CMS DATA EXPRESS
TEACHER NOTES

DESCRIPTION

CMS Data Express is a short investigation using events from the Compact Muon Solenoid (CMS) at the Large hadron Collider (LHC). Students are put assigned "on-shift" to CMS Data Quality Management (DQM). They check the data quality to see that CMS is performing to specification by giving a good fit for the Z mass and/or the W+W- ratio. They:

- Separate Z candidate events from other events by visual inspection and create a mass plot for the Z boson.
- Separate W candidate events from other events by visual inspection and determine the ratio of W+ to W- candidates.

While this activity is richest pursuing both goals, each can stand on its own as a separate activity. This activity helps prepare students for a masterclass or to give students a masterclass-like experience in a short time (1-2 class periods.)

The Z boson is important in LHC discovery science. It is a well-known particle, so the location and width of the mass plot give physicists a good idea of how the detector is performing. Z candidate events are "dimuon" events; the Z can decay into a muon-antimuon pair. Z candidates are identified by 2 long muon-type tracks.

W candidate events consist of decays into single muons and neutrinos. However, the neutrinos do not interact with the detector and hence leave no tracks or energy deposits. Their momenta are estimated by summing all the momenta in the event to determine what is "missing." Thus, a W candidate appears as a single long muon–type track.

STANDARDS ADDRESSED

Next Generation Science Standards

- Science and Engineering Practices
  - 4. Analyzing and interpreting data
  - 5. Using mathematics and analytical thinking
  - 8. Obtaining, evaluating and communicating information
- Crosscutting Concepts

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

- MP1. Make sense of problems and persevere in solving them.
- MP2. Reason abstractly and quantitatively.
- MP4. Model with mathematics.

ENDURING UNDERSTANDINGS

1. Particle physics research uses indirect evidence to support claims.
2. Scientists continuously check the performance of their instruments.

LEARNING OBJECTIVES

Students will know and be able to:

1. Determine the identities of force carrier particles by their decays into leptons.
2. Identify the electric charge of a particle from its motion in a magnetic field.
3. Give examples of charge conservation in particle decays.

4. Develop pattern recognition skills for identifying data that fit a well-known system.

Prior Knowledge

Students should be aware of the Lorentz Force on charged particles moving through a magnetic field and how to use the right hand rule to determine the (positive or negative) charge of the particle.

Background Material

The images the students analyze are CMS events. There are a variety of resources on CMS and the LHC at http://cms.cern.ch. Other resources are available from the web page (see below).

Resources

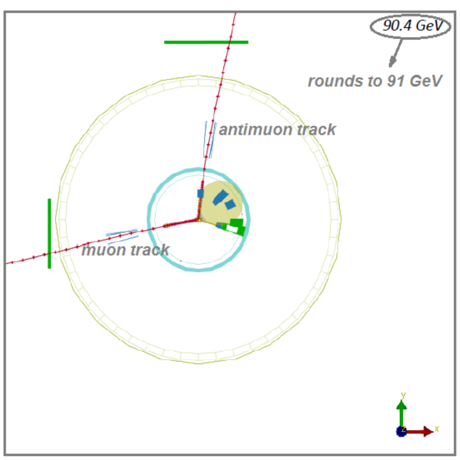
Data file: https://quarknet.i2u2.org/sites/default/files/cms_deevents_mass.pdf
Screencast: http://leptoquark.hep.nd.edu/~kcecire/drupal_lib/video2014/2014-08-19_1456.swf

Implementation

Students start with background from the two topmost videos at http://cms.physicsmasterclass.org/cms.html.

There are 80 events in the PDF data file (linked above in Resources), one per page. Students work in pairs. Two students working together on one analysis (Z or W) should be able to do about 40 events in perhaps 10-15 minutes; working on both, 20 events is a more reasonable number. Since different students have different interpretations, this will likely give fairly good results.

For Z analysis, students identify Z candidate events as those with two red tracks indicating a muon-antimuon pair. They can check if these are "good" Z candidates by looking at the curvature of the tracks: the two tracks should have opposite curvature indicating opposite electrical charge. The Z boson being neutral, it must decay into both a negative muon and a positive antimuon to conserve charge. Each event has a mass printed at the upper right. Students should round these to the nearest odd number and record the mass for the events that they determine are Z candidates. Students should count the number of events they have at "mass bin" (e.g., 2, at 83 GeV, 7 at 89 GeV, 12 at 91 GeV. . .) and contribute these to a class data table. The class creates a mass plot by summing up the events in each mass bin and creating a histogram. One of the most successful ways to construct the histogram is with sticky notes.

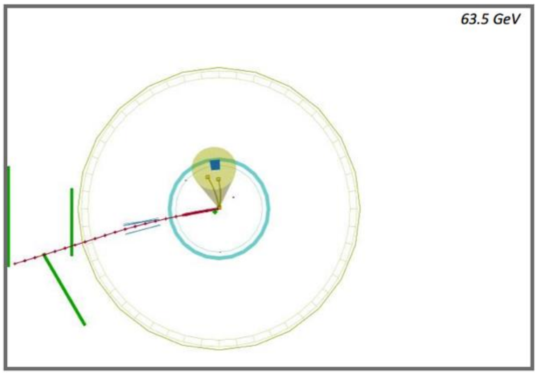


Typical Z candidate event.

Mass plot of Z candidates.

Since the W is charged, it can only create one charged decay product; this conserves charge. Students identify W candidates as those with only one muon or antimuon track. The decay also creates a neutrino; this conserves momentum. The neutrino is not directly detected. To find if the possible W particle is a

W+ or a W-, students use the curvature of the muon (or antimuon) track. A track with clockwise curvature indicates the positive charge carried by the antimuon after its decay from the W+. An anti-clockwise cuvature indicates the presence of a muon decaying from the W-. Students count and report the number of W+ and W- candidates. The total number of W+ candidates divided by the total number of W- candidates in the class yields a W+ to W- ratio. Students ignore the mass of these events



Typical W- candidate event.

Teachers lead a discussion at the end of the activity; it is crucial to understand the significance of the results. The initial results of the investigation are:

- A readable mass plot of the events that appear to contain Z bosons..
- A count of W+ and W- particles..

Students use the evidence from their analysis to make a claim about the mass of the Z boson and the ratio W+ to W-.

Then the discussion digs deeper into the evidence with questions like:

- How sure are we of the results we have?
- What affects the accuracy of our results?

Introduce the expected values: approximately 91 GeV for the mass of the Z and approximately 1.4 for W+/W- . Then ask: Are your results reasonable based on what we know?

ASSESSMENT

Assessment is based on claims, evidence, and reasoning. Students complete a “Shift Report” in which they assess based on evidence and reasoning the accuracy of the claims and how useful the results are.

CMS Data Express

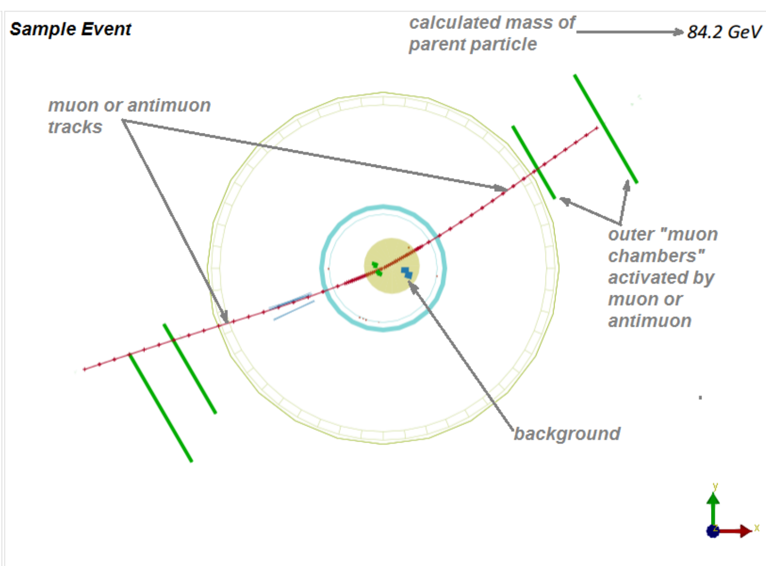
You are *on shift* to analyze actual events from the CMS detector in the Large Hadron Collider at CERN.

Welcome to your CMS student operations shift. Today you are on the Data Quality Management (DQM) team. You will be given a sample of actual events from CMS and will have two possible assignments:

- Determine which events are from the decays of Z particles and use these to see if you can construct the mass of that particle from your data.
- Determine which events are from the decays of W+ or W- particles and use these to see if you can find a meaningful ratio of W+ to W- events.

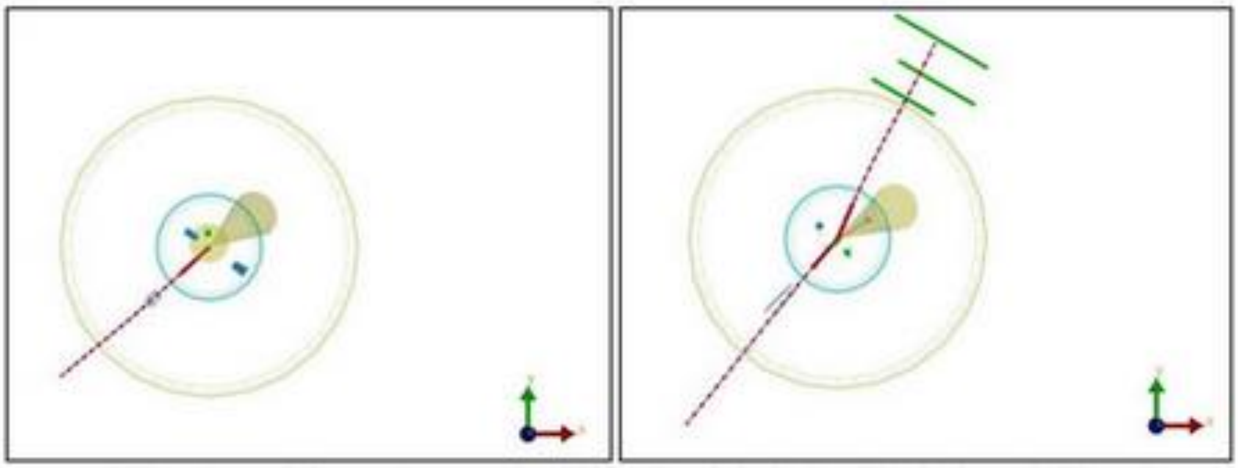
What do we know?

1. The events we will use come from the collisions of protons. Pieces of those protons (quarks or gluons) come together to make Z and W particles.
2. Z particles are neutral. W particles are singly charged: either W+ or W-.
3. All of the decays in our data are into negatively-charged muons, positively-charged antimuons, or neutrinos, which have no charge and are virtually undetectable. Muons and antimuons generally show up in our event display as long red tracks. Other collision by-products (background) also show up in our displays.
4. Momentum, energy, and charge are conserved in decays.
5. The paths of charged particles are bent in a magnetic field: in our events, the paths bend clockwise if the particle is positively charged and anti-clockwise if the particle is negatively charged.
6. The energy of parts of the proton colliding can be converted to a Z or W particle. The mass and the momentum of that particle become the energies and momenta of its daughter particles when it decays. Physicists use these to calculate the mass in GeV of the presumed parent particle in each event, shown at the upper-right of the display.



This Sample Event shows the main features of the events you will see. The details of each event will vary, of course.

The CMS detector is roughly cylindrical. This event display shows a cutaway view of the middle of the detector. The proton-proton beam and the collision point are at the center of the two circles.



Which of these events is a Z candidate? Which is a W candidate? Can you tell the charge of the W candidate?

Learn about the Large Hadron Collider and CMS from the two topmost videos at: http://leptoquark.hep.nd.edu/~kcecire/mc/cms.html.

View the screencast:
http://leptoquark.hep.nd.edu/~kcecire/drupal_lib/video2014/2014-08-19_1456.swf.

What tools do we need for our analysis?

We need a straight-edge to determine particle curvature (clockwise or anti-clockwise), pencil and paper for notes and figuring, and some materials on hand to use to make a histogram. We need our data file.

What will we do?

We will work in teams of two. The shift manager will help us determine which events to examine, which analyses to do, and how to incorporate our results into overall results for the DQM team.

What are our claims? What is our evidence?

We claim that we can make one or both of these:

- A readable mass plot with a clear peak which reveals the mass of the Z particle.
- A count of W+ and W- particles that enables us to find the ratio between them.

Once you have assembled your evidence and analyzed it, you can refine these claims and make them more specific. It is very important that we do this analysis as *blind* study. We must not aim at a known value but rather construct the value from our data and our analysis. We will hand these DQM results over to the shift manager who can then use them in the calibration of the detector or adjustment of analysis software.

After your class has discussed results, you may make your CMS Student Operations Shift Report.

Student Operations Shift Report: CMS Data Express

Research question:

____

Reason:

____

Physics principles:

____

Hypothesis and reasoning (refer to research question):

____

____

____

Claim:

Questions to consider: What is the mass of the Z boson according to your measurements? What is the ratio of W+ to W- particles?

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? How is this data presented?

Use your number of W+ and W- or use your mass plot. Attach any plots or calculations.

Reasoning:

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.

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

Sources of Uncertainty in Measurement:

How much would a change of a few W+ results for W- results (or vice versa) change your value for W+/W-? How wide is your Z mass peak compared to its height?

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

Practical Applications:

What is the value of what you learned?

Questions to consider: How might this information be useful to the CMS collaboration? To the future runs of the LHC?

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!