ATLAS Run-2 status and performance *

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Abstract

During the 2013/2014 shutdown of the LHC the ATLAS detector has been improved. A new silicon pixel detector layer has been installed, and the muon detector coverage has been improved substantially. In addition nearly all other parts of the detector have also been revised to adapt them to the higher pileup conditions or make them more robust in general. This talk will describe these improvements, and how they affect the performance of physics objects. The initial results showing the detector performance as obtained from cosmic runs and/or initial beam data will also be shown.

Keywords: ATLAS, commissioning, Run-2

1. Introduction

The ATLAS experiment [1] is designed to record the results of proton-proton collisions from the Large Hadron Collider (LHC) [2]. During the so called Run-1 (2010-2012), the LHC delivered luminosity at two different centre-of-mass energies: 5.46 fb^{-1} at 7 TeV and 22.8 fb^{-1} at 8 TeV. ATLAS recorded 94% of all p-p collisions and certified 95% of this sample as good data. The success of this campaign peaked with the first observation of the Higgs boson in 2012, as the main missing ingredient of the Standard Model, and is demonstrated by the publication of more than 400 physics papers and 600 conference notes.

Having been designed as a discovery experiment, ATLAS explores extensions beyond the Standard Model (BSM), either via direct observation of new TeV-scale particles or via indirect measurements of anomalies in already well established signals. With Run-1 data, precision measurements of the Higgs mass (at the 0.2%

level in combination with CMS), its couplings and spin/parity are still ensuring consistency with Standard Model [3]. Concurrently, many ATLAS studies are directed toward top quark measurements, considered as good probes for searching BSM (with correlated studies of W, Z bosons), focusing on $t\bar{t}$ resonances and simultaneous measurements of the quark properties. Direct observations, with different extension models, are mainly focused on electroweak production of charginos and neutralinos, squark pair production and a variety of inclusive SUSY searches, as well as observations of narrow resonances at high mass [4].

1.1. New energy horizons

Expectations are very high for the just-started Run-2 (2015-2018), where the LHC is colliding protons at unprecedented centre-of-mass energy: 13 TeV. The ATLAS physics program will continue with extended potential: for example at this energy Higgs production will mostly increase by a factor two, even more in associated productions (up to four times in $t\bar{t}H$).

After two-year shutdown (Long-Shutdown-1, LS1), the LHC is ready to operate at new Run-2 design parameters, rising maximum peak luminosity up to $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with a maximum of 50 interactions per collision (also called pile-up) and 25ns bunch spacing,

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for a total integrated luminosity of 100-150 fb⁻¹. Initial LHC commissioning progressed quite fast, with no single source of problem, starting on April 5th with the first protons circulating in the ring. The full commissioning phase is expected to last 57 days, while the planned Run-2 proton physics period is ~30 weeks at 50ns bunch-spacing and ~70 weeks at 25ns. Summer is dedicated to 50ns to 25ns bunch spacing transition. During this first commissioning phase, ATLAS collected different types of data: beam-splashes (deluge of particles across the detector during the injection tests) and collision data during the LHC energy ramp-up, from 900 GeV to 13 TeV, with different beam conditions. On June 3rd, the first stable beam collisions were established: the ATLAS infrastructure was ready, with detector control system, trigger and monitor infrastructure working smoothly. Overall, the detector readiness at the start of beam injection period was higher than 98%, the remaining few % being under final commissioning.

2. What's new in ATLAS

During LS1, ATLAS performed tasks to consolidate all its components and, where possible, upgrading them to be more eco-friendly: CO₂ cooling added for new components, leaks repair campaigns, addition of shielding and a new aluminium beam pipe to reduce radiation. In the infrastructure, big changes of components were aimed at increasing the up-time of the detector: new electrical and power network, vacuum loop, magnets operations, He compressors, cooling and ventilation. Upgrades of detectors, described in detail later, are aimed to consolidate and to increase robustness against high radiation level. They also include: extension of acceptance, as described in the Technical Design Report, installation of one new component, the Pixel Insertable-B-Layer (IBL[5]), and a new Trigger/DAQ infrastructure. Computing and software were also upgraded with new data management and analysis tools.

The Point-1 ATLAS cavern was a hive of activity for more than two years. The integration of all sub-detectors started in February 2014, with full shift crew and millions of cosmic ray data collected, useful for alignments of tracking detectors and muon systems. At LHC startup, low luminosity collisions and beam splashes were used for internal timing alignments at bunch-crossing level and adjustments of the LHC clock phase for all signals distributed by the new Central Trigger Processor.

In the following sections we will give an overview of upgrades and current performance of all ATLAS components.

3. Muon spectrometer upgrades and performance

Upgrades of the muon spectrometer during LS1 were driven by two main ways of improvements.

The first set of improvements were targeted towards increasing the muon acceptance, with new or repaired chambers. There were almost 30 thin gap chambers (TGC) and a few cathode strip chambers (CSC) repaired or replaced, accessed with specially designed lifting devices and acrobatic operations. The production of new chambers started in 2012 and the installation was concluded by the end of 2014. Final completion of the spectrometer acceptance was already foreseen for this shutdown period, with new resistive plate chambers (RPC) placed in the barrel holes due to the toroid feet and elevators (+2.8% acceptance) and extra endcap chambers. Other improvements were the reduction of level-1 trig-

Figure 1: Dimuon invariant mass distribution for oppositely charged, combined muon pairs with transverse momentum above 4 GeV and pseudo-rapidity $|\eta| < 2.5$ GeV. The following resonances are clearly visible in the spectrum: J/Ψ , Ψ' , Y resonances, and Z [6].

ger rates in the endcap region ($|\eta| > 1.05$), dominated during Run-1 by slow particles not coming from the interaction region. Significant improving of muon purity is expected, with a 30% rate reduction, by adding coincidences with inner TGC layers and with external Hadronic/Tile calorimeter (this part will be commissioned later during Run-2).

At the beginning of Run-2, the overall system is timed-in and aligned: toroid magnets were off during first collisions to facilitate alignments of the new muon stations. The newly designed readout system for the CSC is installed and fully operational up to 100 kHz (it was limited in Run-1). The achieved performance of the

muon spectrometer is demonstrated by the good quality identification of all main known resonances in di-muon invariant mass spectrum, as shown in Fig.1.

4. Calorimeters upgrades and performance

A common strategy for the calorimeter subsystems during LS1 was to increase reliability of detectors. New on-detector power supplies, consolidated electronics and improved data and power transmission have been the major improvements. They will result in smaller systematics uncertainties in Run-2, including those for jet energy scale and resolutions.

The hadronic calorimeter (Fe/Sci Tile) underwent consolidation of electronics, with new low-voltage power supplies and Cs calibration system. During the shutdown, a campaign to recover inactive readout channels reduced the fraction of masked channels to less than 2%.

The liquid argon calorimeter (LAr) extended consolidations on LV power supplies and FE boards, with the addition of a new FE demonstrator for future Run-3 (a good example of R&D during data taking). The full system was 100% ready at the beginning of Run-2 and recorded beam-splash events for internal timing calibrations.

The level-1 calorimeter trigger electronics is enriched with new modules to reach higher flexibility with limited change of electronics, based on new technologies, for processing the trigger algorithms (and ASICs replaced by FPGAs). For example extended memories and processing capabilities allow powerful signal processing for missing-energy calculations, with dynamic pedestal subtraction based on global cell occupancy and in-bunch train positions, in order to increase energy resolution. Moreover this system required upgrades to interface to the new level-1 topological trigger, discussed later in this paper.

The calibration of calorimeters started with the first collisions at 13 TeV, during the May 2015 commissioning. Good performance, compared with Run-1 and simulations at 13 TeV, is visible since then. For example, we observed the correct π^0 peak in the invariant mass of di-photon candidates, even without any data-driven energy scale correction. The spectrum of jet transverse momentum, measured with topological clusters and calibrated at the electromagnetic scale, shows good agreement with expectations. Missing energy resolution, measured with topological clusters using LCW (Local Cluster Weighting) and with quiet beam conditions, are comparable with Run-1 performance studies at 7 TeV (as shown in Fig.2).

Figure 2: Resolution of missing- E_T components as a function of total transverse energy, as measured in a data sample at 13 TeV during quiet beams in May 2015. The resolution compares favourably with the results shown in performance studies at 7 TeV ($0.49 \sqrt{\Sigma E_T}$) over an enlarged energy range [7].

5. Inner tracker upgrades and performance

Being in the inner core of the ATLAS detector, upgrades of the tracking system have been the most challenging project during LS1 and its installation drove all the cavern activities. In particular, a big effort was pursued for the delicate extraction of the most inner detectors, which allowed extensive repairing campaigns of the sub-detectors.

The external tracking detector (transition radiation tracker, TRT) operates to its limit in the new high radiation environment, but is still crucial for reducing fake electrons and photon conversions, orthogonally to the calorimeters. To cope with gas leaks (abundant during Run-1 due to ageing corrosion of outflow pipes), the recovery strategy included the change of Xe as active gas with Argon, when needed (less expensive, but with 10 times reduced absorption of transition-radiation), and the addition of remote gas regulation. The first collected data showed that the tracking performance is not affected by this change of active gas.

More internally placed, the semiconductor strip tracker (SCT) detector was upgraded with additional readout drivers for operations at higher collision rates. New faster electronics, with improved optical transmitters, increases the readout robustness. The new system is fully operational and timed-in. The most inner tracker, closer to the beam-pipe, is composed of Silicon Pixel detectors. During LS1, the original 3-layer detectors were made more robust against optical link failures with a new service panel, at easy access.

As anticipated, the major upgrade project for LS1 is the IBL, an additional 4th inner pixel layer, mounted directly on the beam-pipe. It greatly increases the res-

Figure 3: The radial vertex position distribution for hadronic interaction candidates reconstructed from multiple tracks with $> 5\sigma$ transverse impact parameter significance. The distribution exhibits peaks consistent with hadronic interactions occurring within the new ATLAS beam pipe and the insertable B-layer (IBL) in addition to the original three Pixel layers. The hadronic interaction candidates are required to be reconstructed within $r > 20$ mm and $|z| < 300$ mm. Due to impact parameter cuts, the efficiency depends on the radius. No attempt has been made to correct for this [8].

olution in track and vertex reconstruction (crucial for b-tagging) and ensures good performance against radiation damage, even recovering the loss of efficiency of the original detectors. Three different technology sensors are now operational in the Pixel detector, for future upgrade studies (both planar and 3D sensors are mounted). The IBL installation, anticipated by almost two years, suffered from wire-bonds corrosion, so new modules were produced in record time. Now it shows more than 99% live channels. Being routinely readout during cosmic ray runs and first collisions, a larger than expected thermally-induced twisting of the staves was observed, at the level of a few $\mu\text{m/K}$: it might require refinements of operating procedures, with careful temperature control at the level of 0.2 K.

Since first "quiet beam" collisions, the full inner tracker was operational and the tracking performance monitored, based on new optimised tracking and vertex algorithms. A global monitor of the tracking system is shown in the so-called tracking radiography as in Fig.3: the radial position of reconstructed vertices indicates hadronic interactions along the way from the interaction point, across the new beam-pipe and IBL, towards the external layers.

6. Forward detectors for luminosity measurements

To reach the ultimate precision at the 2-3% level on luminosity measurements, ATLAS uses the combined effort of different detectors, which also have been upgraded mostly because of radiation damage.

The upgrades include: new minimum bias trigger scintillators (MBTS), useful for low energy/low interaction rate runs, such as first collisions, calibration scans and heavy ion runs; new LUCID (luminosity Cherenkov integrating detector) for high quality luminosity measurements, suitably made radiation hard; upgraded ALFA-system (four Roman Pots on each side of ATLAS), with new heat protection system and additional horizontal Roman Pots to improve acceptance.

All these detectors were active during first collisions and started monitoring collision quality (for example measuring the average number of pp-interactions per bunch crossing) and providing first luminosity measurements. A few pre-calibration with mini Van Der Meer scans were made during dedicated LHC commissioning runs.

7. Trigger/DAQ upgrades and first commissioning

The ATLAS trigger and data acquisition system had major upgrades during LS1, prepared to deal with trigger rates globally increased five times compared to Run-1: factor two due to the energy increase (higher for high p_T jets) and factor two-three due to the rise of luminosity. All the improvements are meant to reduce the trigger rates to acceptable levels, while maintaining or even improving efficiencies compared to Run-1, in the most challenging conditions and with limited upgrades of the electronics. The strategy is to enrich the selections with more sophisticated and flexible algorithms, both in hardware and software.

The first level of selection (called level-1) is applied in custom hardware processors, within $2.5 \mu\text{s}$ latency, and reduces the rate from the initial bunch-crossing rate (40MHz) to 100 kHz (was 75kHz in Run-1). This system, which makes use of the calorimeters and muon coarse information, had a few upgrades. As already described in the previous sections, the calorimeters and muon level-1 triggers have enhanced performance in Run-2. In addition, a new topological processor was added, which can select specific exclusive signatures at low energy, combining event-level quantities (such as angles and invariant masses). This new component allows mainly to increase the acceptance for those final states based on missing transverse energy, jets and τ 's (like $ZH \rightarrow \nu\bar{\nu}bb$ and $H \rightarrow \tau\tau$). As a result of the more complex selections, a new Central Trigger Processor (which processes all the trigger signals) was deployed, with limited latency and an increased number of input and output signals. All the level-1 sub-systems used first collisions for timing adjustments and then provided triggers for collecting data at low luminosity, with online

monitoring and calibrations running smoothly. The new level-1 components are under final commissioning. Detailed studies of latency and deadtime are still on-going to protect detector readouts (expected few % deadtime at 100 kHz), and will be decided by detector occupancy.

In Run-2, the ATLAS trigger system has a reduced number of levels: the original two high-level software triggers that worked successfully in Run-1 were merged into one single level (called high level trigger, HLT). This reduction allows to decrease the data transfer by a factor 2.5 and to improve trigger algorithms (optimised during LS1 to reduce CPU resources). Consequently, the DAQ system was simplified and significantly upgraded (in both software and hardware), with a single network and a single farm of processors (running merged algorithms), instead of two. Remaining Run-1 bottlenecks were removed, with increased data bandwidth for the Readout System, exploiting advantages of new technologies, and the final recording rate raised from 400 Hz to 1 kHz, thanks to computing upgrades. The new HLT system has the same Region-of-Interest approach as in Run-1, but with a flexible event-building strategy, so that algorithms can access both partial and complete event data, with the advantage of having more offline algorithms used online, with easier maintenance and increased sharing of resources.

After testing the new trigger/DAQ architecture successfully, the validation of the trigger selections started, slowly enabling HLT selections during low-luminosity stable collisions runs at 13 TeV. In total the larger number of level-1 (~300) and HLT (~1000) selections and the addition of more dedicated multi-object selections give rise to larger flexibility and extended potential. A new upgrade phase is expected by the end of 2015, when the installation of the fast tracker (FTK) [9] is foreseen, an hardware processor that will enable tracking feature extractions in less than 100 μ s.

8. Computing, software and analysis

The computing resources do not scale accordingly with new Run-2 challenges, characterised by higher pile-up (30 to 40 interactions per collision), more complex events and a target higher trigger rate (1kHz, 1.5GB/s data throughput). During LS1, a lot of effort was put into ensuring more flexibility and less artificial boundaries within the computing architecture, giving rise to newly designed computing model, production system and data management tools. We also developed a new analysis data model, with new analysis tools and reduced analysis dataset types, to improve data storage capability and processing. Since the first LHC col-

lisions, data transfers and processing on the grid was ready and the new architecture started being commissioned (with Tier sites recently organised in Clouds). Data processing software has been made more robust against high level of pile-up, with a factor four gain in CPU resources (20% gain measured for full simulation). The expected 48-hours calibration loop started after first 13 TeV collisions: three to four days were needed for reconstructing complete physics objects, four to six days for data intended for end-user analysis. The heavy Monte Carlo production is now running at full speed in the new architecture, producing simulated events for the current 50ns bunch-crossing and preparing for the coming 25ns.

9. Conclusions and plans

After two years of hard activities to improve the detector and the full experiment infrastructure, ATLAS is ready to explore new energy and luminosity scenarios offered by the LHC proton-proton collisions in Run-2, with improved discovery potential.

Millions of cosmic rays, beam splashes and first collisions at 13 TeV are used to tune the full infrastructure and confirm that ATLAS is performing as expected, starting from the detector operation to data processing and analysis. Fast commissioning of all the subsystems allowed to have first physics results promptly during the summer.

The ATLAS collaboration is preparing candidates for cross-section measurements with first 1 fb⁻¹ data, recorded during the 50ns intensity ramp. The expected rapid LHC luminosity raising during the first weeks of September, with a target of 5 to 10 fb⁻¹ for 2015, and the final 100 fb⁻¹ planned for full Run-2 will be useful to establish the Higgs decays into fermions ($\tau\tau$ and $b\bar{b}$) and observe rare decays (like $H \rightarrow \mu\mu$), but also to explore the TeV scale, while using precision Standard Model measurements as discovery tools.

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