MASS CALC: Z
CALCULATE THE Z MASS
TEACHER (SHIFT MANAGER) NOTES

DESCRIPTION

Students use momentum conservation, energy conservation and two-dimensional vector addition to calculate the mass of the Z boson. They gather data from event displays of candidate Z decays from the ATLAS and CMS experiments at CERN's Large Hadron Collider (LHC). The eight events from 2010 were chosen carefully; the momenta of the muons from the Z decay were relatively small in the direction along the beam line. Thus these events were nearly two-dimensional in the plane transverse to the beam line. Treating them as two-dimensional gives reasonable results for the mass of the Z.

STANDARDS

NSES Physical Science Content Standards for Grades 9-12:

- Content Standard A
  - Abilities necessary to do scientific inquiry
- Content Standard B
  - Structure and properties of matter
  - Conservation of energy and increase in disorder
  - Interactions of energy and matter

ENDURING UNDERSTANDING

- We can discover the properties of undetected particles by measuring their decay products and using conservation laws.
- Conservation laws and mass-energy conversion govern the behavior of particles.

LEARNING OBJECTIVES

Students will know and be able to:

- Apply momentum and energy conservation to particle decays.
- Calculate the invariant mass of a decaying particle.
- Use energy conservation to determine the mass of an object undergoing decay.
- Combine results statistically to get a better result.

PRIOR KNOWLEDGE

Students must be able to add vectors in two dimensions and be able to use energy and momentum units common to particle physics. (Momentum–eV/c, energy–eV)

BACKGROUND MATERIAL

These event displays are real data. However, most high school students think of data as numbers, perhaps columns of numbers. Use the event displays to prompt a discussion of data forms and the fact that they can use this real data to calculate the Z mass. The students are teams doing a "double-blind" analysis of candidate Z event data. They are members of a collaboration trying to determine how well the mass of event candidates matches the mass of the particle established in previous experiments. If they match well, then the detector is properly calibrated and can be used to search for more Z events.

Background for teachers and students: http://leptoquark.hep.nd.edu/~kcecire/zweb/resources.html

IMPLEMENTATION

Students use printed event images, ruler and protractor to analyze the data. This activity requires averaging many independent calculations of the invariant mass determined from the six events. Students analyze events whose decay products had little momentum in the direction of the beam. This makes resolving vector components much simpler. Students will: use a ruler and protractor to measure momentum magnitude and direction, resolve momentum components and add particle momentum vectors. They will use these data to determine the mass of the Z.

Each event shows the decay of a "candidate Z" into two muons. The detector can only "see" the muons, shown on events as tracks. Each muon carries away energy from the decay region. Resolving this energy will tell us if the muons may have been produced in a decay. Muon pairs with combined energies and momenta, which resolve into the range of the invariant mass of the Z may indeed come from a Z decay. Teachers should help students to identify what information they need from the event plots in order to resolve the invariant mass.

Teachers can use this activity to reinforce the addition of vectors or to explore the conservation of momentum and energy. The students may have difficulty in two different areas: resolving and adding vectors and determining mass from the vector sum. It is important to stress that these are real events and that the answer is the result of their analysis. Nature doesn't provide an answer key. Students can publicly share their results by entering their value for the Z mass into a table on the board.

The events are available at: http://leptoquark.hep.nd.edu/~kcecire/zweb/data.html

ASSESSMENT

The accepted mass of the Z boson is 91.2 GeV. Individual calculations should be very close to this value. Large discrepancies may come from incorrect vector addition. Consider asking the students questions such as:

- What did we calculate the Z mass to be? How does the value compare with the value physicists use?
- How close are these values to each other? Are there outliers? Are they all valid measurements? How do you *know*?
- If there are outliers, talk with the class about what the differences in analysis might be.
- Why can we use vector addition to find the Z mass with these events?
- How does our calculation rely on conservation laws?
- How do you use the experimental data to determine the mass of the Z? Are energy and mass the same thing?
- What is the best way to combine results from the whole class? Why should we do this?

You may use the following "LHC Student Operations Shift Report" as a tool to gather student responses and assess what they have learned. The student pages follow the shift report in this pdf.

LHC Student Operations Shift Report: Mass Calculation: Z Boson

Research question: ____

Reason: ____

Physics principles: ____

Hypothesis and reasoning: ____

____

____

Claim:

Evaluate the accuracy of your hypothesis as an answer to the research question.

Evidence:

Questions to consider: How did we test the hypothesis? What data supports the claim?

2-3 pieces of evidence (data, observations, calculations) that support the claim

Reasoning:

Questions to consider: Why does the data compel this claim? Is anything left out?

Justify how and why the evidence backs up the claim. Use scientific principles to explain ***why*** you got this data. Use and explain relevant scientific terms.

Sources of Uncertainty in Measurement:

Question to consider: Why and to what extent can we trust your results?

How much do results vary in calculation of the Z mass? Why? Are their outliers? Why?

Practical Applications:

Questions to consider: How might this information be useful to the ATLAS and/or CMS collaborations? To the future runs of the LHC?

What is the value of what you learned?

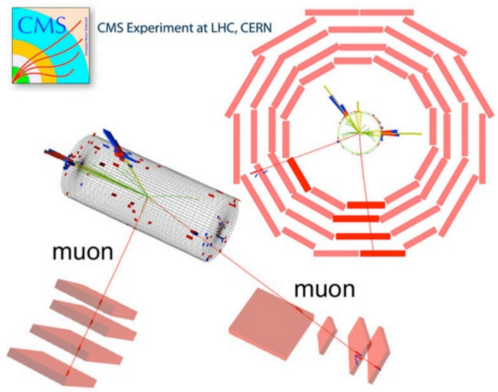
Now, write your formal scientific conclusion statement. Combine your ideas from the previous pages into two or three well-constructed paragraphs that include the research question, your hypothesis, your evaluation of the hypothesis (claim, evidence and reasoning), possible sources of error (specific to your data) and practical applications for your discovery. Spelling and grammar do count; be thorough and persuasive!

MASS CALC: Z

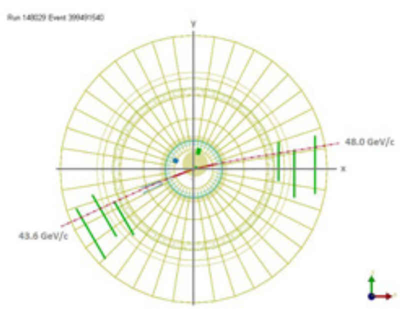
RELATIVITY USED IN THE CREATION OF THE Z BOSON!
ANALYSIS OF LHC DATA FROM CERN

Welcome to your LHC student operations shift. Today you will use (a form of) Einstein's famous equation with experimental data collected in the ATLAS and CMS experiments at CERN to determine the mass of the **Z Boson**.

The image to the right shows what happens in one of these events. The tracks (at about 6 and 8 o'clock) are the paths of a muon and an antimuon. These were created from the prompt decay of a Z boson (invisible here). The Z itself was created in the collision of two protons from the LHC beam.



You will receive a more detailed plot from data collected by ATLAS or CMS. A sample of one of these "events" is below. You will need to determine the total energy of the muon-antimuon pair and their net momentum.



Data from LHC events are displayed in images like the one to the left. It shows the recorded momentum (in GeV/c) of the particle debris that came from the collision. Your class has eight event displays.

Identify the muons in this event. Physicists do not detect the Z boson directly but reconstruct it from the muon data. These muons carry the momentum and mass-energy of the Z boson parent.

What do we know?

1. Momentum is conserved. Energy is too.
2. Momentum is a vector. Energy is not.
3. The invariant mass and the momentum of the Z boson become the energies and momenta of the muon-antimuon pair.
4. The net momentum of the muon-antimuon pair is the same as the net momentum of the Z boson.
5. Muons have small mass. In these events, we can say that their energy and momentum are equivalent.
6. Einstein really wrote $E^2 = p^2 + m^2$ (This requires using units that make the speed of light = 1.) This allows us to solve for energy, momentum or mass if we know the other two.

What tools do we need for our analysis?

Ruler, protractor, and pencil to make a **momentum vector diagram** from an event image

What are our claims? What is our evidence?

Fill in a data table like this one for each event that you analyze. Note that muon 1 and and muon 2 refer to the two tracks. One is a muon, the other an antimuon, *but you do not need to make this distinction for your calculations.*

You will be assigned to study one, two or more events, and you may be working with a partner or in a larger group.

Event Number:______________________________

Exp: ___ATLAS ___CMS	**Measured/Calculated Results**		**Remarks**
Momentum of muon 1			Vector: Report two quantities
Momentum of muon 2			Vector: Report two quantities
Net momentum			Vector sum
Energy of muon 1			
Energy of muon 2			
Total energy			
Mass of Z candidate			Calculate from above.

After your class has discussed results to get a better class value for the measured Z mass, you may make your LHC Student Operations Shift Report.