Particle Physics in the High School Classroom
Exploring the Data Activities Portfolio

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QuarkNet: The Data Activities Portfolio (DAP)

- accessible and free to use for ALL, not just teachers affiliated with QuarkNet
- 40+ lessons, with background info and student activity sheets!
- QuarkNet website: www.quarknet.org and select “Data Activities Portfolio” from the menu at the top!
- Bookmark it: https://quarknet.org/data-portfolio

Description of the DAP, from the DAP:

The Data Portfolio is a compendium of particle physics classroom activities organized by:

- Data Strand
- Level of student engagement (0 - 4)
- Curriculum Topics
- NGSS Standards

While each level can be explored individually, students who start in one level and progress to more complex levels experience increasingly engaging and challenging tasks.

Each Curriculum Topic provides connections between topics routinely covered in physics class and particle physics content and methods. Use the menus to find activities related to the content you are currently covering.

We are making Spanish Language versions of the activities. To find the activities with Spanish versions, use the Curriculum Topics menu, scroll to the bottom, select Spanish Language.

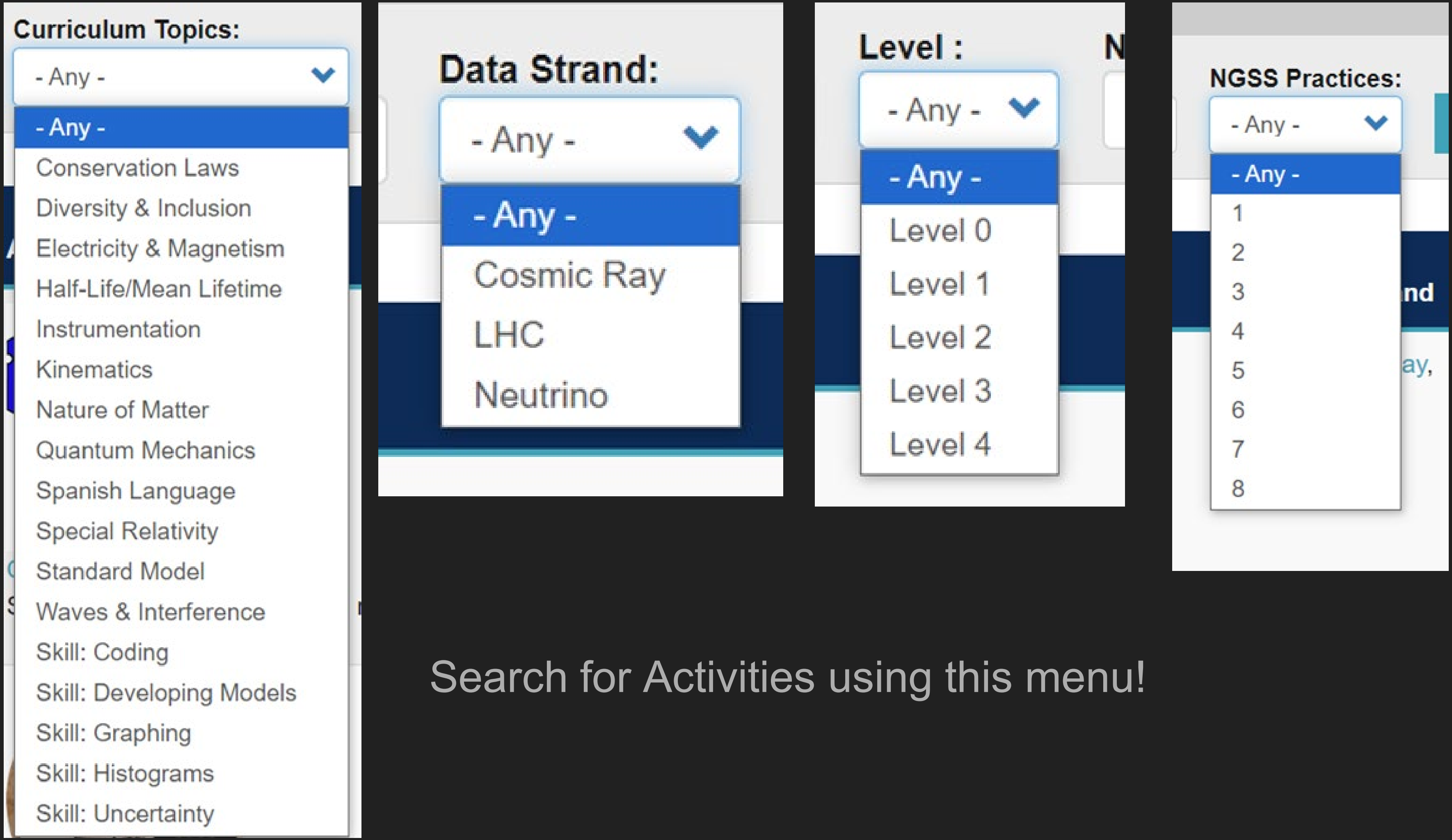
Data Activities Portfolio

The Data Portfolio is a compendium of particle physics classroom activities organized by Data Strand, Level of student engagement, Curriculum Topics and NGSS Standards. Follow the links provided for information about using the Data Portfolio to plan your students' experience. Level descriptions explain the data analysis skills that students apply at each level: tasks in Level 0 are simpler than those in Levels 1 and 2...

+ Read More

Search/Filter

Curriculum Topics: - Any -
Data Strand: - Any -
Level : - Any -
NGSS Practices: - Any -
Apply



Search for Activities using this menu!

DAP Example: Mass of US Pennies

Click on any activity, and you will be linked with background material, teacher notes, student pages, and other useful resources that are largely ready-to-go!

Mass of U.S. Pennies

Submitted by xeno
Published: Fri, 09/05/2014 - 06:47 | Group(s):

Students create and interpret a histogram of penny masses.

Students will represent data through histograms for analysis and interpretation. Students will use an electronic balance to determine the mass of many, many U.S. pennies (a one-cent coin) of varying ages. The metallic composition of the penny has changed over the years. Different compositions can have significantly different masses. A sufficiently random selection of hundreds of pennies should allow the students to discover the years in which the composition changed.

Materials

Teacher Notes	185.52 KB
Student Pages	110.47 KB

Mass of US Pennies

Search/Filter Categories that will return the Penny Mass Activity:

Attributes

1.5 hours

Data Strand

Cosmic Ray

LHC

Level

Level 0

Curriculum Topics

Skill: Developing Models

Skill: Histograms

Skill: Uncertainty

Next Generation Science Standards (NGSS) Practices

1

2

3

4

5

6

7

8

Technology Requirements

Spreadsheet

Penny Mass: Teacher Notes

MASS OF U.S. PENNIES
TEACHER NOTES

DESCRIPTION

Students often struggle with the concept of isotopes: atoms of the same element but different atomic masses. Particle physicists deal with a similar situation when trying to determine the mass of particles that are predicted by the Standard Model. In this activity, students work in groups of two or three to represent data through histograms for analysis and interpretation. Students use an electronic balance to determine the mass of a large number of U.S. pennies (one-cent coins) of varying ages. The metallic composition of the penny has changed over the years. Different compositions can have significantly different masses. A sufficiently random selection of hundreds of pennies should allow the students to discover the years in which the composition changed.

Pennies, continued

STANDARDS

(From the Teacher Notes)

-Useful if you need to add to your lesson plans, etc!

STANDARDS

Next Generation Science Standards

Science and Engineering Practices

1. Asking Questions and Defining Problems
2. Developing and Using Models
3. Planning and Carrying Out Investigations
4. Analyzing and Interpreting Data
5. Using Mathematics and Computational Thinking
6. Constructing Explanations and Designing Solutions
7. Engaging in Argument from Evidence
8. Obtaining, Evaluating, and Communicating Information

Crosscutting Concepts

1. Observed patterns . . . guide organization and prompt questions.

Common Core Literacy Standards

Reading

9-12.3 Follow precisely a complex multistep procedure . . .

9-12.7 Translate quantitative or technical information . . .

Common Core Mathematics Standards

MP2. Reason abstractly and quantitatively.

MP4. Model with mathematics.

MP5. Use appropriate tools strategically.

MP6. Attend to precision.

IB Physics Standard 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.

IB Physics Standard 7: Atomic Nuclear and Particle Physics

7.3 The structure of matter

Pennies, continued (from the Teacher Notes)

ENDURING UNDERSTANDINGS

Scientists can analyze data more effectively when they are properly organized; charts and histograms provide methods of finding patterns in large data sets.

LEARNING OBJECTIVES

In this activity, students will know and be able to:

- Make a histogram to determine if the mass of all U.S. pennies is the same within experimental uncertainty.
- Determine the year that the composition of the U.S. penny changed.
- Explain how this method of determining the change in U.S. penny composition relates to the concept of isotopes from your study of chemistry.

PRIOR KNOWLEDGE

Students must be able to keep careful records of observations and know how to make histograms.

Pennies, Background Material (from the Teacher Notes)

BACKGROUND MATERIAL

Plan ahead to make sure you have enough pre-1982 pennies so that they represent approximately 10-50% of your total sample of pennies.

A histogram is a common data representation in particle physics. Histograms are graphical representations of a frequency table. If your students can learn how to make histograms by completing the activity *Histograms: The Basics*.

You can find inexpensive small balances that read to the hundredth place at Amazon and other vendors for less than $20.00. The mass scale should have a minimum reading of 0.01g.

Pennies, Implementation (from the Teacher Notes)

IMPLEMENTATION

One method of starting this activity is to instruct the students to write down as many characteristics of each penny as they can. Many of these characteristics are qualitative and a few are quantitative. Help the students focus on the characteristics that are measurable in the lab and can be represented with a number value. The most important characteristics for this activity are mass and mint date, but if students want to record things like diameter or thickness, they can draw conclusions from those data as well. If time is a factor, then limit data to mass and mint date.

Have student groups construct a data table to organize their data. Make sure that mass is one of those quantities. Students should document their procedure before experimentation and review it after completing the experiment so they can include any changes made during data collection. They can make a histogram for each characteristic they study. They may also make scatter plots to see how one quantity might affect the other. The most telling of these is mass as a function of mint date but lead them to this rather than simply assign it.

Pennies, Implementation (from Teacher Notes)

A data table with several quantities may look like this:

Penny	Mass (g)	Mint Year	Diameter
1			
2			
3			

It is also useful to help them with making their first and most important histogram with a table like this:

Mass bin (g)	Number of pennies/0.1 g
0.0-0.1	
0.1-0.2	
0.2-0.3	

Pennies, Background/Results (from Teacher Notes)

The mass of the U.S. penny changed significantly in 1982. You can ensure that your *class* "discovers" this by inspecting your penny collection to see if there are enough pre-1982 pennies to show the mass difference. The lab works quickly if each group has 10–20 pennies with various mixtures of pre-1982 and post-1982 pennies.

Have the students make a histogram of their group data, but the sample size is too small to see a consistent effect. It is best if there are at least 100 data points to make the *class* histogram. The mass histogram will very likely reveal that pennies come in two different masses: "light" and "heavy." However, there is nothing to suggest *why* the masses change. The answer to that question requires more investigation.

If students record the mass *and* mint year of each sample, they'll have enough information to begin to answer the question about *why* the mass changes. For this part of the investigation, it is best to create is mass vs. mint date scatter plot. This plot provides information about when the change in mass occurred. Students *may* make a more advanced analysis using the radii, thicknesses, and masses of pennies to find their densities and use these data to possibly indicate whether a there was change in composition of the pennies in 1982. Here, knowing the uncertainty in those measurements is critical. You can also suggest additional tools and measurements that the students should make in order to determine why the mass changes. This is the nature of science; one experiment leads to another.

Pennies, Assessment (from Teacher Notes)

ASSESSMENT

One technique for reporting out is to ask students to confer in their group, present their answers on a white board and share their ideas and answers with the class.

You might ask students questions such as:

- What do you conclude about the masses of pennies from your histogram? What is the evidence that supports your conclusion?
- Is there a single best value for the mass of a U.S. penny? Is there more than one best value for the mass of a U.S. penny? Do the values agree within uncertainty? What evidence can you provide to support your answer?
- What do you conclude from the mass vs. mint date plot? What is the evidence that supports your conclusion?
- Is there evidence from your data to support the claim that the composition of a U. S. penny has always been the same? Explain your claim.
- What additional measurements might you make to learn more? What tools might you need?

Extension questions:

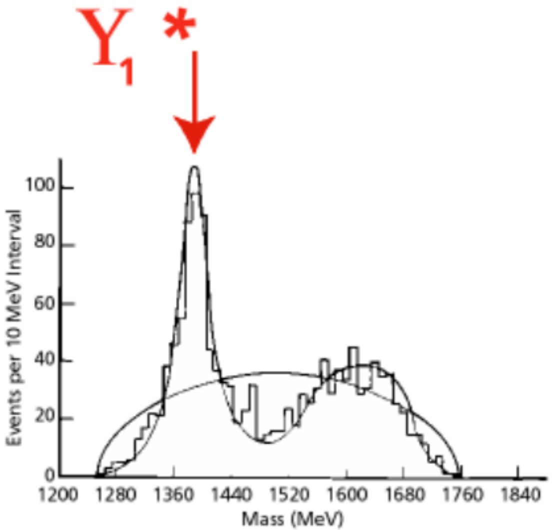
- If they collected other quantitative data for each penny, what conclusion can they draw from the plots made with those data?

Pennies, Student Pages

MASS OF U.S. PENNIES

Name(s)____Date ____________________

Particle physicists use graphs like the one shown to look at the results of their experiments. By putting mass readings on a histogram, they can see that the peaks show separate particles.



Since we don't have ready access to particles or machines to make them, we are going to look at something more readily available: U.S. pennies. There are lots of pennies in circulation. Are they all the same? They all represent $0.01 and may be similar in color, but is that the only thing that they have in common?

Pennies, Student Pages

Divide into groups of two or three students. Obtain a set of pennies from your teacher.

Begin by brainstorming characteristics of a U.S. penny. Identify the characteristics that can be measured or described with a number value. Measure and record as many properties of each penny as you can observe. Be sure the mass in grams is one of them!

Organize your data in a table. It should look something like this (but with more cells):

Penny	**Mass (g)**	**Other quantity**	**Other quantity**
1			
2			
3			

Now make a new "frequency" table with masses in 0.1 g bins and the number of pennies that fall in each bin, something like this:

Mass bin (g)	**Number of pennies/0.1 g**
0.0-0.1	
0.1-0.2	
0.2-0.3	

Pennies, Student Pages

Draw a histogram of your group data; then make a class frequency table and a histogram of the class data. If you have other data that you made into frequency table form, discuss with your group and the class about whether to make histograms for these as well.

Answer the following questions on another sheet of paper. Show all calculations.

1. Describe the masses of the pennies in your set. Be as specific as you can.
2. Describe the masses of the pennies in the class set. Are there any differences between your set of data and the class set?
3. Can you suggest an explanation for the mass distribution that you see? What evidence can you provide to support your explanation?
4. Are there more pennies from more recent years or from prior years? Can you suggest an explanation for this? How would you test this idea?
5. Which year is represented by the most pennies? By the second most? By the third most?
6. What conclusion can you draw based on the evidence provided by your two histograms?
7. What additional measurements might you make to learn more? What tools might you need?

Extension

If other characteristics were recorded, you might construct histograms for these results. In some cases, you may get more insight by trying "scatter plots" or A vs B type graphs. A graph of mass as a function of one of the other quantities you measured would be a scatter plot. What conclusion can you draw from your new plots? Did any of the new plots contribute to your conclusions? How?

Penny Mass: Implementation in MY Class

- As you can see, this activity is essentially ready-to-go for some classes!
  - Format is very student inquiry-based
- Some instructors may need to adjust the materials to suit their needs or their class
  - Student/Instructional Level
  - Differentiation
  - District Required Lesson Plan formats, etc
- For my own classes, I have found that more explicit procedures are useful (introductory physics, algebra based, and I implement this activity early in the course)
- All DAP activities can be modified and leveled up and down, rewritten for virtual instruction, and more- but it is so useful to have a place to start!

Penny Mass: Implementation in MY Class

- I teach a short and ‘simple’ particle physics unit at the beginning of my course
  - This is the first lab, to introduce the data analysis concepts required for particle physics experiments

- For my classroom, I have expanded the given materials into a more formal lab assignment, with an explicit procedure and conclusion questions that draw connections to real particle physics data
- I also mixed a few nickels, dimes, quarters, and Canadian coinage into the sample to provide an extra challenge: ‘noise’

Penny Mass: Implementation in MY Class

Student Directions

Procedure:

1. Open your copy of the Google Sheet for taking your data.
2. Use the scale to find the mass, to the hundredth of a gram, of each coin.
3. Record in your data table: the mass, the year the coin was minted, and also the condition of the coin (this last is a more subjective measure, of course).
   a. Use 1= Good, 2= Fair, 3= Poor for Coin Quality.
4. Once you have recorded the mass of at least 100 coins, you can begin data analysis!

Example: Penny Mass Google Sheet

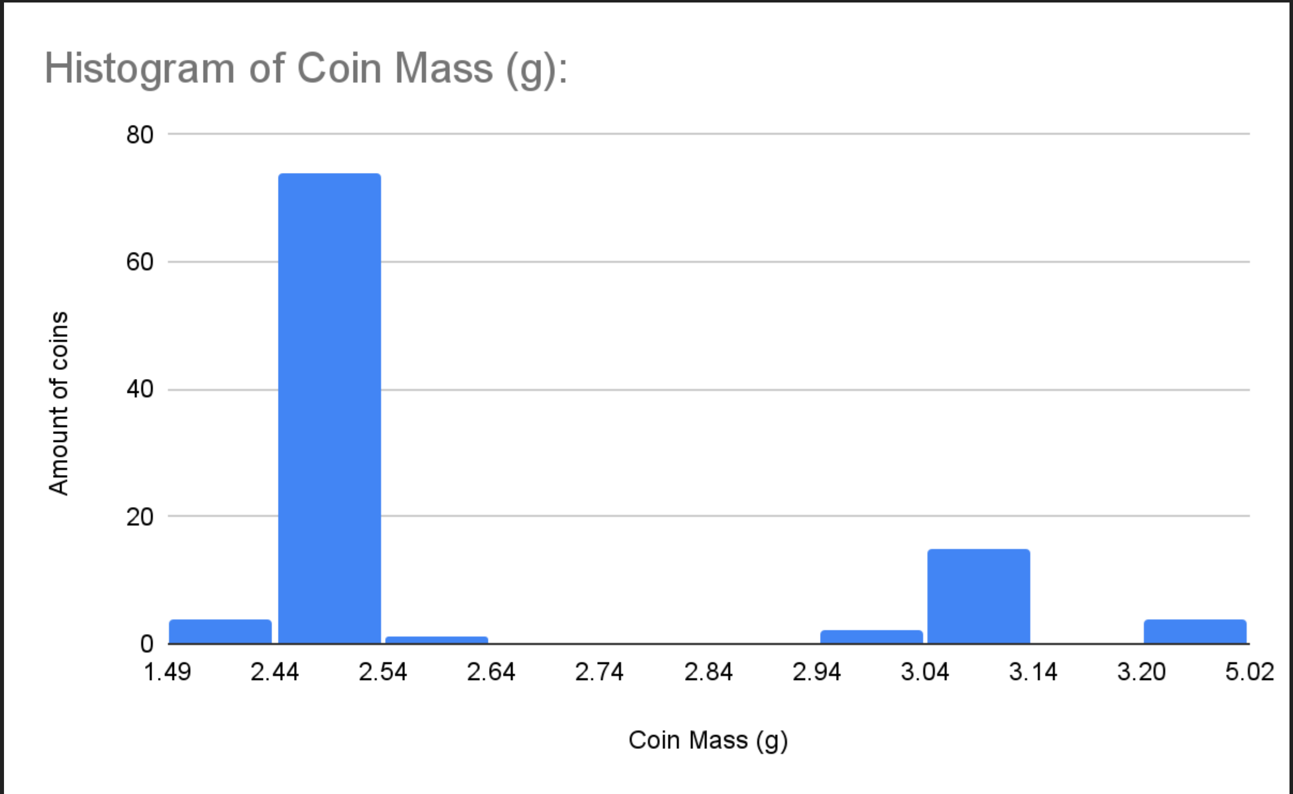
	A	B	C	D	E	F	G	H
1	Use this spreadsheet to record your data. Each student should make a copy of the data, as you must individually do the analysis.							
2	Record each coin's mass in grams (to the hundredth of a gram) but **do not include units**, as it will confuse the software.							
3	Coin Mass Data							
4								
5	Coin Number:	Coin Mass (g):	Coin Date:	Coin Quality:	(For Quality, use a numerical system: 1= Good, 2 = Fair, 3 = Poor)			
6	1							
7	2							
8	3							
9	4							
10	5							
11	6							
12	7							
13	8							
14	9							
15	10							
16	11							
17	12							

Penny Mass: Implementation in MY Class

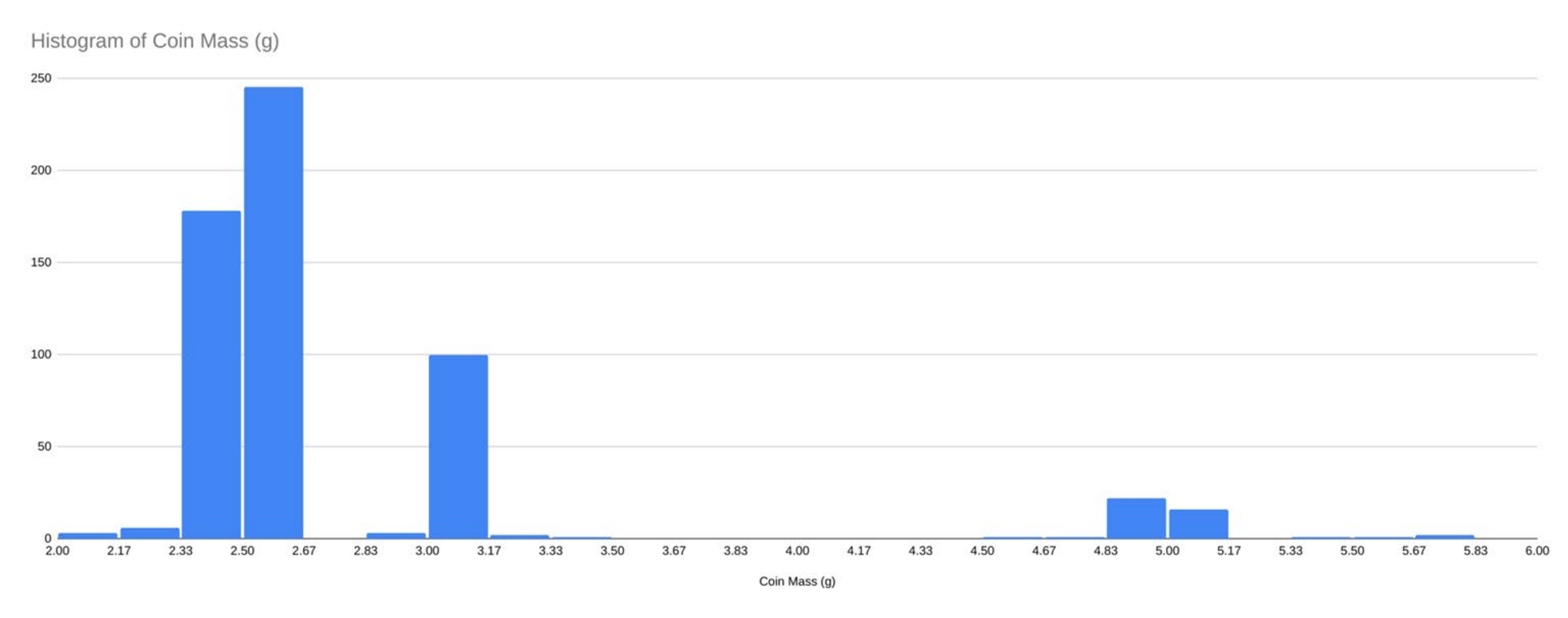
- In my class, the experimental procedure is more structured (I tell them WHAT data to take, HOW and WHERE to take it)
- This allows me to better guide their analysis to ensure they can take-away the skills and understandings that will help them most in my class

- Students make histograms and scatter plots of their data
  - For each, they must interpret their results
  - They also need to explain the uses of each type of plot!
  - Using Google Sheets to do this helps them to develop computer skills they will NEED!
- They pool their results into a class data set
  - We make a class totals histogram so students can better visualize how more data leads to increased statistical significance

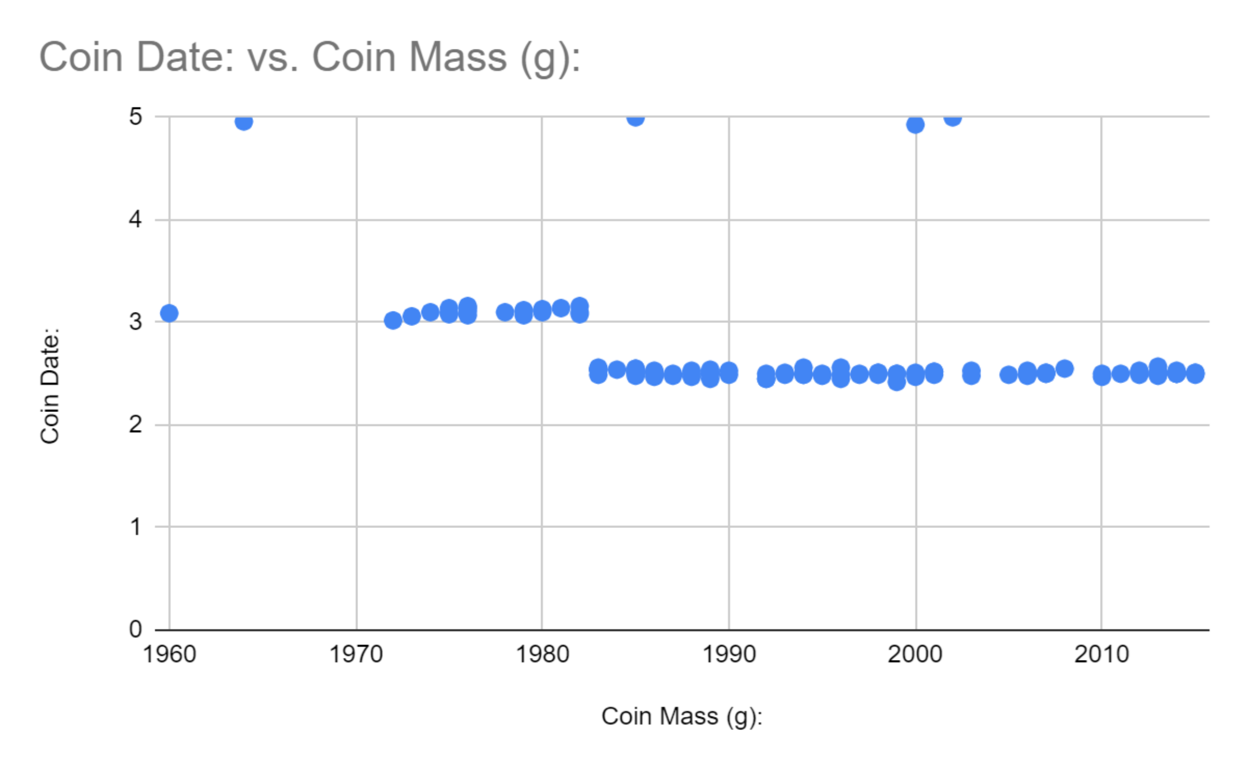
Sample Student Work: Histogram of Coin Mass



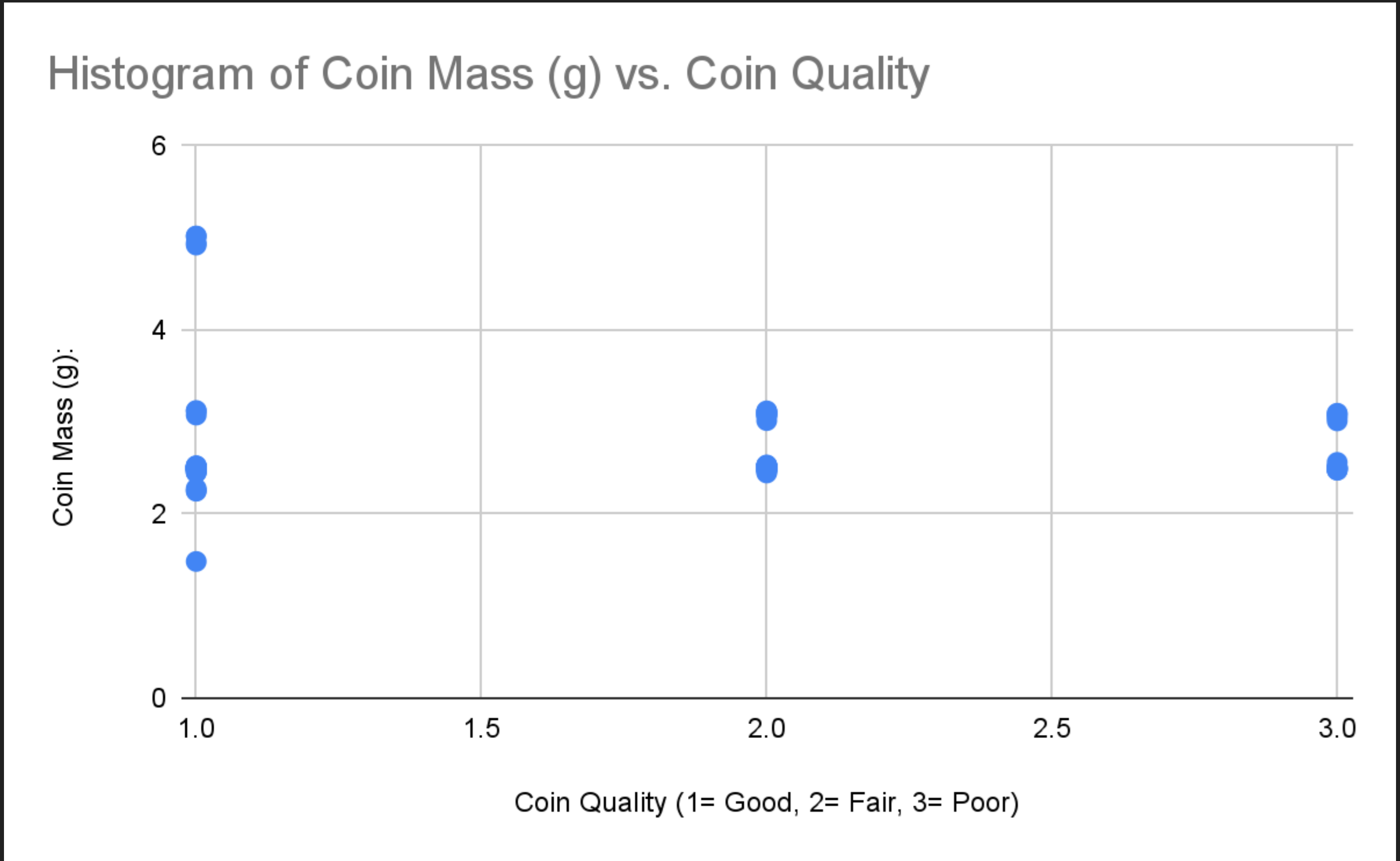
Class Histogram: Mass of US Pennies



Sample Student Work: Mass of US Pennies



Sample Student Work: Mass of US Pennies



Penny Mass Histogram vs CMS Data Histogram

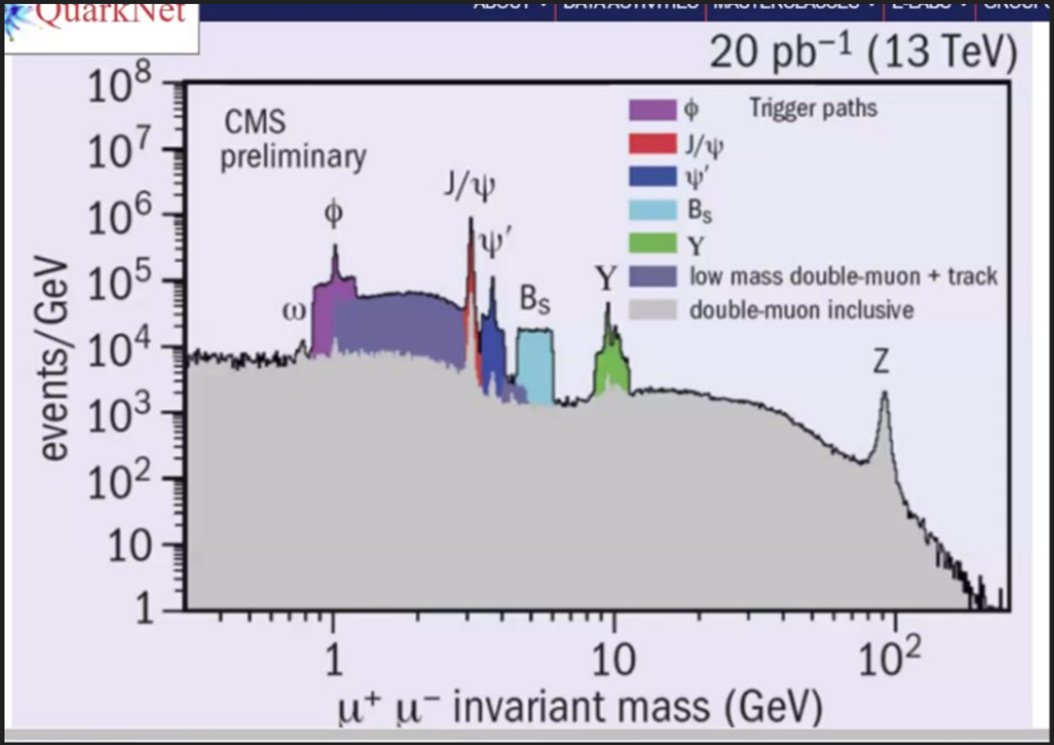


Image Credit: QuarkNet BAMC (Big Analysis of Muons) Lecture, Spring 2020.

Sample Student Work: Penny Mass Conclusion

Conclusion:

1. Look at your histogram. What mass values show ‘peaks’, and what coins do you think caused each peak? **Around 2.5, 3.1 and 5.1. The lower two are regular coins and the 5.1 are the nickels.**
2. What information can you learn from the histogram that is hidden by calculating the mean of the data? **There are outliers.**
3. What conclusions can you draw from your scatter plot of mass versus year? **They are (just about) all a similar mass from ‘72-’82, they drop all at once in ‘83.**
4. What conclusions can you draw from your scatter plot of mass versus quality? **Not much.**
5. How does your data compare to the class data? **It looks just about the same**
6. Which is likely a more accurate data set, yours or the whole class? Why? **Whole class, there is more data to compare.**

12. The histogram shown below is taken from CMS data at the LHC, CERN. These mass events are the result of the collision of protons at near lightspeed. New particles were created, which then (in this data) decayed into a muon and an anti-muon. Both muons were measured by the CMS detector, and this plot was created.
    a. From the plot, what is the mass of the Z particle, in GeV? **A little under a hundred**
    b. From the plot, what is the mass of the Y particle, in GeV? **A little under 10**
    c. From the plot, what is the mass of the ϕ particle, in GeV? **Around 1**
    d. How can you tell the particles apart, even though they decayed into the same muon/antimuon pair? **The masses were different.**
    e. The gray area on the plot represents ‘noise’, or background. This could be uninteresting events, events that were partially not detected, or caused by things like cosmic rays, as well as imperfections with the equipment.
        i. How many events, above background, were required to create a distinct peak that shows the presence of a particle? *Make your best estimate.*
    An order of magnitude above the surrounding noise level.

Implementing the Data Portfolio: 2 Common Methods

Dedicated Particle Physics Unit

- Some QuarkNet teachers add Particle Physics at the end of the course if time allows
- I choose to teach a short Particle Physics unit at the beginning of the year to make sure it happens!
- I can then loop concepts back to Particle Physics while teaching Mechanics the rest of the year

‘Sprinkle’ Method

- Traditional Introductory Physics covers Mechanics and E&M
- Those concepts have many applications in Particle Physics!
- Some QuarkNet teachers select Data Portfolio activities that relate to specific concepts and use them throughout the year

Method 1: Dedicated Particle Physics Unit

Agenda:

Day 1: Particle Card Sort, Notes Part 1, and Particle Adventure Part 1

Day 2: Particle Adventure Part 2 and Particle Reactions (Notes and Problems)

Day 3: Notes Part 3 and Particle Adventure Part 3

Day 4: The Ghost Particle

Day 5: Penny Lab Part 1

Day 6: Penny Lab Part 2

Day 7: CRMD Lab Part 1

Day 8: CRMD Lab Part 2

Day 9: Review and Particle Physics Bingo!

Day 10: Test

Objectives:

Students will be able to.....

- describe the Standard Model of Particle Physics
- identify and classify fundamental particles according to the Standard Model
- balance particle reactions
- conduct a particle physics-type experiment
- collect and analyze experimental particle data

Success Criteria:
In order to show mastery, students will...

- define leptons, quarks, hadrons, bosons.
- use conservation laws to determine allowed particle reactions
- design an experiment to measure muon data
- create histograms to analyze large data sets

Method 2: ‘Sprinkle’ the DAP into your curriculum

- For this method, teach your course as usual, but if you are looking for new resources, labs, or extension assignments check out the DAP!
  - For Nature of Science
    - Multiple Activities use authentic data and focus on graphing skills, building models, experimental design, asking questions, and other basic science skills…..particle physics background is *not* required
  - For Kinematics
    - Several Activities use kinematics concepts such as relating speed, distance, and time
  - Conservation Laws
    - Conservation of energy and linear momentum are common themes in DAP activities
  - Electricity and Magnetism
    - Units: definition of the electronvolt
    - QED vs Field theory
    - charges of particles and charge conservation
    - Best Use of DAP: E&M applied in Accelerator and Detector science!

Sample Assignment: Mass of Z Boson

- Data Portfolio Activity: Calculate the Z Mass
- Assigned at the end of a unit on Momentum and Collisions
- Involves concepts including graphical vector analysis (adding non-perpendicular vectors), conservation of energy and momentum, dimensional analysis, and more!

Lab Practical: Mass of the Z Boson!

Rebecca Jaronski • Apr 8, 2020 (Edited Apr 8, 2020)

100 points | **Due Apr 17, 2020**

You will be working in a group of 6. Your group is using data from the ATLAS (A Toroidal LHC ApparatuS) Experiment at CERN (Conseil Européen pour la Recherche Nucléaire).

Each student will be assigned an event (attached) to analyze, but you are welcome to look at all the events if that helps you. Please talk to each other, in the comments below, in order to figure out how to do this analysis. Your task: measure the mass of a Z Boson. You are indeed being thrown in the deep end- let's see if you swim!

Blake and Andrew, you both have Event 1 (CERN only provided us with 4 events, so you are doubling up. I expect slightly different numbers though as your analysis will likely be different, especially when it comes to vector angles).
Caleb and Bryce, you are assigned to Event 2.
Seth, you have Event 3.
Matt, you have Event 4.

The ATLAS Key is provided for reference. The Lab Procedures and Instructions are posted below, your data will be recorded in the Google Doc. You will likely want scratch paper, a calculator, a protractor, and your textbook for assistance.

The rest of the class is analyzing events from the CMS experiment. You cannot collaborate with them until the very end when you compare answers!

Z Mass Lab Sheet Classroom
Google Docs

ATLAS Experiment Key.pdf
PDF

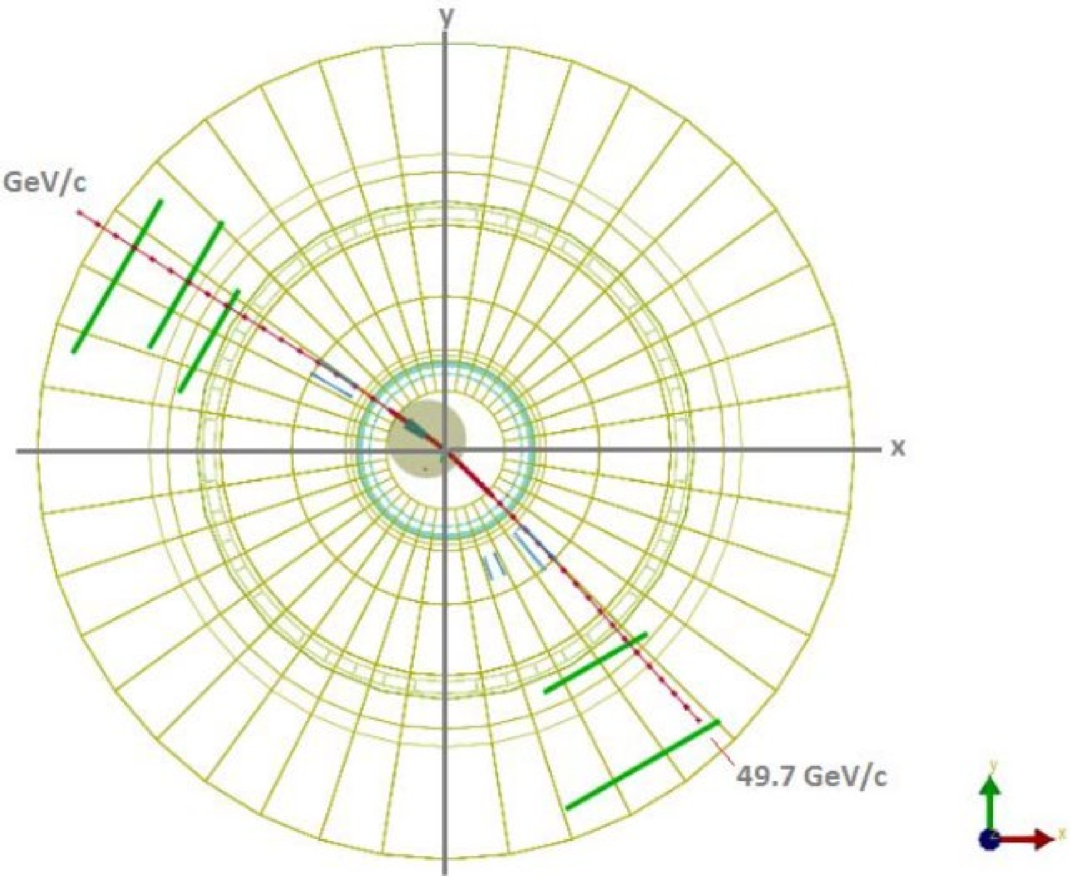
ATLAS Event 4.pdf
PDF

ATLAS Event 3.pdf
PDF

Sample Data: Mass of Z Boson

CMS: Z → μμ events for 2-dimensional analysis

Run 148031 Event 267892947



Samples of Student Work: Mass of a Z Boson

Event Number: 2

	Total Momentum (GeV/c) and Angle (degrees)	Momentum in the X direction (GeV/c)	Momentum in the Y direction (GeV/c)	Total Energy (GeV)
Muon 1	48.8 GeV/c, 10.5 degrees North of West	47.5 GeV/c	8.84 GeV/c	48.8 GeV
Muon 2	44.5 GeV/c, 22.6 degrees South of East	41.08 GeV/c	17.10 GeV/c	44.5 GeV

	Net Momentum (GeV/c)	Net Energy (GeV)
Both Muons	10.58 GeV, 38.67 degrees West of South	93.3 GeV

Mass of Z candidate (GeV/c^2)	93.3 GeV

Group Data:
Your teammates (whether CMS or ATLAS) each had a different event to analyze.

Share your value, and record the Z Masses of your entire team in the data table below.

Answer the following questions:

1. How will you know that all members of your team correctly analyzed their Z boson decay event? **The found values will be relatively similar**

3. Why is it important that two separate teams, with different detectors (CMS and ATLAS), are searching independently for this mass?
So there is no bias and there is a sufficient pool of data

Teammate Name	Z Boson Mass Result
Bryce (me)	93.3
Seth	90.451
Matt	96.262

Your Team's Predicted Z Boson Mass (GeV/c^2)	93.337

Data Tables

Event Number: 1

	Total Momentum (GeV/c) and Angle (degrees)	Momentum in X direction (GeV/c)	Momentum in Y direction (GeV/c)	Total Energy (GeV)
Muon 1	48 GeV/C	47.27 GeV/C	8.335 GeV/C	48 GeV
Muon 2	43.6 GeV/C	-40.912 GeV/C	-14.912 GeV/C	43.6 GeV

	Net Momentum (GeV/c)	Net Energy (GeV)
Both Muons	9.1477 GeV/C	91.6

Mass of Z candidate (GeV/c^2)	90.73 GeV/C^2

Group Data:
Your teammates (whether CMS or ATLAS) each had a different event to analyze.

Share your value, and record the Z Masses of your entire team in the data table below.

Answer the following questions:

1. How will you know that all members of your team correctly analyzed their Z boson decay event? If all of our answers are reasonably close
2. How will your team combine data to come up with a probable mass for the Z boson based on this data set? Take the average (mean) of all data
3. Why is it important that two separate teams, with different detectors (CMS and ATLAS), are searching independently for this mass? Just in case one team is making a mistake

Sample assignment: Mapping the Poles

Need a lab to either introduce, or have students apply, the right hand rule?

Search/Filter

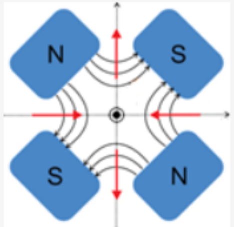
Curriculum Topics: Electricity & Magnetism

Data Strand: - Any -

Level : - Any -

NGSS Practices: - Any -

Apply

Activity Name	Data Strand	Level	Curriculum Topics	NGSS Practices
 Mapping the Poles Students explore some basics of magnetic fields that can be related to experimental particle physics.	LHC	Level 0	Electricity & Magnetism, Skill: Developing Models	2, 4, 6, 7

Sample DAP Assignment: Mapping the Poles

Introduction:

Magnets are at the heart of the Large Hadron Collider (LHC). You will explore magnetic fields around bar magnets and the effect of these magnetic fields on moving electrically charged particles such as the protons in the LHC. You will learn about the two main types of LHC magnets and the function of these magnets to ensure that the protons collide inside a detector.

Pre-Lab Questions:

1. What is the (electric) charge of a proton in fundamental/natural units?

2. What is the (electric) charge of a proton in SI units?

3. How and why do electric and magnetic fields affect the movement of charged particles?

Procedure Part 1, Mapping Dipoles:

You will need several blank sheets of paper, one small magnetic compass, and four rectangular bar or dipole magnets. (Dipole magnets have opposite poles on opposite sides.) As you do each part, work with your partner to make observations and claims based on the evidence provided by your investigation.

1. Check to see which end of your compass needle points towards the north wall of your classroom. That end of the compass needle represents the arrow head of the magnetic field vector.
2. Place two magnets, as shown in the Diagram A, about 15 cm apart on a blank sheet of paper. Outline the positions of the magnets on your paper.

A.

Mapping the Poles: Dipole Analysis Questions

Part 1 Analysis:

1. Compare your vector maps with another group. Are your results the same?
2. What can you say about the magnetic field between ‘like’ poles? Between ‘unlike’ poles?
3. Predict: If a proton were placed in-between the magnets in each of the situations above, what do you think might happen?

Procedure Part 2: The Right-Hand Rule

Background:

In the maps you made in Part 1, the most important region of a map is the region between the poles as shown in Figure 1 below.

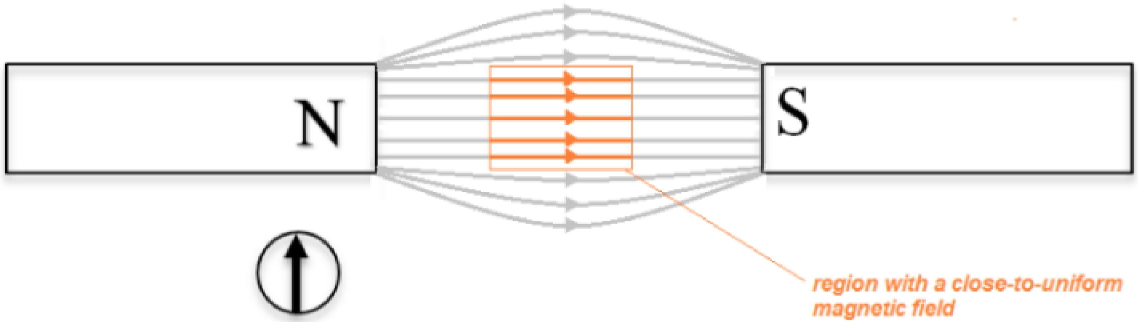


Figure 1. Location of region with uniform magnetic field•.

In Figure 1, the uniform magnetic field region is directed to the right as represented by the orange arrows.

Figure 2 shows how to represent arrows that point into the page (X) and arrows that point out of the page (•).

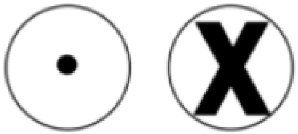


Figure 2. Representing the magnetic field direction.

The right-hand rule allows us to determine the direction of the force acting on an electrically charged particle entering a region of uniform magnetic field.

Figure 3 shows the resulting direction of the magnetic force in this case.

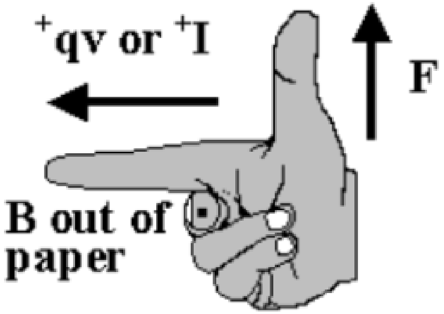


Figure 3. Right-hand rule for magnetic interactions.

There are a few things to notice in Figure 3.

- All of the direction arrows are at right angles.
- This is why the magnetic force, F, can be considered a sideways force acting perpendicular to the plane containing the moving positively charged particle, qv, and the magnetic field vector, B.
- In Figure 3, the positive charge motion is also labeled I for electric current. Remember that electric current is defined as positively charged particles in motion.
- An important thing to notice is that if the magnetic field, B, is parallel to qv, the moving electrically charged particle does not interact with the magnetic field B and the *motion of the particle does not change.*

What happens to electrically charged particles moving through the regions between the poles?

That is where the right-hand rule comes in. Figure 4 shows a wire with current in a region of uniform magnetic field.

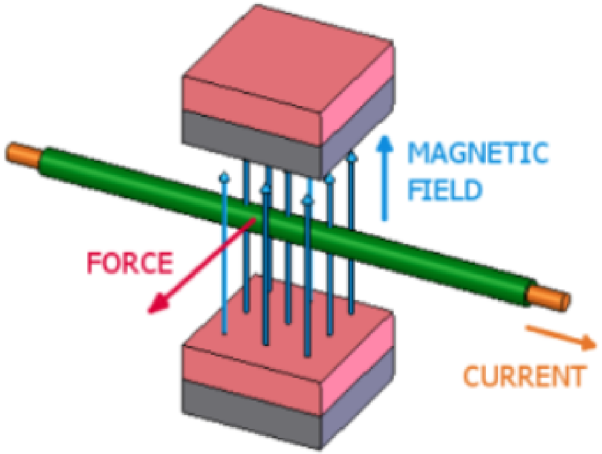


Figure 4. Magnetic force on current in a uniform magnetic field.

1. Using the right hand rule (explained in Figure 3) to determine the direction of the force on a positively charged particle in figure 4 above. Does your application match the Force drawn on the diagram?
2. Identify and draw a box around the magnetic field vectors in the region between the poles on your papers for Diagrams A, B, and C.

Mapping the Poles, RHR Analysis and Application

Part 2 Analysis and Application:

Consider the diagram shown in Figure 5 in which electrons enter a region of uniform magnetic field from the blue region in the diagrams. The yellow arcs represent particle paths. You may want to refer to the posted copy of this lab on Google Classroom to see the color version!

Figure 5. Electron paths entering regions of uniform magnetic field.

1. If you assume that the particles are protons with an initial velocity vector pointed toward the top of the page, what is the direction of the uniform magnetic field given the curvatures shown in Figure 5? Why?

2. These particles are actually electrons, not protons. Therefore, what is the direction of the uniform magnetic field that results in the curvatures shown in Figure 5? Why?

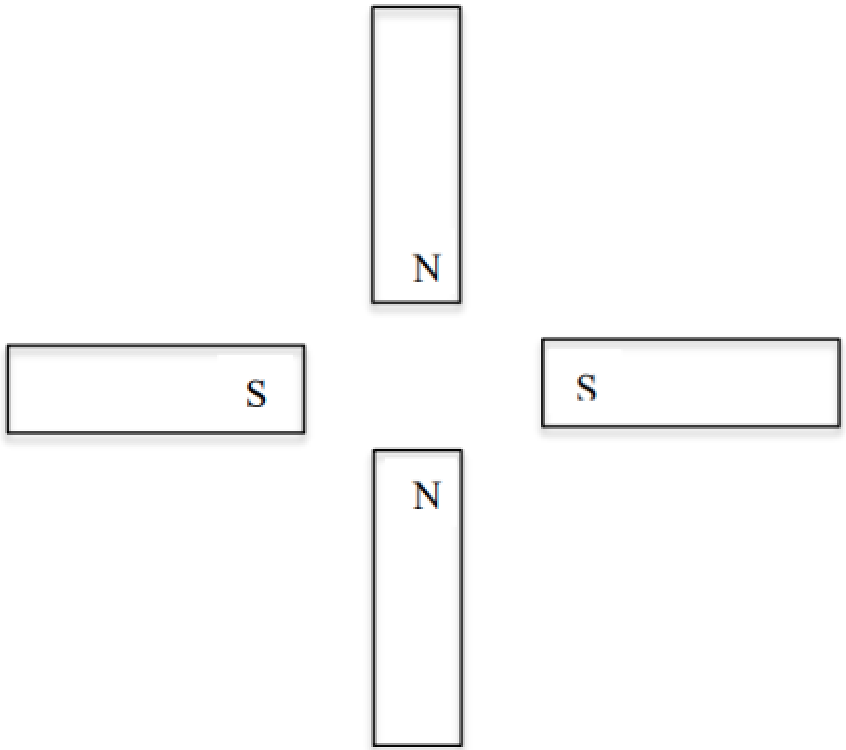
3. Rank the diagrams based on the speed of the protons from greatest to least. Explain your reasoning.

4. Explain why the magnetic force can be considered a sideways force. Use evidence to support your claim.

5. Based on the evidence from this activity (and your basic knowledge of mechanics and kinematics), explain how the protons in the LHC (and other colliders) can be fired from a linear accelerator, and then maintained in a large circle. Justify *all* your reasoning.

Part 3: Mapping the Quadrupoles

1. Make an arrangement of four magnets as shown below on one more sheet of paper.
2. Repeat the mapping procedure from Part 1 for the center region of the magnets.
3. This configuration of magnets is called a *quadrupole!*



At the LHC, the quadrupoles are always placed in pairs where the second quadrupole is oriented 90º from the first quadrupole.

In Figure 6, the direction of motion of the protons is represented by the yellow arrow, the black lines are the magnetic field, and the red arrows are the direction of the force in the region between the poles.

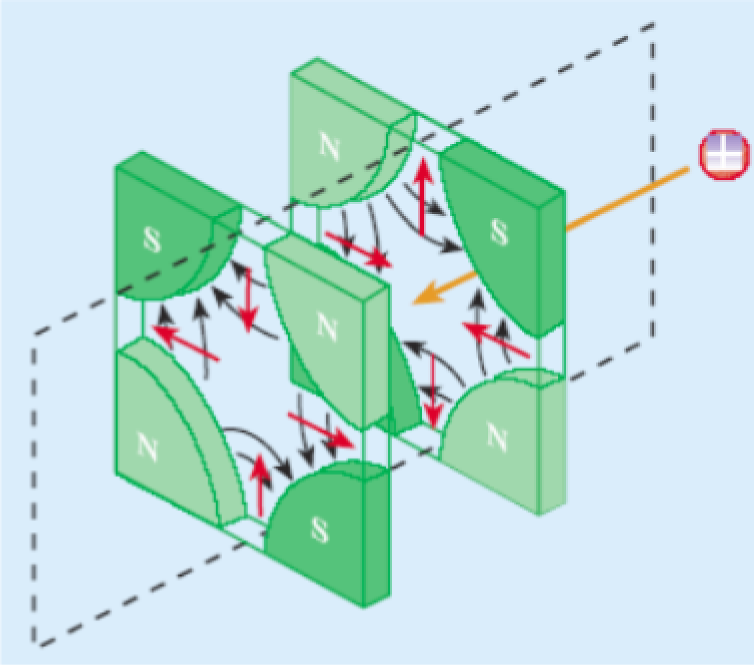


Figure 6. Focusing the proton beam using a pair of quadrupole magnets.

Claim, Evidence, Reasoning: Mapping the Poles

8. Does the direction of the red magnetic force arrow follow the right-hand rule?

9. Make a claim about the effect of the paired quadrupoles on the paths of the protons.

10. Explain your reasoning for #9.

11. Based on the evidence gathered from this activity, explain the purpose of the quadrupole in the LHC.

Conclusion: Data Portfolio = Awesome!

- Need a new lab? Find it here!
- Scale it up and down! You could find inspiration from middle school to collegiate levels
- Easy search filters!
- More activities are always being added, as well as variations (virtual compatibility, spanish language, and more)
- Wide application of concepts- and MINIMAL laboratory equipment needed-it’s cheap!
- All activities in the Data Portfolio are inquiry based, involve Claim-Evidence-Reasoning process, and connect many concepts!
- Try it out! See What YOU Find!

VT QuarkNet is looking for more teachers!

Images taken during 2024 QuarkNet Lead Teacher Camp at SURF!

- If you are a high school science teacher (or know one) from Virginia, West Virginia, North Carolina that is interested, please contact me:

  rebeccajaronski@mcps.org

- We offer workshops every summer (stipend and travel support included!)
- We can also sponsor a trip to Fermilab's Data Camp
- Thank you very much!
  - ANY QUESTIONS?