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FEATURE STORY

Looking for SUSY at the LHC

Prof. Mihoko Nojiri of KEK's Theory Center studies supersymmetric particles and dark matter in conjunction with the Large Hadron Collider's experiments. She hopes to find evidence of such particles in the new data which is just now beginning to be produced.

With the exciting start of 7 TeV collisions at the Large Hadron Collider at CERN, both the theoretical and experimental worlds of high energy physics are beginning the exploration of a vast range of new physics beyond what is currently known. Learn here about one new theory to be explored at the LHC, supersymmetry, and the work of a KEK theorist who hopes to find evidence of new physics.

The beginning of a new era of physics was announced last week at CERN. Particle collisions at a record-setting energy of 7 TeV have begun. The Large Hadron Collider (LHC), the most powerful proton-proton smasher in the world, will run continuously for the next 1-2 years. The goal of the LHC is to look for the last missing piece of the Standard Model of particle physics, the Higgs particle, and to look for new physics beyond the Standard Model.

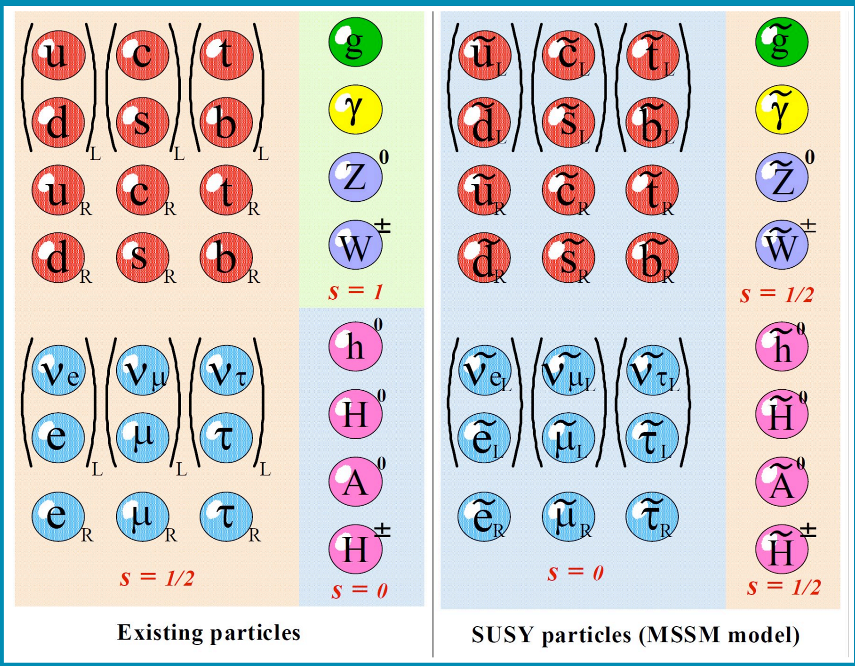
Prof. Mihoko Nojiri of KEK's Theory Center is looking for new particles called supersymmetric particles at the LHC. This is part of her phenomenological studies of dark matter. "The LHC's high energy collisions will be able to produce many heavy particles, including supersymmetric particles," explains Nojiri."These supersymmetric particles can decay into many different types of particles. For each supersymmetric particle decay, there is at least one stable particle called the lightest supersymmetric particle, a candidate particle explaining the dark matter. These particles will appear as 'missing' energy and momentum."

Supersymmetry, or SUSY for short, is a proposed theory which relates two families of particles: bosons and fermions. In the Standard Model of particle physics, Higgs particles and force carriers (such as photons, gluons, and Z/W particles) are called bosons. A different family of particles, one which includes electrons, neutrinos, and quarks, is called fermions. What distinguishes the two families of particles is a quantity called 'spin' that measures the small magnet-like property of particles: bosons have integer values for spin, while fermions have half-integer values for spin.

SUSY relates bosons to fermions by introducing a new particle for each of the currently known particles in both families. Each new particle is a superpartner of one of the current particles, having similar characteristics, but with its spin differing by one-half. This means that every fermion has a bosonic counterpart, and vice versa.

Why SUSY?

The reason that physicists introduced this symmetry is purely theoretical. The introduction solves a problem called the



Supersymmetry, or SUSY for short, states that there is an undiscovered bosonic counterpart to every fermion in the Standard Model, and an undiscovered fermionic counterpart to every boson. (image credit: T. Kondo)

hierarchy problem. The hierarchy is the difference of the sizes of parameters among the interactions in nature. There are four types of interactions—forces—in our universe. In order of strength in the environment around us, they are the strong force, the electromagnetic force, the weak force, and gravity. The scale of weak force and gravity is different by 10^{17}. The first three forces are governed by theories called quantum gauge theory, and the difference among them is much smaller. However, the strong force is more than 100 times stronger than the electromagnetic force.

There is a theory, called Grand Unified Theory (GUT), where three forces are unified at the very high energy scale. At the beginning of the universe when the temperature was extremely high, the three forces are thought unified; namely, the three forces are indistinguishable from each other. The GUT scale, where this unification occurs, is however much larger than the scale of weak force; the GUT scale is around 10^{16} GeV while the weak scale is around 100 GeV. The GUT scale is close to the Planck scale, at 10^{19} GeV, where all four forces appear equally strong (the strength of forces changes depending on the energy scale). Here, the possibility that all forces can be understood in a single theory emerges.

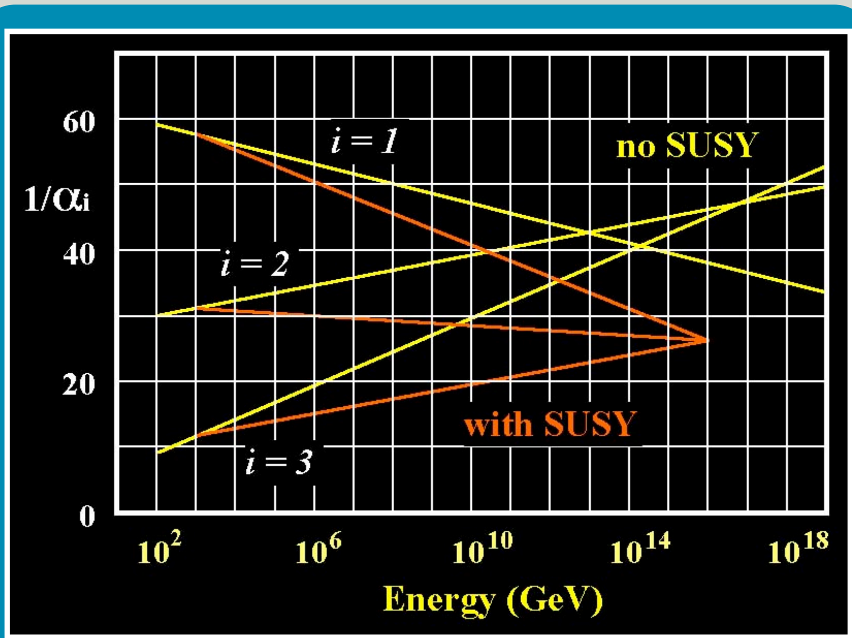
However, a difficulty arises due to the hierarchy among the scales. Theorists' challenge is to reconcile the lightness of the Higgs boson, predicted to be at the energy region of TeV, which LHC explores. If the fundamental scale really is around the GUT or Plank scale, a naïve calculation of the quantum theory tells theorists that the mass of the Higgs boson should also be at this scale. Their calculation showed that to keep the Higgs at the TeV region requires fine-tuning of a Standard Model constant to the precision of startling 32 decimal places. The slightest deviation of the constant will soon result in an unwanted mass divergence of the Higgs boson, and require mass correction at the scale of the fundamental scale.

To fix the problem surrounding the mass scale of the Higgs particle, one solution was to introduce the SUSY to the theory. This requires introduction of fermionic counterparts to all bosons and bosonic counterparts to all fermions. The importance of the symmetry is that it controls mass correction. Without SUSY, masses of fermions are subject to mass correction that is proportional to only the logarithm of the fundamental scale, not the fundamental scale itself. SUSY tells us that the mass correction to a bosonic particle should be same as that of the fermionic partner. Thus, if there were a fermionic superpartner to the Higgs, the Higgs mass correction should also be same as the correction of the fermion, and should reduce from the order of 10^{16} to some manageable level. The SUSY approach is one of several solutions proposed to deal with the problem of the Higgs boson mass.

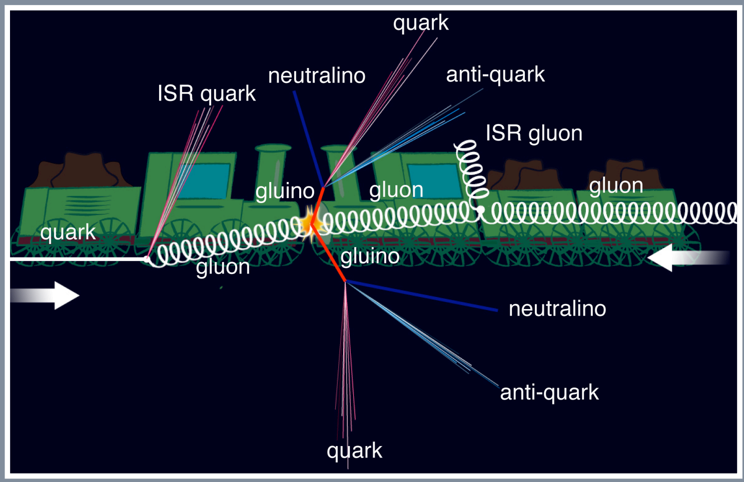
The idea of SUSY introduced to account for the hierarchy issue, however, made things more complicated than the theorists had anticipated. The theory would have been much more compact if the fermionic counterparts of the bosons were the fermions in the Standard Model, and vice versa. To make the theory consistent with the unification theory, however, theorists needed to rule out the Standard Model, and instead work on the SUSY picture. In the end, the only reasonable solution involved having as many new superparticles as known particles. Quarks partnered with squarks, electrons with selectrons, neutrinos with neutralinos, photons with photinos, and so forth.

To the further frustration of these theoretical physicists, SUSY theories contain a great many free constants. A simple addition of this symmetry to the Standard Model, called the Minimally Supersymmetric Standard Model (MSSM), has 125 free constants, compared to the 20 of the current Standard Model. This large quantity of unknown numbers means it is hard to make testable predictions with SUSY theories.

As unsettling as these properties may sound, SUSY actually attracts great many theorists. There are many reasons for this, but one important feature of SUSY theories is that they



At the beginning of the universe, three of the four forces in nature were unified. The Standard Model predicts different scales of energy at which forces unify. SUSY theories naturally unify the three of the four fundamental forces at the energy scale, without requiring any adjustments. (image credit: T. Kondo)



Heavy particle production is associated with emissions of quarks and gluons from incoming quarks and gluons. This emission is called initial state radiation (ISR), and can contaminate the jet environment.

clearly and naturally unify the three of the four fundamental forces, without requiring any further adjustments.

“SUSY is a little more theoretically self-consistent than other theories which try to explain physics beyond the Standard Model,” says Nojiri. “I believe it could be true.”

Testing SUSY with experiments

If SUSY is real, physicists should see evidence of it at the LHC. At the previously unexplored energy levels produced in the LHC, most physicists expect that they will see something new, something that is not explainable by currently known theories of physics.

More specifically, they would know that they've found something new if they see missing particles. The first question you may ask is, "How do you see a missing particle?" The rule of thumb of physics is that a system must conserve its total energy and momentum at all time. When the total energy and momentum after a collision don’t add up, that will be the indication that some new invisible particles arose from the collision. By calculating the missing energy and momentum, physicists are able to account for missing particles.

The second question is, “How would you know that the missing particles are SUSY particles, and not products of some other type of new physics, such as extra dimensions?” This is where phenomenological theorists like Nojiri work, preparing for the big physics results about to emerge within a year or two.

In a recent collaboration with physicists at SLAC, the Institute for the Physics and Mathematics of the Universe (IPMU), and Tohoku University, KEK's Nojiri worked out a better way than previously available to use experimental data to reconstruct the mass of squarks and gluinos that might be produced in the LHC. This is a significant step forward, in that it provided a solution to handle background radiation of quarks and gluons that had long been SUSY physicists’ plight.

Protons are composed of quarks and gluons. If, for example, a pair of gluinos (the superpartners of the gluons) is produced in a collision, SUSY theory predicts that each gluino would decay into a quark, an antiquark, and a neutralino (the superpartner of the photon, Z bosons, Higgs bosons). Because strongly interacting particles cannot be separated from their neighbors, the collisions at the LHC will likely result in jets of particles spraying out from the interaction point. “What complicates the situation is that gluon and quark jets can also originate from just outside of the interaction point,” explains Nojiri. “For example, when two trains collide head-on and splash small pieces at the collision point, collisions between each compartment would also splash broken pieces. Just as so, gluons and quarks colliding at high energy can emit jets before the most energetic interaction occurs.” These jets produced by unwanted interactions are called initial state radiation (ISR). They were long thought an obstacle to searching for the new particles, as they contaminate the environment.

One objective of the LHC experiment for SUSY physicists like Nojiri is to determine physical characteristics, such as mass, charge, momentum, of the new particles. However, this is no easy task. First, the initial conditions, the center of mass of the partons (constituents of protons), is not known. Second, a SUSY event always produces two invisible SUSY particles that are very light, and so hard to measure. Because of these uncertainties, it is impossible to reconstruct the masses directly.

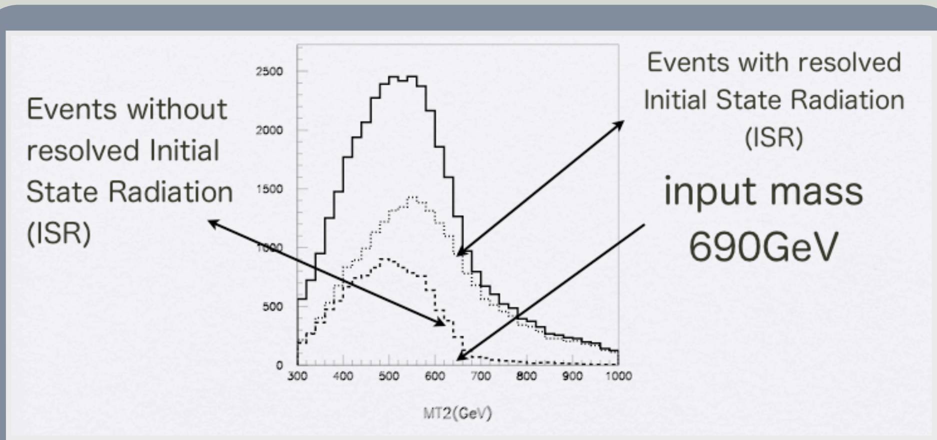
Instead of looking at the masses of the SUSY particles directly, physicists have been considering indirect values that they can use to estimate some physical properties of superparticles. One such indirect parameter is called M_{T2} where ‘T’ stands for transverse to the direction of beams. M_{T2} is calculated from the transverse momentum of the jets. The resulting gluino decay products would come out in different direction each time. Each event would also have one missing momentum that is the composition of two invisible light SUSY particles, which means that the momentum of the two invisible SUSY particles are not exactly determined. These uncertainties give rise to a distribution over the gluino mass in transverse direction, M_{T2}.

“It has recently been found that, if we can correctly identify the two jet pairs that arise from a gluino decay, then the masses of the gluino and neutralinos can be reconstructed precisely by looking at the end point of the M_{T2} distributions,” says Nojiri. The problem, however, is that this end point is blurred by the ISRs.

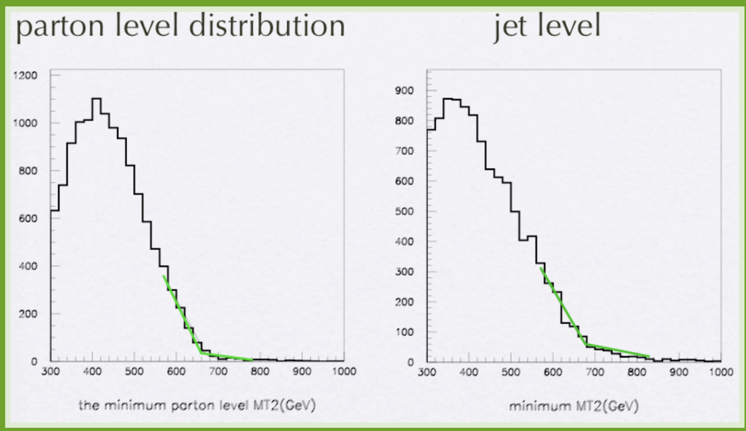
Filtering out the ISR effect

“When two gluinos are produced in a collision, there will be four jets that arise from gluino decays, in addition to the ISR jets. So when there are more than four jets, we don’t know which quark jets come from the gluino event,” says Nojiri.

Generally, the ISR quarks can have as much transverse momentum as the ones from the gluino decays. Knowing this, Nojiri and her



This plot shows the number of events with respect to the mass of gluino in transverse direction that results from the gluon decay. The jets that arise from the initial state radiation (ISR) smear out the upper end of the distribution, making it difficult to predict the mass of the superparticles.



The transverse mass distribution reconstructed using the new scheme. This method successfully eliminated the noise from the ISR jets.

collaborators considered a five-jet system instead of four. Here, it is not possible to directly identify which of the jets is the ISR jet. Instead, there are five possible situations in which an ISR jet is assigned to one of five jets. Nojiri and her collaborators considered each of the five situations, and calculated the end-point M_{T2} for each of these situations. They then took the smallest value of the five, M_{T2}(min). The end point of the M_{T2}(min) gave an astonishingly accurate match to the theoretical mass of the gluino.

What happens if two jets arise from the ISR? “Our simulation showed that, if there is a second jet, the second jet has smaller transverse momentum events than the first one, so it would not contribute much to the distribution in the high-mass end,” says Nojiri.

The state-of-the-art of Monte Carlo

To understand phenomena at the hadron collider requires not only good theoretical understanding but also many steps of numerical calculations. At the hadron collider, interactions of elementary particles in proton, often called parton level interactions, are accompanied by the process called hadronization as well as the initial state radiations.

After the collision events take place, the partons generated fly apart from the interaction point. At this stage, the strong interactions of QCD kick in, preventing quarks and gluons from being separated from each other. This leads production of the many low energy quarks and gluons along the direction of the original partons, and they end up in a bound state of quarks and anti-quarks. This process is called hadronization. After the hadronization process, the final state particles pass through detectors.

The numerical calculation to reproduce the events as results of observation should include all these processes. Many groups in the world take parts to develop such simulation tools, and with those theorists can predict the event distribution expected at LHC. “These tools are the result of coherent efforts to understand the LHC physics, and I make a full use of those tools to deal with the physics I am interested in,” says Nojiri. In particular, Nojiri and her team needed to make sure that ISRs were accurately modeled in their parton-level shower generator. They worked with MADGRAPH, which is one of parton-level event generators that can calculate additional quark and gluon emission together with a SUSY particle. MADGRAPH can be easily combined with other parton shower generators to produce full events.

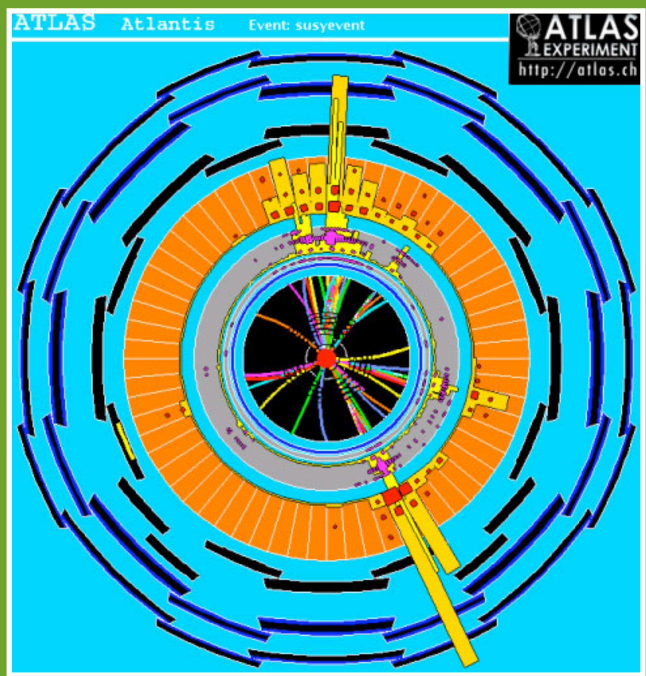
The era of new physics

To establish models for SUSY, it is important to estimate the mass of the SUSY particle. There are other models which produce similar signature with multiple jets and missing momentum, such as the little Higgs model with T parity and Kaluza-Klein model. The relation between the mass and cross section is one of the key features to distinguish those.

Nojiri and her collaborators have proven their scheme of reconstructing gluino M_{T2} distribution. Now, they are doing the same for more complex and realistic system that includes both gluinos and squarks production.

“It is important to study what we will see at the 7 TeV run and the following 14 TeV run,” says Nojiri. “It will be another year or more before the time comes that the LHC starts exploring SUSY particles. I am really looking forward the time to come.”

Nojiri’s primary interest, besides SUSY, has been dark matter. Dark matter is the unknown matter that does not interact via the electromagnetic force or the strong force. Current estimates suggest that about 23 percent of the energy contents of our universe is the dark matter. The superpartner of the neutrino, the neutralino, is one of the strongest candidates for such matter due to the expected high mass and high stability of these particles. If such SUSY particles are found, either at LHC or other searches, this means dark matter, one of the greatest mysteries of our universe, is explained. At the same time, it would pose many new theoretical questions for us. The first question would be, why are there so many elementary particles and so many free constants? An exciting era of new physics is closing in on us.



At a particle collider, dark matter and SUSY particles will be evident in the form of missing energy and momentum. (image credit: CERN ATLAS group: http://www.atlas.ch/photos/events-simulated-supersymmetry.html)

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