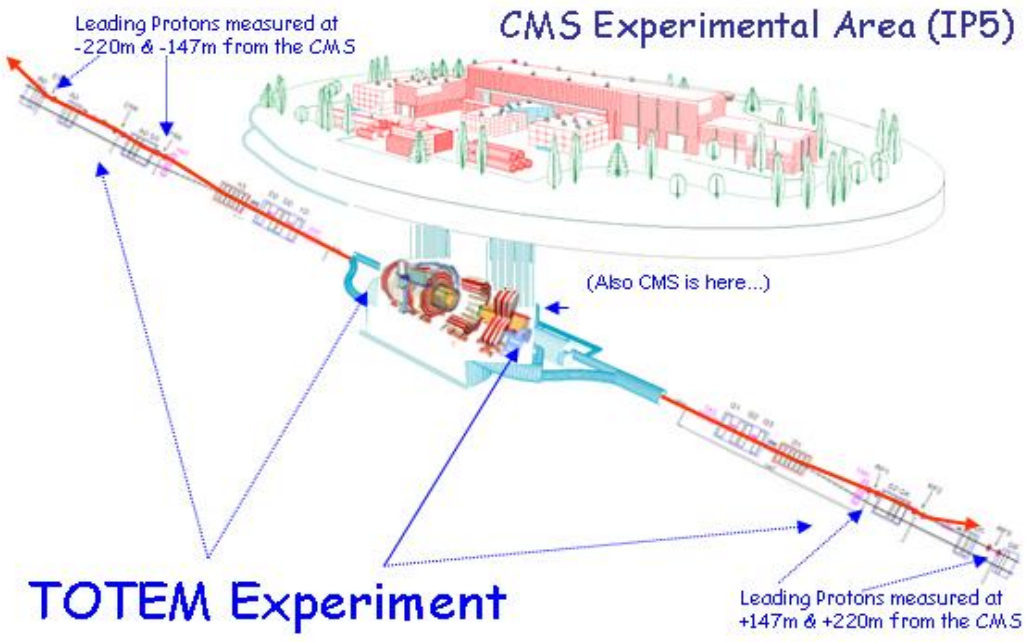
TOTEM 2 INTERFERENCE
STUDENT PAGES

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 the size of the earth to you. Is the proton small enough to be treated as a quantum object with wave-like properties? If so, we can model protons which scatter off each other in CERN's Large Hadron Collider (LHC) as a single proton diffracting around another proton. We can use what we know about diffraction and results from the TOTEM detectors to identify the diffraction pattern and even estimate the size of the proton.

The *TOTal cross section, Elastic scattering and diffraction dissociation Measurement* (TOTEM) experiment is designed to understand the elastic collisions of protons in the Large Hadron Collider (LHC) at CERN. As stated on the TOTEM website, "TOTEM's physics program is dedicated to the precise measurement of the proton-proton interaction cross section, as well as to the in-depth study of the proton structure which is still poorly understood." TOTEM detectors are installed just adjacent to the LHC beamline far forward (220 m) on either side of the Compact Muon Solenoid (CMS) detector. While CMS looks at the results of elastic and inelastic scattering of quarks and gluons in near or completely head-on collisions of protons of which they are components, TOTEM looks at the results of more glancing collisions from which the protons emerge intact. The scattering of these protons is at extremely shallow angles, generally on the order of one ten-thousandth of a radian or a thousandth of a degree.



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

RESOURCES:

To learn more about these topics, check out the following links:

- TOTEM:
  - Experiment home page: http://totem-experiment.web.cern.ch/totem-experiment/
  - Explanatory video: https://www.youtube.com/watch?v=YsZhwu32Zaw

- The de Broglie Wavelength:
  - http://en.wikipedia.org/wiki/Matter_wave
  - http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/debrog2.html
  - https://www.youtube.com/watch?v=ZqspDsQSZuI (video) **NOTE**: The presenter refers to "relativistic mass" which gets larger when the particle is traveling at speeds close to the speed of light. Particle physicists prefer to use "invariant mass" and the relativistic effect is to increase the energy of the particle.
- Diffraction:
  - http://en.wikipedia.org/wiki/Diffraction

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.

What analysis tools do we need?

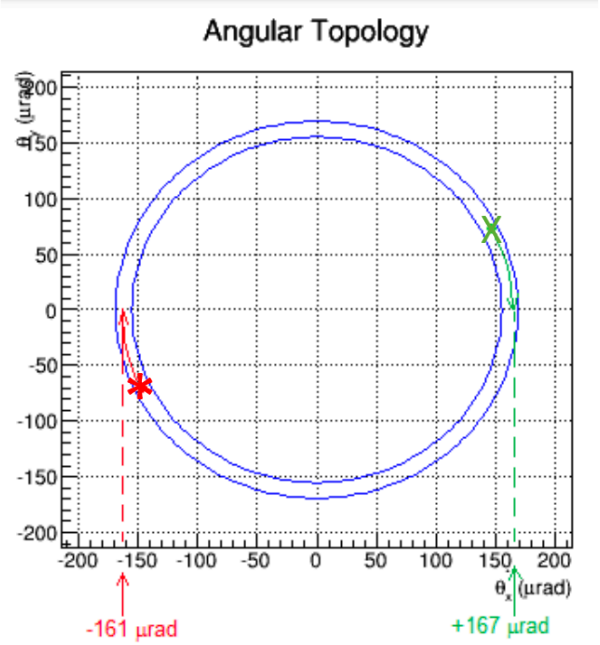
- Our data file: https://quarknet.org/sites/default/files/totem_events_sm_1.pdf
- The data tally sheet: https://quarknet.org/sites/default/files/totem_tally_0.pdf
- A method for making a histogram of scattering angles from -240 to +240 μrad with bin widths of 10 μrad – 20 μrad.

What do we do?

Part A

Research Question: What are some of the characteristics of protons that collide elastically in the CMS detector?

- For each event, **read the scattering angle** for each of two protons. You must **record both** on your tally sheet.



The TOTEM detectors are embedded into 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 event display shows a planar view, with the beam occupying an area in the middle; there is a gap in the detector there. By tracing each star and X around the circle to the "θ_x-axis," we can read the value of scattering angle θ in μrad. See the figure on the left.

- **Analyze** the events assigned to your group.
- **Generate** class data by combining your results with those from other groups.
- **Create** a histogram from the class data.
- **Notice** patterns in your histogram. Do these patterns remind you of anything?
- **Make a claim** about the pattern you have observed.
- **Support your claim** with evidence and reasoning.

Part B

Research Question: Is there a relationship between an estimate of the size of a proton using the wave model and the size as reported by the Particle Data Group?

- **Assumptions of the model**:
  - The proton is a quantum object, so the radius of a proton is not like the radius of a marble.
  - When protons collide in elastic collisions, one proton acts as a barrier around which the other proton can diffract.
  - The proton, as a wave, is diffracted in two dimensions similar to a wave diffracting around a thin barrier.
  - The barrier width represents the proton diameter.
- **Use** the histogram to estimate the diameter of the beam pipe.
- **Apply** diffraction wave properties and the de Broglie wavelength to calculate the size of a proton.
- **Compare** the result for the diameter of the proton found from these data with the accepted values for the diameter of a proton reported by the Particle Physics Group: 1.6818 fm.
- **Discussion questions:**
  1. What are the parts of the model that you used to find your result?
  2. What evidence supports the model?
  3. Describe which assumptions cause our model to fall short.