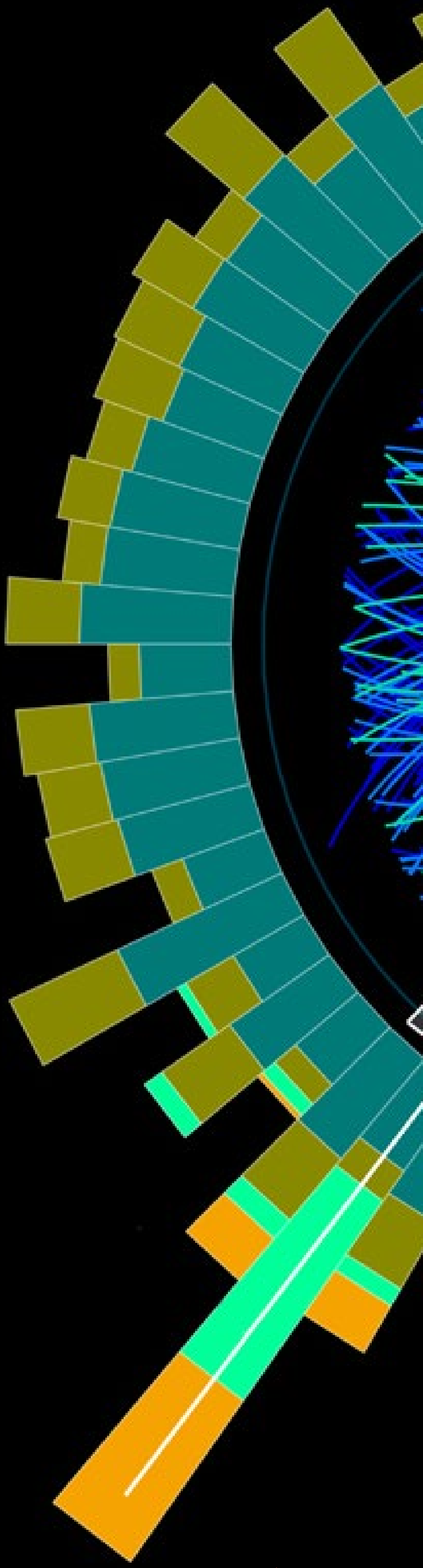
Jetting through

the Quark Soup

by Yen-Jie Lee



The 21st century has seen major advancements in our fundamental understanding of the strong nuclear force which governs the subatomic world of nuclear physics. New experiments that involve colliding heavy ions—specifically, the nuclei of gold and lead atoms—at high energy have created a new state of matter, the quark-gluon plasma (QGP), in which the strong force in a super high-density environment can be studied in unprecedented detail. With these new experiments have come new challenges and new opportunities. Among the most exciting is the phenomenon of *jets*: sprays of particles in one direction that originate from a quark or a gluon created in the initial collision. These jets carry extraordinary amounts of information about the details of the QGP medium through which they move. Because of this, jet physics has become a central focus of the high-energy nuclear physics community over the past 15 years and provides us with a guide for where the field is headed in the near future.

Free the quarks

Everything we see and touch is due to electromagnetic forces—the exchange of photons between charged particles. In contrast, the strong force (the exchange of gluons between subatomic nuclear particles) is about two orders of magnitude stronger, yet we never see or feel it. It is responsible for phenomena that are beyond our senses: the formation of nucleons (protons and neutrons) and their binding together to form atomic nuclei. But why is our experience of the strong force so limited? The answer is that the properties of the strong force confine its participating particles, the quarks and gluons, into a very small range: the volume of the nuclei. All experiments looking for free quarks have thus far failed. Indeed, recent supercomputer calculations of the strong force show that under the conditions common to our normal lives, quarks and gluons cannot be free. This leads us to important questions: Can we ever "free" the quarks, perhaps at conditions far from our common life experience? What would the world look like with free quarks and gluons?

If protons and neutrons were both elementary and incompressible, then the high-density limit of matter would be a state of closely-packed nucleons. Experimental evidence suggests, however, that this is not the case. In 1968, teams led by Jerome Friedman and Henry Kendall (MIT), and Richard Taylor (Stanford University), were the first to discover that nucleons are not elementary: they observed point-like constituents (quarks) inside the proton (and received the 1990 Nobel Prize in Physics as a result). If one could increase the nucleon density, each nucleon's constituent quarks and gluons would approach closer to each other until a state is created in which each constituent has a considerable number of constituents from other nucleons within its immediate vicinity. That is, if one adds more and more nucleons into a very small volume, at a certain point the concept of individual isolated nucleons loses its meaning. Thus we expect a transition at high density from matter made of atomic nuclei to a new phase of matter whose basic constituents are unbound quarks and gluons—the quark-gluon plasma (QGP).

The QGP is a phase of strongly interacting matter in which many quarks and gluons are deconfined in a volume of roughly the size of a few nucleons. What do we hope to learn from this kind of matter? One motivation is that we may discover new phases and properties of nuclear matter. In comparison to electromagnetism—which is described by the theory of quantum electrodynamics (QED) with a single type of electric charge and force-mediating particle (the photon)—the strong force is much more complex. It is described by the theory of quantum chromodynamics (QCD) with three "color charges" and force mediators (gluons), which themselves also carry the color charge, resulting in complicated interactions between them. Although we understand the electromagnetic force very well, it was extremely difficult to predict from first principles the existence of exotic phases of matter such as superfluidity and superconductivity, which derive from electromagnetism. One would expect that the structure of the phases of matter deriving from QCD could be even richer than that in QED.

A second motivation is that understanding the QGP may teach us about the universal properties of strongly coupled matter—a topic of intense interest in many areas of physics, from condensed matter and atomic physics to string theory. The equations of QCD are extremely difficult to solve due to the large coupling strength. Yet, to predict particle behavior we mostly employ perturbative calculation techniques that only work when the coupling constants are small, *i.e.*, when the interactions are weak. Unfortunately, strong-force interacting systems are only "weak" in this sense for very high-energy scattering processes; therefore, our techniques fail for the case in which we are most interested. Numerical calculations of QCD using techniques known as lattice gauge theory are now possible with the help of powerful computers. These calculations show that a transition from normal matter to the QGP is expected at around two trillion degrees, which is about 5,000 times hotter than the core of a nuclear bomb and compatible with the temperature of the universe just one microsecond after the Big Bang. It is fascinating to be able to explore the properties of this novel kind of matter in the laboratory.

Relativistic heavy ion collisions and elliptic flow

There are two ways to create a super high-density environment. The first possibility is to increase the pressure such that the nucleons dissolve into a continuous phase consisting of free quarks and gluons. This extremely high-pressure environment, similar to the conditions at the center of a massive neutron star, cannot yet be created in the laboratory. The other way is to increase the energy density in a small volume so that the energy density is far higher than that of atomic nuclei. This approach is realized by powerful heavy ion colliders. Atomic nuclei which have been stripped of their electrons—heavy ions—are first accelerated close to the speed of light and then brought into collisions. Due to relativistic length contraction along the direction of motion, the colliding heavy ions become "pancakes" with a radius of a few femtometers (10^{-15} meters). In head-on collisions of two heavy ions, a fraction of the kinetic energy of the ions is pressed into a very small volume and an extremely hot medium is created.

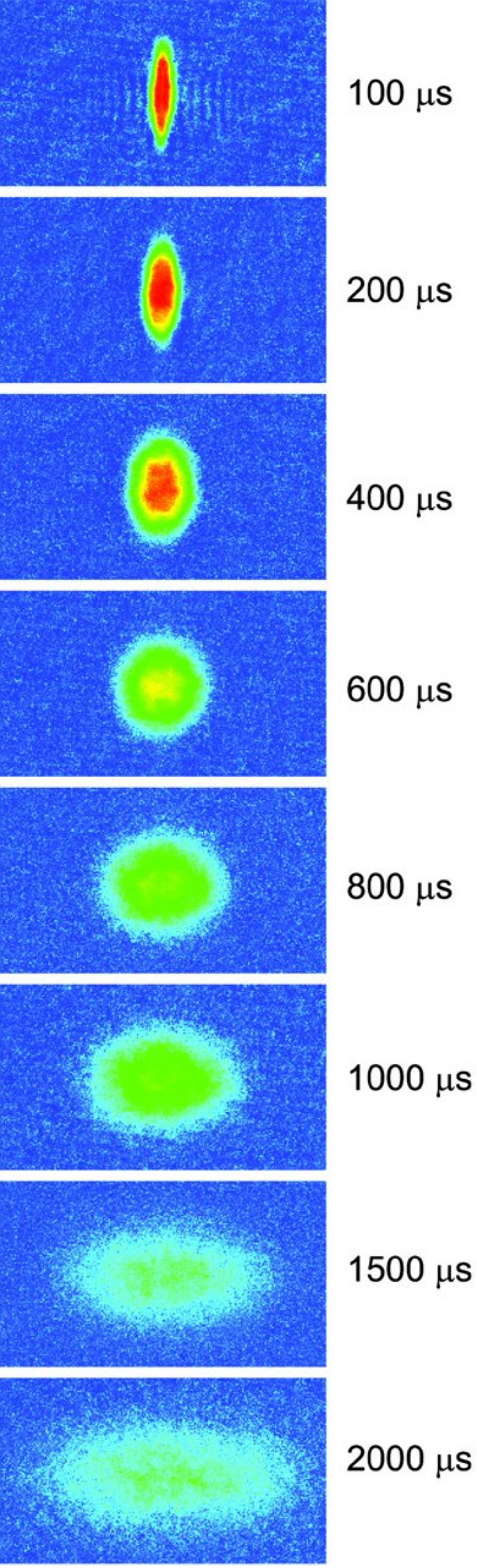


FIGURE 1

Images of a strongly interacting Fermi gas *as a function of time after release from a full laser trap. [Courtesy Prof. John Thomas, Department of Physics, North Carolina State University]*

There are two heavy ion colliders presently active: the Relativistic Heavy Ion Collider (RHIC) located at the Brookhaven National Laboratory and the Large Hadron Collider (LHC) located at the European Center for Nuclear Research (CERN), which is the highest-energy heavy ion collider to date. MIT has a long history in leading the studies of heavy ion collisions. This includes the PHOBOS experiment, one of the four experiments at RHIC (initiated and led by Wit Busza) and the Compact Muon Solenoid (CMS) heavy ion program at the LHC, led by Boleslaw Wyslouch, Gunther Roland and Yen-Jie Lee.

Studies of the properties of the QGP at heavy ion colliders and the interpretation of the experimental data they produce are highly challenging because the QGP, once created, cools down rapidly and breaks into particles of normal matter. This means that particle detectors only measure the particles emerging from the QGP, but not the QGP itself. Complicated analyses are employed to extrapolate the measurements of the detected normal matter particles (a few meters from the collision), back to the underlying properties of QGP (with a typical size of a few femtometers). This is like trying to study an object of the size of our solar system by detectors at the edge of the universe.

Based on measurements of the particles' angular distributions, the most exciting effect discovered at RHIC is *elliptic flow*. In each collision event, the measured particle densities are enhanced on a specific axis and reduced along a perpendicular axis. The particles produced in these heavy ion collisions seem to "know" each other rather than move independently of each other. The common interpretation is that the produced medium (the QGP) is not simply a superposition of many independent radiating sources, which would result in isotropic distributions; instead, the whole system undergoes a pressure-driven expansion. This phenomenon is similar to that observed in a strongly interacting Fermi gas after release from a full laser trap, shown in *Figure 1*, where the pressure gradient in the horizontal direction is larger than that in the vertical direction. The observed particle angular anisotropy in heavy ion collisions is also reproduced by hydrodynamics calculations. Remarkably, these calculations require the QGP to be almost frictionless so that the initial geometrical information is not washed out in its expansion.

Probing the QGP

To go beyond studies of the debris, we can study the passage of particles through this fascinating medium. However, these studies are not easy because of the extremely short lifetime of the QGP, on the order of 10^{-24} seconds (one yoctosecond), and its small volume with a radius on the order of femtometers.

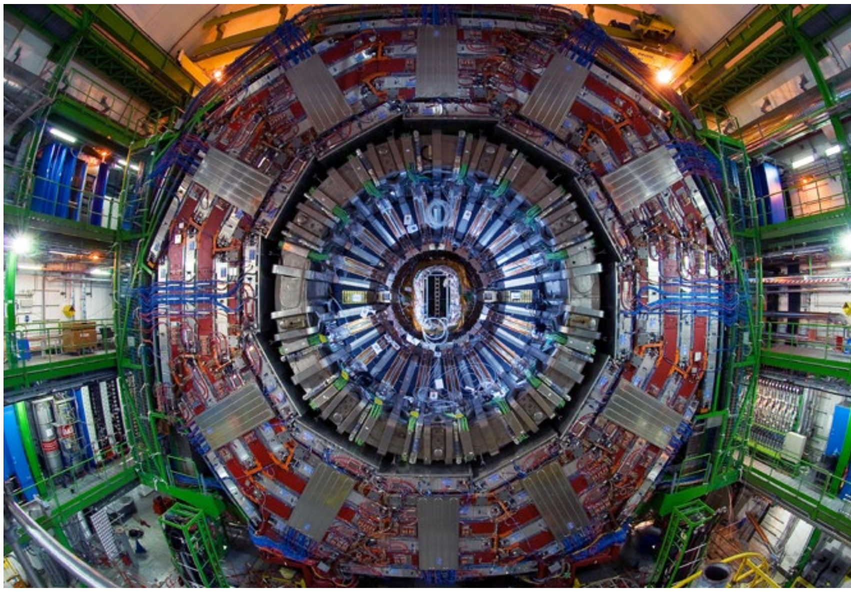


FIGURE 2 (TOP)

Photograph of the central part of the CMS detector *which shows the inner tracking system, calorimeters, superconducting magnet, and muon detectors. [Courtesy CERN/CMS collaboration]*

FIGURE 3 (BOTTOM)

Photograph of CMS heavy ion group members *at the CMS center at CERN led by Prof. Lee during the 2015 lead-lead data-taking period. [Photo credit: Camelia Mironov]*

In 1982, James Bjorken proposed to study the energetic quarks produced together with the QGP as "probes" to overcome these difficulties. When these quarks pass through the QGP, they lose energy along the way. After an energetic quark exits the high density environment of the QGP, it no longer behaves as an unbound particle, but instead transforms into a jet, a spray of many particles that cluster into a tight cone around the initial quark's direction of travel. By measuring the particles in the jets, information about the initial quark is reconstructed. Measurement of quark in-medium energy loss, often referred to as jet quenching, is of great interest because the modification of those energetic probes enables the measurement of the transport properties of the QGP, such as its temperature, density and stopping power (dE/dx).

Pioneering jet quenching studies were performed at RHIC in the 2000s. A strong suppression of the high-energy particles was observed, but these studies were difficult because there were only a few high-energy probes in the available datasets due to the low collision energy and the limited size of the datasets.

At the LHC, the first heavy ion run in 2010 collided lead ions at an energy of 2.76 TeV, a factor of 14 increase in the energy with respect to RHIC. This was exciting because the production rate of the energetic probe particles was increased by many orders of magnitude. The larger separation of momentum scales between energetic probes and the debris particles produced by the medium itself have opened a new era for the study of the QGP. After the discovery of the QGP at RHIC, Wyslouch, Roland and Busza immediately realized that powerful jet detectors like CMS (the same detector used for the discovery of the Higgs; *see Figure 2*), are ideally suited for the studies of high momentum probes in heavy ion collisions.

Several MIT physicists are involved in the CMS experiment *(Figure 3)*. Wyslouch, Roland and Lee are responsible for organizing the efforts at CMS during the heavy ion data-taking period. And critical support from Christoph Paus and Markus Klute from the MIT Particle Physics Collaboration on data operation and computing enable us to store and analyze the large data samples at MIT.

In 2015, lead-lead collisions at 5.02 TeV, a new record, were delivered for the first time. One of the biggest challenges we faced was the much higher collision rate (up to 20 kHz), and the complicated algorithms needed for triggering on high-energy probes, *i.e.*, deciding when a collision event is worth recording. The

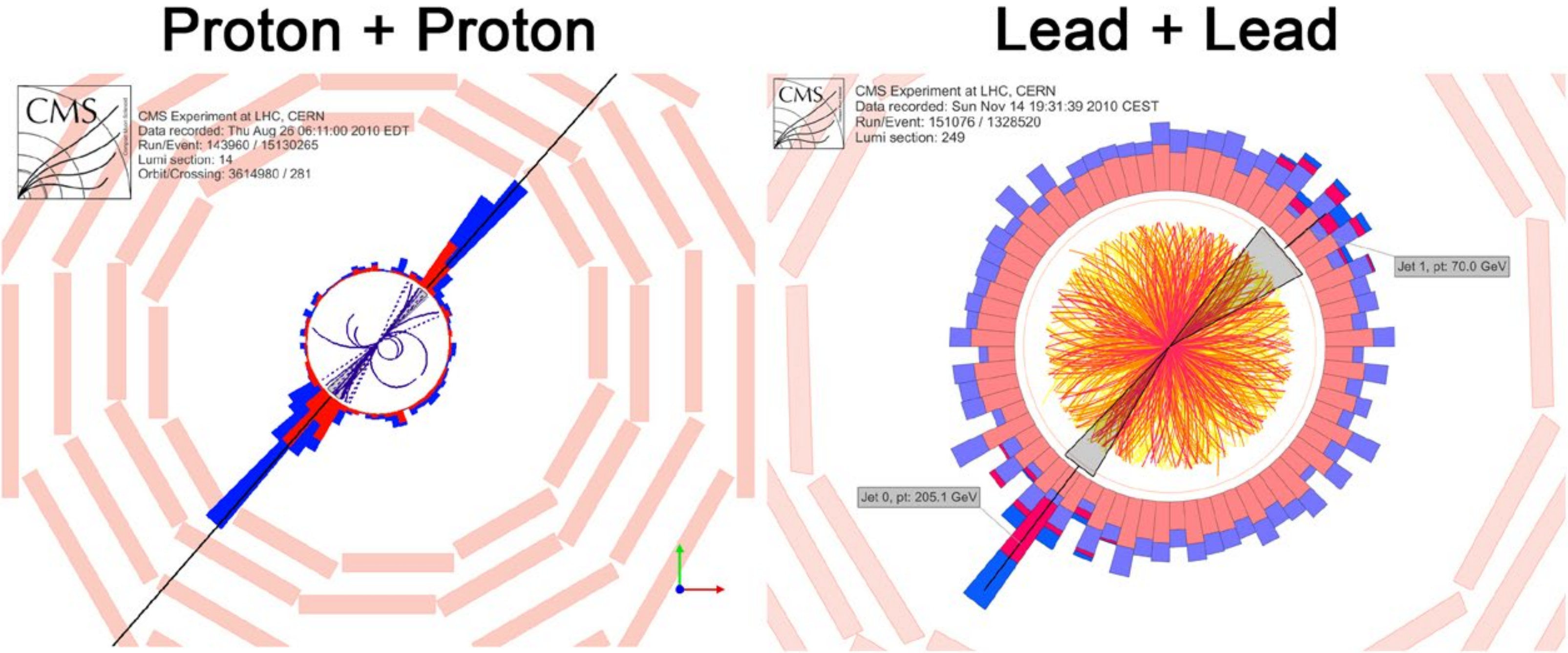


FIGURE 4

Back-to-back di-jet events *in proton-proton collisions (left) and lead-lead collisions (right). [Courtesy CERN CMS collaboration and Y.-J.Lee group]*

MIT group led the Level 1 trigger upgrade, which was a great success. Moreover, a sophisticated trigger strategy was developed by Lee's group, which was used to collect data with massive quarks produced with the QGP in order to see how they are "kicked around" inside the medium.

Jet quenching with jets

Jet quenching was discovered at RHIC as a suppression of the high-momentum particle production with respect to that measured in proton-proton collisions. However, the interpretation of the result and the extraction of the medium properties are not easy. This is because the link between daughter particles and the initial quark energy was weak. Very often, an energetic quark fragments into a bunch of particles flying in roughly the same direction (*Figure 4*). Due to the limited information available, a suppression of energetic particles in a heavy ion collision can be explained by models which modify the way the quark fragments into particles, and by models which slow down the quark in the medium.

Much more precise measurements of the quark energy loss could be achieved by clustering those particles into jets to measure the quark energy very precisely. At the same time, the constituents of the jets could hold information on how the medium modifies the way quarks turn into daughter particles. At RHIC, measurements of fully reconstructed jets are difficult due to the limited detector capabilities and smaller dataset. At the LHC, MIT physicists have made enormous progress on fully reconstructed jets with the CMS detector. One of the most striking results from Lee's group is the direct observation of jet quenching using back-to-back di-jet and boson-jet events. Since the energetic probes are produced in pairs, on average their momentum should balance in the transverse direction. This is indeed observed in proton-proton collisions in *Figure 4, left*. In lead-lead collisions, asymmetric di-jet pairs are observed more frequently. This means that the quarks (or gluons) which produce the two jets lose a different amount of energy while passing through the QGP. This result shows that the stopping power of the QGP is incredibly strong. A significant fraction of the quark (gluon) energy is transported out of the jet cone by the medium.

One significant drawback of the di-jet analysis is that both jets are quenched. To study the absolute energy loss out of the jet cone, photon-jet processes are particularly interesting because photons carry no color charge and do not participate in the strong interaction. Recently, an analysis of a huge sample of photon-jet processes was performed by Lee's group and it was shown that roughly 10% of the quark energy is transported out of the jet cone. Moreover, no significant signal of back-scattering was observed in the photon-jet angular correlation measurement. This QGP Rutherford experiment shows that the QGP is very smooth, and no hard core (similar to the nuclei inside an atom) was detected in the current experimental data. These results could be compared both to perturbative QCD and to a hybrid model of QCD and string theory-based calculations, developed by Krishna Rajagopal's group in the MIT Center for Theoretical Physics (CTP), which could help us learn how quarks lose energy inside the QGP.

Sound waves in the QGP

With the high energy lead-lead data, Lee's group has carried out measurements of energy flow with charged particles in di-jet events, showing that a significant amount of lost energy is carried by low momentum particles that are far away from the di-jet axis. This could be the first measurement of the medium responding to the energetic probes, *i.e.*, a shockwave created in a deconfined medium. On the other hand, mechanisms such as medium-induced gluon radiation could create a similar effect, which makes a conclusive interpretation of the result difficult.

Recently, many new jet substructure tools have been developed and proposed by Jesse Thaler of the MIT CTP. Those new algorithms were originally proposed for searches for new physics in proton-proton collisions. We hope to design experimental observables for heavy ion physics that have more sensitivity to sound waves in the QGP, which is a signature of a deconfined medium. Very systematic and precise measurements of jet substructures will be able to disentangle the effects of the quark energy loss; modification of the way quark branches to particles; and the medium response. These developments and future measurements will leave no room for ambiguity in the interpretation of the jet quenching results.

Future direction

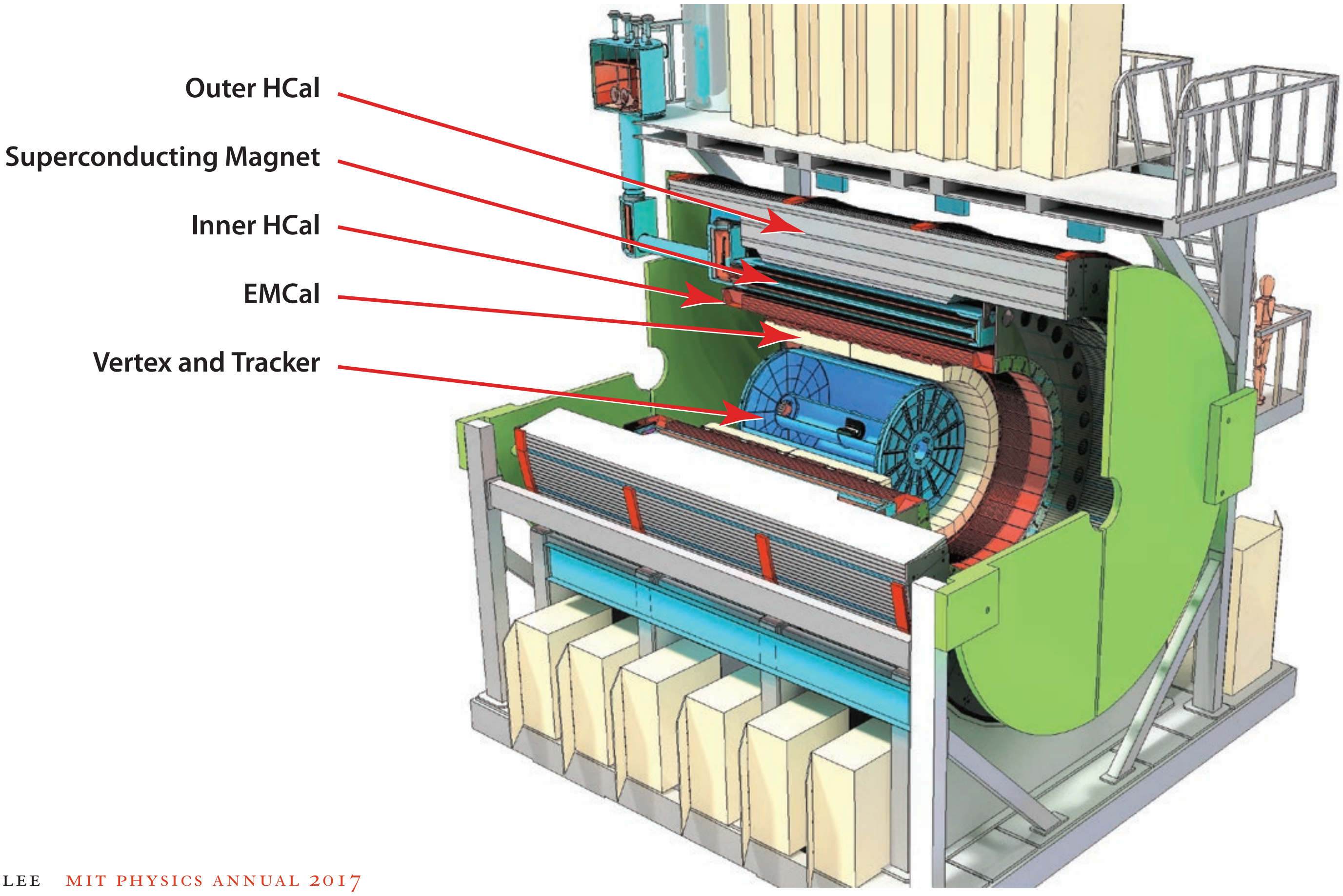
The strong coupling constant's strength depends on the energy scale governing its interactions. This motivates precision jet quenching studies back at RHIC, where the collision energy for gold nuclei is 25-700 times lower. The lower collision energy will produce a cooler initial QGP state compared to high-energy collisions at the LHC. This means that if we compare quarks and gluons with the same kinetic energy at RHIC and the LHC, we will be able to vary the temperature and the jet-medium coupling strength.

However, due to limitations on data-taking speed and the capabilities of the existing RHIC detectors, it is not yet feasible to perform high-precision jet measurements. At MIT, Gunther Roland is leading the effort to design a new experiment, sPHENIX, at RHIC (*Figure 5*). The goal is to build a new particle detector that has the capability to collect very large and high-precision data samples of gold-gold collisions. This will enable studies of high-energy jets that overlap with the jet momentum range analyzed at the LHC. Such an experiment would allow a direct comparison between RHIC and LHC jet data to be performed for the first time.

Since the discovery of the perfect quark soup at RHIC, a tremendous amount of effort has been made to characterize the properties of the QGP. However, we still do not understand how the strongly interacting medium emerges from point-like quarks and gluons which are governed by an asymptotically free theory, QCD. With the high statistics and high-precision RHIC and LHC data to be taken in the next decade, we will be able to watch how a bunch of particles, which are initially very far from equilibrium, thermalize in the QGP. With the newly developed jet substructure tools and the large precise new data samples, we will gather important insights to answer fundamental questions about high-density QCD, by jetting through the quark soup.

FIGURE 5

***A schematic of the proposed sPHENIX detector**, showing several key components: inner and outer hadronic calorimeters (HCal); electromagnetic (EMCal) calorimeter; tracking systems; and the superconducting solenoid magnet. [Courtesy sPHENIX collaboration]*



YEN-JIE LEE *is the Class of 1958 Career Development Assistant Professor of Physics at MIT and a emerging leader in the field of proton-proton and heavy ion physics, primarily studying quark-gluon plasma (QGP), a hot and dense matter created in the collisions of heavy nuclei predicted by lattice Quantum Chromodynamics (QCD) calculations. He has an impressive record of extracting information about strong interactions. For example, his work at the CMS experiment at the LHC has helped to show that energy lost by energetic partons (quarks or gluons) traversing the quark-gluon plasma is converted to lower energy particles emitted at large angles. Recently, Lee launched a heavy ion physics program aiming for precision measurement of charm and beauty mesons in the CMS collaboration.*

Yen-Jie Lee completed his undergraduate and master's degrees in physics at the National Taiwan University, followed by doctoral work at MIT in 2011, under the supervision of Wit Busza. After postdoctoral work at the MIT Laboratory for Nuclear Science, he completed a combined CERN and Marie Curie Fellowship at CERN from 2012 to 2013. Lee joined the MIT physics faculty in September 2013 and served as one of the Heavy Ion Physics Group's co-conveners in the CMS collaboration from 2014 to 2016. In 2016, Lee was appointed as heavy-ion physics executive board representative in the CMS collaboration.

Lee received an Early Career Research Award from the U.S. Department of Energy in 2015, an NEC Corporation Fund Award from the MIT Research Support Committee, and a Sloan Research Fellowship from the Alfred P. Sloan Foundation in 2016.