Vertex resolutions of ~ 0.01 mm in the transverse plane and < 0.1 mm in the beam direction are routinely obtained — performance that contributes to LHCb as a being successful competitor to experiments at e^+e^- beauty factories.

8.7 Large Silicon Trackers: Fast, Precise, Efficient

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Precise tracking is indispensable for any collider experiment. Lepton signatures, based on the combined information of the central tracker and the e-m calorimeter, or the muon system, are privileged signals for potential discoveries allowing to separate new phenomena from the huge background. At the LHC, Z and W bosons are identified via their leptonic decays and are used both to calibrate the detectors and to search for new physics phenomena. About 60% of the energy of jets is due to charged particles: by combining measurement of their momenta with the calorimetric information the jet energy can be determined with good resolution.

The capability to reconstruct detached vertices, combining the information of the central tracker and the vertex detector, allows the identification of hadrons with a b quark. This is an important tool for the precise study of the top quark and for discovery physics in all cases when the new particles have a preferential decay to heavy quarks, such as Higgs bosons or supersymmetric particles [Box 7.2].

The transverse momentum p_t of a charged particle curling in a magnetic field B is derived from the sagitta s of the projection of length L on the plane transverse to the magnetic field

$$s = 750\,\mu\mathrm{m}\left(\frac{B}{1\,\mathrm{T}}\right)\left(\frac{L}{1\,\mathrm{m}}\right)^2\left(\frac{50\,\mathrm{GeV}}{p_t}\right).$$

The transverse momentum resolution, i.e. the momentum measurement precision, is proportional to $1/(BL^2)$. The trajectory is measured at N points with spatial resolution σ, and the momentum resolution scales as $\sigma/\sqrt{N}$. With a magnetic field of 4 T and some 15 points having a resolution of $\sigma = 40$ μm each the momentum resolution is 1% at $p_t = 50$ GeV. With this resolution the width of the peak of a 125 GeV mass Higgs boson decaying to four muons is about 1% and the signal to background ratio in the interval 110–130 GeV is near 2.

The high luminosity and the bunch crossing frequency of the LHC pose severe constraints on the response time of the tracking devices [Box 8.3]. Typically, some 800 particles are produced together with the rare particles of physics interest in the many collisions at each bunch crossing and traverse the detector simultaneously. The pattern recognition algorithm must be able to reconstruct all these tracks belonging to the same collision event. Tracks from different collisions in a bunch crossing can be identified because they originate from a different primary collision vertex. Since the collision area of LHC has a Gaussian distribution along the beam direction with a σ of about 6 cm, the vertices of the different inelastic collisions are separated by about 1 cm on average. Figure 8.16 shows a 4-muon event selected by the ATLAS analysis searching for the Higgs boson.

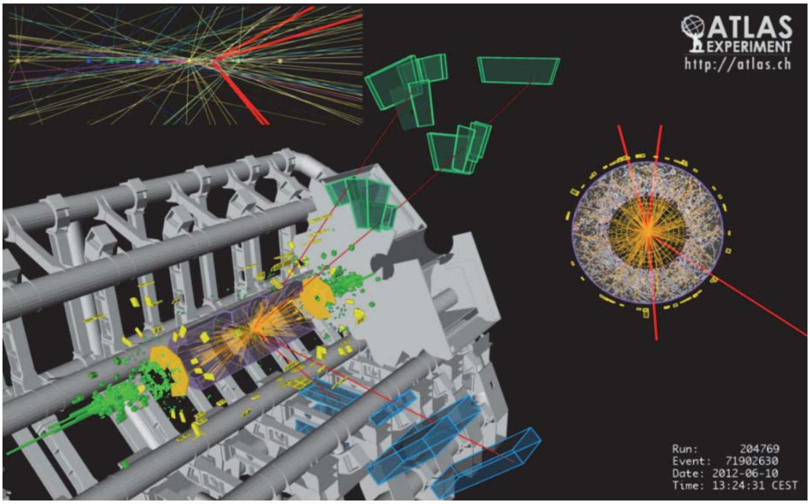

Fig. 8.16. Event display of a 4μ Higgs boson decay candidate reconstructed by the ATLAS detector. The muon tracks are shown in red and cross the muon chambers located in the external part of the detector. The insert on the right is a projection perpendicular to the beams showing all charged tracks reconstructed in the same bunch crossing (yellow lines). The insert on the top left shows a region of about 10 cm length where the beams cross with more than 10 recostructed vertices and their associated tracks.

The complexity of pattern recognition increases as a function of "occupancy", the average number of hits per event in one elementary detection element. High efficiency pattern recognition requires occupancy below 1% and correspondingly small detection elements. A 10 mm^2 surface covered by a 10 cm long and 100 μm wide silicon detector strip placed at 20 cm from the beam line is hit by charged particles only once every 100 bunch crossings at nominal LHC luminosity.

ATLAS and CMS use 300 micron thick silicon detectors for the innermost part of their tracking systems. In these detectors charge collection time is comparable to bunch crossing period and using fast read-out electronics the pile-up is limited to one bunch crossing. This calls for very large surfaces of the silicon detector. The ATLAS SCT [9] has 15 912 silicon sensors mounted in 4088 modules for a total silicon surface of 63 m^2 and 6 million electronic channels. CMS also uses silicon for the outermost part of detector: the silicon strip tracker [10] has 24 244 sensors mounted in 15 148 modules for a total silicon surface of 198 m^2 and 9.3 million electronic channels. The concept of these large silicon trackers was revolutionary; their development and construction represented an enormous engineering and logistic advance, considering that the largest silicon trackers existing at that time had a surface of some 6 m^2 [Highlight 5.9].

The silicon sensors for CMS were manufactured for the first time on 6-inch wafers in a standard planar process. This led to significant cost reduction per unit area compared to standard 4-inch wafers, making possible the construction of large (~ 85 cm^2) sensors for the outer layers, and greatly reducing their total number.

The precise (~ 10 μm) assembly of the sensors and the readout electronics into modules is challenging, and was traditionally performed by trained technicians. This was not possible for the CMS tracker because of the huge number of modules, so the experiment commissioned an automated mounting system based on a precision X–Y coordinate machine with large two-dimensional coverage, video pattern recognition capability and innovative glue-dispensing and pick-and-place tools. These robotic machines could assemble three modules precisely in less than an hour. Several were transferred to collaborating institutes where over 15000 modules were assembled in one year. The total of 25 million electrical connections between strips of two silicon sensors mounted on the same module and between sensors and readout electronics were made using fast (1 Hz) bonding machines.

Particles produced by collisions and secondary interactions in the detectors irradiate the detectors. All elements of the detector, including read-out electronics and cables must therefore be appropriately radiation resistant. The radiation dose (especially high close to the interaction point) degrades the detector response during the 10-year design lifetime. Radiation damage is mitigated by housing the detector in a dry nitrogen gas environment and cooling the sensors to –10°C.

The central trackers of ATLAS and CMS are similar. About 2 m in diameter and 6 meter in length, they enclose the central part of the detector and cover the polar angular range from 10° to 170°. Both operate in a solenoidal magnetic field, 4 T for CMS and 2 T ATLAS. In both trackers the innermost detector layers are built with silicon pixels, with a pixel size of about 0.02 mm^2 to provide space points with ~ 10 μm resolution and occupancies smaller than 0.06%. The intermediate layers use silicon strip detectors with high strip density; they provide 6–8 measurements with about 25 μm resolution of the coordinate perpendicular to the strip and have occupancies below 2%. Some detector layers are mounted with strips rotated by a small angle to provide spatial resolution along the strips. The technology used for the outer layers is different: CMS uses 500 μm thick silicon strip detectors with coarse pitch providing eight measurement points with resolution of < 50 μm while ATLAS uses a Transition Radiation Tracker with 4 mm diameter gas straw tubes providing 35 points with about 130 μm resolution.

The huge number of front-end electronics channels located on the detectors consumes about 30 kW of electrical power that requires cooling and results in considerable additional material. The total amount of material varies from about 40% of a radiation length to near 2 radiation lengths at places where the services (cables, pipes) are concentrated. The large amount of material spread along the trajectory of electrons affects the measurement of their energy in the calorimeter. Hadrons are also affected: depending on the angle, some 5%–20% are not reconstructed due to interaction within the tracker volume. The tracker material limits the momentum resolution at low momentum due to multiple scattering.

The intrinsic resolution of the tracking detectors is usually better than that of the detector assembly. The position of the detectors varies with time due to changing environmental conditions (temperature, magnetic field strength, etc. that mainly occur during LHC stops). Alignment procedures are used to measure and monitor their position over time to recover the intrinsic resolution. The corrections from the nominal to the real positions of all detector elements is computed using a large set of reconstructed trajectories of particles from pp collisions and cosmic rays [39]. The statistical error of this method is small, provided a sufficiently large set of tracks is used. A subset of silicon detectors is constantly monitored with optical alignment systems. As stability is imperative, the silicon detectors are mounted on carbon fibre supports with thermal expansion coefficients smaller than 10^{-6}. Depending on the number of independent detectors to be aligned, the simultaneous fit of a large number of parameters can be computationally challenging. The most complex case is the CMS silicon tracker with about 2×10^5 parameters.

The ATLAS and CMS trackers have been operational since the beginning of LHC data taking and perform at design specifications [40, 41]. Less than 3% of the channels are defective. The track quality agrees with simulation to within 2%. Medians of the track-hit residual distributions after alignment indicate that the individual modules are aligned to substantially better than 10 μm. The muon track reconstruction efficiency is at the 99% level. The muon momentum resolution measured with di-muon events agrees with simulation to better than 5%, and the muon momentum scale is known to better than 0.1% [9, 10].

The success of the development and operation of these silicon trackers is the basis for the next generation at the LHC, capable of handling the increase in LHC luminosity with collision rates in excess of 5×10^9 collisions per second. This will require Si trackers with increased radiation resistance, readout electronics with ten times the data transmission capacity and novel approaches for electrical powering.