Aske Project 2018
Distinction
First Prize
Physics

Exotic Particles: The Hunt for the 'Baby Higgs'

Fundamental particles are the building blocks of nature. However, exotic particles are where the mystery lies. Do they exist or are they purely theoretical? Is there evidence for ones we have not yet seen? Detection of the Higgs Boson was believed to have completed the Standard Model. Recent proton collisions at CERN prove otherwise, alluding to an extremely rare boson that is not only invisible to our detectors, but exists for under a billionth of a second. Through this investigation I shall attempt to find this undiscovered exotic particle, the Baby Higgs.

Jared Richard
Meadows

Jared plans to read Physics at university. Jared chose this topic for research as fundamental particles make up all known matter and are a key pillar of physics. With the construction of the Large Hadron Collider, the world's biggest particle accelerator, research into the pursuit of previously unseen particles and their different flavours is one of the most promising fields in modern physics. Through this topic he has attempted to deepen his understanding of the particles that make up our own bodies and the world around us, whilst also looking forward and hopefully assisting with future discoveries in particle physics.

Jared's interest in the project was sparked by having access to millions of proton collisions directly from CERN which instigated his initial questions. Might there be evidence in just one of these collisions for a particle that has yet to be discovered? What he most enjoyed about his research was the freedom to creatively choose how he would analyse the data and the outcomes he would draw from this.

From the Examiner's report: Jared has produced an excellent, wide ranging analysis of cutting-edge Particle Physics. Along with his investigation of over 2,000 events from CERN data, he has produced a research paper worthy of a graduate physicist. He has clearly read around his topic in great detail and written with good clarity and detail.

From the Viva Examiner's report: Jared is a delightful and enthusiastic communicator. He is well read in Physics and we talked at some length about the philosophy of Physics. He communicated complex ideas in a mature, reasoned fashion.

Introduction

Over centuries of collaboration, physicists have gradually expanded our understanding of the Universe through multiple theories. Each plays a pivotal role in our breadth of knowledge; however, the most important underpins them all. The Standard Model is a theory about the fundamental particles of nature. These building blocks cannot be broken down further, some fundamental particles make up matter, while others determine how the matter particles interact. These particles are split into three families: fermions, the matter particles which consist of hadrons and leptons, and bosons, the exchange particles for forces between fermions (Berkeley Lab, 2013).

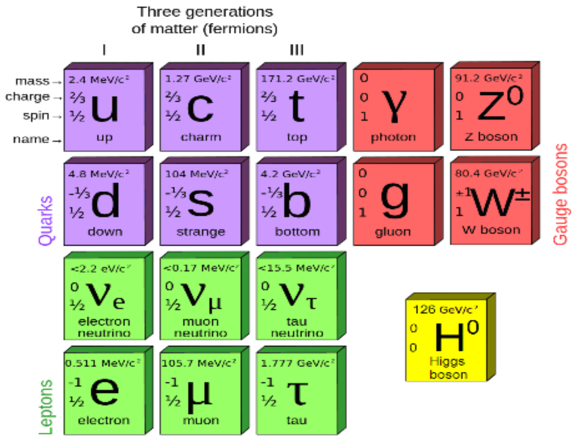


Figure 1 - The Standard Model [Philosophical Explorations, 2015]

Hadrons are the only particles that experience the strong interaction, an attractive and repulsive force that acts between nucleons to maintain the nucleus. This group of particles also contains two subsets, Baryons and Mesons. Examples of Hadrons are protons, neutrons and pions; however, they are not fundamental particles because they are made up of smaller particles called quarks.

Quark/Antiquark	Symbol		Charge /e		Baryon Number		Strangeness	
Up	u	$\bar{u}$	+2/3	-2/3	1/3	-1/3	0	0
Down	d	$\bar{d}$	-1/3	+1/3	1/3	-1/3	0	0
Charm	c	$\bar{c}$	+2/3	-2/3	1/3	-1/3	0	0
Strange	s	$\bar{s}$	-1/3	+1/3	1/3	-1/3	-1	1
Top	t	$\bar{t}$	+2/3	-2/3	1/3	-1/3	0	0
Bottom	b	$\bar{b}$	-1/3	+1/3	1/3	-1/3	0	0

Table 1 - Quark Properties [Author's own, 2018]

There are six types of quark, each with individual properties such as charge and strangeness. Baryons consist of three quarks, whereas mesons consist of only a quark and antiquark. We know that the proton has a relative charge of +1, hence it consists of two up quarks and one down (2/3 + 2/3 - 1/3 = 1).

Leptons themselves are fundamental particles and can experience all forces except the strong interaction. Examples of leptons are electrons which orbit the nucleus, and muons which eventually decay to electrons.

Lepton/Antilepton	Symbol		Relative charge		Relative Mass
Electron/Positron	e^-	e^+	-1	+1	1
Electron neutrino/antineutrino	ν_e	$\overline{\nu}_e$	0	0	≈ 0
Muon/Antimuon	μ^-	μ^+	-1	+1	207
Muon neutrino/antineutrino	ν_μ	$\overline{\nu_\mu}$	0	0	≈ 0
Tau/Antitau	τ^-	τ^+	-1	+1	3500
Tau neutrino/antineutrino	ν_τ	$\overline{\nu}_\tau$	0	0	≈ 0

Table 2 - Lepton Properties [Physbot, 2015]

Bosons are specific exchange particles for the fundamental forces (of which there are four: Strong Nuclear force, Weak Nuclear force, Electromagnetic force and the Gravitational force). Exchange particles transfer charge, energy and momentum, amongst other quantities, during interactions between particles. The Standard model groups the fundamental particles of matter (fermions) and corresponding exchange particles for these fundamental forces (bosons), the diagram below outlines this:

force	boson symbol	boson name
strong	**g**	*gluon*
electromagnetic	**γ**	*photon*
weak	**W^+, W^-**	*W bosons*
	Z°	*Z boson*

Figure 2 - Fundamental forces and their exchange particles [Manchester University Particle Physics Group, 2003]

These describe the main constituents of fundamental particles. However, there is another subset. Exotic matter is non – baryonic. It consists of particles that are not made of baryons such as protons and neutrons. An example of an exotic particle is the Higgs Boson and the Baby Higgs itself.

Higgs Field and the Higgs Boson

In 1973, it was realised that the weak nuclear force and the electromagnetic interaction can both be described with the same theory, stating that they both stem from a single force known as the electroweak force (HyperPhysics, 2014). However, according to this theory, fundamental particles did not have mass.

Heisenberg's uncertainty principle and Einstein's energy-mass equivalence, which I will explore later, tell us that a massless particle will have zero rest energy. As its energy is zero, it will be

able to exist for an infinite amount of time and have infinite range. Figure 3 is a Feynman diagram of the electromagnetic interaction in which the virtual photon acts as the gauge boson:

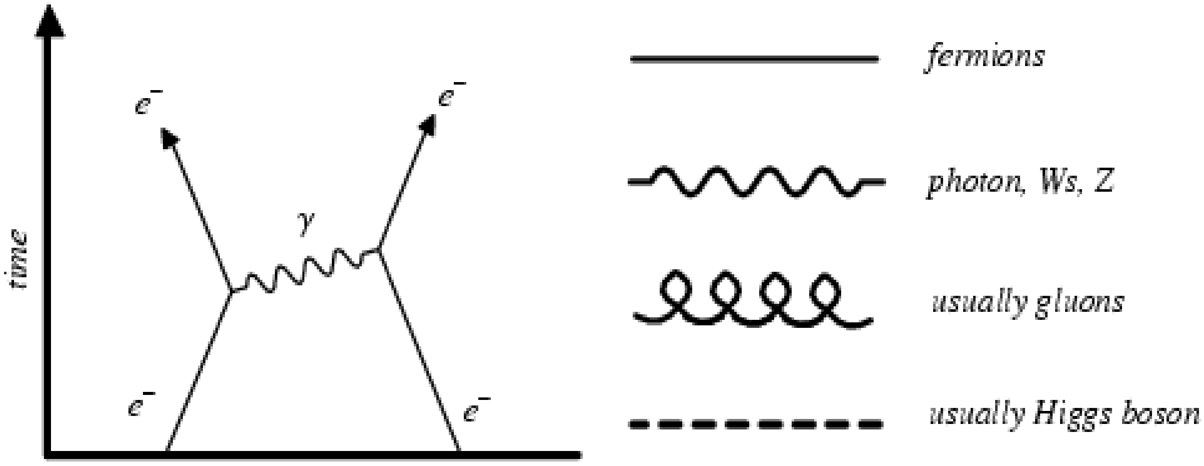


Figure 3 - Feynman Diagram of Electron-Positron Annihilation via Electromagnetic interaction [Weisstein, 1996]

On the contrary, W^+ and W^- bosons, the gauge bosons for the weak interaction, do have mass. This mass means the weak interaction is not infinite and instead acts over a very short range of approximately 0.001 fm. Heisenberg's uncertainty principle can be used to show that W bosons act over a short distance and so must have a relatively large mass.

Heisenberg's uncertainty principle states it is impossible to simultaneously know the exact position and momentum of a particle. However, there is a different version relating the lifetime and energy of supposed particles in a vacuum:

$$\Delta t \Delta E \geq \frac{\hbar}{2}$$

Where Δt is the lifetime of the virtual particle, ΔE is the energy required to form the virtual particle and $\hbar$ is a constant h-bar (1.05×10^{-34} Js) equal to Planck's constant h divided by 2π. The uncertainty principle tells us that something can come from nothing, provided that the something created returns to nothing within a specified time Δt, so short it is immeasurable. By applying this idea to a vacuum, Heisenberg's uncertainty principle infers that empty space is not truly empty and instead consists of virtual particles that continuously form and annihilate in these immensely short time periods. As the rest energy of a W boson is known (80 GeV), their maximum lifetime Δt can be calculated:

$$\Delta t = \frac{\hbar}{2\Delta E}$$

The energy of 80 GeV is equal to 1.28×10^{-8} J:

$$\Delta t = \frac{1.05 \times 10^{-34}}{2 \times (1.28 \times 10^{-8})}$$

$$\therefore \Delta t = 4.12 \times 10^{-27} \text{ s}$$

The maximum distance the W boson can travel is then equal to $c\Delta t$:

$$c\Delta t = 1.23 \times 10^{-18} \text{ m}$$

This maximum distance is also approximately the range of the weak interaction which I stated earlier, 1×10^{-18} m (0.001 fm). The ranges are congruent because the W boson is the exchange particle for the weak interaction, hence the distance travelled by the W boson determines the range of the weak interaction. As the weak interaction has a range much shorter than the infinite range of the electromagnetic interaction, the W boson must have a mass larger than the zero mass of the photons. This shows that the electroweak theory was correct for photons, which are massless, however W and Z bosons do have mass and so the picture was not complete.

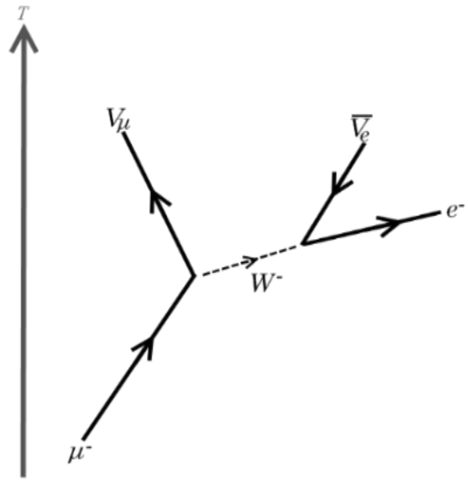


Figure 4 - Feynman Diagram of Muon Decay via Weak Interaction [Physics Stack Exchange, 2016]

Quantum Field Theory describes fundamental particles as quanta: waves whose amplitude and energy are the minimum values possible in their respective field. For example, electrons are quanta in the electric field. Although QFT was a strong theory, it also predicted that constituents of the atom, including electrons, would have no mass. If the electron had no mass, then it would always travel at the speed of light and consequently experience no time. However, electrons have an intrinsic quantum spin called chirality. This can be either left or right handedness, relative to the direction of motion. Seeing as the spin of an electron can change from left to right, it evolves and therefore must experience time. The electrons experience of time means it does not travel at the speed of light and hence has a mass. Photons also have spin, but it does not change therefore the photon does not evolve and does not experience time. If photons and electrons are both quanta, why does the electron have mass if the photon does not?

When electrons pass through an electromagnetic field, they are accelerated and emit electromagnetic waves. These waves have energy, the law of conservation of energy tells us that this energy cannot have simply been created and so must have come from the electrons, hence the electrons must lose energy equal the energy of the emitted waves. Work must be done to the electrons to supply the energy they lose.

$$w = Fd$$

For work to be done over a certain distance, a certain net force must act on the electron. Newton's second law of motion says that the net force applied to a body is proportional to its acceleration (The Physics Classroom, 2015).

$$F = ma$$

Since the electrons have an acceleration and a force is applied to them, they must then have a mass. This explanation for mass is sufficient for charged particles which will interact with the electromagnetic field and be accelerated. However, uncharged particles such as Z boson also have mass but do not interact with the EM field, hence there must be yet another cause for the mass of fundamental particles.

To rectify these problems, Peter Higgs, François Englert and Robert Brout proposed a mechanism explaining why particles have mass. Entitled the Brout-Englert-Higgs mechanism (Higgs mechanism theory), it implied there is an invisible three-dimensional field named the Higgs field that pervades all of space (CERN, 2011). The degree to which particles interact with this field determines their mass. Imagine moving balls through a viscous liquid, where the slower they fall, the greater their mass becomes. For example, the top quark is the heaviest fundamental particle and so it must interact the greatest with the Higgs field. However, photons, being massless, do not interact with the Higgs field at all. Left handed electrons have a weak hyper charge which allows them to feel the weak nuclear force, similarly to how normal electric charge allows charged particles to feel the electromagnetic force. The electrons can flip from left handed to right handed by losing their weak hyper charge and vice versa, which is known as parity violation. The Higgs field is believed to allow this gain/loss of weak hyper charge.

Einstein's equation of mass – energy equivalence tells us:

$$E = mc^2$$
$$\therefore m = \frac{E}{c^2}$$

The energy E of the quanta can also be defined as Planck's constant h (6.63×10^{-34} Js) multiplied by the frequency of the wave f. Seeing as quanta are waves with the minimum possible frequency, this will be $f_{\min}$.

$$E = hf_{\min}$$

Therefore, the quanta of each field have a specific mass:

$$m = \frac{hf_{\min}}{c^2}$$

In contrary to other fields, the equilibrium value of the Higgs field throughout the universe is not zero. This is shown by the "Mexican Hat Potential" which says that for the Higgs field, the point of equilibrium is not the origin of the energy – field strength graph. This means that for all points in space the value of the field will not be zero.

This can be thought of as a ball resting on the centre of the slope, it is in unstable equilibrium at the peak and so will roll into the "brim" of the hat where it will form a stable equilibrium away from the centre where the value of the field would have been zero. Since the value of the field is not zero, it will constantly act on the fundamental particles.

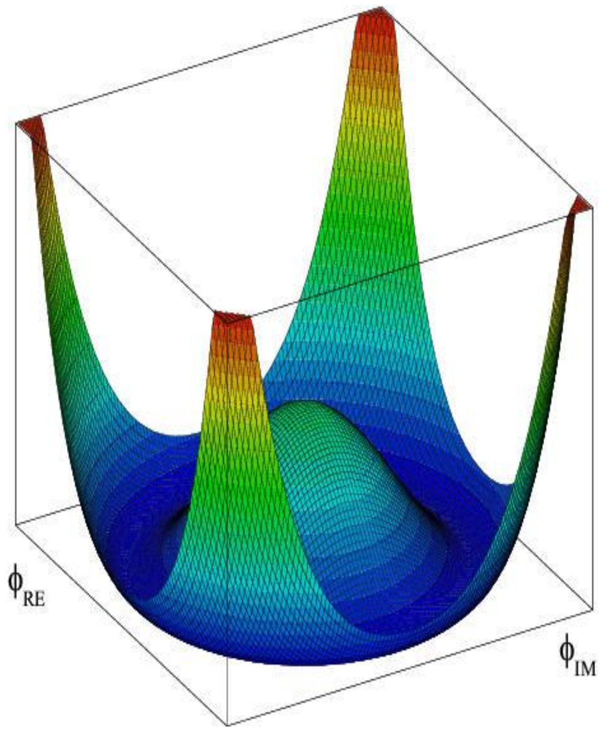


Figure 5 - "Mexican Hat Potential" of The Higgs Field [Wikipedia, 2018]

As stated earlier, all forces that interact with particles do so through an exchange particle. The Higgs field must have a boson which acts as an exchange particle between fundamental particles and the Higgs field itself. Hence, there forms the prediction for the Higgs boson, the quantum of the Higgs field, an excitation in the Higgs field which acts as the exchange particle.

Large Hadron Collider and Detection of the Higgs Boson

The Large Hadron Collider (LHC) inside CERN accelerates protons to 99.999999% the speed of light around the circumference of a 27km long tunnel. These protons then collide with each other in the ATLAS detector, producing an array of fundamental particles. The muon detector in the coating of the ATLAS detector indicates the presence of muons and the calorimeters measure the energies of particles passing through them. The innermost layer consists of trackers which record the trajectory of the particles and pixel detectors highlight any photons produced. This information is collated into a computer image produced representing the collision, referred to as an event.

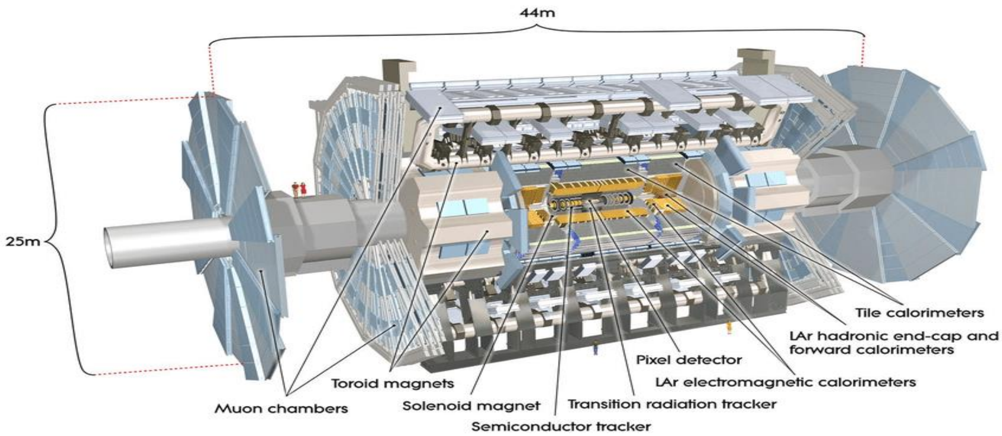


Figure 6 - A Toroidal LHC Apparatus (ATLAS) Detector [LMU, 2012]

CERN condensed thousands of events producing a variety of diphoton masses represented by $m_{\gamma\gamma}$, against the number of weighted events. The data are weighted by the ratio of signal to signal plus background. This produced a histogram showing an exponential curve where the number of weighted events was inversely proportional to the diphoton mass. The bump in the curve at 125 GeV was the evidence for the detection of the Higgs boson.

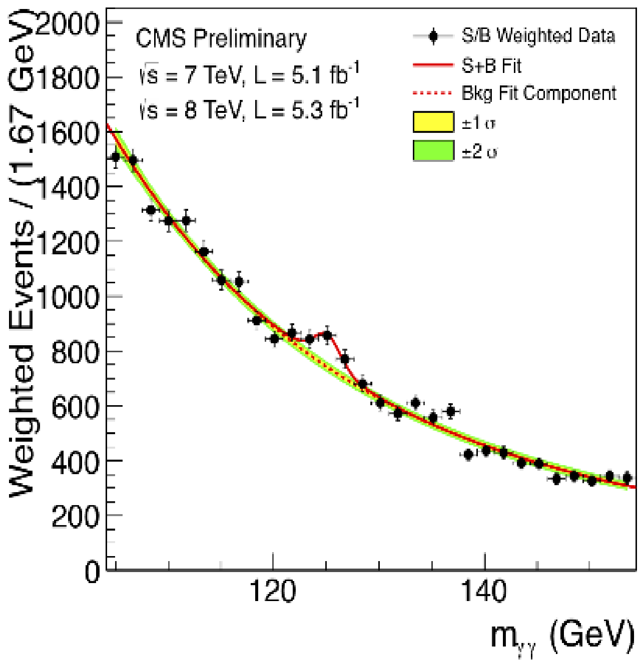


Figure 7 - The detection of the Higgs Boson [Physics Stack Exchange, 2012]

Baby Higgs

The Higgs Boson must also interact with the Higgs field to gain its own mass. However, seeing as it is a quantum of the Higgs field, it is technically interacting with itself. This would produce a very strong interaction and so would cause the Higgs boson to have a large mass of approximately $125\ \mathrm{GeV}$. This relatively large mass would cause the Higgs boson to decay after production in approximately $1.56 \times 10^{-22}\ \mathrm{s}$, a time too short to observe the Higgs Boson directly in the detectors. Therefore, another approach was taken by scientists at CERN in which the products of the decay would be observed and collisions that produced the correct decay products and corresponding energy would provide sufficient evidence for the Higgs Boson detection.

There are currently five different decay modes for the Higgs Boson H to take, being:

$H \rightarrow b + \bar{b}$ (bottom quark and its antiquark)

$H \rightarrow \tau^- + \tau^+$ (tau and antitau lepton)

$H \rightarrow \gamma + \gamma$ (two photons)

$H \rightarrow W^+ + W^-$ (W boson and its antiparticle)

$H \rightarrow Z^0 + Z^0$ (two Z bosons)

However, I will be investigating a possible unproven sixth decay mode for the Higgs Boson using raw data I have obtained from CERN. In this theoretical decay the Higgs Boson H decays to two "Baby Higgs" Bosons represented by ϕ:

$$H \rightarrow \phi + \phi$$

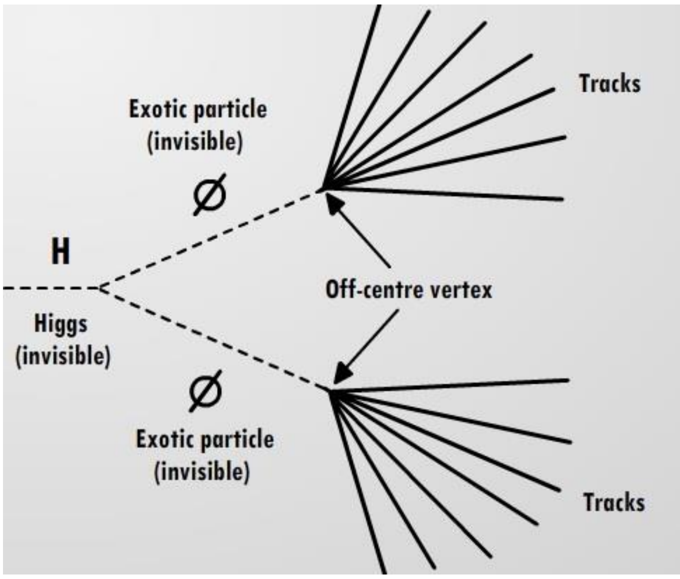


Figure 8 - Representation of Higgs Boson decay to two ϕ Bosons [Higgs Hunters, 2014]

These ϕ particles interact with standard model particles weakly meaning they will have a smaller mass hence a slower decay rate and therefore a longer lifetime than the Higgs Boson. In theory this will cause the Baby Higgs to travel a greater distance from the collision point before decaying and producing visible particles. If this is the case, the visible fundamental particles will be produced away from the collision point of the protons. These are known as off-centre vertices and will referred to as OCVs. An example of this is shown in figure 9:

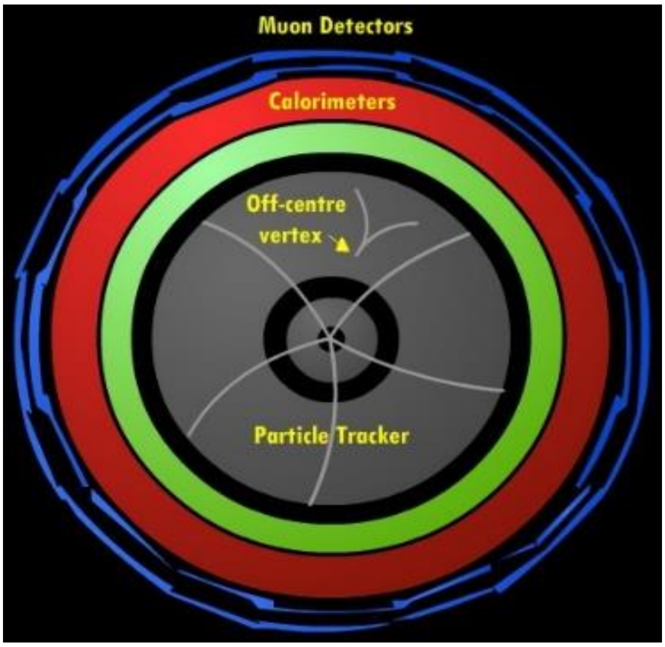


Figure 9 - Simplified example of an event [Higgs Hunters, 2016]

The decay mode of the Baby Higgs boson is dependent on its mass m_ϕ. If the mass is smaller than double the mass of a b quark but greater than double the mass of a tau lepton t, i.e. within the range $2m_t < \phi < 2m_b$, then the baby boson is likely to decay to a tau lepton and antitau lepton:

$$\phi \rightarrow \tau^- + \tau^+$$

However, if the mass of the baby boson is greater than double the mass of a b quark, it will likely decay to a bottom quark and a bottom antiquark:

$$\phi \rightarrow b + \bar{b}$$

The expected distance that the ϕ bosons will travel can be calculated. From the baby bosons reference frame, it exists (from production to decay) for a time t_ϕ . From simple mechanics the distance travelled by the ϕ boson would be expected to be equal to ct_ϕ. However, the bosons have mass and so will not be travelling at the speed of light but instead they will be travelling at a speed v, a value lower than c. Seeing as the speed of light must remain constant in all reference frames, the time t_ϕ will be time dilated by the Lorentz factor γ.

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Therefore, the approximate distance travelled by the ϕ boson:

$$c(\gamma t_\phi)$$

Under the assumption that all energy from the Higgs Boson is split evenly between the two ϕ bosons, seeing as the energy of the Higgs Boson is $m_H c^2$, the energy of each boson E_ϕ is equal to:

$$E_\phi = \frac{m_H c^2}{2} = \gamma m_\phi c^2$$

$$\therefore \gamma = \frac{m_H}{2m_\phi}$$

As we know the mass of the Higgs Boson and the expected mass of the ϕ boson, γ can be calculated, which allowed CERN to calculate the distances travelled by the Baby Higgs in the simulated data.

Click set ID	User ID	Logged in?	Zooniverse	Timestamp	click X	click Y	N tracks	type	mass	decay leng	projection	true X1	true Y1	true X2	true Y2
546e258d	2	1	AHH00000	2014-11-2	385.481	629.927	2	hZ	8GeV	1mm	XY	513.262	512.739	498.073	524.553
546e2628	2	1	AHH0000h	2014-11-2	521.547	521.578	05-Oct	hZ	20GeV	100mm	XY	537.659	519.132	560.901	595.724
546e264c	2	1	AHH0000a	2014-11-2	409.418	511.499	2	hZ	50GeV	10mm	XYzoom	509.098	512.533	530.401	523.946
546e264c	2	1	AHH0000a	2014-11-2	652.574	629.927	2	hZ	50GeV	10mm	XYzoom	509.098	512.533	530.401	523.946

Figure 10 - Example of Excel data of click coordinates and decay lengths [Author's own, 2018]

Data from CERN

As the sample size for simulated data was 800,000 events and for real data was 60,000 events, CERN decided to use the following requirements for an event to be analysed to reduce the sample size:

- Minimum two muons detected. This is because approximately 2% of the time that a Higgs Boson is created, a Z boson is also created. 3.3% of the time a Z boson is created, the boson decays to two muons. Applying this parameter increases the probability of finding a Higgs decay to 150 in 5 million.

- The Z boson travels away from the proton collision point. Events containing a Z boson increase the probability of finding a Higgs event. This is since virtual Z bosons may emit Higgs bosons through the "Higgs-Strahlung" process. An isolated Z boson may decay while stationary however, when the Z boson decays with a Higgs boson the two particles tend to move away from each other, hence also away from the proton collision beam. Applying this parameter increases the probability of finding a Higgs event to 90 in 300,000.

- There should be missing momentum present. The ϕ boson is foreign to the ATLAS detector and invisible, so it will not be picked up by the detectors. The ϕ boson will correspond to the missing momentum represented by a dashed red line on the projection. Applying this parameter increases the probability of finding a Higgs event to 1 in 1000.

The detectors within ATLAS process their readings into tracks of charged particles. Since the particle accelerator contains immensely strong magnets, there will be an electromagnetic interaction between the magnets and the charged particles causing their tracks to curve. Neutral particles such as photons and neutrons therefore cannot be traced, however their energy will still be detected by the peripheral calorimeters. The yellow and red blocks in the calorimeters represent energy detections, the translucent white fields represent areas of high energies named "jets". The rectangular red blocks at the end of green muon tracks represent the muon energy. Blue blocks may appear opposite a muon and represent the energy from the decay of a b quark.

A computer algorithm was a potential method for my analysis, however through investigation, CERN determined that human analysis is more reliable for this type of data. The efficiency of the two methods were evaluated by comparing the rate of correct classifications made and the rate of false classifications made. This suggested human analysis is more efficient as our natural ability for pattern recognition is of a higher degree. Figure 11 is an example of a simulated event in the XY projection:

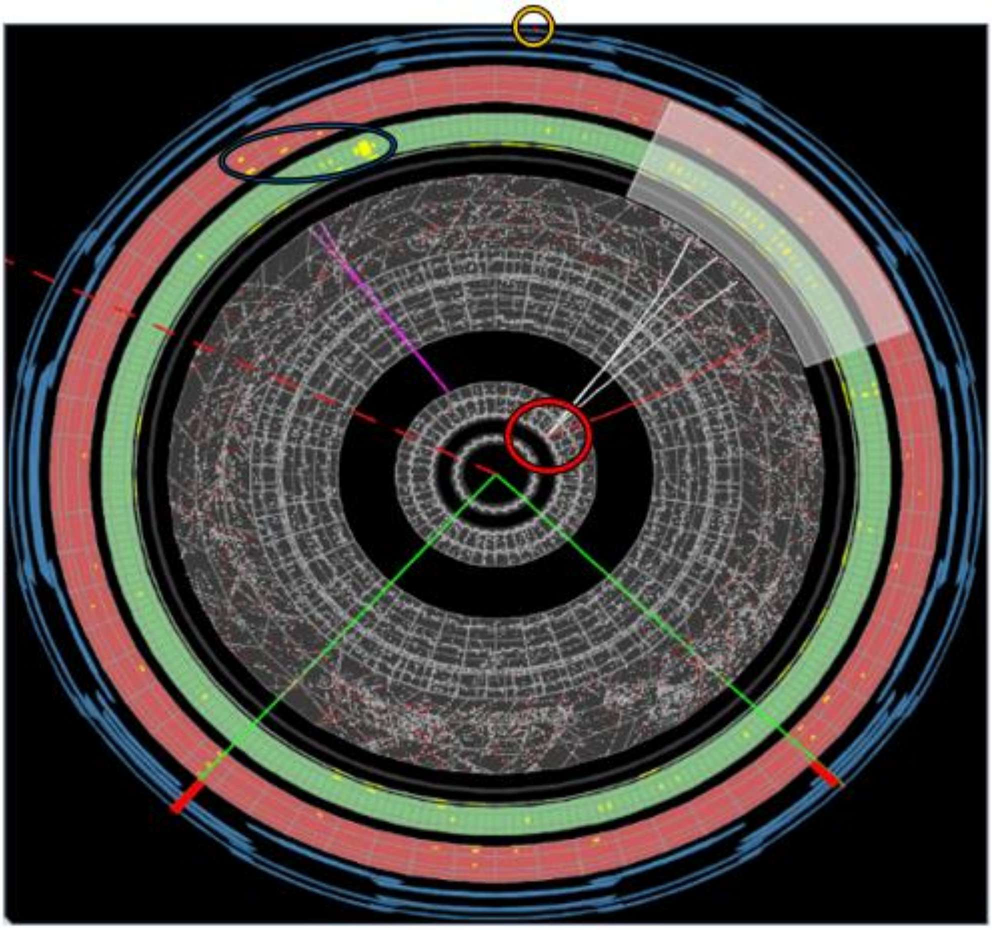


Figure 11 - AHH0000hlk Simulated Event [Zooniverse, 2016]

Key:

Symbol	Name
	Muon Detection
	Off Centre Vertex
	Energy detection
	Muon Track
	General Particle Track
	Missing Momentum Track

Simulated Data

CERN formulated simulated data for citizen scientists to analyse so that patterns in analysis and common mistakes can be identified. Collisions in ATLAS are recorded in three viewing angles (projections): XY, XY Zoom and RZ. I have used a systematic sampling technique to select every 8,000th simulated event from a collection of 800,000 events in each projection. By inserting the raw data of the users' click coordinates in addition to the true coordinates of the decays for a chosen event into excel, I selected the X and Y coordinates of the clicks of all users for that event, inserting this data into a scatter graph with scale axis 0 - 1024 and the vertical y axis flipped. After underlaying the image projection as the background so that it lines up with the coordinates, I identified any imperfections with the chosen event, such as the detectors incorrectly detecting particles or glitches in the formatting of the event which may hinder the citizen scientist analysis.

After comparing the coordinates of the public clicks to true decay coordinates for 100 events in each projection, totalling 300 events, I calculated the percentage error of each click and took an average percentage error in accuracy for each type of projection, my results are stated below:

Projection Type	Percentage error in analysis /%
XY	31.9
XY Zoom	39.4
RZ	56.3

Author's own (2018)

The XY projection produced the lowest percentage error in public analysis as expected, hence I will investigate this projection further for evidence of the Baby Higgs.

Real Data

Over the course of four months I have investigated 2021 events in the XY projection. In my analysis, I searched for events which meet the stated parameters which will therefore show sufficient evidence for the Baby Higgs. The proportion of events containing a Baby Higgs is expected to be 2 out of 2000. The following two events have been selected as successful:

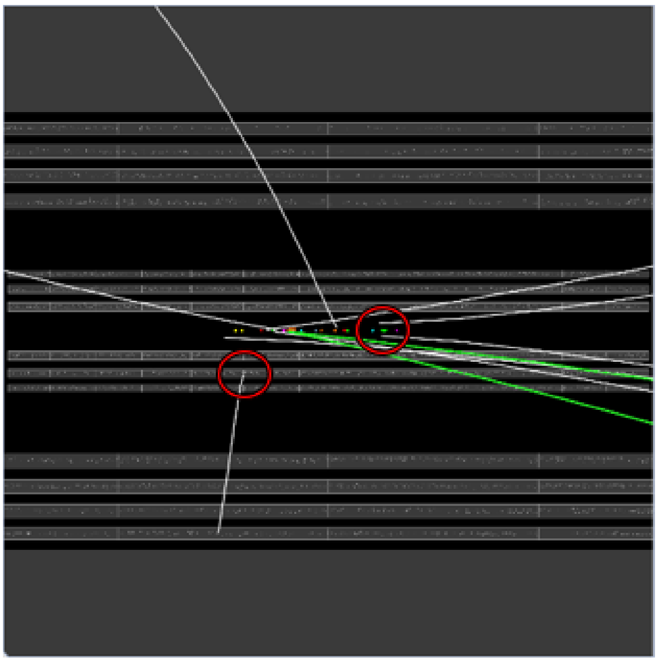


Figure 12 - AHH0000oji RZ projection [Zooniverse, 2016]

The XY projection successfully shows off-centre vertices, highlighted by the red rings. Along the same path as the direction of the off-centre vertex are multiple muon detections in the muon detectors highlighted by the yellow rings. This shows that the particles produced at the off-centre vertex will then decay further to muons and antimuons, as predicted as a possible decay mode of the Baby Higgs. The missing momentum is in a similar region to the muon detections and so may possibly represent the Baby Higgs which the detectors lack the capability to detect yet. The RZ projection also shows an OCV which supports the findings in the XY projection.

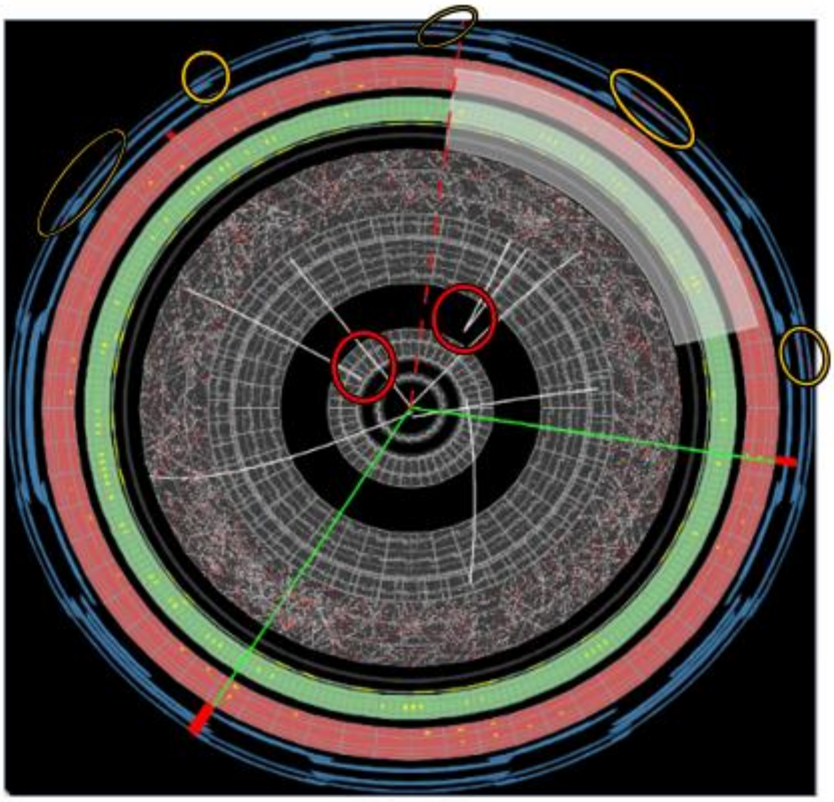


Figure 13 - AHH0000oji XY projection [Zooniverse 2016]

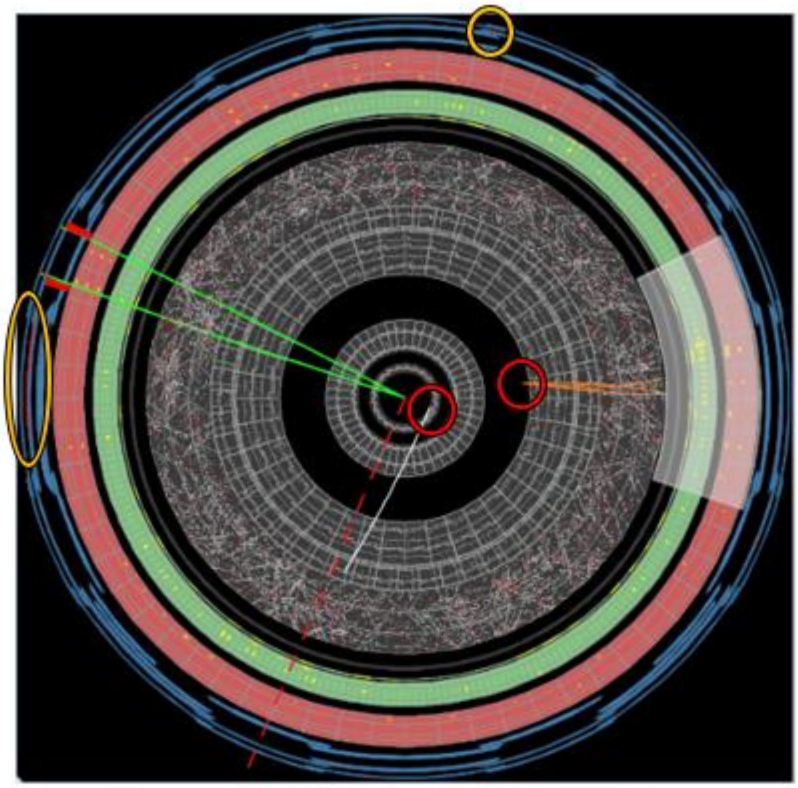


Figure 14 - AHH0000ytb XY projection [Zooniverse, 2016]

The XY projection shows an OCV which decays to five particles. In the direction of the OCV are two muon detections which may represent the muon-antimuon production from decay of the Baby Higgs. The OCV is noticeably further in this projection which shows the exotic particle may interact with the Higgs field to a weaker degree, and so has less mass causing it to be more stable allowing it to travel further before decaying. The OCV is reinforced in the RZ projection. Although the direction of missing momentum does not agree with the OCV, an exotic particle may still have been produced which was neutrally charged. This means it would be still be accounted for in the missing momentum calculation however direction cannot be detected because it does not interact with the magnetic fields. The presence of a possible neutrally charged particle is also shown by energy detection in the same direction of the missing momentum and the opposite direction where no particles are seen to be travelling through.

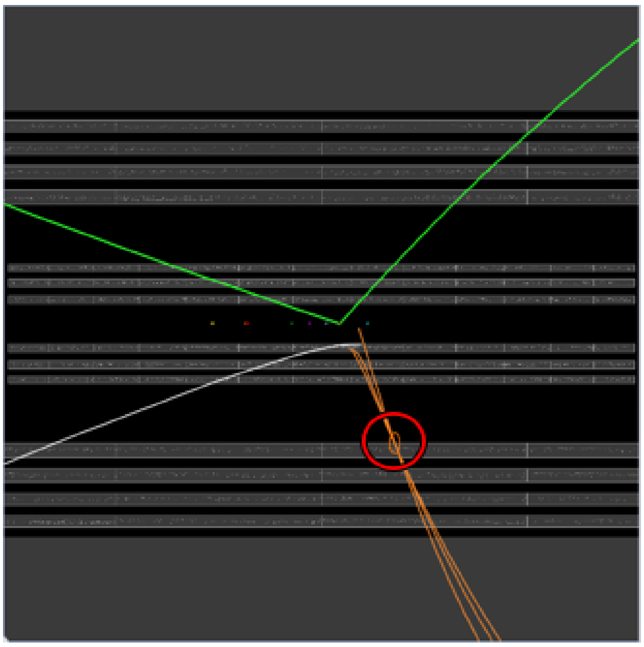


Figure 15 - AHH0000ytb RZ projection [Zooniverse, 2016]

Conclusion

Through my analysis of 2021 events from data at CERN, I have selected two events which show strong evidence for the presence of Baby Higgs particles. By proportion, using the parameters set by ATLAS, I predicted to find only two events containing OCVs out of my sample of 2021 events. The two successful events consist of a range of two – five muons.

From my findings I conclude that there is insufficient evidence to reject the existence of a Baby Higgs particle. Although the sample size is small and systematic sampling introduces bias if there is a repeated trend in the results, the number of events containing OCVs is equal to the predicted number and each clearly shows decay to muons. All successful events with OCVs contained missing momentum, showing an undetected high energy exotic particle has been produced. This could either be the Higgs Boson or the Baby Higgs Bosons; however, in one event, the particle has approximately the energy of the rest mass of two muons (211 MeV) because it produces two muons. The mass of the Higgs Boson is 125 GeV, which is approximately 600 times larger than the mass of this exotic particle. If an exotic particle such as the Higgs Boson, of mass 125 GeV, decayed straight to detectable fundamental particles, much heavier particles such as tau leptons would be produced. As this is not the case, this suggests the Higgs Bosons do first decay to Baby Higgs bosons of smaller mass which then themselves decay to muons, leptons of smaller mass than tau. This supports my proposal that this evidence is sufficient for the existence of Baby Higgs Bosons.

On the contrary, my successful events have a range of muon numbers produced, totalling an energy range of 211-538 MeV. The Higgs Bosons decay is insufficient to explain this as it would produce heavier particles; however, if the Baby Higgs exists and is only of one form, why would there be a range of energies that can be produced? This conundrum leads me to believe that there may be multiple versions of the Baby Higgs, identical in properties such as spin and charge, yet consist of different masses and so can decay to a range of number of muons.

There are many implications from my findings, with the most important being evidence that the standard model is not complete and must be investigated further. Along with phenomena such as dark energy and dark matter, the search for more fundamental particles will provide a broader picture of the universe.

To improve my methodology, I would increase my sample size and also analyse events in the RZ projection. Completing this investigation as an independent scientist enforced limitations for my sample size. A larger sample size would provide a lower uncertainty in my findings, by increasing reliability and reducing the implications of anomalous results. The use of a computer algorithm may have allowed for a greater sample size; although, there may be many imperfections which I identified in my analysis which the algorithm may have missed. My investigation into the most reliable projection was sound and increased efficiency in collection of results. However, this may mean I missed interesting events only visible from the RZ projection.

Higgs Hunters

Jared Richard – The Haberdashers' Aske's Boys' School

Summary

2012 saw the detection of the Higgs Boson, a particle which was thought to complete the standard model. However data from CERN suggests that the Higgs boson may decay to lighter and longer living particles called "Baby Higgs" or "Baby Bosons". I will analyse data from proton-proton collisions at CERN to assess the reliability of the public click data results and reach a conclusion on whether any valid detections are substantial for proof of the Baby Higgs.

Research Aims

- To understand the images and what constitutes as evidence for the Baby Higgs
- To compare "click data sets" citizen scientists with original images to investigate the reliability of the analysis from the citizen scientists.
- Identify common errors from public analysis, highlighting imperfections in CERN's data and how this affected the public analysis
- To select data which I believe is reliable and use this to suggest existence of the Baby Higgs.

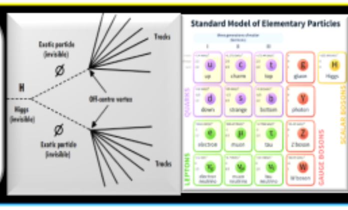


Figure 1 – Standard model of fundamental particles

Background Information

The Large Hadron Collider (LHC) at CERN is the world's largest particle accelerator and accelerates beams of protons to 99.999999% the speed of light to be collided in the atlas detector. Using Einstein's E = mc^2 equation, we know that their energy will be converted into small mass in the form of fundamental particles (particles that cannot be broken further). The Higgs field causes particles to slow and gives them mass relative to their interaction with this field. E.g. top quarks move slowly, interact greatly, hence they have a large mass. However photons move quickly, hardly interact with the Higgs field which is why they are massless. The Higgs boson, detected in 2012, is an excitation in this field and enforces the Higgs field.

The Higgs Boson decays to fundamental particles in five ways already observed, however the Higgs boson may decay in another previously unseen way: first to two Baby Higgs which then themselves will decay to fundamental particles. Baby Bosons exist for longer and are lighter so they travel further from the collision point before decaying, producing off-centre vertices. These displaced vertices act as proof for the baby bosons, however the reliability of the analysis of their positions must be tested. 40,000 events (collisions) were uploaded for public analysis and each event had 3 projections (viewing angles). These images contain simulated and real data to help determine the patterns and reliability of public analysis.

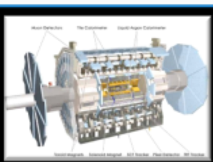


Figure 2 - ATLAS (A Toroidal LHC Apparatus)

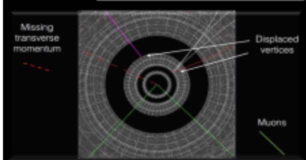
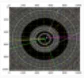


Figure 3 – labelled example of an event

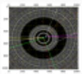
Experimental Method

- Use a systematic sampling technique to select every 10,000th simulated event, using its zooniverse ID.
- For each event selected, analyse the accuracy of the XY zoom and RZ projection.
- To do this: insert the raw data of the users' click coordinates for a chosen event into excel. (This data should include the coordinates of the clicks made by users and the coordinates of the true values of decays.)
- Select the X and Y coordinates of the clicks of all users for that particular event, inserting this data into a scatter graph with scale axis 0-1024 and the vertical y axis flipped.
- Underlay the image projection as the background so that it lines up with the coordinates and the accuracy of the clicks can be compared.
- Identify any imperfections with the chosen event, take these into consideration when analysing the accuracy.
- Calculate the percentage error of each click and take an average percentage error in accuracy for each event.
- Take an average of the percentage error for the XY and RZ projection.
- Compare the percentage errors and infer which projection leads to the most accurate analysis (lowest percentage error) .

Results



XY/XY Zoom Projection analysis



XY zoom projection:

The XY zoom projection shows a magnified transverse cross section of the Atlas detector, essentially a face on view. This produces a more understandable view of the decays and therefore will likely provide more reliable public analysis.

- AHH00000a5:

$$X\%\ error = \frac{513.62-385.481}{513.62}\times 100 = 24.9\%\ error \quad Y\%\ error = \frac{512.739-629.927}{512.739}\times 100 = 22.9\%\ error$$
$$total\ \%\ error = 24.9 + 22.9 = 47.8\%\ error$$

- AHH00002wa

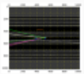
$$X\%\ error = \frac{509.333-505.163}{509.333}\times 100 = 0.82\%\ error \quad Y\%\ error = \frac{514.874-500.424}{514.874}\times 100 = 2.81\%\ error$$
$$total\ \%\ error = 0.82 + 2.81 = 3.63\%\ error$$

- AHH0000ece

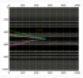
$$X\%\ error = \frac{512.89-494.43}{512.89}\times 100 = 3.60\% \quad Y\%\ error = \frac{383.481-647.793}{383.481}\times 100 = 68.9\%\ error$$
$$total\ \%\ error = 3.60 + 68.9 = 72.5\%\ error$$

Average % error from the selected sample of XY zoom projections

$$= \frac{(47.8)+(2.36)+(3.63)+(0.37)+(72.5)+(61.1)+(38.7)+(16.8)+(1.59)+(74.1)}{10} = 31.9\%\ error$$



RZ Zoom Projection analysis



RZ zoom projection:

The RZ projection shows a longitudinal cross section of the Atlas detector, a side on view. There is a greater error of uncertainty when images are transferred to the RZ projection and its distorted appearance will likely produce less accurate public analysis.

- AHH00002kh

$$X\ \%\ error = \frac{511.175-537.312}{511.175}\times 100 = 5.11\%\ error \quad Y\ \%\ error = \frac{554.127-583.422}{554.127}\times 100 = 5.29\%\ error$$
$$total\ \%\ error = 10.4\%\ error$$

- AHH00008c1

$$X\ \%\ error = \frac{708.163-636.175}{708.163}\times 100 = 10.2\%\ error \quad Y\ \%\ error = \frac{510.761-571.097}{510.761}\times 100 = 11.8\%\ error$$
$$total\ \%\ error = 10.2 + 11.8 = 22.0\%\ error$$

- AHH0000ed7

$$X\ \%\ error = \frac{534.831-438.261}{534.831}\times 100 = 18.0\%\ error \quad Y\ \%\ error = \frac{537.21-504.965}{537.21}\times 100 = 6.00\%\ error$$
$$total\ \%\ error = 18.0 + 6.00 = 24.0\%\ error$$

average % error from the selected sample of RZ projections

$$= \frac{(10.4)+(22.0)+(98.6)+(20.4)+(91.3)+(19.5)+(31.8)+(3.12)+(21.2)+(97.7)}{10} = 41.6\%\ error$$

The percentage error of coordinate analysis in the XY zoom projection is lower than the RZ projection (31.0 < 41.6), therefore there is sufficient evidence to accept the XZ projections as more accurate and reliable.

Analysis and Conclusions

A comparison between the percentage error of the citizen scientists analysis in the two projections from the selected sample shows that, on average, the percentage error in XY was lower. There are many factors that affect this, however a significant one is the visibility of XY and how it is generally more easily understandable. As mentioned by users on ATLAS online, the RZ projection is often found to be confusing and distorted, producing large uncertainties in coordinate transformation. This can lead to incorrect clicks which will alert LHC of "weird" decays when in fact the scientist was not able to correctly decipher what they were seeing.

There are several potential solutions, for example: offering extensive training would allow users to be more comfortable with handling RZ projections, therefore producing more accurate analysis, however this is costly and time consuming. Less people may be willing to participate if they must train for it. Another option is to use a computer algorithm to analyse any irregular decays, however the simulated and non simulated projections had many imperfections, as highlighted by scientists, which would confuse the algorithm possibly causing a significant systematic error. Therefore human analysis is most likely more reliable option.

To conclude, because XY shows a greater accuracy, any decays identified as "weird" in the XY projection should be further analysed as they have a greater chance of providing substantial proof for Baby Bosons.

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