Robert Craig Group

Research Statement

What are the most fundamental pieces of our Universe? What are their properties and how do they interact with each other to form the Universe and the phenomena we observe?

Answering these questions is the goal of experimental particle physics. In this field, large accelerators are used to force particles to collide and complex detectors are used to study the results of these collisions. Higher energy collisions make it possible to produce and study the properties of heavier particles in the lab. In addition to high energies, high-intensity beams can be used to discover and study rare processes. Major progress has been made in this field in the last 50 years toward composing a "standard model" (SM) of particle physics. Although this model is capable of describing nearly all observed phenomena, there are many questions left to answer.

Recently, our field answered a major question: in the SM the particles are allowed to carry mass due to the Higgs mechanism. In this model, masses are generated through the mechanism of spontaneous symmetry breaking of the electroweak force by the Higgs field. In addition to the field, the theory requires a massive particle called the Higgs boson. In the summer of 2012 a particle consistent with the Higgs boson was discovered at the Large Hadron Collide (LHC) in Europe.

At the time the LHC discovery was taking place, I was serving as the co-convener of the group searching for the Higgs boson at the CDF experiment. CDF was a major particle physics experiment utilizing the Fermilab Tevatron collider with approximately 500 scientists from 50 institutions. The Higgs boson search was an extremely high-profile effort with 10 or more active search analyses and close to 100 scientists and students actively involved. During my convenership we incorporated the full CDF data set and combined all of these searches into a single result. The summer of 2012 was a very exciting time for our effort and **the combination of our results with the other Tevatron experiment (D0) resulted in evidence for a particle consistent with the Higgs boson**. This result was concurrent and complimentary to the LHC discovery, it has been highly cited, and it provides evidence of a process that the LHC didn't see until 2017.

The Top quark is the heaviest of the known fundamental particles and it requires the high energies of the Tevatron or LHC colliders to study its properties. It was discovered at the Tevatron in 1995 in a process in which it was produced in pairs via the strong force. **Fourteen years later I was a leader of the group on the CDF experiment that first observed a second process in which the Top quark is produced singly via the weak force**. In one of the final impactful measurements from the Tevatron, my graduate student, Hao Liu, drove the effort that lead to the first observation of an even more rare single-top production process (s-channel production). **I mentored Hao on this project, I coordinated the combination effort with the D0 experiment, and I was a primary author of both the CDF and the Tevatron papers that reported this observation**. Hao Liu, my first UVA student, graduated in 2014 based on this observation and his contributions to the Higgs boson search at the Tevatron.

Interesting questions also remain in neutrino physics. The mass ordering of the neutrino mass eigenstates is unknown. That is, if we consider the mass state that is predominantly composed of the electron neutrino, we do not yet know if this is the lightest mass state (the normal case), or if it is actually heavier than the state with the smallest component of electron neutrino (the inverted case). Another important question regards the CP-violating phase in the neutrino mass mixing matrix. We don't yet know if this phase is non zero, and if it is non zero we don't know if it is large enough to play an important role in the development of the matter/antimatter asymmetry of the universe. Recently, due to precise measurements of θ_{13}, θ_{23} has become the least precisely known mixing angle. The NOνA experiment is shedding light on all of these interesting unknowns.

The NOνA far detector is finely-instrumented and large (14,000 tons). Early in data taking, our group at UVA investigated the possibility to use this unique tool to answer physics questions that are outside of the realm of standard neutrino measurements. For example, **my group took on the leading role in implementing a trigger for upward-going muons. This new trigger opened the door to the possibility of using the NOνA far detector for several new programs of physics**. For example, my former student, Cristiana Principato, used the NOvA detector as a telescope to search for signs of dark matter particles interacting with each other at the core of our Sun, and successfully defended her Ph.D. thesis in 2021.

In order to improve the understanding of the NOvA detector, a smaller version of the detector was placed in a beam of known particles at Fermilab. **My students, Anna Hall and Andrew Sutton, played leading rolls on the test-beam experiment at Fermilab**. In fact, Andrew Sutton received a prestigious Graduate Student Fellowship (SCGSR) from the DOE with full financial support to work on the test-beam for one full year. His contributions were critical in getting the test beam experiment commissioned and understanding the data. Analysis is ongoing and results from the test-beam will provide important constraints that will improve NOvA's final results.

More recently, our group has focused on the core neutrino measurements that NOvA was designed for. **My student, Andrew Sutton, implemented a new machine learning technique called domain generalization that is designed to minimize the effect of systematic uncertainties on the measured results**. He successfully defended his thesis in 2022. Another student, Anna Hall, is working on a data-driven method to use muon-removed events from data to study the electromagnetic shower produced through bremstraulung or muon decay in flight. Through these methods she hopes to constrain the uncertainties on our electron ID tools that are critical for the flagship $\nu_\mu \to \nu_e$ measurements.

Now, even though the Higgs boson has been discovered and the Top quark has been carefully probed at the Tevatron and the LHC, questions still remain. Astronomers observe an unknown source of matter through observations of galaxies and clusters of galaxies that cannot be explained by the SM. It is possible that the particles making up this 'dark' matter could also be produced via the collisions of high-energy particles and studied at the LHC. If not, then perhaps we can observe these particles using intense beams rather than the high-energy beam of the LHC. For example, maybe these particles could be discovered with intense beams in fixed-target experiments or the effects of the interactions of these particles could cause deviations from the rates expected for other SM processes, thereby yielding indirect evidence of their existence through precision measurements.

Since 2009 I have been on the Mu2e experiment, an approved experiment that will search for the conversion of a muon into an electron in the presence of a nucleus. This process is unobservable in the SM, but many extensions to the SM include charged-lepton-flavor-violating interactions that would force this process to occur at a much higher rate. For example, many supersymmetric theories provide a candidate for the mysterious dark matter, but also include lepton-flavor-violating interactions that could lead to a signal at Mu2e. An observation of this reaction would be an absolute sign of physics beyond the SM.

One process that can fake the Mu2e signal is caused by cosmic ray muons. Our group at UVA is played the leading role in the design of an apparatus that will surround the Mu2e experiment and veto these events. **For the last 8 years I have served as the level−3 project manager for the fabrication of this critical veto system**. My duties include estimating the cost, understanding and testing the design, designing the fabrication factory, and managing all aspects of the fabrication and testing effort. The cosmic ray veto (CRV) system is a major project (∼$10M) and we are building it here at UVA in the HEP lab at UVA.

CRV fabrication started in 2018 and this has been my primary research focus since my last promotion. **I have lead two technicians, three post-docs, 5 graduate students, and over 30 undergraduate students on this fabrication since we started building the detector**. There have been many challenges along the way: the stress of the first few detectors, my brain tumor, many COVID-related issues, several large purchases, and turnover in personell - just to name a few. But, we have still been successful, and completed about 85% of this project. I'm proud that the 68 (out of 83) large detector modules that we produced have all performed at the required level, and no major issues have been discovered with any of the modules. We are on pace to finish fabrication in early 2023, well in advance of data taking. Mu2e plans to improve sensitivity in the mu-to-e conversion channel by 4 orders of magnitude and this provides a great possibility for a major fundamental physics discovery this decade. We fabricated the largest part of the Mu2e detector system right here at UVA, and are looking forward to running the experiment!

Most recently I have begun to shift my attention to a new effort dedicated to the search for Dark Matter. **I am the principal investigator for our group's contribution to the Light Dark Matter eXperiment, LDMX**. The mass and particle nature of dark matter is almost completely unknown. If one assumes that the dark matter was in thermal equilibrium in the early universe (the SM particles were, so maybe this is a reasonable assumption), then the mass can be constrained to a much smaller range. The range of a GeV and above has been the focus of most efforts and strong constraints have been placed on the dark matter in this range. Modules with masses between about 1 MeV and 1 GeV are less constrained and LDMX plans to provide 2 orders-of-magnitude improvement in sensitivity compared to current results in this mass range. LDMX will use an electron beam on a fixed target and look for a signature where the electron loses most of its energy in the target and no other SM particles are produced. If we observe this we can infer that an extra particle was produced that escaped detection. In order to make sure no SM particles were produced, a large hadronic calorimeter must be designed which has a high efficiency for detecting SM particles. Our major hardware contribution to LDMX will be to fabricate this hadronic calorimeter here at UVA. The design uses similar detector components to the Mu2e CRV, and we are experts in building such detectors.

Since my last promotion, my focus has been: getting physics results, Ph.D. theses, and papers out of the NOvA experiment; building the Mu2e cosmic ray veto and writing technical papers related to the fabrication effort; and planning the LDMX experiment. For the next five years my group will wrap up our work on NOvA, finish fabrication of the CRV, commission the Mu2e experiment, and start to produce physics results on Mu2e, and we will work to get LDMX approved and build the experiment. The plan beyond that time scale is naturally a little more vague, but I've been involved in efforts to plan a higher-intensity upgrade to the Mu2e experiment and I'm keeping my eye out for other long-term opportunities. Certainly, I will continue to build on my connections at Fermilab and make large contributions to the US particle physics program for decades to come.

Due to the abundant possibility for discovery, these are truly exciting times to be a particle physicist! As a young physicist I had the pleasure of making contributions to several important measurements at the Tevatron before I transitioned to leadership positions on the NOνA and Mu2e experiments. Most recently, I have taken a leading roll on the LDMX experiment. I look forward to the future of these three experiments with the expectation of exciting discoveries!