Is there a mass exchange particle smaller than the Higgs Boson?
Acknowledgments

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Summary

This report will investigate whether the Higgs Boson particle can decay into smaller mass exchange particles. If this can be proved or disproved it will change the current particle physics theories as well as changing the future of how we understand the universe. In order to investigate this problem, particle collision tracks from CERN were analysed and compiled looking for the exotic particles that the mass exchange particles decay into. Although the results were ultimately inconclusive due to the data size analysed, they suggested that there are mass exchange particles smaller than the Higgs Boson. However, the results also suggest that the true nature of the mass exchange particle is different to the current ‘little Higgs’ and ‘Supersymmetry’ theories but combines elements from both.
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### Introduction

Sub-atomic particles (such as the proton, electron and neutron) are all around us and can collect together to form atoms and molecules. According to the standard model, these sub-atomic particles are split into three fundamental particle families:

1.1 – **Hadrons**

In 1968 the Stanford Linear Accelerator Center\(^1\) proved that some of these sub-atomic particles were in fact made up of smaller particles called quarks. These quarks each had specific characteristics that gave the sub-atomic particles their characteristics. For example, a proton (with +1 charge) is made up from a down quark and two up quarks, where as a neutron (with 0 charge) is made up from two down quarks and an up quark\(^2\). The bottom quark was the last to be experimentally found in 1995, by the Tevatron accelerator, and completed the three quark families\(^3\). This meant that a total of six quarks have been discovered: the up quark, down quark, strange quark, charm quark, top quark and bottom quark\(^4\). The six quarks are split into the following three groups, called generations:

![Image from: http://global.jaxa.jp/article/interview/vol43/p2_e.html](http://global.jaxa.jp/article/interview/vol43/p2_e.html)

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1 & 3 - [https://www.learner.org/courses/physics/unit/text.html?unit=1&secNum=5](https://www.learner.org/courses/physics/unit/text.html?unit=1&secNum=5)
2 - Revise edexcel AS/Alevel physics, Pearson, Steve Woolley, Pg 91
4 - [https://home.cern/about/physics/standard-model](https://home.cern/about/physics/standard-model)
1.2 - **Leptons**

Leptons are not made up of quarks and are themselves fundamental particles. There are six known leptons\(^5\): the electron, electron neutrino, muon, muon neutrino, tau and tau neutrino. The electron, muon and tau particles all have a charge of -1 and the only varying characteristic between them is their mass (the electron is the lightest and tau is the heaviest). Each of these leptons has its equivalent neutrino which is effectively a packet of energy as it has negligible mass and charge. These six leptons are also split into three generations:

<table>
<thead>
<tr>
<th>1(^{\text{st}}) gen.</th>
<th>2(^{\text{nd}}) gen.</th>
<th>3(^{\text{rd}}) gen.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>e^-</strong> electron</td>
<td><strong>(\mu^-)</strong> muon</td>
<td><strong>(\tau^-)</strong> tau</td>
</tr>
<tr>
<td><strong>(\nu_e)</strong> electron neutrino</td>
<td><strong>(\nu_\mu)</strong> muon neutrino</td>
<td><strong>(\nu_\tau)</strong> tau neutrino</td>
</tr>
</tbody>
</table>

Image from: http://www.hep.manchester.ac.uk/dzero/teaching/glossary/lepton.html

1.3 - **Bosons**

The final fundamental particle family is the Boson family. Particles interact by exchanging forces and Bosons carry these forces between the particles\(^6\). For example, in the nuclear model of an atom the nucleus is made up of protons and neutrons tightly compacted together (and this is then surrounded by electrons which are arranged in shells). In theory the protons in the nucleus should repel each other because they have the same charge, however, because of Rutherford’s gold foil experiment) we know that this is not what happens inside an atom. The particles in the nucleus of an atom are held together by the strong nuclear force which is stronger than the repulsion force pushing the protons apart. The strong nuclear force is exchanged between the particles by the Gluon Boson. The three other Bosons are the photon (responsible for the electromagnetic force), the W and Z bosons (responsible for the weak nuclear force) and the graviton (responsible for the gravitational force)\(^7\). Unlike the other fundamental forces, Bosons aren’t put into generations.

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5 & 7 - https://home.cern/about/physics/standard-model
6 - Revise edexcel AS/Alevel physics, Pearson, Steve Woolley, Pg 91
1.4 - Generation decay

Leptons and quarks (fermions) are split into three generations. The first generation are stable fundamental particles – these do not decay into other fundamental particles. However, generation 2 fermions (which have more mass) are relatively unstable meaning that they decay into lighter fundamental particles (generation 1 fermions). Generation 3 fermions are even heavier which means, like generation 2 fermions, they are unstable resulting in them quickly decaying into lighter fundamental particles; ultimately decaying into generation 1 fermions\(^8\). This is why atoms are made from protons (which are made from generation 1 quarks), neutrons (also made from generation 1 quarks) and electrons (a generation 1 lepton) as these particles are stable.

1.5 - Bosons decay

All Bosons are unstable particles which means that they all decay. Depending on their mass, Bosons can decay into any of the 12 fermions: with heavier Bosons decaying into heavier fermions (although these ultimately decay into lighter fermions). For example, the W boson can decay into an electron and an anti-electron neutrino – which is the anti-particle of the electron neutrino\(^9\). And 70% of the time, the Z boson decays into a quark and an anti-quark\(^{10}\).

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Literature review

2.1 - The Higgs Mechanism theory

In creating the standard model scientists implied that electricity, magnetism, light and some types of radioactivity are all results of the electroweak force. This correctly described the photon, and the W and Z bosons characteristics and behaviours apart from mathematically these particles emerged without mass: while the photon has no mass, we know that the W and Z have a mass of nearly 100 times that of a proton. This meant that the current theory didn’t explain the entire picture. As a result, physics theorists Robert Brout, François Englert and Peter Higgs came up with the Brout-Englert-Higgs mechanism theory (the Higgs mechanism theory) 11.

According to the Higgs mechanism theory, all fundamental particles interact with an invisible field that gives them mass; the stronger they react with this field the heavier they appear12. For example, the tau particle is 3500 times heavier than the electron13, therefore, the tau particle must have a much stronger interaction with the Higgs field than the electron does. Without this part of the standard model we would not be able to explain how or why particles gain mass.

Like all forces that interact with particles, the Higgs field must have a Boson that acts as the exchange particle between the field and the fundamental particles – this particle was called the Higgs Boson.

2.2 - Higgs Boson mass

It was suggested that the Higgs Boson (the Higgs) itself also interacts with the Higgs field in order to gain mass14, however, as it theoretically also part of the Higgs field at the same time it would interact very strongly with the Higgs field meaning that this mass was predicted to be incredibly large for a fundamental particle (about 125 GeV15) and thus would decay extremely quickly (in a predicted 1.56x10^-22 seconds16).

11 - https://home.cern/topics/higgs-boson/origins-brout-englert-higgs-mechanism
14 - Introducing the little Higgs, Martin Schmaltz, Pg. 23, Physics world November 2002
15 & 16 - http://www.nature.com/nphys/journal/v10/n8/full/nphys3005.html
2.3 - Discovering the Higgs Boson

Because of the decay time involved with the Higgs, physicists decided that in order to prove the existence of it they must detect the particles that it decays into. Unfortunately, as the Higgs interacts with mass, and all particles (but the photon) have mass, this means that there are many different decay modes that the Higgs can travel. These are:

\[
\begin{align*}
\text{Higgs} & \rightarrow b + \bar{b} & \text{(b quark and its antiquark)} \\
\text{Higgs} & \rightarrow \tau^+ + \tau^- & \text{(\(\tau\) lepton and its antiparticle)} \\
\text{Higgs} & \rightarrow \gamma + \gamma & \text{(two photons, also called gammas)} \\
\text{Higgs} & \rightarrow W^+ + W^- & \text{(W boson and its antiparticle)} \\
\text{Higgs} & \rightarrow Z^0 + Z^0 & \text{(Two Z bosons)}
\end{align*}
\]

The quark - antiquark mode is the most commonly seen, however there are several other processes that can produce these particles. This means that even if you observe these particles, it’s hard to tell if it came from the Higgs particle decaying or from another decaying particle. For this reason, the best decay modes to try and detect the Higgs are the photon-photon and Z boson-Z boson decays\(^{17}\). These two decay combinations were detected by the ATLAS and CMS experiments at CERN which, after two years of graphing and analysing data\(^{18}\), led to the discovery of the Higgs Boson at CERN on the 4th July 2012\(^{19}\). This was finally evidence that the Higgs mechanism existed.

\(^{17}\) - http://particleadventure.org/the-higgs-boson-decays-into-other-particles.html
\(^{18}\) - Pg. 14, Higgs Hunters analysis guide, The institute for research in schools
Although the Higgs Boson has been discovered, there is much more to find out about the Higgs mechanism and the Higgs boson itself. There are several theories as to the nature of the Higgs boson.

2.4 - The ‘baby Higgs’

The ‘baby Higgs’ theory suggests that like protons are made from a combination of quarks, the Higgs Boson is made from a combination of undiscovered exotic particles, called the ‘Baby Higgs’. The ‘baby Higgs’ are unique to the Higgs Boson and these particles then decay into particles that we can detect (as shown below).

It is thought that since the Higgs itself has been proved by the ATLAS detector to be a scalar exotic particle, it may be possible that the Higgs decays into two scalar exotic particles. However, like the Higgs, these particles would interact with the Higgs field in order to gain mass. Since these particles makeup the Higgs bosons (that are the force carriers of the Higgs field, so in a way they are interacting with themselves) they are unstable, meaning that they would decay quickly. If the Higgs Boson is made up of two of these particles, then their mass would be approximately 62 GeV (half the mass of the Higgs Boson). Using this information and the physics conservation principles (that energy, charge, spin, momentum, etc. must always be conserved) physicists were able to narrow down the theoretically possible decay modes of these particles.

20 - https://blog.higgshunters.org/category/the-higgs-boson/
This image shows the possible theoretical decay modes where current detectors can easily detect the elementary particles produced. After physicists studied all of these decays, it appears the two best channels are:

1) Where both of the produced ‘Baby Higgs’ particles decay to a bottom quark – anti-bottom quark pairing\(^{24}\).

2) And where one of the ‘Baby Higgs’ particles decays to a bottom quark – anti-bottom quark pairing and the other decays to a muon- anti-muon pairing\(^{25}\).

Both of these decay modes appear when the proton-proton collision that occurs in the LHC produces a Higgs Boson and a Z-Boson\(^{26}\). Because of the low energies involved with these decays, these channels may already be present in the current data available from 2012 when the Higgs Boson was discovered\(^{27}\).

2.5 - The importance of the ‘Baby Higgs’

If discovered, the ‘Baby Higgs’, which is not expressed in the standard model, will prove that there are new particle physics theories that need exploring and experimenting on. It will also narrow down the number of theories that are currently available that do not include the ‘Baby Higgs’ as a part of how the Higgs mechanism works\(^{28}\).
Another theory that has gained notability from the conformation of the Higgs mechanism and Higgs Boson is the idea of supersymmetry.

2.6 - Supersymmetry (before the Higgs Boson)

Supersymmetry states that every type of particle has one or more super-partners. If a particle is a fermion, its super-partner is a boson and vice versa. We have currently discovered 10 fundamental particles\(^{29}\) (not including the Higgs Boson or any of the anti-particles) but none of them have the right properties to be super-partners of each other. This is because super-partners\(^{30}\):

1) Share exactly the same interactions with other particles and their super-partners as normal particles.

2) Have exactly the same mass as their normal partners.

This clearly isn’t the case in our world because we would have discovered many years ago in particle accelerators if there were other particles that had the same charge as a proton but weren’t protons\(^{31}\). We would also have discovered atoms with electrons in them and atoms with selectrons (the electron super-partner)\(^{32}\) in them. Not only would that increase the number of different atoms and molecules that we would have found but since fermions and bosons would behave completely differently in atoms\(^{33}\), molecules would behave in completely different ways. So this means that exact supersymmetry is not a correct theory of nature.

For supersymmetry to be true something must be spontaneously breaking it\(^{34}\). Symmetry can be observed breaking by doing a simple experiment:

The laws of physics are the same no matter where you are standing: as you rotate a person in deep space the hair on them would be symmetrical all the way around (as shown on figure 2)\(^{35}\). However, when you rotate someone on earth (although the same laws of physics apply) their hair changes depending on their orientation to the Earth (as shown on figure 1). The rotational symmetry on Earth is spontaneously broken by gravity\(^{36}\).

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This meant that the supersymmetry theory had to be changed in order for it to be correct. As a result, it was hypothesised that there must have been something interacting with particles in order to hide their super-partners. This was hypothesised to be the Higgs field. It was said that the Higgs field made the super-partners appear to be much heavier than the fundamental particles even though they have the same mass (they have a stronger interaction with the Higgs field).

2.7 - Supersymmetry (after the Higgs Boson)

The finding of the Higgs Boson meant that the Higgs mechanism was confirmed. This also confirmed that supersymmetry could exist if it was being spontaneously broken by the Higgs field. Taking into account the breaking by the Higgs field it is hypothesised that the masses of the known particles and their superpartners could be in this pattern type:

![Diagram showing particle interactions]


However, for the relevant conservation laws to be true this means that there must be heavier Higgs Boson particles that have identical properties to the already found Higgs (except from mass) and that also transmit the Higgs field.

It is now hoped that as we increase the energies of the proton-proton collisions in CERN we would start to see the lighter of the super-partners and Higgs Bosons.

Methodology

3.1 - ‘Zooniverse’
By using the citizen science project ‘Higgs Hunters’, that uses the citizen science platform ‘zooniverse’, I have been classifying particle tracks taken during the 2012 running of the ATLAS particle detector\(^\text{42}\) experiment at CERN. This project hopes to identify the decay modes of the Higgs Boson in the hope of discovering the ‘Baby Higgs’ and confirming the little Higgs theories.

3.2 - The ATLAS detector
The ATLAS detector is one of four detectors inside CERN\(^\text{43}\). The LHC accelerates protons to 99.99999% the speed of light in a 17-mile-long tunnel\(^\text{44}\) before colliding them together inside the ATLAS detector. Since the particles are travelling so fast they have a lot of energy, which means that they can become many different particles including the Higgs Boson. The ATLAS detector collects data on all of the properties of the particles created using six different detecting sub-systems\(^\text{45}\), arranged in layers, and then computer imaging allows us to build up a 3D image of the particle collision.


- **Muon detector**: Detects muons that pass through it.\(^\text{46}\)
- **Calorimeters**: measure the energies of the particles passing through it.\(^\text{47}\)
- **Trackers**: Detect the paths of the particles to locate their origin.\(^\text{48}\)
- **Magnets**: Bend the particles paths so that their momentum can be calculated.\(^\text{49}\)
- **Pixel detector**: Detects photons given out by the particle collisions.\(^\text{50}\)

\(^\text{43}\) - Pg. 10, Higgs Hunters analysis guide, The institute for research in schools
\(^\text{45}\) - [https://home.cern/about/experiments/atlas](https://home.cern/about/experiments/atlas)
3.3 - Data volume

In 2012 protons where colliding every 25 Nano-seconds (that’s 40 million collisions every second!)\(^5\). This would mean that the chances of randomly picking a Higgs event would be 1 in 10 billion\(^5\). Unfortunately, since Higgs Hunters are looking for an exotic particle that the Higgs decays into, with unknown characteristics, they can’t narrow down particle tracks with its likely decay modes like the other Higgs experiments have done\(^5\). Therefore, to be able to narrow this data set down the Higgs Hunters project applied some parameters to the data set. Using information gathered from the experiment that found the Higgs Boson they decided that they would only analyse the tracks that presented the following characteristics:

- At least two muons where detected. This is because 2% of the time a Higgs Boson is created a Z boson is also created and 3.3% of these times the Z Boson decays into two muons. This increased the chances of finding a Higgs event to 150 in about 4 million tracks\(^5\).

- The Z boson must be moving away from the Proton beam. When a Z boson decays on its own it is stationary, however, when it decays with a Higgs Boson the two particles normally (not always) move away from each other and thus away from the proton beam\(^5\). This increased the chances of finding a Higgs event to 90 in about 200,000 tracks\(^5\).

- There should be some missing momentum. Since the ‘baby higgs’ is an exotic particle it should leave the detector without being detected by any of the layers (or it would have been detected in earlier experiments). This means that there should be some missing momentum somewhere on the track\(^5\). This again increases the chances of finding a Higgs event to 1 in about 1000 tracks\(^5\).

Applying these parameters to the data set leaves around 60,000 images to analyse\(^5\). Normal ATLAS tracks only show the particle paths that start from within 10 mm of the proton beam line, however, since these particles are travelling so fast, and to be able to detect the desired particles we have to wait for at least two decays to occur, Higgs hunters reconstructed the particles paths that start up to 10 cm from the collision point\(^5\). The particle tracks are then ‘cleaned up’ and only high energy particle tracks (such as the muon) are left on the image\(^5\).

\(^5\) - Pg. 11, Higgs Hunters analysis guide, The institute for research in schools

52, 54, 55 & 58 - Pg. 16, Higgs Hunters analysis guide, The institute for research in schools

53, 56, 57, 60 & 61 - https://blog.higgshunters.org/2014/12/06/what-youre-seeing-on-higgshunters/

3.4 - Why use humans for data analysis?

Although it would be quicker to write a computer algorithm that can analyse the data much quicker than humans can, experiments have shown that the collective work done by the civilian scientists on Higgs Hunters was more efficient than the computer algorithms at finding the points of interest. The efficiency of candidates is measured in two ways:

1. The rate at which correct classifications are made.
2. The rate at which fake classifications are made.

When these two data points where compared, for particles smaller than 20 MeV, in 11/18 tests the Civilian scientists where more efficient at identifying the Baby Higgs decay modes. As well as this, the scientists at Higgs Hunters are looking to improve their detection algorithms for the future; to do this they compare the analysis of some tracks between the computer and humans so that they can change the algorithms to find the irregularities that the human eye can easily find. This will help the discoveries of other exotic particles in the future.

3.5 - What do you look for on a particle track?

From the little Higgs theory, we know that the only evidence that we could find of the exotic particle existing is by finding the products of its decay modes and we also know that the two most common decay modes are the bottom quark–anti-bottom quark pairing and the muon-anti-muon pairing. However, the bottom quark–anti-bottom quark pairing can also be produced from various other decay modes of known particles. As a result, scientists are looking primarily for the muon-anti-muon decay mode. The muon–anti-muon would be moving away from each other meaning that a vertex would be produced where this decay took place. When this is combined with the decay mode only being present after two decays, the particle would have moved a visible distance away from the original particle collisions so this vertex would be considered as an ‘off centre vertex’ (OCV).
This is computer simulated data for scientists to see what an OCV may look like; this is an example of the ‘front view’ of a particle track. The highlighted lines are the computer algorithm trying to find OCVs (and can be ignored) and the red dashed line shows where there is missing momentum. I have circled in red where the OCV can be seen on this image.

From the front view, it appears that an OCV has been found, however, by looking also at the side/slice view it can be seen that there isn’t an OCV. For an OCV to be conclusively found it must be confirmed in both views since the views look at the 3D tracks from different viewpoints (front and side). Only about 0.1% of all the images analysed will have an OCV present in both viewpoints.
Results

Over the last several months I have analysed 5019 tracks on Higgs Hunters to see whether any of the tracks had an OCV present with in both viewpoints (front view and side view). Below are the collated images from the data analysis:

4.1 - OCV’s

Circled in red are the corresponding OCVs. On image 1 a particle decays into two muons (muon creation supported by the interaction with the muon detector – yellow ring on image 1) from an OCV that is a long distance away from the original particle collision (the origin). Because of this distance the particle decaying into this OCV must have not interacted very strongly with the Higgs field allowing it to travel away from the origin.

There is also some missing momentum found, indicated in image 1 by the red dotted line. This suggests the presence of undetected (perhaps currently undetectable and exotic) particles.

This is confirmed by the OCV that can be observed in image 2 that was not formed at the origin.
On image 3 an OCV producing two muons (supported by the interaction with the muon detector) which is a long distance away from the origin is circled in red. However, this distance is smaller than the distance between the OCV and origin on image 1 meaning that the decaying particle must have had a stronger interaction with the Higgs field than the particle in image 1 and thus decayed quicker. The stronger interaction with the Higgs field also suggests that the particle is heavier, however, because it produced the same amount of muons that would be travelling at the same measurable speed this cannot be confirmed. This decay is also perfectly in line with the missing momentum from the collision (red dotted line) indicating the presence of an exotic particle.

When looking at image 4 (the slice view of this particle collision) it can be seen that there are two OCVs shown. Although only one of these is an actual OCV (because there is only one OCV in the front view), it does confirm that there is an OCV made from this collision.
On image 5 an OCV producing possibly three muons (supported by the three separate interactions with the muon detector) which is separate from the origin is circled in red. This distance is smaller than the OCVs in images 1 & 3 suggesting that this particle was heavier than the other two. Supporting this is the fact that this particle decays into three muons, because of the conservation of energy, this means that the decaying particle must be heavier than the decaying particles in images 1 & 3 because they only created two muons. This decay is also in the same direction as the indicated missing momentum from the collision indicating the presence of an exotic particle.

Image 6 shows an OCV with three particles confirming the findings from image 5.
Image 7 also shows an OCV that produces three muons (supported by the three circled interactions with the muon detector). The distance the particle has travelled from the origin before decaying compared the decaying particles in images 1 & 3 suggests that it has a much smaller mass so is stable for longer. However, because this particle decays into three muons instead of two it means that due to the conservation of energy that particle must have a much bigger mass than the decaying particles in images 1 & 3. The extra distance it travels can be explained by it reacting less with the Higgs field meaning that it can travel for longer before decaying.

Even though the missing momentum isn’t in the same direction as the OCV, an exotic particle could have still been created. If neutrally charged particles were emitted during the proton collision, they would have been included in the momentum calculations but excluded from the track. Neutrally charged particles being created is supported by the energy detection in the calorimeter (in the blue circle) even though no particles are seen travelling through it.

Image 8 supports the OCV found on image 7 as you can also see an OCV with three particles decaying from it a long distance away from the origin.
In image 9 you can see that an OCV is produced that has five particles emerging from it. By looking at the muon detector these can be identified as five (in the four yellow circles) muons. As the decaying particle has decayed into five muons it must have an extremely large energy level and mass (more than 530 MeV\textsuperscript{68}). This is supported by it only travelling a small distance compared to the other particles meaning that reacts strongly with the Higgs field and thus suggesting that it has a large mass. The missing momentum is also in the same direction as the OCV suggesting the presence of an exotic particle that we can’t measure on the current equipment that we have.

The OCV seen in image 10 supports the evidence found in image 9 by having five particles tracks emerging from it and by only being a small distance away from the origin.
4.2 - Something weird

Note: the slice view for all of these tracks were completely blank so are not included.
All four of these images show that, although there was no detectable particle collision or particles decaying, a lot of muons were detected all around the detector. If only one of these particle tracks had been seen, they could have been explained by the detection or computing software making a mistake. However, as I discovered four of these particle tracks, it suggests that in every 1250 tracks there is roughly 1 track that appears like this.

Unfortunately, these events are not caused by exotic particles that interact with the muon detectors, but are instead caused by energetic cosmic rays. During a super-nova millions of very energetic particles are emitted, all travelling at nearly the speed of light. This energetic particle has travelled through the Earth’s atmosphere and have collided with the rock above ATLAS creating hundreds of lower-energy muons traveling into the detector. These muons are detected by the muon detector and create the observed pattern. This illustrates how even when an unusual event in the LHC occurs, it is often due to something we have not considered in the original analysis. It is only after further and more in depth analysis that a conclusive decision is reached on the reason for this unusual event.

69 - https://talk.higgshunters.org/#/boards/BHH00000007/discussions/DHH00001i7
Conclusion

Out of the 5019 images that I analysed from the Higgs Hunters project I found: five images with that had a clear OCV in both viewpoints, four images with no visible particles but extremely high muon detections and 109 images that only had an OCV present in one of the viewpoints. Due to how the data was narrowed down, I was only expecting to find five OCVs out of the 5019 images that I analysed; this suggests that the theory behind the little Higgs is correct in at least its prediction of when exotic particles form. From the five images with OCVs in both of the viewpoints I found the following:

- Two tracks with OCVs creating two muons
- Two tracks with OCVs creating three muons
- One track with OCVs creating five muons

5.1 - Supersymmetry and the little Higgs theory

The only way that an OCV can occur is if a particle travels from the origin and then decays into other particles. Because there was missing momentum calculated in all of the tracks that involved OCVs, this means that a high energy exotic particle (with more than the energy of two muons - 212 MeV\(^1\)) has been formed at the origin, travelled away from it and then has decayed into muons. The Higgs Boson was discovered to have about 126 GeV\(^2\), 1000 times more energy than this particle, which suggests that the exotic particle decay we observe is not that of the Higgs Boson itself or we would likely observe heavier particles than the muons being created due to its decay, such as the Tau particle which is 10 times heavier than the muon (at around 1.77 GeV\(^3\)). This means that the OCVs detected show that the Higgs Boson must decay into smaller exotic particles that then subsequently decays into muons which is the evidence needed for the little Higgs theory to be confirmed.

However, this data could support the supersymmetry theory involving the Higgs Boson. Although the discovered Higgs Boson has enough energy to decay into the five muon OCV that I found, it is very unlikely that it would decay into the range of OCVs that I found (between two and five muons - 212 MeV and 530 MeV), this would suggest that there is more than one Higgs Boson mass. With the lighter Higgs decaying eventually into the two muon OCV and heavier Higgs Bosons decaying into the three and five muons OCVs. This supports the supersymmetry theory and suggests that the little Higgs theory is not the entire answer since it only suggests the existence of one ‘Baby Higgs Boson’.

\(^1\) http://physics.nist.gov/cgi-bin/cuu/Value?mmuc2mev
\(^2\) https://home.cern/topics/higgs-boson
\(^3\) http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/lepton.html
5.2 - My solution

From my track analysis, I have concluded that neither the supersymmetry theory nor the little Higgs theory are the complete answer in explaining the Higgs mechanism. Instead, from the data I have collected, I think that the answer lies within a mix of the two theories. Because of the missing momentum and muon (instead of heavier particles) decay, I think that there must be a smaller exotic particle that is created when the Higgs Boson decays. However, because of the differing energy levels of the decays (from 212 MeV to 530 MeV) I think that, much like the lepton family, there must be different exotic particles that are identical apart from their mass level that can be created when the Higgs Boson decays. For example, there may be three or 4 smaller particles that each have 0 spin or charge and that only last a fraction of a second before decaying (due to being part of the Higgs field while also interacting with it) but have differing mass and, depending on the exact energy of the Higgs Boson that is created, can be decayed into by the Higgs Boson.

5.3 - The limitations

Unfortunately, I was only able to analyse 5019 images, finding only 5 OCVs. Although this can give some early indication to the makeup of the Higgs mechanism, it will take further analysis to determine whether these events are valid or not. It could be possible that exterior interferences have provided the evidence for the finding of an OCV in roughly 1 in every 1000 tracks, such as cosmic ray interference or other particles making it into the detector at the same time as the proton-proton collision occurred. So, like the weird particle tracks (pg. 23), more analysis will need to be done on each image to determine its validity.

As well as this, only after hundreds of thousands of these tracks have been analysed, from the 2012 data and from higher energy data that will be recorded when CERN is operational again, will we be able to conclusively say whether we think the truth is one of the already known theories or is completely different to what we had hypothesised and predicted.
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