FEATURE

Principal Investigator Mihoko Nojiri

Research Area: Theoretical Physics

LHC and Dark Matter

Invisible dark matter fills the universe

The universe consists mainly of matter that does not emit light (called "dark matter" because it is invisible). This fact, based on the motions of stars in galaxies and clusters of galaxies, has been known for some time. Thanks to advances in observational techniques, we now know that so-called dark energy comprises 70% of the universe's energy while dark matter comprises about 23%. Baryons, such as protons and neutrons, comprise only 4%. Recently, a team of scientists used NASA's Chandra X-ray Satellite and other telescopes to trace the shadows of dark matter in two colliding clusters. The shadows are passing through each other without interference, while the normal matter in the two clusters is being slowed by the collision (Figure 1). This indicates that particles of dark matter rarely interact with other types of particles.

Dark matter particles have significantly affected particle physics. Although the standard model of particle physics well describes the properties of all of the particles that have been investigated to date, this model does not include dark matter candidates.

While the properties of dark matter are not clearly understood, the reasons for its existence in the universe are. According to the Big Bang scenario, the universe contracts as we move into the past. This implies that all types of matter in the early universe were extremely hot and dense and their particles

Figure 1. The separation between the material shown in pink (hot gas of normal matter, observed by the Chandra X-ray Observatory) and blue (dark matter observed by the Hubble Space Telescope and other telescopes using a technique known as gravitational lensing). Dark matter regions pass through each other without interference. Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

frequently collided. Those collisions must have created many particles that do not exist today. If some of the particles created in high-energy collisions happened to be stable, they may have survived to the present day as dark matter. If dark matter was created in this way, then the interactions among them must be weak. Otherwise, they would have quickly disappeared in the collisions. This idea agrees well with those properties of dark matter that can be observed only by gravitational means.

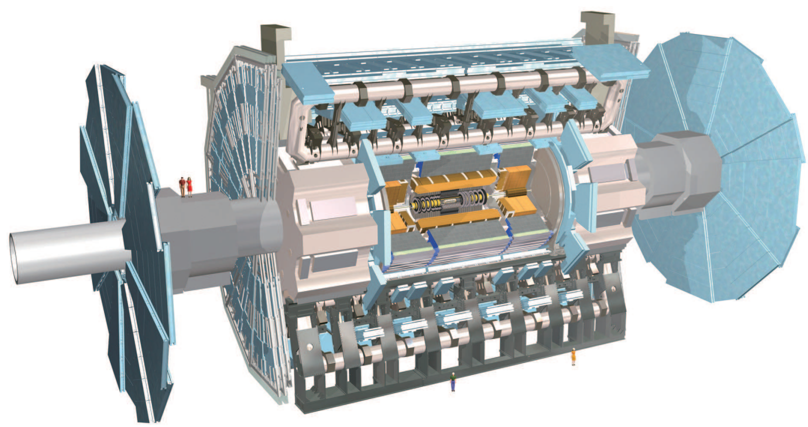

Figure 2. Computer-produced image of the detector for the ATLAS experiment at the LHC.
Copyright © CERN, Photograph by Joao Pequenao

On the other hand, dark matter was not predicted by particle theory. The particles we normally observe—protons (a composite of u- and d-quarks, gluons, and other small components), electrons, and neutrinos—are stable because of the laws of conservation in particle theory. If dark matter is unstable, then its lifetime must exceed the age of the universe. Therefore, some unknown (approximate) conservation law must be preventing the decay of dark matter.

LHC can create dark matter

It may be possible to create dark matter. CERN (European Organization for Nuclear Research) has built the world's largest colliding beam accelerator, the LHC (Large Hadron Collider), near Geneva. Completed last year, the LHC can collide 14 TeV protons. The energy of these collisions roughly corresponds to that of the particle collisions that took place one ten billionth of a second after the creation of the universe (when the temperature of the universe was 100 trillion degrees). If the early universe could create dark matter, then the LHC experiments also should be able to create it.

Theorists have proposed various models to explain the properties of dark matter in ways that do not change the properties of known particles. A common feature of these models is a partner particle for each of the known particles. For example,

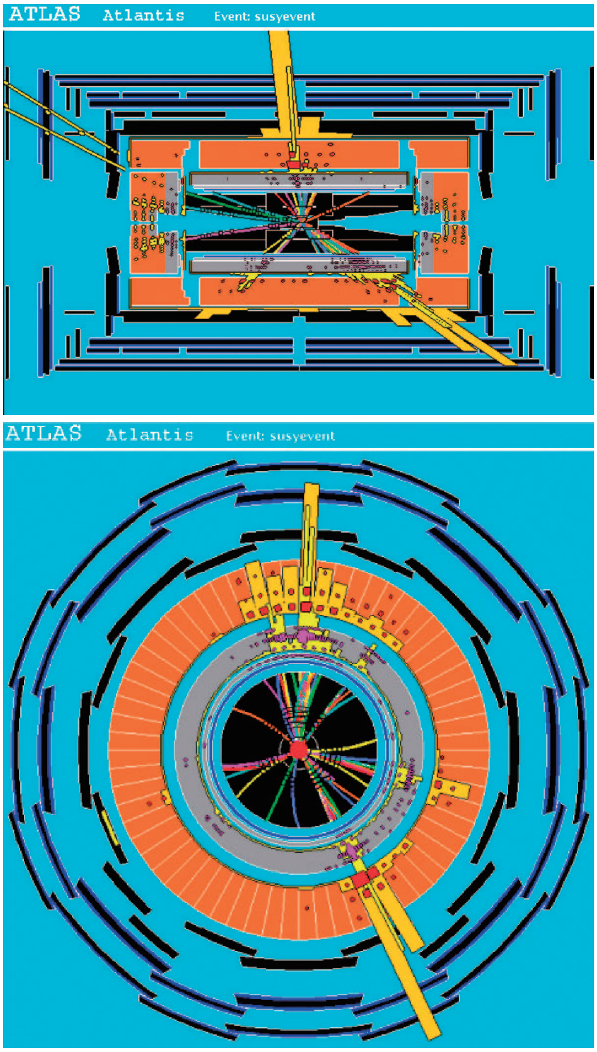

Figure 3. Simulation showing how the ATLAS detector observes an event that produces a pair of supersymmetric particles.
Credit: The ATLAS Experiment at CERN, http://atlas.ch

the supersymmetry model predicts the scalar quark as the partner of the quark and the gluino as the partner of the gluon. We already know that these predicted particles are heavier than their partners by a factor of 500 or more. The particles that qualify as dark matter candidates are the partners of photons, Z bosons, and Higgs bosons, all of which have masses that should be lighter than scalar quarks.

In these models, all of the particles have a conserved quantum number called parity,* which is either +1 or -1. All of the particles in the standard model have a parity of +1, while all of their supersymmetric partner particles have a parity of -1. The product of parity is always conserved. For example, if an initial particle has a parity of -1, then the product of the parity of all of its decay particles also must be -1. Likewise, when two standard model particles having a parity of +1 collide and produce particles with a parity of -1, those particles are produced in even numbers. Therefore, proton-proton collisions at the LHC produce supersymmetric particles in pairs. As each supersymmetric particle decays into a final state containing another supersymmetric particle, the collisions produce an even number of dark matter particles as well as many standard model particles.

Measuring trails of invisible particles

The LHC's detectors cannot directly observe dark matter. However, non-conservation of the momentum sum of the observed particles tells us that dark matter particles were created but have escaped detection. This is because nearly the entire momentum sum is conserved in most of the events that produce only standard model particles. Therefore, the contribution of dark matter production to the momentum sum can be inferred from the contribution of invisible momentum.

Moreover, we should be able to estimate the masses of dark matter particles by looking at the momenta of the visible particles. We also should be able to determine the interactions of supersymmetric

* "Parity" usually refers to the conserved quantum number associated with the space inversion operation. In this paper, however, "parity" refers to the conserved quantum number associated with supersymmetric transformation. It is usually called R-parity.

particles by looking at the distributions of the visible particles. Twenty years ago, the LHC was thought capable only of discovering new particles. Today, however, we believe that the LHC can reveal much more knowledge about dark matter. I'll skip the details of the data analysis and explain our final goals.

LHC experiments can test the Big Bang scenario

The density of dark matter particles created in the hot universe of the past is known to be inversely proportional to the probability of their disappearance through collisions with each other. (The stronger dark matter particles interact, the lower their density in the present universe becomes because they continue to collide each other and disappear as the temperature of the universe becomes lower.) In other words, if we know the properties of dark matter, we can know its density. Will the results of experiments on dark matter properties at colliders such as the LHC be consistent with the observed dark matter density in the present universe? The two must agree in order for the universe, which created the dark matter, to be a simple Big Bang universe. But if dark matter is created by a different mechanism or if the history of the universe is more complicated, then the two will differ. This means that we can explore the history of the universe from a completely different perspective.

The reactions that occurred in the early stages of the universe can be reproduced by bending protons into a circular ring using a magnetic field, accelerating them, and then colliding them. Larger rings are more effective, so the LHC ring is 27 km in circumference. Protons circulate inside the ring 40 million times every hour and collide. Efficient collisions require precisely controlled proton-beam positions. Superconducting magnet coils create the strong magnetic field required to bend high-energy protons. The protons are housed in liquid helium tanks cooled to below 1.9 K. The beams that are guided by the magnets are kept at a temperature lower than the present day universe (2.7 K), resulting in collisions that produce energy corresponding to a temperature of 100 trillion degrees.

The LHC produced its first collision on September 11, 2008. Unfortunately, the LHC developed a liquid helium leak soon thereafter and is now undergoing repairs. Incidents such as this are not uncommon in the startup stages of pioneering experiments. We have seen such incidents in the past, but they have always been resolved by the efforts of specialists and, eventually, good scientific results are produced. We look forward to the expected start of full-scale experiments later this year.

Figure 4. The first LHC magnets to be installed in the LHC tunnel.
Copyright © CERN, Photograph by Maximilien Brice