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BACHELOR THESIS

The trigger of the ATLAS experiment and analysis of first experimental data

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2010

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3. Simulační a analyzační software ATHENA.
4. Struktura triggeru v ATLAS; mionový trigger.
5. Analýza prvních dat; studium proton-protonových srážek s produkcí mionů.
6. Shrnutí a závěr.

Práce bude vypracována v jazyce anglickém.

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1. Atlas HLT/DAQ/DCS Group, High-Level Trigger data Acquisition and Controls, 2003
2. Detector and physics performance, Technical Design Report Vol.1 & 2, 1999
3. High-Level Triggers, DAQ and DCS, Technical Proposal, 2000
4. Aktuální informace na webovských stránkách experimentu ATLAS

Jméno a pracoviště vedoucího bakalářské práce:

Prom. fyzik Václav Vrba, CSc., Fyzikální ústav, AV ČR

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Abstract: At the beginning of this work brief history of the Standard Model is presented. Furthermore, in first chapter there are outlined basic principles of quantum physics and basic concepts of high-energy physics experiments. In second chapter the CERN laboratory and LHC with it's experiments are presented. The ATLAS detector is described in more detail. Structure of ATLAS trigger and ATLAS software framework Athena are introduced in third and fourth chapter. Last chapter attends to first data analysis - study of proton-proton collisions with production of muons and search for J/Psi meson in particular.

Keywords: ATLAS trigger, early data analysis, LHC, CERN, Standard Model

Název práce: **Trigger v experimentu ATLAS a analýza prvních experimentálních dat**

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Abstrakt: Na začátku této práce je stručny historický vývoj teorie Standardního modelu. Dále jsou v první kapitole nastíněny principy kvantové fyziky a základní pojmy experimentů fyziky vysokých energií. Ve druhé kapitole se nachází informace o instituci CERN a experimentech na LHC. Samostatně je popsaný detekční systém experimentu ATLAS. Struktura triggeru experimentu ATLAS a softwarový framework Athena jsou zpracovány ve třetí a čtvrté kapitole. Poslední kapitola se věnuje analýze prvních dat z experimentu ATLAS. Konkrétně studiu proton-protonových srážek s produkcí mionů.

Klíčová slova: trigger experimentu ATLAS, analýza prvních dat, LHC, CERN, Standardní Model

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Jakub Cúth

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Contents

Introduction

This thesis has been written in time of early LHC running and first data from 3.5 GeV collisions on ATLAS experiment has been used here. At beginning of this thesis (chap. 1) there are summarized fundamentals of Standard Model, followed by the brief introduction of quantum physics and basic principle of HEP particle detectors, which are used in rest of this thesis. It is necessary to know the measurement instrumentation, therefore in chapter 2 the LHC and ATLAS detector operation are described. For data collection powerful trigger and data acquisition system are needed, which are described in chapter 3. Chapter 4 contains information about Athena – the ATLAS software framework. My first data analysis is written in chapter 5. It contains calculation of low-p_T dimuon invariant mass.

Contemporary problems of particle physics

Mankind was trying to find basic construction elements of the universe from the very beginning. One of the first ideas was, that the fundamental elements are: fire, water, earth and air. In the Ancient Greece there was philosophical view called *atomism*, which concluded, that the all matter is composed of small parts – atoms (from Greek "$\alpha\tau o\mu o\varsigma$" – uncuttable). Atomic view on the world had been forgotten for many years and reopened again by Pierre Gassendi in half of the 17^{th} century. His work influenced "newage" atomists as were Boyle, Hooke, Huygens, Newton and many others [1]. As Feynman said, the most important knowledge of physics is, that all the things are composed of small particles, which are in permanent motion [2]. But our present knowledge is, that the atoms are not the smallest and uncuttable. Therefore, at the end of the 19^{th} century started new section of physics – particle physics.

1.1 Basic constituents of matter

1.1.1 Who order that?

In many books we could find, that the first mention of particle physics considered the discovery of electron by J.J. Thompson in 1897 (Nobel Prize in 1906) [1, 3, 4] (this experiment was hinting about inner structure of the atom). The further correction of atomic structure was the Ernest Rutherford experiment in 1911 [1]. The result of his experiment was, that the atom is composed of electron cloud and atomic nucleus. Nuclei are objects in the centre of the atoms, which are five orders of magnitudes smaller than atoms and carry almost all mass of these atoms. Consequently, next elementary particle, which was discovered, was proton (as nucleus of hydrogen atom). However, the structure of atomic nuclei was not clear. More obvious view have brought the discovery of new neutral element of the nuclei – neutron – by James Chadwick in 1932 [1].

The natural radioactive decay was discovered by Henry Becquerel in 1896 (Nobel Prize in 1903) [1]. He noticed that emitted radiation consisted of three particles and he named them α, β and γ. During inspection of the radiation β in 20^{th} century it was found, that it is made of electrons and it corresponds to decay of neutron to electron. But the spectrum of observed electrons was continuous (violation of energy conservation law). Wolfgang Pauli make a bold postulation, that there is new particle, which had not been observed till that time (eq. 1.1). This particle has to be electrically neutral and very light. Enrico Fermi named this particle neutrino (neutral and small). The neutrino (strictly speaking antineutrino) was first time seen as late as 1956 on nuclear reactor in South Carolina in USA (Nobel Prize for Frederick Reines in 1995) [1].

$$n \to p + e^- + \bar{\nu}_e \tag{1.1}$$

It looked the four particles could be enough. But invention of new detection device – cloud chamber (Nobel Prize to Charles Wilson in 1927) – enabled the discovery of new particle in cosmic radiation. Carl Anderson and Seth Neddermayer have detected new particle, muon (denote μ), in 1937. They identified it in the cloud chamber as particle, which is 200× heavier than electron, 10× lighter than proton and with electric charge $|q| = 1$ e. In connection with this discovery, Isidor Rabi asked popular phrase: “Who order that?” Hideki Yukawa had the potential answer. In his theory of strong nuclear interaction, he figured intermediate particle, which has mass somewhere between the electron and proton (therefore, he named it meson). Yukawa won Nobel Prize in 1949 for prediction of this particle. However, the muon could not be the Yukawa's particle, because it has been noticed, that muon exhibits good penetration in nuclear material (no strong interaction). Around 1947 turned out the existence of two particles with “in-the-middle” mass. It was known, that heavier Yukawa's particle decay into slightly lighter muon. This decay again violates conservation law of energy. And again, the solution was the neutrino [4].

We know, that there are three Yukawa's particles today. We denote them $\pi^\pm$ and π^0 mesons (pions), according to their electric charge. “By discovery of pions was opened Pandora's box with plenty of new particles”, as is written in [4]. New mesons (η, K^+, K^0, ...) and baryons (Σ, Ξ, Λ - common name hyperons) had appeared. Due to this fact, physicists felt, that not every at that time known particle is elementary, it was needed to make some classification, which covered up all particles [4].

In 1925 two PhD students, Samuel Goudsmit and George Uhlenbeck, published article explaining result of the experiment performed by Otto Stern and Walter Gerlach [1]. Their idea was, that the electron have some kind of inner rotation. As have been showed later, this physical quantity is not corresponding to any real rotation, in spite of that, it has same mathematical properties as angular momentum. This physical quantity was called spin (denote S or J), and as angular momentum it is quantized, which means that only integral multiples of $\frac{\hbar}{2}$ values are allowed. All the particles have spin and therefore, it is basic method of assortment.

Fermion: particle with half-integral spin ($\frac{1}{2}\hbar$, $\frac{3}{2}\hbar$, ...). It following Pauli's exclusion principle, which postulates, that two fermions can not exist in same quantum state. Basic building constituents of our world – electrons, protons and neutrons – are fermions. Fermions undergo Fermi-Dirac's statistic and their wave function is antisymmetric.

Boson: particle with integral spin. Since they are not underlying Pauli's principle, it allows them to create low energetic state known as Bose-Einstein's condensate. All particles of intermediating force interactions (photons, gluons, ...) are bosons. Bosons abide Bose-Einstein's statistics. The wave function of bosons is symmetric.

Assorting by spin was, and still is, important for experimental confirmation of theories, but is not enough for classification of all particles. Next option was sorting according to mass [1].

Hadron: name from Greek "$\alpha\delta\rho o\varsigma$" means stout, thick. Are (almost always) heavier then leptons. This group could be divide into two subgroups:

- **Baryon:** heavier hadrons, e.g. here belongs nucleons. Baryons, heavier than nucleons, are sometimes called hyperons. All baryons are fermions. Examples: proton, Λ hyperon, ...

- **Meson:** get the name because their mass somewhere between electron and proton masses. All mesons are bosons. Examples: kaons, pions ...

Lepton: from Greek "$\lambda\varepsilon\pi\tau o\varsigma$" means thin. Leptons electron (e), muon (μ), tauon (τ) and their neutrinos. All leptons are fermions with spin $\frac{1}{2}$.

The significant person in classification of the particles was Paul Dirac. He connected relativity and quantum mechanics into one theory. Generally, the Dirac's equation (eq. 1.13) has two solutions. One with positive energy and second with equally large but negative energy. On first sight, we could say that second solution is physically not allowed. Even though, there are some calculations, where we cannot neglect it. Dirac came up with conception of vacuum filled with electrons of negative energy, called Dirac's sea. This explained, why electrons are not falling into negative energy level. If we take some "negative" electron from vacuum and put it to the positive energetic level, the hole will appear in the sea. This could be represented as new particle, or better antiparticle. Even though, it looks unnatural and artificial, the antiparticles really exist. The first ever observed antiparticle was anti-electron – positron – in cosmic radiation by Carl Anderson in 1932. Each particle has their anti-partner, which should have same mass, lifetime, spin etc.; but opposite electric charge and magnetic moment. Some particles are anti-partners to themselves, e.g. photon [4].

Actual knowledge shows, that leptons are elementary particles – with no inner structure (whereas hadrons are not). Nobody was able to see building block of hadrons, therefore, there was prediction to think, that hadrons are elementary too. Nevertheless, Heisenberg supposed, that proton and neutron are two states of one particle – nucleon [3]. Mathematical formulation of this suggestion is, that nucleons has inner quantity similar to spin, which is not influenced by spatial transformations. This quantity was named isospin (denote I) and nucleons has magnitude of isospin $I = \frac{1}{2}$. It means, that there are two possible projections into third coordinate I_z (sometimes I_3). It was assigned, that proton has $I_3 = +\frac{1}{2}$ and neutron has $I_3 = -\frac{1}{2}$. Isospin is conserved in strong interactions.

Another important quantum number of hadrons is baryon number B. The baryon number is defined as $B = 1$ for baryons, $B = -1$ for anti-baryon and $B = 0$ for mesons. Baryon number is conserved in all standard model reactions (except the chiral anomaly). For every lepton family

[1] In present, this classification is not according to mass, but according to number of containing quark. Concept of quark will be discussed later.

there exists conserving quantum numbers too, i.e. muon and muon neutrino have muon lepton number $L_\mu = 1$ and others lepton number $L_e = 0$, $L_\tau = 0$.

After discovery of K mesons in cosmic radiation, Murray Gell-Mann started to think about new quantity, which he named “strangeness” (because of weird behaviour of kaons). Moreover, he postulated conservation law of the strangeness. This law explains suppression of some decay channels and why kaons are produced only in pairs. Strangeness S, isospin I, electric charge Q and baryon number B are joined together into Gell-Mann – Nishijima equation (eq. 1.2) [4].

$$\frac{Q}{|e|} = I_3 + \frac{B+S}{2} \tag{1.2}$$

Cosmic radiation is still source of unanswered questions, e.g. where high energetic part of cosmic radiation comes from. The invention and application of particle accelerator has had enormous benefit in particle physics. Basic principle of accelerator is, that we speed up particles and we let them collide to other particles (discussed more in 2.1.2). Accelerators made more “mess” among the uparticles than cosmic radiation. New baryons have appeared with quite short lifetime. These particles are noticed as peaks in invariant mass plots, so they were called resonances [4].

About 30 hadrons has been detected until 1962 and this number was still increasing. Since only isospin and strangeness could not describe this amount of particles, Murray Gell-Mann and Yuval Ne’eman separately suggested theory of inner symmetry denoted SU(3). This symmetry contained not only the isospin and the strangeness, moreover, it systematically grouped hadrons and have predicted new resonances. Hadrons were grouped into multiplets according to their spin (figure 1.1) [4].

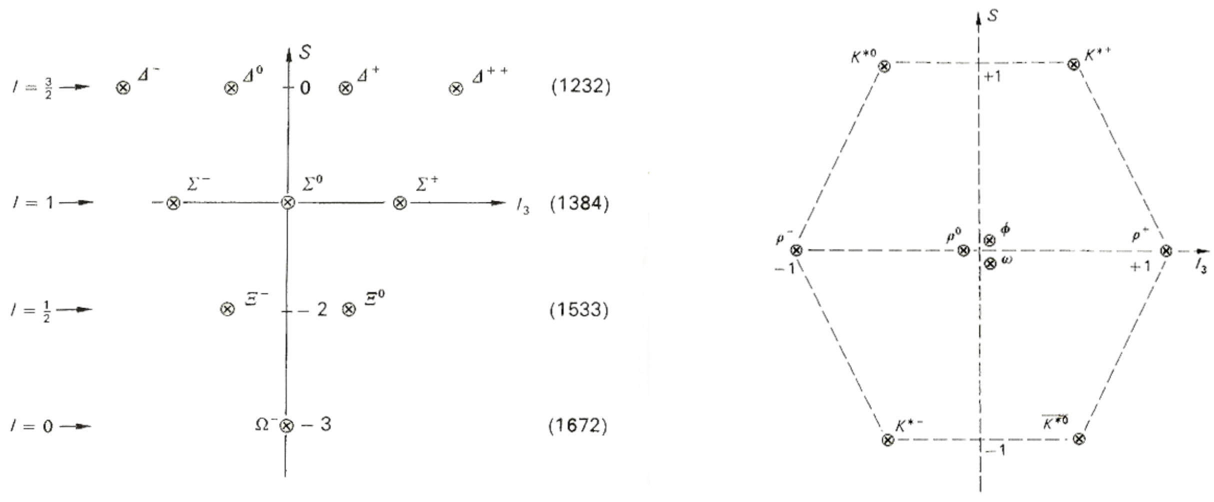

Figure 1.1: Baryonic decuplet and meson octet, from [3].

Gell-Mann affirmed, that known resonances belong to baryonic decuplet and predict existence the Ω hyperon. Interesting fact of his prediction was, that he supposed, that Ω will decay by β-

decay. The β-decay is distinguished by long lifetime of decaying particle. Therefore, the Ω should not have been a resonance. And he was right [4].

In the times of discovery of Ω hyperon (at beginning of 1964), Murray Gell-Mann and George Zweig, independently from each other, suggested that hadrons are composed of new elementary particles – quarks. Word "quark" comes from James Joyce's novel Finnegans Wake: "Three quarks for Muster Mark". Gell-Mann postulated three quarks and named them: up (u), down (d) and strange (s). The up and down quarks correspond to isospin ($I_z = \pm\frac{1}{2}$) and strange quark carry strangeness number $S = -1$. All quarks are fermions and we consider nowadays, that they are elementary. Now, we redefine baryons as hadrons consisting of three quarks (or anti-quarks) and mesons as hadrons consisting of two quarks (quark – anti-quark pair). Multiplets of baryons mentioned before could be presented as multiplets of multi-particle coupling state, as shown in 1.2 [4].

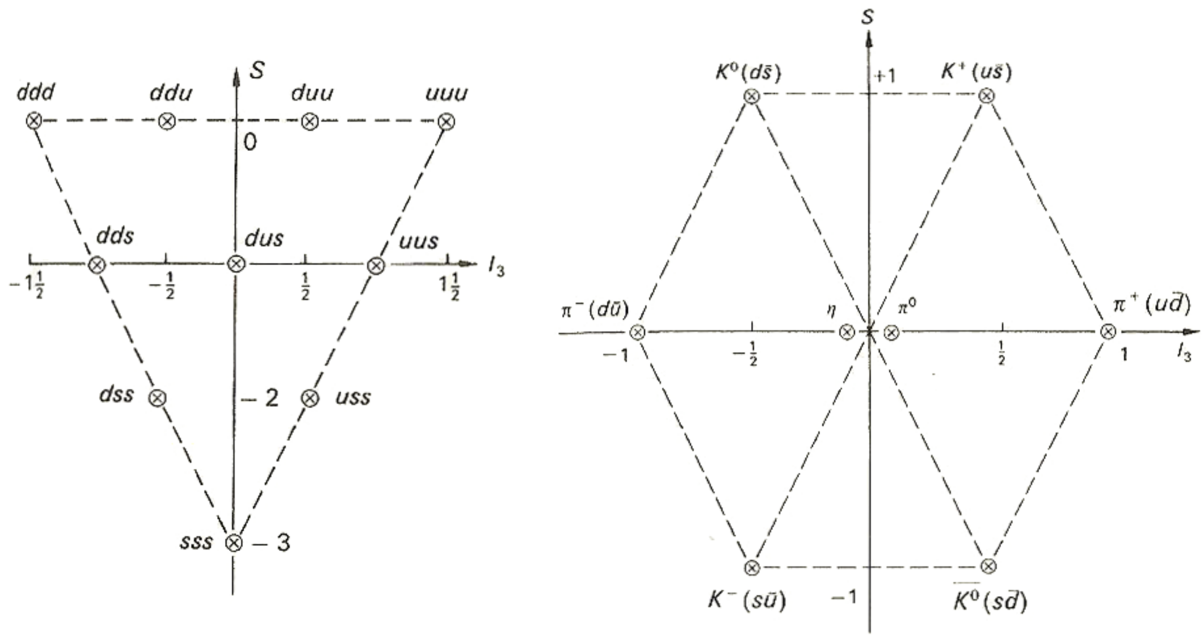

Figure 1.2: Quark content of baryonic decuplet and meson octet, from [3].

This multiplets could be mathematically represented as decomposition of direct product of groups into irreducible representations. Which is symbolically written as

$$3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$$

Left side matches arrangement of three kind of the quarks into three particle structure. Right side matches how could be the hadrons grouped by spin magnitude. Interesting fact is, that the singlet have antisymmetric wave function, octets have mixed symmetry and the hadrons from decuplet are fully symmetric against all exchanges [3].

The multiplets are determined not only by spin, but there is another attribute, which is identical for all elements in the multiplet. It is parity and it represents behaviour of wave function when sign of spatial coordinate is flipped (same as seeing the particle in the mirror). Parity is one of the discrete transformation in physics, with charge conjugation (exchange particle for antiparticle) and time reversion (inverse time flow). The combination of all these three transformation into one is called CPT. The violation of CPT symmetry is another important question of particle physics [3].

Because of fact, that free quarks have not been seen, other experimental confirmation had to be founded. One option is to explore the nucleons by lepton scattering, This measurements showed, that quarks must be almost as heavy as nucleons, because "knocking the quark out" was not observed. Feynman postulated, that nucleons consist of some particles, which carry part of the their momentum, therefore, he named them partons. Lately, was approved, that distribution function of partons in nucleon corresponds to the 3 quarks, which are strongly coupled inside the nucleon [3, 4].

The decuplet, as we mentioned it before, describes particles with spin $\frac{3}{2}$. From angular momentum couplings we get, that spin of all three quarks have the same third projection. Therefore, e.g. in Δ^{++} resonance with 3 u quarks, are quarks in same quantum state. This is forbidden by Pauli's exclusion principle (remind quarks are fermions). It implies that quarks have some inner freedom, which was not observed on hadrons. This physical quantity was named colour [4].

The image of particles started to have some form. There were fermions – four leptons (e, μ and their neutrinos), three quarks (u, d, s); and boson γ, which intermediate electromagnetic interaction. But what about intermediate bosons of nuclear forces? Before we look at them, we recapitulate the quantum theory of electromagnetic interaction called quantum electrodynamics (QED). This theory was born in '20 and '30 of 20$^{\text{th}}$century and gives first template for modern quantum field theory. Handy and popular aid, which was developed by Richard Feynman, are Feynman diagrams. It is symbolic image of complicated calculation in perturbation theory. The perturbation theory is guide for approximate calculations in quantum physics. The principle is, that calculation is expanded into power series of unit-less parameter. In QED is the parameter called fine structure constant and its values is $\alpha = \frac{e^2}{4\pi\varepsilon\hbar c} \simeq \frac{1}{137}$ [4].

Weak interaction is not so simple-describable as electromagnetic. The reason is, that weak force intermediations can not be explained in classical physics. The only way how to inspect nuclear forces is only indirect observation of subatomic particle reactions. Simplified image is, that weak force acts on infinitesimally small distance. If this was a true, the mass of weak intermediate boson will be infinite and this is not good for calculations. Next factor forming the character of weak force was β-decay. It was observed positive and negative decay and therefore, it was supposed, that there are two interaction bosons of weak force (denote $W^{\pm}$). Next assumption was that W has the largest mass of all at that time known particles [4].

As in QED perturbations were expanded by α, in quantum theory of weak interaction is expanded by Fermi's constant $G_F = 1.166 \times 10^{-5}$ GeV^{-2}, which is smaller than fine structure constant. This means, that rate of weak processes will be smaller too (thereby "weak"). The problem is that non-zero mass of interaction bosons cause divergence in perturbation calculations. The similarity of weak and electromagnetic force inspired attempt to unify this two interactions into one. With first conception of electroweak theory came Chen Ning Yang and Robert Mills. They used gauge theory and basic triplet γ, W^+, W^-. Again there appeared problem of divergence in perturbation loops. Consequently, Sheldon Glashow saw the solution in new neutral boson of weak interaction Z^0. New boson is something like bridge between electromagnetic and weak force. The mass of Z^0 needs to be nonzero, because we do not observe new long-distance force in particle physics [4].

Because the masses of weak bosons was high above energy level of accelerators at that time, and there still was unanswered questions, this theory was forgotten. New wave of gauge theory came in 1964, when Peter Higgs find out that the mass in gauge theories could be explained by sophistically selected scalar field. Steven Weinberg as the first use this to generate masses of W and Z. He predict their value by formula (eq. 1.3). Independently on Weinberg, Abdus Salam made same calculations and this theory was named GWS (Glashow-Weinberg-Salam). The only unknown variable in boson masses formula was Weinberg angle θ_W (sometimes called weak mixing angle), which have been determined after discovery of neutral current [4].

$$m_W = \left(\frac{\pi\alpha}{G_F\sqrt{2}}\right)^{\frac{1}{2}} \frac{1}{\sin\theta_W} \quad m_Z = \left(\frac{\pi\alpha}{G_F\sqrt{2}}\right)^{\frac{1}{2}} \frac{1}{\sin\theta_W \cos\theta_W} \tag{1.3}$$

But there still was problem between Gell-Mann's theory of three quarks and GWS. There was idea of a new quark. The presumption was that new quark c (called "charm") have charge $+2/3$ and new quantum number C ("charmness"). In 1974 it was confirmed the charm existence by discovery of new meson J/ψ. Group on SLAC (Stanford Linear Accelerator Center) led by Burton Richter discover resonance at 3.1 GeV and called it ψ. At the same time, group on BNL (Brookhaven National Laboratory) led by Samuel Ting discover resonance at 3.1 GeV too, and they called it J. The groups inform each other and they announced the existence of new particle J/ψ. The model of particles had two families of quarks (u, d and c, s) and fermions (e, ν_e, μ, ν_μ) [4].

It did not take much time and new lepton was discovered. In e^+e^- collisions there were observed events with production of one electron and one muon (μ^+e^- or μ^-e^+) and no hadrons. This was interpreted by Martin Perl (Nobel Prize 1995) as decay of tau lepton (τ) and his mass was somewhere between $1.6-2.0$ GeV (today 1.777 GeV). The asymmetry between count of quarks and leptons appeared. In 1977 it was found another narrow resonance similar to J/ψ, but with energy $9.5 - 10$ GeV. This resonance was named Υ meson and was interpreted as coupling of new quark b and anti-quark $\bar{b}$ called bottom ($m_b = 4.5$ Gev and charge $-1/3$). For symmetry conservation between quark-lepton families was supposed existence of sixth quark t "top" [4].

All these discoveries was just indirect verifications of GWS, nevertheless Glashow, Weinberg and Salam won the Nobel Prize in 1979. In 1981 started to work new collider S$p\bar{p}$S (Super proton–

anti-proton Synchrotron), which should have provided proton–anti-proton collision with total CMS energy 540 GeV. This energy level was enough for W and Z production, as was predicted by GWS. There was first identified W signal from collected data in 1982 and Z little later. The masses of bosons fitted to theoretical calculations. This proof definitely confirmed GWS model. Later production of Z boson and high statistics of its decay show, that there are exactly three lepton families. On figure 1.3 is plotted prognosis of Z cross-section according to number of the neutrinos. Measured data agree with three neutrinos model [4].

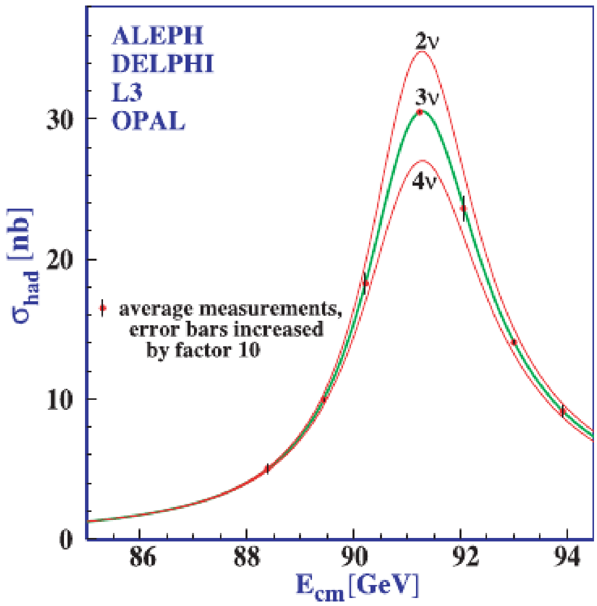

Figure 1.3: Cross-section of e^+e^- anihilation into hadronic final state as function of CMS energy near Z^0 pole. The curves predict Standard Model with two, three and four species of light neutrinos. Picture from [5].

Because the mass of top quark is higher than W and Z, it was last observed particle. In 1994 it was firstly observed at Fermi National Laboratory (on $p\bar{p}$ collider Tevatron with CMS energy 1.8 TeV) and affirmed one year later. The top mass is 171.2 ± 2.1 GeV and its mean life-time is 10×10^{-25} s [4].

The last but not least interaction is strong nuclear force. As was written, the quarks have quantum number called color, there is no observation of free quarks and only way how to study strong force is by subatomic particle reactions. If we look at Δ^{++} resonance, we find out that each quark needs to have different number of color. Therefore it was postulated, that there are three types of color and they were named "red", "green" and "blue". In baryons quarks together create colorless state (could be named "white"). Mesons are colorless too, therefore inside is one quark with color and one with anti-color (e.g. "red"–"anti-red"). It was predicted, that interaction between quarks is exchange of particles called gluons (from glue), which are bosons with spin 1. The idea was, that gluons create color exchange octet. Gell-Mann named the quantum theory of strong force quantum chromodynamics (QCD), because “chromo” means color. The building brick of QCD was theory of asymptotic freedom of non-abelian gauge fields. The specification of strong interaction is, that they allow several orders of gluon and quark loops. If there were too many quark types, the loops will cause that QCD lose asymptotic freedom. In our world there are six types of quarks and in this model asymptotic freedom works. But what is asymptotic freedom physically? It means that quarks and gluons act like free particles at small distances or higher energies [4, 3].

To summarize, we talk about particles, their properties, their behaviour and interaction types. Now we know, that there are three families of basic fermions, which build up the matter. In each family we found two quarks (one with charge -1/3 and one with +2/3) and two leptons (one with charge -1 and one neutral). Then, there are four interaction bosons, which intermediate three particle forces: electromagnetic force (γ), weak ($W^{\pm}$, Z^0) and strong (g) nuclear forces. Every particle has its anti-particle with same mass, life-time but opposite electric charge. Some particles are anti-particles to themselves. Basic instrument of description of the interactions is quantum physics. For electromagnetic and weak interaction we have electroweak theory and for strong QCD. This knowledge is considered as standard model of particle physics, often shortly “the Standard Model”.

1.1.2 Quantized variables

If we explore matter at small distances, we find that some of the physical values are quantized. That means they could have only integral multiples of specific value. Physics, which deals with these fact, is called quantum physics. Because particles are really small objects, particle physics is strongly connected to quantum physics. Therefore, we are going to illustrate some basic principles of quantum physics now.

The first hint of quantized variables was Planck's radiation law. The question was how does look radiation spectrum of absolute black body. The absolute black body is object, which does not reflects electromagnetic radiation, for example heated cavity. The radiation spectrum of cavity does not agree with classical physics calculations. But, if we postulate that energy of electromagnetic waves in box is quantized, we will get right relation (eq. 1.4) [6].

$$I(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1} \tag{1.4}$$

This deduction leads in forging of several postulations, which quantum physics is based on. The basic object in quantum physics is wave function. The wave function $\psi(x, t)$ is function of spatial coordinates and time and it describe state of the particle. But how? Answer is in Born's statistical interpretation. This interpretation says that square of absolute value of the wave function $|\psi|^2$ gives the probability of finding particle at the point in space. More accurately, the integral from a to b of $|\psi|^2$ gives the probability of finding the particle between a and b at time τ (equation 1.5) [7].

$$P[x \in (a;b), t = \tau] = \int_a^b |\psi(x,t)|^2 dx \ . \tag{1.5}$$

This statement has deep impact on the way how we look at problems of quantum physics. It means, that we can not get deterministic solution, but only probability of possible results. As we know from statistical mathematics, each probability density function have to be normalizable. In our case, it could be written (eq. 1.6). Or in other words, the particle is surely in some state [7].

$$\int_{-\infty}^{\infty} |\psi(x,t)|^2 dx = 1 \ . \tag{1.6}$$

Paul Dirac introduced notation of "brackets", where a "ket" $|\psi\rangle$ is vector (or function) from Hilbert space and "bra" $\langle\psi|$ is hermitian conjugated vector to $|\psi\rangle$. The scalar product of two functions from Hilbert space is represented by integral (eq. 1.7). This means that square of norm represents mentioned probability [7].

$$\langle\phi|\psi\rangle = \int \phi^*\psi \quad => \quad ||\psi||^2 := \langle\psi|\psi\rangle = \int \psi^*\psi = \int |\psi|^2 \ . \tag{1.7}$$

How to measure physical quantities in this representations? Each observable in classical mechanics correspond to linear hermitian operator $\hat{Q}$. The mean value of measured variable Q is represented by mean value of the operator $\hat{Q}$ [7].

$$\langle\hat{Q}\rangle = \langle\psi|\hat{Q}|\psi\rangle = \int \psi^* Q \psi \ . \tag{1.8}$$

Next postulate states that only measurable values of observable Q are the eigenvalues of its operator $\hat{Q}$. We could say, that every measurement change primal state into eigenstate of measured observable. The eigenvalue equation (eq. 1.9) shows, that $|\psi\rangle$ is eiqenvector of $\hat{Q}$ with eigenvalue q [7].

$$\hat{Q}|\psi\rangle = q|\psi\rangle \ . \tag{1.9}$$

We already know, that result are not deterministic, therefore, the state of particle is not deterministic too. The probability that state $|\phi\rangle$ will transit to another state $|\psi\rangle$ is defined by (eq. 1.10) [7].

$$P_{\phi\to\psi} := \frac{|\langle\phi|\psi\rangle|^2}{\langle\phi|\phi\rangle\langle\psi|\psi\rangle} \ . \tag{1.10}$$

The energy of the system is observable. Therefore, it has hermitian operator $\hat{H}$ called Hamiltonian. The eigenvalues of Hamiltonian are allowed energies of system (could be discrete or continuous). The Hamiltonian (as in classical physics) has kinetic part $\hat{T}$ and potential part $\hat{V}$. The kinetic part is in non-relativistic quantum mechanics described by $\hat{T} = \frac{\hat{p}^2}{2m}$, where m is mass of the particle. The operator of momentum $\hat{p}$ is represented by $\hat{p} = -i\hbar\nabla$ ($i^2 = -1$ – imaginary unit,$\hbar$

– reduced Planck's constant, $\nabla := (\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z})$ – nabla or gradient). The evolution of the system is described by time-dependent Schrödinger equation (eq. 1.11), which is the eigenvalue equation actually [3].

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + \hat{V}\psi \ . \tag{1.11}$$

For relativistic system, where energy relation is $E^2 = p^2c^2 + m^2c^4$. If we replace the values E and p by operators $\hat{E}$ and $\hat{p}$ we get Klein-Gordon (eq. 1.12) [3].

$$\frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} = \nabla^2\psi - \frac{m^2c^2}{\hbar^2}\psi \ . \tag{1.12}$$

This equation is second order in time and space too. This is undesirable and therefore, Dirac "find the square root" of this equation and write it for massless particle (eq. 1.13),

$$\frac{\partial\psi}{\partial t} = \pm\vec{\sigma}\nabla\psi \ . \tag{1.13}$$

where $\vec{\sigma}$ is vector of Pauli's matrices (eq. 1.14) [3].

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \ . \tag{1.14}$$

1.2 Beyond the Standard model

Nonetheless, the Standard Model is well working and elaborated theory, is obvious, that it does not explain all observed processes in particle physics. Consequently, there are additional theories waiting for their confirmation. Deep scrutiny of this theories is out of the scope of this thesis, therefore, we will make a slight introduction into some of them [3].

1.2.1 Super symmetry

Super symmetry or SUSY postulates, that every known particle have super-symmetric partner. If the particle is boson (fermion) its SUSY-particle is fermion (boson). It assumes, that mass of super-particles will be at order of m_W, m_Z. In table 1.1 there are selected particles with partners and their spin. The most usable scheme is minimal super-symmetric standard model (MSSM), where is expected not one Higgs particle, but two dublets of Higgs bosons ($H^0_{1,2}$, $H^{\pm}$) [3].

1.2.2 Grand Unified Theory

After success of unification of electromagnetic and weak interactions, there is tendency to add strong force and create one super-interaction. The idea is to combine SU(2)×SU(1) electroweak symmetry with SU(3) colour symmetry into one SU(5) at energy high above electroweak scale (Georgi–Glashow model). The theory, which adds gravitation into this unification process is called theory of everything (TOE) [3].

Table 1.1: Particle, their SUSY partners and their spin. Table from [3].

Particle	Spin	Sparticle	Spin
quark q	$\frac{1}{2}$	squark $\tilde{q}$	0
lepton l	$\frac{1}{2}$	slepton $\tilde{l}$	0
photon γ	1	photino $\tilde{\gamma}$	$\frac{1}{2}$
gluon g	1	gluino $\tilde{g}$	$\frac{1}{2}$
$W^{\pm}$	1	wino $\tilde{W}^{\pm}$	$\frac{1}{2}$
Z^0	1	zino $\tilde{Z}^0$	$\frac{1}{2}$

Table 1.2: Units in high energy physics. Table from [3].

Quantity	High energy unit	Value in SI units
length	1 fm	10^{-15} m
energy	1 GeV = 10^9 eV	1.602×10^{-10} J
mass, E/c^2	1 GeV/c^2	1.78×10^{-27} kg
$\hbar = h/2\pi$	6.588×10^{-25} GeV s	1.055×10^{-34} J s
c	2.998×10^{23} fm s^{-1}	2.988×10^{8} m s^{-1}
$\hbar c$	197.5 MeV fm	3.162×10^{-26} J m

1.2.3 String theory

In this theory particles are not 0-dimensional objects, but 1-dimensional strings. The string can vibrate, what translates into properties that are observable (charge, spin, flavour ...). Additional dimensions (except space and time) are needed for fully functionality of this theory. The Superstring theory, which goes from string theory, connects strings with super-symmetry. It is expected, that length order of the string is at Planck scale. The Plank length is $l_P = \frac{\hbar}{M_P c} = 1.6 \times 10^{-35}$ m, where M_P is Planck mass $M_P = \sqrt{\hbar c/G_N} = 1.2 \times 10^{19}$ GeV (G_N – Newton's gravitation constant). The idea is, that string creates closed loop and different mode of oscillation represents different particle [3].

1.3 Experiments in high energy physics

In high energy physics (HEP) we work at small distances, energies and momenta compared to classical mechanics. Therefore, it is convenient to use other unit system than SI units. In table 1.2 are constants and units widely used in HEP [3].

From quantum physics we know that every state transition has some probability of realization. Because interaction of particle leads to state transition, it is possible write and count the probability of interaction or reaction. This probability is called cross-section σ and is measured in [m^2] or [b]. The basic characteristic of the accelerator is luminosity $\mathscr{L}$. The luminosity of two bunches with number of particles n_1, n_2 is defined by (eq. 1.15), where f is frequency of bunch crossing and σ_x,

σ_y characterize Gaussian beam profile in horizontal and vertical direction [5].

$$\mathscr{L} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y} \ . \tag{1.15}$$

The rate R of the event with cross section σ on collider with luminosity $\mathscr{L}$ is (eq. 1.16) [5].

$$R = \sigma\mathscr{L} \ . \tag{1.16}$$

Modern particle detectors usually have cylindrical structure and projective geometry, which is advantageous for production and reconstruction. That is the reason for using cylindrical coordinate system except cartesian. Basically the cartesian system on detector is right-handed, the z-axis is in beam-line direction and x-axis points into center of collider. The cylindrical system have same z-axis, r represents perpendicular distance from beam-line and φ is azimuthal angle in x-y plane (fig. 1.4). Useful quantity for relativistic particle description in this system is pseudorapidity. The pseudorapidity η is defined by (eq. 1.17), where θ is angle of flight from beam-line [5].

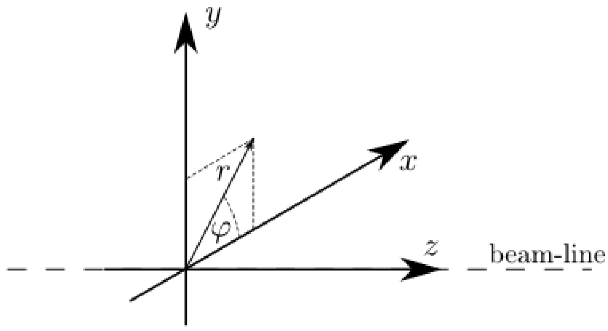

Figure 1.4: Scheme of detector coordination system.

$$\eta = -\ln\tan\frac{\theta}{2} \ . \tag{1.17}$$

Then we can defined distance in η-φ plane $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$. According to cylindrical symmetry we could count missing transversal energy E_T (i – index of produced particle), transversal momentum p_T and transversal mass m_T (eq. 1.18) [5].

$$p_T^2 = p_x^2 + p_y^2; \quad E_T^{miss} = \sum_i p_T^{(i)}; \quad m_T^2 = m_0^2 + p_T^2 \ . \tag{1.18}$$

Often used quantities in detector physics are track impact parameter d_0 and z_0. The d_0 is defined as closest approach distance to beam-line and z_0 corresponds to coordinate along the beam-line [5].

Chapter 2

ATLAS experiment at CERN

Before we will talk about the ATLAS, we mention some basic information about CERN, LHC and another experiments, which are held at CERN.

2.1 European Organization for Nuclear Research

Abbreviation CERN is from French *Conseil Europen pour la Recherche Nuclaire*. After Second World War there was requirement for institution associating nuclear research program in Europe. Few years of discussions lead into ratification of CERN Convention in 1953 by the 12 founding Member States: Belgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom, and Yugoslavia. As a site of the future Laboratory was chosen Geneva, Switzerland. Today CERN is global endeavour organization with not only European collaboration (fig. 2.1).

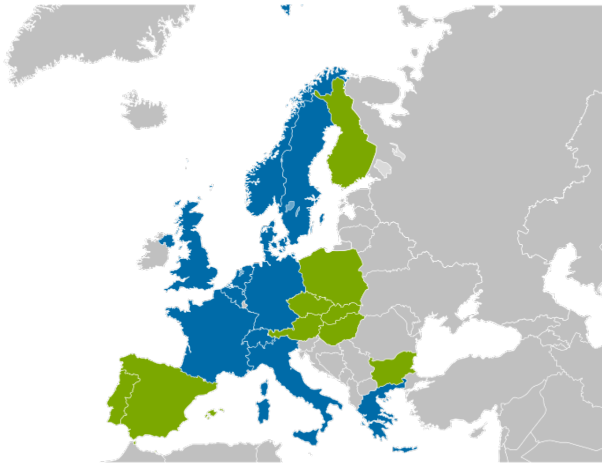

Figure 2.1: European CERN Member States as of 2008. Founding states are blue, latter joined are green coloured, picture from [8].

Except the Member States, CERN cooperates with many other states, which could be mark as Observers or Non-Member states. These states are not allowed to taking part in decision-making processes, but they have access to documents, informations and are involved to research program. Recent CERN council inherited open world politics, where every state could be CERN member independently on their geographical position. [9]

2.1.1 CERN accelerators

In 1957 CERN build first accelerator, the Synchrocyclotron (SC). During 33 years SC accelerated beams of maximal energy 600 MeV, e.g. for ISOLDE experiment. After its long-term it service was replaced by more powerful Proton Synchrotron (PS) in 1967. At that time it was most powerful accelerator in the world with beam energy 28 GeV. In January 1971, world's the first proton-proton collider, called ISR (Intersecting Storage Rings), was launched. Difference between the fixed target collision (accelerator) and beam-beam collision (collider) is same as difference between a car smashing to wall and two counter-moving cars crash. This simple idea again promoted the research of the particle physics. But PS did not stop working. Moreover, it was used as pre-accelerator for

ISR and is still using today. In 1976 new, bigger accelerator was build and commissioned. The Super Proton Synchrotron (SPS) measures 7 km in circumference and it extends across French border. It was constructed for beam energy about 300 GeV, nowadays it operates at 450 GeV. Beside proton beams it was used to accelerate beams of electrons, positrons, anti-protons and heavy ions [10].

Next accelerator, which was build at CERN, was Large Electron-Positron Collider (LEP). Three machines started to dig tunnel with length 27 km in circumference in February 1985. This was and still is the biggest tunnel for accelerator ever build. After four years of construction LEP consisted of 128 RF (radio frequency) cavities and 5176 magnets. With beam energy 100 GeV it was device for exploring the weak interaction and weak intermediate bosons. During eleven years it hosted ALEPH, DELPHI, L3 and OPAL experiments and in November 2000 has been replaced by Large Hadron Collider (LHC) [10].

2.1.2 Large Hadron Collider

The biggest accelerator in the world with radius 4.3 km – LHC – installed in LEP tunnel, which is spreading 100 m under ground of two European states, France and Switzerland, near the Geneva city. The fabrication has been started after CERN approval in December 1994. LHC is synchrotron which accelerates the protons or the heavy ions [11].

Synchrotrons are circular (or nearly circular) toroidal machines, with vacuum tube inside. On LHC there are two tubes with pressure 10^{-11} Torr, and particles moving in each tube in opposite direction. The bending of particle beam is done by dipole magnets. The quadrupole and higher multi-poles magnets focus and form the shape of the bunch. On LHC there are installed 1232 dipoles, 400 quadrupoles, 2464 sextupoles etc. (total 6700). The superconducting magnets need to be cooled down to 1.9 K by super-fluid helium. The particles in synchrotrons are accelerated by variable electromagnetic field. This field is in RF (radio-frequency) cavities, on LHC are RF cavities situated in Point 4. The Point 6 is place, where the beams are dumped. There are four places, where the beam-lines are intersecting, and where are the detectors situated: at Point 1 - ATLAS, at Point 2 - ALICE, at Point 4 - CMS and at Point 8 - LHCb (see 2.2). The total nominal CMS energy available in collision is $\sqrt{s} = 14$ TeV, which makes the LHC the most powerful collider on the world [11].

The story of proton beam starts in bottle of hydrogen gas. After ionization of the gas are protons drifted by electric field and injected into linear accelerator LINAC2 where they get the initial kick. From LINAC2 are protons, with energy about 50 MeV, injected into PSB (Proton Synchrotron Booster). The PSB accelerates the protons to energy 1.4 GeV and then injects the beam into PS, where protons get energy 25 GeV. From PS, protons are sent to SPS. The SPS is last stage of beam injection into LHC. The LHC is filled with particle bunches of nominal energy 450 GeV during ~ 10 min in both direction. After ~ 20 min of ramping the two beams protons have kinetic energy

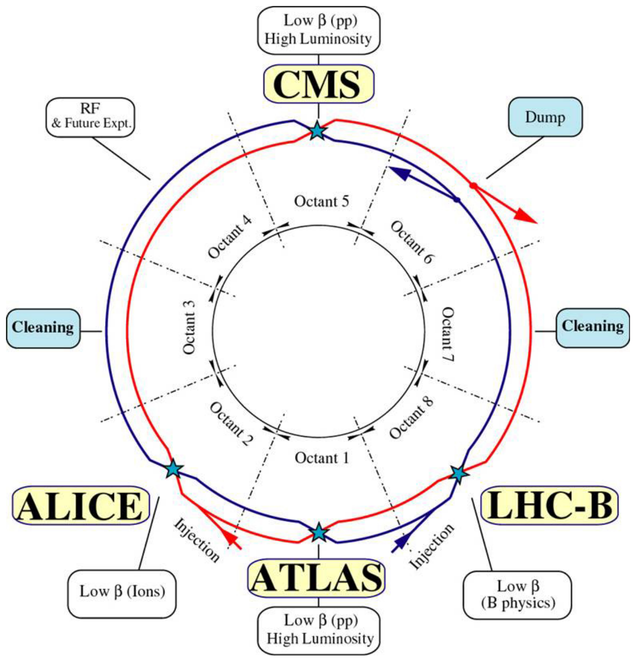

Figure 2.2: Schematic view of experiments at LHC. Picture from [12].

7 TeV[1] [11].

2.1.3 LHC experiments

On LHC are situated six experiments, which covers the work of many scientists, mechanical, electrical, programing engineers and many others. Each time it is international collaboration of several countries. Since each experiment is focused on different physics, there are differences in particle detection method, detector structure, data acquisition and organization structure. The ATLAS experiment will be discussed in individual section (see 2.2).

ALICE (**A** **L**arge **I**on **C**ollider **E**xperiment) is experiment focused on QCD and strong interaction processes in heavy ion collisions. It is only detector at LHC designed for heavy ion collision purposes. ALICE physics program is wide aimed. For instance, research of elliptic current, parton distribution, chiral symmetry etc. Specification of Pb-Pb collision is high multiplicity of particle tracks production. High density and temperature in interaction point could create state of matter known as QGP (Quark Gluon Plasma). All these circumstances formed the detector structure and data taking procedure. Detector system could be divided into several groups [13].

Firstly, the tracking device, which consist of inner tracking system (ITS) and time projection chambers (TPC). For more precise measurements of p_T in central central region was mounted transition radiation detector (TRD). The function of ITS is e.g. finding of secondary vertex of heavy flavour particles decays with resolution better than 100 μm. High multiplicity of particle tracks led to choose TPC as main tracking device, with reliable acceptance of ten thousands charged

[1] The beam energy at early run in 2010 is 3.5 Tev

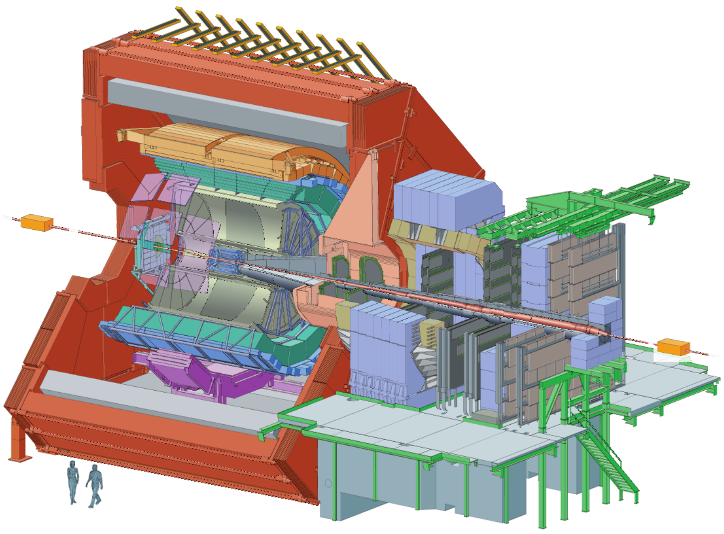

Figure 2.3: ALICE schematic layout from [13].

particles. The TPC covers full azimuth and η-region up to $|\eta| < 1,5$ [13].

Secondly, the particle identification is done by time of flight detectors (TOF) optimized for large acceptance. In ALICE was developed novel type Resistive Plate Chamber (RPC) the Multi-gap RPC. High momenta particle identification detector (HMPID), one arm with 10 m^2 of active surface, is installed for Cherenkov's radiation detection. Electromagnetic calorimetry is provided by Photon spectrometer (PHOS), which consists $PbWO_4$ crystals, and electromagnetic calorimeter (EmCal), which consists longitudinal fibres of Pb-scintillator. High production of heavy quarkonia needs detector for muons - on ALICE it is Resistive Plate Chambers (RPC). ALICE has on anticlockwise[2] side several forward detectors e.g. Forward Multiplicity Detector (FMD), Photon Multiplicity Detector (PMD), Zero-Degree Calorimeter (ZDC) [13].

CMS (**C**ompact **M**uon **S**olenoid) is heaviest detector at the LHC. It is focused on good muon identification, charged particle resolution and reconstruction efficiency, di-photon and di-electron mass resolution, wide geometric coverage, and good missing E_T and di-jet resolution. Core of CMS is 13 m long, 6 m inner diameter, 4 m superconducting solenoid, which has the name of the detector divided from. Magnet is placed before muon system to be able to measure μ momenta from bending [14].

Pixel detector and Silicon tracker make most of the inner part and provide the tracking system of the CMS. The next layer consists of calorimeters - electromagnetic and hadronic (7500 lead-tungsten crystals). Then follows solenoid and after it, most upper part, muon detectors. In high η part, CMS is instrumented with very forward detector CASTOR (Centauro And Strange Objects Research) [14].

LHCb (**L**arge **H**adron **C**ollider **b**eauty) is detector focused on analysis of "beauty" particle (mesons, which contains b-quark). An average luminosity 2×10^{32} $cm^{-2}\,s^{-1}$ implies reduced radia-

[2]Taken from horizontal projection of LHC

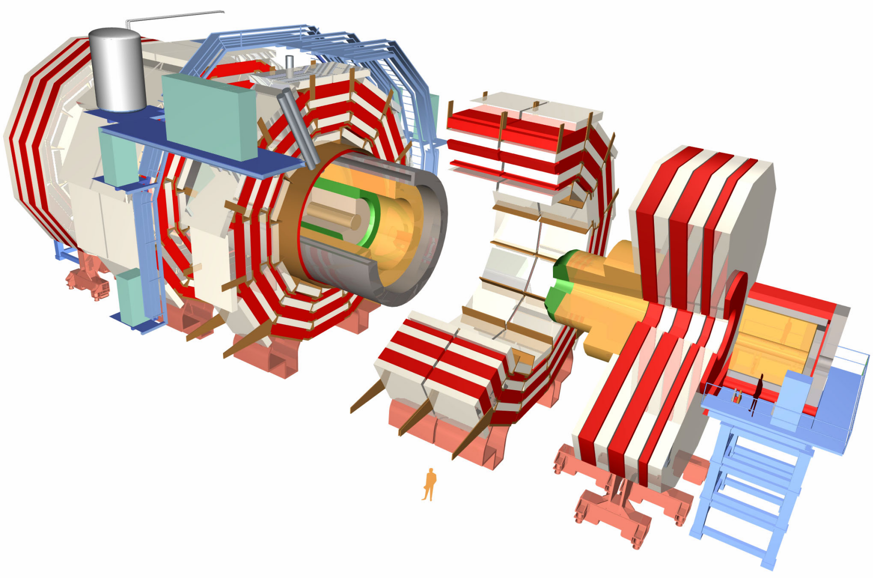

Figure 2.4: Overview of CMS detector. Picture from [15].

tion damage of detector (except VELO, which is very close to beam-line). Production of b-mesons takes place in forward cone part. This is reason for detector design: single arm in forward angular coverage of $10 - 300$ mrad [16].

The LHCb consists of Vertex Detector (VELO) for triggering and precise measurements of vertices; Ring Imaging Cherenkov Detector (RICH) one before and one after magnet; four tracking stations, consisting of Micro-strip Gas Chambers (MSGC) and Gaseous Electron Multiplier (GEM), one before dipole magnet and three after; the electron calorimeter (EmCal), needed for π^0 reconstruction; the hadron calorimeter (HCal), provided by scintillator tiles embedded in iron structure; and five muon station, consisting of Multi-gap Resistive Plate Chambers (MRPC) [16].

LHCf (**L**arge **H**adron **C**ollider **f**orward). The forward physics is important for understanding cosmic radiation processes and high energetic cosmic radiation part (HECR). The main points of HECR air shower are forward π^0 production, leading particle spectrum and total inelastic scattering [17].

LHCf detector consists of Y-vacuum chambers $\sim$ 140 m from Point 1 on both sides, with dimensions 29 cm^l $\times$ 9 cm^w $\times$ 60 cm^h. There are two calorimeters in each chamber, which are similar but not identical. The difference between them is in their inner ordering of scintillator towers. The scintillators are focused on neutral particle detection [17].

TOTEM (**Tot**al Cross Section, **E**lastic Scattering and Diffraction Dissociation **M**easurement), as name says, will measure total proton-proton cross-section and study elastic scattering and diffraction. TOTEM's detectors are mounted in forward region of CMS detector and have some common detectors. The precise determination of the total cross-section is done by sets of Roman Pots (RP) located on each side of intersection point; at 147 m (RP1) and 220 m (RP3). Because RP1 is before LHC dipole magnet and RP3 after it, the magnet creates natural magnetic spectrometer [18].

2.2 ATLAS experiment

This work is mainly aimed on ATLAS trigger and first data from ATLAS, therefore we going to pay attention to ATLAS detector lay-out especially to tracking systems and muon detection devices.

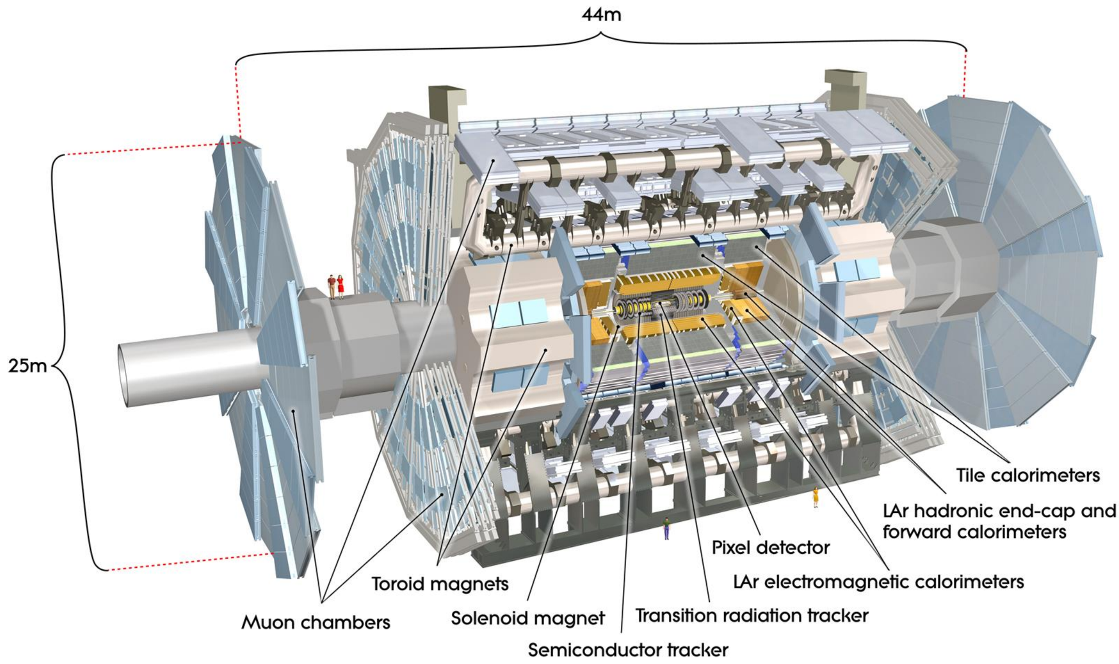

Figure 2.5: Overview of the ATLAS detector. Picture from [19].

The ALTAS experiment is the biggest detector on LHC. It has cylindrical structure with diameter 25 m and is long 44 m. The detector is housed in cavern, whose floor is 92 m under ATLAS surface building at Point 1. During excavation 300 000 t of rocks was harvested and 50 000 t of concrete was used. The cavern has approximately same size as half of Notre Dame. The installation of detector parts was provided by two cranes with lifting capacity 65 t. The heavier parts, e.g. base part of Tile Calorimeter (260 t) was moved by rails and air-pads [20].

ATLAS physics program is aimed on test of QCD, weak interaction and flavour physics. One of the main benchmarks of SM is searching for Higgs bosons. There are several modes according to Higgs mass m_H and their count (in MSSM we assume three neutral and two opposite charged bosons). The experiment will finding possibility new SUSY particle existence, extra dimensions, CP violation etc. [19].

Expectation on detector comprise fast, radiation-hard electronics; large pseudorapidity and azimuthal acceptance; good resolution of charged high p_T particles; calorimetry coverage for good jet and missing E_T measurement; muon identification and momenta resolution. Expectation and function of trigger is fundamental, therefore will be discussed in separate chapter 3 [19].

The detector device (fig. 2.5) could be divided into several parts. Firstly, it could be separated by pseudorapidity into high-η forward region, occupied by end-caps, and low-η barrel region.

In the very center of the barrel region (the nearest to IP) the inner detector is situated containing the pixel detector, the semiconductor tracker (SCT) and the transition radiation tracker (TRT) followed by the solenoid magnet. Then, the calorimetry level, consisting of the liquid argon electromagnetic calorimeter (LAr) and the hadronic calorimeter (HCal). Dominating feature of of ATLAS, the toroidal magnet, is between calorimeter and muon spectrometer, which consist of the muon drift tubes (MDT), resistive plate chambers (RPC), cathode strip chambers (CSC) and thin gap chambers (TGC). The muon spectrometer is the outermost part of detector [19].

End caps are spread in $3.5 < \eta < 4$ on both side and have similar parts: starting with pixel end-caps, then calorimetric end-caps, toroid end-cap magnets and muon end-cap chambers.

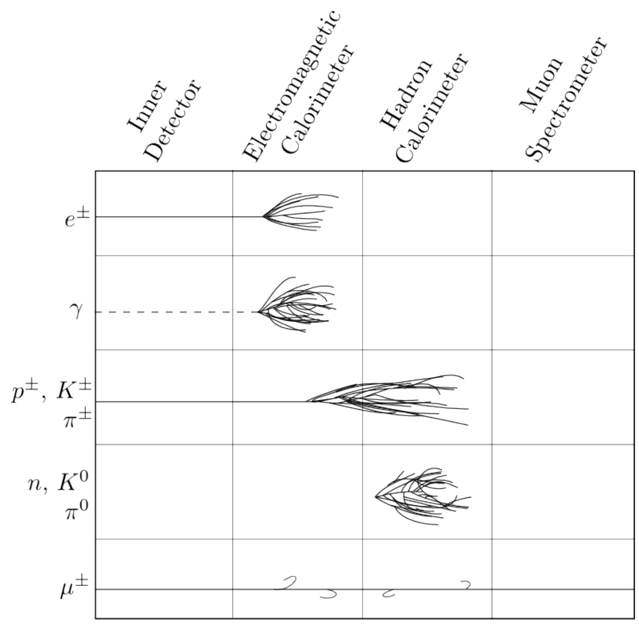

Figure 2.6: Principle of particle identification.

There are only several particles, which could be measured and identified directly: e, γ, p, K, π, n, μ. If we build up detector as shows picture (fig 2.6) each mentioned particle leave specific signal in detector and after reconstruction we get the information, which particle it was and what was its energy.

Now we look at each mentioned part more precisely.

2.2.1 Inner detector

The inner detector (ID) is the first detector, which particles from IP reach. The ID consists of 3 detectors, which each has barrel and end-cap part, namely pixel detector (Pix), semiconductor tracker (SCT) and transition radiation tracker (TRT). Main goal ID is to find primary and secondary vertices and precious track measurements to measure p_T, by 2 T solenoidal magnetic field, of charged particles in pseudorapidity range $|\eta| < 2.5$. Additionally, TRT provides the electron identification in wide momenta range too [20].

The electronics used in B-layer is facing high radiation dose, and even though it's designed for

10 year work, after 3rdyear of production need to be replaced. The Pix and SCT are cooled down to −25 °C to reduce the noise, while TRT works on room temperature [20].

To provide precious measurements all detectors of ID their position hast to be precisely known. Essential role have the alignment and calibration of the detector. [19].

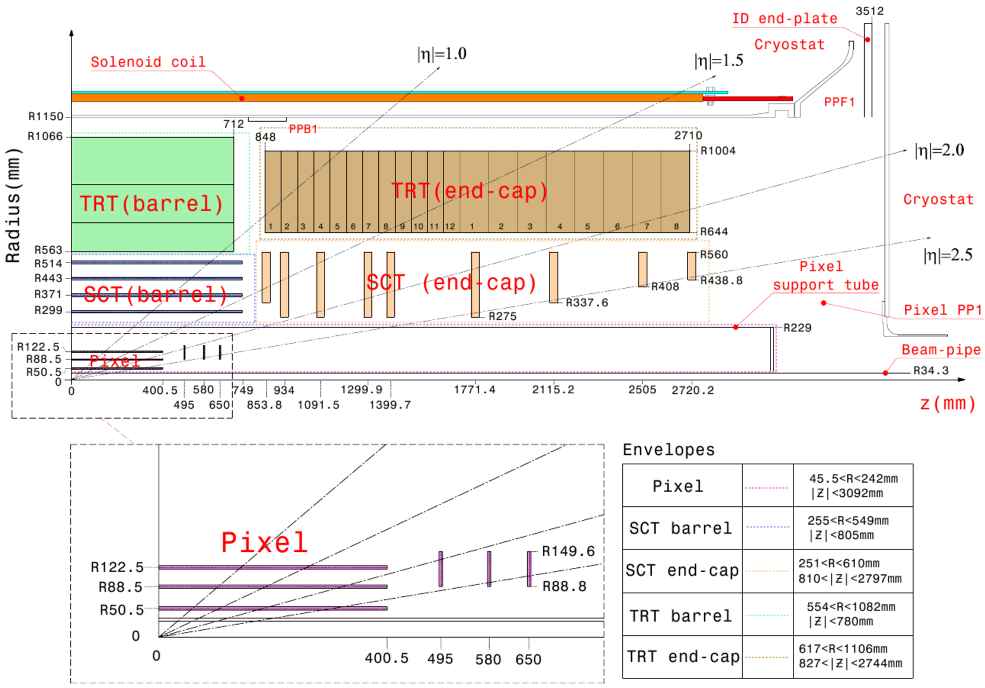

Figure 2.7: Quarter-section of ATLAS Inner detector. Picture from [19].

Pixel Detector the most inner part of whole detector, cover 1.7 m^2 (in 3 layers) around full azimuth, $5-12$ cm from beam line. When charged particle pases through semiconductor (silicon in our case) it creates in quartz holes and free electrons (ionization process). The free e^- are drifted by electric gradient of ~ 150 V and recorded on read out electronics. Barrel has 1744 modules with area of 10 cm^2 each containing 46 000 pixels. The Pix has 80 millions of pixels (barrel and end-caps together) with resolution 14×115 μm^2 [20].

Semiconductor tracker working on the same principle as pixel (free electron drifting in semiconductor), but covers bigger area (60 m^2) with lower resolution (6 millions channels). SCT is build-up from four cylindrical barrel layer and nine end-caps on each side. Every silicon module is made up from two detector plates, which are glued back-to-back and separated by heat transparent layer [20].

Transition radiation tracker. When relativistic charged particle cross interface of two matter with different electrical properties it produce the transition radiation. The intensity roughly corresponds to energy of the particle. On this principle is working TRT [21].

The fundamental part of the detector are cylindrical tubes (straws) with outer diameter about 4 mm. The envelope presents multilayer $\sim 70\ \mu$m thick cathode, which has in the middle 31 μm thick tungsten wire plated with $0.5 - 0.7\ \mu$m gold anode. The tube is filled with gas mixture of 70% of Xe, 27% of CO_2, 3% of O_2. In barrel straws have length 144 cm situated in parallel way to beam line, and in end-caps 37 cm perpendicularly to beam line. The typical electrical potential on wire inside the tube is 1540 V [19].

The read-out electronics are on both side of the tubes and are directly connected to Au-anode. Inside every barrel tube are two ~ 71.2 cm long wires. Because the purity of gas mixture is essential for tracking, at straws are installed sensors monitoring the gas condition. To avoid gas polluting, tubes are in CO_2 envelope [19].

2.2.2 Calorimeters

The function of calorimeter is measure the energy of electromagnetic and hadronic showers (jets) and fully absorb them. All particles except muons must be stopped in calorimeter (for clean muon signal in muon spectrometer).

ATLAS calorimeters cover range $|\eta| < 4.9$ and full azimuthal ϕ-region. For Satisfaction of above mentioned conditions the EmCal is thick $> 22X_0$ (radiation length)[3] in barrel and $> 24X_0$ in end-caps. Now we look little closer to sub-detectors in particularly [19].

Liquid argon electromagnetic calorimeter. This type of calorimeter is designed to measure properties of electromagnetic part of production i.e. electrons e^-, positrons e^+ and photons γ. All these particles produce specific electromagnetic shower while crossing through matter. This shower is in calorimeter stored as electric charge, which is measured. Quantity of electric charge correspond to deposited energy of primary particle [20].

As name indicate LAr EmCal is based on liquid argon at temperature -138 °C. Barrel part is 6.4 m long and 53 cm thick and spread out in $|\eta| < 1.475$. Full ϕ-coverage is disrupted in $z_0 = 0$, where is gap between two barrel parts. End-cap region covers $1.375 < |\eta| < 3.2$. Inner structure makes the accordion geometry and repeating of layers of Pb-absorber covered by stainless steel (grounded); liquid argon gaps; and high voltage anodes (thickness of layer is about 5 mm). Output from detector is processed according to tower. Tower is intersection of calorimeter with fixed $\Delta\eta \times \Delta\phi$ resolution [20, 19].

Hadronic calorimeter. Because hadrons are heavier particles than electrons, HCal needs to be thicker. The principle of charged hadrons calorimetry is same as in EmCal, the only difference is that hadronic showers are more prolate in direction of particle movement. Because neutral hadrons can not interact electromagnetically, they will be stopped by strong interaction in matter or decayed into electromagnetic components [19].

HCal is divided into several parts. The largest, tile calorimeter (based on scintillation), is placed directly outside LAr EmCal and covers $|\eta| < 1.7$. Consists of one central barrel and two

[3]Radiation length is characteristic of material, and presents length in material, where electron lost all but $1/e$ its energy

extended barrels on sides. In end-caps we found HEC (hadronic end-cap calorimeter) formed by two independent wheels of LAr. The last but not least, FCal (forward calorimeter) is LAr providing measurements in $3.1 < |\eta| < 4.9$ region [20, 19].

2.2.3 Muon spectrometer

The muons form high-penetrating radiation, which interacts only electromagnetically, weak interaction influence mainly the decay not interaction with material. Therefore if we shield other particles, we get pure muon signal. The task of muon system is to identify and reconstruct the muon tracks, their momenta and matching it with informations from inner detector. According to amount of processes with muon production, muon spectrometer is important e.g. in search of Higgs boson or B-Physics [19].

The heart of ATLAS muon detection system are three toroid magnets, one barrel and 2 end-caps. The measurements are catered by system of track coordinates detectors [19].

There are two types of detectors having regard to purpose, the tracking system of muon spectrometer makes the monitored drift tubes and cathode strip chambers, while triggering is done by resistive plate chambers and thin gap chambers [19].

Monitored drift tubes – MDT Building stone of MDT are tubes with outer diameter 29.97 mm working as cathode. They are filled with gas mixture 93% of Ar, 7% of CO_2 and $\sim 0.3‰$ of H_2O (to improve high voltage stability) at pressure 3 bar. In the center of tubes there is placed a tungsten-rhenium wire coated by gold. The wire represents anode with potential 3080 V, and is held in end-plugs at the ends of tube. The fixation is end-plugs make precise positioning needed for tracking resolution. As Muon moves through tube it ionizes gas and create free electrons and ions. Maximum drift time is 700 ns and is almost independent to angle of the track. If we preserve environmental condition (temperature pressure etc.), the drift time will reflect the distance between the track and wire. This is principle how we could perform azimuthal track measurement [19].

The chambers are made up of several layers of drift tubes. The size and shape of chambers is adjusted to optimal solid angle coverage. The regular chambers (except extra end-cap chambers and barrel support structure region) consist of two groups of tube layers with mechanical separation. In the most inner layer are two multi-layers with four tube layers. In others (middle and outer) are only three tube layers in each multi-layer [19].

Cathode strip chambers – CSC Because rate in forward region of $|\eta| > 2$ reach safe operation limit of MDT, in this region $2 < |\eta| < 2,7$ the MDT are replaced by CSC. The Cathode strip chambers are multi-wire proportional chambers with high spatial, time and double track resolution. The wires in chambers are oriented in radial direction and signal is read out from cathode strips (perpendicular to wires). The position is estimated from the charge distribution on stripes [19].

The CSC are filled with Ar/CO_2 gas mixture in the rate of 80:20. The diameter of gold plated wire is 30 μm and voltage on wire reaches 1900 V. The resolution of CSC is ~ 45 μm, and as in MDT case the alignment is essential for track measurements [19].

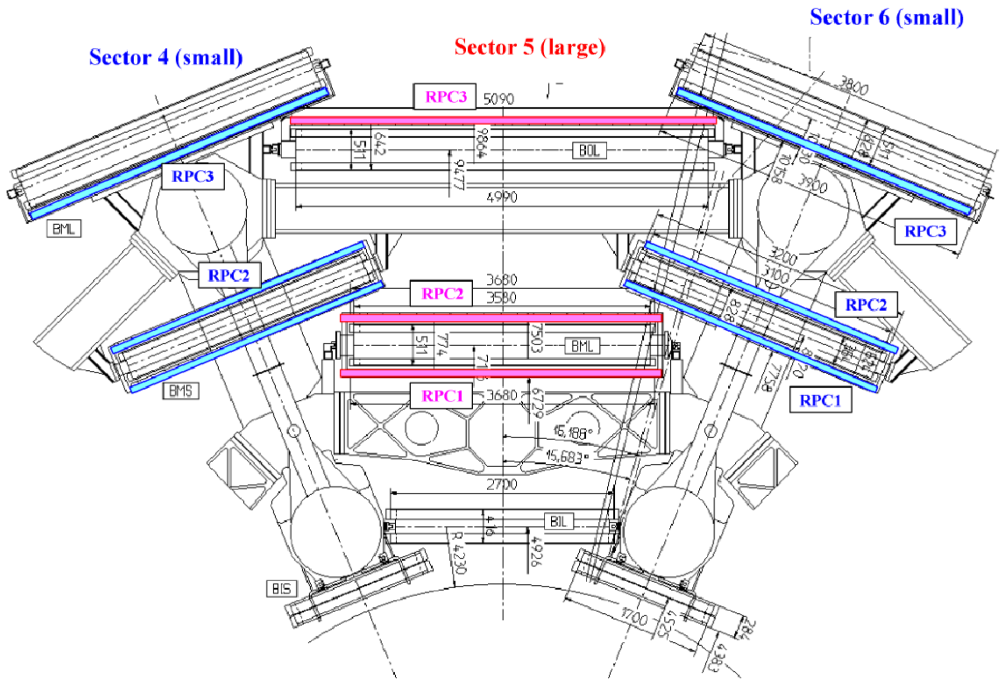

Figure 2.8: ATLAS Muon Spectrometer barrel section. Picture from [19].

Resistive Plate Chambers – RPC Triggering services in barrel region are supplied by resistive plate chambers. The RPC work as gaseous parallel plate electrode detector (there are no wires). Between two resistive plates with separation distance 2 mm is electric field about 4.9 kV/mm, which allows to work in avalanche mode. On the outer sides of resistive plates are installed electrodes to measure capacities. The gas mixture in gaps between the plates consist of $C_2H_2F_4$ (94.7%), Iso-C_4H_{10} (5%), SF_6 (0.3%), which is nonflammable and low cost solution with comfortable plateau for safe avalanche operation. There is used same principle of charge distribution measurement as in CSC [19].

The RPC are mounted on middle barrel MDT module on inner and outer side and in outer barrel MDT on outer side. The naming of RPC modules is: RPC-1 for innermost and RPC-3 for outermost. In triggering RPC-2 is called pivoting plane, RPC-1 is called low-p_T coincidence plane and RPC-3 is called high-p_T coincidence plane [19].

Thin Gap Chambers – TGC There are two functions of TGC in end-cap region: muon triggering and azimuthal measurements complementary to MDT. The TGC are multi-wire proportional chambers, but wire-to-wire distance is larger than cathode-to-cathode. The 2.8 mm wide gaps are filled with quenching gas mixture of CO_2 and n-C_5H_{10} (55:45), which allows to operate in saturated mode. The operating voltage on wires is ~ 2.9 kV. The signal is read out from wire and stripes respectively and stripes again works on same principle as in previous two detectors [19].

End-cap trigger detectors are mounted as seven layers of two concentric rings around the beam-line. They are arranged into one triplet (closer to IP) and two doublets. The outer ring (sometimes called end-cap) covers η-range $(1.05; 1.92)$ and inner (sometimes forward) covers $\eta \in (1.92; 2.4)$.

Again the naming is similar like in RPC. The middle doublet is pivoting plate and others are coincidence plates for low-p_T (inner triplet) and high-p_T (outer doublet) [19].

2.2.4 Magnets

If electrically charged particle is moving in perpendicular magnetic field, it is bended by Lorentz force. The radius of bending depends on momentum of the particle (assuming constant magnetic field). This is way how to measure the momentum with tracking detectors. On the ATLAS are four big magnets, one solenoid and three toroids [19].

Solenoid magnet Solenoid is situated in barrel region between ID and EmCal and presents bending magnet for ID measurements. The thickness of solenoid is only 0.66 X_0 due to desired calorimeter performance. It shares the vacuum vessel with EmCal (to eliminate two vacuum walls). The solenoid has cylindrical structure, 5.3 m long with 2.46 m and outer 2.56 m. The total number of turns in coils is 1154 and total structure weight is 5.7 t. In 9 km of superconducting wire flows current 7.73 kA and creates 2 T magnetic field with stored energy of 38 MJ. Operating temperature is 2.7 K [20, 19].

Toroidal magnets Toroids are part of muon spectrometer. There are three toroids one barrel and two end-caps (one on each side). The barrel toroid is surrounded by MDT from outer and inner side and middle planes are in the middle of coils. The end-caps toroids are between CSC and TGC wheel [20]..

The barrel toroid consist of eight coils, which are 25.3 m long and spread in cylindrical region with inner diameter 9.4 m and outer 20.1 m. The mass of total assembly is 830 t. In each coil is superconducting wire 120 times turned and with nominal current 20.5 kA. The energy 1.08 GJ stored in magnet creates magnetic field $\sim$ 3.9 T. Working temperature is 1.9 K and flow of He-cooling is 0.41 $\mathrm{kg\,s^{-1}}$ [20, 19].

The each end-cap toroid consist of eight coils with 116 turns. They provide bending in forward zone with inner and outer diameter 1.65 m and 10.7 m respectively, and long 5 m. Each end-cap is 239 t heavy and produce 4.1 T magnetic field. Superconducting wires are cold down to 1.8 K and current in wires reach 20.5 kA [20, 19].

ATLAS trigger

Present experiments have enormous demands on recording and manipulation with measurement data. Modern-day particle detectors need to have intricate decision system. On ATLAS experiment this is provided by ATLAS trigger system, therefore we going to look closer on it.

3.1 Trigger and Data Acquisition System

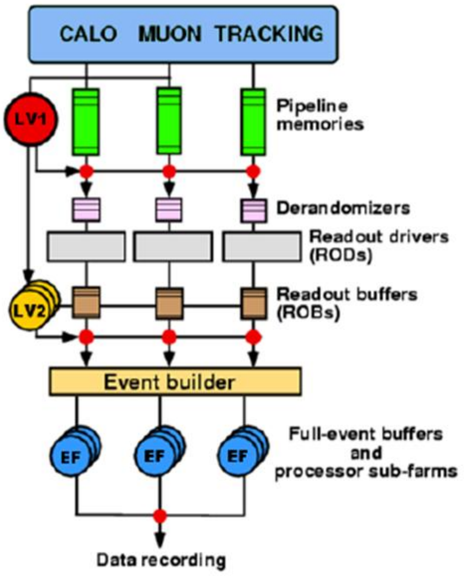

Figure 3.1: Diagram of ATLAS trigger levels. Picture from [22].

The ATLAS trigger is three level online system. The decisions on every level depends on results from previous level. The first, Level 1 trigger (LVL-1), is formed by electronics, which was developed and build by ATLAS collaboration. The second and third, Level 2 trigger (LVL-2) and Event filter (EF), runs on commercial computer system. Because the LVL-2 a EF have similar features, they are often commonly called High Level Trigger (HLT).

The Structure of the ALTAS trigger arises primarily from bunch-crossing rate and physics goals. Initial bunch-crossing rate 40 MHz (up to 10^9 Hz collisions with luminosity 10^{34} cm^{-2} s^{-1}) have to be reduced to $200 - 300$ Hz for permanent storage [23]. This implies that there will be 10^7 Hz of events, which would not be recorded. The endeavour is not to throw out good events, in other words we demand robust, scalable and efficient trigger.

The circumstances on LHC are changing, the bunch intensities, energies beam conditions etc., and the trigger must be able to react to these changes. The pre-scale factors on LVL-1 could be changed during the run, while the HLT pre-scales have to be changed before lumiblock start. Except online triggering, there is an off-line trigger for analysis. Same algorithms, which are used in online HLT, could be launched for off-line analysis. This is important for early data taking, when HLT is working in transparent mode and offline triggering is done for trigger calibration [24].

3.1.1 Level 1 trigger

The first task of Level 1 trigger (LVL-1) is to provide signal decision of each bunch crossing and post the data for further analysis in case of interesting event. The second function is to find RoI (Region of Interest) and post this information to Level 2 trigger (LVL-2) [23].

The LVL-1 has two major decision branches. The muon and the calorimeter trigger. As was mentioned, the LVL-1 runs on electronics. The core of the trigger is formed by Time, Trigger and Control unit (TTC). Except muon and calorimeter inputs there are implemented LHC clock and filled-bunches signal. The TTC needs information about front-end system. According to all these informations TTC will decide, if accept or decline measured data. After confirmation, the RoI information is sent to LVL-2. The decision is sent to read-out electronics and other system. The measured data are sent moved to Read-Out Buffer (ROB) [23].

The calorimeter system is based on towers - constant regions in $\eta \times \varphi$ coordinates. Typical granularity of tower is $\Delta\eta \times \Delta\varphi = 0,1 \times 0.1$. This implies $\sim$ 7200 analog input signals, which needs to be digitized. Then cluster processor will search for high p_T objects like e/γ and hadrons/τ. The Jet/Energy-sum processor will investigate high E_T jets, possible missing E_T and total scalar E_T value [23].

Second LVL-1 branch – Muon LVL-1 – is based on trigger detectors in muon spectrometer. In barrel regions triggering is provided by RPC in barrel and TGC in end-cap regions. The signal is processed by amplifier-shaper discrimination circuits in front-end electronics. The total amount if input channels is about 800 k [23].

3.1.2 High Level Trigger and DAQ

High level trigger (HLT) consist of Level 2 trigger (LVL-2) and Event Filter (EF). At first LVL-2 is starting with RoI data from LVL-1. Each LVL-1 trigger has continuing trigger in LVL-2 and EF. Because LVL-2 has more time to decision it operates with higher amount of data and makes more enhanced analysis than LVL-1. It walks through physics signatures (trigger chains) and searching for acceptable events. The LVL-2 is using track information too, in contrast to LVL-1. The accepted event must fulfil at least one of the active trigger chains [25].

After LVL-2 triggering starts the Event Builder (EB). It runs on many identical computing units, which are independent on each other. If one of this unit is busy or not works, the system excludes this unit from computing without interruption. The task of EB is to collect and convert data about selected event and store it into memory. Then it sends message, that is free for further using [25].

The Event Filter (EF) follow the trigger chains from LVL-2 and LVL-1. The processing runs on computing farms. If some processing node fails or is busy, the system reduces rate and continues on working nodes. The EF reconstructs events with online algorithms. The same algorithms, which are used in EF are ran and developed in offline data analysis. Therefore, EF provide the last online trigger level. The output of EF is byte-stream RAW files filled with interesting event data. Further work with these data is task of offline analysis [25].

3.2 Muon trigger

Because we will use the result from muon trigger system in early data analysis in chapter 5, we will now look at it more closely.

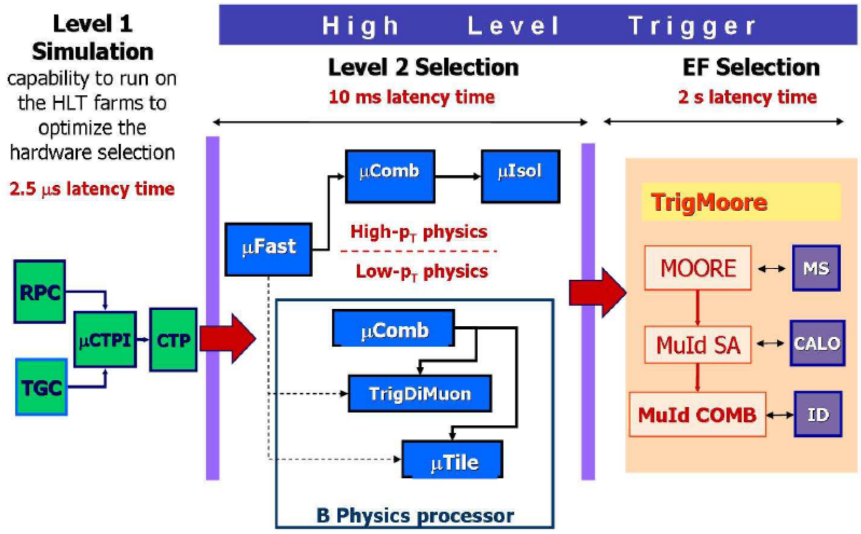

Figure 3.2: Architecture of ATLAS Muon Trigger system. Picture from [26].

3.2.1 Muon LVL-1

The muon LVL-1 trigger has two inputs: from barrel (RPC) and from end-caps (TGC). The selection in both inputs works with method of allowed trajectories. Every hit in pivoting plane opens so called Coincidence Window (CW), which is $\eta \times \varphi$ region. In this region it searches for muon hits in coincidence plane. There are two planes, for low p_T muons is coincidence plane before pivoting plane and for high p_T muons is coincidence plane more outside then pivoting plane. LVL-1 electronic (mainly FPGA technology) have three different p_T thresholds for each mode. Big advantage is that the values could be modified with respect to circumstances. The standard values for low-p_T are 6, 8, 10 GeV/c and standard high-p_T values are11, 20, 40 GeV/c. For early running and cosmic muon triggering are available 0, 4 and 5 GeV thresholds [27].

3.2.2 Muon LVL-2

The LVL-2 refine selection from LVL-1. The main algorithm "μFast" is based on Look-Up-Tables (LUT), which provide fast and more precious p_T computation. All environmental conditions (as magnetic field inhomogeneities) must be accounted for tables. The more enhanced reconstruction of muons is done by "μComb". This algorithm reconstruct tracks from inner detector and matches them with tracks founded by "μFast". There is possibility that the muon reconstructed by this method is from π, K decay. In chapter 5 these muons have author attribute "isCombined-Muon". Next algorithm "μISO" use information from $\eta \times \varphi$ regions (marked by μFast or μComb) in calorimeter and reconstruct number of cells, energies and transverse energies above selected energetic threshold. These informations are then written in AOD for further analysis. The "μTile" is algorithm that search for low-p_T muons, which reached only innermost level of spectrometer and therefore gain the trigger efficiency [26].

3.2.3 Muon EF

Event filter (as was written) use offline analysis algorithms. The offline muon reconstruction package MOORE (Muon Object Oriented Reconstruction) and muon identification package “MuID” have in EF equivalents the “TrigMoore” and “TrigMuID”. The identification could be done in two ways: “TrgiMuIDSA” (SA for standalone) propagating tracks in magnetic field up tu interaction point; and “TrigMuIDCb” (Cb for combined) combining the MS tracks with matching ID tracks [28].

There is another family of tracking and identification of muons called “STACO”. Principle of working is same as before, but use another techniques. In areas difficult for “STACO” ID track extrapolation is used helping tagging “MuTag”. The “MuTagIMO” is an independent tagger using “Moore” reconstruction with hits in all three stations. For muon deposited energy reconstruction is used the “CaloMuonTag” and “CaloMuonLH” [28].

Chapter 4

ATHENA framework

There is long journey from data recording and filtering to physical analysis. This provided by sophisticated computing system. The core of ATLAS offline software is Athena framework. This chapter contain basic information about Athena framework and its task in offline data processing.

4.1 Introduction to ATLAS framework

The software framework is abstract structure, providing basic scheme for writing and using of the algorithms. ATLAS framework – Athena – is based on Gaudi architecture. Gaudi was developed by LHCb. The Gaudi is a kernel of the Athena, which means that there was inserted some essential settings, services and algorithms into Gaudi (e.g. detector geometry, trigger system. . .) [29].

The basic task of Athena is to provide:

- simulation of $p - p$ collision processes, production of particles and their momenta by Monte Carlo method
- reconstruction of the simulated or real data
- analysis tools for physics, calibration, trigger settings and others.

The Athena is mainly written in C++ programing language with Python script control and some parts written in FORTRAN or Java. The architecture of Athena is object oriented and basic scheme is shown on figure 4.1 [29].

The services are globally available software components, which manage when to run the algorithms. The converters are used for data transformation. Inside the Tools and the Algorithms there are instructions what to do. Every process, which Athena runs have three stages: initialization, execution, finalization. The execution could be ran several times (e.g. on each event in processing dataset), while the initialization and finalization have to be ran only one time per job [29].

Users control the Athena by Python scripts called "JobOptions". Here user assigns, which services to use in what order and what has to be done. Often is enough to choose existing package and change only variables for specific occasion. If more complicated changes are necessary, the user could change and recompile existing package or create new one [29].

The package is independent unit wrapping algorithms and informations about their use. Every package has same hierarchical structure and contains: package configuration files, header files for including, source files, Python configuration files and documentation. Package could consist of sub-packages, which could be used separately too. As example, the "JpsiFinderTool" (used in 5) is function from sub-package "PhysAnalysis/BPhys/BPhysExamples" [30].

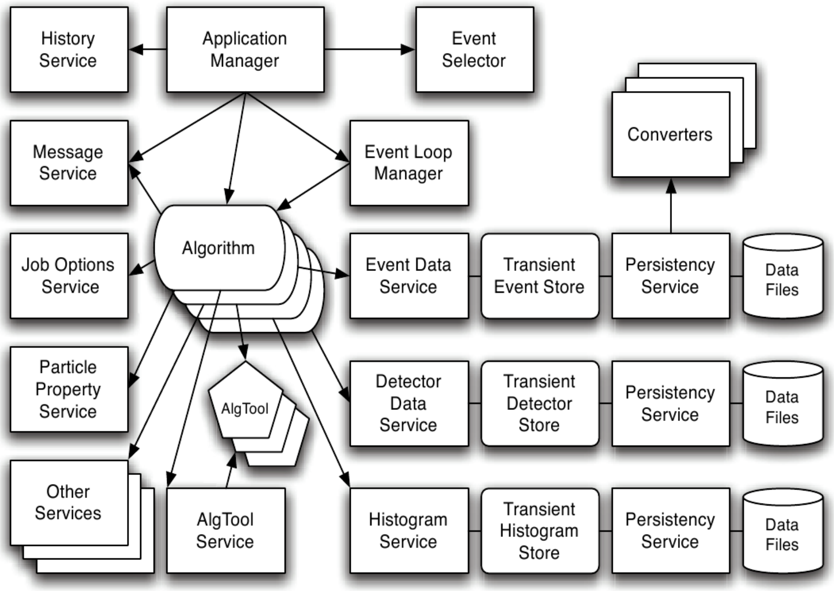

Figure 4.1: Athena computing model scheme. Picture from [29]. Explained in text.

There are many packages to supply all necessary operations, from Monte Carlo generators (Pythia, PhoJet, ...) and reconstruction (GEANT4), to trigger, physics, detector and other analyses. All algorithms runnable in Athena should be used in HLT as EF triggering methods [29].

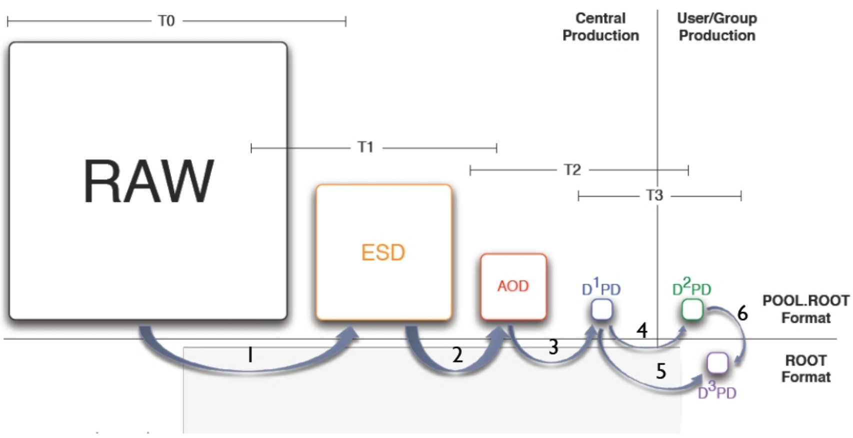

Figure 4.2: Software data reconstruction containers. Picture from [31].

The data from detector in byte-stream format or from simulation are converted into RAW format (too big because it contains whole event). The RAW data are reconstructed and information is saved into Event Summary Data files (ESD). They contain too many information and therefore are not used for physics analysis, but only for specific detector or reconstruction analysis. The main analysis data container called Analysis Object Data (AOD) is derived from ESD. For local using is AOD still big, therefore the working groups produce smaller dESD and dAOD (d for derivative) containing only useful data for the specific analysis. On PC we could work with “ntuple” files by ROOT and run our analysis (plots, calculations). The Athena allows to do analysis directly too [31].

4.2 Athena tools and front-ends

Variability of the Athena makes it user-unfriendly. That is reason for developing more accessible tools and front-ends.

GRID tools The amount of the data produced by ATLAS requires the computer farms for storing and processing. The GRID is a world wide network of computer farms and data storage system. It is leveled into “Tiers”. The first, “Tier-0” is situated in CERN and provide first data collection and redistribution to “Tier-1” for event reconstruction. The “Tier-1” farms are placed all over the world and divided into clouds according to their geographical position. “Tier-1” and “Tier-2” is used for MC simulation too. User access to GRID is in Athena provided by front-ends. The main two are GANGA and pAthena (or PANDA Athena). Both have pros and cons and is good to know all their features [31].

ROOT There is strong demand for simple and helpful offline system for plots and calculations. The widely used physics analysis tool is ROOT. It consists of CINT – C and C++ command line interpreter and useful libraries and templates for physics (fitting, plotting, computing . . .). The ROOT is not only used on ATLAS, but it is employed in other experiments on LHC, CERN or other laboratories in world. ROOT’s biggest advantage is multi-platform code and open source. The ROOT was used in our analysis in chapter 5 [32].

Graphical tools For online graphical study and event plotting was developed the Atlantis programe. It is based on ALEPH’s event display DALI, and is written in Java. Communication between Athena and Atlantis is done by JiveXML C++ converter. Because of its fast and intuitive environment it is used in Point 1 control room [33].

The larger graphical tool is VP1 (Virtual Point 1), It is C++ GUI toolkit Qt4 based with full access to reconstruction and geometric details of ATLAS. It could be integrated into online analysis, where it is working with ESD files. In VP1 there are included lot of useful displaying tools of events and detector [34].

Early data analysis

In this chapter we are going to attend to the early ATLAS data analysis. Particularly, the events with muon production, where we will search for the J/ψ meson candidates.

5.1 Data preparing

The data was chosen according to luminosity and stable beam flag. We aimed at low p_T muons and we have chosen the "MuID" as method for muon reconstruction (principle discussed in 3.2). The "ntuple" file was generated by B-physics analysis skeleton Athena package. This package contains tool (the set of algorithms) for searching the J/ψ candidates from muon production (from decay (eq. 5.1)).

$$J/\psi \to \mu^+ + \mu^- \tag{5.1}$$

The main idea of this tool is to search for fully identified muons with invariant mass lower than 10 GeV. The muons in event must create opposite charged pairs and the tool makes all allowed pair combinations. More informations about the "JPsiUpsilonTools" could be found in [30].

5.2 Dimuon invariant mass

If we plot the invariant mass histogram of the muon pairs found, the resonances (i.e. J/ψ) will appear as peak on the background. Therefore, the mass function will have form $f_{\text{tot}} = f_{\text{bck}} + f_{\text{sgn}}$. We will fit the invariant mass histogram with fit function (eq. 5.2), which means that we chose f_{bck} as exponential and f_{sgn} as Gaussian. Fitted parameters are written in the plot.

$$Ae^{-\frac{x-\beta}{\alpha}} + Be^{-\frac{(x-\mu)^2}{2\sigma}} + C \tag{5.2}$$

On the figure 5.1 is plotted invariant mass of all $\mu\mu$-pairs found by "JpsiFinder" (without any rejections). Our task is to filter the background as much as possible. The existence of background have several reasons:

Misidentification There is possibility that track or hit was wrongly identified as muon.

Other process The muons, that we take into account, could come from another process than J/ψ decay.

Combinatoric Because we can not know which pair is from the J/ψ decay, we have to use all combinations. This leads to disturbing background effect.

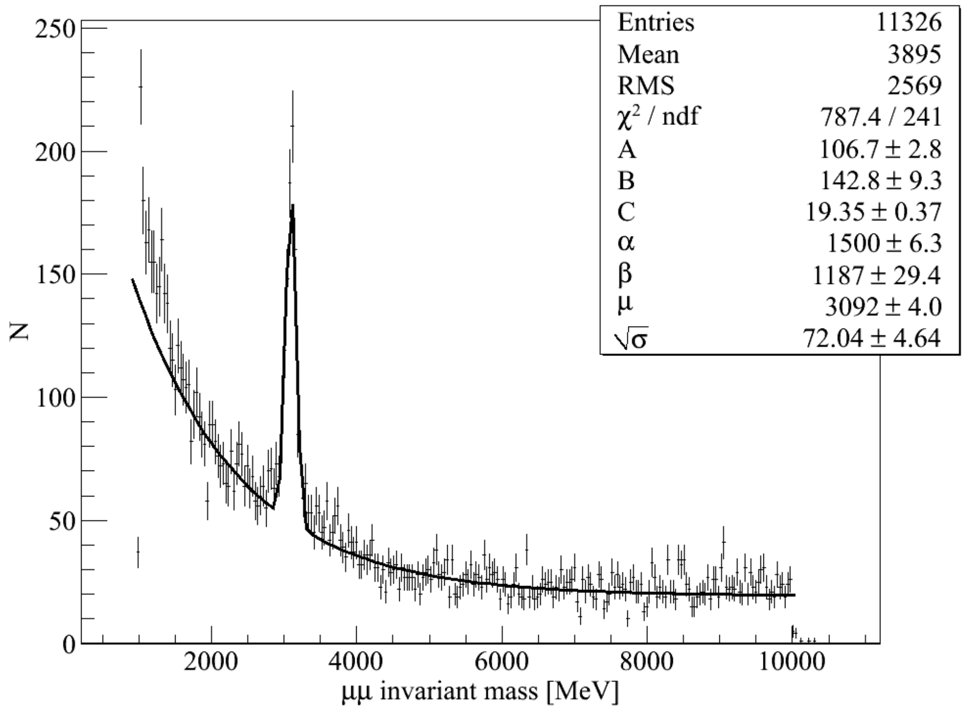

Figure 5.1: The plot of invariant mass of all μ-pairs from “JpsiFinder”.

For reduction of the misidentification background we just leave out the muons identified by the least trusted method. On figure 5.2 we plotted invariant mass of those muons, which was not identified by “MuTagIMO” author (see 3.2.3).

Another source of low p_T muon pairs is decay of light neutral mesons like π or K. To reduce this factor we will demand, that both muons have to be “isCombinedMuon” (see 3.2.3). The result is showed on figure 5.3.

If we use one of the above mentioned filters, it will reduce count of the muon pairs, and therefore it will reduce the combinatoric background.

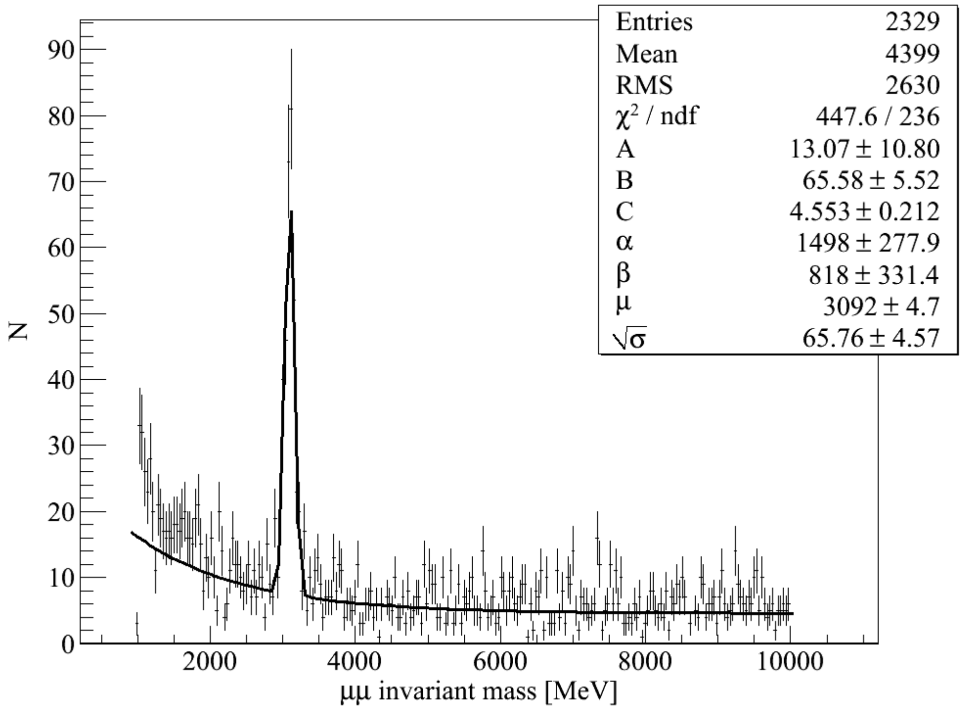

Figure 5.2: The plot of invariant mass of μ-pairs, which were not identified by “MuTagIMO”.

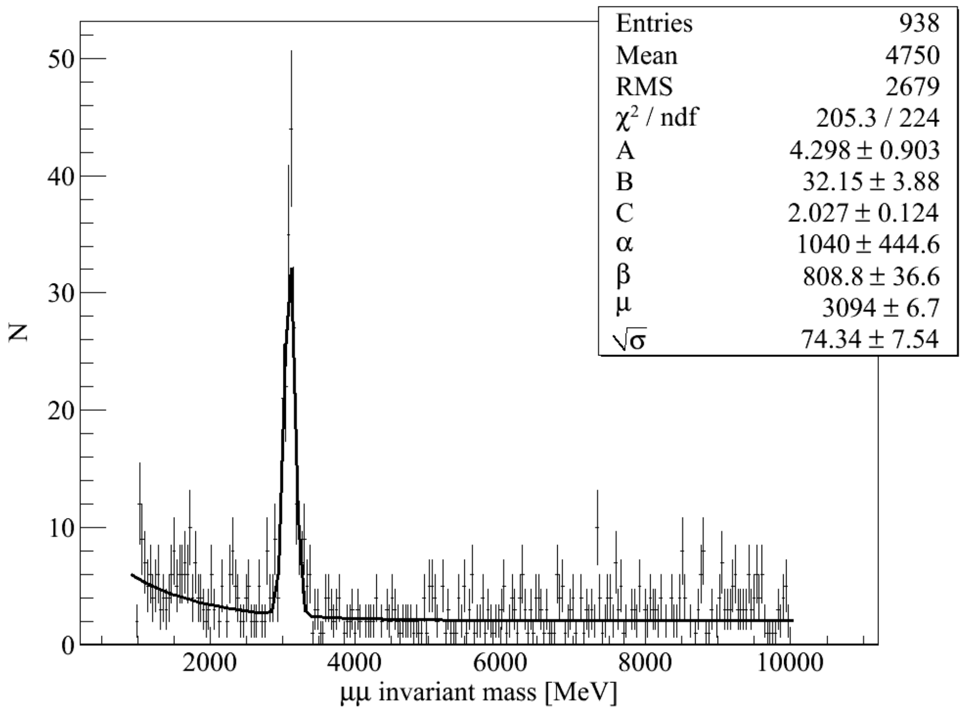

Figure 5.3: The plot of invariant mass of μ-pairs, with “isCombined” muons.

Conclusion

The understanding of particle physics was rapidly developed during last century. Technical progress have great merit of the progress. In second half of 20^{th}century computers and engineering allowed to realize calculations and experiments, which were impossible before. It is not surprising, that in first half of 20^{th}century there were formed methods of approximation of complicated calculations from quantum physics. These approximation are often the only possibility how to enumerate the results of quantum physics.

In my opinion, is useful to know the history of theories, which are used in science or in ordinary life. Moreover, the historical development is simple guidance, how I introduce Standard Model of particle physics in chapter 1. It is understandable, that this theory does not cover all observed phenomenons, but still this model gives good numerical approximations and experimentally verifiable prognosis. One of the last missing pieces of SM is the Higgs boson. Scalar field, which this boson represents, should generate masses of elementary particles like $W^{\pm}$ or Z^0. Presently, there are theories, which predict more Higgs bosons. The most popular is Minimal Super-symmetric Standard Model (MSSM), which came from existence of super-symmetrical partners and fermi-boson symmetry. Another interesting theories are string theory or theories unifying the forces into one, and more others, which have not been mentioned due to aim of the work.

From my point of view the quantum physics is the most pioneering branch of science. Its conception completely change the way how we understand the world. It opens new opportunities in physics or chemistry and encourage in development of new mathematic theories. I consider the probabilistic description is strongest idea of this theory. From probability and statistics follow the principle of present experiments.

The HEP experiments consists of two parts. First, the natural or artificial particle source, and second, the detection system. In European particle institution CERN, which is one of the top worldwide laboratories, is situated the largest collider and most powerful artificial particle source of the world – LHC. On LHC there are hosted six experiments, which are in pairs focused on new physics discoveries, conditions just after the Big Bang and forward physics. Among the LHC detectors the ATLAS experiment is the biggest detection apparatus. In chapter 2 we discussed the tracking and muon identification system of the ATLAS detector.

Because of the collision rate of the LHC, the selection of interesting events is essential. The basic structure of trigger system and particularly muon trigger of the ATLAS is discussed in chapter 3.

In early conditions, energy 3.5 TeV and luminosity of 10^{31} cm^{-2} s^{-1}, is event filter of the ATLAS trigger in transparent mode. But, the event filter algorithms are ran in offline analysis, which enable the study and calibration of the trigger. For data analysis ATLAS developers create many helpful tools and the most widely used are described in chapter 4.

The J/ψ is the resonance with 93.2 ± 2.1 keV mass width [5]. The resonances are represented by Breit-Wigner formula. The Breit-Wigner formula with this width is considered to be Dirac peak. Convolution of Dirac peak and Gaussian is Gaussian distribution. Therefore, we use Gaussian for fitting the signal. The mean value of mean Gaussian represents the mass of the J/ψ. The table value (from [5]) of J/ψ mass is 3096.916 ± 0.011 MeV. Our fitted mass of J/ψ is 3092 ± 4 MeV.

I have used ATLAS tools for analysis in chapter 5. I study early ATLAS events with muon production. I have plotted invariant mass of low-p_T muon–anti-muon pairs and search for peak of J/ψ resonance (fig. 5.1). I was trying to reduce the background from π/K decays (fig. 5.3) and reduce the count of wrongly identified muons (fig. 5.2). The plots shows that algorithms are efficient, but their combination was not realized, due to small sample.

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