ANGLES AND DIMUONS
STUDENT PAGES

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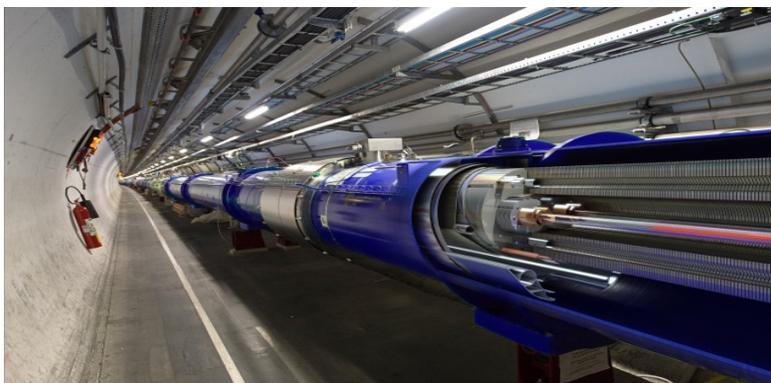
When protons collide, some of the energy of the collisions can become matter in the form of fundamental particles. These particles are extremely short-lived, so they never make it through the beam pipe to enter the ATLAS detector even if they travel at the speed of light.

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

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.
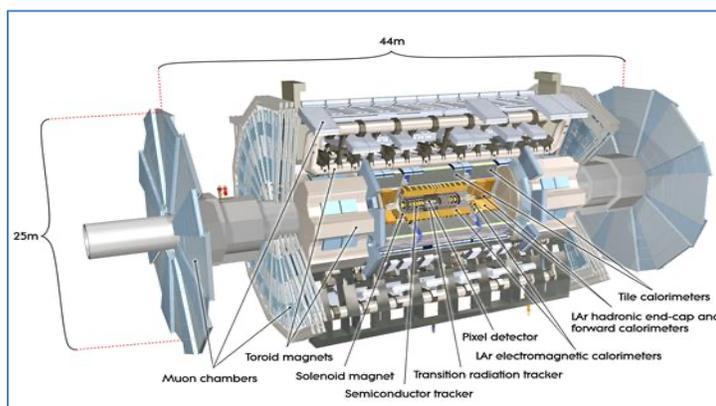
Why do we want to study opening angles?
1. They are easy to study. That matters: You can find and measure these events.
2. We get to use $E=mc^2$ in practice without crazy calculations.
3. Conservation of momentum is in there too. Also, a big deal.
4. All of this allows us to see what sorts of particles decay into dimuons. We can uncover categories of particles that are too short-lived to measure directly!

What do we know?

We know at least these things:
- 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.
- 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.
- Momentum is conserved.
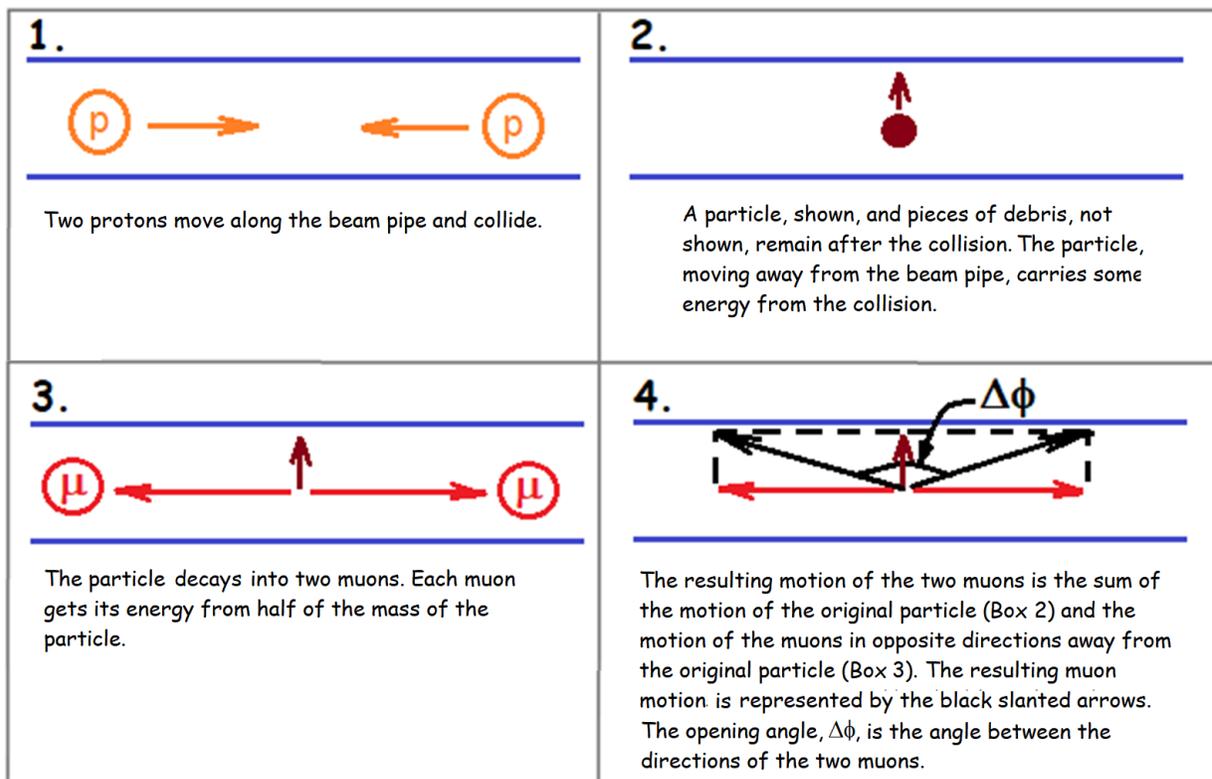- **DISCUSSION QUESTIONS**

1.	2.
Two protons move along the beam pipe and collide.	A particle, shown, and pieces of debris, not shown, remain after the collision. The particle, moving away from the beam pipe, carries some energy from the collision.
3.	4.
The particle decays into two muons. Each muon gets its energy from half of the mass of the particle.	The resulting motion of the two muons is the sum of the motion of the original particle (Box 2) and the motion of the muons in opposite directions away from the original particle (Box 3). The resulting muon motion is represented by the black slanted arrows. The opening angle, $\Delta\phi$, is the angle between the directions of the two muons.

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 $\Delta\phi$. 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).

1. How does the mass of the particle that decayed into muons affect the lengths of the horizontal (red) arrows?
2. How do the lengths of the horizontal (red) arrows affect $\Delta\phi$?
3. Based on Questions 1 and 2, what does a large $\Delta\phi$ tell us about the particle that decayed?
4. What does a small $\Delta\phi$ tell us about the particle that decayed?

RESOURCES

These will help you in your 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).

PROCEDURE

What are we trying to accomplish?

We will measure the opening angles between the tracks of the dimuons in ATLAS events. Here are our possible **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.

What will we do?

We will collect data from ATLAS events to answer the research questions.
- Work with a partner. Teams of two are best for this measurement.
- Open HYPATIA-w2d2 and find the data assigned by your teacher from one of the 80 groups listed (group_01 to group_80). Find the link in the Resources section above. View the screencast for help.
- You will focus on the left image for each event in the event display. This view is known as the forward (x-y) view.
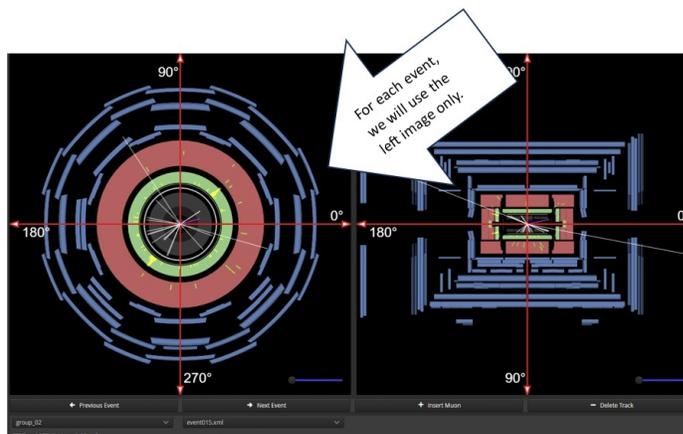
- Advance through the events, only stopping for dimuons. Dimuon events have two long tracks that pass beyond ECal (the innermost ring in the event image) and usually as far as or beyond the Muon Chambers (the outermost rings in the event image). We are looking for dimuon events only, that is, a muon track and antimuon track. The remaining events are

considered background and therefore can be ignored for this analysis.
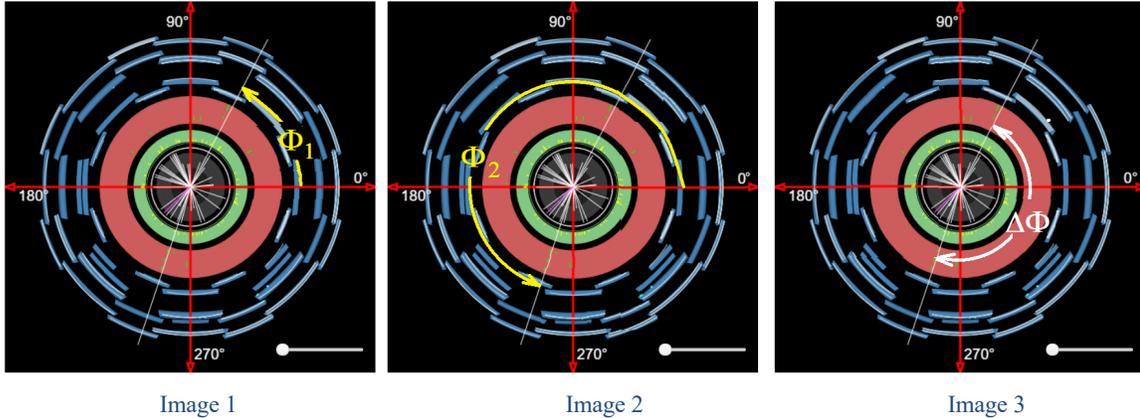- Refer to the diagrams below to help you understand what we are about to measure.

<p align="center">Image 1   Image 2   Image 3</p>

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, you will measure the smallest angle between the two muon tracks using your protractor. Image 3 shows $\Delta\phi$ for this event.
- Record your 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 you to record the number of events in bins that represent 20-degree intervals.
- Continue measuring and recording values for $\Delta\phi$ for all of your dimuon events.
- When you are finished with your dataset, add up the number of tick marks in each bin of $\Delta\phi$ and fill in the histogram on your tally sheet.
- Contribute your results to the combined histogram for the class data.

What is next?
With the guidance of your teacher, you will build a histogram of opening dimuon angles in ATLAS. Note the differences, if any, between the histogram on your tally sheet and the class histogram. Explain these differences.

Recall the 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.

Discuss the class histogram in light of your research objectives. Consider mass-energy conversion and conservation of momentum. Your teacher can guide you with some helpful hints. 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.