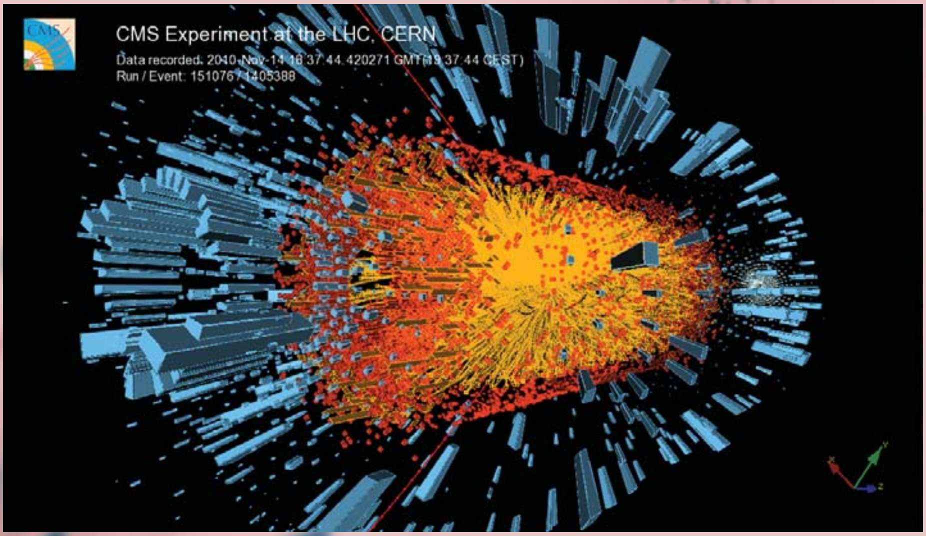
Starting **small**

Dr Manuel Calderón de la Barca Sánchez explains why he is excited about his latest research on Quark-Gluon Plasma, which is shedding light on the very beginning of our universe

Quarks are often discussed but rarely explained. Can you clarify their significance to the study of matter?

Protons and neutrons are not elementary particles, they are made up of even smaller constituents – quarks and gluons. A very important finding has been that they respond to a new force, the strong nuclear force. One can think of a proton or a neutron as being made up of three quarks, which are glued together by this force. I got excited about them partly because this new force is the strongest in nature. Since the particles that hold the quarks together are acting as the strongest of all possible glues, physicists dubbed them 'gluons'. One can infer the strength of the force by remembering that another of the forces of nature, electromagnetism, says that objects that have the same type of electrical charge repel each other, and those with opposite charges attract. Electromagnetism is the force that is responsible for keeping negatively charged electrons orbiting the positively charged nucleus. But why do the protons, which are all positively charged, not escape the nucleus, if electromagnetism says that they should repel each other? The reason is that the strong nuclear force, in addition to keeping quarks bound within protons, indirectly keeps protons and neutrons glued together to form an atomic nucleus. This force must be stronger than electromagnetism, because it overcomes the electrical repulsion of the protons in the nucleus. Without this force, the protons that make up the nuclei in all the atoms in our bodies, and in all the objects around us, would be blown apart by electrical repulsion. In a very real sense, without this strong nuclear force, without quarks and gluons, we would not exist.

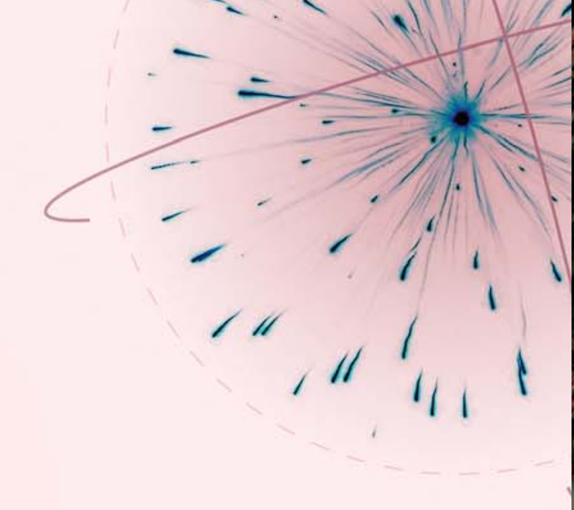


Could you explain the aims and objectives of your project - Heavy Quarkonium Production in Relativistic Heavy-Ion Collisions?

One of the main goals of Relativistic Heavy-Ion Collisions is to study the strongest of all the forces of nature at the highest temperatures achievable in the lab. We collide heavy ions, such as lead or gold, where each ion has about 200 nucleons. The energy released in this collision produces a new state of matter which we wish to study, the Quark-Gluon Plasma. This permeated our universe around one microsecond after the big bang. I am part of two large experimental collaborations which have been studying these collisions, trying to understand this new state of matter. My particular interest is in studying how hot the plasma gets. The problem is that the matter we make is hundreds of thousands of times hotter than the sun and lasts less than a billionth of a billionth of a second, so we cannot simply insert a thermometer and read the temperature. We have to use particles that are also made of quarks to study this plasma.

You mentor undergraduate students and present findings to fellows. Do you believe this to be the best form of outreach and dissemination?

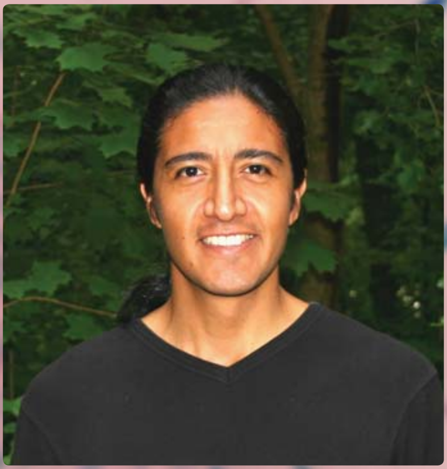
This is certainly one of them. I became interested in working with particle colliders when I was an undergraduate in college. So I would like to communicate the enthusiasm we have for our research to our

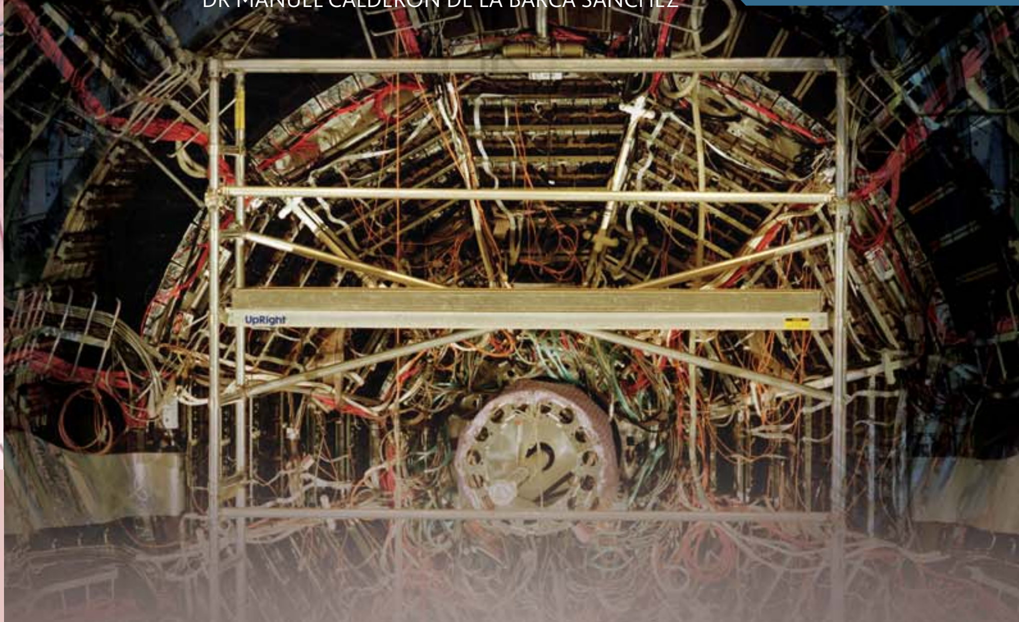


undergraduates, and to help those that are interested get started in this work. I also talk to high school students and elementary school students, and while many of them arrive thinking that physics is hard, after talking to them about how atoms are made of tiny protons, neutrons and electrons, and that protons and neutrons are made of even tinier quarks and gluons, their outlook changes.

How do you view collaboration within your work?

This type of research relies on a huge number of people, all working together. This was one aspect of that attracted me as a student. It drove home the point that when we study our universe, the findings we obtain are also universal. It does not matter where you are from, whether you come from humble backgrounds, what you look like or what language you speak. We are all made of the same kind of matter, and we are all subject to the same laws of nature. In high-energy physics, we work every week with people who come from all continents, and from a multitude of backgrounds. Through the application of maths and science, we all end up arriving at the same conclusions about nature. In our science, we have a common ground, a unifying thread, and this weaves ties of friendship around the globe, and I am always thrilled to participate in this.





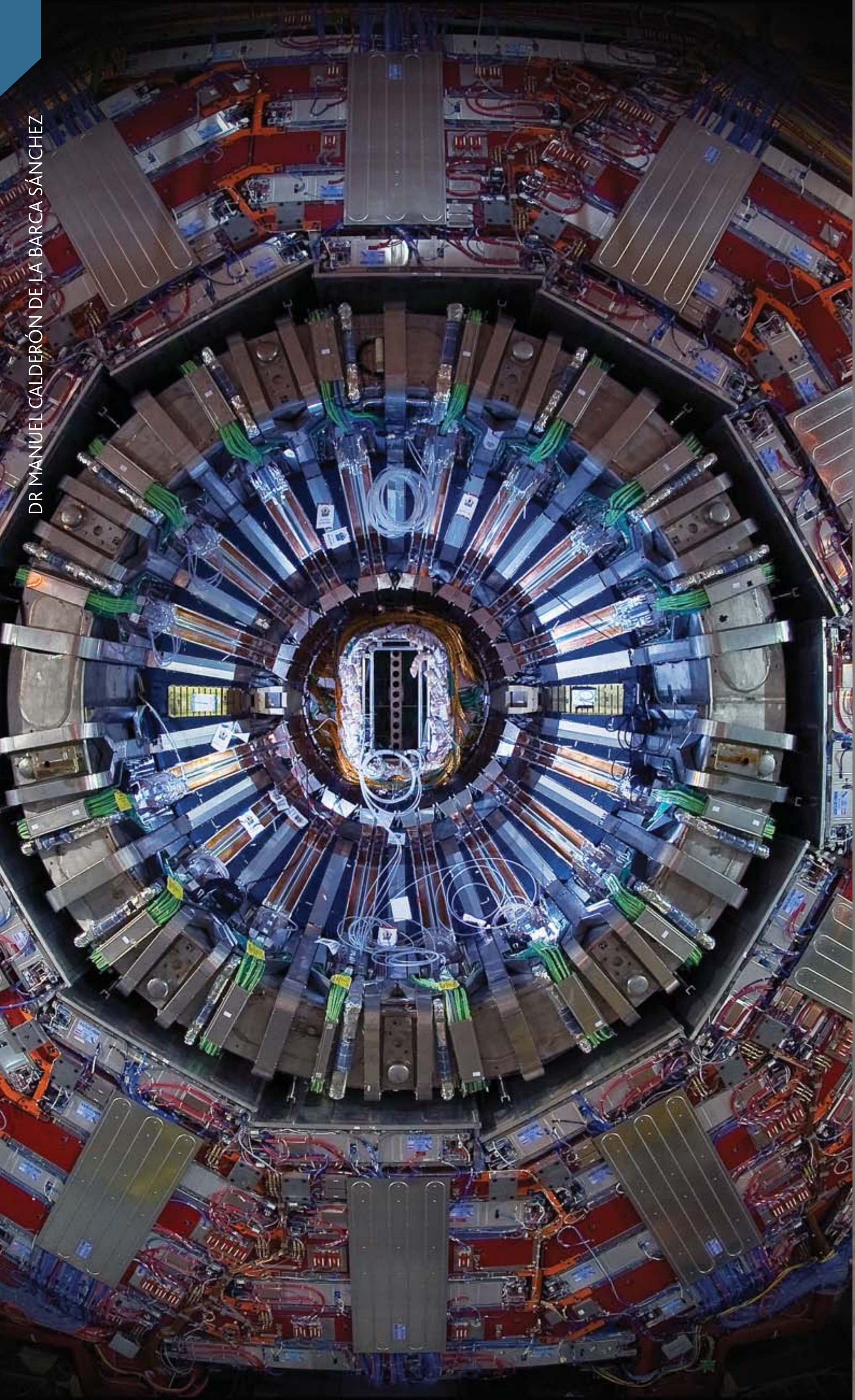
Dense problems

A team of researchers at the **University of California** is using high energy collisions to literally melt and break apart atoms in order to study Quark-Gluon Plasma, as well as the strong nuclear force

PROBING THE MOST fundamental states of the universe, believed to have existed around one microsecond after the Big Bang, is fraught with difficulty. A team based at the University of California is attempting to uncover new and exciting information about Quark-Gluon Plasma (QGP), an extremely hot and dense state of matter. Matter exists in a range of states, and this hierarchy has a longer continuum than is often appreciated. Beyond the usual solid, liquid and gas, there is also plasma. In a plasma state, nuclei and electrons are separated, the electrons being ripped from the atom, making an electromagnetic plasma. Any electron which enters an orbital is swiftly knocked out because of the high energy collisions which occur. Temperatures of millions of degrees are required for electromagnetic plasma to be formed, but it happens within the sun. In order to reach QGP, the temperature must be increased to a hundred thousand times that of the sun. Here, protons and neutrons are torn apart into their constituent quarks, melting the atomic nucleus into the fundamental particles of quarks and gluons. Making an analogy with the electromagnetic plasma, scientists call this state Quark-Gluon Plasma.

One aspect of QGP which the team hopes to investigate further is how ground and excited states of heavy quark-antiquark interactions manifest themselves within the plasma. A similarity can be made to electrons in orbitals. Here, the movement between ground states, the lowest temperature and most stable positions for electrons, and excited states, moving outward from the nucleus, requires energy. Conversely, as the energy drops, electrons will move to orbitals closer to the nucleus and release energy in the form of photons of specific wavelengths. From the emissions scientists are able to infer the difference in energy between the ground and excited states. A heavy quark-antiquark state can be treated in the same way, although the interaction is based on the strong nuclear force, not electromagnetism. The states decay into particles which have different energy or mass, providing us with the means to measure the relative population of ground and excited states. A further analogy is that just as the higher energy electron states are where it is further from the nucleus, so too the higher energy quark-antiquark states are those where there is the most space between the particles.

The similarities with electromagnetic plasma can be continued in the way in which quark-antiquark pairs react when introduced into the QGP. It appears that when they melt, their interaction strength is reduced by the presence of other high energy strong force interactions, just as the electromagnetic bond between protons and electrons is diluted by numerous other interactions once they enter the electromagnetic plasma. The nature of this interaction means that different quark-antiquark states are affected differently within the QGP. Esseentially, interactions where the quark and



antiquark are further apart are affected at lower temperatures than those where the two particles are close together. Consequently, the research being done by the Californian team is focused on measuring the ground and excited states of heavy quark-antiquark particles produced in collisions, looking for the temperature variable effects which they have described. The hope is that these experiments will bring to light some of the properties of these interactions, which will have an impact on their understanding of both QGP and heavy quark-antiquark interactions.

GRAPPLING WITH THE STRONG INTERACTION

Attempting to fully understand the strong nuclear interaction is notoriously hard because of the power of the attraction between the particles, which makes calculations difficult. The analogy with electromagnetism is useful in general, but misses important differences. Yet by viewing the development of work on electromagnetism, the team can compare its own difficulties. Electromagnetic equations were established in the late 19th century, but superconductivity was not discovered until 1911, and the first widely accepted theory of this phenomenon was not forwarded until 1957. Dr Manuel Calderón de la Barca Sánchez, who is leading the team at the University of California, draws the comparison with electromagnetism to demonstrate the importance of experimental data: "Even though the theory of the strong interaction is well established, we are only just beginning to understand the QGP as a very hot, dense and almost perfect fluid; in this field of research I find it exciting that every new experimental measurement can be a surprise". The group aims to uncover the details of QGP interactions through the gathering of experimental data, a lengthy and challenging task, which it is hoped will provide ample rewards.

Yet there are a number of obstacles to overcome if the group is to produce the results which it is seeking. The first of these is the rarity of the heavy quark-antiquark bound states. Practically, this means that one of these is produced in the right decay mode in the range of the detector every two billion collisions. In the Solenoidal Tracker at the Relativistic Heavy Ion Collider in the Brookhaven National Laboratory, this results in many months of experiments in order to gain the data which is required to make a measurement in a given collision system. In the Compact Muon Solenoid (CMS) at the Large Hadron Collider at CERN they have to run for less time, but large particles are only collided for one month a year, providing further limitations to investigation. Calderón de la Barca Sánchez is positive about other issues the team are facing: "A challenge in this particular topic comes from one of the things that makes it exciting, the difficulty in understanding the strong interaction as applied to heavy ion collision starting from first principles”. Trying to get around this involves the modelling of the phenomena, as well as numerous collaborations, but the strength of the team means it is confident in achieving its desired results.

COLLIDER COMPARISONS

The two colliders at the centre of the work are large multipurpose colliders, and hundreds of scientists working on STAR are matched by thousands at CMS. The Californian team’s work searches for electrons and positrons or muons and antimuons, the particles which quark-antiquark pairs decay into. Muons are similar to electrons, but around 200 times heavier. STAR is geared towards reconstructing the momentum of electrons and positrons, and CMS focuses instead on the muons and antimuons of a given collision event. Working back from this fundamental particle shrapnel, researchers calculate momenta, masses and energies of the parent particles. They have found that certain mass ranges are more likely to create electron-positron or quark-antiquark pairings. The work involves calculating how many are seen in a single heavy particle collision, and comparing this to the hypothesis that without QGP there will be the same number as in the equivalent number of proton-proton collisions, which can number in the thousands for heavy ions. What they have found is that heavy quark-antiquark particles are suppressed, and excited states are suppressed more than ground states.

> The team aims to uncover the details of QGP interactions through the gathering of experimental data, a lengthy and challenging task, which it is hoped will provide ample rewards

WEIGHTY ISSUES

One of the major areas of research which the group are pursuing is the specific properties of QGP, and in particular its temperature and density. This cannot be directly measured, but instead is calculated by passing quarks and gluons through the QGP. The more energy which these particles lose as they pass through the plasma, the more dense the plasma is. What has been discovered is that they lose an extremely large amount of energy. Calderón de la Barca Sánchez has been surprised by the results: “Sometimes the particles lose nearly all of their energy, and it is amazing for me when I think that this loss of energy suffered by the quarks happens over a distance of a millionth of a billionth of a meter”. The discovery in the last decade that a quark does not lose energy when passing through a normal nucleus means that the astounding energy loss only occurs through QGP. As the team push ahead with their research, it is hoped that their experiments will continue to uncover important elements of these interactions from the birth of the universe.

TECHNOLOGICAL ADVANCEMENT

There are a number of concomitant developments which work alongside the investigations. Given that the World-Wide-Web was first developed at CERN, many of these are in the realm of information technology. What is currently testing the group’s is the huge datasets which are forcing the development of new tools in order to extract useable information from them. The team also need to find efficient ways of visualising the data which they are producing, another technical challenge. These visualisation protocols are swiftly finding larger applications, since the production of accessible visuals for large amounts of data is an incredibly powerful mechanism, allowing easy paths through expansive datasets. Yet for Calderón de la Barca Sánchez, these are not reasons for completing the work: “For many of us, the main goal will remain the sheer excitement and enjoyment of exploring and understanding nature”. This drive and excitement is leading the scientists from the early stages of our understanding to the strong nuclear force into unexplored areas, though other benefits may well occur along the way.

CONTINUING COLLISIONS

This research is set to continue for some time, moving in two important directions. The first of these is the study of ‘beauty’ quark-antiquarks, which has only just begun. Alongside this, they are also examining the Z particle, transmitter of the weak nuclear force, which should allow them to quantify the energy loss of quarks in the QGP. Calderón de la Barca Sánchez is driving this work forwards: “It is thrilling to combine several particles which transmit a number of these exotic forces together in one study, and it is advantageous that the Z particle does not interact at all with the QGP”. In effect, where a Z particle is created alongside a quark or gluon, the Z particle will not interact with the QGP because it is unaffected by the strong interaction, meaning that it can inform the scientists what energy the quark should have been. What has been holding back efforts thus far is a lack of collider power, but with the advent of the LHC at CERN there is the available technology in order to complete the experiments. It is hoped that this breakthrough will continue to drive results for the Californian team.

INTELLIGENCE

STUDIES OF HEAVY QUARKONIUM PRODUCTION IN RELATIVISTIC HEAVY-ION COLLISIONS AT UC DAVIS

OBJECTIVES

To measure the production of the heaviest available quark-antiquark bound states in heavy ion collisions. The investigations will be carried out at the highest energy accelerators for heavy ion collisions: with the STAR detector at the Relativistic Heavy-Ion Collider located in Brookhaven National Laboratory (Long Island, NY) and with the CMS detector at the Large Hadron Collider in the European Laboratory for High Energy Physics (CERN, Geneva, Switzerland).

KEY COLLABORATORS

Professor Daniel Cebra, University of California, Davis

FUNDING

National Science Foundation – contract no. 0645773

CONTACT

Dr Manuel Calderón de la Barca Sánchez
Principal Investigator

Department of Physics
University of California
One Shields Avenue
Davis, CA 95616-8677
USA

T +1 530 554 2209
E mcalderon@ucdavis.edu

MANUEL CALDERÓN DE LA BARCA SÁNCHEZ was born in Mexico City and went to college in Monterrey, majoring in Engineering Physics. After a summer at CERN, he attended graduate school at Yale doing research in the STAR experiment at Brookhaven Lab. His research continues there, as well as in the CMS experiment, studying heavy ion collisions at the highest available energy.