamma\gamma$ has been achieved recently [24]. The $\gamma\gamma\gamma\gamma$ vertex is forbidden in the Standard Model, but it occurs via box diagram. The process is rare ($\propto \alpha_{EM}^4$), but the two photons rate in the initial state is enhanced by the atomic number of lead nucleus ($\propto Z^2, Z = 82$). Figure 10 shows the observation of this process.

4 Conclusion and Future

The ATLAS Collaboration is exploiting the LHC potential to extend our knowledge on elementary particles and their interactions. Next steps in the Higgs sector will be the improvement of its measured couplings and measuring $t\bar{t}H$ coupling and Higgs boson self-coupling. Such measurements will validate the mass generation mechanism in the Standard Model. Searches for new particles are ongoing. Top quark, electroweak and QCD measurements are constraining the Standard Model and could give indirect access to new physics in near future.

The immediate future will be the end of the LHC Run 2 by the end of 2018, with an accumulated data sample which will certainly be higher than the ex-

pected 120 fb^{-1} . During the two years of the following shutdown (LS2), ATLAS will upgrade its calorimetric trigger and replace the inner endcap muon chambers. During the three foreseen years of Run 3 (2021-2023), ATLAS expects 150 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$. LS3 will then be devoted to prepare the High Luminosity LHC (HL-LHC) by installing a new tracker, replacing the readout electronics of calorimeters and muon system and upgrading trigger and data acquisition. The HL-LHC era will start in 2026. About 3000 - 4000 fb^{-1} are expected, which will allow new measurements like Higgs boson self-coupling and rare decays and will extend search limits.

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