ANGLES AND DIMUONS

TEACHER NOTES

INTRODUCTION

Figure 1 shows the Large Hadron Collider (LHC), located at the CERN laboratory just outside Geneva, Switzerland. It is the most powerful particle accelerator on Earth. Protons travel at high energies in opposite directions in the 27 km diameter LHC ring and collide at specific points. At Point 1 of the LHC ring, the ATLAS detector, shown in Figure 2, surrounds the collision.

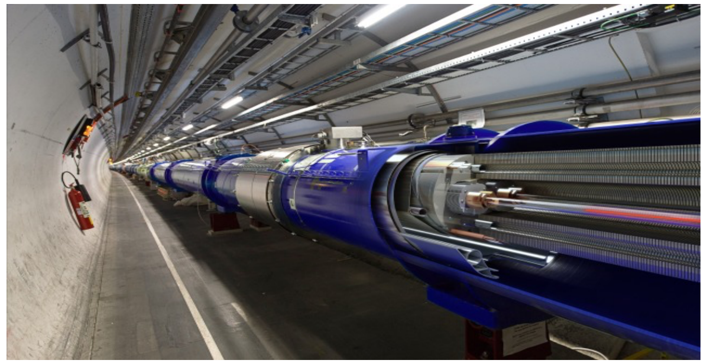


Figure 1. Image courtesy of CERN, https://cds.cern.ch/images/OPEN-PHO-ACCEL-2014-003-8/file?size=medium.

When protons collide, some of the energy of the collisions can become matter in the form of fundamental particles. These particles are extremely short-lived, so they never make it through the beam pipe to enter the ATLAS detector even if they travel at the speed of light.

However, these short-lived fundamental particles transform into high energy, low mass particles. These particles have a longer lifetime which allows them to travel into the ATLAS detector.

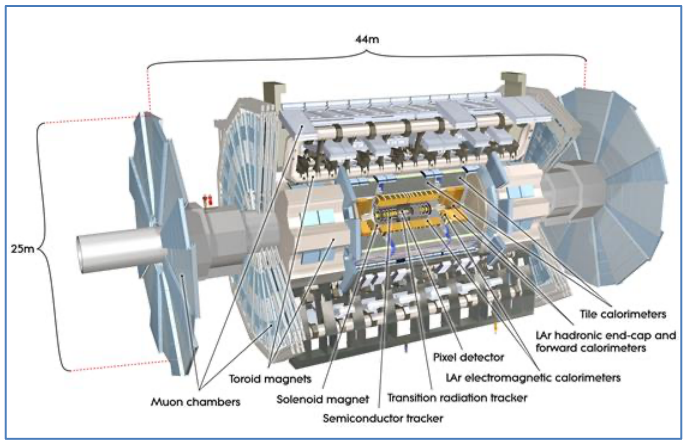


Figure 2. Image courtesy of CERN, https://mediastream.cern.ch/MediaArchive/Photo/Public/2008/0803012/0803012_01/0803012_01-A5-at-72-dpi.jpg

When a neutral particle from a collision decays, it can produce a muon and anti-muon. This is usually called a "dimuon event." These events are seen in abundance in the ATLAS detector. We will examine such events to determine the opening angles between muons and anti-muons. The distribution of these opening angles tells us about the parent particles from which the dimuon events came.

STANDARDS

Next Generation Science Standards

Science Practices

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.

1.3.1 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.

ENDURING UNDERSTANDINGS

- Scientists can use data to develop models based on patterns in the data.

LEARNING OBJECTIVES

Students will be able to:

1. Describe the pattern in the distribution of these opening angles.
2. Determine if the dimuons come from one type of particle or more than one type of particle.
3. Explain how the opening angle is influenced by the mass of the parent particle.

PRIOR KNOWLEDGE

The students need to know:

- How to measure angles.
- How to make and interpret a histogram.

BACKGROUND MATERIAL

In this experiment, we are looking for muon-antimuon pairs, referred to by physicists as "dimuons." Protons collide in the LHC from opposite directions in the beam pipe, the direction defined as the z-axis. Very short-lived neutral particles can be made in these collisions. These neutral particles each carry momentum in different directions. These same neutral particles can decay into dimuons. The simplest opening angle measurement, $\Delta\phi$, is in the x-y plane, perpendicular or transverse to the beamline. Thus, we are only looking at the x and y components of the motions of the muons and anti-muons. Remember that mass converts to energy. More mass converts to more energy. Less mass converts to less energy. The same goes for energy converting to mass. The more energy a particle has, the greater its momentum. And of course, momentum is conserved.

RESOURCES

These will help your students in their investigation:

- Background information
    - ATLAS: https://atlas.cern/
    - LHC: https://www.home.cern/science/accelerators/large-hadron-collider
    - About histograms: https://quarknet.org/content/making-histograms.
- Tools
    - HYPATIA-w2d2 event display: https://hypatia.iasa.gr/w2d2/
    - Tally sheet: https://web.quarknet.org/files/DeltaPhiTally_29mar2023.pdf
    - Explanatory screencast: https://web.quarknet.org/media/mc/dletaphi-sc-29mar2023.mp4
    - Protractor (you can use a physical protractor or a protractor app).

IMPLEMENTATION

Figure 4, below, shows the collisions and products that we are investigating in this activity.

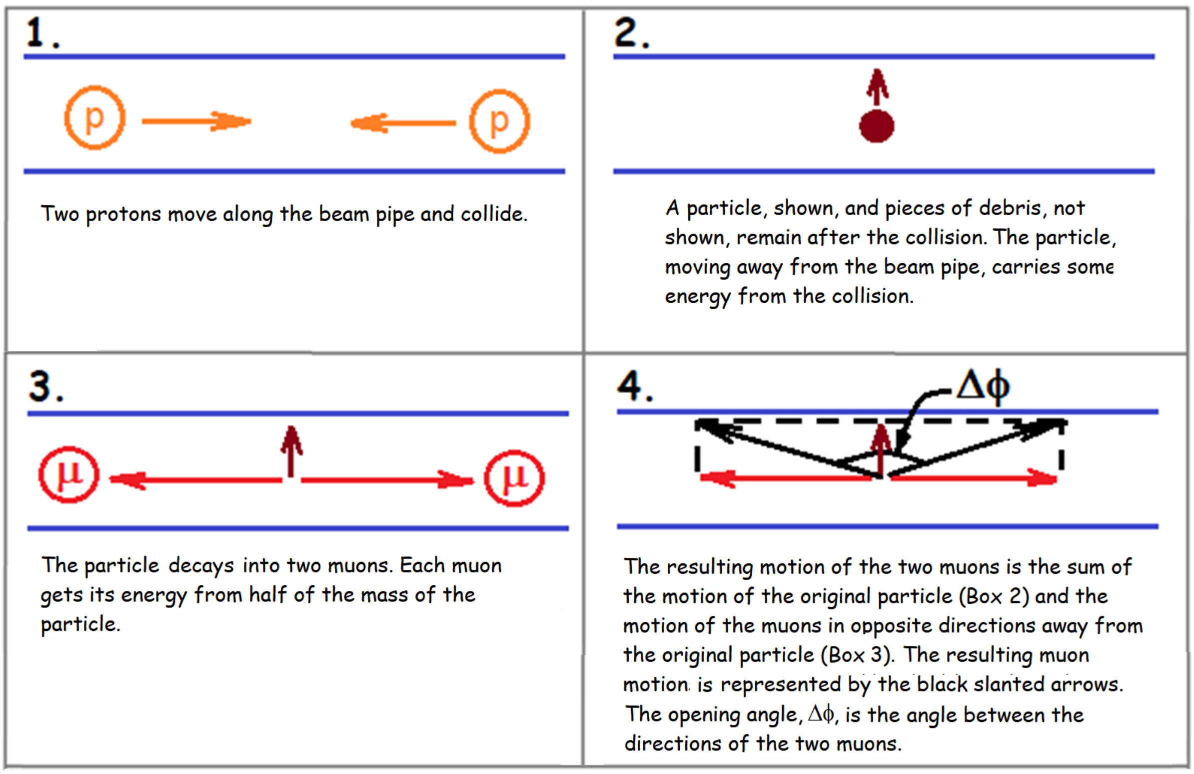


Figure 4. Illustration of creation of a neutral particle and its decay into muons,

In Figure 4, the length of each arrow represents the energy and momentum of a particle. Box 4 shows that there are two factors that affect the size of Δϕ. The brown arrow represents the motion that the particle carries out from the collision (box 2). The red arrows represent the motion of the muons traveling out from the decay (box 3). The following discussion questions are designed to guide the students on ways to draw meaning from the data:

1. How does the mass of the particle that decayed into muons affect the lengths of the horizontal (red) arrows?
   The greater the mass of the particle that decayed, the greater the length of the horizontal (red) arrows.
2. How do the lengths of the horizontal (red) arrows affect Δϕ?
   The greater the length of the horizontal (red) arrows, the greater Δϕ.

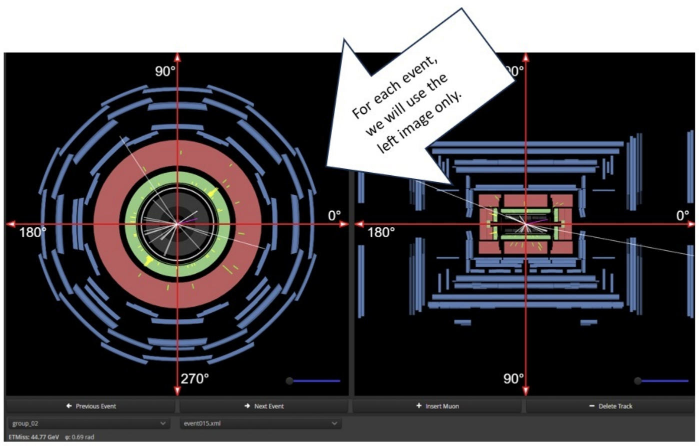
3. Based on Questions 1 and 2, what does a large $\Delta\phi$ tell us about the particle that decayed?
   The greater $\Delta\phi$, the greater the mass of the particle that decayed.
4. What does a small $\Delta\phi$ tell us about the particle that decayed?
   The smaller $\Delta\phi$, the smaller the mass of the particle that decayed.

Your students will measure the opening angles between the tracks of the dimuons in ATLAS events. Here are our possible **research questions**:

1. Describe the pattern in the distribution of these opening angles.
2. Determine if the dimuons come from one type of particle or more than one type of particle.
3. Explain how the opening angle is influenced by the mass of the parent particle.

Teams of two are best for this measurement. Instruct the students to open HYPATIA-w2d2. Find the link in the **RESOURCES** section above. Assign each pair one of the 80 groups listed (group_01 to group_80). If your students struggle, encourage them to view the screencast for help.

Remind your students that they are to focus on the left image for each event in the event display. This view is known as the forward (x-y) view.



Your students advance through the events, only stopping for events with dimuons. Dimuon events have two long tracks that pass beyond ECal (the innermost ring in the event image) and usually as far as or beyond the Muon Chambers (the outermost rings in the event image). Your students are looking for dimuon events only, that is, a muon track and antimuon track. **The remaining events are considered background and therefore can be ignored for this analysis.**

Refer to the diagrams in Figure 3 below to help you understand what we are about to measure.

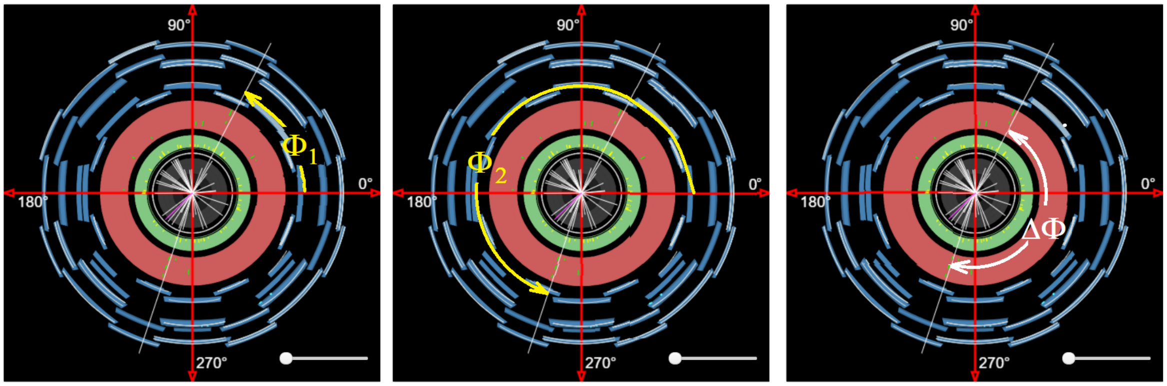


Image 1 | Image 2 | Image 3

Figure 3. Opening angle as seen in ATLAS x-y plane.

The angle between the x-axis and the first muon track is shown in Image 1. The angle between the x-axis and the second muon track is shown in Image 2. You do not need to measure these angles.

- For each dimuon event, your students will measure the smallest angle between the two muon tracks using a protractor. Image 3 shows $\Delta\phi$ for this event.
- Your students then record their values for $\Delta\phi$ in the tally sheet by placing the tick marks for each value of $\Delta\phi$ measured using the closest values that appear in the sheet. (For example, 17 degrees is closest to 10 and 23 degrees is closest to 30.) This will allow your students to record the number of events in bins that represent 20-degree intervals.
- Students continue measuring and recording values for $\Delta\phi$ for all of the dimuon events.
- When a pair of students is finished with their dataset, they need to add up the number of tick marks in each bin of $\Delta\phi$ and fill in the histogram on their tally sheet.
- Each pair contributes their results to the combined histogram for the class data.

Remind the students of the **research objectives**:

1. Describe the pattern in the distribution of these opening angles.
2. Determine if the dimuons come from one type of particle or more than one type of particle.
3. Explain how the opening angle is influenced by the mass of the parent particle.

Discuss the class histogram in light of the class research objectives. Consider mass-energy conversion and conservation of momentum. Guide your students with some probing questions and helpful hints. Ask your students to consider:

- What does the evidence from your histogram tell you? Do you see a pattern?
- Why do you think the histogram appears the way it does? Remember to provide evidence and reasoning to support your claims.

Assessment

You can choose to assess using formative techniques in which the students answer the objectives in class discussion of results.