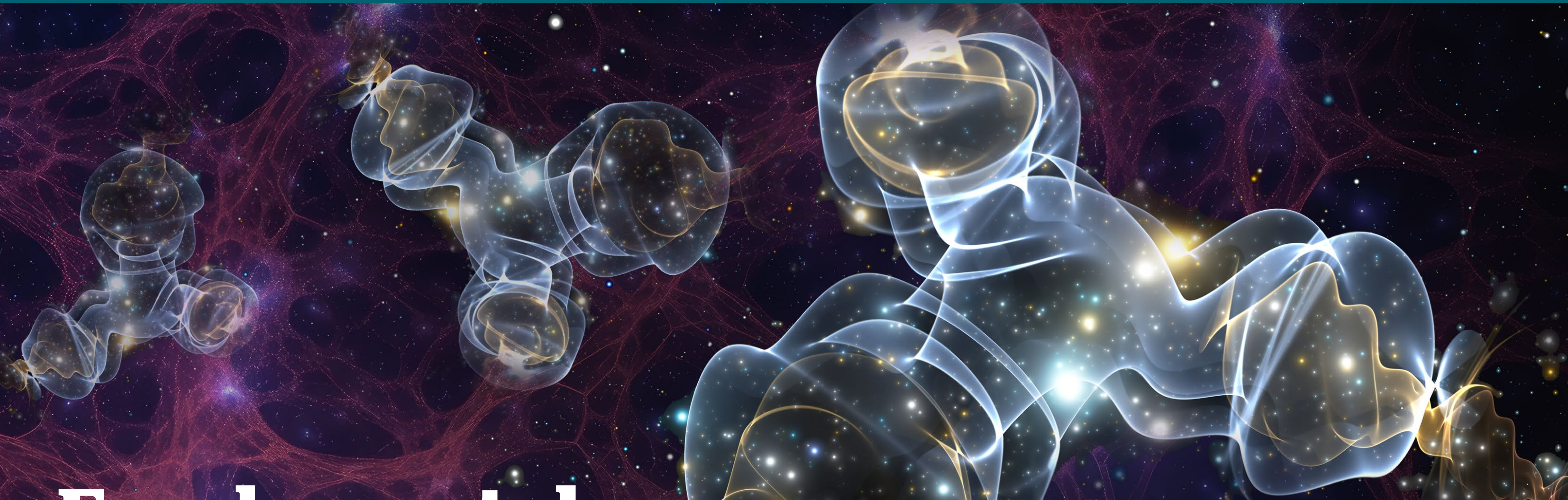


Fundamental symmetry in particle physics

Rules that tell the most when broken

- The standard model, one of the boldest models in physics, has stood the tests of theory and experiment for almost 50 years.
- However, most physicists still expect to find new physics beyond the standard model.
- Novel theories may explain why there is more matter than antimatter and the nature of dark matter.
- To find out, Professor Liping Gan at the University of North Carolina Wilmington, USA is measuring the decays of light mesons, neutral pion, and eta mesons with ever-increasing precision.

When theorist Steven Weinberg coined the term 'standard model' in 1974 to capture the best working theories for how matter is put together, he had intended to give physicists a better-defined argument to grapple with, as theory and experiments inevitably pointed onwards and upwards to finer models. Yet almost 50 years on, it remains the best model we have for explaining the Universe and everything in it. However, its shortcomings suggest the standard model is not yet complete. For example, it fails to explain the dominance of matter over antimatter or the nature of dark matter – the vast quantities of stuff we cannot seem to catch a glimpse of but for the effect it has on the motion of regular matter in galaxies. Exploring this new physics beyond the standard model is the goal of Professor Liping Gan at the University of North Carolina Wilmington in the USA.

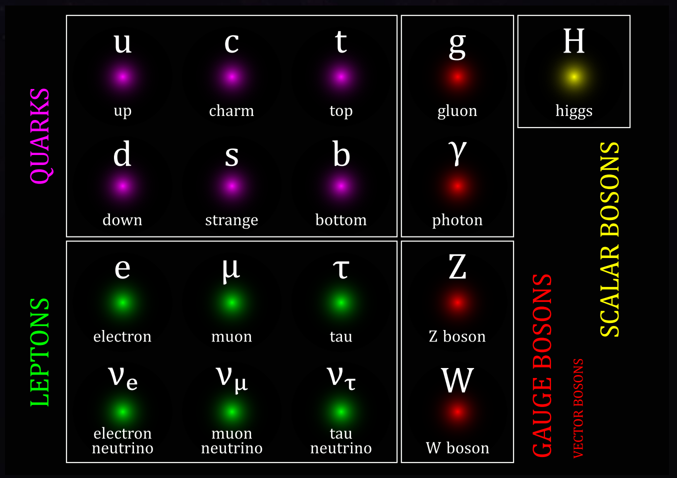
Quarks quirks

Among the many cherished notions that 20th-century physics swept away, was the idea of the proton as a fundamental particle. A cornucopia of different types of apparently 'fundamental particles' was generated in particle physics accelerator experiments, prompting physicists to consider the potential of a more fundamental common denominator. In fact, both protons and neutrons are now considered to be comprised of three quarks, which have very little mass and positive or negative charges equal to a third or two thirds of an electron's charge. When two or any other even number of quarks combine, they form another type of particle called a meson.

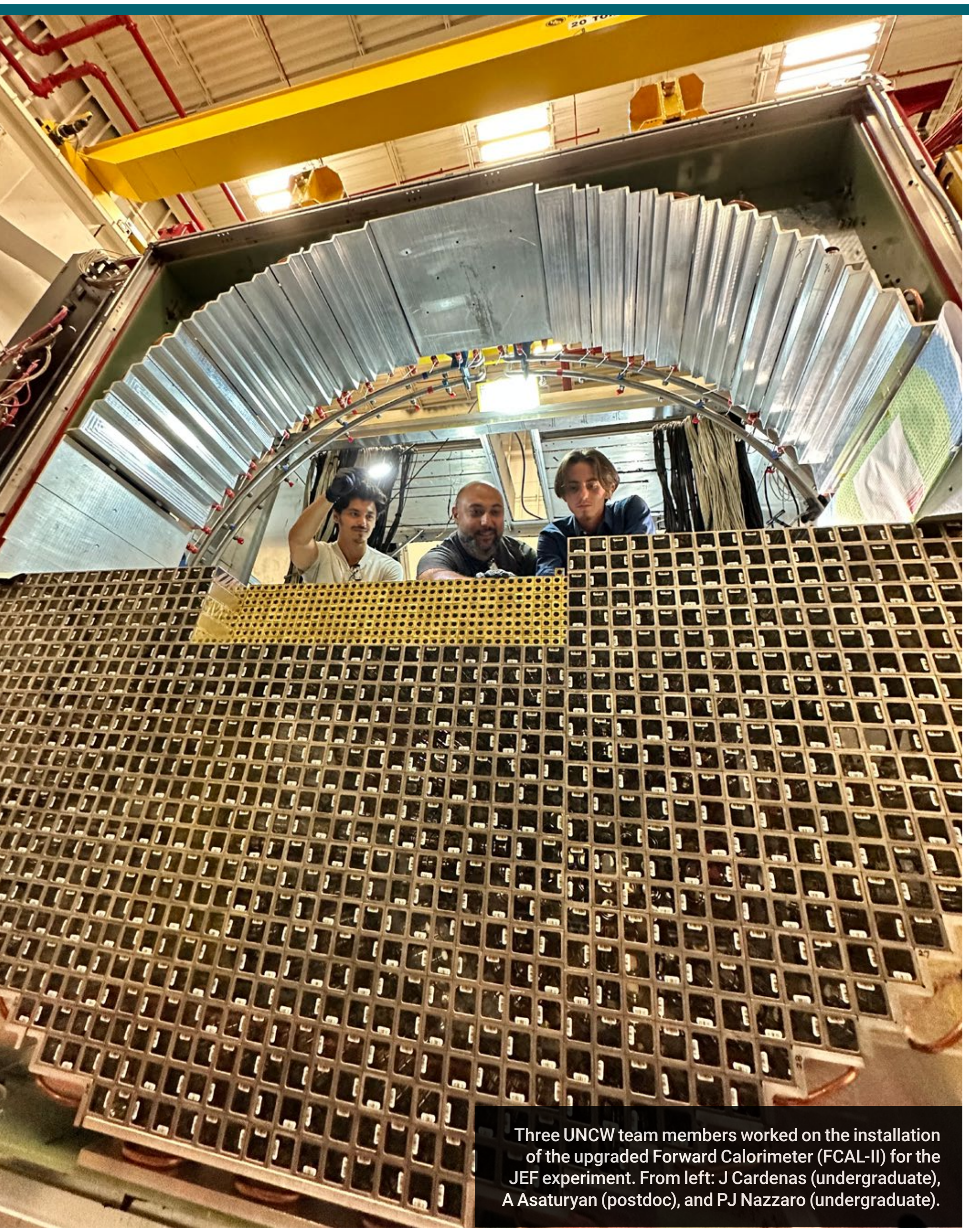
In the current standard model, there are six flavours of quarks, two in each of three increasingly heavy generations: up and down (from which neutrons and protons are made), strange and charmed, and top (sometimes described as truth) and bottom (alternatively termed beauty). The remaining constituent of the atom, the electron, belongs to the family of 'leptons' comprising electrons, muons, which are heavier than the electrons, and tau particles, which are also heavier, and their associated almost massless and chargeless neutrinos.

Quarks and leptons interact through bosons, which carry the fundamental forces: the electromagnetic force felt by charged particles, the weak force responsible for beta decay, and the strong force which holds particles together in the nucleus.

> **'One of the fundamental questions for our field is where the matter comes from and how it has evolved.'**



The standard model of elementary particles.



Three UNCW team members worked on the installation of the upgraded Forward Calorimeter (FCAL-II) for the JEF experiment. From left: J Cardenas (undergraduate), A Asaturyan (postdoc), and PJ Nazzaro (undergraduate).

A matter of confinement

The existence of quarks remains inferred, since they are confined to exist within protons, neutrons, and mesons. The theory of quantum chromodynamics (QCD) explains this confinement by dictating that, in addition to electrical charges, quarks also carry another type of charge termed 'colour' – a quark can have red, green, or blue colour charges, and an antiquark can have corresponding anti-colours – that must be combined to make white. Mesons, such as neutral pion (π^0) or eta (η), with just two quarks meet the requirements because they are comprised of a quark and an antiquark. In fact, the proton's three constituent quarks comprise barely 1% of the proton's mass; the rest comes from the energy-mass equivalence identified by Einstein. Amidst the strong interactions within the nucleus, quark and antiquark pairs are constantly popping into existence, although it is only in accelerator experiments that the quark-antiquark pairs that make up a meson are spotted outside a nucleus. 'One of the fundamental questions for our field is where the matter comes from and how it has evolved', Gan told the communications office of the Jefferson Lab, a national accelerator facility run by the Department of Energy where she has been leading a series of experiments.

As Gan points out in a review article, titled *Precision tests of fundamental physics with η and η′ mesons*, co-written with researchers Bastian Kubis at Universität Bonn in Germany, Emilie Passemar at Indiana University in the US, and Sean Tulin at York University in Canada, 'a parallel approach based on symmetries has largely shaped our understanding of QCD at low energies.' Symmetries identify conserved quantities – stand in a boundless empty space and you can move to the right or left without any perceptible change to your environment – it remains as if you hadn't moved at all because of the spatial symmetry of the space. The fundamental symmetries physicists identify in the interactions of basic particles, such as charge conjugation (C), parity (P), and time reversal (T), help them to define conserved quantities from which they can predict how they expect particles to behave. QCD has chiral symmetry at the massless quark limit, which means take something and its mirror image – some fundamental particle system equivalent of your left and right hand – and you can rotate the left-handed and right-handed components independently. It turns out that the interactions of pions (π) and eta (η) mesons are great tests of QCD calculations that hinge on chiral symmetry.

> **Experimental measurements of the π^0 lifetime with adequate precision were only recently made possible, thanks to the PrimEx collaboration.**

Standing the test

The first of Gan's targets at Jefferson Lab was the lifetime of the neutral pion, π^0. Chiral symmetry is broken by the QCD ground state – for instance as quarks and antiquarks pop up out of energy – and gives rise to π^0. An axial symmetry breaking, called 'chiral anomaly', shortens the lifetime of π^0, a rare but useful quantity that can be calculated from QCD accurately. Experimental measurements of the π^0 lifetime with adequate precision to compare with theory were only recently made possible, thanks to nuclear physicists from 16 national and international groups coming together to form the PrimEx collaboration. They are named after the Primakoff effect, where a photon from a beam collides with a photon from the charge field of a target nucleus to create a pion. They measured the pion lifetime at 83 quintillionths of a second with an uncertainty of just 1.5%, a convincing validation of theoretical calculations so far.

Next, Gan aims to measure the decay of eta (η) meson into two photons; she hopes this will wrestle with the discrepancy between collider measurements and previous Primakoff measurements. In addition, measurements of other η decay modes expected from the JLab Eta Factory (JEF) experiment later this year could shed light on many other fundamental queries in physics. Not only could it help further probe theories of chiral symmetry and QCD, but it may elucidate on possible gauge bosons that are candidate particles for explaining dark matter. With a future Jefferson Lab 22-GeV upgrade, plans for further π^0 experiments based on the Primakoff reaction off an electron target to achieve sub-percent precisions will test calculations based on fundamental symmetries, chiral symmetry in particular, in the hunt for new physics beyond the standard model.

Personal response

When did you first start to take an interest in the fundamental building blocks of the Universe?

When I was a middle school student, I was fascinated by some questions which I was not able to answer. I asked my science teacher if there is a limit to the space of the Universe. If yes, what are the things beyond the limit? I once raised a hen as a child. I noticed that a chicken can lay eggs and an egg can become a chicken. I wondered which one started the first, chicken or egg? To search for answers to questions, such as 'what are the fundamental building blocks of the universe?', I chose nuclear and particle physics as my major when I went to university.

What is the greatest challenge in making these high-precision measurements?

There are two types of uncertainties in the experimental measurements: one is systematic, and the other is statistical. The systematic uncertainty generally refers to uncertainty due to limitations in the measurement process or method. The greatest challenge in making high-precision measurements is to control the systematic uncertainty.

How did you feel when the results came through from the PrimEx collaboration giving the most precise measurement of the π^0 lifetime?

The π^0 lifetime is widely considered as one of the most important quantities to bridge our understanding of confinement QCD and the underlying chiral symmetry and symmetry breaking. To achieve a 1.5% precision of measurement, our collaboration performed two experiments (PrimEx I and II) and took about 20 years from the initial designing experiment, developing the experimental apparatus, data collection and analysis, to final publication. I felt that all those efforts had been finally paid off.

These experiments are incredibly expensive to run – why do you think they are important?

Scientific research will not only expand our knowledge of the physical world, but also advance the technology, which benefits the well-being of society. Though it is expensive to run experiments, it is important for us to invest in our future.

Professor Gan and a group of collaborators in the experimental Hall D at Jefferson Lab.

Details

Jeff P. Janowski, UNCW

e: ganl@uncw.edu
t: +1 901 962 3583

Funding

USA NSF awards PHY-1812396 and PHY-2111181

Collaborators

- The PrimEx collaboration
- The GlueX collaboration

Bio

Liping Gan is a Professor of Physics at the University of North Carolina Wilmington. Her current research interests focus on precision tests of low-energy quantum chromodynamics and searching for new physics beyond the standard model via the light meson decays.

Further reading

- Gan, L, et al, (2022) Precision tests of fundamental physics with η and η′ mesons, *Physics Reports*, 945, 1–105.
- Afansasev, A, et al, (2022) Proposal to PAC 50: Precision measurement of the neutral pion transition form factor [online] Jefferson Lab. www.jlab.org/exp_prog/proposals/22/PR12-22-003.pdf [Accessed 26/09/2023]
- Karter, C, (2020) Precise measurement of pions confirms understanding of fundamental symmetry [online] Jefferson Lab. www.jlab.org/news/stories/precise-measurement-pions-confirms-understanding-fundamental-symmetry [Accessed 26/09/2023]
- Gasparian, A, (2020) Precise measurement of pions confirms understanding of fundamental symmetry [online] U.S. Department of Energy. science.osti.gov/np/Highlights/2021/NP-2021-04-c [Accessed 26/09/2023]
- Larin, I, et al, (2020) Precision measurement of the neutral pion lifetime, *Science*, 368(6490), 506–509.
- Ghoul, H A, et al, (2017) Update to the JEF proposal (PR12-14-004) [online] Jefferson Lab. www.jlab.org/exp_prog/proposals/17/C12-14-004.pdf [Accessed 26/09/2023]
- Gasparian, A, et al, (2009) A Precision Measurement of the η Radiative Decay Width via the Primakoff Effect [online] Jefferson Lab. www.jlab.org/exp_prog/proposals/10/PR12-10-011.pdf [Accessed 26/09/2023]