The ATLAS and CMS Detectors and Triggers for B physics

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The ATLAS and CMS detectors are the two general purpose experiments which will be operated at the LHC, and these have been designed to explore the full range of physics that can be accessed at LHC energies. With the large b production cross section and high luminosity foreseen, a substantial number of b-flavoured hadrons can be expected to be recorded. For both experiments, a brief description of the most relevant detectors, the trigger systems and the trigger strategy envisaged for B physics is presented.

The LHC is a proton-proton collider with a centre-of-mass energy of $\sqrt{s} = 14$ TeV and a bunch crossing time of 25 ns. For the first three years, a first phase with an instantaneous luminosity of up to $2 \cdot 10^{33}$ cm^{-2}s^{-1} is foreseen (*low luminosity*), for an average integrated luminosity of 10 fb^{-1} per year. The instantaneous luminosity in the initial running period is nevertheless expected to be lower. After this period, the luminosity will be raised to 10^{34} cm^{-2}s^{-1} (*high luminosity*), for an average integrated luminosity of 100 fb^{-1} per year. ATLAS and CMS are the two general purpose experiments which will be operated at the LHC, and these have been designed to explore the full range of physics that can be accessed at LHC energies.

With a total $b\bar{b}$ production cross section at $\sqrt{s} = 14$ TeV expected to be as high as 500 μb, a substantial number of b-flavoured hadrons can be expected to be recorded. Nevertheless, since this represents only a small fraction of the total pp cross section, a high background has to be dealt with. The performance of the B physics program is strongly dependent on the trigger menu and efficient trigger strategies are neccessary to identify decays of b-flavoured hadrons. Since the main emphasis of the ATLAS and CMS experiments is on high transverse momentum physics such as the search for the Higgs boson, only a limited trigger bandwidth will be available for B physics. Moreover, acceptable trigger rates have been reduced due to a reduction of the DAQ system at start-up. Both experiments will therefore concentrate on certain well defined topologies, such as decays to two muons, either from the decay of an intermediary J/ψ meson or from rare decays. B physics studies will be experimentally easiest at the initial low luminosity, where pile-up effects are small and vertex detectors very close to the beam pipe are expected to survive for several years. Much of the B physics program will therefore be performed during the first few years of LHC operation, although searches for rare decays can probably also be performed at higher luminosities, albeit at the price of higher background and reduced efficiency. Furthermore, it will be of special interest in the initial data-taking period, since many decay channels yield J/ψ mesons which are very useful for understanding the detector (calibration, alignment, B-field).

Both experiments have two-level trigger architectures. The Level-1 triggers are hardware-based triggers with custom-designed electronics. They use coarsely segmented data from calorimeter and muon detectors, while holding all the high-resolution data in pipeline memories in the front-end electronics. The trigger tables are focused on the detection of high energy electrons, muons and taus, on the presence of jets with large transverse energy, and of large missing energy. The High Level Triggers (HLT) are software triggers implemented in standard commercial computers, where b candidates are identified by doing a partial reconstruction of the decay products in the tracker in restricted tracking regions (also called *Regions of Interest – ROI*) and imposing invariant mass and vertex requirements.

Most of the B physics program will be based on the Level-1 dimuon triggers, with some use of single muon triggers. To confirm the muons and the decay in the HLT, the tracking regions are chosen around the direction of the muons identified at Level-1. The tracking regions can also be chosen around a Level-1 jet candidate, which would allow to identify hadronic decays. The single muon Level-1 trigger would then have to be used to select the muon arising from the decay of the second quark of the $b\bar{b}$ pair.

To fulfil this task, a robust and versatile tracking system within a strong magnetic field is essential. Track reconstruction will be a very challenging task due to the high number of tracks foreseen. At high luminosity, an average of 20 minimum bias events are expected per bunch crossing, which will produce more than 1000 reconstructible tracks in the tracker. This will result in track densities which can be as high as 10 tracks per cm^2 per bunch crossing at a radius of 2 cm. A very fine granularity is thus needed to resolve nearby tracks and a fast response time is needed to resolve bunch crossings. Reconstruction efficiencies have to be high and track parameters have to be measured with a good resolution over a large momentum range. The resolution on the transverse momentum is required to be between 1 and 2% at a track-momentum of 100 GeV/c to be able to reconstruct narrow resonances, and good impact parameter resolutions are needed to reconstruct secondary vertices. Furthermore, the trackers will see harsh radiation environments with very high particle fluxes. Therefore, to contain reverse annealing and limit leakage current, the silicon detectors will have to be operated between $-7°$ C and $-10°$ C.

1. The ATLAS experiment

1.1. The detector

Located inside a solenoid magnet generating a 2 T magnetic field, the Inner Detector (ID) [1] is a 110 cm-radius, 7 m long tracker composed of three sub-detectors, each employing a different technology. The first two detectors, a Pixel detector followed by a silicon strip tracker (SCT), offer precision tracking, and the outer straw tube Transition Radiation Tracker (TRT) offers continuous tracking and electron identification.

The Pixel detector [2] is composed of three cylindrical layers in the barrel, located at radii of 5.05 cm (*B-layer*), 9.85 cm and 12.25 cm, and three symmetric pairs of disks in the end-caps located at $|z| = 49.5$ cm, 56.0 cm and 65.0 cm. This layout ensures that only 2% of tracks up to $|\eta| < 2.5$ have less than three measurement points. The pixel size is of 50×400 μm^2.

The SCT is composed of four cylindrical layers in the barrel and nine symmetric pairs of disks in the end-caps. The barrel layers are approximately 1.53 m long and are located at radii between 30.0 cm and 51.4 cm. The end-cap disks are located between $|z| = 83.5$ cm and 278.8 cm.

The modules composing the SCT are all double sided, with detectors glued back-to-back with a stereo angle of 40 mrad. In the barrel, modules have axially oriented strips of 80 μm pitch, while in the end-cap, modules have a trapezoidal shape with keystone-shaped radially oriented strips. Four types of end-cap modules exist, depending on their radial placement on the disks, and each type has different dimensions and pitches, ranging from 63 to 85 μm at the centre of the module.

The TRT is a straw tube tracker. Its detecting elements are 4 mm diameter straws filled with a fast and robust gas mixture (70% Xe, 27% CO_2 and 3% O_2), with a 15 μm gold-plated tungsten wire in the middle. The straws are interspersed with a radiator to stimulate transition radiation (TR) from electrons In the barrel, 72 layers of axial straws are placed at radii between 56 and 107 cm. The end-caps consist of 18 pairs of multiplane wheels of radial straws. The straws in the first 14 wheels extend from $r = 64$ cm to 102 cm, and the inner radius of the straws in the last four wheels is reduced to 48 cm in order to extend the coverage to higher rapidities.

The readout electronics has two thresholds. The lower threshold detects ionisation signals in the gas, for which the *time-over-threshold* is also measured, while the higher threshold detects the

TR. To improve spatial resolution, the drift-time is measured. These informations can be used to separate electrons from pions. For an electron efficiency of 90%, a pion rejection factor of a 100 is obtained. In addition, by using dE/dx information, a K/π separation might be achieved.

The muon system [3] is located after the electromagnetic and hadronic calorimeters in an air-core toroid system which generates a 4 T toroidal field. It is composed of Resistive Plate Chambers, Thin Gap Chambers and Monitoring Drift Tube chambers.

1.2. The trigger

The Level-1 trigger [4] achieves a reduction from the initial 40 MHz bunch-crossing frequency to an accept rate of approximately 75 kHz with a latency time of 2.5 μs. The minimal threshold to retain a muon at Level-1 is 6 GeV/c. At a luminosity below 10^{33} cm^{-2}s^{-1}, it is foreseen that the requirement of a single muon above a p_T of between 6 and 8 GeV/c will be sufficient. For luminosities above that, two muons will have to be required, each with a p_T above 6 GeV/c.

The HLT [5] is then able to combine information from all detectors and is divided loosely in two stages. The first, called Level-2, performs a fast rejection within 10 ms to an accept rate of approximately 2 kHz. The second stage, the Event Filter, reduces the accept rate, with a latency in the order of one second, to approximately 200 Hz, of which between 10 and 20 Hz would could be used for B physics. It can be seeded by the Level-2 result and can access the full event. For the muon triggers, a more precise reconstruction of the muons would first be done in the muon chambers, followed by their reconstruction in the Inner Detector. A partial reconstruction of the event would then be undertaken in ROI around the Level-1 muon candidates and b candidates would be selected imposing invariant mass and vertex requirements.

Since the luminosity drops in the course of a run, it is foreseen to use the spare capacity for additional B physics triggers. Among these, to recover dimuon events where one of the two muons is below the p_T threshold, an enlarged ROI could be used around the single Level-1 muon. Additional triggers would also use single Level-1 muons with clusters in the electromagnetic or hadronic calorimeters to select hadronic decays or decays with electrons or photons.

2. The CMS experiment

2.1. The detector

The Tracker [6] is located, together with the electromagnetic and hadronic calorimeters, inside a solenoid magnet generating a 4 T field. CMS has chosen an all-silicon configuration, relying on a few measurement layers, each able to provide robust and precise coordinate determination. The tracker is thus composed of a Pixel detector, providing two to three measurement points, followed by a Silicon Strip Tracker (SST) providing 10 to 14 measurement points per track. Due to the fine granularity, and hence the low occupancy obtained, pattern recognition problems are solved after the first few layers, and track parameter resolutions reach an asymptotic value after using only the first five to six hits.

The Pixel detector is composed of three cylindrical barrel layers and two pairs of disks in the end-caps, such that three points are measured per tracks for $|\eta| < 2.2$. In the barrel, the three layers are located at radii of 4.4 cm, 7.3 cm and 10.2 cm, and in the end-caps, the two pairs of disks are located at $|z| = 34.5$ cm and 46.5 cm. A later upgrade to a third pair of disks is envisaged. The pixel size is 150×150 μm^2

The SST is divided in four parts. The *Inner Barrel* (TIB) is constituted of four cylindrical layers, enclosed by three pairs of disks (*Inner Disks* – TID). It is then followed by the six cylindrical layers of the *Outer Barrel* (TOB), and the *End-Caps* (TEC) are made of nine pairs of disks. The disks of the TID are composed of three rings of modules and the TEC disks of 7 rings. The first two layers of both the TIB and the TOB, the first two rings of the TID, and rings 1, 2 and 5 of the TEC are instrumented with double sided modules, where the detectors are glued back-to-back with a stereo angle of 100 mrad. With this variety of detectors, there are 14 different sensor geometries, with pitches ranging from 80 to 205 μm.

The muons system [7] is located in the return yoke, and the first muon chamber is located immediately after the solenoid to extend the lever arm of tracks to improve the p_T measurement. It is composed of Drift Tube Chambers and Resistive Plate Chambers in the barrel and Cathode Strip Chambers and Resistive Plate Chambers in the endcaps.

2.2. The trigger

The Level-1 trigger [8] achieves a reduction from the initial 40 MHz bunch-crossing frequency to an accept rate of approximately 100 kHz with a latency time of 3.2 μs. The dimuon trigger requires two muons above threshold, and a requirement that these muons have opposite charge can be used. At low luminosity it is foreseen that it will be possible to use a identical p_T threshold of 3 GeV/c for each muon, while still keeping a low bandwidth occupancy of 0.9 kHz [9]. Such a low p_T threshold ensures a very high selection efficiency on decays of b-flavoured hadrons to two muons, with a rate low-enough to allow the use of lower quality muon candidates in the endcap region, recovering full geometrical acceptance of the muon detector up to $|\eta| < 2.4$. The single muon trigger would have a much higher threshold, approximately 14 GeV/c. It might nevertheless be possible to use a lower threshold by requiring the presence of a jet.

The HLT [9] reduces the accept rate to approximately 150 Hz with a latency in the order of one second and uses similar reconstruction algorithms as the offline reconstruction. Indeed, at this stage, tracks can be reconstructed in the tracker in restricted (η, ϕ) regions via a partial reconstruction algorithm, by stopping the reconstruction once enough information is available. The precision attained by using only the first 5 to 6 hits is then sufficient to reconstruct and identify b candidates through invariant mass and vertex requirements [10].

3. Conclusion

The ATLAS and CMS experiments are well suited for B physics, due to the large b production cross section and high luminosity. These experiments will operate in a very challenging environment, with very harsh radiations and very high rates, and a high accuracy is necessary. An extensive R&D program to devise detectors which meet these requirements has been conducted. The installation of the detectors is now taking place to be ready to start operation in 2007.

Both experiments have a powerful muon system which is invaluable in the Level-1 trigger and a robust and versatile tracker and track reconstruction algorithms. These have sufficient redundancy to operate in this challenging environment and show good performance in the High Level Trigger already. This will allow to collect a large number of b-flavoured hadrons, which can be reconstructed with high precision. Most B physics measurements will be done at low luminosity, although the searches for rare decays may also be continued at high luminosity. The exact trigger strategies and trigger-menus are now being prepared to be ready for the first collisions and the first measurements.

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