Activity 5
Finding the Top Quark

NAME :

In 1995, Fermilab discovered evidence for the sixth and final quark of the Standard Model. This was done by accelerating and colliding protons and antiprotons together to form a top quark and an antitop quark. The energy of the protons was converted into the mass of the quarks via $E = mc^2$. The two quarks cannot be detected directly because they decay immediately into other particles. In this activity, you will use the mometum and energy of the decay particles to determine the mass of the original pair.

Part 1: Top Quark

1. Protons and antiprotons were accelerated to equal and opposite speeds of over 99% of the speed of light. When they collided, as shown in Figure 1, the following interactions occurred:

   - They annihilated and produced a top-antitop pair with almost no momentum.
   - This quark pair decayed almost immediately into lighter particles with lots of momentum which moved approximately at right angles to the original proton beams.
   - Three of these particles continued to decay into other particles, producing four "jets" that were measured in the inner sections of the detector.
   - The fourth particle decayed into a muon that was detected in the outer part of the detector and a neutrino that was not detected.

   Model these interactions with beach balls, tennis balls, and marbles. Be sure that momentum is conserved at each step.

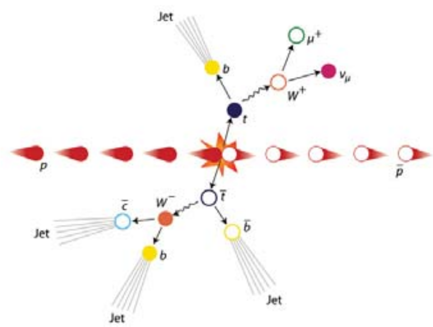

Figure 1 A Top Antitop Quark Event from the D-Zero Detector at Fermilab

2. Figure 2 shows an event display from one of these collisions. Draw the horizontal and vertical components for each of the five labelled momentum vectors. Measure the length of each vector and each component. Record these lengths in the table below (the first one has been done as an example). Add the numbers in each direction and then convert these lengths to momentum units, using the scale: 1 mm = 1 GeV/c.

						Total (mm)	Total (GeV/c)
Magnitude (mm)	95.5						
Horizontal (mm)	-94						
Vertical (mm)	-14						

3. The momentum vectors do not add up to zero. Conservation of momentum demands that the initial and final momenta must be equal. D-Zero detects most particles, but neutrinos slip through unobserved. Use conservation of momentum to determine the momentum of the missing neutrino. Draw this momentum on the event display.

4. The equation $E = mc^2$ is for a particle at rest. The full equation is $E^2 = (pc)^2 + (mc^2)^2$, where p is the relativistic momentum of the particle. The top and antitop quarks decay and produce jets of high-momentum particles. The momenta of these particles is so large that we can ignore the $(mc^2)^2$ term here and the equation can be simplified to $E = pc$. This means that a small particle with 95.5 GeV/c of momentum has 95.5 GeV of energy. Find the total energy of all of the particles, including the neutrino, by adding their energies. (Remember that energy is added as a scalar, not a vector.)

5. The energy released by the collision of the proton and antiproton is just enough to produce a top-antitop pair that is at rest in this particular, carefully-chosen event. The momentum of the top-antitop pair is extremely small compared to their rest-mass energy. The first term in $E^2 = (pc)^2 + (mc^2)^2$ vanishes and the equation simplifies to $E = mc^2$. Use this to find the mass of a top quark.

6. In order to find the top quark, Fermilab collided a proton and an antiproton together at very high speeds. You have a friend who studies biology. Your friend thinks that this is a rather sloppy way to dissect protons to see what is inside them. Explain to your friend how this collision is not like a dissection. Be sure to refer to the masses of protons (0.938 GeV) and top quarks (172 GeV).

Part 2: Higgs Particle Simulation

In 2010 the LHC began colliding protons at the unprecedented energy of 7 TeV. This ambitious project was designed to detect the only particle in the standard model that had not yet been found—the Higgs particle. Based on previous experiments, it was expected to have a mass of between 115 and 185 GeV. Fermilab had hoped to discover it, but reached the limits of its energy without finding the elusive particle. The LHC is now the only accelerator with enough energy to produce the Higgs.

If the Higgs is found at the lower end of possible energies, it will most likely be detected through a decay into two photons. Lancaster University in England has a simulation that lets you look at data to find evidence for a Higgs particle. Your job is to find collisions that produce two photons, measure their energies, and use the energies and the angle between them to determine the mass of the particle that formed them. There are a lot of other interactions taking place, so there is a lot of noise in the data. You need to look at many examples for your results to be statistically significant.

1. Go to http://www.lppp.lancs.ac.uk/higgs/higgs.html. Go to Measurement and scroll to the bottom of the page. Press *Fire*. You should see an image similar to the top quark data in Figure 2 Look for two towers that do not have any lines leading to them. That is the signature of two photons. You will probably not find them at first. Go to *Options* and select an energy cutoff of 20 GeV, then press *Fire*. Try other energy cut-offs. What energy cut-off lets you find photon events most rapidly? What happens when the energy cut-off is too high or too low?

2. Find an event with two photon towers. To calculate the mass of the particle that created the two photons, select *Measure* energies and click on the two photon towers. Then select *Measure angle* and click on the angle. Finally, select *Calculate* mass. The mass will be displayed on a histogram on the bottom left. To confirm the detection of a Higgs particle you need to get a lot of events. Your challenge is to collect as many events as possible in 10 minutes and to develop the largest significance value. How many did you find? Click on the *Fit* button in the bottom right when it is red. What was the significance of your findings? You are aiming for a significance greater than 5.