CALCULATE THE Z MASS
TEACHER NOTES

DESCRIPTION

In 1983, the physicists at CERN were exuberant when they discovered a new particle, dubbed the Z boson. Today, these particles are important to physicists as they calibrate the detectors at CERN's Large Hadron Collider (LHC). Despite the use of gigantic detectors using groundbreaking technology, the data analysis involved concepts that are a part of the standard curriculum for high school physics.

This activity helps students learn how physicists determine that their detector is calibrated and whether they have discovered something new. Students use momentum conservation, energy conservation and two-dimensional vector addition to calculate the mass of the Z boson. Data are from ATLAS and CMS event displays of candidate Z decays from CERN's Large Hadron Collider (LHC). We chose eight events from 2010 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. These events are analyzed using two-dimensional analysis to determine the mass of the Z boson.

STANDARDS

Next Generation Science Standards

Science Practices

1. Asking questions
2. Developing and using models
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

Disciplinary Core Ideas – Physical Science

PS1.A: Structure and Properties of Matter
PS2.B: Types of Interactions
PS3.B: Conservation of Energy and Energy Transfer

Crosscutting Concepts

1. Patterns.
3. Scale, proportion, and quantity.
4. Systems and system models.

Common Core Literacy Standards

Reading

9-12.4 Determine the meaning of symbols, key terms . . .
9-12.7 Translate quantitative or technical information . . .

Common Core Mathematics Standards

MP2. Reason abstractly and quantitatively
MP6. Attend to precision.

IB Physics Topic 1: Measurement and Uncertainty

1.2.6 Describe and give examples of random and systematic errors.
1.2.8 Explain how the effects of random errors may be reduced.

1.2.11 Determine the uncertainties in results.
1.2.12 Identify uncertainties as error bars in graphs.
1.2.13 State random uncertainty as an uncertainty range (±) and represent it graphically as an "error bar".
1.3.1 Distinguish between vector and scalar quantities.
1.3.2 Combine and resolve vectors.

IB Physics Topic 2: Mechanics

2.3.6 Use the principle of conservation of energy to compare an initial state to a final state.
2.4.3 Use conservation of linear momentum to compare an initial state to a final state.

IB Physics Topic 7: The Structure of Matter

Aim 4: particle physics involves the analysis and evaluation of very large amounts of data
Standard 7.3.4: Apply the Einstein mass-energy equivalence relationship

IB Physics Additional Higher Level Option Topic A.4: Relativistic Mechanics

A.4.6 Use MeV c^{-2} or as GeV c^{-2} the unit of mass and MeV c^{-1} or GeV c^{-1} as the unit of momentum.
A.4.7 Describe the laws of conservation of momentum and conservation of energy within special relativity
A.4.10 Solve problems involving relativistic energy and momentum conservation in collisions and particle decays

ENDURING UNDERSTANDINGS

- Particle physicists use conservation of energy and momentum to measure the mass of fundamental particles.
- Well-understood particle properties such as charge, mass, momentum and energy provide data to calibrate detectors.

LEARNING OBJECTIVES

Students will be able to:

- Apply momentum conservation to real-life situations.
- Calculate the invariant mass of a decay particle.
- Use energy conservation to determine the mass of an object undergoing decay.

PRIOR KNOWLEDGE

Students must be able to:

- Plot a histogram
- Differentiate mass, energy and momentum units as used by particle physicists (Energy-eV, Momentum–eV/c, mass–eV/c2)

BACKGROUND MATERIAL

These event displays are authentic 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 authentic 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 see if the selected event candidates all have the same mass. If they do, then the detector is properly calibrated, and physicists can use it to search for more Z events.

RESOURCES/MATERIALS

The links below provide useful background material.
Detectors at the LHC:

- http://aliceinfo.cern.ch/Public/Welcome.html
- https://atlas.cern/
- https://cms.cern/
- http://lhcb-public.web.cern.ch/lhcb-public/

Histograms, useful units:

- http://quarknet.fnal.gov/toolkits/new/histograms.html
- http://quarknet.fnal.gov/toolkits/ati/whatgevs.html
- http://en.wikipedia.org/wiki/Full_width_at_half_maximum

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 eight events. Students analyze ATLAS and CMS events chosen because the decay products had little momentum in the direction of the beam. This makes resolving vector components much simpler. Students will use a protractor to measure momentum direction, resolve momentum components and add these to determine the mass of the Z.

Each of these events shows the decay of a "candidate Z" into two muons. The detector can only "see" the muons. These are shown on these 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 in the range of the Z's invariant mass may indeed come from a Z decay. You should help students identify what information they need from the event plots to resolve the invariant mass.

You 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 authentic events and that the "answer" is the result of their analysis. Nature doesn't provide an answer key. Students can share their results publicly by entering their value for the Z mass into a table on the board.

You can also use this activity to introduce calibration. In early runs, CMS used the determination of the Z-mass as a confirmation that the detector was behaving as expected. If the values from new data differed from early results, their detector had problems.

The teacher pages for the activity *Calculate the Top Quark Mass* has step-by-step instructions for making the necessary calculations for this activity.

The events are available at https://quarknet.org/page/z-mass-calculation-event-images.

ASSESSMENT

- Quality of the plots
  Check for the following: correct labeling of axes; identifying the background level; appropriate bin size selection.
- Interpretation
  - Check for the following: correct identification of the peak and the particle mass; indication that the width of the peak represents the uncertainty in the value of the mass.
  - Did the analysis indicate that the detector is well calibrated? That is, did the mass plot yield a result in agreement with accepted values for the Z mass? (91GeV/c^2)

- Discussion
  Divide the class into groups. Each group presents their findings to the class with open discussion of the claims, evidence and reasoning provided by each group. Questions addressed during the discussion include:
    - What is the most likely mass of the Z boson?
    - What is the range of Z boson masses sampled in your data?
- Written report
  A written report should stress *claims*, *evidence*, and *reasoning*:
  What claims can scientists make based on the Z plot?
    - *Examples: mass, discovery, uncertainty.*
  - What is the evidence for and against the validity of the claims?
    - *Examples: signal-to-background, width.*
  - Explain the reasoning linking the evidence to the validity of the claim.
    - *Example: the Z signal is large compared to background, with a width narrow compared to the height of the peak.*

  Provide the evidence for these claims, and the reasoning behind them over to the shift manager in your *Shift Report*. The link to the *Shift Report* is on the front page of the activity.

EXTENSION

This activity is well suited to a more detailed analysis of error, using readily available tools in a spreadsheet or graphing calculator. Below is a selection of indicators from the IB standards, with a description of how these indicators can be met using this activity.

UNDERSTANDINGS

Random and Systematic Errors

On a histogram with a "bell-shaped" distribution, random error can be quantified by determining the "width" of the distribution, and systematic error can be related to the mean of the distribution. Examples in the case of a Gaussian distribution would be by calculating the FWHM (full width half-maximum) or the standard deviation. In either case, a narrow peak (such as the narrow mass distribution of the Z Boson in muon production events in CMS) can be identified as one with a small random error, while a broad peak (Z Boson candidates from electron-positron production, for example) would represent a large random error.

- *Examples: signal-to-background, width.*

Explain the reasoning linking the evidence to the validity of the claim.

- *Example: the Z Boson signal is large compared to background, with a width narrow compared to the height of the peak.*

Are some claims more valid than others? Why?

- *Example: a smaller signal-to-background ratio gives weaker evidence of discovery.*