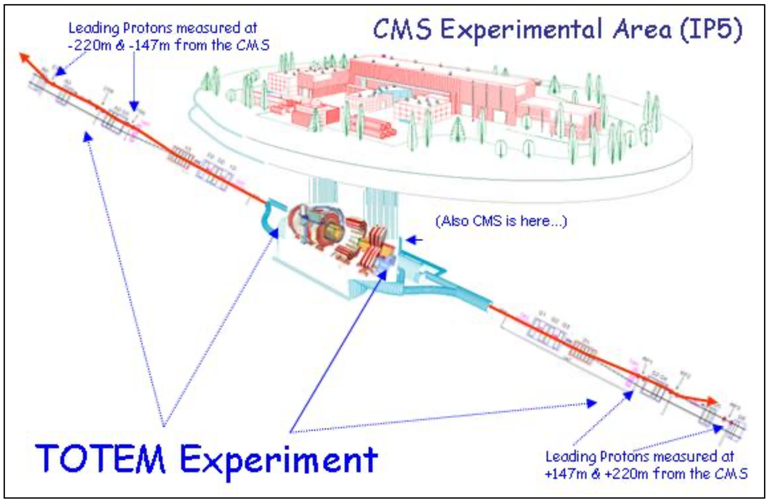
TOTEM 1: MOMENTUM
STUDENT GUIDE

Take a look at a metric ruler. One millimeter is pretty small on that scale. The cells in your body are about a hundredth that size, and bacteria are about a tenth of that. Comparing the size of a bacterium to the size of a proton is like comparing you to the size of the earth.

If billiard balls or freight cars collide, they conserve linear momentum. But what about small particles like protons? Do they obey different rules? You can find out by investigating protons that scatter off each other in CERN's Large Hadron Collider (LHC). You can use results from the TOTEM* detectors to test whether small-angle elastic collisions of protons behave according to the law of conservation of momentum.

TOTEM is a system of small detectors embedded in the LHC beamline in two spots located 220 meters in either direction from the center of the much larger Compact Muon Solenoid (CMS) experiment. These small detectors are designed to measure the scattering of protons that do not quite collide but bounce off each other in glancing collisions. These collisions are controlled by the strong nuclear force so the protons scatter elastically just like marbles in your physics lab.



https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.totem

***TOT**al cross section, **E**lastic scattering and diffraction dissociation **M**easurement at the LHC

RESOURCES
To learn more about all of this, go to the following links:

- TOTEM:
  - Experiment homepage: https://totem-experiment.web.cern.ch/
  - Explanatory video: https://www.youtube.com/watch?v=YsZhwu32Zaw
- Collisions
  - Elastic and Inelastic Collisions video: https://totem-experiment.web.cern.ch/
  - Large Hadron Collider video: https://www.youtube.com/watch?v=debQ60QVtYQ
  - Protons and Momentum screencast: https://web.quarknet.org/media/protons-momentum.mp4

WHAT DO WE KNOW?
- TOTEM events come from very high-energy proton collisions.
- Protons scatter elastically and have very small scattering angles that TOTEM measures in microradians (μrad).
- The protons hit each other almost head-on. Each proton in our data has a momentum of approximately 2.15 x 10^{-15} kg-m/s or, in particle physics units, 4 TeV/c.
- If momentum is conserved in elastic collisions of protons, then the angle one proton makes with the beamline (z-axis) after the collision is equal and opposite to the angle the other makes with the beamline after the collision: $\theta_1 = -\theta_2$. See Figure 1 below.

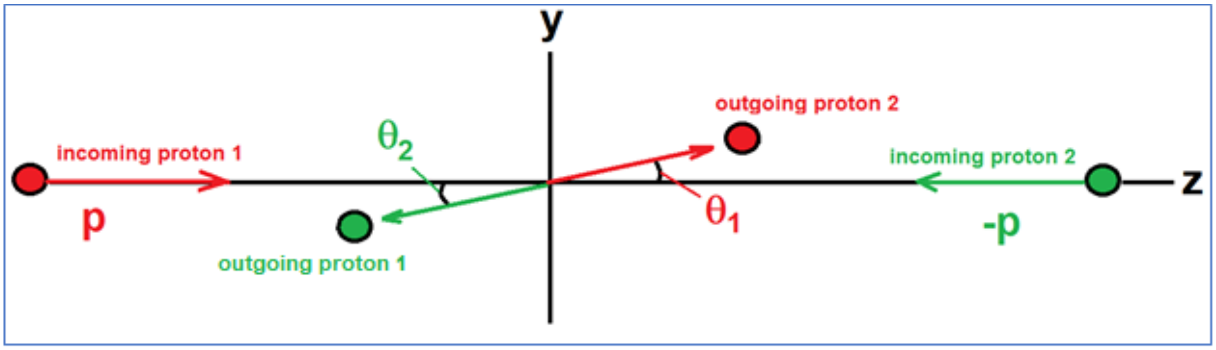


Figure 1

WHAT ANALYSIS TOOLS DO WE NEED?

- Data file: https://quarknet.i2u2.org/sites/default/files/totem_events_sm_1.pdf\
- Tables in this Student Guide.

WHAT DO WE DO?

You can measure angles from the data file. They are given as x- and y-components of the angles the protons make with the beamline (z-axis) after each collision. The protons going one way from the collision are marked red; those going opposite are green. Is there a relationship between the angle with the z-axis formed by the two protons? To find out, you must read the event display in our data file and record it in the tally sheet, after which your class can combine results to see what you get overall.

The event display at the left shows a planar view, with the beam occupying an area in the middle; there is a gap in the detector there. Figure 2 shows the main features of a typical event.

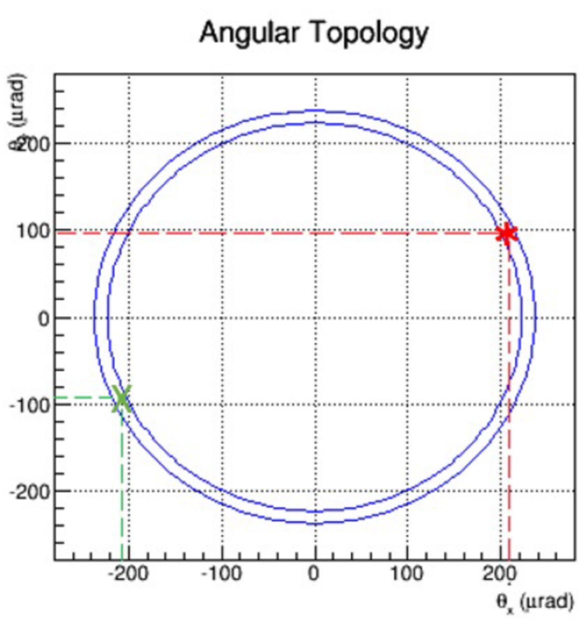


Figure 2

The TOTEM detectors are embedded at the edges of the LHC beam pipe. Each records a "hit" where a scattered proton strikes. The red stars and green Xs represent these hits.

The path of the proton forms an angle with the z-axis. The detector surrounds the beam line. The blue circles represent all the possible locations of a proton that hits the detector at that angle. See Figure 3 below. The space between the blue circles represents the uncertainty in the angle measurement.

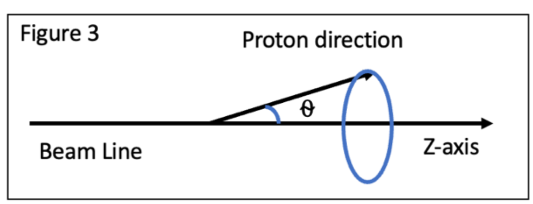


Figure 3

You can measure θ_x and θ_y of the red star and the green X found between the two blue rings in Figure 2 by dropping perpendiculars, shown here as red and green lines, to the θ_x and θ_y axes. Be careful to correctly read the gradations on the axes: they are in units of 10 µrad for some events, 20 µrad for others. Here, θ_x = +208 µrad and θ_y = +100 µrad for the red star and θ_x = -208 µrad and θ_y = -102 µrad for the green X. Details of each event will vary.

We would enter this event as:

Table 1: θ_x

Event Number	θ_x (µrad, red star)	θ_x (µrad, green X)
112	+208	-208

and

Table 2: θy

Event Number	θ_y (µrad, red star)	θ_y (µrad, green X)
112	+100	-102

In the table below, record θ_x and θ_y for red stars and green Xs. The colors indicate opposite directions from the collision point.

Each student or group of students will analyze a set of events as above, recording $\theta_{x(red)}$, $\theta_{x(grn)}$, $\theta_{y(red)}$, and $\theta_{y(grn)}$ in the two tables below.

Table 1: θ_x

Event Number	θ_x (µrad, red star)	θ_x (µrad, green X)

Table 2: θy

Event Number	θ_y (µrad, red star)	θ_y (µrad, green X)

Check to be sure values have been transcribed properly and that the event numbers in each table are identical and in the same order. Use additional paper if you need more space.

Finally, your class will put the data together to make two plots: $\theta_{x(red)}$ vs. $\theta_{x(grn)}$ and $\theta_{y(red)}$ vs. $\theta_{y(grn)}$.

Questions

- Is each plot a straight line? Should they be?
- Why is a lot of data missing in the middle of each plot?
- If the plot is a straight line, what are the slopes and the y-intercepts?
- Are these results consistent with the law of conservation of momentum? Why or why not?