ATLAS 13 TeV Data Analysis using Particle Flow

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Acknowledgements

I would like to thank ...

You should probably use `\chapter*` for acknowledgements at the beginning of a thesis and `\chapter` for the end.

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CHAPTER 1

Introduction

The Particle Flow algorithm is a promising way of data analysis and has already been approved on CMS data aswell as on ATLAS 2015 data. The combination of tracker and calorimeter information allows to improve the the resolution and overall results especially in lower energy regions and can therefore reduce the energy threshold for analysis. For my thesis I have worked on creating an analysis framework to allow Particle Flow analysis on 2016 13 TeV data and showing the improvements the new algorithm can bring. The first chapter of this thesis gives a brief introduction to the Standard Model of particle physics, the approved model that is used to describe most particle interactions, decays and crossections. Before describing the actual particle flow algorithm and its results I give a description of the ATLAS detector and its components and furthermore a more general explanation of the attributes of tracking detectors and calorimeters to explain why one expects better results from the combination of both. Last but not least the algorithm is explained in detail before the results of using it on 2016 data and Monte Carlo are given.

CHAPTER 2

Theoretical and experimental basics

2.1 The Standard Model of Particle Physics

The Standard Model of Particle Physics summarizes the current knowledge of fundamental particles and their interactions. The model holds at scales of 1 fm and below. Gravity, being the fourth fundamental force is not included because it is negligible for most phenomena at this scale.

The current view is that all matter is made out of three kinds of elementary particles being leptons quarks and mediators. There are six leptons falling into three families according to charge, electron number, muon number and tau number.

Similiar to that there are six flavors of quarks separated by Strangeness (S), charm (C), Beauty (B), and truth (T). As well as the leptons the quarks fall into three generations. For both kinds of particles the mass rises with the generations and every generation comes as a doublet. The first particle of each lepton doublet is not charged and referred to as a neutrino while the second particle has charge -1. For each quark doublet there is an element with fractional charge $-\frac{1}{3}$ and an element with fractional charge $\frac{2}{3}$. To every of these particles there is an anti particle with opposite charge.

The third kind of particle included in the standard model is the mediator. Mediators are gauge bosons whose exchange allows the particles to interact. There are four kinds of of elemtary interactions of which the strong electromagnetic and weak interaction are included in the model. The fourth interaction is the gravitational interaction. The gauge particles for the strong interaction are the gluons carrying colour charge, the electromagnetic mediator is the photon (γ) and the weak mediators are the $W^{\pm}$ and Z bosons. Tables 2.1, 2.2 and 2.3 summarize the particles and their important properties.

Table 2.1: Lepton properties

	symbol	Charge	L_e	L_μ	L_τ
First generation{	e	-1	1	0	0
	ν_e	0	1	0	0
Second generation{	μ	-1	0	1	0
	ν_μ	0	0	1	0
Third generation{	τ	-1	0	0	1
	ν_τ	0	0	0	1

Table 2.2: Quark properties

	Symbol	Charge Q	mass	D	U	S	C	B	T
First generation {	d	$-\frac{1}{3}$	4.8 MeV	-1	0	0	0	0	0
	u	$\frac{2}{3}$	2.3 MeV	0	1	0	0	0	0
Second generation {	s	$-\frac{1}{3}$	95 MeV	0	0	-1	0	0	0
	c	$\frac{2}{3}$	1 275 MeV	0	0	0	1	0	0
Third generation {	b	$-\frac{1}{3}$	4 180 MeV	0	0	0	0	-1	0
	t	$\frac{2}{3}$	173 210 MeV	0	0	0	0	0	1

Table 2.3: Mediator properties

Interaction	Theory	Mediator	Charge	Coupling
Strong	QCD	gluons (8)	colour	1
Electromagnetic	QED	photon γ	electric charge	10^{-1}
Weak	GSW	$W^{\pm}, Z$	weak isospin	20^{-6}

Given this the standard model of particle physics has been a very successful model for a very long time and still holds for most cases. Nevertheless the model has some commonly known weaknesses and does not claim to be complete. For example the gravitational force is not included and in the standard model neutrinos are massless.

Should there be an outline here ?

2.2 The LHC and ATLAS

The analysis for this thesis has been performed in the ATLAS collaboration. The ATLAS-Detector is one of the four big experiments at the LHC at Cern. Therefore this chapter gives a brief overview over the LHC and ATLAS focusing on the properties directly relevant for Particle Flow Analysis.

After a description of the ATLAS detector in general I will give a little bit more information about the detector components directly relevant for the explanation of particle flow being the tracking detector and the calorimeter. To make the advantages of particle flow understandable to the reader I will give a general description of these detectors and their properties irrespective of their detailed construction at ATLAS.

2.2.1 The LHC

The Large Hadron Collider ("LHC") is part of the facilities of the European Organization of Nuclear Research ("CERN") and was built to extend the frontiers of modern particle physics by delivering high luminosities and unprecedented high energies. The Collider is circular with a circumfence of 26.659 km and is located 10 km underground close to Geneva.
The LHC is designed to collide bunches of up to 10^{11} protons at a luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The beams are collided at three collision points being the four main experiments at the LHC. Tw of these are special-purpose detectors, namely LHCb and ALICE while the other two are general-purpose detectors. The general-purpose experiments are CMS and ATLAS. The analysis in this thesis has been performed on ATLAS data. Figure 2.1 shows the LHC, the four detectors and its general location.

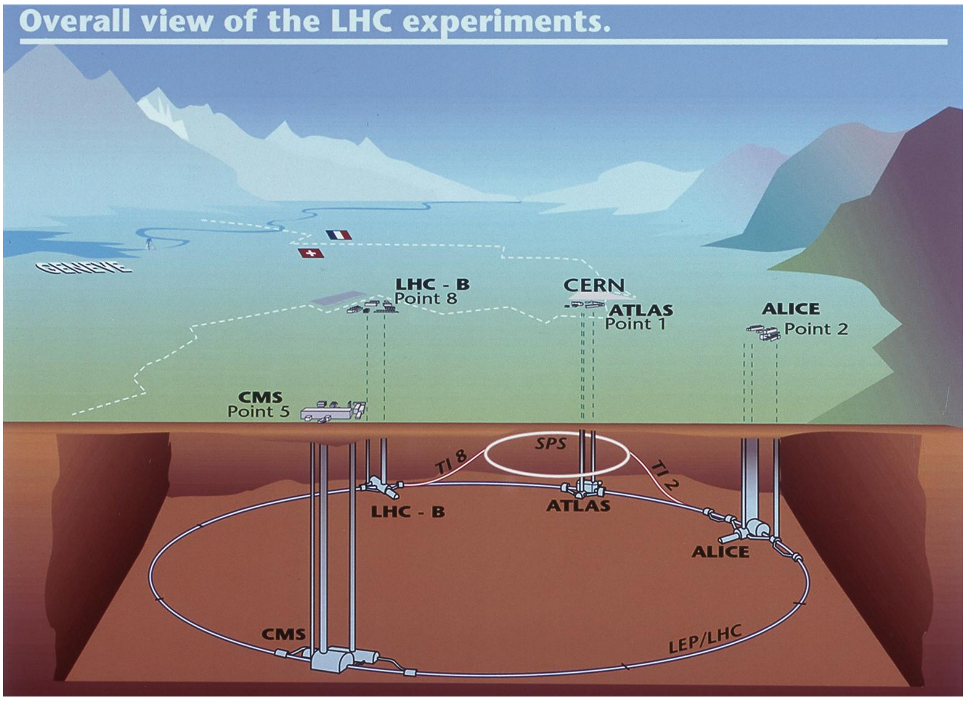

Figure 2.1: Sketch of the LHC ring, the position of the experiments and the surrounding countryside. The four big LHC experiments are indicated. The location of the injection lines and the SPS are also shown. [1]

2.2.2 The ATLAS Detector

The ATLAS-Detector is built to take advantage of the high energy available at the LHC to observe highly massive particles that lower energy accelerators were not able to create and that way bring new physics theory beyond the standard model of particle physics. It is designed to be able to observe a maximized number of final stages being a so called general purpose-detector. This means that the detector should be able to identify every kind of particle and still provide a accurate information about angle and momentum. Figure 2.2 shows the outline of the ATLAS detector together with a rough scale in size. In the following explanations of the components from the inside to the outside are given.

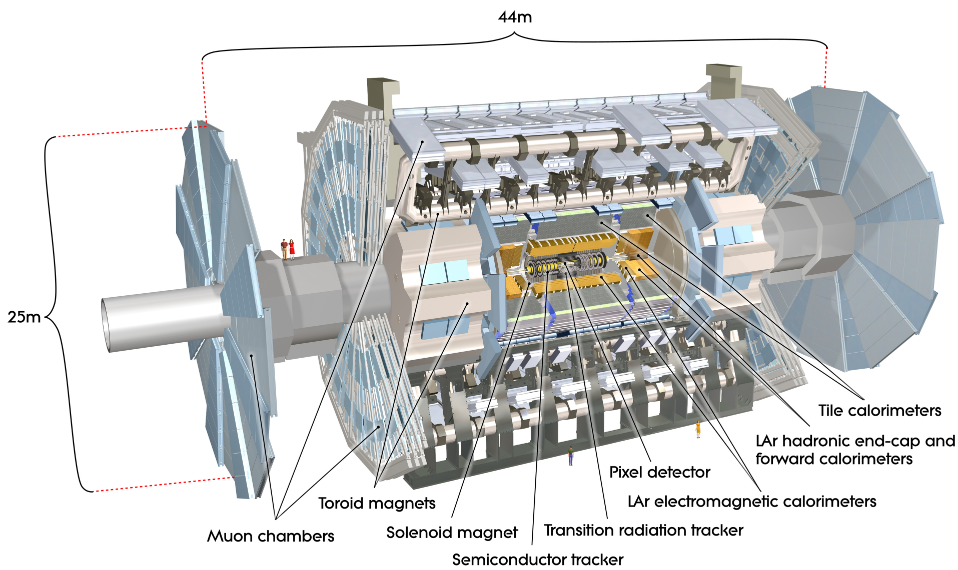

Figure 2.2: Sketch of the ATLAS detector [1]

Figure 2.3 shows the detector's components in a simplified way and allows to understand the order of the important detector parts in detail. The innermost part of the detector is a tracking detector in a field of a large solenoid coil to obtain charge and trajectory of charged particles. The following two parts are the Electromagnetic and Hadronic Calorimeter which together build the Calorimeter part of the detector. One of them focuses on measuring the energy in electromagnetic showers while the other one is optimized for hadronic particle showers. The outermost part is a Muon spectrometer because most of the particles that cross the calorimeters undetected are muons.

Tracking detectors

The Tracking detectors of the ATLAS detector are called the Inner Detector. It consists of three sub-components being the Pixel detector (Pixel), the Semi-Conductor Tracker (SCT) and a Transition Radiation Tracker (TRT). Each one of this sub-detectors is divided in a barrel part and two end-caps. The Inner detector covers a region of $|\eta| < 2.5$ which also limits the region in which particle flow can be used.

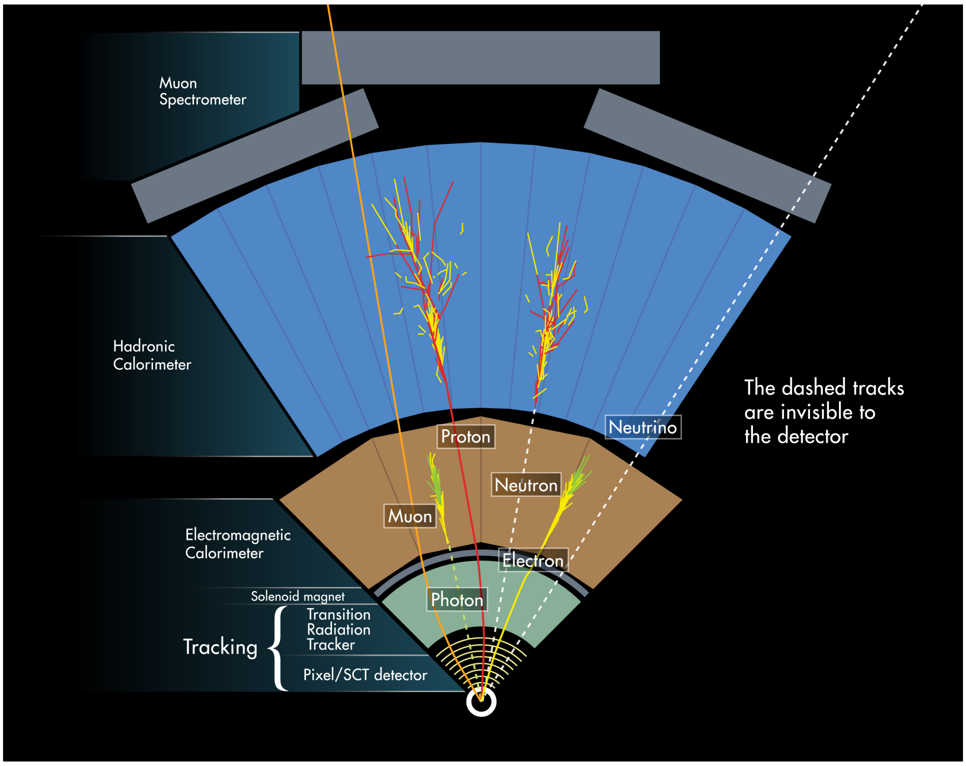

Figure 2.3: Scheme of the ATLAS-detector [1]

EM-Calorimeter

Hadronic Calorimeter

Muon spectrometer

The outermost part of the detector are the Muon tracking chambers or the so calles muon spectrometer. The task of the spectrometer is to detect charged particles transversing the calorimeter undetected and to both trigger on them and to measure their energy. Due to these two functions the spectromeer is divided into two parts each dedicated to one of the tasks. The first part is the trigger chamber covering a range of $|\eta| < 2.4$ and with a range of $|\eta| < 2.7$ comes the high-precision chamber as the second part. The main detectors support feet cause a further gap at about $\phi = 300°$ and $\phi = 270°$.

The hih-precision detector uses Monitored Drift Tubes (MDTs) while the trigger chamber uses Resistive-Plate Chambers (RPCs). The momentum calculation then is performed by the field of the torroid magnet.

2.2.3 Tracking detectors

The go to method to measure the momenta of charged particles is the usage of tracking detectors These detectors are based on charged particles leaving a track of ionisations in any given medium and therefore by detecting this ionizations being able to reconstruct the particles trajectory. There are two main categories for tracking detectors in use. The first one uses a large gaseous volume in a strong electric field and filled with a structure of wires. The electric field lets the liberating electrons drift towards the wires where they cause a detectable signal. However the second kind of detectors is based on semiconductor technology and used in most modern detectors like ATLAS. Therefore I will give this kind of tracking detectors a deeper discussion. If a charged particle traverses a appropriately doped semiconductor wafer for example a doped silicon wafer it creates electron hole pairs along his trail. If an eletric field is applied to the semiconductor material the holes will drift in the direction of the electric field and then be collected b p-n junctions.

Usually a tracking detector is divided into semiconductor strips or pixel in a magnitude of $25 \mu m$. That way a signal at a certain junction can be used to reconstruct a trail and position. The common way to reconstruct a track is s set of cylindrical semiconductor wafers in a magnetic field.

$$p \cdot cos\lambda = 0.3BR \tag{2.1}$$

2.2.4 Calorimeter

In particle physics a calorimeter is a device to measure first and foremost the total energy of a particle. Most of the time also some positional information is taken. The idea is that most particles loose all their momentum crossing the calorimeter-structure. Measuring the energy deposited this way gives a measurement for the particle's energy. Usually a particle deposits its energy by initiating a particle shower. the shower's energy is then collected and measured. Calorimeters are distinguished by the main interaction of the particles one wants to detect.

Electromgnetic Calorimeter

Electromagnetic calorimeters are designed to detect charged particles and measure their total energy.

$$\frac{\sigma_E}{E} \sim \frac{3\% - 10\%}{\sqrt{E/GeV}} \tag{2.2}$$

Hadronic calorimeters

Hadronic calorimeters are used to obtain the energies o hadronic particle showers. Due to the relatively large distance between interactions these calorimeter soccupy a significantly large space in the detector.

A common technique to construct these calorimeters is a sandwich like structure of alternating layers of high density absorber material and active material. The absorbers are used to develop the particle showers which then hit the active material and deposit the energy there.

$$\frac{\sigma_E}{E} \gtrsim \frac{50\%}{\sqrt{E/GeV}} \tag{2.3}$$

CHAPTER 3

Particle Flow Analysis on Run 2 data

One of the goals of this thesis was to check the results of Particle Flow in Run 2 data. Therefore this chapter will give an overview of the results that the new algorithm gives especially in data MC comparison. Before showing the results this chapter gives a description of the algorithm based on the Particle Flow Paper [2]. Then an update on how the algorithm has evolved is given. Then the framework is described and finally the results are shown.

3.1 The Particle Flow Algorithm

Recently only either the Calorimeter or the tracker information was used to reconstruct Jets in ATLAS events. The Particle Flow Algorithm combines tracker and calorimeter information to achieve better resolution especially at lower energies. The main advantages of including the tracker information into reconstruction are listed here:

- For low energy charged particles the momentum resolution of the tracking detector is superior to the calorimeter.
- The Tracking detector is able to reconstruct softe particles, which would not pass the noise threshold of the calorimeter.
- The ATLAS traking detector has a superior angular resolution for single charged particles.
- Low p_T charged particles may be swept out of the cone before reaching the calorimeter by the magnetic field. The tracker information allows to cluster these particles into the jet.
- a better vertex determination could lower the pileup-contribution.

The advantages of Particle Flow have already been shown for Run 1 data in

Figure 3.1 sketches the important steps of the Particle Flow algorithm. The algorithm uses clusters from the calorimeters and tracks from the tracking detectors as input information. The first step is to match a track spatially to a cluster. After a pair has been found the algorithm checks if the particle's momentum matches the energy deposited in the cluster within the expected deviation. If the energy matches a subtraction algorithm starts deciding which cells belong to the given event. If the energy deposited in the cluster is too low the algorithm includes all other clusters in a given area and then starts the subtraction.

After the subtraction the algorithm gives information about matched clusters and trackers. Furthermore energy deposited in cells that got not subtracted can be identified as remnants.

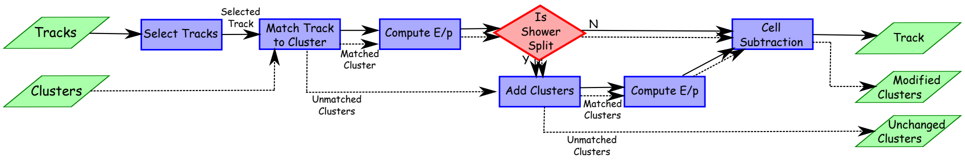

Figure 3.1: Flowchart of the steps of the Particle Flow algorithm [2]

3.1.1 Track selection

In spite of the clusters the algorithm has some requirements on tracks to be selected to minimize the amount of fake tracks. The requirements are at least 9 hits in the PIXEL and SCT and no missing hits in the PIXEL at all. The tracks have to be in a pseudo-rapidity region of $|\eta| < 2.5$ and $500\,\mathrm{MeV} < p_T < 40\,\mathrm{GeV}$.

3.1.2 Clustering

The algorithm uses information from the tracker and the calorimeter as input. The information from the calorimeter is give as topological clusters. The construction of these clusters is briefly described in this chapter to give the reader a basic understanding which input information the algorithm uses. Every cluster is being constructed around a so called seed cell. A seed cell is a cell for which the deposited energy exceeds the expected noise by four times the standard deviation. If a seed is found all the neighboring cells which exceed the noise by at least two times the standard deviation are added to the cluster. Lastly all the cells neighboring these clusters are also added.

3.1.3 Matching Track to Cluster

The algorithm tries to match every track to one or more calorimeter clusters. First the algorithm tries to match a single best-match topo-cluster to every selected track. To do so first the distances in $\Delta\phi$ and $\Delta\eta$ from the track are extrapolated to the second layer of the EM calorimeter and then topo clsuter. then the topo-clusters get ranked based on the metric:

$$\Delta R' = \sqrt{\left(\frac{\Delta\phi}{\sigma_\phi}\right)^2 + \left(\frac{\Delta\eta}{\sigma_\eta}\right)^2} \tag{3.1}$$

where σ_η and σ_ϕ refer to the angular topo-cluster width, computed from the standard deviation of the displacemtens of the topo clusters. If the energy in this cluster is greater or equal than the energy estimated from the track p_T the algorithm goes to cell subtraction. If not all clusters in a cone of $\Delta R < 0.2$ are matched to the track. In that case R is calculated on the metric:

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} \tag{3.2}$$

3.1.4 Cell Subtraction

The last step in the Particle Flow algorithm after matching a set of topo-clusters to a track is the cell-wise subtraction of energy deposits to remove remnants and determine which energy depositions belong to the given particle. If the energy deposited in the set of clusters falls below the expected energy the clusters are simply removed. Otherwise, a cell by cell subtraction is performed.

The first step of the cell subtraction is generating a shower shape from the extrapolated track. Around the extrapolated track rings in η, ϕ space are generated, being just wide enough to independently contain at least one one cell from the extrapolated position. Furthermore the rings are restricted to one layer and for each layer have the same radial size. After the generation of rings in each layer the average energy density in each ring is computed and the rings are ranked by energy density in descending order. The layer is not used in any way for this ranking. The subtraction then starts from the ring with highest energy density and proceeds successively to rings in lower order until the next ring's energy exceeds the remaining expected energy. If the ring's energy exceeds the energy still to be substracted the energy in each cell is scaled down by the fraction needed to reach the expected energy then the process halts and the remaining cells are removed as remnants. An example of the process is sketched in figure 3.2.

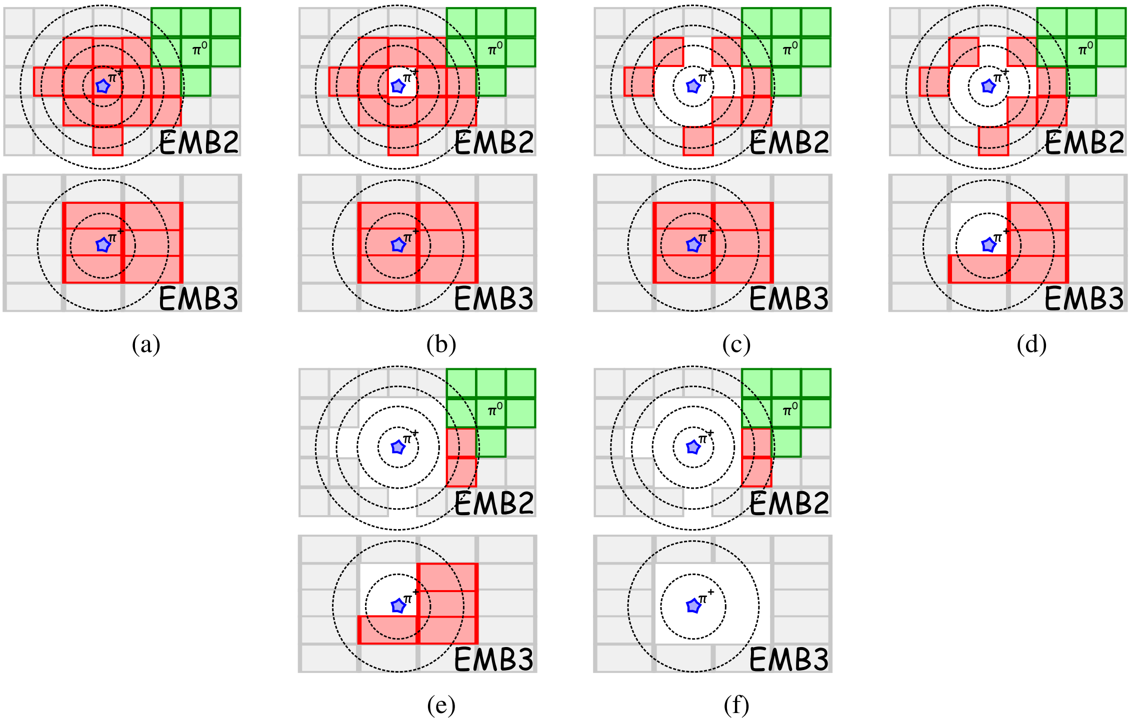

Figure 3.2: Example of cell subtraction. In red the depositions originating from the π^+ of interest are shown and in green a cluster from a π^0 are shown. [2]

3.1.5 Recent updates in eflowrec

3.2 The analysis framework

In order to analyze Run 2 data with the Particle Flow algorithm a framework had to be created whose main parts have been tested in this thesis. This description gives an overview of the framework and then briefly explains the difficulties of the usage at the time.

3.3 Calibration in Particle Flow and its difficulties at the time

At the time of this thesis the calibration of Particle Flow Jets still is not perfected which means that some important tools are only optimized for Topo Jets which are the most common object to work on. Therefore I will give a short summary of the tools used and their possible limitations. A further reason to do this is to give the interested reader an easy introduction into the analysis framework created during my thesis.

CHAPTER 4

Results

4.1 Event Selection

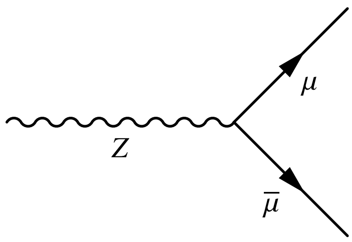

Figure 4.1: Decay of a Z-Boson to two muons

For this thesis $Z \rightarrow \mu\mu$ events were used. The deay channel of a Z boson into a muon and a antimuon has a crossection of 3.366 ± 0.007 [3]. The event was chosen for this analysis because the Z boson is very easy to trigger on and it allows a very clear event selection. Furthermore the event has exactly one recoiling jet that analysis can be performed on. The criteria for the event selection were no good electrons and exactly two good muons, with opposite charge where good means that the particle passed all selection filters itself. The reconstructed Z-Boson is required to be in an range of (90 ± 10) GeV and to have a transversal momentum greater than 30 GeV while the muons are required to have a transversal momentum greater than 25 GeV

I know nothing

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APPENDIX A

Useful information

In the appendix you usually include extra information that should be documented in your thesis, but not interrupt the flow.

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