Rheinische Friedrich-Wilhelms-Universität Bonn

Advanced Laboratory Course

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E214: ATLAS

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Abstract

Contents

Chapter 1

Introduction

... This report closely follows the student lab manual from [1]. All the constants for Standard Model (SM) particles were taken from [2].

Chapter 2

Theory

2.1 The Standard Model

The Standard Model (SM) is one of the most tested theories in physics. It classifies all the known elementary particles into fermions and bosons and describes three of the four known fundamental forces of nature, strong, weak and electromagnetic force [2]. It is a gauge quantum field theory which contains the internal symmetries of the product group, $SU(3) \times SU(2) \times U(1)$. The fermions are spin-$1/2$ particles and are further classified into quarks and leptons, each with three generations. The bosons are categorized by their spin with gluons, photons, Z^0 and $W^{\pm}$ boson having spin 1 and the higgs boson with spin 0. Apart from the gluons and photons, the other bosons are massive. The elementary particles of the SM are shown in Fig. 2.1.1.

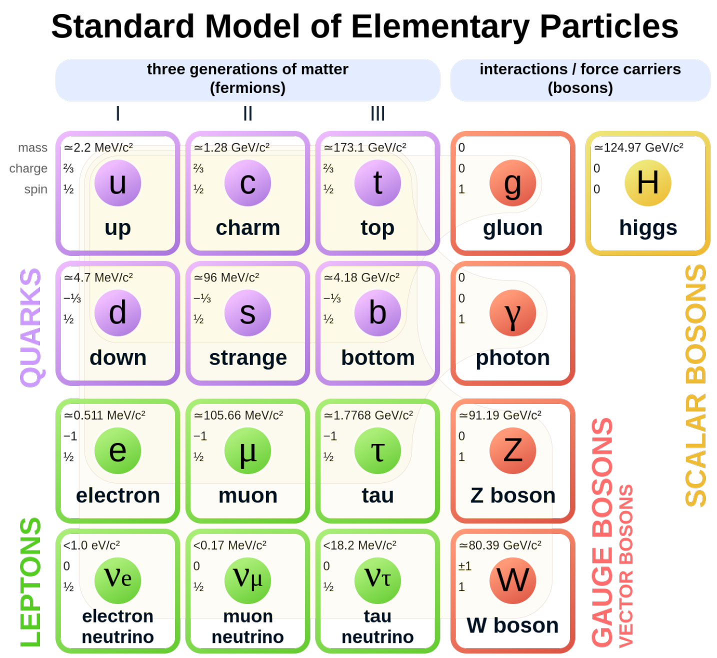


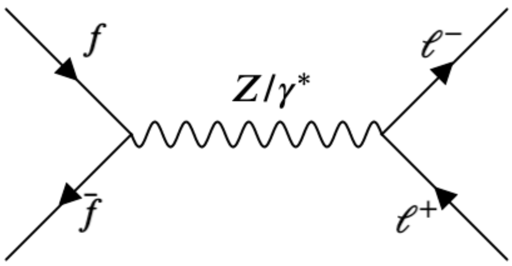
Figure 2.1.1: The Standard Model particles [3].

Despite its huge success, the SM fails at several fronts. It fails to explain matter-antimatter discrepancy, neutrino oscillations, dark matter and hierarchy problem to name a few. In order to test the SM and build a better theoretical framework that tries to answer all of the issues with SM, the Large Hadron Collider (LHC) was built between 1998 and 2008.

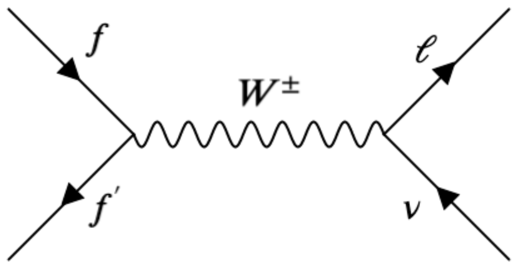
2.2 LHC and the ATLAS Experiment

2.3 The Heavy Gauge Bosons

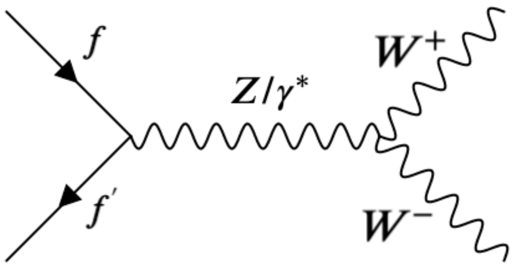
The $W^{\pm}$ and Z^0 are massive bosons which are responsible for the weak forces. The electromagnetic and the weak interactions are unified in the SM to give the electroweak force. The electromagnetic force arises due to $U(1)_Y$ (Y is hypercharge) gauge symmetry and the weak force arises due to $SU(2)_L$ gauge symmetry. After Spontaneous Symmetry Breaking (SSB), the $W^{\pm}$ and Z gain mass while the photon continues to be massless. In this experiment, our aim to is learn the methods of measuring the mass of the W boson. Some important vertices of weak interaction are shown in Fig. 2.3.1.



(a) Fermion anti-fermion going to Z boson or a virtual photon to give lepton anti-lepton pair.



(b) Fermion anti-fermion going to $W^{\pm}$ to give lepton (anti-lepton) and anti-neutrino (neutrino). This process is the weak Drell-Yan process.



(c) Fermion anti-fermion going to Z boson or a virtual photon to give $W^{\pm}$ pair.

Figure 2.3.1: Important weak interactions at LHC. Here f stands for fermion and l for leptons.

The mass of the Z boson has been measured with high precision at the LEP accelerator in the year 2006 [4]. Its mass was found to be $91.1876 \pm 0.0021\,\mathrm{GeV}/c^2$. Since the Z boson decay to leptons (as shown in Fig. 2.3.1a) gives the cleanest signal to reconstruct its invariant mass, these events are usually studied. However, in the case of W boson, which decay to $W \to e\nu_e$ or $W \to \mu\nu_\mu$, the invariant cannot be reconstructed directly. This is because neutrinos interact very weakly and are not detected. This makes measuring the mass of the W boson a challenge and it is also one of the less known parameters of the SM. As of writing this report, a high precision measurement by the CDF collaboration of W boson mass was made in April, giving a value of 80.433 ± 0.009 GeV$/c^2$ [5]. This result has a 7σ deviation from the SM prediction, suggesting inaccuracies in the calculations or possibility of new physics. Before this, the most precise measurement was made in 2018 and found to be 80.379 ± 0.012 GeV$/c^2$ [6].

There are two notable ways to measure the mass of the W boson. The first utilizes the variable $\mathrm{M_T}$, which is defined as

$$\mathrm{M_T} = \sqrt{2p_{T_e}p_{T_\nu}(1 - \cos(\phi_e - \phi_\nu))}, \tag{2.3.1}$$

where p_{T_e} and p_{T_ν} are the transverse momentum of the electron and neutrino respectively, ϕ_e and ϕ_ν are the azimuthal angles. If we consider the mass of the electron to be zero, $\mathrm{M_T}$ is equal to W mass. The distribution of $\mathrm{M_T}$ gives us a Jacobi peak at the W mass. The advantage of using this method is that the transverse of momentum of the W boson does not significantly affect the position of the peak.

The disadvantage is the use of p_{T_ν}, which as mentioned before, cannot be measured directly. Hence, it must be approximated using $\not{E}_T$, which is missing transverse momentum, given by

$$\vec{\not{E}}_T = -\sum_i E^i \sin\theta_i \vec{n}_{i,\perp}, \tag{2.3.2}$$

where E^i is the energy of the i-th entry in the calorimeter, θ_i is the polar angle of the entry and $\vec{n}_{i,\perp}$ is the unit vector pointing towards energy entry in the x-y plane. Which means, that in order to measure $\mathrm{M_T}$ accurately, $\not{E}_T$ has to be well calibrated.

The second method to measure the W mass is by studying the transverse momentum spectrum of the leptons using

$$\frac{d\sigma}{dp_T} = \frac{d\sigma}{d\cos\theta^*}\left|\frac{dp_T}{d\cos\theta^*}\right|^{-1} = \frac{d\sigma}{d\cos\theta^*}\frac{2p_T}{M_W}\frac{1}{\sqrt{1/4\ M_W^2 - p_T^2}}. \tag{2.3.3}$$

This gives a Jacobi peak as shown in Fig. 2.3.2. The peak is at half of W mass, therefore, one can measure this peak in order to deduce the W mass. However, the figure shows the ideal case, in which the W boson does not have an initial transverse momentum. As shown in the same figure, if W has an initial momentum, there is a spread in the distribution and a shift in the Jacobi peak. Other factors that can increase the spread are the resolution of the detector and W-decay width. However, the advantage of using this method is that it does not require the complicated calibration of $\not{E}_T$. In this experiment we use this method. An interesting side note, the recent high precision measurement from 2022 used the first method to measure the W mass [5].

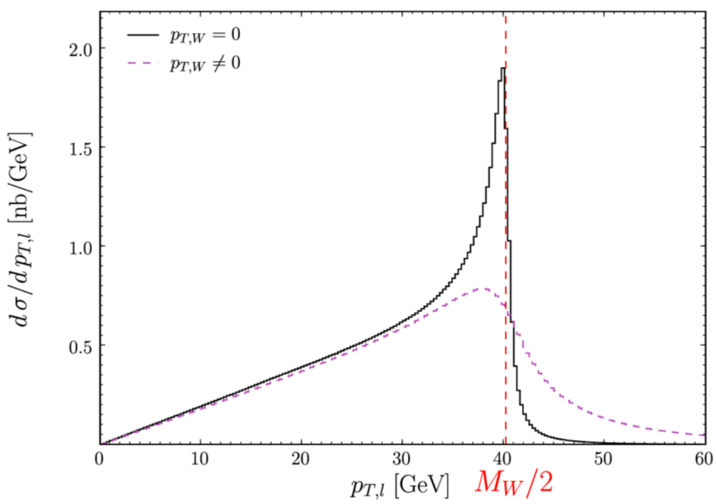


Figure 2.3.2: p_T spectrum of leptons from the $W \to l\nu$ decay. We see a Jacobi peak at half the mass of W boson [7].

Chapter 3

Pre-lab Questions

3.1 Part 2: Calibration of Electrons

1. Which value does the momentum of an electron have in the decay of a Z^0 boson $Z^0 \to e^+ + e^-$, if the Z^0 is at rest?

<u>Solution</u>:
Given that the Z^0 boson is at rest, $\vec{p}_Z = 0 \implies E_Z^2 = \vec{p}_Z^2 + m_Z^2 = m_Z^2$ so that $E_Z = m_Z$. This implies that the 4-momentum of the Z^0-boson is $p_Z = (m_Z, \vec{0})$. Now by conservation of 4-momentum, we know that $p_Z = p_{e^+} + p_{e^-} \implies p_{e^+} = p_Z - p_{e^-}$.
Now taking the dot product of p_{e^+}, we have that:

$$p_{e^+} \cdot p_{e^+} = m_e^2 = (p_Z - p_{e^-}) \cdot (p_Z - p_{e^-}) = m_Z^2 + m_e^2 - 2p_Z \cdot p_{e^-} = m_Z^2 + m_e^2 - 2m_Z E_e$$

$$\implies m_Z = 2E_e => E_e = \frac{m_Z}{2}$$

where the property $(p \cdot p) = E^2 - \vec{p}^2 = m^2$ was used.
To then determine the momentum of the electron, we use the energy-momentum relation again:

$$E_e^2 = \vec{p}_e^2 + m_e^2 \implies |\vec{p}_e| = \sqrt{E_e^2 - m_e^2} = \sqrt{\left(\frac{m_Z}{2}\right)^2 - m_e^2}$$

$$\implies |\vec{p}_e| = \sqrt{\left(\frac{91.18\text{GeV}}{2}\right)^2 - (5.11 \times 10^{-4}\text{GeV})^2} \approx 45.59\text{GeV}$$

where the mass of the electron was neglected.
Thus the momentum of the electron from a Z^0 boson decay at rest is $|\vec{p}_e| = 45.59\text{GeV}$.

2. How large is the momentum of tau leptons in the reaction $e^+ + e^- \to \tau^+ + \tau^-$, if the reaction takes place in the center-of-mass system (center-of-mass energy = 5 GeV)?

<u>Solution</u>:
We know that the mass of the tau lepton is $m_\tau = 1.776$ GeV. Given that the CoM energy is $\sqrt{s} = 5$ GeV, by conservation of energy we have that:

$$s = (2E_e)^2 = (2E_\tau)^2 = 4(\vec{p}_\tau^2 + m_\tau^2) \implies |\vec{p}_\tau| = \sqrt{\frac{s}{4} - m_\tau^2}$$

$$\implies |\vec{p}_\tau| = \sqrt{\frac{(5\text{GeV})^2}{4} - (1.776\text{GeV})^2} = 1.7595\text{GeV}$$

3.2 Part 3.1: W-Boson Measurement

1. As before, the analysis is based on ROOT trees. One of the tree variables is `ptw` - the estimated transverse momentum of the W boson candidate. This variable can be constructed from the other tree variables. Please think about how this could be done. The tree variables are listed in section B.

Solution:
Given that the weak interaction is described by $W \rightarrow l + \bar{\nu}_l$, we can calculate the transverse momentum of the W-boson from the transverse momentum of l and $\bar{\nu}_l$. The formula to evaluate this is:

$$p_{T_W} = \sqrt{p_{T_l}^2 + p_{T_\nu}^2}$$

which is derived from the conservation of 3-momentum.
This is defined in ROOT as `el_pt` and `etmis`, so that the transverse momentum of the W boson candidate can be calculated as such: $\sqrt{\texttt{el\_pt}^2 + \texttt{etmis}^2}$.

2. When fitting measurements to a linear function, the two parameters of a best fit straight line are y-intercept and slope. The errors on these parameters are typically correlated. Using these parameters for the error analysis will require a treatment that takes correlations into account. For example the simplest form of Gauss' error propagation law requires that the errors are uncorrelated. Please look up the correct form of the Gauss error propagation law in the presence of correlations. You will need that for the final error on the W mass. On the other hand, is it possible to minimize correlations by choosing an appropriate coordinate system?

Solution:
The Gauss error propagation law in the presence of correlations is given as such:

$$\sigma_f^2 = \left(\frac{df}{dx}\right)^2 \sigma_x^2 + \left(\frac{df}{dy}\right)^2 \sigma_y^2 + 2\left(\frac{df}{dx}\right)\left(\frac{df}{dy}\right)\rho_{xy}\sigma_x\sigma_y$$

where ρ_{xy} is the correlation coefficient which yields zero for uncorrelated errors. The correlation matrix is then defined with the variance σ_x^2, σ_y^2 in its diagonals with the correlations $\rho_{xy}\sigma_x\sigma_y$ in the off-diagonal components.
To minimize correlations, we can convert to an appropriate coordinate system in which the correlation matrix becomes diagonal. This will allow the cross terms to vanish.

3.3 Part 3.2: New Physics

1. What is the minimum invariant 4-lepton-mass, when the four leptons originate from a Z^0 pair? Why do you find 4-lepton-events with invariant mass beneath this threshold?

Solution:
In theory, the minimum invariant mass of the each lepton should be $m_Z/2$. In addition to the lowest order Feynman diagrams, there are two higher order diagrams where the photon is radiated by initial-state quarks, called Initial State Radiation (ISR), due to which there is a shift in the energy of the ingoing particles, leading to a distortion in the shape of the Z resonance curve. Therefore, the effect of ISR is reduce the effective centre-of-mass energy of the ingoing particles, which leads to some fraction of Z boson invariant mass to be beneath this threshold. Another possible reason can be that in the case of more than one Z boson, the other Z boson will not be on-shell due to kinematic reasons. Due to this, we get one Z boson and another virtual Z* boson. Hence, the mass of the 4 leptons, would be below the threshold.

2. Consider a Higgs boson which decays into two Z^0 bosons. How does the distribution of the 4-lepton-invariant-mass look like?

Solution:
The distribution will follow a Voigt function peaked at 125 GeV (Fig. 3.3.1).

3. Assume you have an ideal detector. What is the typical $\not{E}_T$ if a Z^0 pair has been produced and both Z^0 decay into electron or muon pairs? What $\not{E}_T$ will you expect when you have a real detector?

Solution:
In an ideal case, the expected $\not{E}_T$ is 0. In the case of real detector, $\not{E}_T$ will be non-zero due to inefficiencies in the detector and reconstruction algorithms. Further, not all muons and electrons will be detected. Or, one of the leptons could be extremely soft and not be detected at all.

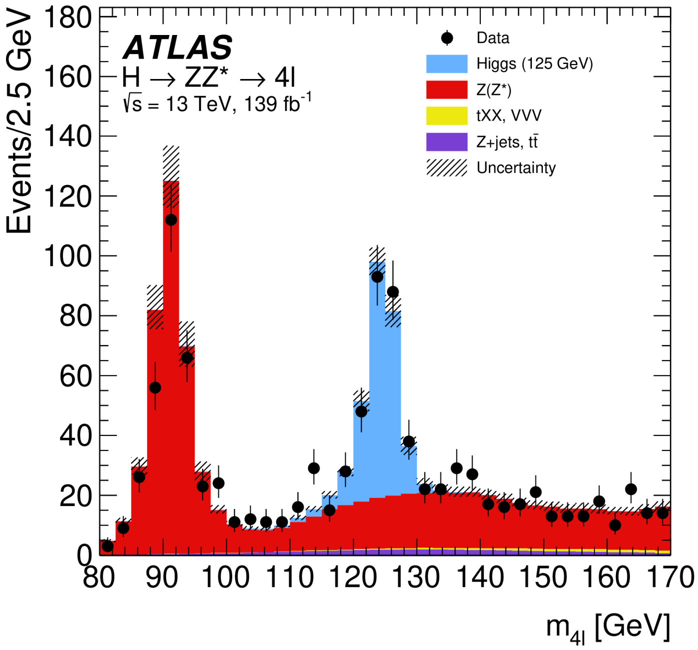


Figure 3.3.1: Higgs invariant mass distribution [8].

4. The Branching ratio of $t \to Wb$ is almost 100%. If you have a top anti-top pair in an event, both particles decay instantly via $t \to Wb$. If both W bosons each decay leptonically ($W \to l\nu$), one finds two leptons in the event. What could explain the occurence of four leptons in a $t\bar{t}$ event?

Solution:

- One of the leptons radiates a photon/Z* boson which gives lepton-antilepton pair, $l \to l + \gamma \to l + l^{+} + l^{-}$.
- b-quark can decay semi-leptonically, giving us hadrons plus a lepton (Fig. 3.3.2).

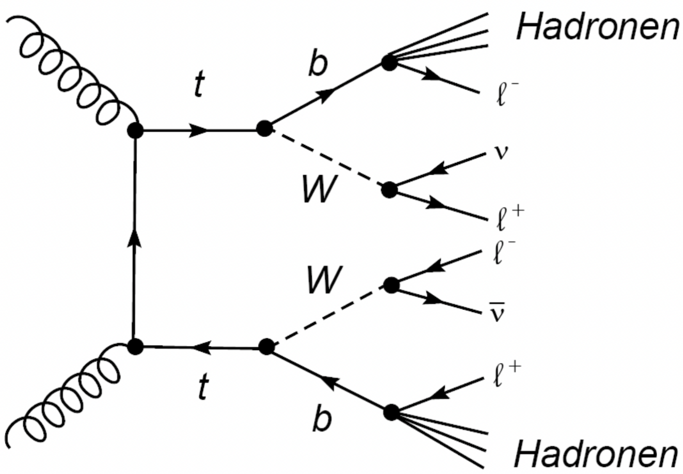


Figure 3.3.2: Top and b-quark decay process [1].

Chapter 4

Analysis

4.1 Part 1: ATLANTIS

In this part of the lab, we get familiar with the program `ATLANTIS`, which displays particle reactions in the ATLAS detector, graphically. ...

Next, we work with two of the assignments listed in the lab manual. Since we were allowed to pick the assignments on our own, we choose to work with the `mystery-035-f.dat` data set and `xxx.dat` data set.

4.1.1 Mystery Data set

In this data set, a pre-selection is applied, in which at least two leptons (e or μ) are required to be in each event. The goal of this exercise is to look at the graphics and identify various Standard-Model processes by studying them. Further, we must try to rule out certain processes, if any. In Fig. 4.1.1, we see the graphical view of event 13. Fig. 4.1.2, gives us the zoomed in view of the vertex for the same event. We start our discussion from the vertex.

A zoomed in view of the vertex shows that most tracks originate from the vertex, but some a reasonably far away from the vertex. The tracks originating far away from the vertex must come from a particle which has decayed after a certain period of time. This gives us the following three possibilities for the original particle: $\tau^{\pm}$ lepton, top quark or b-quarks (b-jet). Since W and Z boson decay almost immediately, the track reconstruction resolution would not be able to pick on the slight differences in the vertex due to those decays.

As these particles start heading towards the detector, we see that charged particles are bent based on their momentum and leave a “hit” in the inner detector. Some particles are too “soft” and hence their tracks disappear before reaching the ECAL. Looking at the deposition at the ECAL and HCAL, we see that most depositions between them align with each other. This indicates the presence of charged electrons and photons in jets. We know that b-jets contain leptons, as in 25% of all B decays, a lepton is produced. We can get this b-quark from the top quarks via $t \to W^{+}b$. The figure in the bottom half also shows the presence of isolated jets, without leptons. Since τ leptons can decay purely to hadrons and neutrinos, one of the ways to identify them is to look for collimated “mini” jets.

Two other interesting tracks we see in the ECAL and HCAL are the isolated depositions in ECAL which do not have a corresponding deposition in the HCAL. This means that these charged electrons can come from the following sources: photons, W bosons, Z bosons and τ leptons. The presence of missing energy in the event confirms the existence of neutrinos and hence, confirms the possibility of W boson decays. The other interesting track corresponds to the deposition in HCAL and then a track in the muon detector. This confirms the presence of muons in the event, which was probably surrounded by jets. Ths could be either due to top quarks or b-quarks.

We look at one more event in Fig. 4.1.3, event 12. In this event as well, we see all of the properties discussed above. Some thing which are slightly different is a higher number of isolated deposits in ECAL (without the corresponding deposit in HCAL) and the presence of two muons instead of a single one, both in the presence of jets. By selecting the missing energy track, we can look at the numbers. The following output was shown in the terminal:

```
ETMis:
 storegate key: MET_Final
```

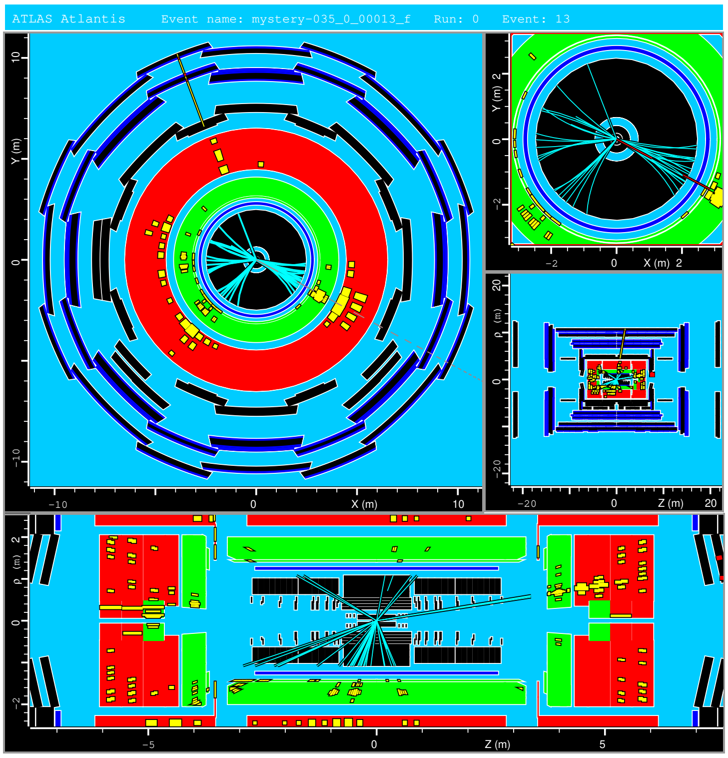


Figure 4.1.1: Event name: `mystery-035-f`, Event: 13.

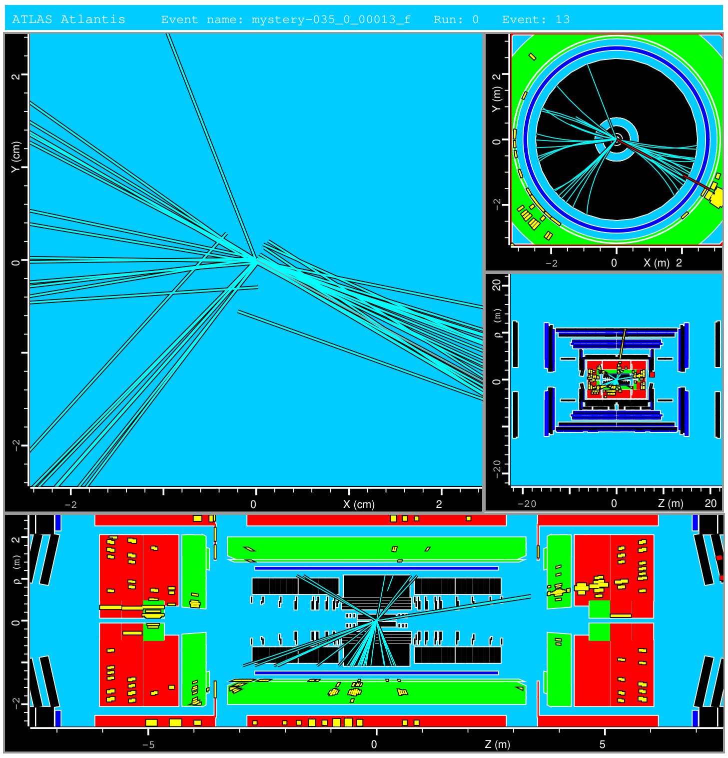


Figure 4.1.2: Event name: `mystery-035-f`, Event: 13.

```
Sum-ET   = 1087.585 GeV
ET-Mis   = 30.292 GeV
ETx-Mis = -30.055 GeV
ETy-Mis = 3.781 GeV
```
ϕ = 172.829°

Since the $\not{E}_T$ is quite high, we can confirm the existence of one or more neutrinos in the event. Based on the discussion above, it is not possible to rule out any SM process for two lepton events.

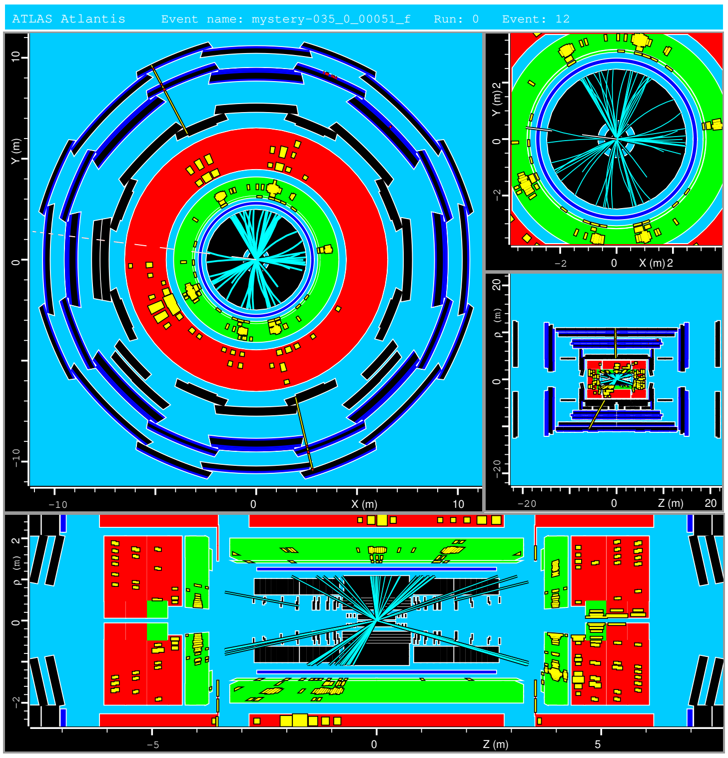


Figure 4.1.3: Event name: `mystery-035-f`, Event: 12.

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