Physicists find that an ultrahigh-energy proton looks like a black disk

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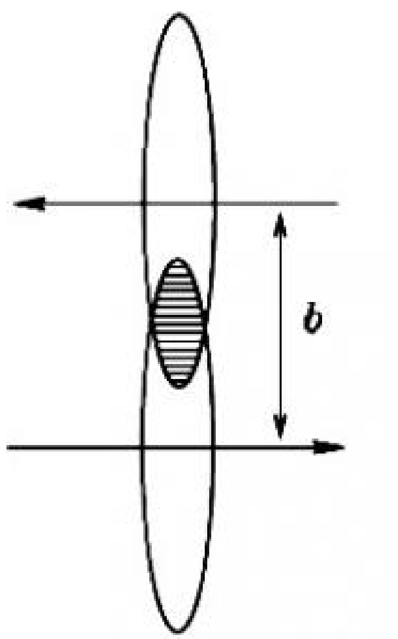

This figure shows two protons crossing each other at the LHC at an impact parameter, b. Because of their velocity near the speed of light, the protons are contracted to thin disks. An analysis of the proton-proton cross section suggests that high-energy protons are black disks. Image credit: LHC

(PhysOrg.com) -- What does a proton look like? The common answer to this question is that protons are much too small to scatter light, and since light is necessary for us to see things, protons do not “look” like anything. But in a new study, physicists have gathered sufficient evidence to show that, at least at very high energies, the proton is a black disk – sort of an elongated hockey puck. This description fits only for protons at such ultrahigh energies that even the most advanced experiments will probably never be able to detect them.

The physicists, Martin Block, Professor Emeritus at Northwestern University in Evanston, Illinois, and Francis Halzen, Physics Professor at the University of Wisconsin in Madison, Wisconsin, have published their analysis of the proton in a recent issue of *Physical Review Letters*.

As every student learns in physics class, a proton is a very small (about 1.6 femtometers [10^{-15} meters] in diameter) positively charged subatomic particle found in the nucleus of an atom. A proton is made of two "up" quarks and one "down" quark. The three quarks are held together by the strong force, which is mediated by other particles called gluons. A lot of activity goes on inside a proton: quarks bounce around and exchange gluons, and virtual particle-antiparticle pairs constantly pop in and out of the vacuum. When accounting for these complex dynamics, and also that the wave-particle duality of quantum mechanics postulates that protons have properties of both waves and particles, visualizing a proton is not a simple matter.

However, thanks to relativity, physicists have some hints of what a proton should theoretically look like when its velocity approaches the speed of light. Due to Lorentz contraction, the proton should contract into a disk with no thickness, or in other words, a two-dimensional disk. This shape is due completely to relativity, and has nothing to do with the interactions between quarks, gluons, etc., which are instead described by quantum chromodynamics.

In their study, Block and Halzen have now discovered that this disk is likely black. To reach this conclusion, they analyzed the results of three different experiments and developed their own numerical model that is completely independent of the experimental data in order to try to get a better glimpse of the proton's structure. These investigations involve determining what happens when two protons interact, which occurs when physicists accelerate one proton to very high energies and "shoot" it at a second proton.

"In our model, at least asymptotically [i.e., as the proton's energy approaches infinity], a proton will scatter any particle (for instance another proton) like a billiard ball half of the time (elastic collision) and totally absorb it the other half of the time (inelastic collision)," Halzen told *PhysOrg.com*. Such behavior is very similar to the way a black disk should behave.

Physicists have been investigating proton-proton collisions for several decades. By calculating the fraction (or cross section) of proton-proton inelastic scattering processes and comparing it to the proton-proton total (elastic plus inelastic) cross section, researchers have gained a better understanding of the inner structure of protons. (Scientists have been investigating the growth of the proton-proton total cross section ever since it was discovered in the early 1970s by a team at CERN, of which Block was a member early in his career.)

In this study, Block and Halzen analyzed measurements of the inelastic and total cross sections that were recently taken at two different energies by three independent experiments. At an energy of 7000 GeV, the Atlas collaboration measured an inelastic cross section of 69.1 millibarn (a millibarn [mb] is an area equal to 10^{-27} cm^2), and the CMS collaboration used a completely different technique to measure it at a compatible 68 mb. At 57,000 GeV, the Pierre Auger Observatory collaboration used cosmic ray measurements to calculate an inelastic cross section of 90 mb. For comparison, Block and Halzen's purely numerical calculations predict inelastic cross sections of 69.0 mb at 7000 GeV and 92.9 mb at 57,000 GeV, both of which agree closely with the experimental data.

Block and Halzen also explain that 57,000 GeV is likely the highest energy at which such experiments can be performed, making it as close to asymptopia (defined here as the behavior of the cross section as the energy level approaches infinity) as scientists will ever get. However, the experimental measurements are still quite far from asymptopia.

Yet in spite of these limitations, the data do provide some evidence of how the inelastic and total cross sections behave when the energy approaches infinity. When combining the experimental measurements with the predictions of their purely numerical approach, Block and Halzen found that, as the energy increases to infinity, the ratio of the inelastic cross section to the total cross section is about 0.509. In other words, an asymptotic proton scatters another proton half the time and absorbs it half the time.

Interestingly, the predicted ratio of the inelastic cross section to the total cross section for a black disk is 0.5, which agrees with Block and Halzen's result for the asymptotic proton, within measurement error. For this reason, the new findings provide the first experimental evidence that a proton becomes a black disk as its energy approaches asymptopia.

The physicists' model provides some further details about the asymptotic proton in terms of quantum chromodynamics. The scientists explain that, at ultrahigh energies, the proton structure is totally dominated by the gluons instead of quarks. In contrast, at sub-asymptotic energies, the quarks play a more significant role and there aren't enough gluon constituents to form a shape that is totally black or a complete two-dimensional disk. The scientists' model even predicts the mass of the lightest particle state made from gluons, dubbed the glueball. This clue to the glueball's mass may aid in the search for glueballs, which has been a challenging goal of several experiments. In addition, the physicists' calculations predict that the black disk is expanding, which is in accordance with very general theoretic predictions from the 1960s.

Even though the ultrahigh energy of asymptotic protons makes it unlikely for them to be produced in experiments, the scientists say it's possible that these highly energetic protons do exist in nature.

"Asymptotic protons may exist as cosmic rays but with a tiny flux that even large air shower arrays such as Auger are insensitive to," Halzen said. "Maybe someday we will develop cosmic ray detection techniques that will give us access to data at yet higher energies."

He added that understanding proton-proton interactions not only reveals hints of what high-energy protons look like, but it may also help scientists in their research.

"[The proton-proton total cross section] value at very high energies is one of the ingredients for extracting physics from cosmic ray experiments such as Auger and the Telescope Array," he said. "In that sense, our work has also some more practical value."

More information: Martin M. Block and Francis Halzen. "Experimental Confirmation that the Proton is Asymptotically a Black Disk." *PRL* 107, 212002 (2011). DOI: 10.1103/PhysRevLett.107.212002