Activity One -- Fundamentally Speaking (Student Page)

"What is the world made of?
What holds it together"

Democritus (460-370 B.C.)

People have asked these questions for thousands of years. But only recently has a clear picture of the "building blocks" of our universe been developed. The scientists who have developed this picture work in an exciting and challenging field called high-energy particle physics. Their discoveries are summarized in the chart, Standard Model of Fundamental Particles and Interactions.

How much do you know about the latest theories and research on these ancient questions? You can find out by reading each of the statements below and placing a check mark in the proper box to indicate whether you agree or disagree.

1. There are subatomic particles that have no mass and no electric charge.	Agree	Disagree
2. Some particles can travel through billions of miles of matter without being stopped (interacting).		
3. Antimatter is science fiction and not science fact.		
4. Particle accelerators are used for cancer treatment.		
5. The smallest components of the nucleus of an atom are protons and electrons.		
6. Particles and antiparticles can materialize out of energy.		
7. Particle physicists need larger accelerators in order to investigate larger objects.		

8. Magnets are used in circular accelerators to make the particles move faster.		
9. Work done by particle physicists at accelerators is helping us understand the very early development of the universe.		
10. Gravity is the strongest of the fundamental forces of nature.		
11. There are at least one hundred different subatomic particles.		
12. All known matter is made of leptons and quarks.		
13. The protons in the Large Hadron Collider (LHC) at the CERN lab in Geneva, Switzerland will cross the French-Swiss border 11,000 times each second (without a passport), when LHC is completed in 2007.		
14. Friction is one of the fundamental forces of nature.		
15. The world's largest magnet (which is at a particle physics lab) weighs half has much as the Eiffel Tower.		
16. Many of the physicists who will run the particle physics experiments now under construction are still students in high school.		

"What is the world made of?
What holds it together"

Murray Gell-Mann (b. 1929)

Activity Two -- Psyching Out the System (Student Page)

When scientists study any system they must ask two basic questions:

1) What are the basic objects, or "building blocks," from which this system is made?

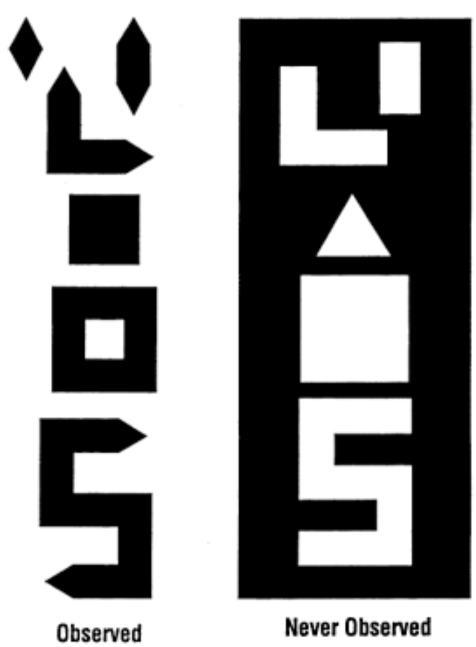
2) What are the interactions between these objects?

The answer to these questions depends on the scale at which you study the system. Particle physics plays this game on the smallest possible scales -- seeking to discover the basic building blocks of all matter and the fundamental interactions between them.

The connecting rules of these interactions, or basic forces, explain why some composite objects are observed and others are not observed. The basic forces are as important as the "building blocks" in explaining data, and what does not happen is as important a clue as what does.

This puzzle shows the challenge that particle physicists face. Imagine that the puzzle presents information that was obtained about particles from an accelerator. The black figures represent objects that were observed, while the objects shown in white have not been observed. In this puzzle, "objects" are all two-dimensional shapes, and "interactions" are ways in which they can combine.

The shapes that are not observed provide important clues to the answers.



Write your answers in these spaces. Note that you need to answer both questions to explain why the objects that are not observed are not possible.

The observed figures are constructed from:
1. ____
____
2. ____
____

The rules for connecting these shapes are:
1. ____
____
2. ____
____

[Puzzle adapted from Helen Quinn, "Of Quarks, Antiquarks, and Glue." The Stanford Magazine, Fall, 1983, p.29.]

Activity Three -- Rutherford's Discovery (Student Page)

In this activity, you and your team members will use the methods pioneered by Ernest Rutherford in the early 1900s and still used by particle physicists in their accelerator experiments today. These methods enable scientists to identify the characteristics of particles that they cannot actually see. You will learn how precise your measurements must be when you can't see what you are studying.

On your team's experiment table there is a large wooden board, under which your teacher has placed a flat shape.

Your team's job is to identify the shape without ever seeing it. You can only roll marbles against the hidden object and observe the deflected paths that the marbles take. Your team will have five minutes to "observe" a shape.

Place a piece of paper on top of the board for sketching the paths of the marbles. Then analyze this information to determine the object's actual shape. Draw a small picture of each shape you studied in the boxes below, and answer the following questions.

Shape 1	Shape 2

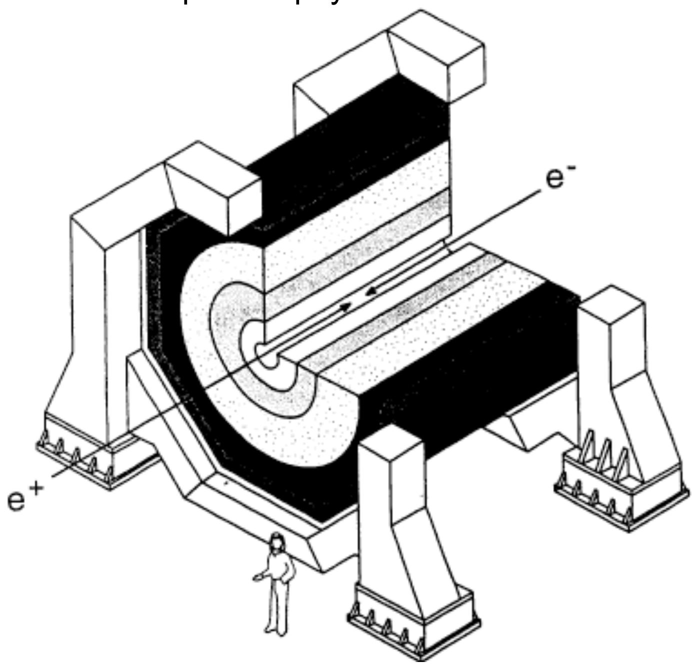
1. Can you tell the size of the object as well as its shape?

2. How could you find out whether the shape has features that are small compared to the size of your marbles?

3. Without looking, how can you be sure of your conclusions?

Activity Four -- Tracking Unseen Particles (Student Page)

This experiment demonstrates how particle detectors work and why they are multi-layered, as shown in the cutaway and schematic illustrations on this page. Using a few simple materials you will be able to track the paths of magnetic marbles in the same manner that particle physicists track the movements of fundamental particles.



You will need these materials:

- Two shoe or shirt box lids, turned upside down
- Small objects to prop up the lids
- Magnetic marbles
- Ordinary marbles
- Fine iron filings

Follow these directions:

1. Place one lid upside down on the table and insert props at each corner to raise it just enough so that any of your marbles can roll under it.

2. Sprinkle iron filings in the lid so as to cover all of it. This is your simulated detector.

3. Roll a magnetic marble rapidly under this simulated detector. Write your observations here.

____
____
____

____
____

4. What property of the marble would you say your detector is recording?

____

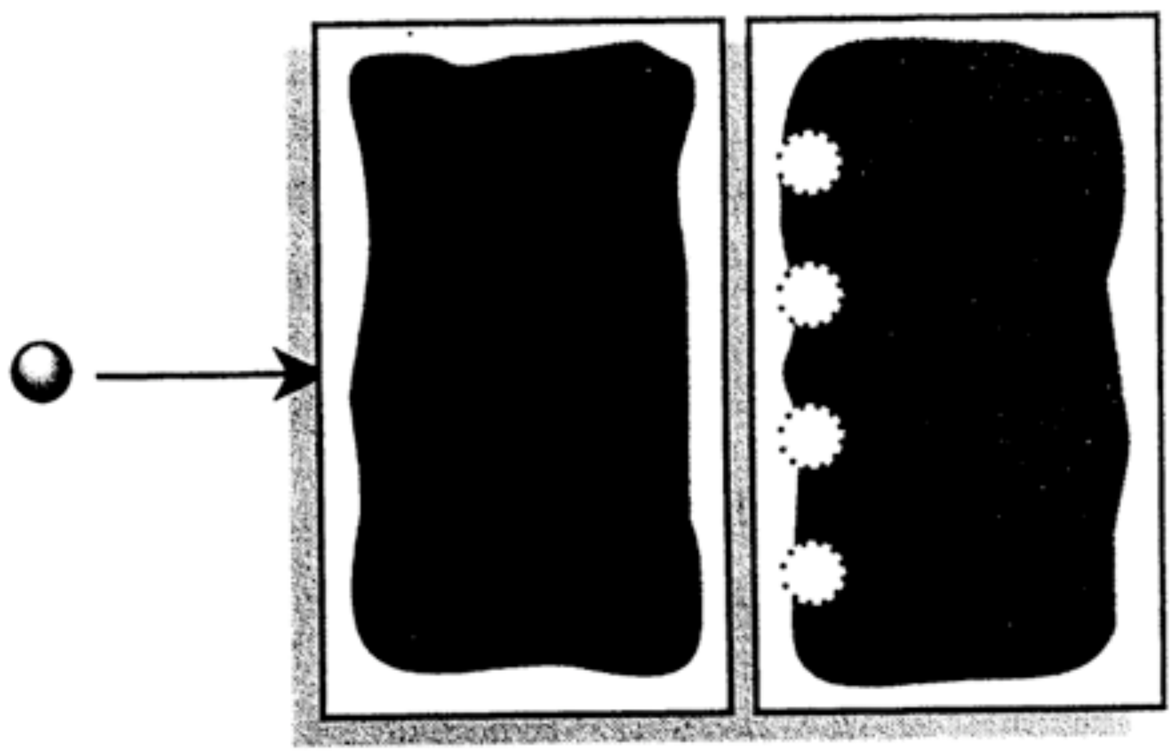
5. Roll an ordinary marble under your detector. Record your observations here.

____
____
____

To which particle's behavior is this observation similar?

____

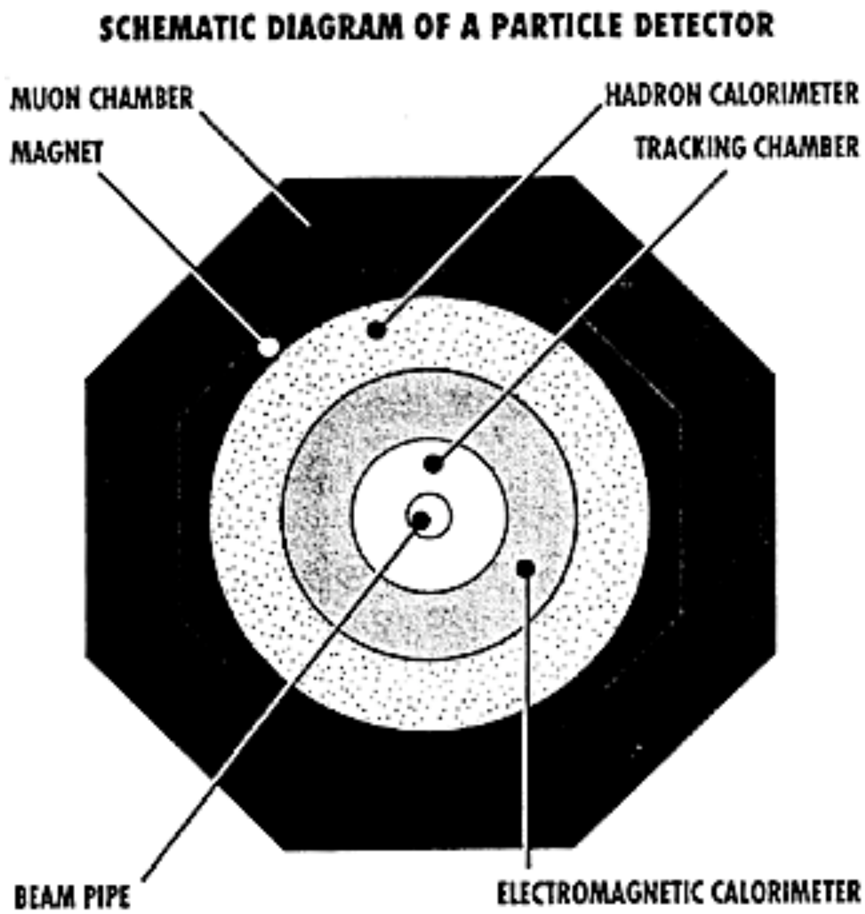
Now construct a two-part detector that can be used to track "neutral" or "uncharged" particles by making a line of four or more magnetic marbles immediately beyond the first lid, and placing a second lid over them (see diagram below). Your two-stage detector will be complete when you have sprinkled iron filings in the second lid.



6. a) Roll an ordinary marble under the first detector. If it hits a magnetic marble, what does the resulting trail in the second detector tell you?

____
____

b) To which particles is this behavior similar?



Activity Five -- The Rules of the Game (Student Page)

Scientists in every field devise rules that explain what they have observed. They then use these rules to interpret new observations. This activity will give you the chance to discover rules, called *conservation laws*, that play a crucial role in the study of particle physics.

The most common type of observation in particle physics is called an *event*. An event is similar to a chemical reaction in chemistry, in the sense that one set of particles is formed from another.

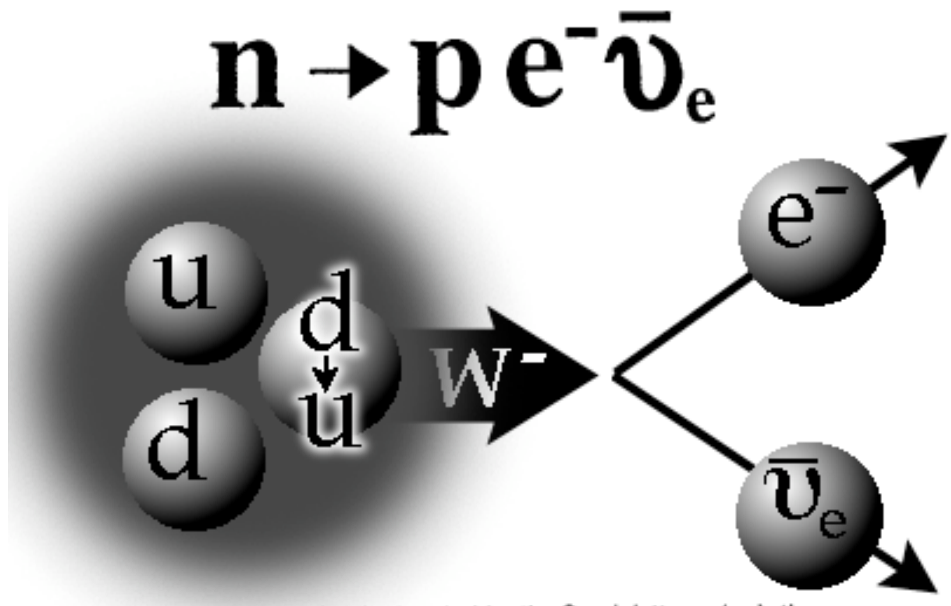
The following particle charts can help you identify the types and charges of particles in a number of events given below. As indicated, each particle can have an electrical charge of +1, -1, or 0.

Note that antiparticles are denoted by a bar over the name of the particle (e.g., p-bar = antiproton, nu-bar sub-e = antielectron -- neutrino); or simply by the charges (e^- = electron, e^+ = positron = antielectron); pi^+ and pi^- are particle and antiparticle, and similarly K^+ and K^-. An antiparticle has the same mass as its corresponding particle, but the opposite value for all charges.

BARYONS		MESONS		LEPTONS		PHOTON	
Symbol	Charge	Symbol	Charge	Symbol	Charge	Symbol	Charge
p	+1	π^+	+1	e^-	−1	γ	0
$\bar{p}$	−1	π^-	−1	e^+	+1		
n	0	π^0	0	ν_e	0		
Δ	0	K^+	+1	$\bar{\nu}_e$	0		
		K^-	−1				
		K^0	0				

Two sets of particle events are shown in the table at right. The set in the left column consists only of events that are known to take place, and the set in the right column consists only of events that are believed not to take place (they've never been observed). By examining the two sets, along with the preceding chart of particles, we must determine what quantities are or are not conserved in these particle physics events. These are the "rules of the game" played by nature.

All of the quantities whose conservation can be deduced from the following events can be found by counting. All such quantities are conserved in every "observed" event, but at least one of these quantities is not conserved in each "unobserved" event. Assume that the incoming particles have sufficient energy to generate the outgoing particles.



*A neutrino is denoted by the Greek letter υ (nu); the symbol υ_e denotes an electron-type neutrino.

OBSERVED EVENTS	UNOBSERVED EVENTS
1. $n \longrightarrow p + e^- + \bar{\upsilon}_e$	**11.** $n + p \longrightarrow p + p$
2. $\pi^+ + n \longrightarrow p + \pi^0$	**12.** $p \longrightarrow \pi^+ + \pi^0$
3. $\pi^- + p \longrightarrow n + \pi^- + \pi^+$	**13.** $p \longrightarrow \pi^+ + \pi^-$
4. $\pi^- + p \longrightarrow p + \pi^0 + \pi^-$	**14.** $\pi^+ + n \longrightarrow K^+ + K^0$
5. $\Delta \longrightarrow p + \pi^-$	**15.** $\Delta \longrightarrow \pi^+ + \pi^- + \pi^0$
6. $\Delta \longrightarrow n + \pi^0$	**16.** $\Delta \longrightarrow K^+ + K^-$
7. $n + p \longrightarrow p + p + \pi^-$	**17.** $\pi^0 + n \longrightarrow \pi^+ + \pi^-$
8. $p + p \longrightarrow p + n + \pi^+$	**18.** $\pi^0 + n \longrightarrow p + \bar{p}$
9. $e^+ + e^- \longrightarrow p + \bar{p}$	**19.** $\Delta \longrightarrow n + \pi^0 + \upsilon_e$
10. $e^+ + e^- \longrightarrow \gamma + \gamma$	**20.** $\pi^- \longrightarrow e^- + \gamma$

1. What is meant when we say that a quantity is "conserved?"
____
____
____

2. What quantities or numbers of object types are conserved?
a) ______________________
b) ______________________
c) ________________________

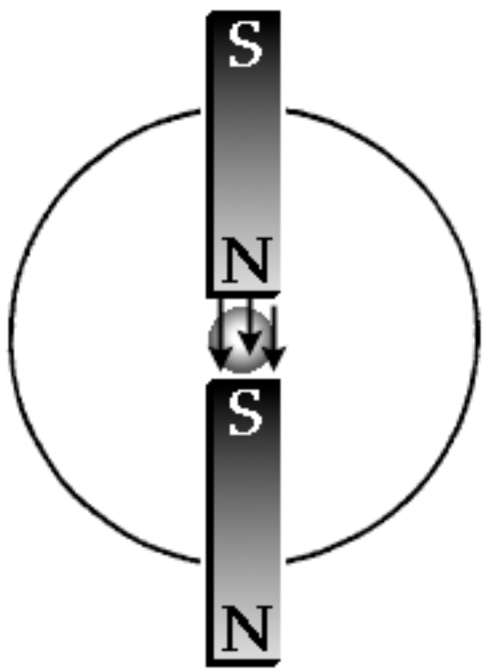
3. What is an "event" in particle physics?
____
____
____

4. Which of the above events are decays?
____
____

5. For each of the unobserved events, indicate what is not conserved (there may be more than one answer).
Event #:
11: ________________ 16: ________________
12: ________________ 17: ________________
13: ________________ 18: ________________
14: ________________ 19: ________________
15: ________________ 20: ________________

Activity Six -- Observing Magnetic Effects on Particle Beams (Student Page)

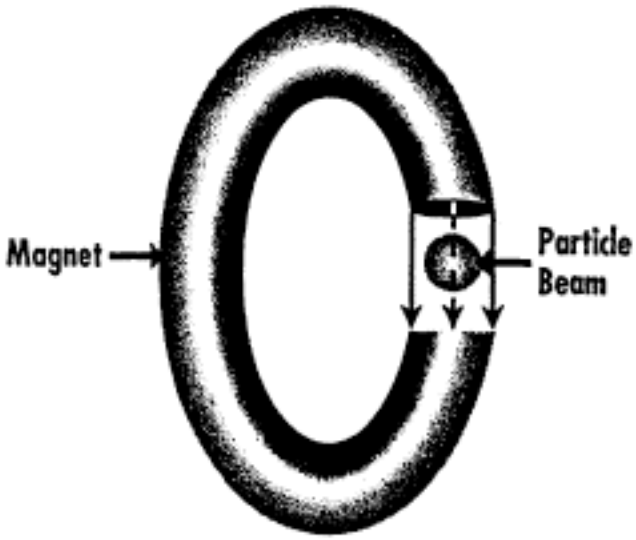
An ordinary oscilloscope and two small bar magnets can enable you to see two of the important ways in which particle beams are controlled in accelerators.
There is an electron beam in the oscilloscope that moves in a nearly straight line from back to front, as a result of a potential difference of tens of thousands of volts. To show how a magnetic field can deflect a beam of charged particles, set an oscilloscope to produce a well-focused spot near the center of the screen. Position the north pole of one bar magnet directly above the beam of the oscilloscope, and position the south pole of another magnet directly below the beam as shown here. (Be careful to avoid bumping or scratching the screen with the magnets.)



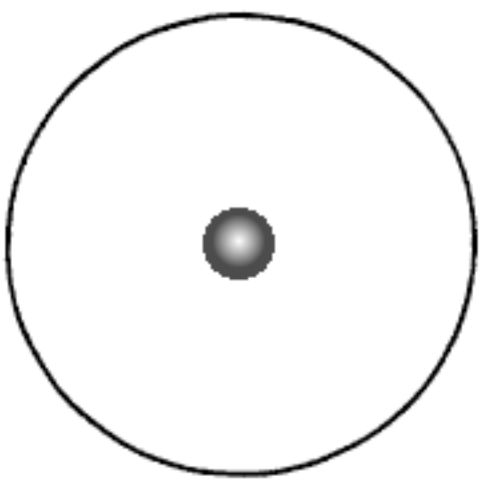
Magnetic field produced at oscilloscope screen by students using two bar magnets:

Explain the direction in which the beam is deflected.

By using C-shaped magnets (as shown below) placed regularly around the beam pipe of a circular accelerator, physicists are able to continuously bend a particle beam through a near-circular path.



Particle beam within the magnetic field of a C-shape magnet
Next, you can demonstrate how a magnetic field can focus a beam of charged particles by setting an oscilloscope to produce an unfocused beam (turn the focus knob until the spot on the screen is as large as possible). An unfocused beam results in a large spot on the screen, as shown at top right. In particle accelerators, unfocused beams are undesirable because they result in low rates of collisions between beam particles.



Unfocused oscilloscope without magnets
Place a bar magnet (with the north pole up) against the oscilloscope screen and to the left of the beam (as shown below). Then place another bar magnet with the north pole down against the oscilloscope screen and to the right of the beam. The spot on the screen should now be vertically compressed and horizontally expanded.

Unfocused oscilloscope with magnets

Try to visualize the situation you've just set up by looking at the next diagram and using the "left-hand rule" (the beam is negative).

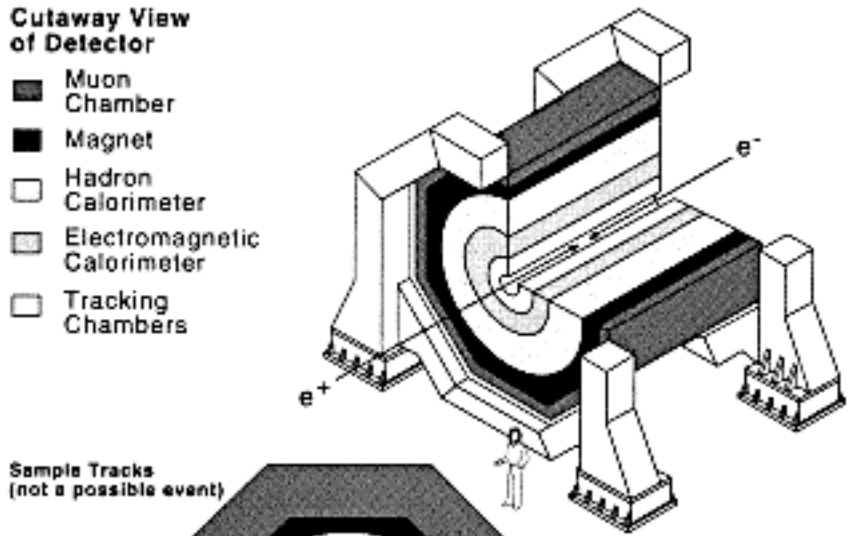
The arrangement of magnets you've just used is called a *quadrupole*. As you've seen, one quadrupole arrangement will improve the focus of a particle beam in one direction, and worsen it in the perpendicular direction. By using two quadrupole arrangements with the right spacing along the beam path -- and one set rotated 90 relative to the other -- it is possible to improve the overall focus of a particle beam. This is how physicists improve the focus of beams in particle accelerators.

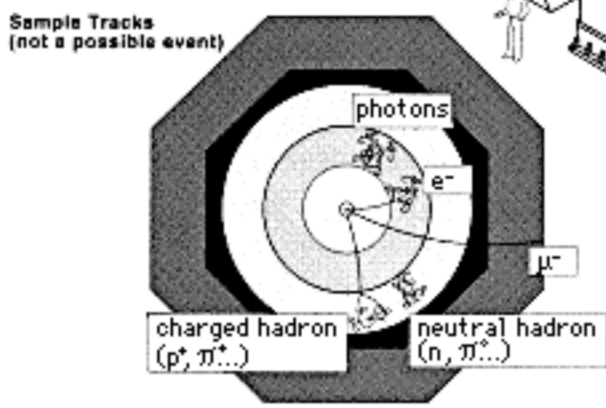
Activity Seven -- Picturing Particles (Student Page)

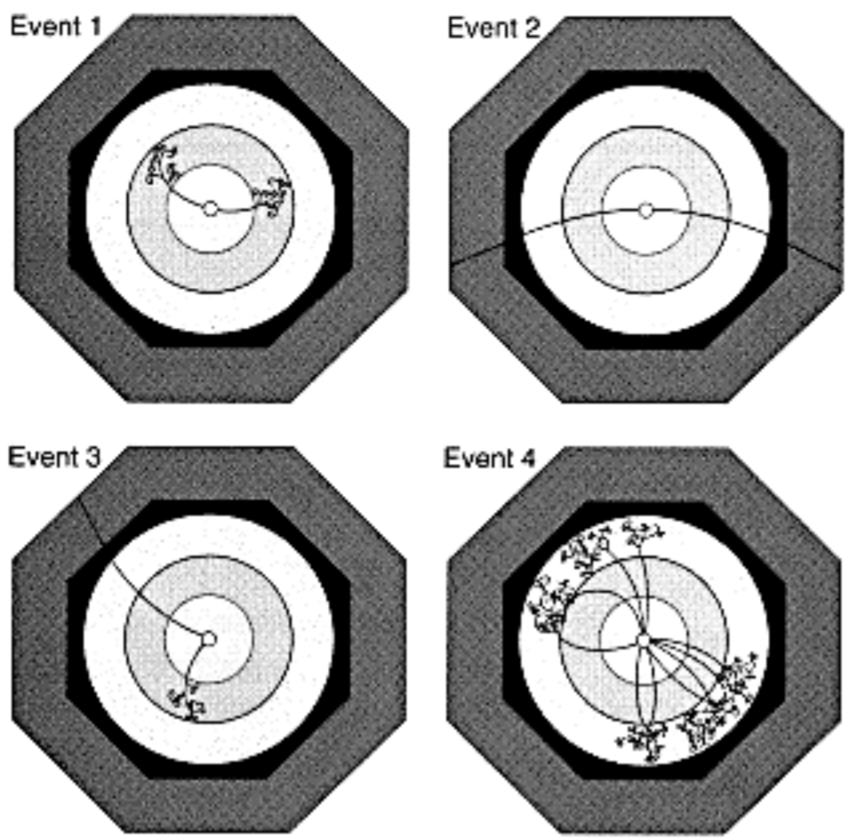
Whether they are called *atom smashers, accelerators* or *colliders,* the massive devices used for research by particle physicists all produce new particles by colliding two high-energy particles with one another.

For this activity, imagine that an electron and positron are traveling at nearly the speed of light. They collide head-on, carrying equal and opposite momenta and produce many particles that spread out in all directions.

Surrounding the collision point of these particles in the accelerator is a multi-layered *particle detector*, shown here in a cutaway view. Detectors are the sensors used by particle physicists to gather information about the particles produced by an event. Each layer of the detector senses a different property of the particles. The tracking chamber shows the paths of charged particles. In the calorimeter layers, only the total energy deposited is measured; the actual tracks cannot be reconstructed. The electromagnetic calorimeter collects energy from photons, electrons and positrons. Hadrons deposit their energy in the hadron calorimeter.


Cutaway View
of Detector
Muon
Chamber
Magnet
Hadron
Calorimeter
Electromagnetic
Calorimeter
Tracking
Chambers
e⁻
e⁺


Sample Tracks
(not a possible event)
photons
e⁻
μ⁻
charged hadron
(p⁺, π⁺...)
neutral hadron
(n, π°...)


Event 1
Event 2
Event 3
Event 4

Notice the large magnet in the detector. The magnetic field inside the magnet (parallel to the beam pipe) causes the paths of charged particles moving out from the collision point to curve. The paths of positive and negative particles curve in opposite directions.

Now imagine that you are a physicist trying to analyze the tracks shown in the four cross-section "event" illustrations at bottom left, which are taken from actual experiments. Use the labeled cross section of a detector, showing sample tracks of various particles, as a reference (along with the given "rules" of conservation).

Rules of the Game:

1) Charge is conserved. (The event started with a negative electron and a positive proton, so the total charge is always zero.)

2) Momentum is conserved. (The original particles had equal and opposite momenta, so the total momentum is always zero.)

After analyzing these event pictures, complete the following chart. Check off each column representing a detector layer where the track appears. Compare your findings with the particle tracks shown in the "Sample Tracks" cross section at left. Then answer the questions for each event below the chart.

Track	Tracking Chamber	Electromagnetic Calorimeter	Hadron Calorimeter	Muon Chamber
Event 1				
Event 2				
Event 3				
Event 4				

1. Events 1-4:
From your chart, what could the particles be?
Event 1 ______________________
Event 2 ______________________
Event 3 ______________________
Event 4 ______________________

2. In events 1 & 2, are the particles of the same or of opposite charges?
____
____

3. In event 3, the two tracks are not back to back. What does this tell you?
____
____
____
____