ATLAS EXPERIMENT : HOW THE DATA FLOWS

(Trigger, Computing, and Data Analysis)

In order to process large volumes of data within nanosecond timescales, the ‘trigger’ system is designed to select interesting events quickly and efficiently. At the LHC design intensities, one billion events per second occur within the ATLAS detector but only one Higgs boson is produced in 10 seconds. It is not technically possible to store the data for all events, nor is it wanted; therefore the trigger is used to reject large numbers of events and retain only the interesting events. This is done in three successive stages by the trigger system, called the Level-1, Level-2 and the Event Filter triggers. Figure 6 shows a simplified drawing of the data flow, which is discussed in more detail below.

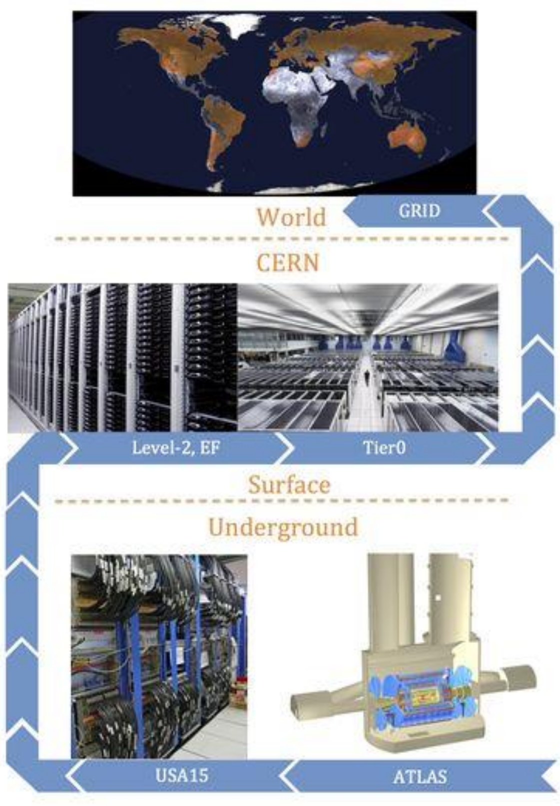

Figure 6: An illustration of the data flow path from the ATLAS detector to permanent storage on disk and tapes as described in the text.

The goal of the Level-1 trigger is to reduce the event rate from 40 MHz to 75 kHz, within a time frame of 2.5 microseconds. Some of the most interesting events, such as Higgs decays, contain energetic leptons, photons and jets and the Level-1 trigger uses specialized hardware to find these objects. This is done with two dedicated systems: the Level-1 calorimeter trigger and the Level-1 muon trigger. The Level-1 calorimeter trigger receives 7,200 analog signals from the electromagnetic and hadronic calorimeters, which are a sum of several calorimeter cells and therefore have a reduced granularity, with respect to that shown in Table 1. Using these signals, specialized hardware is used to search for patterns as expected for electrons, photons, τ-leptons and jets. The Level-1 calorimeter system can also calculate the amount of missing transverse energy in an event. Muon tracks are found by measuring hits in one plane and then searching for additional hits in nearby planes along pre-determined patterns. In parallel during this time, the analog signals from the interacting particles have been processed by the front-end electronics for all the sub-detectors. These signals are digitized and stored (either as analog or digital signals) in the so-called Level-1 buffer. The data waits in these buffers until the decision from the Level-1 trigger system is made. For each object found by the Level-1 systems, a 'region-of-interest' is identified. The number of identified objects passing different energy thresholds is then sent to the central trigger processor, which determines, for example, if a sufficient number of energetic objects has been found in this event. The central trigger has up to 128 different criteria to which to compare the event. If the event passes one of these criteria, a so-called Level-1 accept is sent to the detector, which signals to the front-end hardware to send the data to the Readout Drivers (RODs) for further processing. Otherwise, the data is removed from the Level-1 buffer.

Unlike the front-end hardware, the RODs are not located in the detector hall but in a room several dozen meters away, which is shielded from radiation. Here the data is stored and can be requested by the Level-2 and event filter trigger systems. To minimize the data transfer volume, the Level-2 system only requests detector information within the region-of-interests as specified by the Level-1 systems. Using commercial computers, the Level-2 systems runs more complex lepton, photon and jet identification algorithms using information from the tracking detectors, the muon spectrometer and in addition the full granularity information from the calorimeters. This system reduces the event rate to 3.5 kHz within 10 milliseconds. If the event passes one of 256 different Level-2 event criteria, the full detector information is transferred to the event filter system, where a final selection is run using commercial computers. The event rate is reduced at this stage to a few hundreds of Hz within one second. Over 17,000 computing cores are used in the Level-2 and event filter systems. If the event is selected, the data is transferred to permanent storage at the CERN computing centre. If it is not, the event is deleted from the RODs.

Once the event is saved, it still needs to be processed so that it can be analysed by ATLAS members. Here the computing system faces many challenges; it must process high volumes of data quickly and distribute that data to ATLAS collaborators around the world. For this a pyramid-structured computing model is used, called the Worldwide LHC Computing Grid (WLCG).

The CERN computing centre, called the Tier-0, processes all the data for the first time. This first processing plays an important role in understanding the detector. The conditions of the detector components and therefore the response can change over time or even malfunction. Some detector changes, such as the failure of a single channel can be corrected for but other problems, such as a malfunctioning power supply affecting many channels must be addressed immediately. An ATLAS member therefore monitors the data from each stage of the trigger live in the control room. At the Tier-0 a small set of data is processed within one hour, so that analysers can study the data in more detail within the next 24 hours. Data, which are unusable, are flagged so that analysers can reject these events. But a large fraction, approximately 95% of the data, is usable for analysis.

After processing at the Tier-0, the data is then copied to one or more of the Tier-1s, which are approximately a dozen large computing centres located worldwide. The Tier-1s re-process the data when needed. Small sub-sets of the data are copied to one or more of the roughly 150 Tier-2s, which are located mainly at universities and are the most convenient sites for ATLAS members to access the data. The Tier-2s are also the main production sites for generating the large samples of simulated events. For analysis, the data is stored in user-friendly formats, which contain information about the reconstructed objects for each event. Analysers then process this information on local computers and produce histograms of the data. This model enables researchers including students to analyse the data from their home institute.

Commissioning and Performance

The calibration of the ATLAS detector is a complex task and has involved the work of thousands of physicists. Two examples of the calibration are highlighted here: the determination of the detector's response to electrons, photons, muons and jets and the alignment of the tracking and muon systems.

The detector response refers to the determination of both the energy or momentum scale, which is an estimate of the amount of energy/momentum a particle had and the resolution, which is an estimate of how precisely that energy/momentum is measured. Before the detector was fully installed in the cavern, one important first study of the response was to place a small but complete slice of the ATLAS detector in a particle beam test at CERN. In this test in 2004, the beams of electrons, photons, pions and muon with energies between 1 and 350 GeV, were targeted on the detector components. The response of the detector is measured and then using the known energy of the beam, this response is calibrated into an amount of deposited energy.

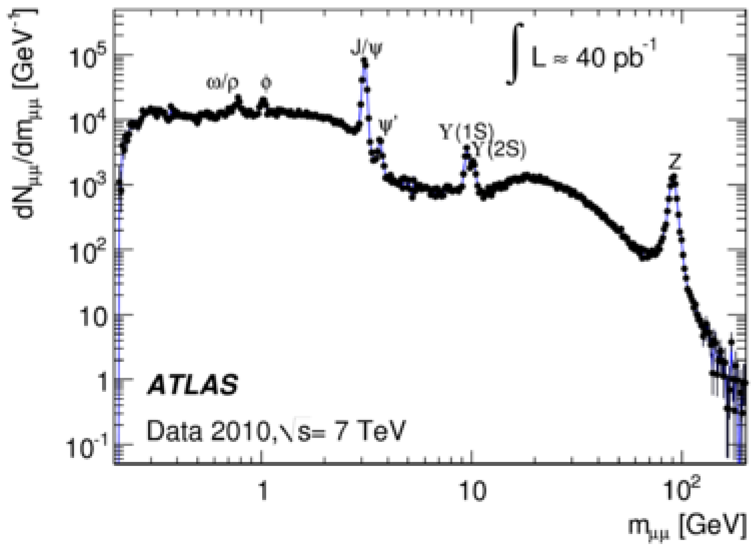

Figure 7: Invariant mass in GeV of events with two muons. The resonance peaks for the various mesons and the Z boson are labelled. EF_mu15 refers to the name of the trigger used to select the events.

To verify the detector response using particle beam test data as well as to monitor that response over time, well-known Standard Model particles are used. The Z boson, whose mass is well measured from the LEP collider experiments, can decay to two electrons or two muons with opposite charge. The invariant mass distribution, which is a reconstruction of the Z mass using its decay products, is then used to determine the energy scale and resolution of electrons and muons. Figure 7 shows the invariant mass distribution for muon pairs. The Z boson mass peak, as well as the mass peaks from the decays of mesons such as the J/ψ, are clearly visible. Studies of the decay products of the Z boson are also used to estimate the efficiency with which the detector finds electrons and muons.

Another important calibration for the tracking and muon systems is their alignment, which refers to the determination of the exact location of each tracking module or muon chamber. In order to precisely measure the bending of tracks from charged particles in the magnetic field, the location of each pixel or silicon module, for example, must be known to better than 15 microns. To test the alignment before the start of the LHC, the only available source of energetic particles were muons from cosmic rays. Between 2008 and 2009, the ATLAS detector collected signals from over 300 million cosmic ray muons. These events were used to establish a first, rough alignment and they were also a critical test of the full ATLAS readout system from the Level-1 trigger to the processing of the data on the Grid. To determine the final alignment, charged particles from the beam interactions are used. To achieve this, the trajectory of single, isolated tracks (i.e. a track which has no other tracks nearby) is measured and any misalignment of the components can be determined. Several million tracks are needed in order to determine the alignment of the pixel and silicon detectors.

The detector performance has immediate impact on physics measurements; a worsening of the photon energy resolution, for example would lead to a worsening of the two photon invariant mass distribution used for the Higgs discovery. Overall the performance of the ATLAS detector has been spectacular. Within only three years of LHC running, the calibration and performance of the detector has reached its design goals. The relative resolution for electrons, photons and muons is at the percent level over large momentum and energy ranges. These resolutions are summarised in Table 2.

Detector component	**Resolution**
Tracking	$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$
Hadronic calorimetry (jets)	
barrel and end-caps	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$TeV

Indicative resolutions of the ATLAS detector components. The units for energy E and transverse momentum p_T are in GeV. The symbol $\oplus$ means adding both parts in quadrature.

Source : http://www.scholarpedia.org/article/The_ATLAS_experiment