E214: ATLAS

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Abstract goes here

1 Introduction

Introduction text

2 Theory

Our current best understanding of particle physics is the Standard Model of particle physics (SM). This model describes our discoveries of fundamental particles and their interactions with each other, mediated by fundamental forces. It furthermore describes the way these particles and forces combine to form atoms, from which many of the physical phenomena we encounter in everyday life can be explained. The main shortcoming of the SM however, is its inability to be united with gravity. That said, due to the relative weakness of gravity in comparison to the other fundamental forces, it rarely has an effect in particle physics and thus is mainly ignored (also in this paper).

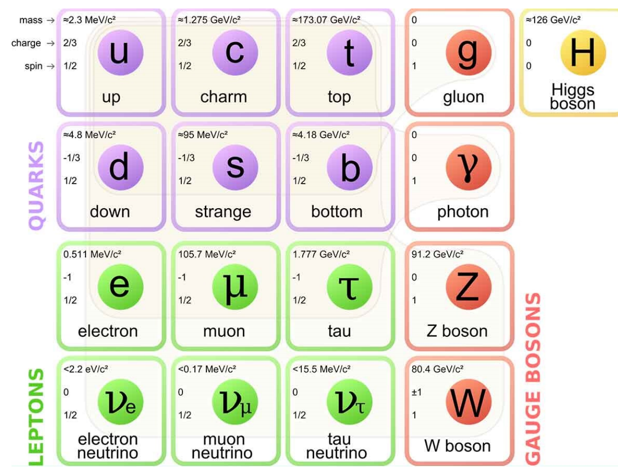

Figure 1: Illustration of the elementary particles in the SM. Quarks are in purple and Leptons in green, arranged into generation columns from left to right. The gauge bosons are in red, with the scalar Higgs boson in yellow.[?]

2.1 The Standard Model

Figure 1 give a summary of the particles in the SM with their most basic properties. Furthermore, there also exists anti-particles of many of these particles. An anti-particle, such as a positron, is identical to its particle (electron) apart from having the opposite electric charge. A neutral particle is often its own anti-particle such as the Z boson, though neutrinos have anti-particles which are merely distinct by having opposing spin projections. All matter particles and the W bosons have anti-particles while the rest are their own anti-particles. Quarks and leptons make up all the matter particles that have been discovered. These are given in three generations of particles, shown with the columns from left to right in the figure. Matter that is encountered everyday is largely structured from the first generation, namely the electron, electron neutrino, up quark, and down quark. For example, atoms are made up of electrons, protons, and neutrons, the latter two being composed of up and down quarks. The second and third generations are composed of particles which are otherwise exactly identical to their first generation counterpart apart from being heavier, the third generation being the heaviest of them all. This is only known to be true for the charged leptons (electron, muon, and tau) and quarks however. Though the neutrinos are known not to be massless, they have very small masses which have not been accurately measured. It is unknown which is the most massive and which the least.[?] Figure 2 illustrates the relative masses of the matter particles. The main reason why the second and third generation of particles are largely not existent in everyday phenomena is due to the requirement that higher energies are needed to produce these heavier particles. Furthermore, these heavier particles have shorter lifetimes due to their favourable decay into lighter particles, such as those in the first generation, due to the fundamental tendency of physical systems to higher kinetic energy states. Particle physics experiments need to be performed at increasingly higher energies in order to produce more massive particles that we do not readily observe. This is illustrated in Figure 3. It should

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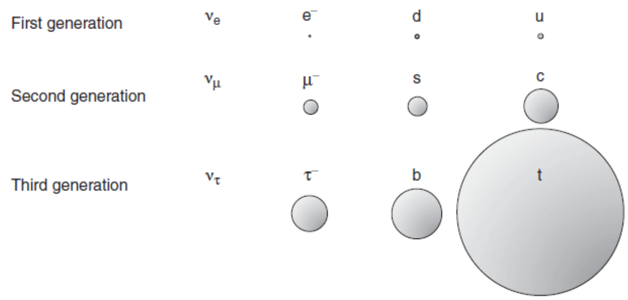

Figure 2: Illustration of the relative masses of the matter particles in their respective generations. The neutrinos are left blank to show that their masses are extremely small in comparison the other particles.[?]

be noted that though neutrinos are not seen, trillions of solar neutrinos pass through your body each second, oscillating between their three different flavours.[?] They are extremely difficult to detect due to the fact that they have a small mass and no electric charge.

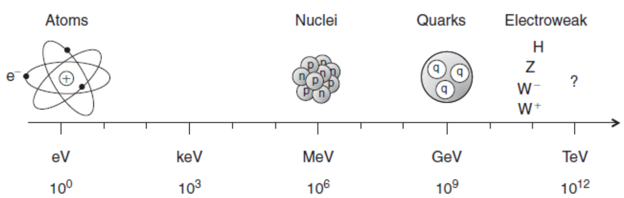

Figure 3: Illustration of the energies required to probe different structures and particles.[?]

Figure 1 also shows the fundamental forces in the SM which are all mediated via the exchange of a gauge boson. The most familiar of these is the photon γ which mediates the electromagnetic force, responsible for electricity, magnetism, and light. The photon interacts with all particles that have an electric charge and thus with all matter particles in the SM apart from the neutrinos. It also interacts with the W bosons as they are electrically charged. The gluon gauge bosons mediate the strong force, thus called as it is the strongest force and binds nuclei and hadrons together, explained in Section 2.2. The gluons interacts only with particles which have a so-called "colour" charge, another property of particles similar to electric charge. Only quarks have a colour charge and the eight differently coloured gluons. Next, the oppositely charged $W^{\pm}$ and Z bosons mediate the weak interaction, the weakest force apart from gravity. This force is responsible for radioactive decay and interacts with all matter particles in the SM. Finally, the Higgs boson is the most recently discovered particle which gives mass to all the matter particles in the SM by interacting with them.

2.2 Hadrons and the Strong Force

Though quarks are elementary in the SM, they cannot be observed as free particles. This is because quantum chromodynamics (QCD) of the SM, the theory of the strong force, states that colour is confined such that systems with a colour charge cannot propagate freely, termed *colour confinement.* Instead, only colourless composite particles can be observed. As a result, quarks form composite particles called hadrons which are bound by gluons. Hadrons generally form baryons, composed of three quarks, and mesons, composed of one quark and one anti-quark. The reason for the these two types is a result of there being three colours, red, blue, and green, for the quarks, and three anti-colours, anti-red, anti-blue, and anti-green, for the anti-quarks. Colourlessness is achieved by combining all three colours (or anti-colours) in a baryon, or a colour and its anti-colour in a meson, as shown in Figure 4. Protons and neutrons are examples of baryons, composed of two up quarks and one down quark (written as uud), and two down quarks and one up quark (udd), respectively. Furthermore, exotic hadrons, which

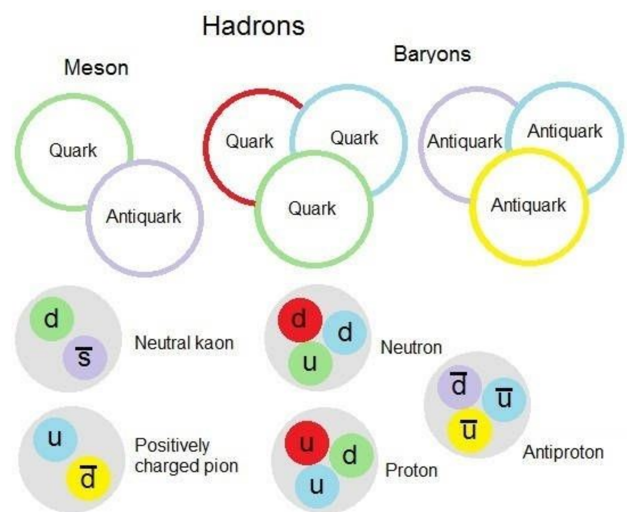

Figure 4: Colour confinement resulting in baryons and mesons, given with some examples.[?]

achieve colour confinement with more quarks, have been hypothesised and observed, though without explicit confirmation that the observations were indeed bound exotic hadrons. Examples include the tetraquark with two quarks and two respective anti-quarks, and the pentaquark with four quarks and an anti-quark. Exotic hadrons are rare however, due to the tendency of quarks to form and decay quickly into mesons and baryons.

2.3 Spontaneous Symmetry Breaking

2.4 Kinematics and Conservation Laws

In order to discover and identify new particles, particle physics experiments primarily analyse the kinematics of particle interactions. The universally fulfilled conservations of energy and momentum in a closed system are largely employed to calculate the mass of unknown particles, such that they can be identified. To do so, the masses and velocities of the other particles involved in the interaction need to be measured, which is easily achieved by analysing bubble chamber photographs in this case. To aid with particle identification, quantum number conservation laws are also employed. These include the conservation of electric charge, angular momentum, baryon number (the number of baryons in an interaction), lepton number, and strangeness. That said, some forces do violate some of these conservation laws, such as strangeness in the weak interaction. Ultimately however, both kinematics and conservation laws are the main techniques used to identify unknown particles and thus make discoveries of new particles. They will be used to analyse the photographs in this paper.

2.5 Extensions to SM

2.6 Parton Model????

3 Experimental setup

3.1 The ATLAS detector

To detect the various particles created by the collisions, the ATLAS detector consists of several layers.

The inner detector helps determining the particle paths as precisely as possible. Determining the momentum of charged particles is made possible by utilizing a solenoid magnet surrounding this system, creating a 2 T magnetic field in which a particle with charge q experiences a force of

$$\vec{F} = \frac{d}{dt}\vec{p} = q\vec{v} \times \vec{B},$$

from which it is possible to calculate the momentum.

- The innermost layer consists of semiconductor pixels (pixel detector, PD), which allow for precise reconstruction of vertices.
- The semi-conductor tracker layer (SCT) serves the same purpose, but with long strips that make covering a larger surface area more practical.
- The transition radiation tracker (TRT) consists of thin, long tubes (drift chambers) with inhomogeneous medium filling in the space between them. A particle passing through this medium emits transition radiation. The photons created this way, along with the particle itself, interact with the gas inside the tubes, causing ionizing. As there is a voltage applied to an electrode in the middle and the tube, the electrons are drawn to the electrode, contributing to an electric pulse. As the transition radiation is strongest for particles with high velocity, the strength of the signal can be used to identify the lightest particles, electrons and positrons.
- The solenoid superconductor magnet mentioned above, creating the magneti field $\vec{B}$ which is parallel to the colliding beams.

The layers surrounding the inner detector are the following:

- The electromagnetic calorimeter (ECAL) is made of accordion-shaped lead and stainless steel sheets responsible for interacting with the particles passing through, creating an electromagnetic shower. The liquid argon between the sheets is ionized by the particles passing through, and the created free electrons are drawn to a copper electrode. The signal strength can be related to the deposited energy. This calorimeter stops photons, electrons and positrons entirely. Hadrons and muons also deposit some energy here, but they pass through to reach the outer layers. The cooling system is a cryostat.
- The hadron calorimeter (HCAL) interacts strongly with the entering particles. The iron tiles induce hadronic showers. The particles thus created enter the scintillation tiles producing light, and these photons are carried away in an optical fiber to a unit which measures light intensity, from which the deposited energy can be calculated. The scintillation material is liquid argon, so a cooling system is used in this layer as well.
- The muon calorimeter is needed to measure the energy of the muons: these particles pass through all the previous layers with losing only part of their energy. This unit is supplemented by a larger magnetic system consisting of toroid magnets; thus the muon system is capable of determining the momentum independently of the inner layers. The tiles making up this layer consist of thin tubes filled with gas, and work on the principle of ionization, similarly to the TRT tubes.

4 Procedure

4.1 ATLANTIS

As our first task, we looked at examples in the event display software ATLANTIS. This way we got familiar with the working of the ATLAS detector. We had to complete two introductory tasks as described below.

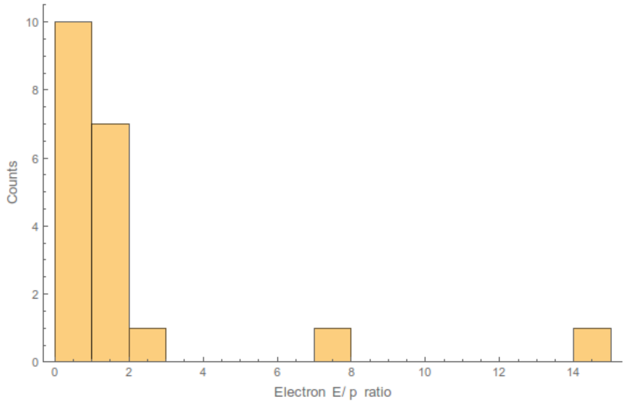

Figure 5: Electron E/p histogram.

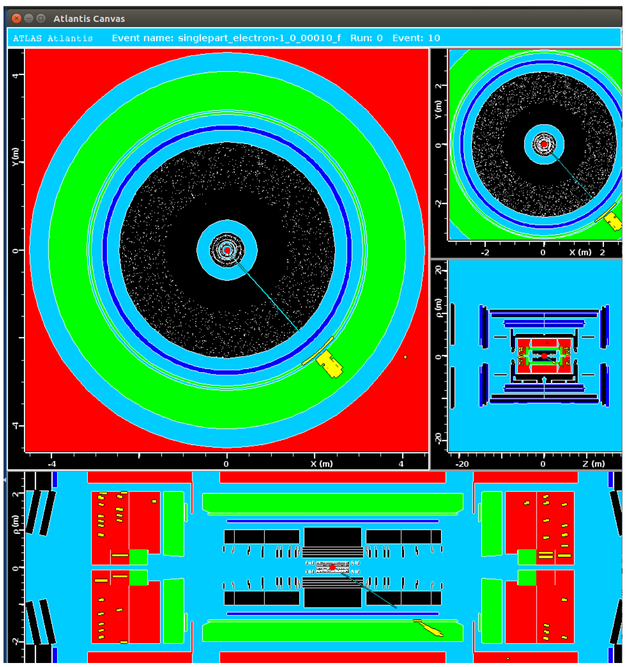

Figure 6: An (artificial) electron track as viewed in ATLANTIS.

4.1.1 Electron energy

We looked at the first twenty electron events in the learning data-set, determining the momentum by the track radius and the energy of the ECAL clusters by manually selecting the region. The results are summed up in Table 1. The histogram made of the E/p ratios is shown in Figure 5

4.1.2 Muon momentum comparison

As our second task, we compared the measured muon momentum in the muon spectrometer and the inner detector. Calculating the differences between the two methods (Table 2), we noticed some cases where the muon seems to have gained momentum. The average energy loss is 6.87 GeV.

#	I.D. (GeV)	ECAL (GeV)	E/p
1	26.2	54.7	2.09
2	22.78	35.2	1.55
3	244.35	223.2	0.91
4	N/A	N/A	N/A
5	N/A	N/A	N/A
6	66.67	78.3	1.17
7	7.55	56.6	7.50
8	129.82	162.9	1.25
9	3.27	47.7	14.59
10	79.01	66.2	0.84
11	95.93	78.7	0.82
12	37.4	30.6	0.82
13	89.35	86.5	0.97
14	235.24	242.3	1.03
15	105.14	105.3	1.00
16	N/A	N/A	N/A
17	28.62	28.1	0.982
18	53.41	46.4	0.869
19	32.92	64.3	1.95
20	105.64	80.8	0.765
21	N/A	N/A	N/A
22	93.52	82.1	0.878
23	113.98	92.7	0.813
24	155.35	283	1.82

Table 1: Electron task

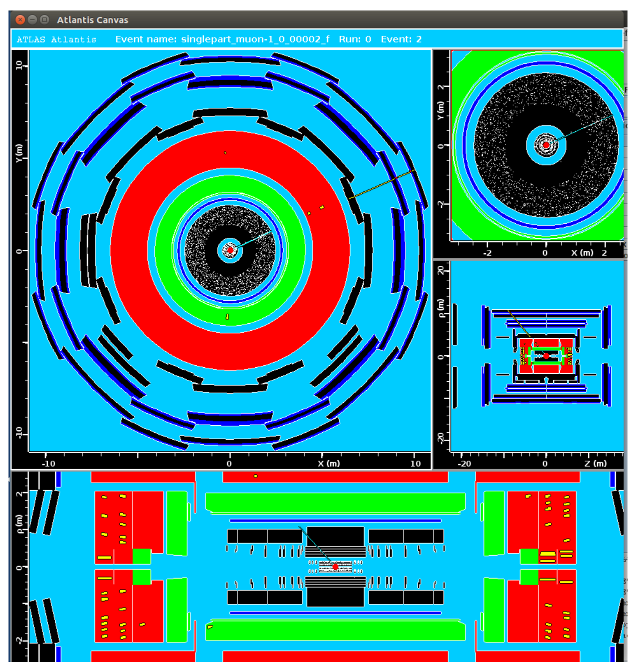

Figure 7: Artificial muon event as seen in ATLANTIS (the panel with quantitive informations has been cropped for better visibility).

#	I.D. (GeV)	M.C. (GeV)	Diff. (GeV)	η	ϕ°
1	85.28	53.92	31.36	1.437	21
2	43.4	43.83	-0.43	-0.767	25
3	241.37	237.02	4.350	-2.438	230
4	48.89	44.77	4.12	0.567	311
5	168.16	177.62	-9.46	-1.809	244
6	117.32	96.56	20.76	1.621	152
7	71.94	64.96	6.98	0.699	3.8
8	199.91	199.44	0.470	1.797	67
9	57.84	50.01	7.830	-0.287	241
10	71.1	0	71.1	1.181	312
11	100.75	94.11	6.64	-1.636	48
12	38.26	34.48	3.78	0.189	326
13	105.19	108.68	-3.490	1.163	224
14	236.12	263.61	-27.49	2.286	103
15	131.69	125.51	6.180	-1.763	255
16	152.24	157.69	-5.450	-1.874	27
17	35.23	32.18	3.05	0.395	326
18	54.19	50	4.19	0.229	336
19	84.75	68.09	16.66	0.773	260
20	104.26	107.98	-3.72	1.421	78

Table 2: Muon assignment. The first column shows the Inner Detector measured momentum values, the second column the muon calorimeter momenta, the third column the loss of momentum (negative values show an increase in momentum), the fourth column η, the pseudorapidity, the last column the azimuthal angle.

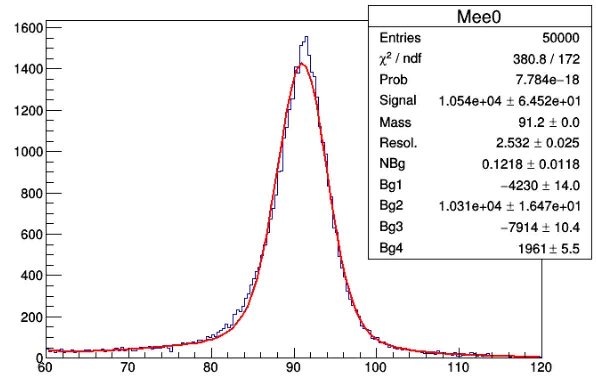

Figure 8: Final iteration fitting of Z^0

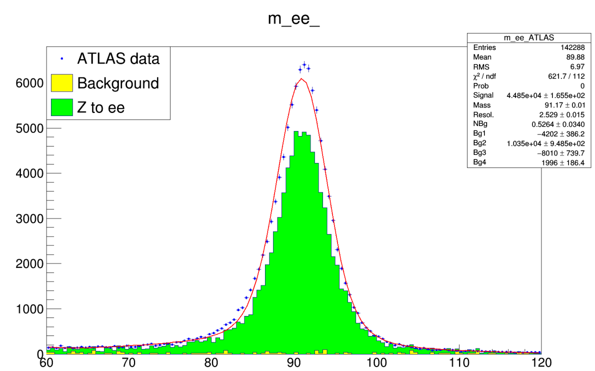

Figure 9: Z^0 mass from ATLAS data

4.2 Electron energy calibration

As the detector is not ideal, we need to calibrate the different regions to account for the differences in their characteristics. We chose sections of $\Delta\eta = 1.25$ and $\Delta\varphi = \pi/2$ $(-2.5 \leq \eta \leq 2.5, -\pi < \varphi < \pi)$. Using the well-known Z^0 mass, we used cuts to limit ourselves to each of these intervals and iterated the process of scaling the individual values. We also introduced a transverse momentum dependent correction, finally a constant shift. Our final *ElecCalib.C* contents can be seen in Section 7. The mass obtained after three iterations is 91.1975 ± 0.0204 GeV, with resolution 2.5315 ± 0.0251, we considered this precise enough for our purposes. Figure 8 shows our fitting.

4.3 Measurement of the W-boson mass

After setting up the electron energy calibration file, we tested it on real ATLAS data, as seen in Figure 9. The mass acquired here is in good agreement with the commonly accepted value. As our next step, we tried scaling the QCD background by comparing the ATLAS data points and our stack-plot. We decided that the scale factor $\alpha = 0.35 \pm 0.05$ gave a fair match (the error was

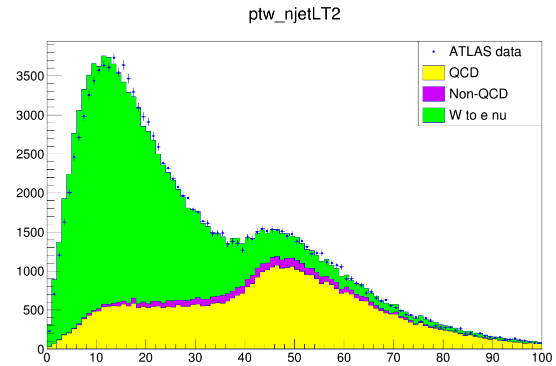

Figure 10: QCD scaled to achieve (by eye) a good match between the stack-plot and the data points.

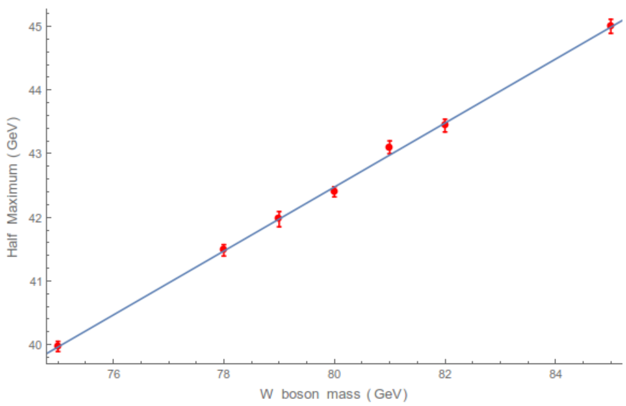

Figure 11: The gauge curve data points with linear fitting.

approximated by manual trial). Following the guide, we then set up a macro file to visualize the effect of our cuts on the different data sets of W-boson events with different masses, all at once. The measured half maxima and a linear fitting is shown in Figure 11. We found the linear fitting to be

$$\mathrm{HM}(m) = (0.50267 \pm 0.00867) \cdot m + (2.2613 \pm 0.6898)$$

For the real data, we obtained the half max to be at 43.04 ± 0.09, which gives, after inverting the previous relation, a mass of $m_{\mathrm{W}} = 81.12 \pm 2.03$ GeV.

4.4 Cross-check using ATLAS *ee* pair data

The gauge curve can be applied in the case of data for electron-positron pairs. Using the inverse of the gauge function again, we get

$$HM^{-1}(48.47 \pm 0.12) = 91.927 \pm 2.171\,\mathrm{GeV}, \quad (1)$$

in good agreement with the literature value, which supports our previous works.

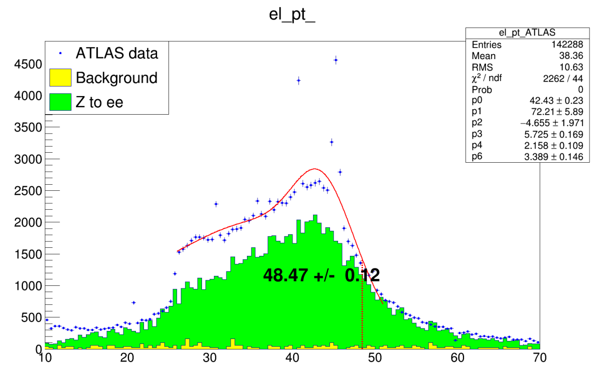

Figure 12: Plot showing the cross-check procedure.

4.4.1 Error sources

5 Results

6 Conclusion

References

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7 Code

```
#include "math.h"
#include "TMath.h"

double ElecCalib(double e_raw, double pt, double eta,
                 double phi, double etiso, double eoverp, double mindrjet)
{
  //double dummy=pt*eta*phi*etiso*eoverp*mindrjet;
  double energy = e_raw ;

if (eta>-2.5 && eta<-2.5/2){
    if (phi> -3.14 && phi< -3.14/2) energy = energy *(91.2/89.79)*(91.19/91.19)*(91.19/91.17);
    else if (phi> -3.14/2 && phi< 0) energy = energy *(91.2/89.76)*(91.19/91.23)*(91.19/91.18);
    else if (phi> 0 && phi< 3.14/2) energy = energy *(91.2/89.69)*(91.19/91.14)*(91.19/91.18);
    else if (phi> 3.14/2 && phi< 3.14) energy = energy *(91.2/89.6)*(91.19/91.09)*(91.19/91.13);
}
else if (eta>-2.5/2 && eta<0){
    if (phi> -3.14 && phi< -3.14/2) energy = energy *(91.2/89.84)*(91.19/91.17)*(91.19/91.15);
    else if (phi> -3.14/2 && phi< 0) energy = energy *(91.2/89.72)*(91.19/91.13)*(91.19/91.17);
    else if (phi> 0 && phi< 3.14/2) energy = energy *(91.2/90.11)*(91.19/91.3)*(91.19/91.25);
    else if (phi> 3.14/2 && phi< 3.14) energy = energy *(91.2/89.92)*(91.19/91.22)*(91.19/91.22);
}
else if (eta>0 && eta<2.5/2){
    if (phi> -3.14 && phi< -3.14/2) energy = energy *(91.2/89.86)*(91.19/91.13)*(91.19/91.16);
    else if (phi> -3.14/2 && phi< 0) energy = energy *(91.2/89.96)*(91.19/91.22)*(91.19/91.22);
    else if (phi> 0 && phi< 3.14/2) energy = energy *(91.2/89.73)*(91.19/91.12)*(91.19/91.16);
    else if (phi> 3.14/2 && phi< 3.14) energy = energy *(91.2/89.91)*(91.19/91.16)*(91.19/91.20);
}
else if (eta>2.5/2 && eta<2.5){
    if (phi> -3.14 && phi< -3.14/2) energy = energy *(91.2/89.92)*(91.19/91.23)*(91.19/91.22);
    else if (phi> -3.14/2 && phi< 0) energy = energy *(91.2/90.01)*(91.19/91.16)*(91.19/91.23);
    else if (phi> 0 && phi< 3.14/2) energy = energy *(91.2/89.82)*(91.19/91.16)*(91.19/91.18);
    else if (phi> 3.14/2 && phi< 3.14) energy = energy *(91.2/89.91)*(91.19/91.12)*(91.19/91.21);
}

if (fabs(pt)>0 && fabs(pt)<20) energy = energy*(91.19/89.26)*(91.19/90.04);
else if (fabs(pt)>20 && fabs(pt)<30) energy = energy*(91.19/90.13)*(91.19/90.79);
else if (fabs(pt)>30 && fabs(pt)<35) energy = energy*(91.19/90.51)*(91.19/90.92);
else if (fabs(pt)>35 && fabs(pt)<40) energy = energy*(91.19/90.68)*(91.19/90.86);
else if (fabs(pt)>40 && fabs(pt)<45) energy = energy*(91.19/91.32)*(91.19/91.1);
else if (fabs(pt)>45 && fabs(pt)<50) energy = energy*(91.19/92.34)*(91.19/91.75);
else if (fabs(pt)>50 && fabs(pt)<60) energy = energy*(91.19/92.31)*(91.19/91.92);
else if (fabs(pt)>60) energy = energy*(91.19/91.89)*(91.19/91.85);

energy = energy - 0.025;


  // if (fabs(eta)>1.5) energy = energy * 91.2/78.2;
  // else if (fabs(eta)>2.0) energy = energy * 91.2/85.4;
return energy;
}
```