Czech Technical University in Prague
Faculty of Nuclear Science and Physical Engineering

BACHELOR THESIS

B-PHYSICS ON ATLAS AT LHC

Monika Panušková

Supervisor: Václav Vrba, CSc.

May 30, 2008

I would like to thank my supervisor Václav Vrba for introducing me to particle physics and especially to particle physics community and giving me the opportunity to do b-tagging . Without him this thesis would never came into being. I also appreciate all discussions about this work we had in the past months.

I am very grateful to Alexandre Rozanov from CPPM, Marseille for introducing me to b-tagging and for numerous consultations we had either in person or by e-mail.

The third person I would like to thank is Grant Gorfine from University of Wuppertal. He regularly organized meetings of our group, where we could have discussed all issues connected to b-tagging, alignment and error tuning. He was always ready to help me with the software as well as physics.

My thanks also go to Wolfgang Liebig - for introducing me to the error tuning and for help with Athena.

I am thankful to Laurent Vacavant for all the time he put in me in CPPM and for being my guide during the first steps with the b-tagging software.

Lastly, I appreciate the advices and help I received from my colleague Pavel Jež during the whole last year.

Prohlášení

Prohlašuji, že jsem svou bakalářskou práci vypracovala samostatně a použila jsem pouze podklady uvedené v přiloženém seznamu.

Nemám závažný důvod proti užití tohoto školního díla ve smyslu §60 Zákona č. 121/2000 Sb., o právu autorském, o právech souvisejících s právem autorským a o změně některých zákonů (autorský zákon).

Declaration

I declare that I wrote my bachelor thesis independently and exclusively with the use of cited bibliography.

I agree with the usage of this thesis in the purport of the Act 121/2000 (Copyright Act).

Praha, May 30, 2008 Monika Panušková

Název práce:
Studium fyziky b-kvarku pomoc aparatury ATLAS na LHC

Autor: Monika Panušková

Obor: Matematické inženýrství

Druh práce: Bakalářská práce

Vedoucí práce: Václav Vrba, CSc., katedra fyziky, Fakulta jaderná a fyzikálně inženýrská, České vysoké učení technické v Praze

Abstrakt: První kapitola této práce stručně shrnuje současný stav teorie částicové fyziky. Vysvětluje základní vlastnosti standardního modelu, obzvláště Higgsova sektoru. První kapitola taktéž obsahuje úvod do fyziky těžkých kvarků. Kapitola 2 se zabývá experimentálními zařízeními a to jak běžícími (Tevatron), tak plánovanými (LHC). V této kapitole je možné taktéž nalézt detailní popis aparatury ATLAS a zvláště vnitřního detektoru. Třetí kapitola je zasvěcena ATLAS offline výpočtům - offline programovému prostředí Athena. V této kapitole jsou také popsány ROOT a GRID. Poslední kapitola je o b-taggingu. Nejprve jsou přestaveny základní koncepty a metody b-taggingu. Potom je vysvětlena užitečnost b-taggingu pro fyziku na LHC. Poslední sekce obsahuje autorčin původní výzkum, který je zasvěcen softwarovým korekcím určování chyb měření.

Klíčová slova: Standardní Model, ATLAS, Athena, b-tagging, ladění chyb

Title: **B-Physics on ATLAS at LHC**

Author: Monika Panušková

Abstract: The first chapter of this thesis briefly summarizes the current state of particle physics theory. It explains the basic features of the Standard Model, especially the Higgs sector. First chapter also contains introduction to the heavy quark physics. Chapter 2 deals with the experimental devices both working (Tevatron) and planned (LHC). Detailed description of the ATLAS detector and especially the Inner Detector can be found in this chapter. Third chapter is devoted to the ATLAS offline computing - ATLAS offline software framework Athena as well as ROOT and GRID are described there. Last chapter is about b-tagging: The basic concepts and methods of b-tagging are introduced, followed by the explanation of usefulness of b-tagging for LHC physics. Final section contains author's original research. It is devoted to the software correction of the determination of the measurement errors.

Key words: Standard Model, ATLAS, Athena, b-tagging, error tuning

Contents

Chapter 1

Current research topics. Heavy quark physics

1.1 Sketch of Standard Model

1.1.1 A Brief History of the Standard Model

People always tried to explain what is the world around them made from. The first ones, who supposed that everything is made from small, indivisible "particles" were ancient Greeks, namely Democritus and his fellows. He called this particles atoms. However, it took more than 2000 years to verify this hypothesis experimentally - this was done by English chemists John Dalton, who proved that all chemical compounds are made from relatively small number of basic elements, which were subsequently identified with the atoms.

More than half a century later, Russian chemists Mendeleev brought an order among chaos of elements by introducing his periodical table of elements. Later on, it was discovered that the periodicity in atomic properties was caused by atomic inner structure.

The first subatomic element - electron, was discovered in 1897 by J. J. Thomson, followed more than ten years later by the nucleus. But nucleus itself has also structure. Proton were discovered quite early (1918) by E. Rutherford, but it took some time to see the neutron for the first time, as neutral particles are much harder to identify. This was done by J. Chadwick in 1932.

By that time it was obvious, that there must be some other kind of interaction besides gravitation and electromagnetism. So the force, which holds nucleus together against electrical forces was called strong, while the force, which expelled electrons from nuclei (β-decay) was called weak.

In the same year as neutrons also the first antiparticle - positron, was discovered. For some time this seemed as a suitable model of the subatomic world, but data from cosmic rays since 1940s and from more and more powerful accelerators since 1950s destroyed this picture for ever.

Suddenly, there were dozens or even hundreds of "elementary" particles, situation much similar to that in chemistry about a hundred years earlier. The order was brought by M. Gell-Mann and his Eightfold way which organized all then known particles into octets, although it did not explain why they could be organized in this way. However, Eightfold way lead to the development of quark model, a theory saying that all *hadrons* (i.e. *baryons* like protons or neutrons and *mesons* like pions and kaons) are made from three (later four, today we suppose six) fundamental particles called quarks. Baryons are three quarks bound together, mesons are bounded states of quark and antiquark.

Because in some baryons were quarks of same charge and spin, another quantum number, color, was developed to rescue Pauli exclusion principle - it was called *color* and it was postulated that there are three types of color (by convention red, green and blue) which mixed together form color neutral state (baryons), or could be neutralized by an anticolor carried by an antiquark (mesons). Subsequently whole theory describing the behaviour of colored particles (that means strong interaction) was proposed in early 1970s (D. Gross, D. Politzer, F. Wilczek) and it was called Quantum Chromodynamics (QCD). This theory has two peculiar features - the first is quark confinement, i.e. we cannot see the free quarks "by definition" - it is because strong interaction becomes stronger on longer distances, so that if we try to separate quarks we at some point have enough energy to create new quarks which form new hadrons. The second feature of QCD is the other side of the first - the strong interaction becomes infinitely weak at close distances ("asymptotic freedom").

Meanwhile, the explanation for weak interaction also developed - this effort was topped by the unification of electromagnetic and weak interaction in the late 1960s by S. Glashow, A. Salam and S. Weinberg. This theory was very ambitious as it predicted four, at that time unknown particles ($W^{\pm}$ and Z bosons and Higgs boson). Nevertheless the first three were found in 1980s in CERN and their properties were exactly like the GWS theory had predicted.

1.1.2 Basic properties of the Standard Model

So that QCD and quark model on one side [2] and the GWS electroweak theory on the other side [1] form what we today call Standard Model and it is the best description of the world which we ever had - although it has many flaws, so far there is no experimental evidence against Standard Model.

As was outlined in the previous section, Standard Model says, that all matter we can see and detect around us is in principle made from 12 particles - 6 hadrons and 6 leptons (see Tab 1.1) - and their respective antiparticles . These could be divided into 3 groups of four particles called families or generations. Second and third generation are essentially higher mass copies of the first. Only the particles from the first generation are stable, the other two generations quickly decay into the particles of the first generation.

Table 1.1: Elementary Particles

	First generation	Second generation	Third generation	Electrical charge
quarks	u-up	c-charm	t-top	+2/3
	d-down	s-strange	b-bottom	-1/3
leptons	e-electron	μ-muon	τ-tauon	-1
	ν_e - e-neutrino	ν_μ - μ-neutrino	ν_τ - τ-neutrino	0

Table 1.2: Fundamental Forces of Nature

Force	Relative strength	Range	Parity conservation	Mediator
Strong	1	10^{-15} m	yes	8 gluons
Electromagnetic	1/137	∞	yes	photon
Weak	10^{-13}	10^{-18} m	no	$W^{\pm}$, Z
Gravity	10^{-38}	∞	yes	graviton ?

Standard Model also says, how these particles interacts via strong, electromagnetic and weak interaction. The gravity is not contained, but on the other hand, it is negligible on the scale of particle physics. Strong, weak and electromagnetic interaction are quite distinct (see Table 1.2), but Standard Model provides common framework for description all of them and, as was advertised, the last two are in fact one electroweak interaction.

Standard Model supposes, that each interaction is mediated by some intermediate boson and, again, we have 12 of them. There are 8 gluons which mediate the strong interaction. Like quarks, they also carry a color charge, and therefore interact with the quarks as well as other gluons. But they do not interact with leptons, so the strong interaction is not universal. Also, as was said, interaction becomes infinitely weak at small distances.

Then there are 3 weak intermediate bosons. Unlike gluons and photons, they have mass, in fact they are one of the most massive elementary particles (80 and 90 times the mass of proton, respectively). They interact with all elementary fermions, but they interact with right-handed (spin in direction of motion) and left-handed (spin opposite direction of motion) particles differently. And it is the only interaction of neutrinos (with the exception of gravity which involves all objects with nonzero energy).

1.1.3 Spontaneous symmetry breaking

From the mathematical point of view, the Standard Model is a gauge theory, i.e. it has some internal (gauge) symmetry. Classical example is Maxwell electromagnetism which is invariant under gauge transformation of potential. This transformation is in fact representation of a group $U(1)$ (complex numbers with modulo 1).

In case of Standard Model, the internal symmetry group is $SU(3) \otimes SU(2) \otimes U(1)$. $SU(n)$ is a group of unitary $n \times n$ matrices with unit determinant. Particles of the Standard Model are then fundamental (elementary fermions) and adjoint (gauge bosons) representation of this group. More about this group and its representation could be found in [1, 2, 4, 5] or standard Group Theory textbooks. Note that we demand that transformation generated by this symmetry is local, i.e. dependent on space-time coordinate.

Nevertheless, such a symmetry forbids massive particles (they are not symmetric under $SU(2) \otimes U(1)$ transformation, for details [1, 4]). On the other hand, we know that the particles have masses. The solution to this problem is called spontaneous symmetry breaking.

It works quite simply. At first, we add a scalar potential which possesses all symmetries to the Lagrangian of the theory. This potential is chosen in such way that the minimum of it does not posses the complete symmetry, so we say that symmetry is spontaneously broken. We also suppose, that this potential oscillates only a little around its ground value.

So far it is only mathematics, but the physical importance is hidden in a theorem [1] saying that for each broken continuous symmetry we obtain a massless particle, which is usually called Goldstone boson. It also known, that at least one massive particle must survive this process (called also Higgs Mechanism) - and is called Higgs boson.

In case of Standard Model we add two complex (i.e. 4 real) scalar fields invariant under $SU(2) \otimes U(1)$ transformation (we are not interested in $SU(3)$ part now - it affects only colored particles). Then the $SU(2)$ symmetry is broken, so we obtain 3 massless Goldstone bosons (for 3 generators of $SU(2)$) and one massive Higgs boson. However, the remaining $U(1)$ symmetry allows us to choose gauge in which all Goldstone bosons are identically zero, so that we have Higgs boson only.

The initial requirement of local $SU(2) \otimes U(1)$ symmetry automatically produced mass terms for weak gauge bosons ($W^{\pm}$ and Z), as well as Higgs-gauge boson interaction. Details in [1, 4]. In a similar way mass terms for fundamental fermions could be obtained.

1.2 Higgs Searches

Last section showed that Higgs boson is really a crucial particle for the Standard Model - without it, the theory would be unrealistic. Ironically, it is the only particle predicted by Standard Model which has not been observed so far.

The reason could be, that Higgs boson can be quite heavy, comparable with the heaviest particles of the Standard Model (the top quark mass is 174 GeV). Also, as a neutral and colorless particle it interacts only weakly, resulting in much smaller cross-sections than strongly interacting top quark.

Prior to LEP (Large Electron Positron Collider, running in CERN from 1989 till 2000), the Higgs searches were sensitive to light Higgs (few GeVs) only. But LEP pushed the limits of searched to much higher energies, because it brought clean environment of electron-positron collider together with extraordinary sensitivity of its experiments. LEP ran in two phases - LEP I allowed production of single Z boson ($m_Z = 91$ GeV), LEP II afterwards increased energy to allow production of $W^{\pm}$ pair and eventually topped at center of mass energy equal to 209 GeV in 2000. Theoretically this value would allow production of single Higgs boson with the mass of 209 GeV, but the electron-Higgs coupling (and therefore the production rate) is so small that it would have taken dozens of years of data taking to have a single event.

Higgs couples to all massive particles and the size of this coupling is proportional to the mass. So it is better to produce Higgs indirectly, through Z boson: a Z boson with high momentum is produced in e^+e^- collision and is scattered away producing Higgs boson and Z boson with smaller momentum. All LEP searches for Higgs were based on this production mechanism. It is easy to see that it allowed production of Higgs boson as heavy as 117 GeV.

Z and Higgs are unstable particles, so that we can identify them only indirectly, through their decay products. Z boson is well known, in 70 % of cases it decays into quarks which quickly hadronize, producing jets, in 20% of cases it decays into neutrinos and in 10 % of cases into leptons [8].

Decay rates of Higgs can be predicted from the theory, but they are strongly dependent on Higgs mass - see Fig 1.1. In case of LEP mass reach, however, decay to $b\bar{b}$ is dominant. So that on LEP they looked for possible combinations of Z and Higgs decay. Each channel has its advantages and disadvantages - for example $ZH \rightarrow b\bar{b}\ell^+\ell^-$ is nine times less frequent than decay into $b\bar{b}$ and two jets, but leptons are much better identified than jets, resulting in smaller background which could ultimately beat larger statistics of other channels.

Unfortunately, none of these events was observed with enough statistical significance, so that combined results from LEP give us only lower bound on Higgs mass at 114.4 GeV. Figure 1.2 shows confidence level (CL) as a function of Higgs mass. In this case it means the probability that signal+background would not be distinguished from the background. Thin horizontal line signalizes 0.05, i.e. 5 % probability that they had produced Higgs, but they did not recognize it. Thin blue line is what was expected from the theory for the background, green and yellow bands marks 1 σ and 2 σ of uncertainty, respectively. Red line is actual experimental result, indicating that they had more events in 115 - 116 GeV mass bin than they have expected, but the difference was not significant enough to claim an discovery.

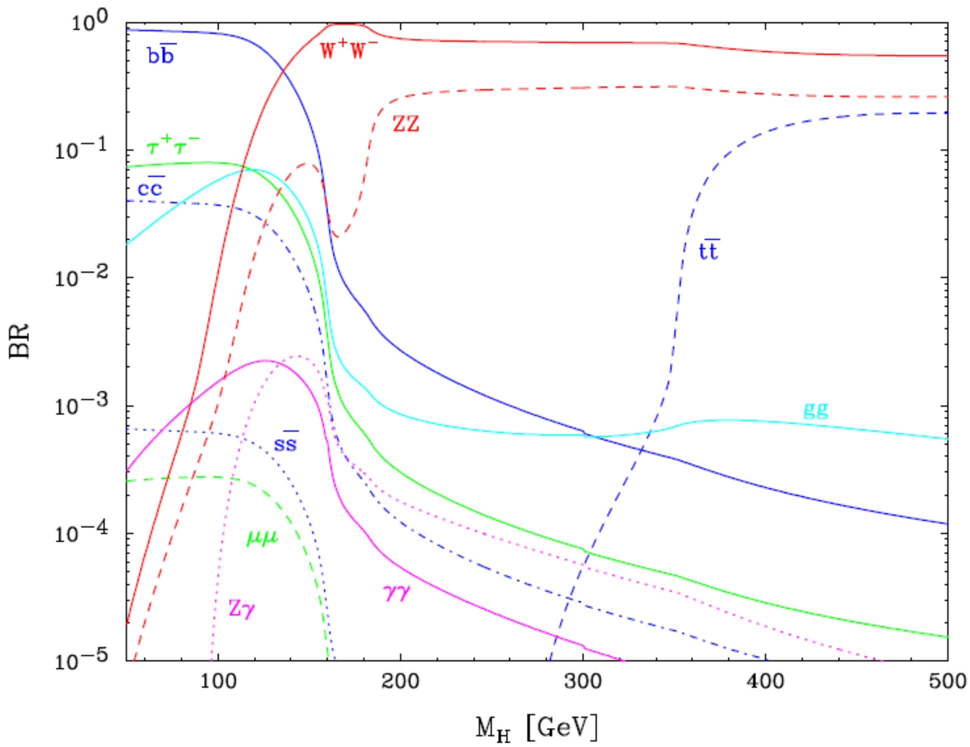

Figure 1.1: Branching ratio of various Higgs decay channels as a function of Higgs boson mass. Figure taken from [8].

The actual most powerful experimental device is Tevatron in Fermilab, USA. It is a proton-antiproton collider, with a much higher center-of-mass energy that had LEP, but as $p\bar{p}$ collisions produce high QCD background, there was no Higgs signal in Run I. Since 2001 Tevatron Run II is in operation, with the center-of-mass energy increased to 1.96 TeV.

At these energies there are other production mechanisms for Higgs (as direct production from $p\bar{p}$ is extremely rare). Main production is from is now gluon fusion, but the radiation from Z or W boson is still important. The last interesting production mechanism is a weak boson fusion [8] which has particularly distinguishable background, but is too rare to play any major role in Tevatron.

Taking combination of production and decay we have now much more possibilities to look for Higgs. However, it is not immediately clear which channel is the most useful. Sure, we can take the biggest production rate to biggest decay rate ($gg \to H \to \bar{b}b$) but the background is such high that it is practically impossible to look for signal there (background is several orders of magnitude higher).

Theoretically, Tevatron could produce much heavier Higgs than LEP could have,

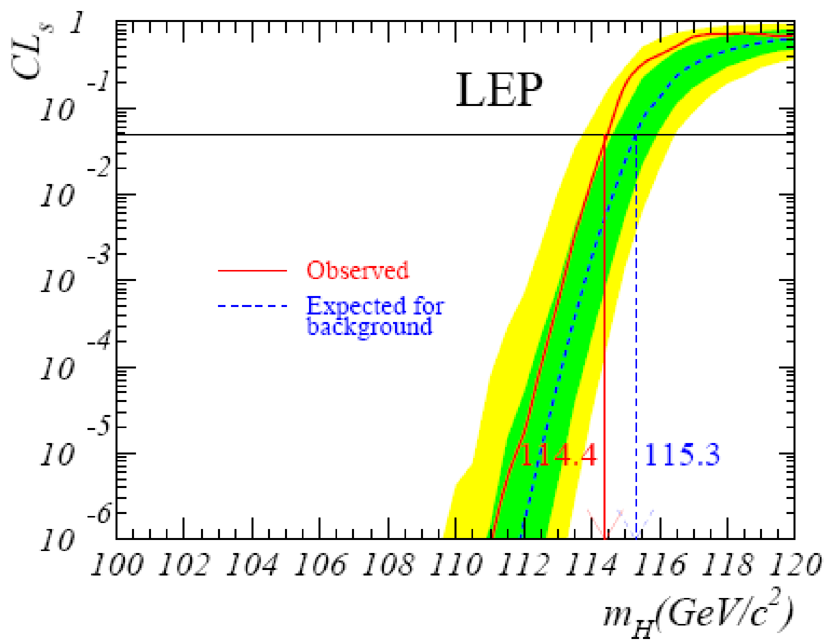

Figure 1.2: Lower mass limit on Higgs mass from LEP. Combined data from all experiments Figure taken from [8].

but because the cross-section of Higgs production at Tevatron is steeply falling with its mass ($\sigma(M_H = 500$ GeV) is about 3 orders of magnitude smaller than $\sigma(M_H = 150$ GeV)), practical reach of Tevetron is only a bit higher than these of LEP. Combined preliminary results from LEP and Tevatron are on Fig. 1.3. The blue curve is the border of the area inside which both mass of the top quark and mass of the Higgs could be fitted with the 68 % confidence level. For fitting are used all data with the exception of direct top quark mass measurements. Yellow band is area excluded by LEP, green belt is actual result from Tevatron with one σ uncertainty.

High hopes are now put into LHC, as it should have capability to discover Higgs up to 1 TeV. More about that in next section.

1.3 Heavy Quark Physics

Previous section showed that heavy quarks (bottom and top) play important role in searching for Higgs - either as a production intermediate state (top quark in case of hadronic colliders) and as decay products of Higgs. The mass of bottom quark is 4.2 ± 0.7 GeV [10], about 4 times higher than the charm quark. Top quark is the

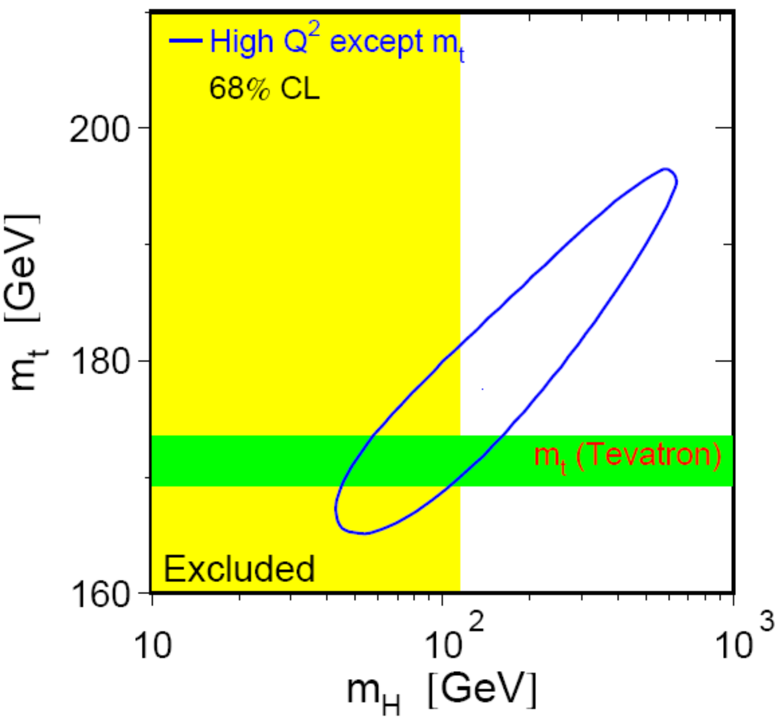

Figure 1.3: Combined constraints on Higgs mass from LEP and Tevatron. Blue contour is 68% confidence level for m_H and m_t fitted to data with the exception of direct top mass measurements. Yellow area was excluded by LEP, green is Tevatron 1 σ result for top mass. Figure taken from [9].

most massive elementary particle (with the possible exception of Higgs boson), it weighs $174.2 \pm 2.0 \pm 2.6$ GeV [10].

As was told earlier, quarks could be found only confined inside hadrons. Bottom quark forms meson states with all lighter quarks, their typical lifetime is $\approx 10^{-12}s$ and decay predominantly into kaons and other lighter mesons. There are also observable leptonic final states. Bounded state of bottom and antibottom is called bottomium or Υ.

On the other hand, there are no bounded states containing top quark - it decays via strong interaction to the bottom quark and other particles (leptons, lighter quarks) and its lifetime is shorter than typical time of strong interaction. So that top decays earlier than some bounded state is formed.

Both bottom and top could be directly produced in colliders, as is the case of Tevatron, and will be the case of LHC. Note that Tevatron has so far been the only machine capable of producing top quark, however LHC is expected to produce top in much higher quantities (8 million pairs a year), so allowing more precise measurements.

Heavy quarks could be used for exploring many physical areas. For example B mesons could be used for studies of CP violation (i.e. system is not symmetric under parity and charge conjugation) in the same way as kaons. But because B mesons are more massive, there is also larger mass gap between CP eigenstates, so that the violation is more obvious. This fact, together with the huge production of b-mesons is the basic motivation for experiment LHCb, which should measure and determine (among others) the level of CP violation and consequently measure the matter/antimatter asymmetry.

Other good use of B mesons could be for testing of the Standard Model through extremely rare decays (for example into $\mu^+\mu^-$ pair only). They have such a low branching ratios, that they are significantly influenced by Standard Model corrections like MSSM (Minimal Supersymmetric extension of the Standard Model) . These could also be observable at LHC.

But by far the greatest use of heave quarks is in the Higgs sector. Bottom-antibottom pair is dominant decay channel of light Higgs, so good detection and identification of b-quark are really crucial.

Bottom quarks decay much earlier than they would reach the detector. Their decay products form a jet, which is quite distinctive from other jets. B quark is also much heavier than anything it decays into. This causes jets to be wider as well as have high multiplicities (number of constituents).

This features are (among others) used in b-tagging, i.e. identifying of b-jets. This subject will be discussed in detail later in this thesis.

1.4 Beyond Standard Model

Although there is no experimental evidence against Standard Model, it is obviously not the "final" theory. The simplest thing we can do is to count the number of parameters in the model. If we do that [1], we would find 24 free parameters (coupling constants, particle masses).

This is the question of mathematical beauty. However, Standard model has other flaws. The most significant of them is divergence in some processes involving top quark and a Higgs [7], called also the hierarchy problem. The solution to this problem can be Supersymmetry (or SUSY).

Then there are several problems which Standard Model cannot answer "by definition". The most obvious is, that it does not contain gravity, so that we do not have a description for gravity at the quantum level. The other problem is, that Standard Model describes only what is made from elementary particles. Unfortunately, observations show that only 4 % of Universe are of this kind ("baryon matter") and we have to find a description for the remaining 96 %.

Another unanswered question is why we have exactly three generations of matter - this fact was experimentally verified with the high degree of precision but was not theoretically explained. Theory only says, that the 3 families are minimum to CP violation occur. This brings more questions - why CP is not an exact symmetry, why there is asymmetry among matter and antimatter and how big it is.

These are just several questions we have to answer even if Standard Model would be completely verified by discovery of Higgs boson (or bosons - this is also not clear). Because this questions are known for long time, there are already several answers to them. For presently available energies, they are experimentally indistinguishable from the Standard Model, but higher energies of LHC could deside in some cases.

The most popular answer is called Supersymmetry. It postulates a symmetry between fermions and bosons. These superpartners cancel divergences of the Higgs sector. Obviously this must be broken symmetry as we have not seen any supersymmetric particle so far - so if they exist, they must be much heavier than their counterparts. Supersymmetry solves the hierarchy problem (to do that, supersymmetric particles cannot have mass higher than ≈ 1 TeV). It also explains and bounds some free parameters.

There are several supersymmetric theories, the most popular is the MSSM which, for example, predicts 5 physical Higgs particles. Why 5? Supersymmetry needs 2 Higgs doublets, i.e. 4 complex (or 8 real) fields. Three of this fields are unphysical, as they could be gauged away in the same way as in the Standard Model. So that we stay with 5 Higgs bosons.

However, Supersymmetry itself is not without problems: although it explains and bounds some parameters of Standard Model, it brings new and often we ends with more parameters than we started.

Chapter 2

Particle accelerators

2.1 Indroduction

Every physical theory would be just sheet of paper if it would not have been experimentally tested. To test the particle physics you of course need the particles - the natural source of them is radioactivity. Naturally (and subsequently artificially) radioactive elements were indeed the source of particles for the first experiments. Second natural source of subatomic particles are cosmic rays. These were known from the 1930s. They contain other types of particles than the radioactivity and, more importantly, they are also much more energetic. This allowed scientists to discover muon and pion.

The main advantage of cosmic rays against radioactivity was the speed and the mass of particles. So that the next logical step was to take some massive particle (from other source) and give it some speed in the accelerator. Then the particle collides with some target and the nature of collision allow us to study the properties of the incoming particle as well as of the target. Note that this basic scheme is the same as the Rutherford experiment.

This idea could be further improved by accelerating particles in opposing direction and then make them collide. The advantage is that the momentum of the center of mass is now zero, so that all energy could be used in the collision (on the contrary, in particle-target setting is substantial portion of incoming particle energy carried away by the momentum of the particle-target center of mass).

So how to accelerate a particle? Probably the easiest way is to take some charged particle and place it into an electrical field. The potential difference will accelerate the particle in the direction of the field. This is the basic idea of linear accelerators. They consist of a number of electrodes and each of them accelerate the particle by its potential difference. Modern linear accelerators are several kilometers long (the longest in SLAC has 3 km) and can accelerate an electron to an energy of several dozens GeV (in case of SLAC accelerator it is 50 GeV).

But a charged particle can be accelerated also by the magnetic field. It makes particles to change its direction, so that the resulting trajectory is circular. There are several types of circular accelerators:

Betatron uses electromagnetic induction to keep electrons on the trajectory of constant radius. Typical energy of accelerated electrons is 50 MeV. They have wide use in nuclear medicine

Cyclotron uses stationary magnetic field to keep particles on a circular trajectory while the electrical field accelerates it. The resulting trajectory is a spiral. Electrons could be accelerated up to 20 MeV.

Synchrotron uses non-stationary magnetic field to keep particles on a track with constant radius. The acceleration is again done by electrical field. Almost all big modern circular accelerators are of this type. They can accelerate electrons to energies higher than 100 GeV (LEP) and protons to more than 1 TeV (Tevatron). This will however soon be overcome by LHC which is designed to accelerate protons to 7 TeV.

2.2 Tevatron

Tevatron was completed in 1983 in Fermi National Laboratory in the United States. It is a circular synchrotron 6.3 km long and currently it is the most powerful particle accelerator in the world, accelerating protons and antiprotons to collide with the center of mass energy equal to 1.96 TeV.

The scheme of the Tevatron is on the Fig. 2.1. The negative hydrogen ions are pre-accelerated by Linac (linear accelerator) up to 400 MeV. After that the electrons are removed and protons go to Booster. When they leave it, they have about 8 GeV. Then they go to the main injector which accelerates protons up to 150 GeV, or antiprotons to 120 GeV. Finally, protons and antiprotons are accelerated by Tevatron up to 1 TeV.

There are two places where the protons and antiprotons can collide - CDF and DØ experiments. They are general purpose detectors, with basic functionalities of subsystems similar to the ATLAS or the CMS which are described in the next chapter in the LHC section.

CDF or Collider Detector at Fermilab was designed to study properties of the Standard Model particles as well as to search for the new physics. Its most remarkable discovery is the top quark in 1995. But CDF also observed oscillations between B_s and $\bar{B}_s$, just as predicted by Standard Model, and also CDF found two new particles: Σ_b^+ (uub) and Σ_b^- (ddb). Last year CDF done the most precise measurement of the top quark mass (Fig. 2.2) - result is 170.9 ± 2.6 GeV - and of the W boson - 80.413 ± 0.048 GeV [22].

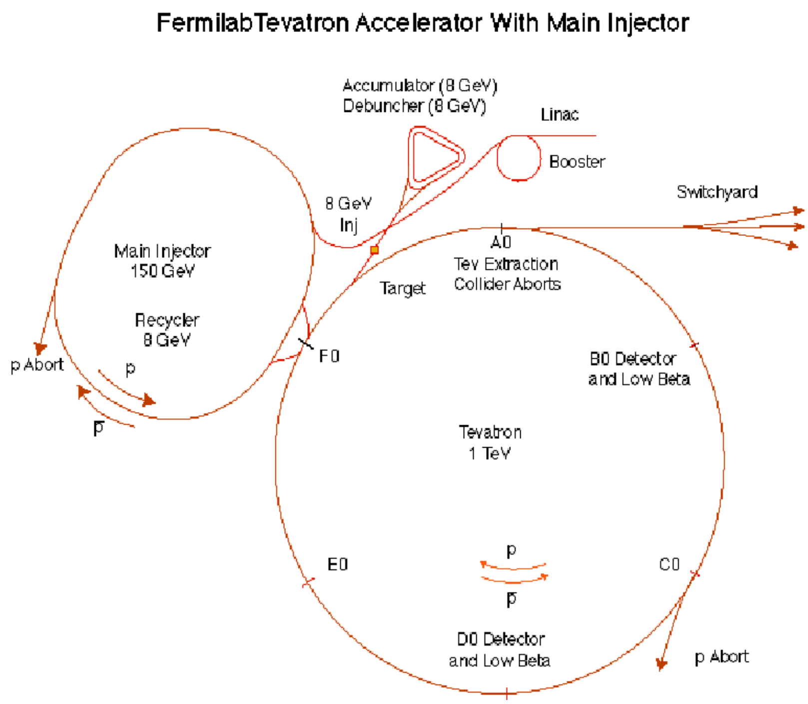

Figure 2.1: The scheme of Tevatron accelerator. It is described in the text. The picture was taken from [21].

DØ is experiment located at the D0 point of Fermilab. It has also discovered top quark in 1995 and seen similar things as the CDF in the last year [23]. Recently, DØ collaboration discovered Ξ_b hadron - it is composed from down, strange and bottom quark, i.e. one quark from each family [24]. Also, preliminary results about single top production are in [25].

Combined results from both experiments also bring some restrictions on the Higgs mass. Figure 2.3 shows Tevatron results combined with LEP. It clearly shows, that lighter Higgs mass is preferred.

2.3 LHC

2.3.1 The Machine

At present[1] the LHC is being finished in CERN, Switzerland. The abbreviation stands for Large Hadron Collider, and indeed, it will be the most powerful hadron collider ever built. As was mentioned earlier, it is designed to collide protons with the center-of-mass energy of 14 TeV. It will be also capable of colliding heavy ions -

[1]Summer 2007

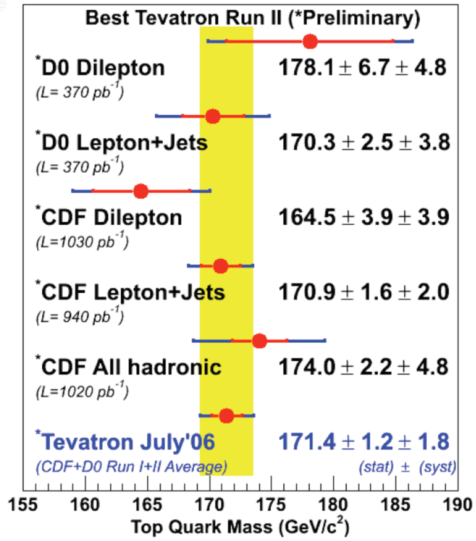

Figure 2.2: Results of top mass measurements at Tevatron - at DØ, CDF and combined (last line). Picture from [26].

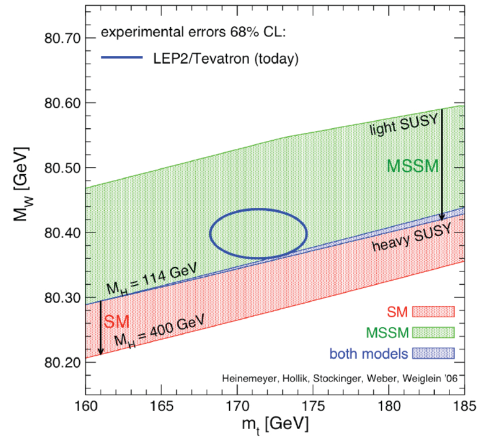

Figure 2.3: Constraints on Higgs mass from combined results of Tevatron and LEP. Picture from [26].

the nuclei of lead (Pb^{82+}). It is the last part of CERN accelerator chain (Figure 2.4), so it hugely benefits from the laboratory's practice of linking accelerators together. Protons are created and initially accelerated in older CERN accelerators like PS and SPS, so that they are injected to LHC with quite high energy (450 GeV). LHC then does the rest of acceleration.

The machine is stored in 27 km long underground tunnel which was previously used for LEP. Because it collides particles with the same charge, it has to have two separate pipes, each for one direction, with differently oriented magnetic field. There are 8 regions (called Insertion regions) where there are no magnets and particles run straight sharing the same pipe (See Fig.2.5). At this places protons can collide.

Important parameter of every accelerator is the luminosity L. It is defined as

$$L = \frac{N_{events}}{\sigma_{events}} \tag{2.1}$$

where N_{events} is the number of events and σ_{events} is their cross-section. LHC aims for very large luminosity of 10^{34} cm^{-2}s^{-1}. With growing energy the cross section decreases like $1/E^2$, therefore to maintain the same physics efficiency, we have to increase the luminosity by this amount.

To achieve this high luminosity, the proton beams have to be particularly dense. In fact, there will be 2835 bunches of 10^{11} particles, separated by 25 ns. On the other hand, the higher density causes quicker degradation of a beam by deflection of protons. So that, there is some "critical" density which should not be crossed

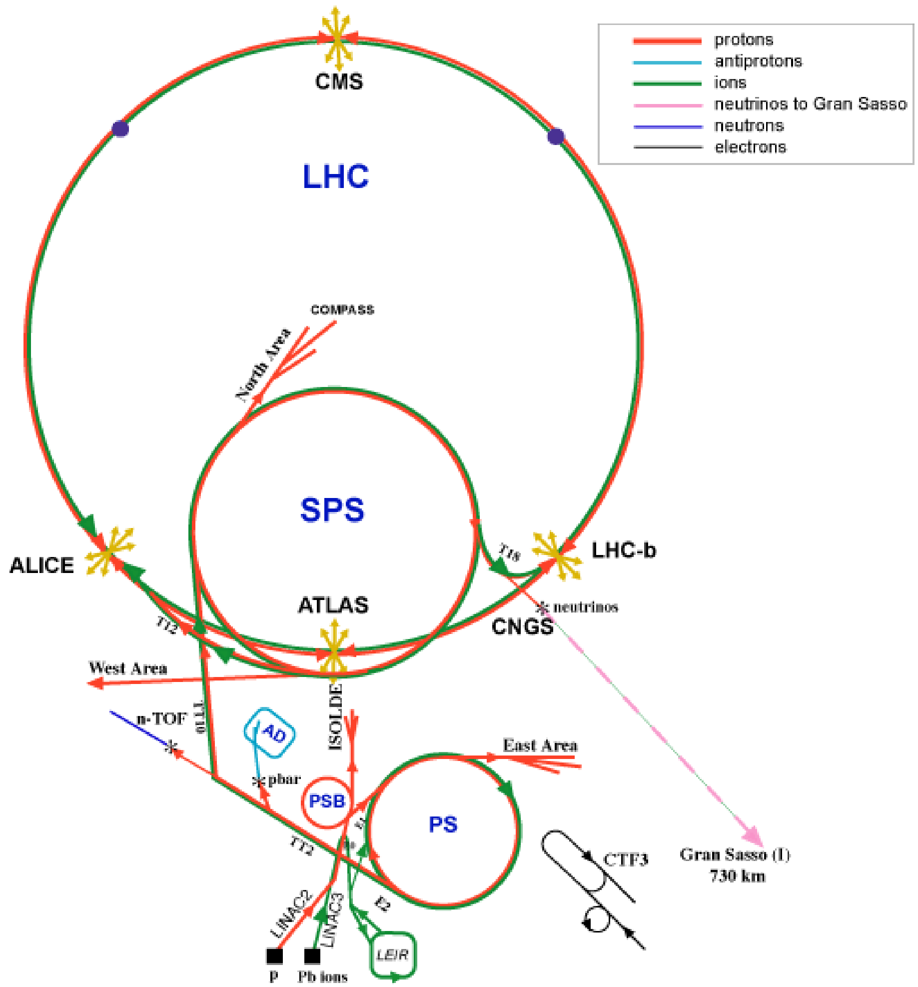

Figure 2.4: The scheme of CERN accelerators chain. It is described in the text. The picture was taken from CERN web [29].

to maintain high luminosity. Altogether, at LHC this would mean some twenty collisions for every bunch crossing at the full luminosity.

Such a lot of particles can be kept on their track only by extremely strong magnetic field. The LHC would in fact generate one of the biggest manmade magnetic fields ever made. This strong field will be secured by superconductive magnets operating at 2K, thus making the CERN one of the coolest places in the (known) universe - LHC temperature will be lower than average temperature of outer space.

Previous paragraphs outlined that LHC is really a technical and scientific challenge. It has very high research potential and it should open a completely new era in particle physics. Its vital parameters are summarized in Table 2.1.

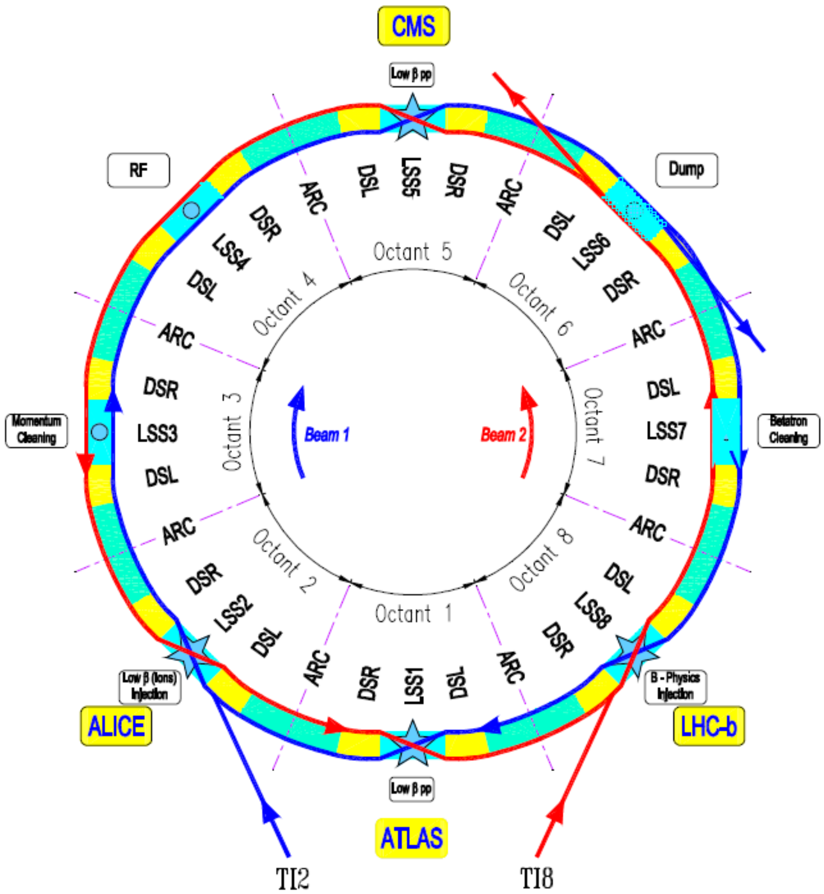

Figure 2.5: The scheme of LHC. It shows the location of experiments and other Insertion regions. The picture was taken from [30].

2.3.2 Physics and Experiments

The main characteristics of the LHC is contained in its name - it is a hadron collider. This means that it will collide particles with color and outcome will be also colorful. Therefore this collider will be "dirty" compared to LEP. The reason is large QCD background.

On the other hand, this collider is also large - in terms of energy. This means that it could (at least theoretically) produce particles with mass as high as 14 TeV. But the production rate of such a particles will be extremely low and thus unobservable. In general, it is agreed, that the particles with mass up to 1 TeV could be spotted at LHC with reasonable statistics. Even this value is quite impressive - the heaviest known particle has 172 GeV.

The main reason why LHC is being built is to put a seal on the Standard Model by finding the Higgs boson. This is not a trivial task, though. Although Higgs

Table 2.1: LHC Statistics

particles used	protons and heavy ions (Pb^{82+})
circumference	26.659 m
injected beam energy	450 GeV (protons)
beam energy at collision	7 TeV
magnetic field at 7 TeV	8.33 T
operating temperature	1.9 K
revolution frequency	11.2455 kHz
power consumption	120 MW

couples to all massive particles, the coupling strength is proportional to the particle mass. What's more the coupling is still very small even for the most massive particles like top quark or$Z$boson. The summary of (so far) unsuccessful searches was in the first chapter of this thesis.

The LHC has also capability to reliable explore the region of energies where the Standard Model is distinguishable from the "Beyond the Standard Model Theories" like Supersymmetry. There are in principal two ways of seeing the Supersymmetry. The first one is the direct observation of the supersymmetric particles. The second one are rare processes of Standard Model like pure leptonic decay of B-mesons (or more generally a flavour changing neutral current). This process is forbidden at tree level, it is only possible in the 1-loop. And if we allow supersymmetric particles to enter in the loop, the corresponding matrix element is somehow increased (albeit still well under current experimental limit [19]). Because LHC would work as a b-factory (producing 10^{12}-10^{13} $b\bar{b}$ pairs a year), we should have enough statistics to actually see this rare decay and tell whether it is governed by the Standard Model, or if there is some other theory in behind.

The high production rate of bottom quarks would be also used in study of CP violation. For long it has been known, that CP violation occur in kaon system, but measurements in SLAC in late 1990s and early 2000s showed that this phenomenon also occur in B-system [20]. The high production rate of LHC and high precision of its experiments will bring more light into this very interesting and important subject (it is tightly bound to obvious matter-antimatter asymmetry in the Universe).

LHC will be also the second machine in the world able to produce top quark. But it will produce much more of them than Tevatron (it is estimated about 10^7 $t\bar{t}$ pairs a year at the luminosity of 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$). Thus, this higher statistics will allow more precise measurements of top quark mass and its couplings.

As was said above, LHC can accelerate also heavy ions. These, when collide, can create a state of matter called quark gluon plasma (QGP), where the quarks should be deconfined, i.e. free. This state is said to be one of the early stages of the Universe shortly after the Big Bang. Today, it should still exist inside quasars.

LHC will have an experiment specially dedicated to study of quark gluon plasma.

Previous paragraphs showed what is expected from the LHC. But the most interesting discoveries come often completely unexpected - for example the discovery of atomic nucleus in Rutherford experiment. Therefore, the LHC detectors must be really robust to see not only the physics we know so far and the physics we expect ("known unknowns"), but also something totally new and different ("unknown unknowns").

All the mentioned physical goals will be pursued at 4 major and 1 minor experiment:

ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**) is a general purpose detector designed to exploit the full LHC potential. It is being built at Point 1 (see fig. 2.5), directly opposite the CERN main entrance. The view of the whole detector is at Figure 2.6 The project involves collaboration of more than 1800 people from 34 countries. Because of the high collision energy and production rate, the ATLAS is the most complex detector ever built. The main lines of the ATLAS research are:

- The search for the Higgs boson or any other mechanism of the electroweak symmetry breaking
- The investigation of CP violation in B-decays
- The precise measurement of mass of heavy particles like top quark or W boson
- The search for supersymmetric particles or any other new models of physics
- The studies of compositeness of fundamental fermions

To fulfil these goals the ATLAS consists of several components which together provide the full information about the collision. These subdetectors will be described later.

CMS (**C**ompact **M**uon **S**olenoid) is also a general purpose detector. The name "compact" means that it is somewhat smaller than ATLAS (about 8 times in volume), but has about twice its weight. It is being built at Point 5 (cf. fig. 2.5) - unlike ATLAS it is being assembled on the surface and lowered to the experimental cavern afterwards. The name also signalizes that CMS is optimized for tracking muons and its magnet will be the largest solenoid ever built, producing a magnetic field of the strength of 4 Tesla. The CMS collaboration involves about 2000 scientists and engineers from 36 countries. The scientific goals of the CMS are similar to that of ATLAS, namely

- The search for origin of the spontaneous symmetry breaking (Higgs boson)

- The search for physics beyond the SM - for example supersymmetric particles
- The study of heavy ion collisions and of the formation of the quark-gluon plasma, thus emulating the very first moments after the Big Bang

Although the construction of two similar detectors may seem as a waste of time and money, it fulfils the natural requirement on experimental physics - that any result should be independently confirmed. Also, combined results from both detectors have reduced systematic as well as random errors.

ALICE (**A** **L**arge **I**on **C**ollider **E**xperiment) is a detector specially designed to study the collisions of heavy ions. Experiments in the CERN in 1990's and in the Brookhaven National Laboratory, USA, in 2000's showed that at very high temperatures the quarks are free in a state which was called the quark gluon plasma.

The LHC should create the QGP by colliding nuclei of lead with an energy of 5.5 TeV per nucleon. The QGP will be then identified thanks to the specific signatures of leaving particles - for example the production of strange particles and the suppression (compared to what is expected from ordinary theory) of the production of J/ψ mesons (made from charm and anticharm pair of quarks), because the turmoil of QGP prevents forming of heavy quark pairs. This was seen both in CERN and in BNAL, and it is supposed, that on higher energy also the production of bottomium (bound state of b and $\bar{b}$) will be suppressed from the same reason.

ALICE is constructed at Point 2 and its collaboration involves more than 1000 people from 28 countries.

LHCb (**L**arge **H**adron **C**ollider **b**eauty) is an experiment devoted to the measurement of CP violation. It is expected that it could be most clearly seen in the difference between the decay of B_d meson ($d\bar{b}$) to J/ψ ($c\bar{c}$) and K^0 ($d\bar{s}$) and the decay of anti-Bd meson to respective antiparticles. By studying the difference in the decay times, we would be able to determine the complex phase of CKM matrix [1].

This type of experiment has been already tried (among others) at the LEP, SPS or Tevatron. Nevertheless, none of these machines produced enough b quarks to observe such a subtle effect like CP-violation. The LHC is able to produce much more b quarks than previous accelerators, thus hopefully making the observation of CP-violation possible.

The LHCb is located at Point 8. This experiment has nearly 900 participants from 13 countries.

TOTEM (Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC) is an experiment dedicated to the measurement of the total cross section, elastic scattering and diffractive processes at the LHC. Because its measuring method is luminosity independent, the results obtained during initial lower luminosity runs will be used as a reference for the normal LHC runs.

The TOTEM is a small experiment which does not require any special infrastructure so it is integrated with the CMS in the Point 5. More than 50 scientists from 9 countries participates at this experiment.

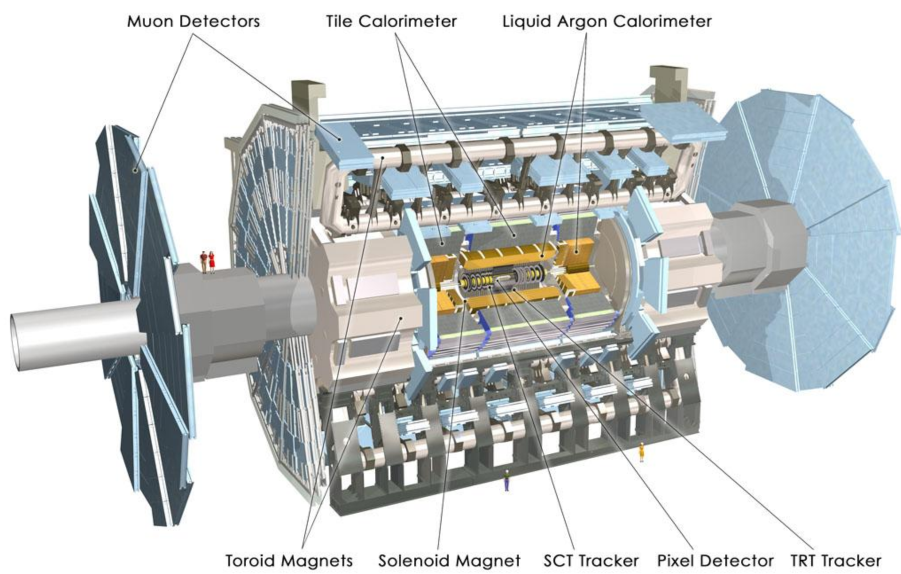

Figure 2.6: The ATLAS detector. The picture was taken from [28].

2.3.3 ATLAS Detector

As was outlined in previous chapter, the physics goals at LHC are really ambitious. And its main tool for accomplishing them is the ATLAS detector. It is huge in size and more complex than any other detector. ATLAS is roughly cylindrical in shape and could be divided into three main layers:

- Inner tracking - done by Inner Detector which measures the tracks of all charged particles coming out of the collision.
- Calorimetry - several types of calorimeters measure the energy of particles which passes through them - most of them will be stopped by the calorimeters so we just measure the deponed energy. Note that neutrinos and muons are able to penetrate the calorimeter system without any problem

- Muon spectrometer - whole detector is surrounded by large muon spectrometer (inner radius 5 m, outer radius 10 m) which helps to identify and track muons, which escape from the detector.

Together with detectors, ATLAS also have a magnet system consisting of central solenoid and several air-core toroid magnets on the perimeter. They produce magnetic field with the strength of about 2 T (central solenoid) and 4 T (toroid magnets) which helps to measure momentum of charged particles. Now let's look at the ATLAS subsystems in detail.

Inner Detector

Inner Detector (ID) is the innermost part of the ATLAS detector. It is a cylinder with the length of 7 m and radius of 1.15 m. ID is a very complex device, consisting of tree subsystems: Pixels, SCT (Semiconductor Tracker) and TRT (Transition Radiation Tracker). The first two systems are in principle high-precision semiconductor detectors, the last one is less precise, but, in the other hand gives large number of hits.

In the central area the detector looks like a series of concentric cylinders (so called "barrel" area), further from center (or, equivalently, in the area, where particles have small angle with respect to proton beam) are detectors glued on a disks perpendicular to the beam axis (these disks are on both end of the detectors and are called endcaps). The total pseudorapidity[2] range covered by the ID is $|\eta| \lesssim 2.5$. The picture of Inner Detector is on Fig. 2.7.

Inner detector subsystems:

Pixel detector In the core of the whole ATLAS detector is the Pixel detector. It consists of three layers (at radii 5 cm, 9 cm and 12 cm) in barrel and three disks in the endcaps. The rectangular pixel modules are mounted on a barrel staves so that their longer axis is parallel with the beam axis. On the endcap disks, the modules are arranged like rays coming from the center of the disk. It is good to note that the number of layers cannot be too high - even if we do not care for the price, each additional layer brings more material into the detector volume and so causes more energy to dissipate, influencing the experiment outcome more than it is necessary.

High granularity is absolutely essential for the whole experiment: it is necessary for high impact parameter resolution and for measuring the lifetimes of

[2]Pseudorapidity is defined as

$$\eta = -\ln \operatorname{tg} \frac{\theta}{2},$$

where θ is azimuthal angle. It is the ultrarelativistic approximation of rapidity.

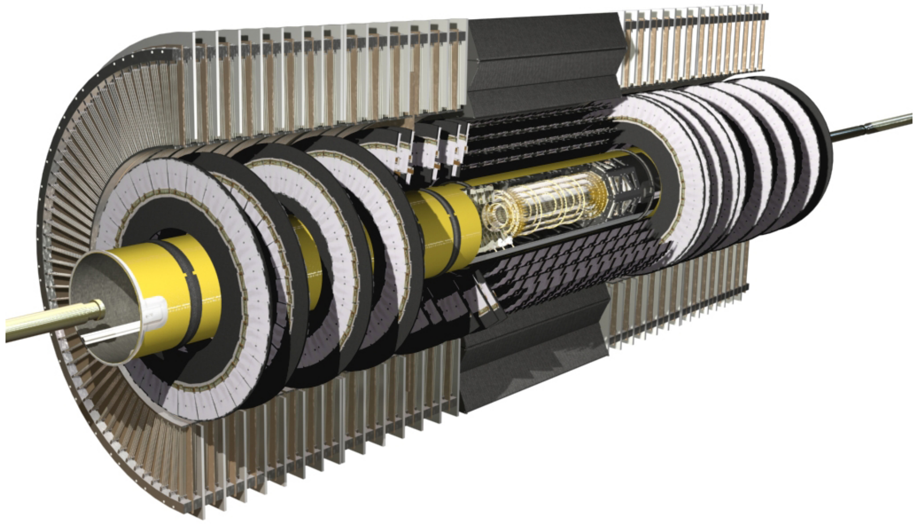

Figure 2.7: The Inner Detector. The visible core is pixel detector. Around it, there is SCT and on the outskirts, there is TRT. The picture was taken from [28].

the heavy particles like B-hadrons. The quality of b-tagging relies mostly on the quality of the data from the pixel detector. Only it can precisely determine the positions of primary and secondary vertices and measure their impact parameters.

To achieve high precision, over 46 000 tiny pixels are on each module. Their size is 50×400 μm and their resolution is 14×115 μm. However, the practical precision is somewhat lower. The reason is, that it is technically impossible to place all modules on the right places, and also, the whole detector degrade in time due to mechanical fatigue. This leads to so-called misalignment, i.e. modules being aligned out of their rightful places. That is why we must do an alignment before any serious physical measurement.

Pixel detector is constructed independently from the other parts of the ID and will be put in place only after the SCT and TRT.

SCT The SCT is constructed similarly to the pixel detector - it has 4 layers in the barrel and 18 disks in the endcaps. The detection of particles is done by silicon microstrip detectors - they are similar in principle to the pixels, but they are longer - meaning that they have worse resolution in longitudinal direction.

The SCT also contributes to precision measurements of tracks and particle momenta and suffer from similar alignment problems as pixels. However, their effect on tracking resolution is not such big as in the case of pixels.

TRT Transition Radiation Tracker is different in construction from the Pixels or

Table 2.2: Inner Detector subsystems parameters

System	Element size	Resolution	η coverage
Pixels	50 $\times$ 400 μm	$\sigma_{R\phi} = 14\ \mu$m $\sigma_z = 87\ \mu$m $\sigma_R = 87\ \mu$m	$\pm$ 2.5
SCT	75 or 112.5 μm $\times$ 12 cm	$\sigma_{R\phi} = 15\ \mu$m $\sigma_z = 770\ \mu$m	$\pm$ 2.5
TRT	4 mm diameter 150 cm long	$\sigma_{R\phi} = 170\ \mu$m per straw	$\pm$ 2.5

SCT. It is based on use of a straw detectors which are aligned parallel with the beam axis. Therefore it has quite good resolution in the plane perpendicular to the beam ($r - \phi$ plane) - about 170 μm, but much worse in the direction of beam. However, there are quite a lot of this straws, so that TRT produces more than 30 hits for each track passing through its volume.

It is composed from 420 000 straw detectors (100 000 in barrel and 320 000 in the endcaps). Electron identification capability is enhanced by Xenon gas which is set between and inside the straws. Each particle create a different number of transition radiation photons, so that the TRT can distinguish between them.

Important facts about ID subsystem are summarized in Table 2.2.

ATLAS calorimeters

After leaving the Inner Detector, particles come into the calorimeters. This device is kind of opposite of the ID - its purpose is to cause particles to dissipate as much energy as possible and do not leave the calorimeter. The dissipated energy is converted into electrical current and than measured. This information is essential in determining the event outcome.

ATLAS calorimeter is composed from several calorimeters - Liquid Argon Calorimeter and Tile Calorimeter.

Liquid Argon Calorimeter is next to the Inner Detector. This calorimeter consists from both electromagnetic and hadronic calorimeters. It is made from absorber plates (made from steel or lead) and filled with liquid Argon. The electrons and photons loses their energy on that plates and decay into showers of less energetic particles. These ionize the molecules of liquid Argon and the resulting electric potential is measured. The same principle is also applied to the measurement of the energy of hadrons. The calorimeter itself has also some degree of granularity, and so it can give us the information not only about the energy but also about the position and direction of the particle.

Tile Calorimeter is the outer one of ATLAS calorimeters. Barrel part is made from 64 wedges, each 5.6 m high and 20 tonnes in mass. Each endcap is also made from 64 wedges (which are however a bit smaller than in the barrel). Tile calorimeter is made from plastic scintillator plates which emits light when a particle passed through. This light is converted to electric signal and measured.

Muon Spectrometer

The purpose of muon spectrometer is to identify and measure muons. As was said before, they are the only measurable particles able to escape from the detector. Muon Spectrometer allows measurement of their tracks and momenta with high precision. This is very important for ATLAS physics, because usually the most popular events are these with leptonic signature - they are cleaner as there is no QCD background.

In principle it is quite similar to the straw detector in ID - the TRT. The only difference is that the straws are slightly larger.

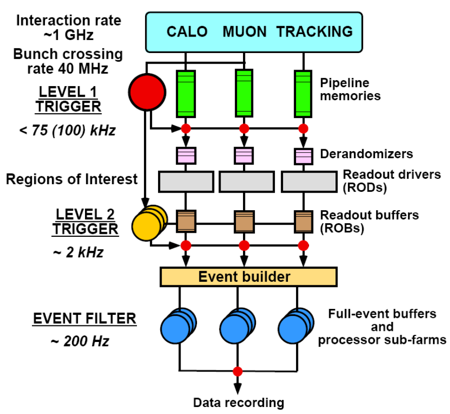

Figure 2.8: The scheme of ATLAS trigger. The picture was taken from [27]

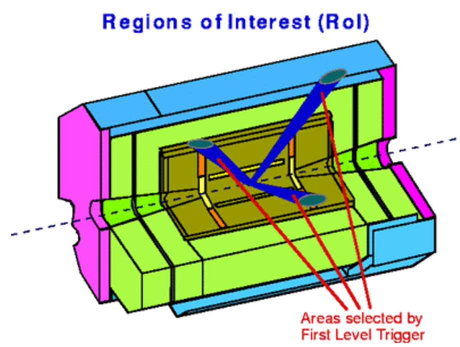

Figure 2.9: Regions of interest in the ATLAS detector. Description of them is in the text. The picture was taken from [28]

2.3.4 ATLAS Trigger

The task of ATLAS trigger is to select bunch crossing containing interesting physics and then record them for the analysis. This is very challenging task because the LHC has very high bunch crossing frequency (one bunch every 25 ns - this is shorter time than it takes photon to travel to the edge of the detector) and because every bunch crossing contains approx. 20 interactions.

The trigger has also to be very selective - the data come with the frequency of about 10^9 Hz, while recording to permanent data storage is done at the frequency of 100 Hz. And, also, it has to be able "to find a needle in a haystack" - for example, the Higgs decay to 4 leptons happens only in one out of 10^{13} events.

To achieve this, ATLAS trigger is divided into 3 levels (scheme is on Fig.2.8). Level 1 (LVL1) uses the data only from muon spectrometer and calorimeters. It has to decide very quickly whether some event interesting or not. LVL1 defines Regions of Interest (RoI), which are simply the areas of detector where something interesting could have happened (Fig. 2.9). The candidates selected by the LVL1 can be high-p_T leptons, photons, hadrons or jets. The information in RoI usually contains direction of the particle (polar angle ϕ and pseudorapidity η), transverse momentum and the energy sums (i.e. also the information about missing energy, which are usually neutrinos. LVL1 reduces the data flow from some 40 MHz to 10-100 kHz.

Level 2 (LVL2) trigger uses the data from all detectors lying in the Regions of Interest to investigate the event in more detail and decide whether the data from the event will be further processed. It reduces data rate to 0.1 - 1 kHz. And finally the third level finally uses the data from the full detector to finally decide if the event will be chosen for permanent storage and further analysis. This is done with the frequency of 10-100 Hz.

I showed that the trigger has crucial meaning in the ATLAS experiment. It really determines what physics we will actually see, so the trigger has to be set as carefully as possible not to miss anything important and the other hand not to accept a lot of uninteresting background events.

Chapter 3

ATLAS offline software

3.1 Introduction

Average LHC event would be made from several hundreds of particles. And these events will be produces at rate 40 MHz at the full LHC luminosity. It is clear that without computers it would be impossible to do any physics at the LHC. The first part of the computing system was already outlined in the previous chapter - I mean the ATLAS trigger which chooses every second 10-100 interesting events out of 40 millions. It is closely related to the Data Acquisition (DAQ), a system which is responsible for that all data will be extracted from the detectors and stored on a long-term storage device (typically a tape). Trigger and Data Acquisition together forms ATLAS online computing. And because it has to be quick, all computers ale placed underground, as near the interaction point as possible.

But there is also ATLAS offline computing - it is something which is done at rest in surface laboratories and research institutes which can be half a planet away from the ATLAS. This is that part of the experiment which produces some publishable results. ATLAS offline computing has rich inner structure, so let's examine it in more detail.

3.2 Main Tasks of Offline Computing

Although one may thing that there is no work for the offline software when no data are available, the contrary is true. There is lively computing activity at every phase of experiment, including the planning and aftermath. The software can be divided into several groups:

Generators are programs which more or less accurately try to generate some event. In principle, this generators take input from the physical theory which tells them what should happen in the terms of probability. Then they employ some Monte Carlo generator which will produce events with the theoretically predicted probability. So the quality of generator is highly dependent on the quality of our theory.

But generators usually not only generates particles with the right probalistic distribution, but also calculate their further destiny which may be parton showers, hadronization, jet forming... etc. However, because we do not have a rigorous theoretical description of this processes, they are mostly model based and experimentally calibrated.

Some generators specialize only in one subprocess (like parton shower), but some are able to do "full generation". Notable example of these are Pythia and Herwig, both written in Fortran, and currently being converted to C++.

The main purpose of this generators is to do "thought experiments" - just to tell us what would happen if... They are crucial in designing the detector and especially in setting the trigger, because they tell us what we should expect.

Simulators are programs which take care of the detector and the surrounding area. They cooperate closely with the generators. In principle, they just add the material of detector into the particle tracks. This influences both the particle, which loses some or all its energy when it meets with the body of detector, and also the detector, which has a "hit". Because of the detector complexity, the simulation is very time-consuming process even on the fastest computer.

The simulation program for ATLAS is called Geant, currently in the version 4. It is feeded by data from physical surveys of the ATLAS cavern, so it has up-to-date detector description. One can even build its oven detector in Geant and look how it will interact with the event outcome.

Digitization software What we get from the detector in reality is basically some electrical current converted to zeros and ones. So digitization takes the hits from the simulation and turns them into an digital signal. It has to be aware of imperfectness of the detectors (i.e. final resolution, noise, defects, etc.) so that the outcome of the digitization is very similar to what will be produced by ATLAS online software. And here we can see one of the main tasks of the offline computing during the construction of the detector - it prepares our computers to what they can see in the actual experiment. This process is called Computing System Commissioning (CSC) and one of its purpose it to find out whether our present calculational and storage capacity will be enough for the ATLAS experimental data.

Of the same importance is also the testing of our reconstruction algorithms. Not only that we test, whether we are able to reconstruct anything from the experimental data, but, if we compare it with the data from software generator ("Monte Carlo Truth") we can test the efficiency of the reconstruction algorithms.

Reconstruction From the experiment or digitization we get some form of detector response to some physics event. The purpose of reconstruction is to determine what happened from the detector response the event had induced. So that the algorithm collects the information about the hits in the tracker and about the energy deposited in calorimeters. From the hits it tries to reconstruct track - by some form of interpolation, and it tries to match the track with the energy in calorimeter.

The output of reconstruction tells us something like: "In event number N there was a particle flying with polar angle ϕ and azimuthal angle θ, with an energy E and momentum p. It had charge Q, spin S and mass m." The amount of stored information of course depends on situation and also on the reconstruction software. It could for example identify the particles - from their mass, spin and charge.

Analysis Analysis is closely related to the reconstruction and sometimes is hard to tell where ends the reconstruction and where starts the analysis. The basic type of physical analysis is (and always has been) the testing of physical hypotheses, i.e. we have some prediction coming from the physical theory and the experiment tests it.

The actual analysis is almost exclusively done by statistics - we extract from the reconstructed data only the important observables and then we do a statistical analysis on them, determining the mean as well as the deviation of measurement.

Now two things may happen - the results are in accord with the theory - this was the case of LEP (the results agreed with the Standard Model up to few per mile) - or there is a disagreement with the prediction. This could mean two things - either we are bad experimenters (that happened a lot of times during past century), or the theory was wrong - this way an atomic nucleus was discovered.

Where lies the border between measurement error and the new discovery? This is not always clear, but generally accepted is that 5σ statistical deviation from the theory expectation ("background") means new discovery. For example, if we want to discover the Higgs boson, we have to know pretty well, how it will look if there is no Higgs boson - and compare it with the data from experiment. The result of such an analysis is on a Figure 1.2. It shows that the experimental result was a bit above the expectations, but not high enough to be statistically significant. A nice article about the statistics and Higgs hunting is [31].

Visualization So far I showed the software which takes a bunch of numbers, do something with them and return another bunch of numbers. Because this is not an ideal input for human mind (yes, with all the machines and computers it is still a physicist who decides what happens in the detector), there is software to convert data about events to something more convenient, typically some picture.

Basically there are two types of this software. The first one are event viewers, which visualize the event in the detector (for experienced physicist, this is the fastest way how to decide whether something interesting happened or not). Example of such a visualization is on Fig. 3.1.

The second way of visualization is to plot the data to make some histograms. They usually have the familiar structure of some flat background with gaussian peaks. This way the physicist loses the contact with the individual events, but on the other hand he acquires a comprehensive view on all interesting data.

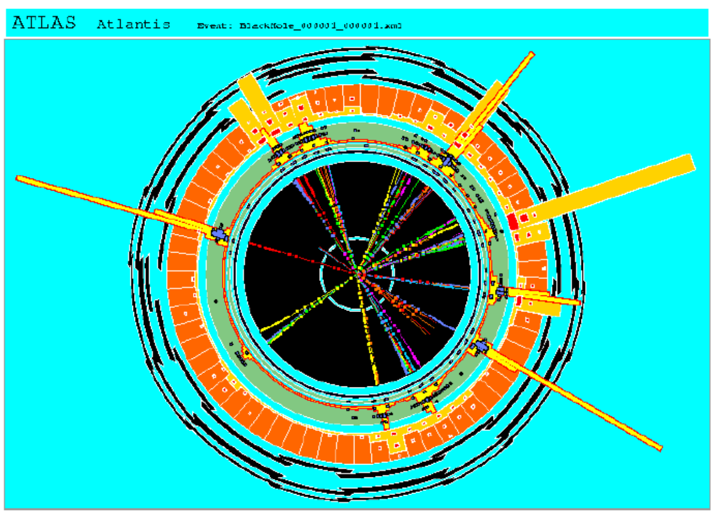

Figure 3.1: Black Hole event in ATLAS. Event View made by Atlantis. From [38].

3.3 Offline Computing at ATLAS

Previous section showed the main tasks of the offline software which are common for all high energy physics experiments. So how is this software implemented in ATLAS?

As we have seen, there is a lot of various programs to do different tasks, but a physicist needs all of them. Also, a physicist has to have a full control over what the programme is doing, mostly he even has to change its code, because every experiment and every analysis is different. And, most importantly, physicist want to implement his own ideas to the software and compare them with the experiment as well as with other physicists. That is why it is impossible to take some program ”out of the box” and use it. If this would be true, all offline computing could be handled by some well trained chimpanzee who would know when to press enter.

The question now is how to work with a lot of programs, written by hundreds of people, usually even in different programming languages when you are not a programmer. In case of ATLAS, the answer is (or rather should be) the Athena.

Athena is a name of the software framework for the ATLAS offline computing. It is based on C++ and among others brings common user interface to all offline software. It provides common tool for installing and managing the software called CMT (Configuration Management Tool), it has shared libraries of important objects and tools, so that all collaboration is using the same. Last but not least, it provides common data format, making the analysis of results easier and more transparent. All this encourages common approach and reusability, making it easier for people to join as well as to go from one physics group to another if they like.

3.3.1 Athena

How to use Athena

Athena consists of the software (i.e. algorithms and libraries) and of the tools which manage this software. It is installed on all computers of CERN public logon service (LXPLUS) and public batch service (LXBATCH). It could be also installed locally using ATHENA kit.

The ATLAS offline software is organized in the forms of small packages, each doing some specific task (for example digitization of pixel detector). These packages can be browsed by CVS local repository ([33]) or by LXR [34] - this tool is extremely useful, because it contains very powerful search engine.

This software packages covers basically all activities user would like to do at ATLAS. So the first thing a physicist should do when he wants to do some calculation, is to find a software package which deals with it.

After that he use the Athena's management tool CMT to ”check out” that package - it means downloading its contents from the central repository to the local machine and making links with the other software which the package uses (for example the description of detector) and usually is common for a lot of other packages. Thanks to Athena, all pieces of software are installed in the same way.

Then the user can change the main algorithm of the package to better suits his needs. Because everything is written in C++ using the same objects and tools, he does not have to learn anything new to work with a new package. When he is satisfied with the code, he compiles it (using the CMT) and runs it - the commands to run a package are also the same for all of them.

However, the modification of the main algorithm is usually not necessary. The code contains dozens of switches which are set independently in so-called Job Options file. This allows the physicist to modify the algorithm to his needs without even knowing the C++, because Job Options are written in much more simple Python language. And because every package contains a lot of already written Job Option files, the user can just pick one of them and change the values. So that even knowledge of Python is not necessary to work with ATLAS software.

Because of the common data format, the output of any package could be used as an input for other packages. There are some restrictions coming from the organization of the software - the output of simulation could be used as input for digitization, but not the other way round.

The output of Athena could be used also outside the Athena framework - most often by the software for statistical analysis called ROOT. Or the user can ask Athena to produce XML file(s), which can be used by Atlantis to do an event visualization.

Where to find help

The functionality of Athena in general is described in ever growing ATLAS Computing Workbook [32], which is part of ATLAS Twiki pages. That means that every user can contribute to it sharing her or his experience.

But Twiki is not only the ATLAS Computing Workbook. It contains hundreds of pages describing how to do some specific task within Athena (for example, there is a page telling how to do a b-tagging, how to do digitization of several parts of ATLAS detector, how to do an analysis...). The contains of Twiki is growing every day, as users write their experience there.

Other useful source of information about Athena is Doxygen [35], which contains documentation to the code itself. It is incomplete (as is normal for software documentation), but also is growing every day.

When using some software, the most valuable information usually comes from the discussion with other users and/or authors of the code. For that reason there is a forum called ATLAS Hypernews [36]. All users of Athena are invited to subscribe and contribute there.

3.3.2 ROOT

In previous section I mentioned ROOT as an important tool for physics analysis. ROOT, in fact, is a software framework on its own. The reason is that every analysis is different - every physicist needs his own analysis routine.

ROOT framework provide common objects and services (histograms, fitting...) which are used in a statistical analysis. Physicists then use them to make the analysis macro they need. And because of common functionality it could be easily taken by some other user and modified to his needs.

ROOT is based on C++ and could be used in two ways: interactively or in a batch mode. In the first case, the user writes commands in simplified C++ and

ROOT interprets them. If the user is not very familiar with C++, he or she can turn on the graphical user interface and do almost everything by clicking on the menus.

For complex tasks it is more convenient to write a short script, rather then repeat the commands in the interactive mode again and again. When user have a script he can run it as many times as he like in a batch mode. The script can even be compiled. After that they are about ten times faster than the interpreted scripts.

ROOT is not a part of Athena, however it is connected with it. For one thing, the Athena uses root files as its input and output data files. Secondly, it is possible to call ROOT directly from Athena and so quickly produce histograms. Also it is possible to use ROOT advanced mathematical tools (in addition to statistics it knows mathematical analysis and linear algebra) in Athena.

Here I showed only some of the ROOT functions. For example it can also draw the Feynman diagrams or make 3D models of ATLAS detector. Comprehensive documentation on all functions (as well as many tutorials and examples) are on ROOT home page [37].

3.3.3 GRID

Particle physics produce huge amount of data which is impossible to analyze with a single computer. For that reason, every particle physics laboratory has established a computer farm. For example the CERN computer farm has now about 5000 processors. Also, such a lot of data cannot be stored on ordinary disks - usually the data are stored on tapes. The CERN storage service is called Castor and has capacity of more than 7500 TB.

But LHC will produce such a lot of data, that even a CERN computer farm will not be able to analyze it. Not surprisingly, Castor will not be able to store and backup all data from LHC.

The solution to this problem is the GRID. It is a network of all big computer centers in Europe and North America, which allows sharing of computing power and storage capacity. It could be used not only for analyzing the LHC data, but also for all other tasks which require big computing power.

From the user point of view, the using of the GRID is quite simple - you decide what should be calculated and the GRID does the rest. It finds a computing center with free capacity and sends the commands there. Finally user is notified that his job was done and where the output was stored. The principle is quite similar to the electrical power grid - when you connect to the electrical socket you do not care which power plant gives you the power. On the GRID you do not care which computing center gives you the computing power.

The GRID also serves for data storage, because it incorporates storage devices of all connected computer centers. There is a database of all files on the GRID called Panda monitor [39] and a tool for accessing them. It is called Don Quijote (DQ) [40].

Chapter 4

B-tagging

4.1 Introduction

In the first chapter I showed how important for LHC physics is proper detection and identification of bottom quarks. There are two areas in which bottom quark plays a major role [11]. The first of them is wide range of studies in B-physics:

- CP violation in events $B_d \rightarrow J/\Psi K_s$, $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow J/\Psi\phi$. From these decays the parameters of Cabibbo-Kobayashi-Maskava matrix ([1]) could be measured
- Measurement of $B_s - \overline{B}_s$ mixing (similarly to the kaon system)
- rare decays like $B_s \rightarrow \mu^+\mu^-$ to test the Standard Model

These will be the main issues of LHCb experiment, but ATLAS and CMS, as they are a general purpose detectors, should also see this. This studies would require very high production rates and precise measurements of slow bottom quarks.

Because we do not need high energy b-quarks, this physics could be done very early at the LHC, even during the proposed calibration run (the period when LHC will not accelerate the particles at all, but rather keep them at the energy from injector, i.e. 450 GeV). In this case, muons coming from the decays of light hadrons in flight can be easily mistaken for muons from B-mesons decays. More about this could be found in [13].

The second area which is "flooded" with bottom quarks is the Higgs and top physics: Bottom jets are typical decay products of light Higgs and top quark. So, if we want to measure mass of this particles, we have to correctly identify the b-jets and their masses. In case of Higgs, the main goal is to distinguish rare events with Higgs decaying to $b\bar{b}$ pair from huge QCD background.

Last, but not least, b-tagging could find clue to some Beyond the SM Physics, like Supersymmetry.

All this would require good b-tagging efficiency together with high rejection of non-b jets. So now, I would concentrate on how b-tagging will be done at ATLAS.

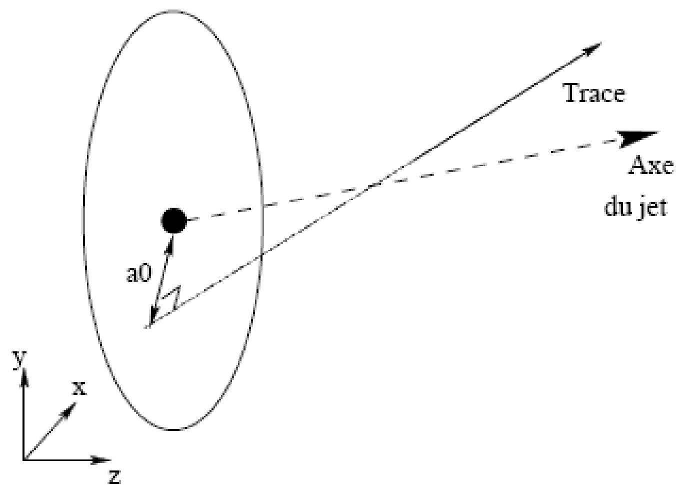

Figure 4.1: Definition of impact parameter, dashed is the jet axis, solid line is track with nonzero impact parameter. Picture taken from [12].

4.2 Methods of B-tagging

B-tagging uses several distinct features of bottom quarks, namely

- Their mass is several times higher than anything they decay into - this means that their decay products have very high momentum
- Their fragmentation is inelastic
- Relatively long lifetime, combined with high energy results in relatively long tracks before bottom quark decays (in order of several millimeters). Moreover, they often decay into charm quark, which has also long lifetime and high energy and therefore long track.

There are, in principle, two ways of identifying the b-jet. The first is called leptonic tagging, the second topological tagging. Leptonic tagging uses first and second property of bottom quark. Leptons, originating in semileptonic decays of bottom quark ($b \to d\ell\nu$) have inevitably large energy, i.e. large transverse momentum. Therefore simple criterium discriminating by some p_{Tmin} could be used for identification. In hadronic colliders, more than 90 % of high energy electrons comes from decay of bottom quarks [12]. However, problem with this method is, that only a small fraction of bottom quarks decay in semileptonic way and also identifying leptons could have small efficiency. Therefore this method is good for high rate events of B-physics, but not for rare Higgs decays.

The second method is topological tagging. It is based on the third bottom quark property - interesting and distinctive event topology. Because bottom quark travel some distance before it decays, the products of its decay do not point towards primary vertex - place of *pp* collision. There are basically two ways of identifying b jet through topology. The first one means reconstructing all vertices in given event (or at least the ones in jet) and if contains at least one vertex distinct from the primary vertex it is said to be a b jet.

However this method is very difficult as it require excellent detector performance in resolution and reconstruction. The second method is easier and, maybe surprisingly, also more effective in general. It is based on reconstruction of tracks which are not going from primary vertex. The main variable is here the impact parameter: the closest distance of track to the point of interaction.

Impact parameter is measured in a z coordinate (1D), $r\phi$ plane (2D) or in $z - r\phi$ in three-dimensional case - see Fig. 4.1. Impact parameter is a signed variable. The sign is determined by the crossing point of the track with respect to jet axis. If it is behind the primary vertex, the sign is negative, otherwise positive. Negative sign could be caused by various reasons - imperfect determination of impact parameter due to low resolution, multiple scattering or the that the axis of jet is different than original direction of bottom quark.

The secondary vertices could also be found in various way. One way is to fit vertices with all pairs of tracks, retaining the fit with the highest probability and fitting the remaining tracks of the jet to this vertex. All tracks below a certain fit probability will be rejected. This approach is implemented in the build-up (BU) algorithm. An other approach is to start with all tracks in the jet, fit a vertex, and reject tracks below a certain fixed fit probability. This has been implemented in the tear-down (TD) algorithm.

4.3 B-tagging with Athena

Most of b-tagging code is stored in two packages:

- `PhysicsAnalysis/JetTagging`
- `Reconstruction/BTag`

So you can see, b-tagging can be done as a part of reconstruction or of analysis. The software implements several taggers (IP1D, IP2D, IP3D, SV1 and SV2). The first three are based on impact parameter in 1, 2 or 3 dimensions. The latter two are secondary vertex tags. They use following tagging variables: Number of secondary vertices, mass of particles at the secondary vertices, fraction of total energy, transverse momentum and track rapidity at secondary vertices. The tests showed that the most effective tagger is IP3D + SV1, which is now also the default tagger [41]. Note that you can also use soft lepton tag, as I mentioned in the previous paragraph, but it has limited use because only about 10 % of b-mesons decay in this way.

Tagging variables are used not only to identify jet, but also do distinguish quark jets of different flavor - this is possible thanks to the rather unique properties of bottom quark. Example of discrimination between b-jets and u-jets is on Fig. 4.2 and on Fig. 4.3.

More information about b-tagging with Athena can be found on Twiki pages FlavourTagging [42] and BTaggingBasics [41]. Useful tutorial is on BTaggingSoft-Tutorials [43].

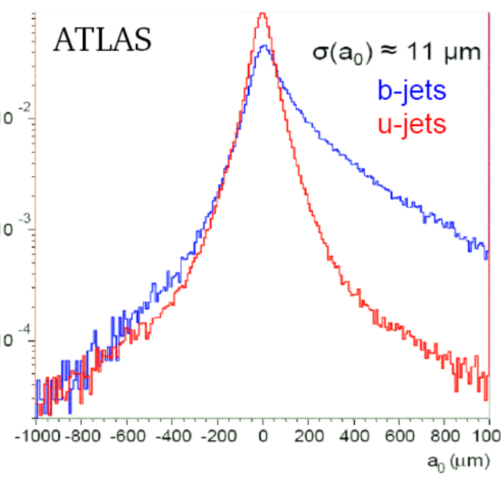

Figure 4.2: Distribution of impact parameters for b-jets and u-jets. The picture was taken from Sebastian Fleischmann [44].

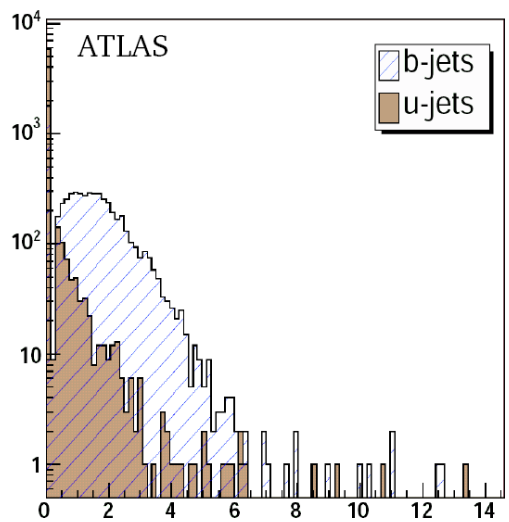

Figure 4.3: Histogram showing the mass of particles at the secondary vertex. The picture was taken Sebastian Fleischmann [44].

4.4 Higgs at LHC

So far I have shown how the Higgs was looked for at LEP and how it is looked for at Tevatron. This was done in the first chapter. Several times I also mentioned, that identifying of bottom quarks via b-tagging is crucial for Higgs searching, so now it is time to be more concrete.

The first reason why we are interested in b-tagging is that Higgs lighter than approximately 130 GeV decays predominantly to $b\bar{b}$ pair (Fig. 1.1). However, we must take into account various production mechanism (Fig. 4.4). The dominant one - gluon fusion, has so big background (about nine orders of magnitude before corrections [8]) that searching for Higgs in events $gg \to H \to b\bar{b}$ is absolutely hopeless. So that we must choose carefully our discovery channels.

One of them is $qq \rightarrow WH$ which is quite similar to the one used in LEP (see chapter 1), that means clear signature of 2 b jets from Higgs and then decay products of W boson - that means predominantly to jets, then to charged leptons and neutrinos [8]. So that the need for precise b-tagging is obvious. However, the background for this channel is $Wb\bar{b}$ and grows QCD-like, that means it could be useful only at lower energies during the start of LHC and/or if the Higgs mass is very close to the LEP limit.

Maybe it would be good to look for more complex channels - LHC is "particle factory" so even channels with low branching ratio should have decent event rate. Typical example for this is $t\bar{t}H$ production (Higgs produced together with $t\bar{t}$ pair), Higgs afterwards decaying into $b\bar{b}$ pair (Fig. 4.5 shows schema of such an event - we require at least one lepton from W for triggering, blue is the possible soft QCD radiation). Into this channel was put a lot of hope - mainly because the backgrounds from QCD processes $t\bar{t}b\bar{b}$, $t\bar{t}jj$ was underestimated. Proper study [14] showed that signal to background ratio in this case is about 1/6 (Fig. 4.6). However, it has one big disadvantage coming from the systematic uncertainties - the significance of Higgs over background cannot be higher than 3 σ no matter how high amount of data we have. So that it cannot be used to claim Higgs discovery (usual demand is 5 σ significance), but could be used for measurements of some parameters, for example Higgs couplings.

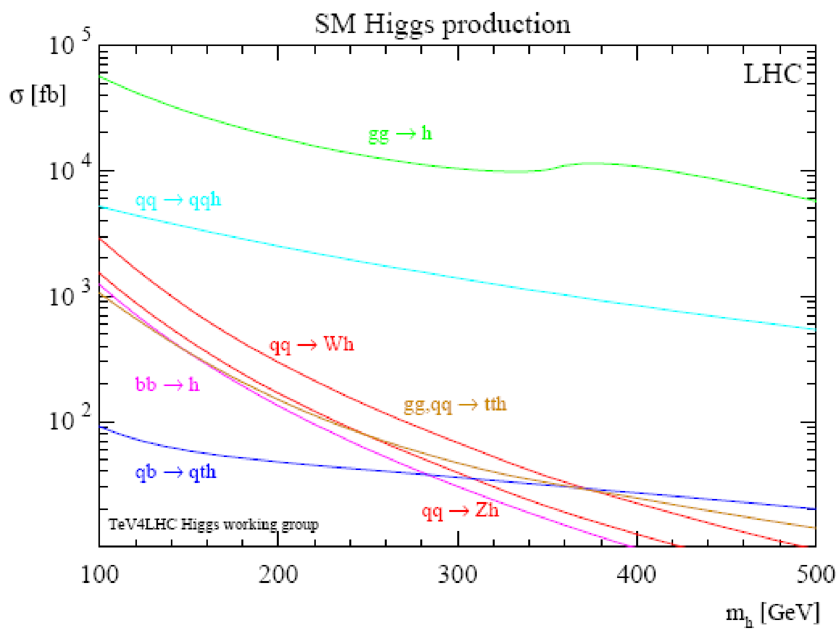

Figure 4.4: Various Higgs production rates for $\sqrt{s} = 14$ TeV. Picture from [8]

Fortunately, there are other channels, which could be useful although they have lower production rate. It could be Higgs decay into photon pair or into $W^{\pm}$ pair -

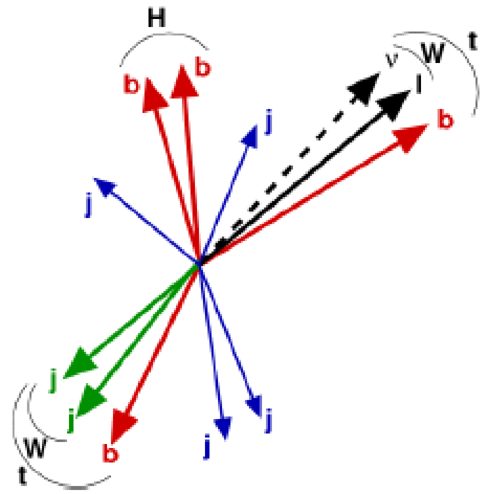

Figure 4.5: Schema of $t\bar{t}H$ event. From [8]

this would also require proper b-tagging - and the most promising channel is vector boson fusion, i.e. $W^{\pm}$ pair is produced in collision and the two particles merge together giving birth to Higgs boson. It is an event with very distinctive topology, and low background so it could be readily used for Higgs searching.

4.5 Error Tuning

Previous chapters showed the importance of b-tagging and precision measurements for ATLAS physics. Because bottom quarks and most of its decay products decay inside the Inner Detector our tracking has to be as good as possible to correctly reconstruct all vertices. Its obvious that we have to know well how big measurements error we have from various detectors. But there exists a difference between measurements error provided by clustering or drift circles and those provided by tracking.

The solution to this problem is so-called error tuning. It is parameterized by two parameters: a and c. The first one correspond to the effect which is correlated with the measurement error, the second describes phenomena which are independent of measurements error, for example caused by residual misalignment (i.e. the misalignment remaining after application of alignment procedures). The formula for application is following

$$\sigma'^2 = a^2 \cdot \sigma^2 + c^2 \tag{4.1}$$

where σ is the error before error tuning and σ' after error tuning.

How many different a, c pairs do we have ? Present software tool for their determination [17] uses one pair for pixel barrel x direction and one for y direction.

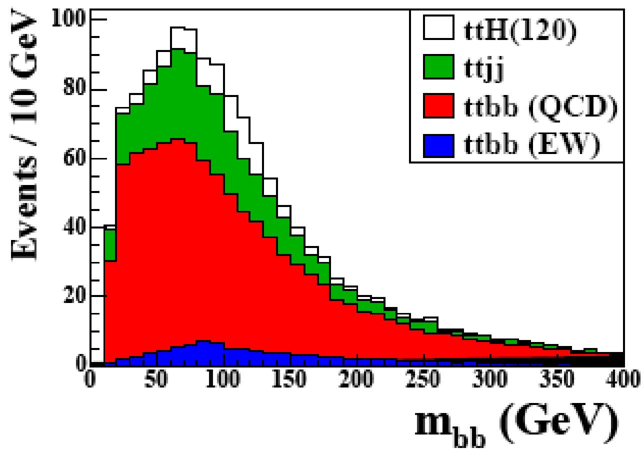

Figure 4.6: Results of a more up-to-date study of ATLAS with 30 fb^{-1} of data [14]

The same is true for pixel endcaps. Note that there is one common value for both endcaps.

One pair of parameters belong to SCT barrel and one to SCT endcaps and the same is true for TRT. So altogether we have 8 pairs of parameters. Another 8 pairs exists for tuning of muon spectrometer.

Error tuning guarantees proper tracking in terms of track scoring, outlier flagging, tracking efficiency and parameter resolution and therefore is essential for alignment of Inner Detector as well as for b-tagging.

I was determining the error tuning constants under the Athena release 12.0.3. This means that I had to check out some extra software packages. Namely

- `Tracking/TrkTools/TrkToolInterfaces`

  version 00-12-02

- `Tracking/TrkTools/TrkRIO_OnTrackCreator`

  version 00-06-11

- `InnerDetector/InDetExample/InDetRecExample`

  version 01-03-37

This was done easily with standard Athena tool - CMT.

The main software was in package `InDetRecExample`, parameters a and c were stored in one of the shared jobOption files of this package. The name of this file was `InDetErrorScaling.py`. I also had to edit the main jobOption file to include this file into simulation as it is not part of the standard release.

Table 4.1: Residual Misalignment Constants. Note that this apply to pixels only - there is no residual misalignment for SCT or TRT. The columns means shift in x,y or z direction and rotation around particular axis. The values are in μm and mrad respectively. Rows shows what is being shifted(tilted)

	X	Y	Z	RotX	RotY	RotZ
Module	10	30	30	0.3	0.5	0.2
Layer	10	10	15	0.05	0.05	0.1
Disk	10	10	30	0.2	0.2	0.1
All	10	10	15	0.1	0.1	0.1

Now the question is what data use for determination of this parameters. I used single muon sample. It is a "clean" sample, so I can isolate the influence of misalignment on the hit residuals from it. Single muons are kind of standard candles for the reconstruction. They have the advantage that material effects on the track are almost totally absent. With other data (for example flavour jets) it would be very difficult to disentangle tracking effects from material effects.

Next step was to choose a geometry for which I would calculate the tuning constants. I chose the perfect geometry with the initial level of residual misalignment [18], because this is the geometry I am likely to meet at the moment when ATLAS begin data taking. The ideal geometry was chosen by standard tag in the main jobOption file, residual misalignment was introduced by a condition database tag in the same file. The size of this residual misalignment is in Table 4.1. Note that at first I ran the reconstruction without this tag as I want to explore effects correlated with measurements error. Residual misalignment was introduced afterwards.

The hits which I reconstructed were generated and simulated in release 12.0.1 in ideal geometry and were stored in a dataset

`testIdeal_07.007234.singlepart_mu200.digit.RDO.v12000201`

I used 5 thousand events to obtain some decent statistics. Parameters a and c are dependent on hit residuals and pulls of the distribution, so information about this variables were stored into a ROOT file during the reconstruction.

This ROOT file can be subsequently analyzed by a ROOT macro contained in package `Tracking/TrkValidation/TrkValTools`. This produces hit residuals and pulls for following categories (and in this order): All – Barrel – Positive Endcap – Negative Endcap – N layers – Residual vs. eta – Pull vs. eta.

Example of a result of such an analysis is in the Fig. 4.7. On the right hand side, there are plots of hit residuals, on the left hand side, there are distribution of pulls (difference between the direct measurement of the variable and its value as obtained from the least squares fit, normalized by dividing by the estimated error of this difference).

Table 4.2: Values of parameter a for various parts of ATLAS inner detector. Note that this parameter is dimensionless.

a	Barrel	Endcaps
Pixel X	0.97	1.03
Pixel Y	0.88	0.98
SCT	0.81	0.89
TRT	0.90	0.82

In ideal case, these distributions should be gaussian, centered on zero and standard deviation σ should be one. However, due to effects mentioned in the first paragraph, we have plots with σ not being one. So that we can find parameter a as a multiplicative discrepancy of the pull width from 1.0, this means we can just take standard deviation sigma of the pulls distribution obtained beforehand. The whole reconstruction and analysis was repeated twice more to obtain reliable numbers. The results are in Tab. 4.2.

Determining the parameter c was a bit more difficult. At first I put the values of a into the reconstruction (in the standard way, by writing them in the jobOptions file in the same way as before) and ran the reconstruction with the residual misalignment tag. Afterwards I analyzed the resulting root file with the same macro as in previous case to obtain similar plots. But here the similarities ends.

The formula for calculating parameter c is

$$c^2 = (p_{obs}^2 - 1)a^2\sigma_0^2 - p_o b s^2 c_0^2 \tag{4.2}$$

where p_{obs} is the observed pull width (from plots), σ_0 is the detector resolution (see below) and c_0 is our previous knowledge of c - typically previous iteration.

What exactly put in place of σ_0's? Natural answer would be to use intrinsic resolutions of detectors - 14 μm for pixel detector, 15 μm for SCT and 170 μm for TRT. However, if we do so, we would find that for the most of detectors values of c diverge - see Fig. 4.8.

The solution to this problem is, when we take not the as-built resolution, but the actual resolution which is represented by the value of hit residuals - these were on the plots (Fig. 4.7) on the right-hand side. Their values are in Tab. 4.3.

If we do so, we find that ultimately values of c converge for all detectors (Fig. 4.9). Their values after eight iterations are in Tab. 4.4)

I regularly presented results and ideas on a group meetings, the summary was shown in May on a b-tagging workshop in Marseille [45].

Table 4.3: Values of σ_0 for various parts of ATLAS Inner Detector. It is taken from the hit residuals (see text). Note that it change slightly in each iteration, this are the values after 8 iterations. All values are in μm

$\boldsymbol{\sigma_0}$	Barrel	Endcaps
Pixel X	36	29
Pixel Y	168	145
SCT	24	29
TRT	170	148

Table 4.4: Values of parameter c for various parts of ATLAS Inner Detector in μm after 8 iterations. They were calculated from pulls of the distribution and hit residuals in the way described in the text

c	Barrel	Endcaps
Pixel X	37	29
Pixel Y	167	143
SCT	23	29
TRT	169	148

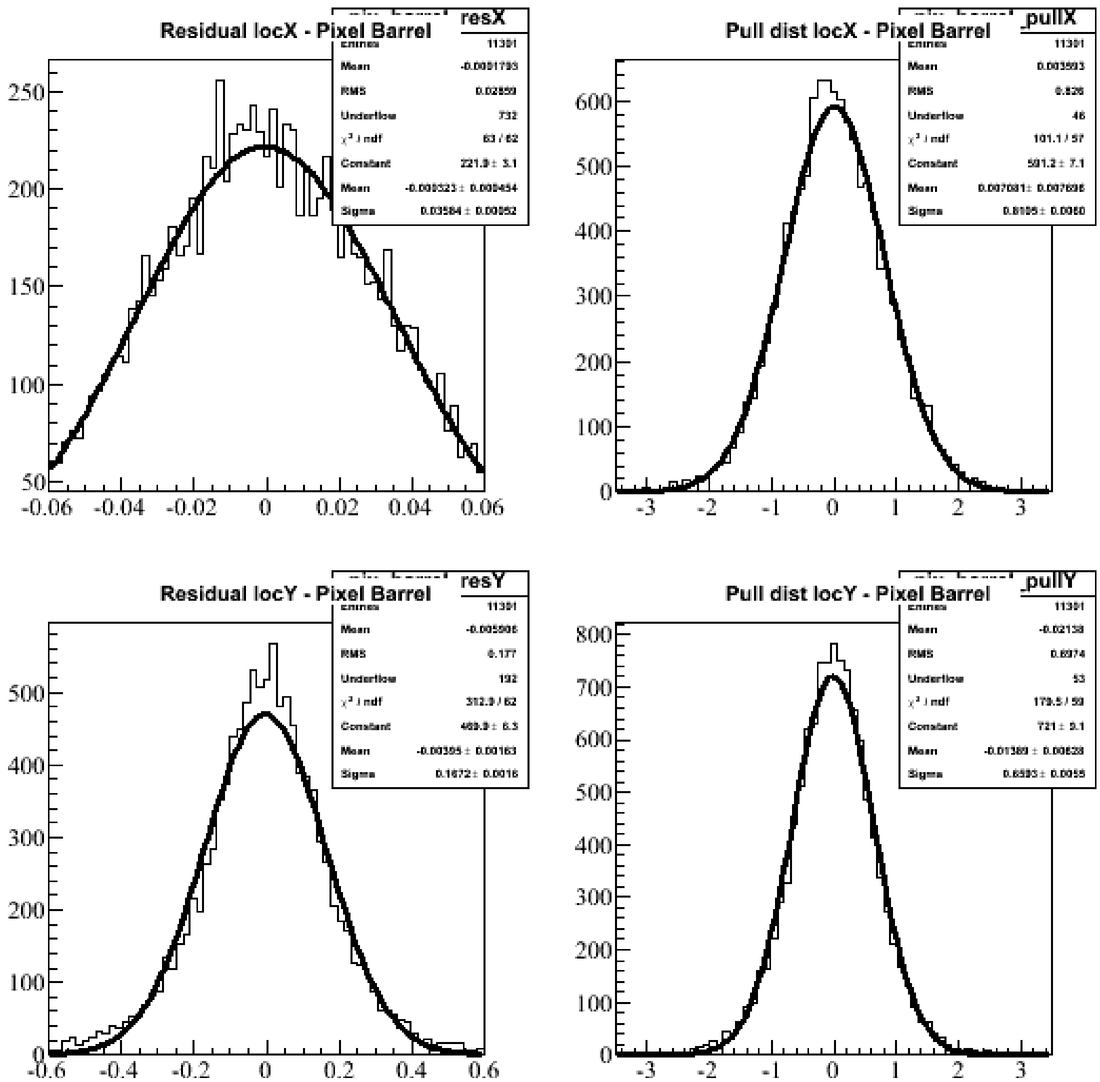

Figure 4.7: Hit residuals and pulls distribution in a pixel barrel. This is the output of the ROOT macro mentioned in the text.

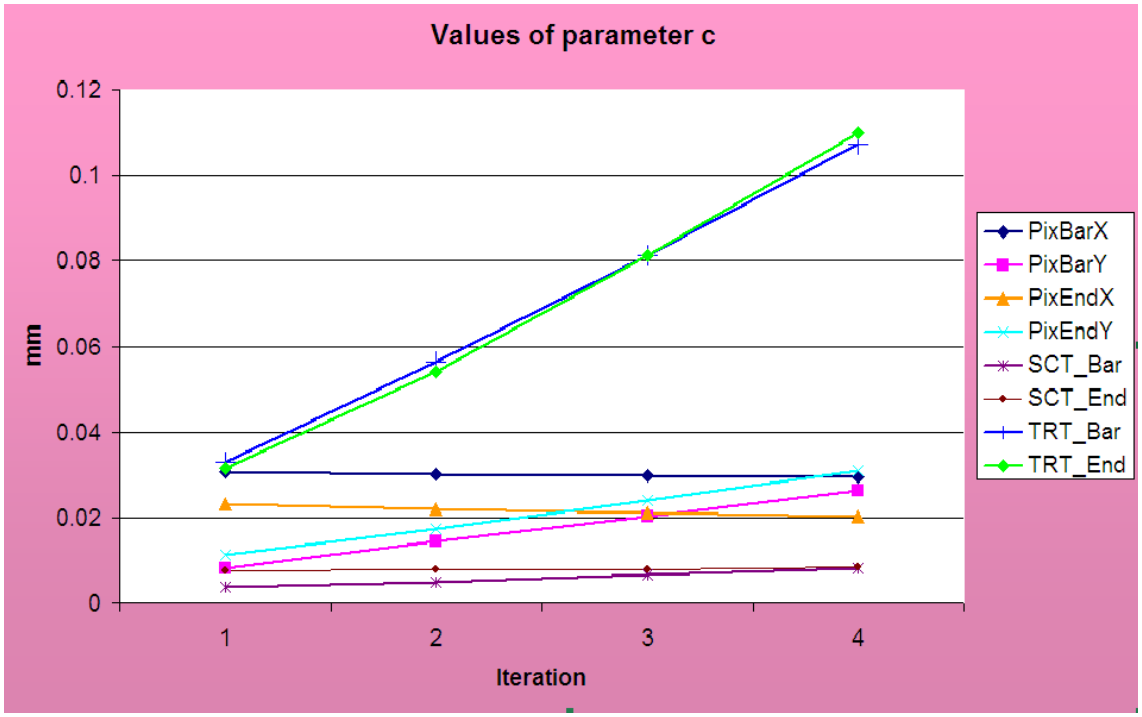

Figure 4.8: Values of parameter c as a function of number of iterations. I am using intrinsic resolutions of detectors

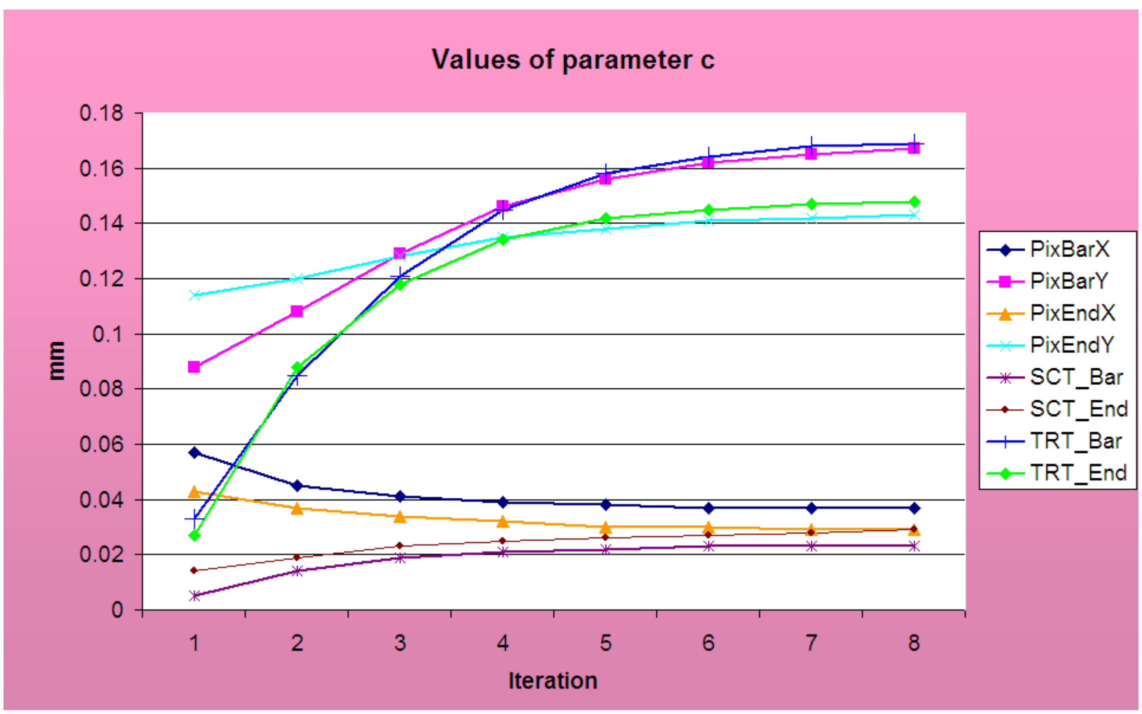

Figure 4.9: Values of parameter c as a function of number of iterations. I am using hit residuals as a σ_0

Chapter 5

Summary

The first three chapters of this thesis have character of literature (and web) search. They are devoted to the present theoretical formulation of the particle physics (Standard Model), experiments in particle physics and offline computing in particle experiments.

The theoretical motivation for present particle particle physics experiments is above all the finding of Higgs boson. Present and past experiments (Tevatron and LEP) gave us only a lower limit on the Higgs mass, which is 114.4 GeV.

Other important research topic is heavy quark physics. This can mean the study of properties of the top quark (possible only at Tevatron and, in future, at LHC), but also the studies of bottom quark. They could be used in a lot of areas - for example Higgs sector, measurement of CP violation or even searches for some Beyond the Standard Model physics.

Last but not least, our particle physics theory is far from final: it contains some intrinsic divergences and has more than 20 parameters. There is a lot of proposed extensions of the Standard Model and LHC should be able to distinguish them from Standard Model as well as from each other. The most popular extension is called MSSM.

To find answers on this questions, a particle accelerators are being built. The most powerful accelerator in the present is Tevatron and the most powerful accelerator under construction is LHC. Each of them hosts several experiments.

Modern particle physics would be unthinkable without computing. At ATLAS, all offline computing is done in one common framework called Athena. Other necessary tools for ATLAS physics are statistical analysis framework called ROOT and system for distributed computing among several computing clusters called GRID.

Author's own work is in the fourth chapter. It is devoted to b-tagging - i.e. method of identification of jets or hadrons which contain b quark.

The most important task of b-tagging is helping in the Higgs discovery. Section 4.4 describes how the Higgs can be found at LHC and where the b-tagging comes on the stage. LHC Higgs searches are quite different from these on LEP and Tevatron. Because it is a hadronic collider, LHC will have much bigger background than LEP.

And thanks to its high luminosity LHC will be able to inspect channels which are extremely improbable at Tevatron.

Precise tracking is essential for b-tagging, so that there is large effort to minimize all possible errors in measurement. Also, because all results are analyzed statistically, we need to know properly how big the measurements errors are. However, there is a difference in measurement error we can get from tracking and these we can get from clustering.

To fight this discrepancy, we introduced the error tuning. It means finding a set of parameters which will tune our measurement errors to right values. There are two types of parameters to describe both effects correlated and uncorrelated with the measurement error.

The results of my study are:

- Single muon data are the data for determination of the tuning constants, because muons are practically unaffected by the material effects.

- Parameters of the error tuning (a and c) were determined by iterative method. The results are in tables 4.2 and 4.4.

- The error tuning constants can be readily used in other analysis. Because in b-tagging the precision is critically important, the usage of error tuning is practically obligatory there.

However, there was a problem with the right choice of detector resolution. The obvious possibility (intrinsic, as-built resolution), led to the divergences. When the detector resolution was chosen more carefully I finally obtained the converging values for all parameters.

To conclude, in this thesis I presented a method how to determine the size of the measurement errors. I tested this method for a particular geometry which is very similar to what we will actually see in the first years of ATLAS running. All results which are in this thesis were presented on the group meetings and also critically reviewed there.

Bibliography

[1] J. Hořejší, *Fundamentals of Electroweak Theory*, Karolinum Press, 2002

[2] J. Chýla, *Quarks, partons and Quantum Chromodynamics*, lecture notes, `http://www-hep2.fzu.cz/Theory/notes/text.pdf`

[3] Y. Dokshitzer, V. Khoze, A. Mueller and S. Troyan, *Basics of perturbative QCD*, Editions Frontiers, 1991

[4] L. H. Ryder, *Quantum Field Theory*, 2nd edition, Cambridge University Press, 1996

[5] M. E. Peskin, D. V. Schroeder, *Introduction to Quantum Field Theory*, Westview Press, 1995

[6] G. Altarelli, *The Standard Model of Particle Physics*, hep-ph/0510281 v1

[7] M. Drees, *An Introduction to Supersymmetry*, hep-ph/9611409v1

[8] D. Rainwater, *Searching for the Higgs boson*, hep-ph/0702124v1

[9] The LEP Collaborations, *A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model*, hep-ex/0612034v2

[10] W.-M. Yao *et al.*, Journal of Physics **G** 33, 1 (2006)

[11] T. Mouthuy, A. N. Rozanov, L. Vacavant, *B-tagging at LHC*, 5th International Workshop on Vertex Detectors - VERTEX '96, Chia, Italy, 16 - 21 Jun 1996

[12] L. Vacavant, *Etiquetage des quarks b par un détecteur de vertex à pixels dans l'expérience ATLAS auprès du LHC*, CERN-THESIS-97-007

[13] J. Günther, P. Jež, M. Panušková, M. Smižanská, P. Šulc, V. Vrba, *Estimates of muons from decays in flights in ATLAS detector for the 900 GeV LHC run*, ATL-COM-PHYS-2006-088

[14] J. Cammin, Ph.D. Thesis [ATLAS], BONN-IR-2004-06

[15] ATLAS collaboration, *ATLAS Technical Proposal for a General-Purpose pp Experiment at the Large Hadron Collider at CERN*, 2nd edition, CERN, 1994

[16] R. K. Bock, A. Vasilescu, *Particle Detector Briefbook*, `http://rkb.home.cern.ch/rkb/PH14pp/node1.html`

[17] Error tuning TWiki page `https://twiki.cern.ch/twiki/bin/view/Atlas/InDetErrorScalingRel12`

[18] Residual Misalignment TWiki page `https://twiki.cern.ch/twiki/bin/view/Atlas/InDetResidualMisalignment`

[19] A. Dedes, *The Higgs Penguin and its Applications : An overview*, hep-ph/0309233v2

[20] BaBar collaboration, *Observation of CP violation in the B^0 meson system*, hep-ex/0107013

[21] Ronald Moor, *An Overview of Tevatron Collider Run II at Fermilab* presentation at RUPAC 2002

[22] CDF public web `http://www-cdf.fnal.gov/`

[23] DØ public web `http://www-d0.fnal.gov/`

[24] V.M. Abazov *et al.*, Direct observation of the strange b baryon Ξ_b^-, 0706.1690v2 [hep-ex]

[25] V. M. Abazov *et al.*, Evidence for production of single top quarks and first direct measurement of $|V_{tb}|$, hep-ex/0612052v2

[26] Fermi National Accelerator Laboratory public web `http://www.fnal.gov`

[27] V. Boisvert *et al.*, A New Implementation of the Region-of-Interest Strategy for the ATLAS Second Level Trigger, physics/0306101v1

[28] ATLAS public web `http://atlas.ch`

[29] European Organization for Nuclear Research public web `http://www.cern.ch`

[30] O. S. Brüning *et al.*, *LHC Design Report v.1*, CERN-2004-003-V-1

[31] E. Gross, A. Klier, *Higgs Statistics for Pedestrians*, hep-ex/0211058

[32] ATLAS Computing Workbook, `https://twiki.cern.ch/twiki/bin/view/Atlas/WorkBook`

[33] ATLAS CVS repository, `http://atlas-sw.cern.ch/cgi-bin/viewcvs-atlas.cgi/`

[34] The LXR Cross-Referencer, http://alxr.usatlas.bnl.gov/lxr/source

[35] Doxygen documentation https://twiki.cern.ch/twiki/bin/view/Atlas/DoxygenDocumentation

[36] CERN hypernews https://hypernews.cern.ch/

[37] ROOT framework homepage http://root.cern.ch/

[38] Atlantis homepage http://www.hep.ucl.ac.uk/atlas/atlantis/

[39] Panda monitor of GRID datasets services.atlascomp.org/?redirect=pandamon

[40] Don Quiote documentation https://twiki.cern.ch/twiki/bin/view/Atlas/DonQuijote

[41] B-tagging basics TWiki page https://twiki.cern.ch/twiki/bin/view/Atlas/BTaggingBasics

[42] Flavour Tagging main TWiki page https://twiki.cern.ch/twiki/bin/view/Atlas/FlavourTagging

[43] B Tagging Software Tutorial https://twiki.cern.ch/twiki/bin/view/Atlas/BTaggingSoftwareTutorial

[44] S. Fleischmann, *B-tagging algorithms*, Top Seminar 27/01/06, Univ. Wuppertal, http://www.atlas.uni-wuppertal.de/Seminar/Top/TopSeminar_WS05-06/btagging-algs.pdf

[45] M. Panušková, *Error Scaling in Release 12.0.3*, B-tagging workshop 10-11 May 2007, Marseille, http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=14475