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Searching for a Higgs Boson with the ATLAS detector

For thousands of years we have been asking questions about the Universe. The aim of this research is to help answer one of the biggest questions of our time: why is there mass?

What is the Higgs Boson?

Every physical phenomenon that we have observed, both on and off the planet, can be explained by the existence of four fundamental forces. These are **gravity**, **electromagnetism** and the **strong** and **weak nuclear forces**.

It is the general consensus that at the beginning of the Universe the **electromagnetic** and **weak forces** were in fact as one, but when the Universe was ~10 trillionths of a second old, a phenomenon known as **spontaneous symmetry breaking** occurred, separating the **weak** and **electromagnetic forces** and resulting in the birth of three massless particles.

Although the theory of **symmetry breaking** fits beautifully within our model of the Universe, the three massless particles predicted by it are not observed in nature, meaning the theory cannot be completely reconciled with the world we observe. To put it plainly, **symmetry breaking explained what we see in an accurate and beautiful way, but for the presence of these three massless particles.**

A solution to this difficulty came in 1964 when Peter Higgs submitted his theory of a mechanism by which we could lose these three particles and gain four more, a photon (observed) and three massive particles, the **W^+, W^-** and **Z Bosons** (known collectively as the **weak Bosons**). The mechanism that causes this effect is now known as the **Higgs mechanism**, and has been given much support by the experimental observation, in 1983, of the three predicted **weak Bosons**.

The **Higgs mechanism** thus became an accepted part of the **standard model of particle physics**, a model that describes to our best knowledge the way in which the physical Universe works at its most basic level.

The mechanism by which particles obtain mass can be visualised as a field stretching throughout space, such that when particles move through it they must pass through it. The mass imparted to the particles varies according to how strongly they feel the field. To understand this one can consider the (**electromagnetic**) field between two magnets; a conductor such as a paper clip will feel the field but a matchstick will not.

A consequence of this **Higgs field** is that there should exist a corresponding particle, known as the **Higgs Boson**. This is the only particle predicted by the **standard model** that remains undiscovered.

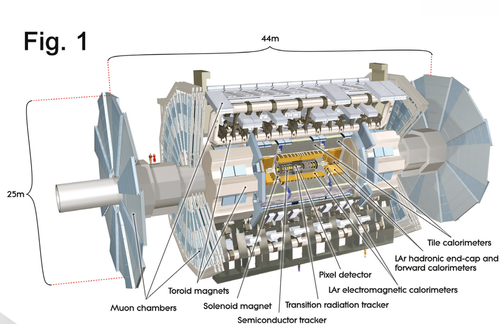
Why the ATLAS detector?

The three Bosons that carry the **weak** force were all discovered at the previous CERN experiment, the **LEP** (Large Electron Positron collider), which was housed in the same tunnel as the new **LHC** (Large Hadron Collider). The maximum collision energy achieved at LEP was 209 GeV. **The LHC will begin with a collision energy of 10TeV: an energy 50 times as high as its predecessor's maximum.** ATLAS is the largest of the four detectors positioned over the beam pipe of the LHC. It is a multi-purpose detector, cylindrical in shape, positioned so that it completely encompasses the crossover between the clockwise and anticlockwise beam pipes.

The ATLAS detector was built with the Higgs search firmly in mind. **If the Higgs Boson exists, the ATLAS detector will find it**. The detector is made up of different layers that do completely different jobs. The **inner detector** is used for tracking charged particles. The **calorimeters** detect energy deposits left by particles. There are two types of calorimeter to account for the fact that some particles, such as electrons, interact **electromagnetically** and others interact via the **strong** force. The outermost layers of ATLAS are known as the **muon chambers**. Muons have their own special detector because they are less likely to interact with the material in the calorimeters, with their preferred decay mode being via the **weak** force. The **inner detector, calorimeters and muon chambers together have been designed to be capable of detecting everything that we know of, or that our imaginations can summon.**

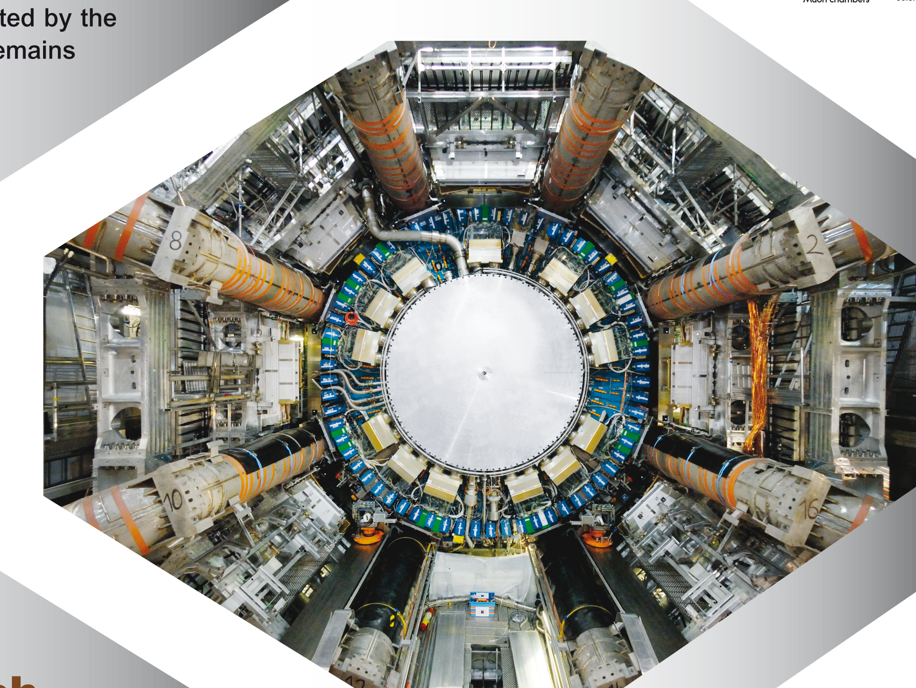
ATLAS will see approximately **600 million collisions per second**. The only way to deal with this amount of data is to first cut it down to size using the **trigger**. The detector sees all of the collisions, but we only want to look at the interesting ones, so we "trigger" on the events that look promising. This reduces the number of events per second to a few hundred. We can store these events for further analysis.

Fig. 1



For this analysis we ask for events that pass a **trigger** which looks for a single isolated electron or muon with high transverse momentum.

Fig. 1, left shows the components of the ATLAS detector.



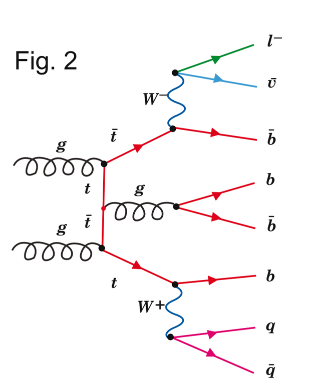
My Research

The **Higgs Boson** can be produced and can in turn decay in many different ways. These production and decay modes are known as channels. Although the **standard model** theory cannot predict the mass of the **Higgs**, we can apply constraints to the range of masses it can take. The allowed mass range for the **Higgs** is 114 to 182 GeV, with the lower end of this range being more probable.

The **Higgs Boson** is unstable. A **Higgs** with a mass of ~120 GeV is most likely to decay into a **b quark** and its antiparticle; it is the jets formed by these **quarks** that we detect rather than the **Higgs** itself, which will not leave any trace in the detector. Pairs of **b quarks** can be produced in myriad other ways, making it virtually impossible to tell whether we are seeing a **Higgs** event or something less interesting. For this reason we need to look specifically at the case where **the Higgs is produced in association with a pair of top quarks**, because then we can look not just for a pair of **b quark** jets but also for the decay products of the **tops**, making the final state topology easier to distinguish as an event we want to work with. We call this production/decay channel **ttH(H->bb)**.

The final state of this channel has in total six jets, four of them from **b quarks**, as well as a high-energy **lepton** and a **neutrino**. Even after identifying all of these objects in an event, we are highly unlikely to be looking at a **Higgs** event; there are many **background processes** (Fig. 2, left) with identical or near-identical final states that swamp our **signal** (Fig. 3, right) by a factor of ~1000:1.

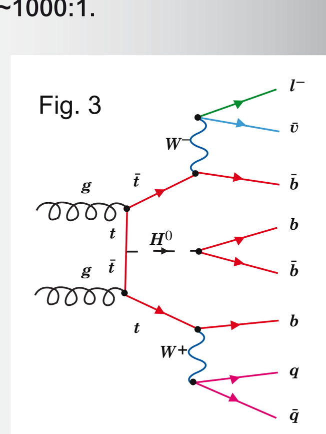
Fig. 2



Analysis methods are, therefore, judged largely on their ability to distinguish our signal from our background: **to select the desirable Higgs signal and reject those events that merely mimic the Higgs.**

To do this we must utilise all our knowledge of the kinematics we expect from a **Higgs** signal event.

Fig. 3



My Results

Once we have selected the events that look like our signal, we must then attempt to reconstruct all the objects in the event correctly, which is largely down to pairing up the jets correctly. A **ttH(H->bb)** event can actually have **up to 20 jets**. This is because it is not only the six **quarks** that create jets in the detector, it is also highly likely that gluons will radiate off any of the particles, also forming jets.

What this means is that even if we select only the signal events during the first part of our analysis, we are highly unlikely to combine the jets in the correct way to reconstruct the **W**, **tops** and **Higgs** without some effort to reduce the **combinatorial background** arising from the abundance of jets being wrongly used in reconstruction.

The most obvious constraint to apply in order that we use the correct jets is to use the **well-known masses of the W and the top quarks.** We can demand that the combined mass of the two jets we use is close to the **W** mass, otherwise we do not use the pair of jets. The same method can be applied to the **W+jet** combination we assign to the **top quarks.**

Another method is to **calculate the charge of the b quark jets** in the event and to use this information to distinguish between the (oppositely charged) **b** and **anti-b jets**, thereby reducing the chance of using the wrong ones for reconstruction.

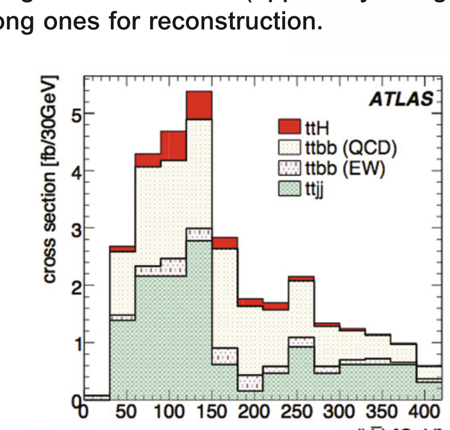


Fig. 4

There are many other subtle discriminators being used, such as the angles between objects and their summed momentum. We combine all of these discriminators to form a **likelihood** of an event being correctly reconstructed. We choose the reconstruction that has the highest likelihood, then if this likelihood score is high enough we accept the event as **ttH(H->bb)** and obtain a value for the **Higgs** mass.

Figure 4, (left) shows the mass of the **Higgs Boson** reconstructed using the signal (**ttH**) events and major backgrounds. The similarity between these highlights the difficulty in reconstructing the **Higgs** for this channel.

Is a Black Hole going to eat us?

The LHC experiment is an international collaboration of thousands of scientists and is based at the CERN Laboratory in Geneva. The ATLAS detector was built with many things in mind. The holy grail of particle physics is, in fact, not the discovery of the **Higgs Boson** but the unification of the four forces; **weak**, **strong**, **electromagnetic** and **gravitational**. The weakest of the forces is the **gravitational** force. One theory, which is at present not supported by any experimental evidence, is that gravity is so weak because it is in fact curled up inside extra dimensions of space.

Some theories (also unsupported by any evidence) state that very high energy events can cause the creation of miniature singularities in the fabric of space-time: **black holes**. The issue with these theories is that not only are they unbacked by any supporting evidence, they are in fact largely disproved; cosmic rays of much higher energies than those we will reach with the LHC enter our atmosphere regularly. ➠

The theories that predict these miniature **black holes** also predict that they would certainly be created in abundance by cosmic rays. We observe nothing of this nature. In any case, if **black holes** were created with the LHC then they would instantly evaporate via Hawking radiation, a phenomenon predicted by the renowned cosmologist **Stephen Hawking**. Crucially, Hawking radiation has actually been observed.

Physicists are unable to state that there is no chance of the LHC producing a **black hole** because **quantum mechanics** tells us that there is in fact a non-zero probability of anything happening. There is also a non-zero probability that we will suddenly fall through the Earth, or that we will all spontaneously turn into cucumbers. But we do not worry about it, because the probability is so vanishingly small that we would have to hang around for a great deal longer than the age of the Universe in order to observe it.

Left: how ATLAS might see a black hole decay if one were produced at the LHC.

Credits and more information

Atlas detector photographs (main centre & top right image) and Black Hole (bottom centre image) © CERN.
Higgs mass plot (Fig. 4) credited to arXiv:0901.0512v2 [hep-ex].
For more information please visit **http://public.web.cern.ch/public/** or **http://www.atlas.ch/**

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