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Electron track reconstruction in the ATLAS experiment

Doctoral Thesis

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Abstract

Before entering the hardware production phase of a HEP experiment, the detector elements that have been chosen during the planning process need to be thoroughly tested. At the LHC, silicon detectors will operate in a high-rate environment which requires low-noise electronics with a shaping time of 25 ns. A prototype silicon-strip half-module equipped with the analogue read-out chip SCTA128-HC was put in a 200 GeV pion beam. An analysis of the collected data is presented. The tested module was found to conform to the SCT-modules specification for the ATLAS experiment.

Electron reconstruction in the ATLAS detector is compromised by the large amount of material in the tracking volume, which leads to frequent emissions of hard bremsstrahlung photons. This affects the measurement of the transverse projections of track parameters in the inner detector as well as the measurement of energy and azimuthal angle in the EM calorimeter for $p_T < 20\,\mathrm{GeV}$. Reconstruction and electron identification efficiencies are both degraded. A detailed analysis of bremsstrahlung effects has been performed and it is shown that a first-order treatment is unsatisfactory. An algorithm for efficient and robust electron reconstruction has been developed which placed a strong emphasis on bremsstrahlung detection and recuperation so as to provide the best possible track parameters from the ID reconstruction. The algorithm was benchmarked against simulated data: single electrons, electrons in jets and electrons in the presence of high-luminosity pile-up.

The $\mathrm{B}^0 \to \mathrm{J}/\Psi \to ee$ and $\mathrm{Z} \to ee$ processes, crucial for EM calorimeter calibration, as well as the potential Higgs discovery via $\mathrm{H} \to \mathrm{ZZ}^{(\star)} \to 4e$ (for m_{H}=130, 150, 180, 200 GeV), were studied using the developed electron reconstruction algorithm. Typically, a 10% improvement of reconstruction efficiency has been achieved for these channels with respect to the results quoted in the ATLAS *Physics Performance TDR*. At low and intermediate electron p_T values, the experimental parameter resolution has likewise been improved with a better understanding and handling of the bremsstrahlung effects.

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	14.80.Bn	Standard-model Higgs bosons
	29.40.Gx	Tracking and position-sensitive detectors

Contents

Preface

As we go deeper and deeper into the smallness of space, mysterious entities are encountered. They do not speak and yet they pose more questions than they provide answers to. One asks these questions in terms of *high–energy physics* (HEP), being either theoretical or experimental in nature. We believe that quantum mechanics (or a physical theory expressed with a mathematical model of higher complexity) governs the domain we are probing. There, the inherent problem of quantum measurement is waiting for us: 'How can a quantum process manifest itself on a classical level?' One can not explain the results of a measurement without an underlying theory and the theory itself is meaningless without an experiment that has the power of falsifying it. The dialectical game has been pushed to a scale of 100 GeV where physics is currently explained with the *Standard Model of elementary particles and their interactions* (SM). Its mathematical formulation is a majestic symphony of non-euclidian geometry, group theory and functional analysis. That's how far we have come from the simple differential formulation of Newton's laws of mechanics. Likewise, we have travelled far from the objects that constitute the world that we live in. We have plunged down, towards the atoms of the world, leaving behind us many levels that are still not completely understood from first principles. By going further and further away from the world of human experience, our senses have become inadequate instruments and the basic concepts of physics have swollen with new meanings needed to incorporate them in different contexts. Nevertheless, there is a certain rationale in pushing experiments and human thoughts up to higher energies. Surprisingly, it is cosmology that makes the best use of the data harvested in HEP experiments. It is a generally accepted scientific fact that our universe is expanding (witness red shifts of light coming from distant galaxies). Therefore there was a time when it was much smaller, having a correspondingly higher energy density. Cosmic microwave background radiation is a relic from the time when the average energy density dropped below the level needed to keep electrons off the scattered nuclei. Neutral atoms were formed, the universe became transparent and photons were caught in the vastness of space. Extrapolation backwards from this time is made in accordance with observations of how matter behaves in high-energy collisions. Furthermore, twisting things around, as the universe had to come from somewhere, there must be a mechanism in nature that makes universes possible. By going to higher energies, we're getting closer to the realm in which our universe was created. It might be that we are still far from that point. However, without trying, without reaching out for what is feasible, we would still be hunting mammoths. I'm not saying we are better off the way we are … but I'm confident that, after embarking on the route of scientific exploration, it would be a great mistake to stop. For the fruits of scientific research have shifted society far out of the equilibrium position with the surrounding nature and it is my belief that science is the only power in human hands that can, if pursued wisely, regain us the lost balance.

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The work presented here was done at the *European Organization for Nuclear Research* (CERN) in the framework of the ATLAS collaboration which is building a general-purpose detector at the Large Hadron Collider (LHC). The main goal of the ATLAS experiment is to search for the Higgs boson (a particle predicted by the SM) and to chart the territory up to, and beyond, 1 TeV in cms energy. As the theory, the instrumentation used to probe the new realms and to verify predictions of the theory has likewise grown in its complexity. HEP experiments in general are craving for the investment of knowledge into the construction of detector elements, into analysis techniques, electronics and computing. For example, the ATLAS experiment will, including the preparation time, and experimental operation, devour more than 10 000 physicist-years of human effort.

The thesis, as a whole, presents most of my work for the ATLAS collaboration, performed during the four years of my engagement. One should understand that ATLAS will begin its operation in the year 2006 and that it is currently in its early experiment-building phase. While the ATLAS physics aims were the determinant of all the goals set in the process, the results can only form a skeleton on which the flesh of real data will attach to form the body of physical results.

My first task, after joining the collaboration and being genuinely puzzled for about half a year, was the performance benchmarking of different pattern recognition programs on simulated single particle events. Through this work I gradually understood parts of the detector, came to grips with their functioning and expected response. I plunged into the depths of detector description and the simulation tools which are used for obtaining the response of the detector to simulated events. Somehow I got involved with electron reconstruction and it suddenly became my main commitment. It soon became apparent that the knowledge of electron behaviour in the ATLAS detector is more sketchy than believed and that bremsstrahlung recuperation is implemented using inadequate algorithms. At that time I was already working with Alan Poppleton, the author of `iPatRec`, a software package for track finding and reconstruction in the ATLAS inner tracker. Under his careful guidance a detailed study of bremsstrahlung effects was performed and the guidelines for an adequate electron reconstruction algorithm were prepared.

Then my battle started. I implemented a very elaborate algorithm, trying to take into account every possible case. It turned out to be rather slow and not to bring as much improvement as anticipated. The words of the guru, Alan Poppleton, saved me once again. He proposed to make the algorithm as simple as possible, pick out the obvious cases and then worry about the rest later. Only at this point did I truly grasp the conclusions that could be extracted from the results of the detailed analysis of bremsstrahlung: there will be some events in ATLAS, for which there is nothing in human power that can be done to reconstruct them properly. After that, my work was easier and much more fruitful.

In spring 1999 I joined a group pursuing the research and development of silicon-strip detectors and a custom-made analogue read-out electronics to be used in the LHC environment. My work was to help in the preparation for a beam-test of a prototype module and, in particular, in the reconstruction of the harvested data. In one sentence, I was analysing the module's response to a passing particle. Before that, I regarded data just as something that you read from a disk or generate on the fly so that your algorithms have something to operate upon. Although I was aware of the fact that there will come a day when the data on disk will be the recorded, experimental data, I saw the transition from a physics event, occurring in the detector, to a series of zeros and ones on the disk, as a taking of a photograph. I couldn't be more wrong ... but the mistake taught me that what is *seen* by the detector is not entirely the same as what *happens* in it. And the results obtained for a silicon-strip module will eventually help us to work out this difference on the scale of the ATLAS detector.

After that I returned to the electron reconstruction. There were many things that needed to be checked and the algorithm itself had to be carefully optimised and benchmarked. After dealing with single particles, the time came to test it on a simulation of the physical events that will be of interest for ATLAS. This was the first time that I had to deal with programs, referred to as *event generators*. The basic idea is simple. You say to it: "Having a *pp* beam at 14 TeV cms energy, generate for me an event where a Higgs boson decays into two Z's and further into four electrons." And it returns a list of particles that fly out of the interaction zone. Looks simple ... and again it isn't. Already the first stage, the Higgs production, is tricky. At 14 TeV the protons are a colourful collage of quarks and gluons, their momentum distributions described theoretically by the proton's structure functions. Different sub-processes compete to be chosen for generation and each of them has different kinematics. After that, the final state has to be generated, with higher-order corrections included in the process. What is really tricky, is how to weight the phase-space so that when you pick a few thousand events, they will form a good representation of the real process. If you ever wondered why some theorists calculate higher order corrections for processes that don't have a slightest chance of ever being measured independently, here is a part of the answer: so they can be used in elaborate event generators that will mix this specific process with others and let it contribute to inclusive cross-sections of complete events that can be observed.

Acknowledgments

As already mentioned, Alan Poppleton played a central role in my understanding of the ATLAS experiment in general and problems associated with the track reconstruction in particular. But what made our cooperation really fruitful, was his willingness to learn from my work and to consult me as an equal when he encountered his own problems. Moreover, the manuscript, as well as my knowledge of the English language, benefitted immensely from his detailed inspection. I am grateful to him more than mere words can describe.

I would like to express gratitude to my supervisors, Marko Mikuž and Allan Clark, who had helped me choose my field of interest, as well as supported and guided my work.

Many thanks to members of the *Solid State Detector Development* group at CERN and *ATLAS group of the Jožef Stefan Institute.* In particular, Vladimir Cindro, Gregor Kramberger and Julio Lozano–Bahilo helped me solve and understand many problems I encountered in the silicon-detector lore.

A short overview

This section is an expanded abstract of material covered in each chapter. The first chapter consists of introductory material merged from various sources so as to provide a complete context for further expositions. Contents of chapters 2 to 4 is what I consider to be, at least in part, an original contribution to the ATLAS experiment and HEP community. Things that have found themselves in the appendix are more technical in nature and they might be of some interest to people solving similar problems.

Ch.1 Context begins with a historical motivation for the LHC project together with its technical specifications and physical processes expected to occur. A discussion of a development and life cycle of a large scale HEP experiment follows, trying to persuade the reader that this is a great scientific and technological undertaking requiring a joint effort of a large group of specialists.

An overview of the ATLAS spectrometer is done in a view of detector components, physics studies and electronic/computing requirements. In preparation for a later discussion the *inner detector* (ID) and *electro-magnetic calorimeter* (ECAL) are described in more detail. In the same spirit a role of electrons in the ATLAS physics is presented.

Ch.2 Beam test of a prototype SCT module sets out by summarizing the role and requirements for the silicon micro-strip detectors in ATLAS. The SCTA128HC read-out chip, the one mounted on the detectors put in the test-beam, is presented. The experimental set-up is described together with the alignment and resolution of the beam telescope. The path leading from raw data, as read off the detector, to reconstructed hits is traversed and the methods used for the determination of a cluster position are discussed. Then the results are presented in terms of efficiency, noise occupancy, resolution, reconstructed cluster properties and charge distribution.

Ch.3 Electron track reconstruction presents the core of my work. Technical difficulties connected with the electron tracking are explained and a detailed study of electron energy losses by bremsstrahlung in the ATLAS detector is presented. Based on these results an algorithm for electron reconstruction, named `ieElRec`, was constructed. Its environment, internal logic and input/output quantities are scrutinized so as to enable a user to understand and make use of the algorithm.

To quantify the results and make the algorithm useful for higher-level analyses in a variety of conditions, a detailed analysis of the results obtained from `ieElRec` on single electrons in transverse energy range form $p_T = 1.5$ to $60\,\mathrm{GeV}$ is presented. Furthermore, pion rejection capabilities of `ieElRec` are addressed and impact of jets and a high-luminosity pile-up on the electron reconstruction are discussed.

Ch.4 Applications of the electron reconstruction algorithm documents analyses of three physical process that will be of interest for ATLAS physics : $\mathrm{B}^0 \to \mathrm{J}/\Psi \to ee$, $\mathrm{Z}^0 \to ee$ and $\mathrm{H} \to \mathrm{ZZ}^{(\star)} \to 4e$. A strong emphasis is put on the quality of reconstruction of electron tracks and derived quantities. Nevertheless, all analyses are carried out till the final results, namely the invariant masses of the decaying particles, are obtained and the corresponding precision of the ATLAS detector studied.