FACULTY OF PHYSICAL SCIENCES AND ENGINEERING

SCHOOL OF PHYSICS AND ASTRONOMY

BACHELOR OF SCIENCE PROJECT:

LHC OLYMPICS

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Contents

Chapter 1

GENERAL INTRODUCTION

Nowadays Sandard Model is the theory of fundamental particles and how they interact which represent the best comprehension of our world [1]. The name was given in 1970s and this theory combine all our knowledges about subatomic particles and include some additional particles. In this model we find sixteen particles: four force carriers which explain the interactions between them except Gravity (bosons) and 12 particles suggested as the building blocks of matter (fermions). The last particles which were discovered were the W and Z bosons (1983), the top quark (1995), the tau neutrino (2000) and the Higgs boson (2012) [2]. If we include the Higgs boson there are five bosons in the standard model.

Despite the fact that it is the most spread out theory it is not complete. Supersymmetry (SUSY) [3] has been proposed to explain some phenomena SM can not interpret. Nowadays the Large Hadron Collider (LHC) [4] is all but turned on and it has powerful enough to look for confirmation of physics beyond the SM. In LHC at CERN cluster of protons have been accelerated in a large accelerator loop in opposite directions to smash together the two beams formed to get maximum energies of 14 TeV [5]. This is a replication of a fraction of second after the Big Bang [5], the very early universe, and this will produce similiar energies to Quark-Gluon Plasma energies. It is great progress which could discover new physics.

However it is not going to be a simple task to get this new physics. Firstly there are 600 million collisions per second at design luminosity of $1034cm^{-2}s^{-1}$ [5] at LHC so we need to reduce data to interesting events. Physical origin of the signal does not appear so theoretical physicists trained themselves in challenges known as the LHC Olympics [6].

For this trainning, simulated collisions with the production, decay and detection in an ATLAS [7] (type detector of particles) are created in computer software. Physicists have to interpret the output of this software (data sheets) without knowing the origin. This is why data files are known as black boxes. This trainning establish a correspondence between theorical and experimental models.

In this project we are going to approach to the LHC Olympics. We are going to examine data files in Microsoft Excel [8] where we are going to apply algorithms of Visual Basic [9]. We are going to use the samples shared [10] and using the Invariant and the Transverse Mass methods [11] obtain the Z, W and Top quark mass.

Chapter 2

THEORICAL BACKGROUND

2.1 Standard Model

The Standard Model (SM) describes the Universe from fundamental particles which we could describe as basic building blocks governed by four fundamental forces (the strong force, the weak force, the electromagnetic force, and the gravitational force). This model has been proved through the years. We can divide the fundamental particles in two blocks which we can difference by the spin [2]:

1. Fermions (half-integer spin)
   These particles are divided in quarks and leptons and there are six of each of them. They form the matter we observe in the universe.

2. Bosons(integer spin)
   There are four gauge bosons and each of them is assigned with one force. We will find the Photon, Gluon and the Z and W Bosons which act as the force carriers for the Electromagnetic, Strong and Weak forces respectively.

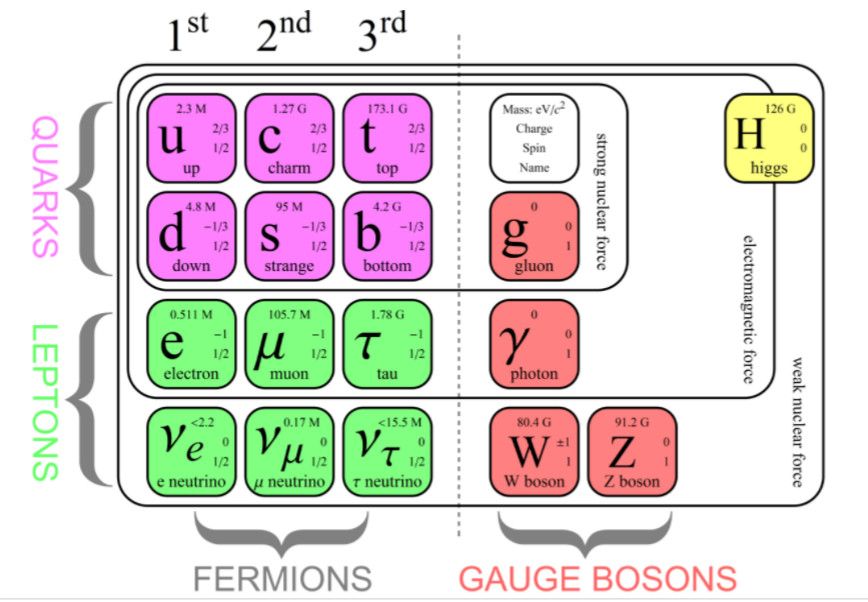


Figure 2.1: Fundamental particles of the Standard Model [12]

In Figure 2.1 we find the different particles with some of their properties included. It is important to know that each particle has an anti-particle with opposite charge.

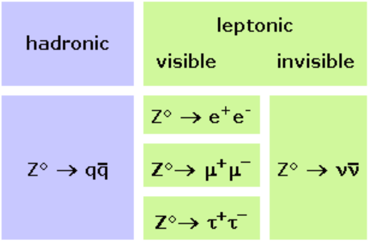
If we analyze the previous image we observe that it appears the three generation of particles. The first generation will be formed by the lightest and most stable particles (all stable matter in the universe is formed of this generation). The second and third generations are formed by the heavier and less stable particles. We conclude that a particle will have a larger mass if it belongs to later generation. We observe that the heaviest particle is the Top Quark ($173.1 \pm 0.6 GeV$) [13], therefore it is extremely unstable and it will decay to lighter particles promptly. This explains why it has been the most difficult particle to be discovered.

This model does not give an explanation of Gravity but it describes how particles aquire mass and thanks to this Higgs Boson was discovered at LHC on 2012 [14].

2.2 Production and decay process

We are interested in the study of the Top Quark, Z and W bosons but we know that they are very unstable therefore we are not able to detect directly these particles, but we can detect their decaying products. There are infinite posibilities of the final state particles. However not all the process have the same probabilities. We are going to use the LHC due to its accuracy: there are millions of collisions every second. For instance in the case of the Top Quark, will produce 80 million pairs annually for design luminosity of $1034 cm^{-2} s^{-1}$ [15]. Feynman diagrams [16] are used to simplify and visualize particle production and decay.

- Z boson [17]
  This particle has a mass of $91.1876 \pm 0.0021 GeV$ GeV [13], so it is a massive particle and it will decay prompty into different particles. Moreover Z is neutral, so we deduce that the sum of the charges of its decay products has to be zero. This means that Z bosons have to decay into a particle-antiparticle pair.
  - In 10% charged lepton-antilepton pairs are produced (Leptonic decay, $l^+ l^-$). The three posibilities are electron-positron,muon-antimuon and tau-antitau.
  - In 20% neutrion-antineutrino pair are produced (Leptonic decay, $\nu\overline{\nu}$).
  - In 70% quark-antiquark pair are produced (Hadronic decay,$q\overline{q}$).



hadronic	leptonic	
	visible	invisible
$Z^\circ \rightarrow q\bar{q}$	$Z^\circ \rightarrow e^+ e^-$	$Z^\circ \rightarrow \nu\bar{\nu}$
	$Z^\circ \rightarrow \mu^+ \mu^-$	
	$Z^\circ \rightarrow \tau^+ \tau^-$	

Figure 2.2: Types of decay of Z boson [18]

Recently the Z boson has been measured extremely precisely at the particle accelerator LEP (Large Electron-Positron Collider, CERN).

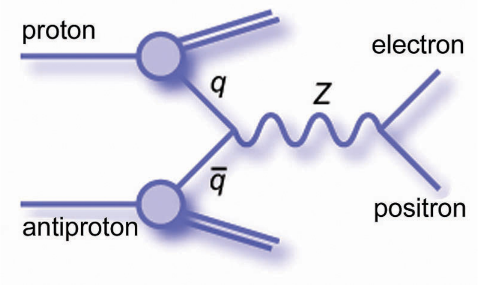


Figure 2.3: An example of production and decay of Z^0 boson [19]

- W boson [19]
  This particle has a mass of 80.4 GeV, so it is heavy and decays almost immediately after its production. The W is two particles: one with positive charge (W^+) and one with negative charge (W^-). There are different paths for the decay products:
  - In two-thirds a quark-antiquark is produced (Hadronic decay, $q\overline{q}$). This pair emerge as jets (spray of light hadrons) in the detector instead of two particles.
  - In one third a lepton (l^+ for W^+ and l^- for W^-) and a neutrino (ν for W^+ and $\overline{\nu}$ for W^-) are produced. It is named as Leptonic decay. In this case, leptons can be an electron, a muon or a tau with the same probability. However tau decays before it can be detected.

leptonic	hadronic
$W^+ \to l^+\nu$	$W^+ \to q\bar{q}$
$W^- \to l^-\bar{\nu}$	$W^- \to q\bar{q}$

Figure 2.4: Types of decay of W boson [20]

- Top quark [15] [21]
  Top Quark has a lifetime of $10^{-25}s$ which is relativily small if we compare with the hadronization time (process of the formation of hadrons out of quarks and gluons) which is $1/\Lambda QCD \approx 10^{-23}s$, so the Top decays so quickly that any effects of quantum chromodynamics (QCD) can commence [11]. The only method to study this particle is to research the decay products.
  There are two main process to produce top quark pairs:
  - The Strong interaction is the principal process at the LHC (mostly Gluon fusion with 90 % of all pairs). We can observe Gluon fusion in the following picture:

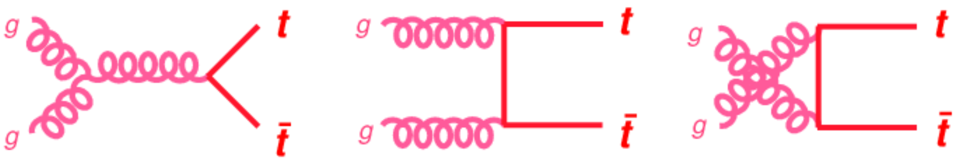


Figure 2.5: Gluon fusion [22]

  - The remaining 10 % is due to Quark- anti Quark annihilation:

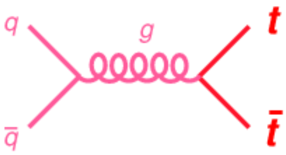


Figure 2.6: Quark Anti-Quark annihilation [22]

Apart from these two process single Top Quarks can be produced by the Weak interaction, although we are not going to consider it here.

We obtain with the Standard Model that the Top Quark t will decay into a $W^+(W^-)$ Boson and Botton Quark $b(\bar{b})$ with a probability of 100%. Although the Bottom Quark is unstable, it lives enough to fragment through QCD interactions.

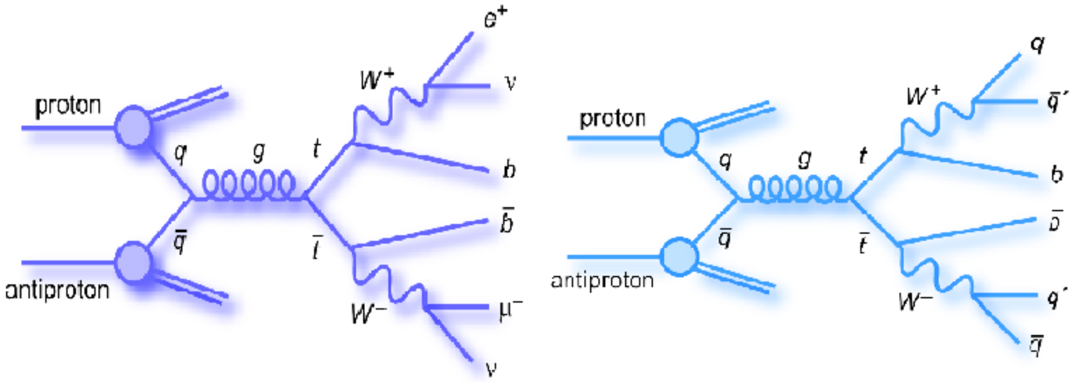


Figure 2.7: Top Quark and Anti Top Quark decay [22]

We can rewrite the two paths as:

$$t \longrightarrow b + W^+ \longrightarrow b + l^+ + \nu \tag{2.1}$$

$$t \longrightarrow b + W^+ \longrightarrow b + q + \bar{q} \tag{2.2}$$

The first routh is known as Leptonic and the second one as Hadronic decay. We observe that there are three decay paths for produced Top Quarks:

- Di-Lepton decay:

$$t\bar{t} \longrightarrow b + \bar{b} + l^+ + l^- + \nu + \bar{\nu} \tag{2.3}$$

- Lepton+Jets decay:

$$t\bar{t} \longrightarrow b + \bar{b} + q + \bar{q} + l \pm + \nu \tag{2.4}$$

- Hadronic decay:

$$t\bar{t} \longrightarrow b + \bar{b} + q + q + \bar{q} + \bar{q} \tag{2.5}$$

Percentage of each path is the following:

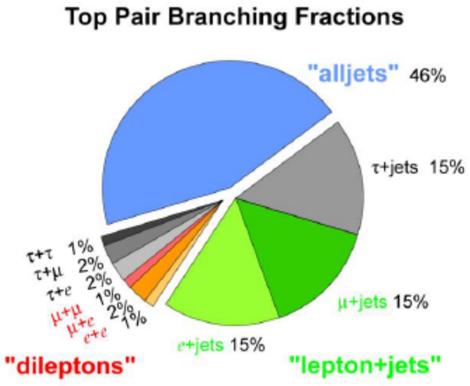


Figure 2.8: Top Quark pairs [22]

In the section (4.2) we will discuss why we study Lepton+Jets channel instead of Hadronic decay which has the biggest percentage (46%).

Finally, Top Quark is really useful in calibrating detectors and critiquing data analysis techniques.

2.3 Colliders and Detectors

2.3.1 Collision geometry

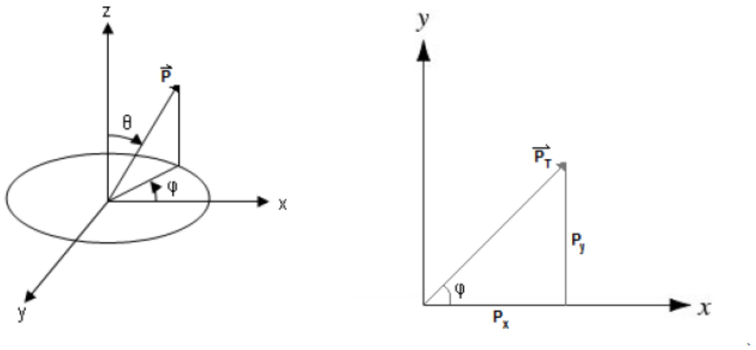


Figure 2.9: Definition of θ and φ for a single particle with momentum $\vec{P}$ and transverse momentum $\vec{P_T}$

In this image the z-axis is what we are going to name beam-pipe. In this axis the two beams of protons after the Hadron colliders are propagating in opposite directions. The two dimensional space x and y axes (perpendicular to the beam pipe) is what we are going to name the transverse plane. Accordingly any particle with momentum vector $\vec{P}$ can be decomposed into one component in the beam pipe $\vec{P^z}$ and one component in the transverse plane $\vec{P^T}$:

$$\vec{P} = \vec{P^z} + \vec{P^T} \tag{2.6}$$

We can define both if we take a look at the Figure 2.9:

$$|\vec{P^T}| = |P||\sin\theta| \tag{2.7}$$

$$|\vec{P^z}| = |P|\cos\theta \tag{2.8}$$

In the same way, we can decompose the transverse momentum into two components: one in the x axis and the other in the y axis.

$$\vec{P}^x = |\vec{P}^T| \cos\varphi \tag{2.9}$$

$$\vec{P}^y = |\vec{P}^T| \sin\varphi \tag{2.10}$$

In this moment we can define the pseudorapidity which is useful to simplify some calculations:

$$\eta = -\ln \tan \frac{\theta}{2} \tag{2.11}$$

2.3.2 Detectors

Firstly, a detector in particle accelerators is compound of different components whereby any particle will progress through each component consecutively. If we examine how particles interact within each layer we will identify the particle. Each thickness is sheathed around the beam pipe:

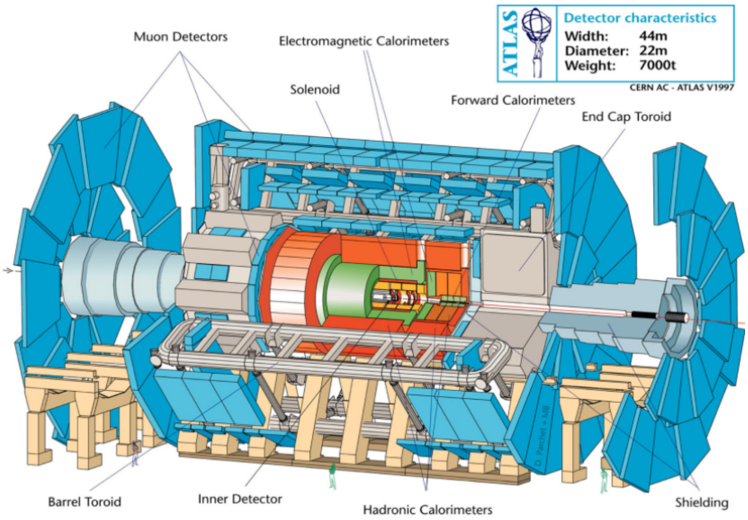


Figure 2.10: ATLAS Detector [23]

The innermost layer is the tracking chamber which will be inserted within a magnet system causing charged particles, positive or negative, to curve in different directions. We can determine the momentum of the particle with the degree of curvature [5]. Short lived particles are captured through the vertex detector. The second and the third layer are Electromagnetic and Hadronic calorimeters, respectively, so they measure the energy of the particles. The Electromagnetic calorimeter will measure particles with electromagnetic interaction, while the Hadronic calorimeter will measure particles with strong nuclear force. These calorimeters will be composed of different materials depending on which particles want to stop. Calorimeters are able to detect invisible particle in the tracking chamber as Photons or Neutrons.

Finally the outermost layer is the Muon chamber as a result of muons need go through metres of material before stop and be detected [5].

However Neutrinos can not be recognised by detectors because of their weak interaction so we need to use some of our knowledge of particle collisions. We have a known momentum of a proton but we do not know how this momentum is scattered amongst its constituent partons: Quarks and Gluons. Nevertheless, Proton is unmoving in the transverse plane, so any transverse momentum held will be negligible if we compare with the longitudinal momentum.

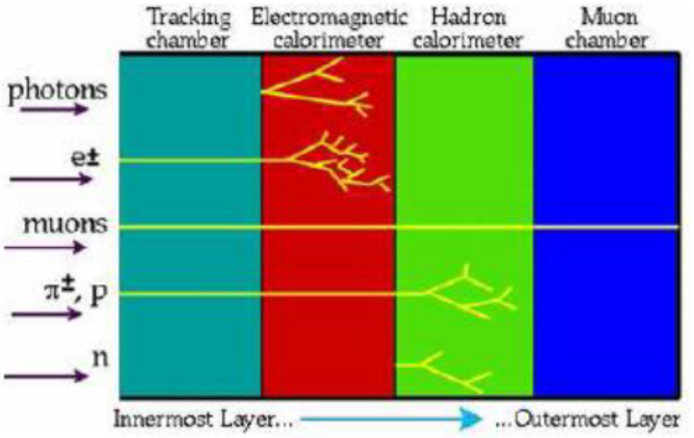


Figure 2.11: Different particles in the layers of the detector [24]

We discover that Quark-Quark or Gluon-Gluon collisions has transverse momentum equal to zero. Finally, if the sum of all the transverse momentum of all visible particle and the result is not zero, this means that another undetected particle is involved which is known as Missing Energy [11].

2.3.3 Triggering

A list of particles or missing energy which are measured by the detector is referred as an event. There is a continuous output of data which is repeated for every event in real-time. At the LHC there are 600 million collisions per second at design luminosity [5], although only 100 collisions per second are useful and interesting. Triggering is the process which compare the 600 million collisions to the requirements that determine the successful events. The un-satisfactory events are thrown away, consequently after triggering we obtain a controlable number of events.

2.4 Computer Simulations and Black Boxes

2.4.1 Creating Black Boxes

There are some computer simulations to generate events and that is what have been used for the LHC Olympics. Data files have been created using this event generators which simulate the production, decay and detection of particles. For instance, PYTHIA [25] and HERWIG [26] are some of them. The creation of these black boxes has three steps:

1. Firstly, the rate for a particular short distance physics production process are determined by Feynman diagrams.

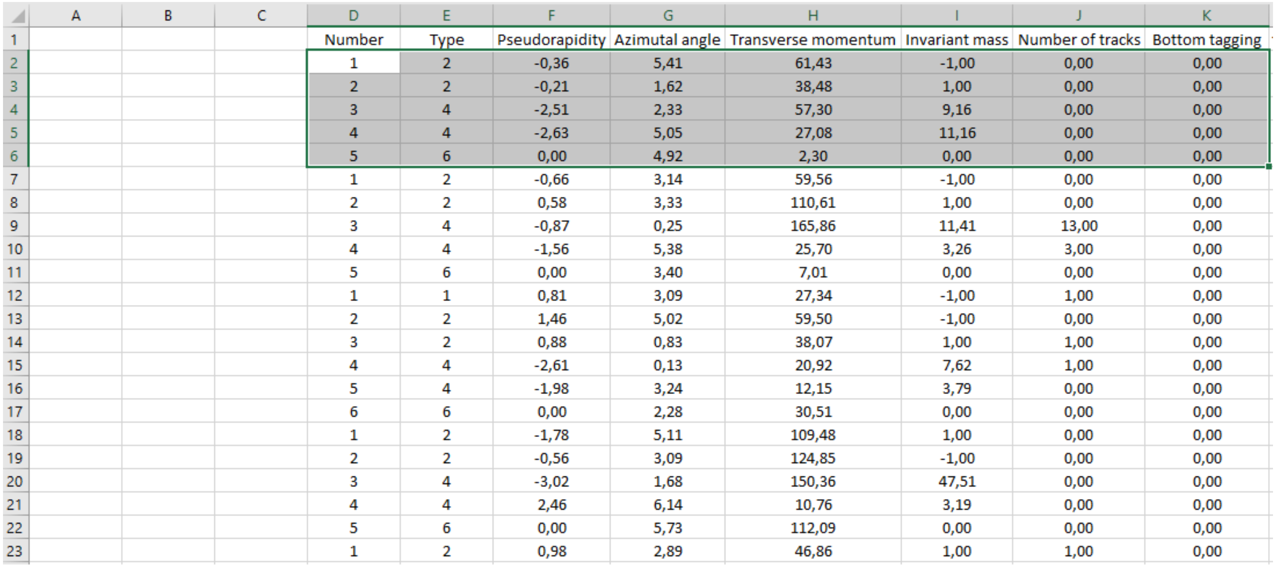
2. Secondly, the evolution os the short distance process is simulated.

3. Thirdly, Pretty Good Simulation (PGS) [27] software process the final state particles acting as a detector. In this step triggering takes place. Finally, black box or calibration sample is the output of the software [28].

A black box file can contain different physics processes however to obtain accuracy there are some limitations on how many processes can be processed. SM background is not contained in the LHC Olympics, so Olympics are unrealistic [29].

2.4.2 Understanding Black Boxes

We have used Microsoft Excel [8] to analyze data files:



	A	B	C	D	E	F	G	H	I	J	K
1				Number	Type	Pseudorapidity	Azimutal angle	Transverse momentum	Invariant mass	Number of tracks	Bottom tagging
2				1	2	-0,36	5,41	61,43	-1,00	0,00	0,00
3				2	2	-0,21	1,62	38,48	1,00	0,00	0,00
4				3	4	-2,51	2,33	57,30	9,16	0,00	0,00
5				4	4	-2,63	5,05	27,08	11,16	0,00	0,00
6				5	6	0,00	4,92	2,30	0,00	0,00	0,00
7				1	2	-0,66	3,14	59,56	-1,00	0,00	0,00
8				2	2	0,58	3,33	110,61	1,00	0,00	0,00
9				3	4	-0,87	0,25	165,86	11,41	13,00	0,00
10				4	4	-1,56	5,38	25,70	3,26	3,00	0,00
11				5	6	0,00	3,40	7,01	0,00	0,00	0,00
12				1	1	0,81	3,09	27,34	-1,00	1,00	0,00
13				2	2	1,46	5,02	59,50	-1,00	0,00	0,00
14				3	2	0,88	0,83	38,07	1,00	1,00	0,00
15				4	4	-2,61	0,13	20,92	7,62	1,00	0,00
16				5	4	-1,98	3,24	12,15	3,79	0,00	0,00
17				6	6	0,00	2,28	30,51	0,00	0,00	0,00
18				1	2	-1,78	5,11	109,48	1,00	0,00	0,00
19				2	2	-0,56	3,09	124,85	-1,00	0,00	0,00
20				3	4	-3,02	1,68	150,36	47,51	0,00	0,00
21				4	4	2,46	6,14	10,76	3,19	0,00	0,00
22				5	6	0,00	5,73	112,09	0,00	0,00	0,00
23				1	2	0,98	2,89	46,86	1,00	1,00	0,00

Figure 2.12: Diboson sample [10] in Microsoft Excel [8]

Each event is made up of a set of rows where each one of them is a different decay product from that event. Each column of the event describes the following characteristics:

Column	Description
D	It is a counter which determines how many objects are in an event. Moreover it determines when an event start and when it finishes to start a new one (1 appears).
E	Label the type of object. We can find any of the integers 0,1,2,3,4,6 which represent a Photon, Electron, Muon, Tau, Jet and Missing Energy respectively.
F	Gives the pseudorapidity η (3 decimal places).
G	Gives the azimuthal angle φ in radians (3 decimal places).
H	Gives the transverse momentum modulus $\|\vec{P^T}\|$ (2 decimal places).
I	If it is a jet we will obtain the invariant mass of the spray of particles (2 decimal places). However, if it is not a jet we will obtain the charge of the particle.
J	Gives the number of different particle tracks within a Jet.
K	It will appear 1 if a decay product is a Jet originating from a Charm or Bottom Quark, otherwise it will appear a value of 0.

Table 2.1: Meaning of each column in an event

We have re-scaled the speed of light to unity, therefore we find the transverse momentum and invariant mass in Giga-Electon-Volts (GeV). The Missing Energy is an invisible particle, so it is not possible to measure θ and therefore pseudorapidity neither. It is important to notice that only 50% of all heavy Jets appear in the data file, so if two Botton Quarks are produced only one or none appear.

Chapter 3

THEORICAL METHOD

3.1 Deciphering the Black Box

We imported each data file [10] to Microsoft Excel [8] until we obtained the aspect in Figure 2.12. The main reason we chose this spreadsheet is Visual Basic [9]. VB is add-in MS Excel and allows us to create macros and algorithms which run over the data file.

Originally we created some simple macros and algorithms in VB to count how many objects of a specific type are in a range or to copy some rows into another data sheet. After that we created more complex macros and algorithms to elect some events with particular requirements or to calculate distinct properties.

We are not going to allude to all algorithms here, but there is a list of all of them in Appendix I with a brief description of each one.

3.2 The Invariant Mass Variable

The invariant mass is a variable used in unstable particles to rebuild the pole mass in a system where we know the total momentum. The invariant mass is defined for N particles as [11] [**?**]:

$$m_{Inv}^2 = \left(\sum_{i=1}^{N} p_i \right)^2 \tag{3.1}$$

where we have used the four momentum of each decay product. Therefore in the case of two particles:

$$m_{Inv}^2 = \left(\vec{p}_1 + \vec{p}_2 \right)^2 \tag{3.2}$$

The four momentum is a vector useful in high energy physics which is composed of four components: it is created with the energy 'E' and three momentum '$\vec{P}$'. This reproduces the relativistic mass:

$$p^\mu p_\mu = \vec{p}^2 = E^2 - |\vec{P}|^2 = m^2 \tag{3.3}$$

Conseguently we can rewrite equation 3.2 as:

$$m_{Inv}^2 = \left(\vec{p}_1 + \vec{p}_2 \right)^2 = \vec{p}_1^2 + \vec{p}_2^2 + 2 \cdot \vec{p}_1 \cdot \vec{p}_2 = m_1^2 + m_2^2 + 2 \left(E_1 E_2 - \vec{P}_1 \cdot \vec{P}_2 \right) \tag{3.4}$$

We can simplify this equation if we use the masless limit [11] where all light Quarks and Leptons in the SM have negligible mass:

$$m_{Inv}^2 = 2 \left(|\vec{P}_1| \cdot |\vec{P}_2| - \vec{P}_1 \cdot \vec{P}_2 \right) \tag{3.5}$$

In the case of N particles we can rewrite equation 3.1 as:

$$m_{Inv}^2 = (\vec{p}_1 + \vec{p}_2 + ... + \vec{p}_N)^2 = \left(\sum_{i=1}^{N} E_i\right)^2 - \left(\sum_{i=1}^{N} \vec{P}_i\right)^2 \tag{3.6}$$

If we remember that momentum can be expressed as a tranverse momentum and a longitudinal momentum (Equation 2.6) we can express the equation 3.6 as:

$$m_{Inv}^2 = \left(\sum_{i=1}^{N} E_i\right)^2 - \left(\sum_{i=1}^{N} \vec{P}_i^z\right)^2 - \left(\sum_{i=1}^{N} \vec{P}_i^T\right)^2 \tag{3.7}$$

There will be no net transverse momentum for a pair produced particles in a Proton-Proton collision:

$$m_{Inv}^2 = \left(\sum_{i=1}^{N} E_i\right)^2 - \left(\sum_{i=1}^{N} \vec{P}_i^z\right)^2 \tag{3.8}$$

Finally we are going to use the massless limit [11] where we can rewrite $E_i = |\vec{P}_i|$:

$$m_{Inv}^2 = \left(\sum_{i=1}^{N} |\vec{P}_i|\right)^2 - \left(\sum_{i=1}^{N} \vec{P}_i^z\right)^2 \tag{3.9}$$

and using Equations 2.7 and 2.8:

$$m_{Inv}^2 = \left(\sum_{i=1}^{N} \frac{|\vec{P}_i^T|}{|\sin\theta_i|}\right)^2 - \left(\sum_{i=1}^{N} \frac{|\vec{P}_i^T|}{\tan\theta_i}\right)^2 \tag{3.10}$$

We can select one type of event and plot its invariant mass in order that a frequency distributions is produced. This frequency satisfy the Breit-Wigner (BW) formula [Ref.11]. The peak coincides with the rest mass but some detector inefficiencies or any background can influence. In this formula N_{max} occurs when the invariant mass of the decay products equals the rest mass of the decay parent and the width of the peak at half maximum is described by the lifetime of the particle.

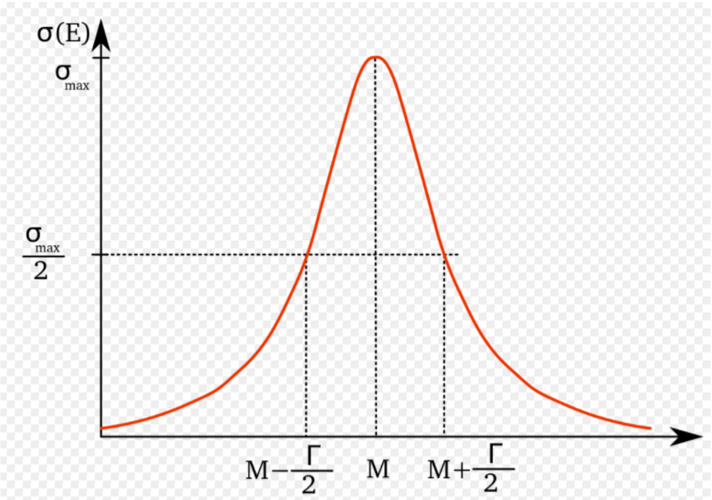


Figure 3.1: Breit-Wigner (BW) formula

3.3 The Transverse Mass variable

We are going to consider two Bosons from a Proton-Proton collision which will produce Lepton decay and Hadron decay products:

$$W^+W^- \to q + \overline{q} + l + \nu \tag{3.11}$$

We can calculate the invariant mass of the Lepton decay products using equation 3.7:

$$m_{Inv}^2 = (E_l + E_\nu)^2 - \left(\vec{P}_l^z + \vec{P}_\nu^z\right)^2 - \left(\vec{P}_l^T + \vec{P}_\nu^T\right)^2 \tag{3.12}$$

We know that neutrino can not be detected because of it is an invisible particle, so θ can not be calculated. To solve this we are going to apply momentum conservation in the transverse plane to obtain the missing transverse momentum:

$$\vec{P}_{Miss}^T = -\sum_{visible} \vec{P}^T \tag{3.13}$$

This is the transverse momentum [11] of the Neutrino in our case. The full invariant mass of the two leptons can not be obtained due to its imposible to set up an analogous term along the beam-pipe. Consequently we are going to overlook the longitudinal momenton and define the transverse mass:

$$m_{Trans}^2 = \left(\sum_{i=1}^{N} E_i^T\right)^2 - \left(\sum_{i=1}^{N} \vec{P}_i^T\right)^2 \tag{3.14}$$

where the transverse energy is:

$$E^T = \sqrt{|\vec{P}^T|^2 + m^2} \tag{3.15}$$

where we can use the massless limit [11]:

$$E^T = |\vec{P}^T|^2 \tag{3.16}$$

Finally we obtain for the two leptons:

$$m_{Trans}^2 = \left(E_l^T + E_\nu^T\right)^2 - \left(\vec{P}_l^T + \vec{P}_{Miss}^T\right)^2 = 2|\vec{P}_l^T||\vec{P}_{Miss}^T|\left(1 - \cos\varphi_{l\nu}\right) \tag{3.17}$$

where $\varphi_{l\nu} = \varphi_l - \varphi_\nu$ is the difference in azimutal angle. Invariant mass develop into equivalent to the transverse mass when we consider that there is no longitudinal motion in a W Boson (the final term of equation 3.7 disappear). If we compare this equation and equation 3.14 we find the following inequality:

$$0 \leq m_{Trans} \leq m_{Inv} \tag{3.18}$$

We can plot the transverse mass and obtain a frequency distribution which will be cut off piercingly at the rest mass due to the BW resonance in the invariant mass distribution. Nevertheless in practice this cut off have a width Γ because of the BW resonance.

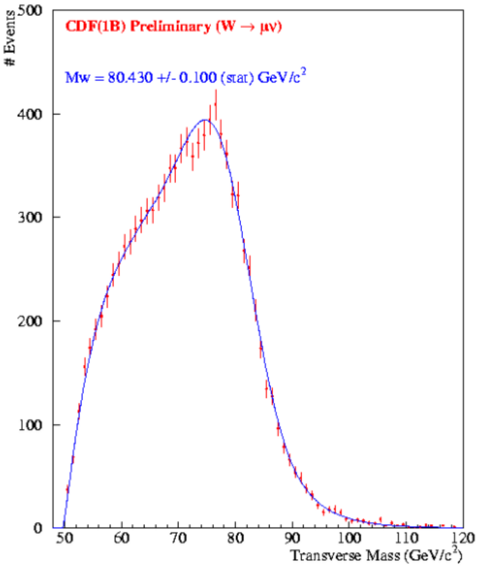


Figure 3.2: CDF collaboration for $W \to \mu\nu$ [30]

Chapter 4

RESULTS

4.1 Diboson sample

In this section we are going to obtain Z boson and W boson masses. To realize this we are going to use the following data files: *diboson_1005.dat.0* and *diboson_1005.dat.1* [10]. The majority of events are W^+W^-, Z^0Z^0 or $W \pm Z^0$ where the possible decay products we find are:

Type of collision	**Final decay products**	**Decay route**
W^+W^-	$(q+\overline{q}+q+\overline{q})$	Both hadronic
	$(q+\overline{q}+l^{\pm}+\nu)$	One hadronic and one leptonic
	$(l^+ + l^- + \nu + \nu)$	Both leptonic
Z^0Z^0	$(q+\overline{q}+q+\overline{q})$	Both hadronic
	$(q+\overline{q}+l^+ + l^-)$ or $(q+\overline{q}+\nu+\overline{\nu})$	One hadronic and one leptonic
	$(l^+ + l^- + l^+ + l^-)$ or $(l^+ + l^- + \nu + \overline{\nu})$ or $(\nu+\overline{\nu}+\nu+\overline{\nu})$	Both leptonic
$W^{\pm}Z^0$	$(q+\overline{q}+q+\overline{q})$	Both hadronic
	$(q+\overline{q}+l^+ + l^-)$ or $(q+\overline{q}+\nu+\overline{\nu})$	Hadronic $W^{\pm}$ and Leptonic Z^0
	$(l^{\pm}+\nu+q+\overline{q})$	Leptonic $W^{\pm}$ and Hadronic Z^0
	$(l^+ + l^- + l^+ + l^-)$ or $(l^{\pm}+\nu+l^+ + l^-)$ or $(l^{\pm}+\nu+\nu+\overline{\nu})$	Both leptonic

Table 4.1: Possible final state particles of W and Z boson collisions

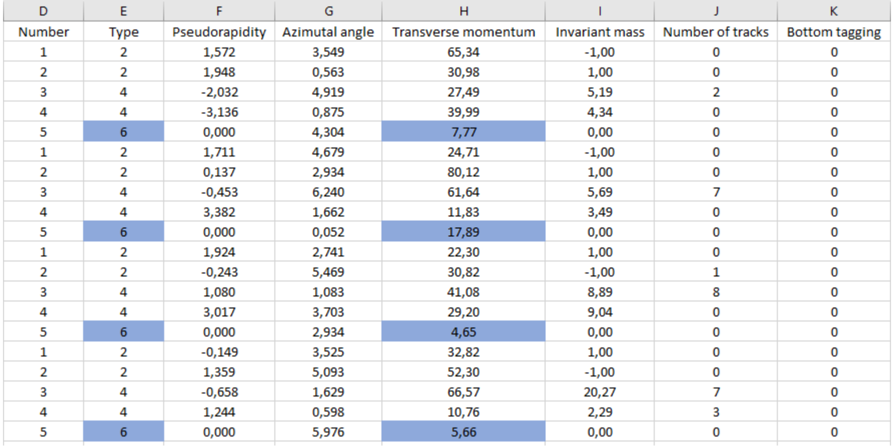
4.1.1 Z boson

We settle that we are going to search are:

$$q+\overline{q}+l^+ + l^- \tag{4.1}$$

We have chosen this decay products because we know absolutely that charged leptons come from Z boson so we can calculate the invariant mass to this charged particles and reproduce Z boson mass. With other decay products we would have doubtfulness to know their origin particles (before collision).

In the first place we are going to use the algorithm *JetStart* to select events as in Equation 4.1 (two leptons with opposite charge and two light jets). However we are going to differenciate the leptons as a pair of electron-positron (e^-e^+) and a pair muon-antimuon ($\mu^-\mu^+$) and we are going to calculate the invariant mass separately in each case.



D	E	F	G	H	I	J	K
Number	Type	Pseudorapidity	Azimutal angle	Transverse momentum	Invariant mass	Number of tracks	Bottom tagging
1	2	1,572	3,549	65,34	-1,00	0	0
2	2	1,948	0,563	30,98	1,00	0	0
3	4	-2,032	4,919	27,49	5,19	2	0
4	4	-3,136	0,875	39,99	4,34	0	0
5	6	0,000	4,304	7,77	0,00	0	0
1	2	1,711	4,679	24,71	-1,00	0	0
2	2	0,137	2,934	80,12	1,00	0	0
3	4	-0,453	6,240	61,64	5,69	7	0
4	4	3,382	1,662	11,83	3,49	0	0
5	6	0,000	0,052	17,89	0,00	0	0
1	2	1,924	2,741	22,30	1,00	0	0
2	2	-0,243	5,469	30,82	-1,00	1	0
3	4	1,080	1,083	41,08	8,89	8	0
4	4	3,017	3,703	29,20	9,04	0	0
5	6	0,000	2,934	4,65	0,00	0	0
1	2	-0,149	3,525	32,82	1,00	0	0
2	2	1,359	5,093	52,30	-1,00	0	0
3	4	-0,658	1,629	66,57	20,27	7	0
4	4	1,244	0,598	10,76	2,29	3	0
5	6	0,000	5,976	5,66	0,00	0	0

Figure 4.1: Example of Equation 4.1 in the data sheet with transverse momentum of missing energy highlighted

It appears a missing energy in each event whose transverse momentum is really small compared with the other particles, so one possibility of its existence is detector wastefulness.
In this moment we can calculate the invariant mass of e^-e^+ and $\mu^-\mu^+$ with algorith *InvariantMass* and *InvariantMassWxy* and plot it using SciDAVIs [31].

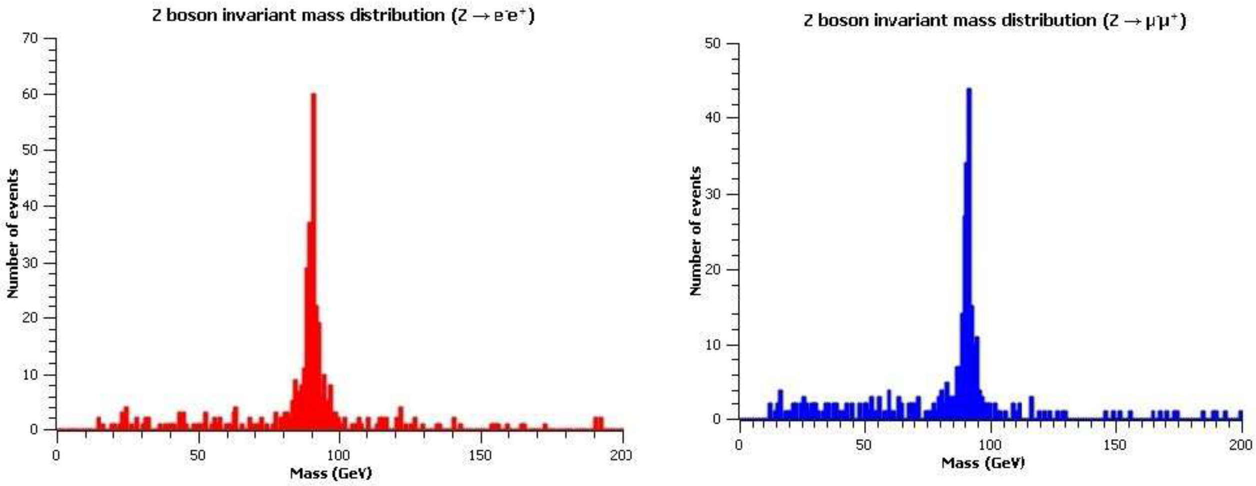


Figure 4.2: Z boson invariant mass from 0 to 200 GeV

We can look at this with more accuracy:

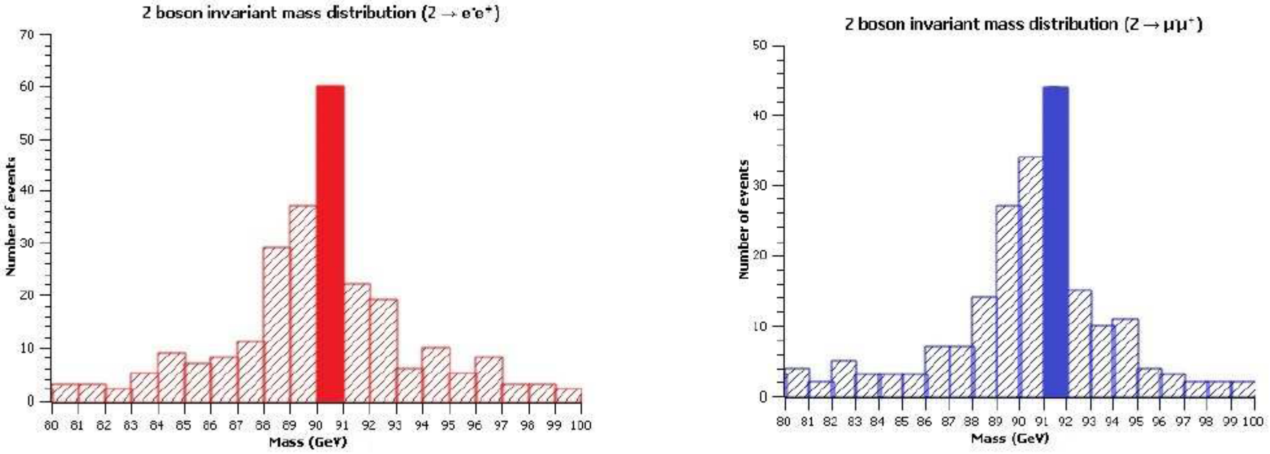


Figure 4.3: Z boson invariant mass from 80 to 100 GeV

The peak of the graphic corresponds to the invariant mass of Z boson. Moreover we can calulate the mean lifetime thanks to the width of the half-maximum value.

$$\tau = \frac{\hbar}{\Gamma} \tag{4.2}$$

We obtain the following results:

- Leptons e^-e^+:
$$m_z^e = 90.5 \pm 0.5 GeV \text{ and } \tau^e = 3.291 \cdot 10^{-25} s \tag{4.3}$$
- Leptons $\mu^-\mu^+$:
$$m_z^e = 91.5 \pm 0.5 GeV \text{ and } \tau^\mu = \cdot 10^{-25} s \tag{4.4}$$

4.1.2 W boson

We can use the same study as in section 4.1.1 for Z boson. We are going to start selecting the decay products for W bosons:

$$q + \overline{q} + l^{\pm} + \nu \tag{4.5}$$

We are going to use algorithm *JetStart* to select events of equation 4.4.We observe that there is a neutrino so, in this case, we are going to calculate the transverse mass for the charged lepton and the neutrino. We apply algorithm *TransverseMass* to calculate transverse mass and we plot by SciDAVIs:

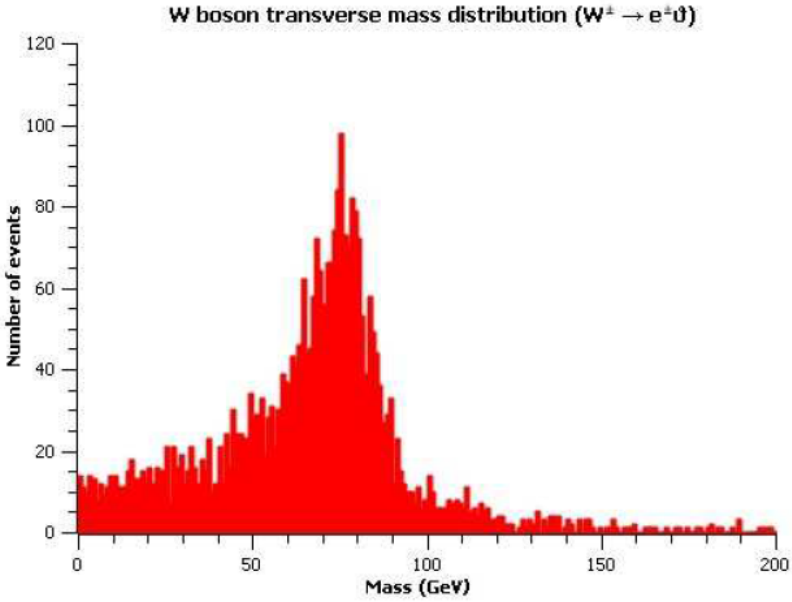


Figure 4.4: W boson transverse mass from 0 to 200 GeV

We can look at this with more accuracy:

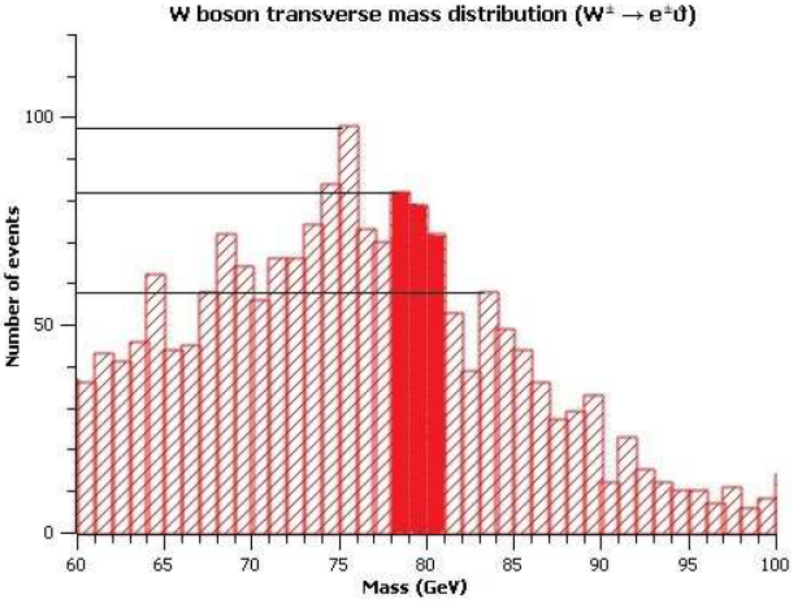


Figure 4.5: W boson transverse mass from 60 to 100 GeV

We observe that highlighted values are comparable and after them there is a cut off, so we choose the three bins as the W boson mass. We observe that m_w is between 78 and 81 so:

$$m_w = 79.5 \pm 1.5 GeV \tag{4.6}$$

4.2 Ttbar sample

Last part of the project is determine top quark mass.
Data files used are [10]: *pgs_objects.dat.0*, *pgs_objects.dat.1*, *pgs_objects.dat.2*, *pgs_objects.dat.3*, *pgs_objects.dat.4*, *pgs_objects.dat.5*, *pgs_objects.dat.6*, *pgs_objects.dat.7*, *pgs_objects.dat.8*, *pgs_objects.dat.9*, *pgs_objects.dat.10*, *pgs_objects.dat.11*, *pgs_objects.dat.12*, *pgs_objects.dat.13*.
Decay products of top quark are:

$$t\bar{t} \rightarrow W^+ + b + W^- + \bar{b} \tag{4.7}$$

Possible decay products are:

- Di-lepton decay:
$$t\bar{t} \rightarrow b + \bar{b} + l^+ + l^- + \nu + \overline{\mu} \tag{4.8}$$
  In this route we obtain two neutrinos (μ and $\overline{\mu}$). There is a problem because detection is only one missing energy, so we do not detect both neutrinos and we do not get the hole information.

- Lepton+jets decay:
$$t\bar{t} \rightarrow b + b + q + \overline{q} + l^{\pm} + \nu \tag{4.9}$$
  There is no problem in this route because $l^+(l^-) + \nu$ comes from $W^+(W^-)$ and $q + \overline{q}$ comes from $W^-(W^+)$

- Hadronic decay:
$$t\bar{t} \rightarrow b + b + q + q + \overline{q} + \overline{q} \tag{4.10}$$
  In this route we detect four jets but we cannot determine which pair quark-antiquark ($q\overline{q}$) comes from which W boson.

We observe that lepton+jets decay route is the only one which we can indentify the original particles without doubt, so it is the best option.
We are going to start as in Z and W boson masses and use algorithm *JetStart* to select the events with equation 4.8 (two heavy jets ($b\overline{b}$), two light jets ($q\overline{q}$), a lepton ($e^{\pm}, \mu^{\pm} or \tau^{\pm}$) and one missing energy (μ). Finally we should calculate the invariant mass to the pair quark-antiquark ($q\overline{q}$) and the bottom quark (b) and calculate the transverse mass to the lepton ($l^{\pm}$), the neutrino (μ) and the bottom antiquark ($\overline{q}$). Nevertheless there is one problem: b and $\overline{b}$ are only detected as heavy jets, so we do not know if they are coming from a top quark (t) or a top antiquark ($\bar{t}$). This implies that we do not know which one we have to use to calculate the invariant mass and which one to calculate the transverse mass.
Our proposal is initially use the algorithm *InvTransvMassTOP* to calculate invariant mass and transverse mass for both possible cases in each event (m_{Inv_1}, m_{Trans_1} for the first case and m_{Inv_2}, m_{Trans_2} for the second case). The only difference between each case is where heavy jets are coming from. In the first case we will use first heavy jet to calculate the transverse mass and the second heavy jet to calculate the invariant mass and in the second case *vice versa*.
However there is only one case possible, so we have to decide which is. To solve this we define variables R_1 and R_2 as:

$$R_1 = m_{Inv_1} - m_{Trans_1} \tag{4.11}$$

$$R_2 = m_{Inv_2} - m_{Trans_2} \tag{4.12}$$

Keeping in mind sections 3.2 and 3.3 we know that due to the rest mass of the decaying particle there is a peak in transverse and invariant mass. So right values correspond to the minimum R. We select correct values using algorithm *SelectTOP*.

4.2.1 Invariant mass distribution

We plot using SciDAVis [31] the invariant mass frequency distribution:

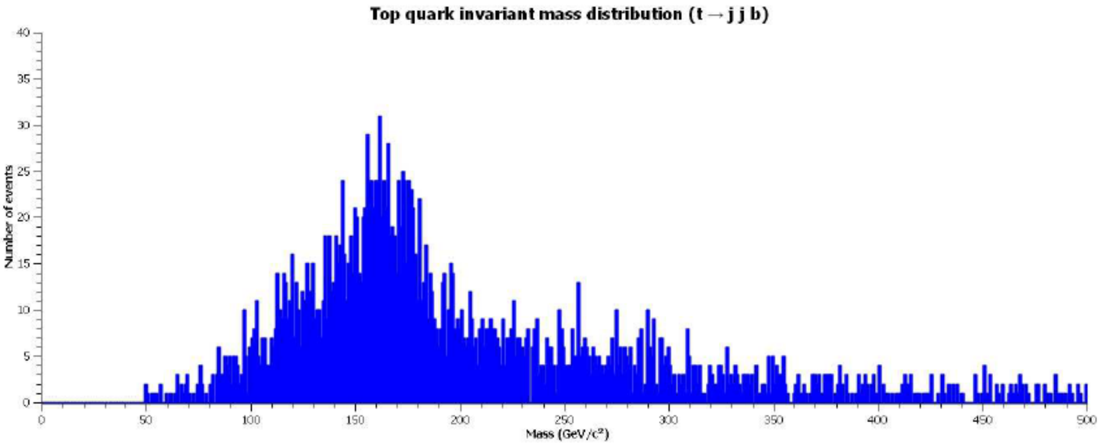
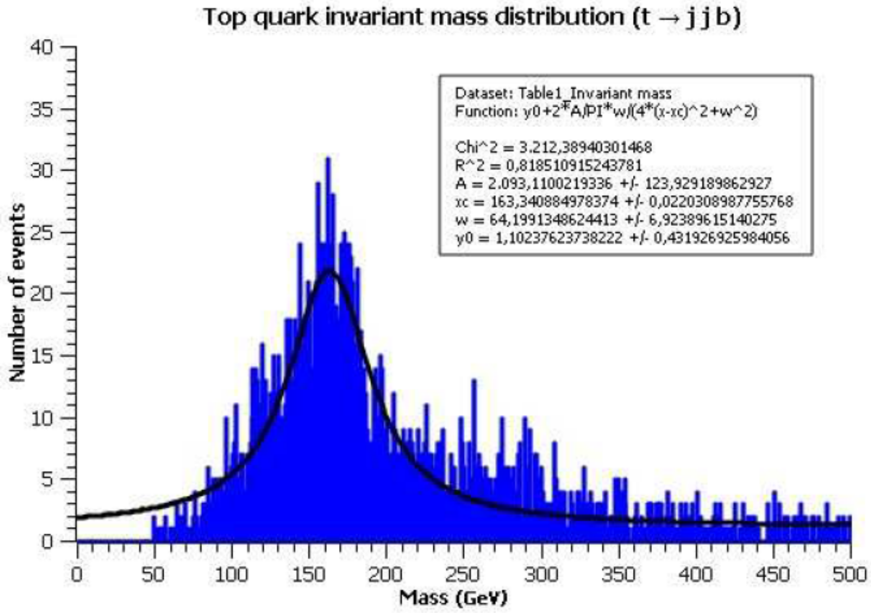


Figure 4.6: Top quark invariant mass frequency distribution from 0 to 500 GeV

We are going to approximate to a Lorentzian function [32]:

$$f(x) = y_0 + 2 \cdot \frac{A}{\pi} \cdot \frac{\omega}{4(x - x_c)^2 + \omega^2} \tag{4.13}$$

After fitting we obtain the following picture:



```
Dataset: Table1_Invariant mass
Function: y0+2*A/PI*w/(4*(x-xc)^2+w^2)

Chi^2 = 3.212,38940301468
R^2 = 0,818510915243781
A = 2.093,1100219336 +/- 123,929189862927
xc = 163,340884978374 +/- 0,0220308987755768
w = 64,1991348624413 +/- 6,92389615140275
y0 = 1,10237623738222 +/- 0,431926925984056
```

Figure 4.7: Top quark invariant mass frequency distribution from 0 to 500 GeV fitting with a Lorentzian function

The corresponding peak is the top quark invariant mass:

$$m_{inv} = 163.34 \pm 0.02 GeV \tag{4.14}$$

If we plot now with a bin size of 2.5 GeV:

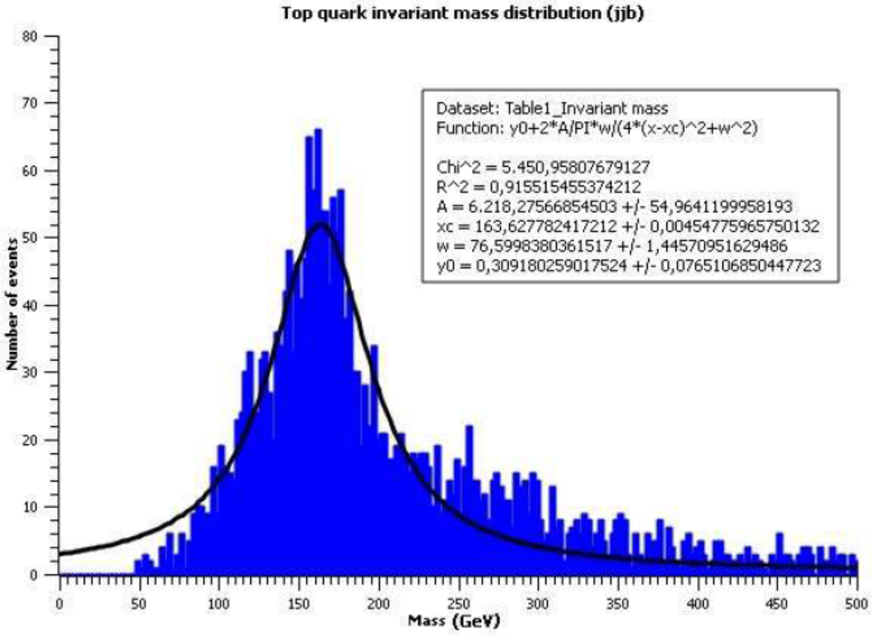


Figure 4.8: Top quark invariant mass frequency distribution from 0 to 500 GeV fitting with a Lorentzian function

We can calculate the mass as before and we obtain the following top quark invariant mass:

$$m_{inv} = 163.628 \pm 0.005 GeV \tag{4.15}$$

4.2.2 Transverse mass distribution

We plot using SciDAVis [31] the transverse mass frequency distribution:

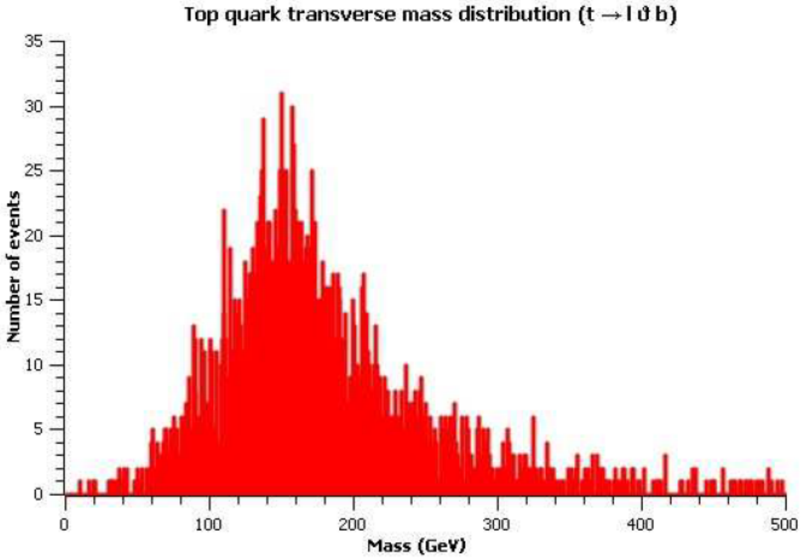


Figure 4.9: Top quark transverse mass frequency distribution from 0 to 500 GeV

If we take a look it is difficult to estimate where the cut off is so we are going to look closer:

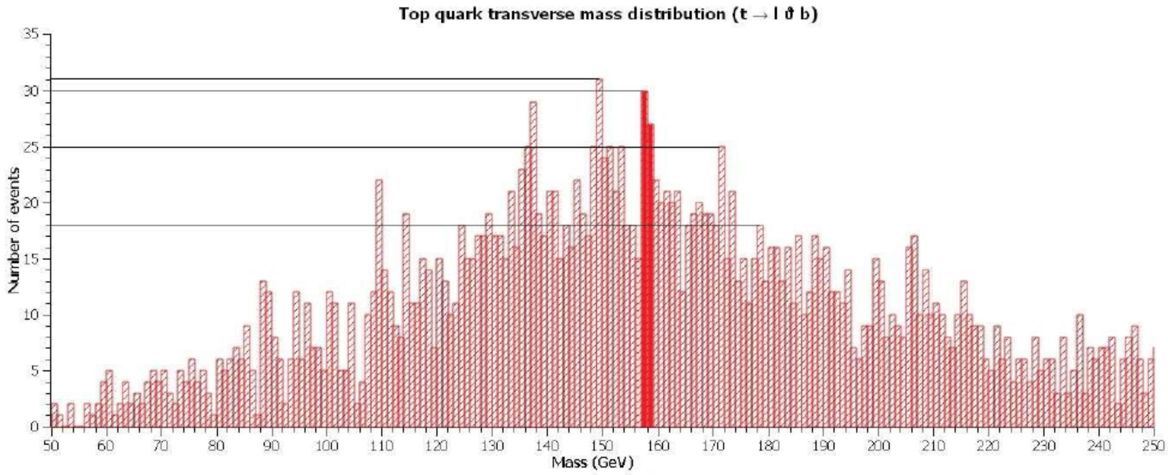


Figure 4.10: Top quark transverse mass frequency fistribution from 50 to 250 GeV. Bin size of 1 GeV.

Lines correspond to peaks to see their maximum events. We select the top quark mass as the mass highlighted because we can see the great reduction of events after this peak. So we deduce that the transverse mass is between 157 GeV and 159 GeV so:

$$m_t = 158 \pm 1 GeV \tag{4.16}$$

Now we are going to look a bin size of 2.5 GeV:

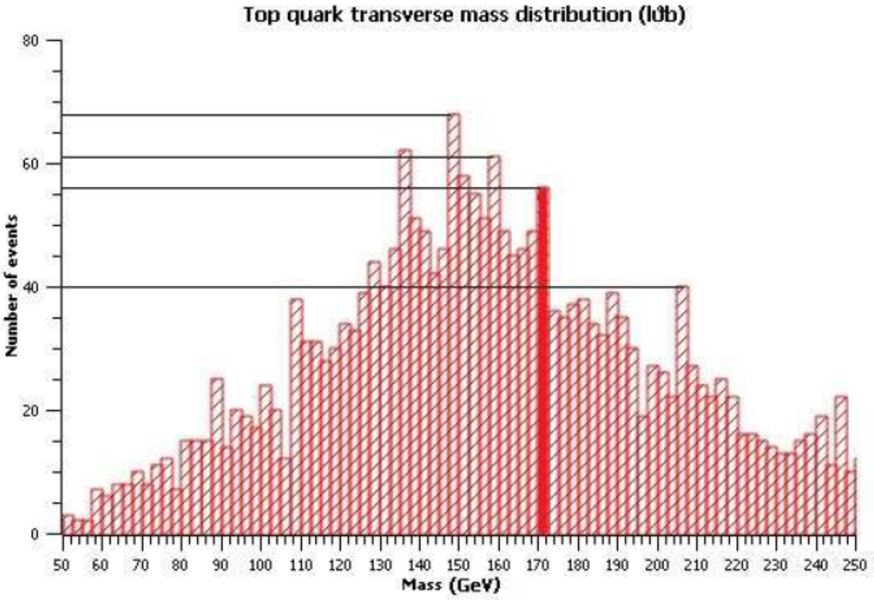


Figure 4.11: Top quark transverse mass frequency distribution from 50 to 250 GeV. Bin size of 2.5 GeV.

We are going to recalculate the transverse mass in this case. We observe that now there is a great reduction when mass is bewteen 170 and 172.5 GeV, so:

$$m_t = 171.25 \pm 1.25 GeV \tag{4.17}$$

Chapter 5

CONCLUSIONS

Theoretically we know that the Z boson mass is m_z=$91.1876 \pm 0.0021 GeV$ [13] and its mean lifetime is $\tau = 2.6 \cdot 10^{-25} s$ [33]. We obtained the following values and we calculated its corresponding mean lifetime:

- $Z \rightarrow e^- e^+$: $m_z^e = 90.5 \pm 0.5 GeV$ and $\tau^e = 3.3 \cdot 10^{-25} s$
- $Z \rightarrow \mu^- \mu^+$: $m_z^\mu = 91.5 \pm 0.5 GeV$ and $\tau^\mu = 2.2 \cdot 10^{-25} s$

We can calculate the average values:

$$m_z = 91.0 \pm 0.5 GeV \text{ and } \tau = 2.8 \cdot 10^{-25} s \tag{5.1}$$

So we observe that the theoretical value of the Z boson mass is between our error interval. If we compare the mean lifetime we observe that they have the same order of magnitude and they have only an relative error of 3.8%.

Theoretically we know that the W bosn mass is $m_w = 80.385 \pm 0.015 GeV$ [13] and we obtained a value of $m_W = 79.5 \pm 1.5 GeV$ in a $e^\pm \nu$ decay so we observe that the theoretical value is inside the error interval. We observe that in this case there is a bigger interval so it is not as accurate as in Z boson mass. There is a relative error or 1.1%.

In the case of top quark ($t\bar{t} \rightarrow b + \bar{b} + q + \bar{q} + l^\pm + \nu$) we know that theoretically it has a mass of $m_t = 173.1 \pm 0.6 GeV$ [13] and we obtained the following results:

- Transverse mass ($t \rightarrow b + l^\pm + \nu$)
  - $m_t = 158 \pm 1 GeV$ with bin size of 1GeV
  - $m_t = 171.25 \pm 1.25 GeV$ with bin size of 2.5 GeV

  We observe that there is a great difference between them. If we compare with the theoretical value we observe that it is not inside any of both interval error. In the first case it has a relative error of 8.7% and in the second case of 1.1 %. We can observe that there is a better result with bin size of 2.5 GeV.

- Invariant mass ($t \rightarrow b + q + \bar{q}$)
  - $m_t = 163.34 \pm 0.02 GeV$ with bin size of 1GeV
  - $m_t = 163.628 \pm 0.005 GeV$ with bin size of 2.5 GeV

  We observe that their values are quite close but there is a great difference with the theoretical value. We find a relative error of 5.6% in the first case and 5.5% in the second case.

We have deduced that in the case of W and Z bosons, invariant and transverse mass are confident methods and we can apply them. However, it is not the same in the case of Top Quark. One reason could be that in top quark there is more than two decay products. Another reason could be that our assumption is not always the good choice.

We have obtained that analysis of top quark sample is not as simple as in section 2.2. One solution could be analyze more data to improve measurements or take into account the SM background.

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Appendix A

VBA functions and subroutines

Function or Subroutine	**General Description**
Function *NObjects*	Counts how many objects (0,1,2,3,4,6) of a type are bewteen a starting and a finishing row. Both variables are inserted by the user.
Function *Jets*	Calculate light jets in a range given by the user.
Function *HeavyJets*	Calculate heavy jets in a range given by the user.
Sub *CopyPaste*	Copy first 15 cells and paste into another data sheet.
Sub *Delete*	Delete blank rows in a range of a data sheet.
Sub *CopyPasteRange*	Carry out *CopyPaste* for a range given by the user.
Function *Signature*	It is introduced number of objects and it compares with selected values given an input of TRUE if they are the same or FAlSE if this does not happen.
Sub *SingleEventJets*	Counts how many objects of each type are using *NObjects*, *Jets* and *HeavyJets*. Then *Signature* is used and if the result is true *CopyPaste* run.
Sub *JetStart*	*SingleEventJets* is produced for each event in a range given by an user.
Sub *InvariantMass*	Invariant mass is calculated using Equation 3.7 for each event in a range.
Sub *InvariantMassWxy*	Invariant mass is calculated using Equation 3.9 for each event in a range.
Sub *TransverseMass*	Transverse mass is calculated using Equation 3.14 for each event in a range.
Sub *InvTransvMass*	Calculates invariant mass using Equation 3.7 of an electron or a muon and a neutrino. Moreover it calculates transverse mass using Equation 3.14 of two light jets for each event in a range.
Sub *InvTransvMassTOP*	Calculates invariant mass using Equation 3.7 of an electron or a muon, a neutrino and a bottom jet. Moreover it calculates transverse mass using Equation 3.14 if two light jets and another bottom jet for each event in a range. Then botton jets are exchanged and both masses are calculated again.
Sub *SelectTOP*	Compares two values in a range and copies the smallest into another data sheet.

Table A.1: Description of each VBA algorithm used in the project