Search for the Z and Higgs Bosons

Be a high-energy physics researcher for a day

Orientation Phase

Orienting and Asking Questions

Provide Contact with the content and/or provoke curiosity

- Have you heard about the ultimate components of matter, the quarks and leptons?
- Have you heard about the most powerful accelerator in the world the LHC, which is built at CERN in order to study the components of matter?
- Have you heard about the Higgs boson discovery in 2012 and how it completed our model of the subatomic world?

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Learn about CERN

CERN is one of the world's largest research centers located near Geneva. It is dedicated to basic research: looking for answers to questions like "what is the Universe made of?", "what are the forces governing the behavior of the smallest constituents?", "what is dark matter made of?".

Watch the video "CERN in 3 mins": https://www.youtube.com/watch?v=PHP13tTjidA

The LHC@CERN

The Large Hadron Collider (LHC) is a gigantic scientific instrument at CERN. LHC is a circular accelerator with a circumference of about 27Km. The LHC tunnel spans the border between Switzerland and France and is about 100m under the ground. It is a particle accelerator used by physicists to study the smallest known particles – the fundamental building blocks of all things.

View the video below for further information

https://www.youtube.com/watch?v=pQhbhpU9Wrg

Two beams of subatomic particles called 'hadrons' – either protons or heavy ions –travel in opposite directions inside the circular accelerator, gaining energy with every lap. Physicists use the LHC to recreate the conditions just after the Big Bang, by colliding the two beams head-on at very high energy. Teams of physicists from around the world analyse the particles created in the collisions using special detectors in a number of experiments dedicated to the LHC.

Watch what happens when two heavy nuclei collide:

Heavy Ion Collision Event Animation

https://www.youtube.com/watch?v=k64s4Ho-8-I

The ATLAS detector/experiment

The ATLAS detector (A Toroidal LHC ApparatuS), which is the focus of this demonstrator, was designed to cover the widest possible range of investigations at the LHC. Its main objectives are/were to discover the Higgs boson, to test the theory of supersymmetry, to study matter and antimatter, the formation of dark matter and to search for extra dimensions and new phenomena.

Involved in the experiment are 3000 physicists from 180 universities and laboratories in 38 countries. The detector with 44m length and 25m height is the largest, in volume, detector ever built. Its size stems from the need for great accuracy in detecting the nature and trajectory of the particles resulting from the particle collisions.

For more information watch the video

https://www.youtube.com/watch?v=ckARmttkTS4

- What happens during the particle collisions that take place in the LHC?
- What are the experiments performed at the LHC trying to achieve?

Teacher Guidelines:

You may begin your lesson with a brief presentation of CERN and the Large Hadron Collider using videos or numerous pictures. Trigger a small conversation with your class by asking your students the questions mentioned above and others like them. Try to guide the discussion towards the introduction of the elementary particles.

You can find more information about accelerators and particle detectors in http://www.particleadventure.org/accelerators-and-detectors.html

Exploratory Phase

Question or Statement

Define Goals and/or questions from current knowledge

What do we currently know about the nature of subatomic particles and the forces that govern them?

Figure 1 shows (on the left with red and yellow) all the known elementary particles today. According to the most successful theoretical model, the Standard Model, all particles can be described on the basis of the six quarks and six leptons that are the fundamental building blocks. The forces that govern the interactions of particles are four and are transmitted via the force mediating particles (the right column of the figure).

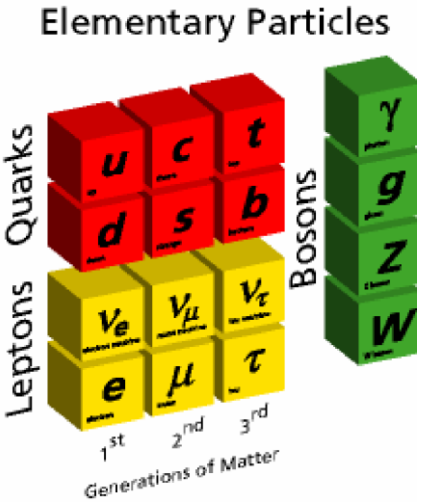


Figure 1 : Elementary particles and force carriers

The photon that has zero mass is the mediating particle of the electromagnetic force, the gluons (also massless) are the carriers of the strong interaction, the Z particles (which will be studied in this demonstrator) and W, are the mediating particles of weak interactions. Finally the graviton for which we know very little, but is different from other mediating particles, is gravity's mediating particle.

Teacher Guidelines:

For more information you can visit the site:
http://www.particleadventure.org/standard-model.html

Generation of Hypotheses or Preliminary Explanations

Particle Collision Products

Some particles are very short-lived and decay almost immediately to more stable particles. In most proton collisions, the protons have gentle interactions, and the majority of the particles continue in the direction of the original particles (rather than perpendicular to the beam). However, rarely a few very massive particles are produced. If particles originate from the decay of a parent particle, their tracks should join together at the same origin point, called a "vertex".

Most massive particle's decays often give rise to several high-energy particles going out at large angles, more or less perpendicular to the original protons in the beam. For this reason we measure the momentum in a plane transverse to the bean plane, the so called transverse momentum (p_T), and we use it to pick up interesting events. By adding up the decay products which come from the same vertex we reconstruct the original "invisible" particle. In this demonstrator you will reconstruct the Z^0 particle which is the carrier of the weak force responsible for the energy from the sun and radioactivity.

Decay of Z^o bosons

Since the Z (Z^0) is neutral the sum of the charges of its decay products must also be 0. This is because in nature charge is conserved. Therefore the Z must decay into a particle, antiparticle pair. The 100% probability of Z decay is divided between groups of particles according to additional conservations laws.

• In 10% of the Z-decays, charged lepton-antilepton pairs are produced. The three possible charged lepton pair types are electron-positron, muon-antimuon, and tau-antitau pairs. Each pair is approximately equally probable. This gives three decay possibilities.

• The Z boson decays in 20% of the cases into a neutrino and an antineutrino pair. The ATLAS detector is not capable of detecting neutrinos since they barely interact with anything (no electric charge).The neutrinos are therefore invisible to us and the only way we can “see” them is when we measure that there is some energy or transverse momentum missing after the collision (since we know that both transverse momentum and energy should be conserved in the collision)

• In 70% of Z decays, a quark-antiquark pair is produced. These appear as particle showers called “jets” in the detector.

In this demonstrator you will have to deal only with Z decays into lepton pairs (electron – positron or muon – antimuon) and will have to distinguish the different traces they leave in the detector.

Higgs boson decays

The Higgs boson which was discovered at CERN by the ATLAS and CMS experiments in 2012 completes the missing part of the Standard Model and through an associated mechanism, called Brout-Engelert-Higgs mechanism, postulated about 50 years before the Higgs boson discovery, the elementary particles and the weak force mediating particles (the W and Z bosons) acquire their mass.

Similarly to the Z boson, the Higgs boson is short-lived and deacys to a number of different particles. The easiest signature to detect is through its decay to a pair of Z bosons, which in turn each decay to a pair of leptons. This is the one that you will look for with the present demonstrator.

Teacher Guidelines

Scientists at CERN analyse the data they get from particle collisions done in the LHC in order to answer their questions. Your students will now be put in the shoes of scientists and will learn how to process the data and make "discoveries". Their work will involve the study of some events recorded by the huge ATLAS detector. But first, they will have to be able to answer scientific questions, such as:

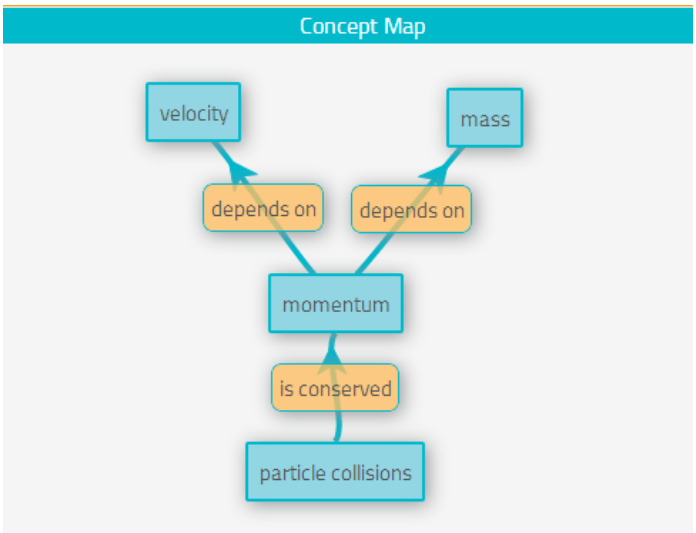
How are elementary particles classified?

When particles collide are new particles created or not?

What does "conservation of momentum" really mean?

Create a map which includes all the concepts that are relative to particle collision in the LHC. Use arrows to connect the different concepts.

An example concept map could be the following:



(1)

Evidence

Plan Investigation

Before starting the data analysis you should

I. Learn how to distinguish the different traces muons and electrons leave in the ATLAS detector
II. Understand how the invariant mass of short-lived particles is calculated using their decay products.

Furthermore try to answer the following questions:

- Do you know what the muons are?
- In order to learn how different particles interact with different components of the ATLAS detector play with the applet given in http://atlas.physicsmasterclasses.org/videos/teilchenidentifikation.swf
- Based on the previous game can you distinguish the signature which a muon leaves in the ATLAS detector from that of an electron?

Figure 2 shows a Higgs boson event recorded by the ATLAS experiment, the green lines are electrons and the red ones are muons

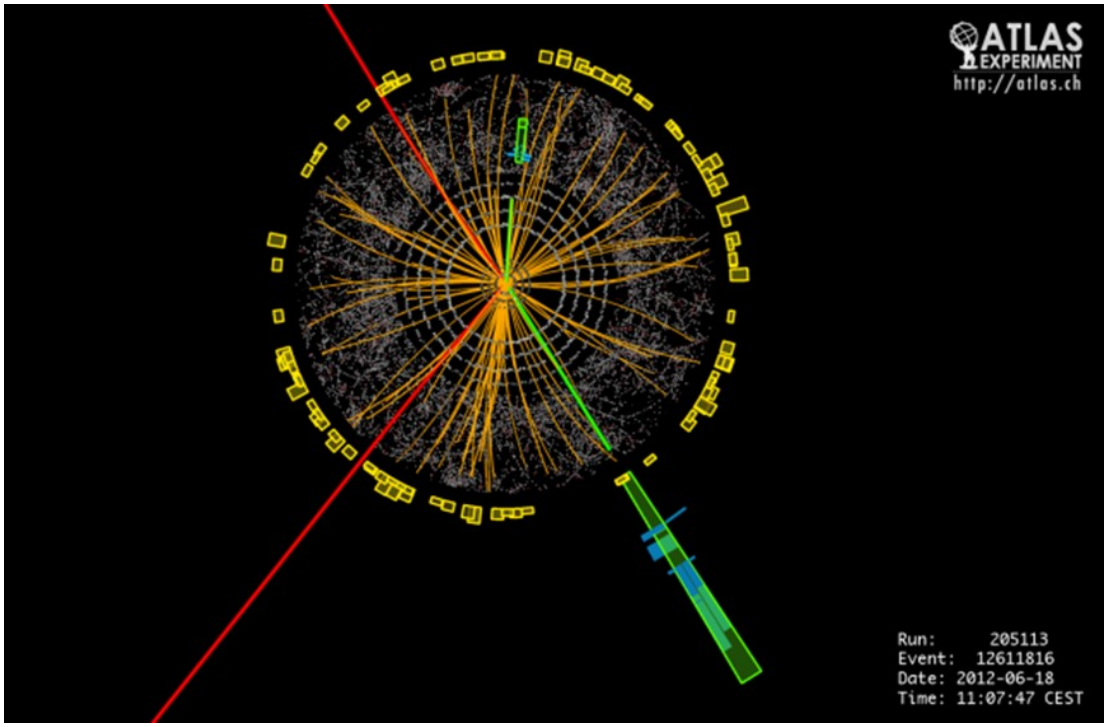


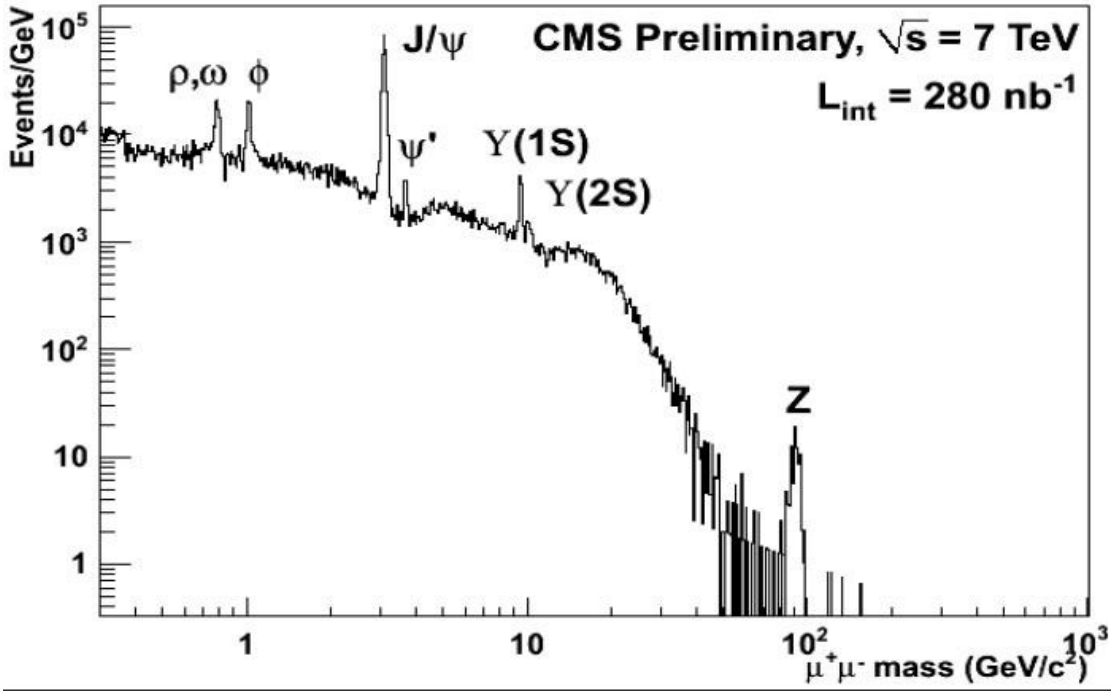
Figure 2: A Higgs boson candidate recorded by ATLAS at the LHC.

In order to calculate the invariant mass you should calculate the total momentum and energy of all decay products of the unstable (short-lived) particle.

- Calculate the total momentum of all particles involved in the decay of the original particle as a vector sum of all momenta:

- $\vec{p} = \vec{p}_1 + \vec{p}_2 + \vec{p}_3 + \ldots$
- Learn how to calculate the invariant mass of a decaying particle from Einstein's formula $E=mc^2$ (where m is the **total** mass of the moving particle) or written in an equivalent form $E^2=p^2+m_0^2$, (where m_0 is the **rest** mass of particle) and therefore the mass can be calculated as
- $m = \sqrt{E^2 - p^2}$ (1)
- **E** is the sum of energies of the decay products and **p** is the vector sum of all momenta of the decaying particles as calculated above.

Figure 3 below shows the invariant mass of two muons measured by the CMS experiment.



Teacher Guidelines

Remind your students that momentum is a vector whereas the energy is NOT.
Try to explain to your students the units system which is commonly used in particle physics (Momentum eV/c, energy-eV/c^2). Discuss also the fact that with careful choice of units (c=1), it is possible to equate momentum and energy only as far as their magnitude is concerned, that is p (in GeV)= E (in GeV) (Gigaelectron Volts)=mass (in GeV), therefore they can use the equation (1).
More information can be found in https://hypatia.iasa.gr/en/help.html

Perform Investigation

Step 1: Getting familiar with the HYPATIA analysis tool

Before we get started with our research let's have a look at the lab we are going to use. The lab that will help us perform our research is called HYPATIA and it is an analysis tool designed to analyse real data obtained from the ATLAS experiment carried out on the LHC at CERN.

You can access HYPATIA at : https://hypatia.iasa.gr/app-en/

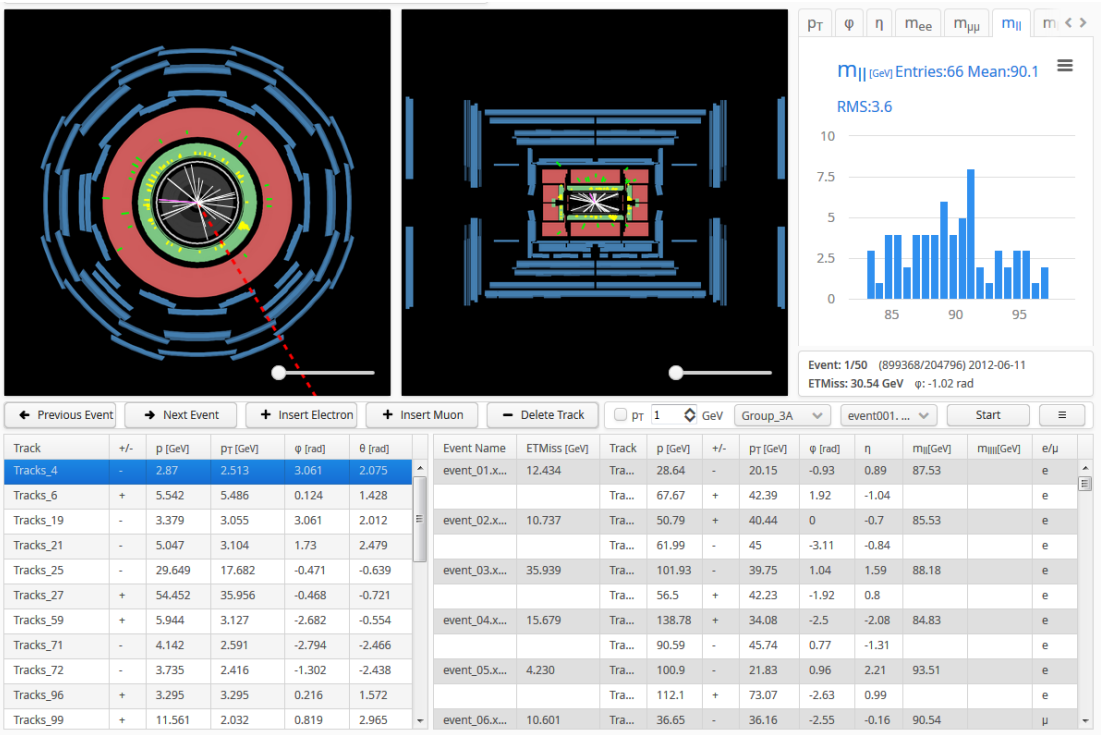


Figure 3: The HYPATIA web application. The left canvas presents a view of the ATLAS detector in the transverse plane, namely perpendicular to the colliding beam direction: only the barrel part of the detector is visible. The right canvas shows a side view parallel to the colliding beams and all parts of the detector (barrel plus two end- caps) are shown. Different components of the detector are coloured with different colours. Below the canvas a table of the momenta and directions of the recorder tracks is given

Step 2: Learn how to identify muons/electrons

In the "plan investigation" part you played with the applet and learnt about the electrons and muon signatures in the ATLAS detector

1. Select the group file 'Group2" from the "Group" dropdown box (use buttons "Previous Event" and "Next Event" to browse through different events) to view the data from the collisions under investigation. This group contains ONLY Z decays to electrons and muons. Try to distinguish muons from electrons.

Look at the data in the table below the detector views. Try to understand to which track depicted in the detector each line of data belongs to, by either clicking on the track or on a line in the table.
For each particle of the table, the angle of the momentum vector in the transverse plane is the angle (ϕ) which is depicted in radians. The angle (θ) is the polar angle,

depicted in radians as well. The magnitude of each momentum vector is the value under the p column given in [GeV].
While browsing through the events, complete the following table with at least 10 muons and 10 electrons.

Event#	P [GeV]	Charge (+/-)	Φ (rad)	Θ (rad)	Kind of particle (e or μ)

Table I: Electron and muon tracks

2. Select event group "Group_3A" from the "Group" tab (use buttons "Previous Event" and "Next Event" to browse through different events) to view the data from the collisions under investigation.

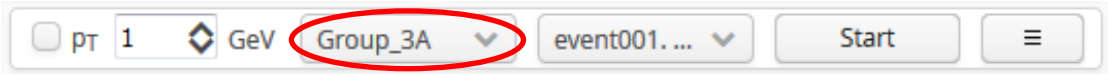


Figure 4: The HYPATIA event group selection menu

3. Try to identify two muons of opposite charge (a muon-antimuon pair) or two electrons of opposite charge (an electron-positron pair) originating from the same point (called vertex).These could be the decay products of a Z boson.

4. Use the "insert e" or the "insert μ" button twice to insert the two members of the pair in the following invariant mass table which appears in HYPATIA. You can also delete a track using the "delete" button and/or replace it with another one.

Event Name	ETMiss [GeV]	Track	p [GeV]	+/-	pT [GeV]	φ [rad]	η	m‖[GeV]	m‖‖[GeV]	e/μ
event_01.x...	12.434	Tra...	28.64	-	20.15	-0.93	0.89	87.53		e
		Tra...	67.67	+	42.39	1.92	-1.04			e
event_02.x...	10.737	Tra...	50.79	+	40.44	0	-0.7	85.53		e
		Tra...	61.99	-	45	-3.11	-0.84			e
event_03.x...	35.939	Tra...	101.93	-	39.75	1.04	1.59	88.18		e
		Tra...	56.5	+	42.23	-1.92	0.8			e
event_04.x...	15.679	Tra...	138.78	+	34.08	-2.5	-2.08	84.83		e
		Tra...	90.59	-	45.74	0.77	-1.31			e
event_05.x...	4.230	Tra...	100.9	-	21.83	0.96	2.21	93.51		e
		Tra...	112.1	+	73.07	-2.63	0.99			e
event_06.x...	10.601	Tra...	36.65	-	36.16	-2.55	-0.16	90.54		μ

Figure 5: The HYPATIA invariant mass table

5. The invariant mass of the pair according to formula (1) will be automatically calculated and appear under the m_{ll} entry. In the last column an "e" or a "μ" will appear depending if the pair was an electron-positron or a muon-antimuon one. When replacing a track, the value of the invariant mass in figure 3, is automatically updated.

6. Now you can also use the histogram facility of HYPATIA and plot the values of the invariant masses calculated, either for both electron and muon pairs together (click on m_{ll}) or for electrons (click on m_{ee}) and muons (click on $m_{\mu\mu}$) separately. The horizontal axis is the value of mass in GeV/c^2.

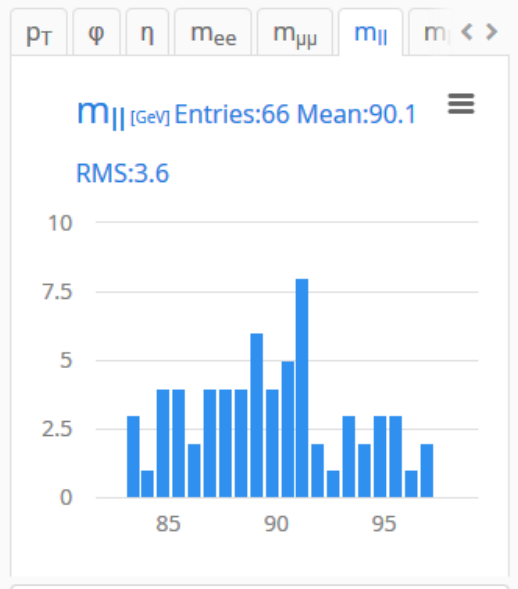


Figure 6: The HYPATIA two lepton mass histogram. Click the tabs at the top to see the other quantities which can be plotted

7. Now that you have learned how to detect, identify and measure the Z particles you can proceed to "discover" the **Higgs particle!**

8. One of the cleanest signatures of the Higgs particle is through its decay to **TWO Z** particles and each of the Z's decaying to two opposite charged leptons (e or μ).

9. Select event group 'Higgs" from the "Group" tab to view the data containing some Higgs candidates

10. Looking at each event try to identify if it contains **TWO Z** particles by their decay products: these could be four muons, or four electrons or a pair of muons and a pair of electrons.

$H \rightarrow Z^0 + Z^0 \rightarrow 2\ e^+ + 2\ e^-$

$H \rightarrow Z^0 + Z^0 \rightarrow 2\ \mu^+ + 2\ \mu^-$

$H \rightarrow Z^0 + Z^0 \rightarrow e^+ + e^- + \mu^+ + \mu^-$

11. Enter the four leptons according to their kind in the invariant mass table, using the "insert μ" or "insert e" buttons but two consecutive particles of the same kind, should be added each time. Check if the mass of each pair is close to the mass of the Z particle. Figure 4 shows the corresponding histogram of m_{llll}. You have discovered the elusive Higgs particle which physicists have searched for in over 50 years! The theorists who predicted its existence received the 2013 Noble prize in Physics!

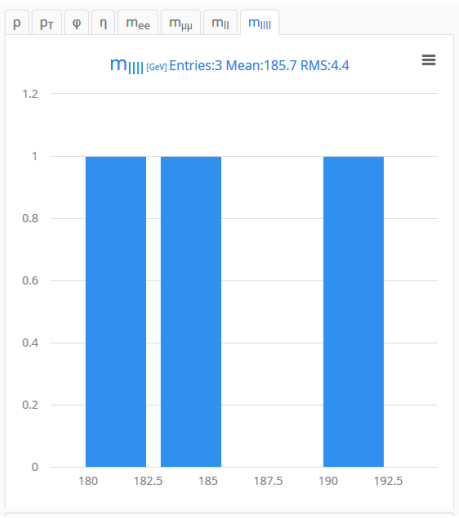


Figure 7: The HYPATIA four lepton mass histogram.

Teacher Guidelines:

The following two youtube MOOC's give you an introduction to HYPATIA https://youtu.be/qGl8UQwMOEg and the Z and Higgs particle exercises https://youtu.be/gHTTtwEavE8

You can divide your students into groups of two.

The main idea of the exercise is for students to discover a short lived particle which decays to easily identified products such as two muons or two electrons. This particle could be any of the know resonances (J/ψ, Y, Z) but for the purpose of this exercise only events which originate from a Z particle are given in the sample. Have your students watch the video given under Part III in http://hypatia.iasa.gr/en/exercise.html to help them complete the histogram of the Z masses.

Explain to them why a combination of an opposite charged electron and a muon cannot be the decay product of a Z boson (this combination will be marked as red "incompatible") in figure 5.

Have your students watch the video given under Part VI in http://hypatia.iasa.gr/en/exercise.html to help them complete the Higgs search.

You may choose to divide the class into groups and give them different event groups in order to do the experiment.

The events of Group3 which contain Z bosons and the ones from the Higgs group which contain a pair of Z bosons are given in the "teacher answer key"

***Tip:** Make sure students understand the connection between the investigation and the hypotheses they have made. In other words make sure they understand why they are doing every single step.*

Analysis and Explanation

Analysis: Analyze evidence to discover a possible answer

Now use the data you have collected to make some further investigation.

1. Study table I and explain why you made each choice.
2. What is the calculated Z mass (from figure 6)?
3. Is it different when you use the electron decay to that obtained from the muon decay? Discuss differences and similarities
4. How does the value from question #2 compare with the one physicists use? Are there any outliers? Are all measurements valid?
5. How did you use energy and momentum conservation in this exercise? Is energy and mass the same thing?

Explanation: Formulate an explanation based on the analysis of your evidence

- How many Higgs bosons did you find? What is their mass?
- Does the value of the average Higgs boson mass agree with the one of the July 2012 discovery?
- Discuss any deviations with your teacher

Teacher Guidelines:

The events provided in the "Higgs" file are not the real ones detected by the experiment but "custom-made" ones from the overlap of two different Z events. This is the reason why the mass of the Higgs will not come out close to its real value (125 GeV/c^2) but a bit higher close to the sum of the two Z masses or even higher.

Consolidation Phase

Connect

Connect explanation with current scientific knowledge

Based on the experiment you conducted, answer the following questions. Note down your answers in order to produce your report.

1. Is the Z mass calculated from the electron pairs the same as the one from the muon pairs?
2. Why doesn't the Z mass histogram give the same mass value for all events entered but rather shows a certain spread of values (the physicists call this the "width" of the particle)
3. Is the energy and momentum equivalent for electrons? For muons? Justify your answer
4. Is the Z width from its decay to electrons the same as the one from its decay to muons? Explain your answer.
5. What is the best way to combine the results from different groups of students? Should you do that?
6. What sources of error are there in the different mass measurements?

Teacher Guidelines:

If you have noted any mistakes that the students made during the previous phases make sure to bring them up and discuss them with your students so they may understand what their mistakes was.

It is useful to point out to the students, that these are real sets of data, but the events have undergone a certain selection. Most events recorded from the collisions DO NOT contain Z or Higgs particles.

Communicate

Communicate and justify your explanation

Make a brief report of your work so you can present your work to your fellow-students. In order to attract their attention try to be as creative as possible. You can make a small video out of it, a prezi, a PowerPoint presentation or a poster like those presented by scientists during conferences

Reflect

Reflect on what you have learned from the learning process

Compare the results of your team with those of other teams. Have you calculated the same values for the invariant masses?

Is there a possibility that other particles that have not been tracked might have been produced? Can you give examples?

Could there be particles which escape the detector “unseen”?

Teacher Guidelines:

Comment on your students results. Point out which are the strong parts of their work and which are the weak ones.

Finally ask your students to comment on the accuracy of the method followed.

You may also discuss the Higgs boson with them, and how scientists are able to track it through data like the ones they used in this activity.

You can book a Virtual Visit of your students in their own language to the ATLAS experiment https://atlas-live-virtual-visit.web.cern.ch/atlas-live-virtual-visit/ or the CMS experiment https://cms.cern/interact-with-cms/book-your-virtual-visit

PSQ

1

There are four fundamental forces in nature (strong, electromagnetic, weak, gravitational). What is the difference between them?

- Their strength is different. In order of decreasing strength, they are classified as follows: strong, electromagnetic, weak, gravitational. [H]
- The electromagnetic and gravitational forces are long-range forces. Strong and weak forces are short-range forces. [M]
- They are mediated by different particles. Gluons for the strong force, photons for the electromagnetic force, W and Z bosons for the weak force and gravitons for the gravitational force. [L]

2

The Z and Higgs bosons are unstable particles. They decay into other particles shortly after they are produced. Are the Z and Higgs bosons special, or is the decay of particles a common thing in nature?

- Every particle in nature decays unless prevented to do so by nature's conservation laws. [H]
- Massive particles usually decay to lighter ones. [M]
- There are many subatomic particles in nature and most of them decay into other particles. [L]

3

Why do we choose to study the decay of the Z boson into electrons or muons?

- The decay of the Z boson into electrons and muons leaves a characteristic signature in the detector which helps us separate the signal of a Z boson decay from the background. [H]
- Since both electrons and muons can be detected with high accuracy by the ATLAS experiment, we choose to study these channels of decay rather than the more complicated ones. [M]
- Electrons and muons are well known particles. They have been discovered long ago and have been thoroughly studied. It is therefore advantageous to study the Z boson decay into electrons and muons. [L]

4

In this exercise we will calculate the invariant mass of the Z and Higgs bosons. What information do we need in order to do so?

- We need to know the energy and the trajectories of the decay products.[H]
- We need to know the momentum and the trajectories of the decay products.[M]

- We need to know the mass of the decay products, that is the mass of the electron and the muon.[L]

5

How is it possible for a particle to escape detection?

- Some particles don't even make it to the detector. There are also particles that neither deposit energy nor leave a charged track in the ATLAS detector. [H]
- It is possible that a particle with very low momentum may not make it to the detector at all. It could, for instance, spiral in the tracking chamber. [M]
- If a particle after the collision moves in a direction parallel to the beam then it will not be detected. [L]

6

You can always click the box labeled PT under the longitudinal view of the detector and adjust the value next to it in order to apply cuts, which means to select a cut-off value so that tracks of particles with momentum less than this value will not be shown at all. What is the privilege of using cuts?

- The Z and Higgs bosons are massive particles. We can use cuts to throw away low momentum particles since the bosons we are looking for decay into particles of relatively high momentum. [H]
- Applying cuts simplifies our analysis significantly. Cuts allow us to throw away the "garbage" and concentrate on the particles of interest. [M]
- By using cuts we can choose the tracks we want to study and concentrate on them. [L]

7

During the proton collisions in the LHC two particles are produced: a light one and a heavy one. Both of them are short-lived and decay almost immediately to two other particles. The initial particles have almost the same, low momentum. What do you qualitatively expect for the decay products?

- The decay products of the heavy particle move in opposite directions. [H]
- The angle between the tracks of the decay products is smaller for the light particle. [M]
- When the decay products are very light particles their mass doesn't significantly affect the calculation of the invariant mass. [L]

8

When you search the World Wide Web for information you find millions of pages, but only a few of them contain useful and reliable information. Comparing the search over the internet with the search for new particles in the LHC, what would you do as a researcher in order to find new particles?

- I would try to isolate the signal from particle decays from the background in order to recognize if a new particle was created or not. [H]
- I would try to minimize the uncertainty of my measurements by gathering lots of data. [M]
- I would compare experimental data with theoretical predictions in order to find inconsistencies and recognize the creation of new particles. [L]