THE CASE OF THE HIDDEN NEUTRINO
TEACHER NOTES

DESCRIPTION

In this activity, students use momentum conservation to examine the decay of top-antitop pairs to determine what is missing from the event. They examine data plots from the DØ experiment at Fermilab. The events were chosen carefully: all of the decay products moved in a plane perpendicular to the beam. Students can analyze the events in two dimensions instead of three. The use of two-dimensional vector analysis fits in nicely with a conservation laws unit or as a practice problem for a vector analysis unit.

This version of the "Top Quark Activity" has been rdesigned to introduce neutrino physics or prepare students for a neutrino masterclass.

STANDARDS ADDRESSED

Next Generation Science Standards

Science and Engineering Practices

4. Analyzing and interpreting data
5. Using mathematics and analytical thinking
6. Constructing explanations
7. Engaging in arguments from evidence

Crosscutting Concepts

1. Observed patterns
4. Systems and system models
5. Energy and matter
7. Stability and change

Common Core Literacy Standards

Reading

9-12.3 Follow precisely a complex multistep procedure . . .
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.
MP4. Model with mathematics.
MP5. Use appropriate tools strategically.
MP6. Attend to precision.

IB Physics Standard 7: The Structure of Matter

Applications and Skills: Applying conservation laws in particle reactions

ENDURING UNDERSTANDINGS

Indirect evidence provides data to study phenomena that cannot be directly observed.

LEARNING OBJECTIVES

Students will know and be able to:

- Use conservation of momentum to determine the magnitude and direction of the net momentum vector of the particles detected in an event.
- Explain the possible significance of "missing momentum" in a collider physics experiment.
- Describe the properties of a neutrino that make it impossible to detect in the DØ detector.

Prior Knowledge

Students must be able to:

- Add vectors in two dimensions.
- Use energy and momentum units common to particle physics, momentum in GeV/c and energy in GeV.

Background Material

Useful links to describe the DØ experiment and how detectors work:
https://www-d0.fnal.gov/
https://home.cern/about/how-detector-works
http://lutece.fnal.gov/Papers/PhysNews95.html

Resources/Materials

Students will need a ruler, a protractor, calculator or spreadsheet and data from the following link:
http://ed.fnal.gov/samplers/hsphys/activities/thumbnails_pdf.html.

Implementation

The DØ experiment involved protons moving at close to the speed of light colliding with anti-protons traveling in the opposite direction at speeds close to the speed of light. Since a proton and an antiproton have the same mass and are traveling in opposite directions, the net momentum of the collision will be zero.

The key to finding the momentum carried away by the neutrino is to determine the "missing p_t" or "missing transverse momentum." The detector cannot detect neutrinos directly because they barely interact with matter. Students have to look at all of the momentum recorded in the event and then apply momentum conservation to determine what is needed to make the system's net momentum zero. Recall that energy in GeV and momentum in GeV/c are effectively the same numbers at these energies; that is, a muon with 30.5 GeV energy will have momentum of 30.5 GeV/c.

The process for measurement and analysis of data is:

- Draw lines through the centers of all jets and muon tracks to the origin of coordinates.
- For each jet and muon track, use a protractor to find the angle θ between the line you drew and the positive x-axis.
- The magnitude of the momentum p for all the jets and muons is given on the plot. Find $p_x = p\cos(\theta)$ and $p_y = p\sin(\theta)$ for all jets and muons.
- Find $p_{x\ total\_observed}$ and $p_{y\ total\_observed}$. Then find the magnitude and direction of $\mathbf{p}_{total\_observed}$.
- Recall that the center of mass momentum before the collision is zero; therefore, since momentum is conserved, the vector sum of momenta after the collision must also be zero. This is the discordant moment toward which you build. If momentum is not conserved, something else must be going on. It takes little guidance for the students to realize that there is an unseen particle, which you can identify as a neutrino if the students do not.
- The neutrino momentum is $\mathbf{p}_{neutrino} = -\,\mathbf{p}_{total\_observed}$. Realizing this, students will understand that they have measured the momentum of a particle that the detector could not detect. The teacher might want to explain that many neutrino detectors use this principle to study neutrinos further: a neutrino is undetected until it interacts with matter (this is rare) and its properties are inferred from measurement of the products of that interaction.

Assessment

Consider asking the students questions such as:

- Can you explain the mathematical model for finding the missing momentum carried off by the neutrino?

- *Choose a coordinate system.*
    - *Measure the angle of all vectors relative to the chosen x-axis.*
    - *Correctly determine the x-component and y-component of each momentum vector.*
    - *Find the sum of the x-components and y-components.*
    - *Indicating that the vector components should add to zero, determine the x-component momentum and y-component momentum of the neutrino that is needed to make the components' sums equal to zero.*
    - *Use the neutrino x-component and y-component to determine the magnitude of the missing neutrino momentum.*
- Determine that the energy of the neutrino must be the same as the magnitude of the momentum of the neutrino when appropriate units are chosen.
    - *Start with Einstein's equation* $E^2 = p^2c^2 + (mc^2)^2$.
    - *In the correct units, the equation reduces to* $E^2 = p^2 + m^2$.
    - *The mass of the neutrino is negligible at these energy levels, so* $E = p$.
- Describe the properties of a neutrino that make it impossible to detect in the DØ detector.
    - *The neutrino has no charge and therefore does not interact with the tracking section of the detector or the electromagnetic calorimeter.*
    - *The neutrino has such small mass, it does not interact with matter and therefore will not be detectable in the hadron calorimeter or the muon detector sections of the detector.*
    - *Neutrinos interact only by the weak interaction and only rarely. Therefore, the probability of interacting with any matter in the detector is vanishingly small.*
- Compare your individual result with the values determined by the rest of the class.
    - *Is there a clear central value for like events (same event number)?*
    - *Is there a clear central value for all events (different event numbers)?*