ATLAS (Large Hadron Collider) Open Data Research Project
Teacher Guide

School of Physics and Astronomy, Queen Mary University of London

1 Introduction

The following information should be used alongside the 'Get Started' book from ATLAS. You may find that certain equations don't load initially, but you can refresh the page to load them. All words in **bold print** are defined in the Glossary.

The goal of this project is to understand the ways in which particle physicists analyse data and to give it a go yourselves.

1.1 Units in Particle Physics

You will be accustomed to using SI units in your school work, however in the world of particle physics they are not very useful. The sizes of these units are based on arbitrary figures which are applicable to more everyday measurements, however they tend to be much too small (for energy) or much too large (for mass) for quantities used in particle physics. So, particle physicists use units that relate to the physical quantities they are studying. For example, instead of using Joules, they use electron volts, eV. An electron volt corresponds to the work done on one electron as it is passed through a potential difference of 1 V. Particles measured at places like CERN are travelling very fast - close to the speed of light. So we need to consider them as being **relativistic**.

- Speed of light:
$$c = 2.99 \times 10^{8}\,\mathrm{m\,s^{-1}}$$
- Energy:
$$1\,\mathrm{eV} = 1.6 \times 10^{-19}\,\mathrm{J}$$
- Mass:
$$m = \frac{E}{c^2}$$
$$\Rightarrow \mathrm{Kg} = \mathrm{JC^{-2}} = \mathrm{eVC^{-2}}$$

For any system (a planet, a person, a particle, etc.) the total energy E, momentum p and mass m are related by the **relativistic** formula:
$$E^2 = p^2c^2 + m^2c^4$$

There are lots of 'c's in this equation and so physicists often set c and other physical constants to be equal to 1. These are called **natural units**. This means that we can treat energy, momentum and mass as being equivalent quantities in order to compare them. It is always possible to add values for c back in later. Using natural units here we can obtain kinematic equations which can be used to calculate particle quantities,
$$m^2 = E^2 - p^2$$

where p is momentum. So by knowing the energy and momentum associated with a particle one can calculate its **rest mass**.

Exercises

1. The Higgs boson has a mass of approximately 125 GeV, what is this in kg?

$$\begin{aligned} m &= 125\text{GeV} \\ &= 125\text{GeV} \times 10^9 \times \left(1.6 \times 10^{-19}\frac{\text{J}}{\text{eV}}\right) \Big/ \left(2.99 \times 10^8 \frac{\text{m}}{\text{s}}\right)^2 \\ &= 2.23 \times 10^{-25}\,\text{kg} \end{aligned}$$

(This uses the fact that $\text{J} = \text{kg}/\text{C}^2$.)

2. An electron has a mass of 9.1×10^{-31} kg, what is this in MeV?

$$\begin{aligned} E &= 9.1 \times 10^{-31} \times (2.99 \times 10^8)^2 \\ &= 8.14 \times 10^{-14} J \\ E &= 8.14 \times 10^{-14}/1.6 \times 10^{-19} \\ &= 508,468\,\text{eV} \\ &= 0.51\,\text{MeV} \end{aligned}$$

3. In the everyday-life version of momenta $p = mv$ we encounter a problem with massless objects like the photon, their momentum would be 0. What happens with the momentum in case of a massless particle in the special relativity version of momentum?

$$\begin{aligned} p &= \sqrt{\frac{E^2}{c^2} - m^2c^2} \\ &= \sqrt{\left(\frac{E}{c}\right)^2 - 0} \\ &= \frac{E}{c} \end{aligned}$$

1.2 The Standard Model

The world as we know it is made up of matter. But what is matter? We know that atoms make up everything, and atoms are made up of protons, neutrons and electrons. Protons and neutrons are then made up of quarks which are **elementary particles** (also called fundamental particles).

The Elementary particles are summarised in a table called The Standard Model as shown in Figure 1 which groups them into categories called generations or families:

There are 6 **flavours** of **quarks**; up, down, strange, charm, top, bottom. There are also 6 flavours of **leptons**; electron, electron neutrino, muon, muon neutrino, tau, tau neutrino. These are all **fermions**.

It also includes **force carriers** which are **bosons**. These are particles which are exchanged between matter and define the four fundamental forces: Strong, electromagnetic, weak and gravity. The most recent addition to the Standard Model is the Higgs boson which is the carrier particle for the Higgs field.

1. A mystery particle is found to have energy, $E = 230\,\text{GeV}$ and momentum, $p = 1.5 \times 10^{11}\,\text{eV}\,\text{c}^{-1}$. Find the mass of the particle, and then see if you can identify it using the standard model.

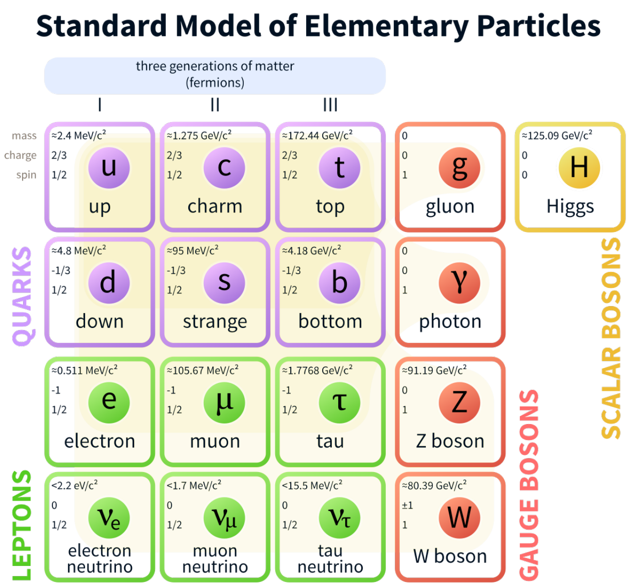


Figure 1: The Standard Model of Elementary Particles

$$
\begin{aligned}
mc^2 &= \sqrt{E^2 - p^2c^2} \\
&= \sqrt{(230 \times 10^9\ \text{eV})^2 - (1.5 \times 10^{11}\ \text{eV})^2} \\
&= 1.74 \times 10^{11}\,\text{eV} \\
&= 174\,\text{GeV}
\end{aligned}
$$

This corresponds to a top quark.

1.3 The Higgs Boson

The Higgs boson is the most recent addition to the standard model. It was theorised by François Englert and Peter Higgs in 1964, and they were awarded the 2013 Nobel Prize for it. Much work has been produced on it since in refining detection of it and physicists are gradually gaining a deeper insight into its mechanisms. It is colloquially known as the 'god particle' due to its role in giving particles their mass.

The mass of the Higgs was not part of the theory and so was unknown until it was first detected and measured. Since then, measurements have become far more accurate.

As a massless particle travels through a Higgs field it can become surrounded by a cloud of virtual Higgs particles causing it to travel slower through the field and gain mass. Only certain particles interact with the Higgs field and to different extents thus giving the range of masses existent in different particles.

A good analogy for the Higgs mechanism is depictedin Figure 2 and works as follows:

> There is a pub full of physicists and Einstein walks in. He wants to get to the bar at the other side of the room, but as he walks through the crowd, people want to talk to him and gather around him slowing him down. He becomes a more massive entity as he walks through and people gather around him. Not just anyone would have this effect on the crowd however, if a normal, uninteresting person were to walk to the bar, they would have no problems at all and go straight through without gaining any followers. A photon works like this.

This explained the unsolved problems associated with **Quantum Field Theory**. It dictated that all particles must be massless which was nonsensical as you couldn't then just add mass on to particles. The Higgs mechanism provided an answer for this.

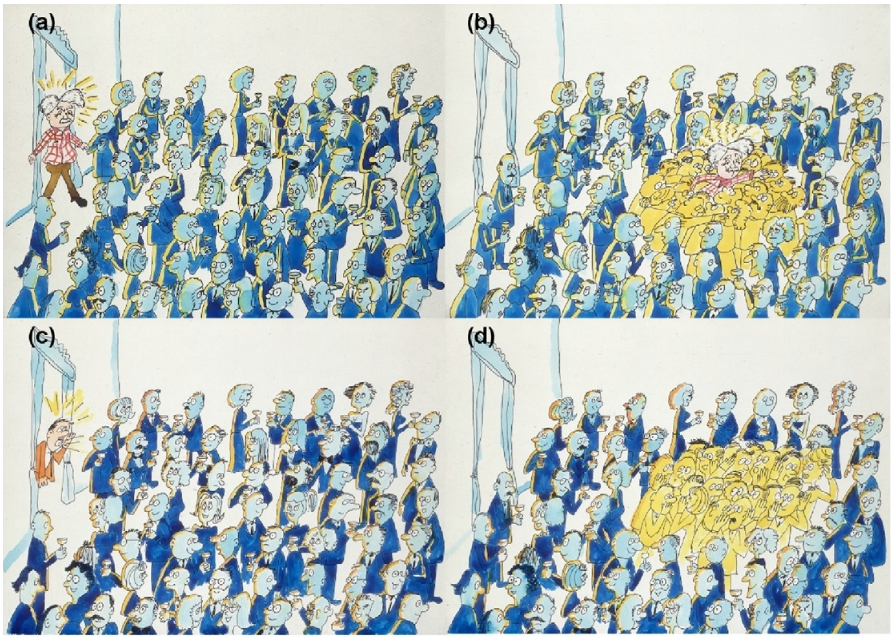


Figure 2: a,b) As Einstein makes his way through the crowd he attracts the attention of lots of people and becomes more massive. This corresponds to a particle gaining mass as it travels though a Higgs field. c,d) A message is passed through the crowd with people gathering together to share it. This is akin to the Higgs boson itself.

The Higgs boson itself can be compared to a generic clumping of people in the pub, think of a message be passed through the room from group to group (see Figure 2). It can be produced through a variety of interactions, the most common at the LHC is gluon-gluon fusion.

The Higgs can **decay** into various pairs of fermions or bosons and depending on the mass of the Higgs particle, different decays have higher and lower probabilities of occurring. These decay products are then detected and so signify the presence of a Higgs in an interaction. Each decay is characterised by a **branching ratio**. Essentially this gives the probability of a certain decay occurring over the other types. Figure 3 shows a graph of the different decays arranged by their branching ratios. The decays with the highest branching ratios aren't always the easiest to detect however.

The significance of the Higgs within the standard model led to a 40 year hunt for it. It had become a very important part of particle physics, but was yet to be observed. It would be the final piece of the standard model. This hunt motivated the construction of the Large Hadron Collider at CERN, designed specifically to be able to try to find it.

2 Particle Detection

The Large Hadron Collider (LHC) at CERN has four main particle detectors: ALICE, ATLAS, CMS and LHCb. These detectors are showered with the particles produced when the two beams of protons circulating around the LHC collide. Each layer of a detector has a specific function, but the main components are semiconductor detectors which measure charged particles and calorimeters which measure particle energy. The semiconductor detectors use materials such as silicon to create diodes - components that conduct electrical current in only one direction. Charged particles passing though the large number of strips of silicon placed around the proton beam collision point create a current that can be tracked and measured.

Calorimeters are calibrated to be either electromagnetic or hadronic. The former will detect particles such as electrons and photons, while the latter will pick up protons and neutrons. Particles entering a calorimeter are absorbed and a particle shower is created by cascades of interactions. It is the energy deposited into the calorimeter from these interactions that is measured. Stacking calorimeters allows physicists to build a complete picture of the direction in which the particles travelled as well as the

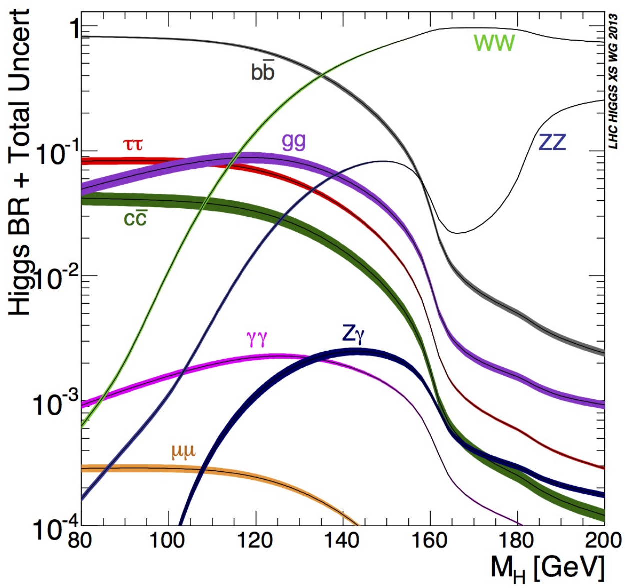


Figure 3: Graph summarising branching ratios of various Higgs decays.

energy deposited, or determine the shape of the particle shower produced.

ATLAS and CMS are also designed to detect muons, particles much like electrons but 200 times more massive, which pass right through the other detection equipment. A muon spectrometer surrounds the calorimeter, and functions in a similar way to the inner silicon detector.

However, there are often particles which are impossible to detect on their own due to short lifetimes, neutral charges etc. However it is possible to infer their existence by detecting their subsequent interactions and decays and extrapolating information on their position, mass or energy from these and tracking back their paths. It is almost like tracing its footsteps back through time. In order to do this it is necessary to build up a relatively accurate map of those particles that can be detected. These interactions are discussed in terms of their **vertices**, with the **primary vertex** being the initial proton collision with the highest **transverse momentum**.

2.1 ATLAS

ATLAS is one of two general-purpose detectors at the LHC. It investigates a wide range of physics, from the discovery of the Higgs boson to the search for extra dimensions and particles that could make up **dark matter**. Beams of particles from the LHC collide at the centre of the ATLAS detector making collision debris in the form of new particles, which fly out from the collision point in all directions. Six different detecting subsystems arranged in layers around the collision point record the paths, momentum, and energy of the particles, allowing them to be individually identified. Figures 4 and 5 show schematics of the detection system at ATLAS.

A large magnet system bends the paths of charged particles so that their momenta can be measured. This works because particles with more momentum bend less than those with greater momentum as they are in the magnetic field for less time. The particles bend according to the following equation.

$$\vec{F} = Q\vec{v} \times \vec{B}$$
$$|F| = |Q|\,|B|\,|v| \sin\theta$$

Where $\vec{F}$ is the force acting on the particle, Q is the charge of the particle, $\vec{v}$ is the velocity of the particle, $\vec{B}$ is the strength of the magnetic field and θ is the angle between the particle's velocity and the magnetic field. The momentum is then calculated by measuring a particle's **gyroradius**, this can then be related to the momentum by the following equation

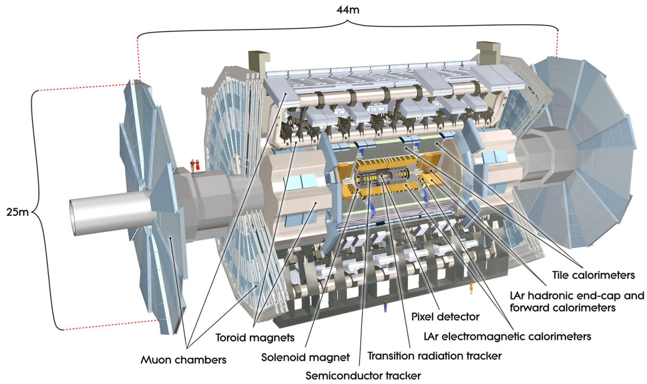


Figure 4: A schematic of the ATLAS detector. This diagram shows it to scale with two people standing on it for size comparison.

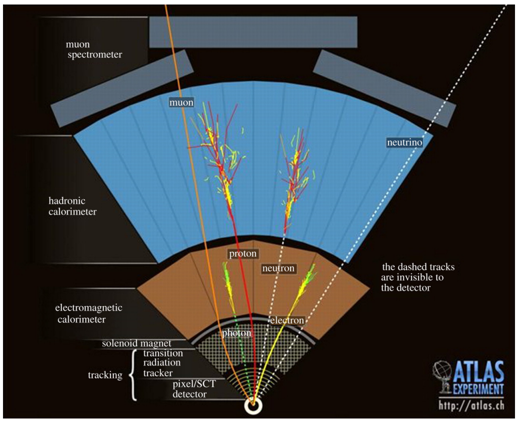


Figure 5: A cross section of the detector showing where each particle would be detected.

$$r_g = \frac{p_\perp}{|Q|B}$$

where $p_\perp$ is the component of momentum perpendicular to the direction of the magnetic field.

Exercises

1. What is the force on a proton travelling at 99% the speed of light at 45° to a 4 T magnetic field?

$$\begin{aligned} F &= QBv\sin\theta \\ &= 1.6\times10^{-19}\times4\times0.99\times2.99\times10^{8}\times\sin 45 \\ &= 1.6\times10^{-10}\,N \end{aligned}$$

   This formula is correct even in the relativistic case, though the definition of a force somewhat changes to $\vec{F} = \frac{d\vec{p}}{dt}$ where $\vec{p}$ is the relativistic momentum.

2. Calculate the gyroradius of a 1 MeV electron in a 2 T magnetic field if its velocity is:

   (a) Directed along the magnetic field.
   Since there is no motion perpendicular to the magnetic field, the Lorentz force is zero and therefore so if the gyroradius. The particle will stream along the magnetic field direction.

   (b) Perpendicular to the magnetic field.

$$\begin{aligned} p_\perp &= \sqrt{E^2 - m^2} \\ E &= 1\times10^{6}\times1.6\times10^{-19} \\ E^2 &= 2.56\times10^{-26} \\ m^2 &= \left(9.1\times10^{-31}\right)^2 = 8.28\times10^{-61} \\ p_\perp &= 1.6\times10^{-13}Kgms^{-1} \\ r_g &= \frac{p_\perp}{qB} \\ &= \frac{1.6\times10^{-13}}{1.6\times10^{-19}\times2} \\ &= 500\text{Km} \end{aligned}$$

   (c) At 30° to the magnetic field.

$$\begin{aligned} r_g &= 500\times10^{3}\times\sin 30 \\ &= 250\text{Km} \end{aligned}$$

The interactions in the ATLAS detectors create an enormous flow of data. To digest the data, ATLAS uses an advanced **trigger system** to tell the detector which events to record and which to ignore. Complex data-acquisition and computing systems are then used to analyse the collision events recorded. At 46 m long, 25 m high and 25 m wide, the 7000-tonne ATLAS detector is the largest volume particle detector ever constructed. It sits in a cavern 100 m below ground near the main CERN site, close to the village of Meyrin in Switzerland. More than 3000 scientists from 174 institutes in 38 countries work on the ATLAS experiment.

3 Histogram Analyser

Here you can take on the role of a real particle physicist and play with some real data from ATLAS using the Histogram analyser. The histograms give data from W boson pair production from Higgs decay - the signature process for identifying Higgs, and three background processes, WW, $t\bar{t}$ and Z (these are separate processes which have similar signature products to the desired Higgs process).

The signature process: $H \to W^+W^-$ goes on to decay to pairs of particles (quark-antiquark, $q\bar{q}$, lepton-antineutrino, $\ell^-\bar{\nu}$, antilepton-neutrino, $\ell^+\nu$) and is one of the most likely decays for a Higgs. In this case we are looking for the following process:

$$H \to W^+W^- \to \ell^-\ell^+\nu\bar{\nu}$$

where the leptons are electrons or muons here. It is identified by an isolated lepton with high **transverse momentum** (p_T). The *Get Started* book then goes into more detail about the background decays and how they are identified. The *Separate Signals* tab describes how you can analyse the signal data to help you know which parts of each graph to cut to increase signal significance and summarises characteristics of each process.

3.1 Significance

Significance is introduced to quantify the probability of a statistical fluctuation expected to observe a certain events or more when you know how many background events you expect. It therefore measures the liklihood that the number of events you observed were just a statistical fluke or whether some other process may be present. The idea is to get as high a **significance** as possible for the H to WW decay, thereby minimising contributions from background decays.

In large counting experiments we use Poisson statistics, which tell us that the standard deviation of the number of events should go as $\sqrt{N_k}$ where N_k is the number of events of type k.

Exercise

1. Flip a coin M times (e.g. 10) and count the number of heads. Repeat this a few times (e.g. 5) and calculate the mean and standard deviation of the number of heads in each try. Is the mean number of heads consistent with the expected value pM, where $p = 0.5$ is the probability of landing heads, and the standard deviation around $\sqrt{pM}$?

2. Retry the experiment this time with a dice, i.e. changing p, and compare again with the theoretical result.

From this fact we can calculate the significance (in units of standard deviations or σ) by using the approximate formula

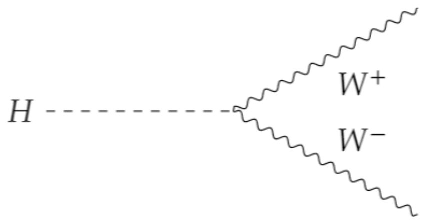
$$z = \frac{\text{Number of signal events}}{\sqrt{\text{Number of background events}}} \tag{1}$$

In Particle Physics, for there to be considered evidence of a new result requires at least 3σ and for a discovery they have to be at least 5σ, corresponding to a 1 in 3.5 million chance of simply being down to statistical fluctuations. By making **cuts** on the different histograms it is possible to filter the total data for each background decay and possibly increase the significance of the signature decay.

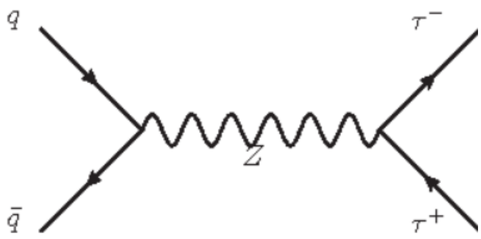
3.2 The Higgs Processes

As previously explained, the Higgs field exists as a way to give mass to the particles of the Standard Model, through their interactions (or couplings) with the Higgs field as they travel. This is important as it means the particles themselves do not need to have an inherent rest mass and this allows our theory of the standard model to work. Higgs bosons are excitations of the Higgs field and their masses is directly related to the how strongly they interact with (or couple to) the Higgs boson.

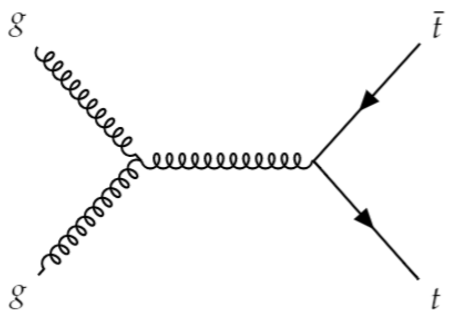
The Higgs boson was discovered in 2012 and was found to have a mass of 125 GeV and found discovered using the $H \to W^+W^-, ZZ, t\bar{t}$ and $\tau^+\tau-$ decay channels; among others. With the open data histogram analyser you are to try isolate specifically $H \to W^+W^-$ and try to distinguish them from any background, that is, any other particles created by the proton-proton collision and that look like candidates for a Higgs boson, but are not. The specific backgrounds you are looking at removing are $t\bar{t}$, $\tau^+\tau-$ and ZZ productions. Figure 6 shows Feynman diagrams for the Higgs decay and 3 possible background processes. Although these events have the same final state particles, they can be distinguished by looking at the properties of the particles involved in the events and checking if they are typical of a Higgs boson decay. If not, we choose to discard the event and hence likely increase the purity of our data.



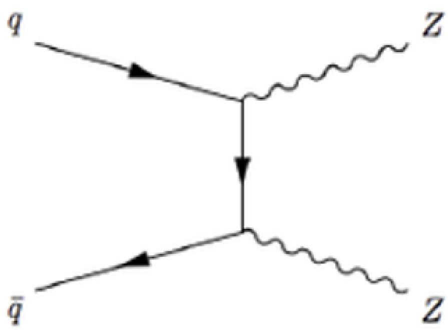
(a) H $\to WW$ production



(b) $\tau^+\tau-$ background



(c) $t\bar{t}$ background



(d) ZZ background

Figure 6: Feynman diagrams showing the WW decay channel for the Higgs boson (a), and background events that produce 'Higgs-like'signal (b), (c), and (d).

When looking at the $H \to W^+W^-$ channel, we generally have that each of the W bosons then go on to decay into a lepton (or antilepton) and a neutrino (antineutrino). If the decay was one of a Higgs particle we know that the invariant mass (or the mass if all of the particles were at rest) should add up to that of the Higgs boson. However, we have some problems with simply just adding up the masses and directly identifying a Higgs particle. As you will have learnt in your physics lessons, in any interaction of more than 2 bodies, the energy that each one leaves with is not fixed and to top it off pesky neutrinos leave the detector without letting us know how much energy they've taken with them due to their weakly interacting nature.

When performing cuts on the data to try and isolate the Higgs processes we have access to the following variables

1. **Leptonic Decay Channel** Because the tauon has such a short lifetime it typically decays before it is detected and so $W \to \tau$ typically also contains electrons and muons. We then choose to restrict the W decays to both electrons, both muons or one of each, for simplicity.

2. **Reconstructed Dilepton Mass** This is the energy (hence mass and they move at relativistic speeds) that the two leptons carried away. We know this must be less than 125 GeV and that together with missing momentum of the neutrinos this should add up to the Higgs mass.

3. **Are Jets B-Tagged?** In the simplest decay scheme, no b jets (b quarks that then break up and shower into hadronic jets) are produced in $H \to WW$. However, quantum mechanics means that

the is a small probability that one is produced in a more complicated interaction. This is called a higher order interaction.

4. **Total Lepton Transverse Momentum and Missing Transverse Momentum** Total Lepton Transverse Momentum and Missing Transverse Momentum: As the protons are collided head-on the overall transverse momentum (in the direction of the cross-section of the detector) is 0. So, any overall momentum in the leptons is due to the neutrinos leaving the detector with a transverse momentum such that overall, it is conserved.

3.3 Find the Higgs

Now use the *Find the Higgs* tab to isolate some Higgs processes. As you're going note down the cuts you have made and the effects they have and take screenshots of the graphs as you go. Try not to just use trial and error, but instead work out exactly which cuts you need to make and why these are making a difference to the significance. As explained in the *Get Started* book, you can separate the signals in order to see what characteristics each signal has on each graph.

Compare the results you obtain from the real and simulated data and see if there is any difference and if so, why that might be.

3.4 BSM Physics

All in all, the with the inclusion of the Higgs, we have the current model of physics – the Standard Model. This is mathematical framework of this allows us to describe in incredible detail processes in the strong, weak and EM forces. Such predictions are made by programming and numerically solving many tedious calculations. The exciting part, however, is that these results for the most part agree with our predictions for how the universes should behave.

Although, something is not quite right... you may wonder what happens with the most well know force of all - gravity. Your concern is well justified. To date theorists do not know how to well formulate a particle for gravity (so that it would be the boson of a quantum field) in a way that is compatible with quantum field theory. The failure to describe gravity is just one of the shortcomings of the Standard Model. It also fails to predict that neutrinos do in fact have mass, nor does it tell us anything about dark matter.

An easy way to extend the Standard Model is to simply add in new forces, these theories are appropriately called Beyond the Standard Model (BSM) theories. One such force could be one that mediates the conversion of dark matter into matter and vice versa; the same way the W bosons allow leptons to couple to quarks. The specifics of what we should look out for depend on the new theory. A simple theory would be to have a new boson appearing at above the energy at which the weak and electric forces become unified (called Electroweak unification). As top quarks have such a large mass, we would expect it to couple highly to this new boson and because they have a mass close to the Electroweak unification energy, then we can expect to see some new physics. Suppose we predict a new boson Z' with an energy

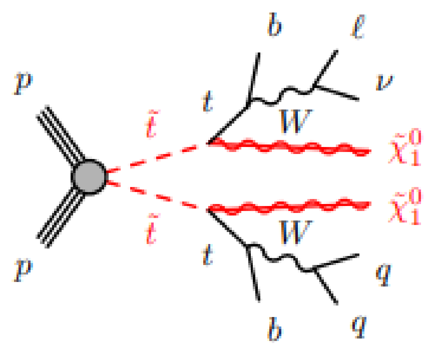


Figure 7: A Feynman diagram for a possible new physics decay, via a new boson Z'.

of 1 TeV that decays into a top-antitop pair along with a few dark matter particles. As the dark matter interacts very weakly, we would expect it to pass through the detector, leaving a large missing transverse momentum. Additionally, we would expect very energetic leptons coming out of the decay and top-tagged or b-tagged jets (from sequential decays of top quarks into b quarks).

Exercise

1. Why is it that at a centre-of-mass energy of $\sqrt{s} = 13$ TeV we are not guaranteed to produce a Z' of 1 TeV in a proton-proton collision, were it to exist

   The proton-proton collision really involves the interaction of two quarks within the protons, as such each only carries some fraction of the momentum of each proton x, there is no guarantee that in any given interaction the quarks that interact carry enough of the CoM energy to produce the new boson.

2. For a top-quark mass of 0.17 TeV, for the decay $Z' \to t\bar{t}$+Dark Matter in Figure 7 what limit could be put of the mass of the supposed dark matter particle?

$$E_i = 1\,\text{TeV}, E_f = 2(0.17)\,\text{TeV} + 2(m_{\text{DM}})$$
$$m_{\text{DM}} = (1 - 0.34)/2 = 0.33\,\text{TeV}$$

3. Suppose 35 'signal-like' BSM events are observed, in a total 10,000 events. What deviation from the standard model would this represent?

$$\#\,\text{signal} = 35, \#\,\text{bkg} = 10,000 - 35 = 9,965$$
$$\sigma_{\Delta\text{SM}} = \frac{35}{\sqrt{9,965}}$$
$$\sigma_{\Delta\text{SM}} = 0.35\,(2s.f.)$$

   In line with expectations of the Standard Model. That is, there are not enough events to rule out the presence of these new physics signals simply being a statistical fluctuation in the amount of background, or just poor event reconstruction.

4 ROOT (optional)

It is possible to analyse the data that ATLAS produces using a piece of software called ROOT. ROOT was designed by scientists at CERN and allows you to manipulate data using C++ coding or Python, and you can save and share data files on it. The *Get Started* documentation guides you through the format of ROOT and shows you how to use the embedded ROOT browser.

You can use the ROOT browser to have a look at what the data looks like and the different graphs available. Having done that, if you would like an extra challenge you can do some analysing for yourself by downloading a **virtual machine**.

Follow the steps in the *Software book* and save your work as you go. The virtual machine comes loaded with codes that you can use in order to do your own data manipulation, similar to the cuts you did on the Histogram analyser. Feel free to edit and play around with the code and even create your own plots.

5 Research

Now that you've gained some first-hand experience with using ATLAS data, it is up to you to continue this work with your own independently motivated research. It is imperative that you perform a literature review before continuing, reading up on and around the underlying particle physics. Here we merely suggest some avenues you may wish to explore in your own research:

- Why do your selected cuts optimise a search for the Higgs boson? This is about what interactions are being selected and rejected and why they occur in certain energy ranges. This will largely be linked to the masses of particles which are decaying (the peak energy) and that particle's lifetime (width in energy due to the uncertainty principle).

- Can you estimate the amount of data you might need for a statistically significant Higgs boson result based on the data so far? This is an extension of the effect size and number of observations statistics assuming the proportions don't change much as more data comes in. As we've seen this is not always the case, statistical fluctuations can appear and disappear, but a back of the envelope (or more sophisticated) calculation to estimate how many measurements might be required can be helpful and could be compared to the actual number of measurements used in finding the Higgs boson at a 5 sigma significance.

- Can you use the data to measure various unstable particles' masses and/or lifetimes? Students can make fits of peaks in the data to estimate these quantities.

- Can you explain any differences between the data and Monte Carlo simulations? This will require students to read up about how Monte Carlo simulations

You may use one of these topics as inspiration or come up with one of your own to research. Be sure to read around your chosen topic and undertake an experiment using the data and tools provided that will address your research question.

If you're still unsure what to do, please tell your teacher to get in touch with us so we can visit and provide guidance and assistance. If at any point if you find yourself unable to continue or completely unsure about something, ask your teacher to get in touch with us so that we can help you. On our website we also have advice on how to integrate and support students with projects, based on other schools' successful experiences. Providing some structure for your students, and mostly just encouragement throughout, is key to their and your success with these sorts of programmes.

6 Glossary

- **Boson** - The particles associated with all the fundamental interactions (forces) and composite particles with even numbers of fermion constituents (quarks) are bosons.

- **Branching ratio** - The fraction of particles which decay by an individual decay mode with respect to the total number of particles which decay.

- **Calorimeter** - An experimental apparatus that measures the energy of particles. Most particles enter the calorimeter and initiate a particle shower and the particles' energy is deposited in the calorimeter, collected, and measured.

- **Dark matter** - Matter that exists but is not visible to us because it emits no observable radiation.

- **Decay** - A process in which a particle disappears and in its place different particles appear. The sum of the masses of the produced particles is always less than the mass of the original particle

- **Elementary particles**- A particle with no internal substructure, i.e. it cannot be broken down into any further parts as far as we know.

- **Fermion** - Fermions obey a rule called the Pauli Exclusion Principle, which states that no two fermions can exist in the same state at the same time. All particles are either fermions or bosons. All quarks and leptons are fermions.

- **Flavour**- The name used for the different quarks types (up, down, strange, charm, bottom, top) and for the different lepton types (electron, muon, tau). For each charged lepton flavour there is a corresponding neutrino flavour. In other words, flavour is the quantum number that distinguishes the different quark/lepton types. Each flavour of quark and lepton has a different mass.

- **Gyroradius** - The radius of curvature of a charged particle in the presence of a uniform magnetic field.
- **Mass**- The rest mass (m) of a particle is the mass defined by the energy of the isolated (free) particle at rest, divided by the speed of light squared. When particle physicists use the word 'mass' they normally mean the 'rest mass' (m) of the object in question.
- **Primary vertex** - The inelastic collision of two protons with the highest overall transverse momentum.
- **Quantum Field Theory** - A field theory that incorporates quantum mechanics and the principles of the theory of relativity.
- **Relativistic** - At speeds close to the speed of light.
- **Transverse momentum** - The component of momentum perpendicular to the beam line.
- **Trigger system** - This selects events with distinguishing characteristics that make them interesting for physics analyses.
- **Vertex** - The point of collision of two particles - the source of the interaction.
- **Virtual machine** - A virtual machine will transform your computer into an analysis machine. Your physical computer will be the "host", while the virtual machine will be a "guest". Most of the guest code runs unmodified, directly on the host computer, and the guest operating system "thinks" it's running on a real machine.

7 Useful links

- Get started: https://cheatham1.gitbooks.io/get-started/
- Histogram analyser: http://opendata.atlas.cern/visualisations/analyser-js.php
- Embedded ROOT browser: http://opendata.atlas.cern/visualisations/root-browser.php
- Software book: https://cheatham1.gitbooks.io/openatlasdatatools/content/
- Video explaining the Higgs mechanism - https://www.youtube.com/watch?v=joTKd5j3mzk
- Video on significance in Particle Physics - https://www.youtube.com/watch?v=Gr1rIikTYac
- Paper on significance in Particle Physics - https://arxiv.org/pdf/hep-ex/0208005.pdf
- Statistics - http://www.phys.ufl.edu/~korytov/phz6355/note_A13_statistics.pdf