Session S Abstracts

Modeling Interactions of Squeezing With the Laser Interferometer Gravitational Wave Observatory at High Frequencies to Improve Sensitivity
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Mentors: Lee McCuller and Sander Vermeulen

The Laser Interferometer Gravitational Wave Observatory (LIGO) uses quantum squeezing to improve its measurement precision. However, this squeezing is degraded upon interactions with the optical components of the interferometer (IFO). This is true especially at high frequencies where the interferometer response to the squeezed state is poorly understood. In this project, we use a simulation package called Finesse to examine how squeezing interacts with the aLIGO interferometers at high frequencies. We use non-vacuum sidebands to simulate what happens to squeezed light. By comparing the modeled IFO response to squeezed light to real data on the quantum noise at high frequencies, we will be able to gain understanding about the mode matching of the arm cavities among other things. This will allow for diagnostics of the issues that limit aLIGO's sensitivity in the signal band where it is operated.

Anomalous Hall Crystal Hosts
Avi Vadali
Mentors: Ashvin Vishwanath, Xie Chen, Tomohiro Soejima, and Junkai Dong

Within two-dimensional systems of charged particles, the quantization of the system's resistance is a well-known phenomenon and is attributed to the quantum Hall effect (QHE). The QHE conventionally quantizes resistance in the presence of an external magnetic field; however, resistance quantization has been observed in the absence of an external field. This phenomenon is called the quantum anomalous Hall effect (QAHE), and it is a result of the topological properties of the system's energy band structure. Recent experiments have observed the quantum anomalous Hall states in rhombohedral pentalayer graphene in the absence of a moiré potential. Such a state is called the anomalous Hall crystal (AHC), and it is a many-body electron state spontaneously breaking time-reversal symmetry and translation symmetry.

We investigate several platforms potentially capable of hosting AHC states including rhombohedral multilayer graphene, surface states of 3D topological insulators, and a simplified model with highly concentrated Berry curvature. We aim to elucidate the physical mechanism behind the spontaneous crystallization and time-reversal symmetry breaking characterizing anomalous Hall crystals.

A Model for the Chemical Kinetics of Cold, Gas-Phase Alkaline-Earth Monofluorides in a Cryogenic Buffer Gas Cell
Adele M. Basturk
Mentors: Nick Hutzler and Phelan Yu

Understanding the chemical yield and stability of the processes inside a CBGC is critical in the design of brighter and colder molecular beams, which serve as the starting point for molecule laser cooling and precision measurement experiments. We model the chemical kinetics of alkaline-earth monofluorides, such as calcium monofluoride (CaF), produced in the gas phase within a cryogenic buffer gas cell (CBGC) with a set of 5-dimensional temporal differential equations. We solve the resulting set of equations numerically by utilizing a 4th-order classical Runge-Kutta (CRK) time-stepping. We study how the interspecies and intraspecies rate constants depend on temperature with the classical Langevin capture model, appropriate for temperature on the order of 0.1K - 10K. Further, we model the effect of helium density on the rate constants of third-body mediated reactions, such as the formation of calcium dimers and difluorides. Finally, we solve the equations for varying sets of initial fractional state populations at a fixed temperature, volume, and helium density to understand how the alkaline-earth monofluoride loss timescale depends on the chemical composition of the constituents inside the cell. From this, we learn that high neutral fluoride and difluoride concentrations lead to the shortest loss time scale.

Construction and Testing of a Galvo-Based Single Mode Fiber Switcher
Anya Mischel
Mentors: Nick Hutzler, Phelan Yu, and Madison Howard

The failure of the Standard Model to explain the cosmologically observed matter-antimatter asymmetry is a longstanding problem in fundamental physics. Experimental searches for charge parity (CP) symmetry-violating shifts in the spectra of cold molecules under laboratory magnetic and electric fields could shed light on the physical mechanisms that created this imbalance. A technical challenge in these precision experiments is the large number of independent laser frequencies needed to address the internal quantum states of the science molecule. In the most advanced cold molecular experiments, over a dozen laser frequencies can be needed to achieve full quantum control, with individual wavelengths spanning hundreds of nanometers. Monitoring and controlling these frequencies requires fast and scalable single-mode fiber switches; however, most off-the-shelf, commercially available systems are both limited in number of input sources (<= 8 channels) and have limited wavelength operating ranges. To remove these limitations, I constructed and tested a 2D galvo-based single mode fiber switcher that leverages the flexibility of free-space fiber optical coupling. Through the construction phase, I 3D printed, machined, and soldered a protective container for the galvo's power supply unit, assembled the optics for the input laser sources, and modified the galvo's controller software to correctly move to the desired locations of the input sources. This galvo setup is able to be expanded to any number of mirrors and will be helpful in improving the range and scalability of current optical setups.

Symmetry Reduction and Truncation Techniques in Quantum Spin Systems
Constantin J. Cedillo-Vayson de Pradenne
Mentors: Efthimios Kaxiras and Xie Chen

This research investigates the Heisenberg model on 2D hexagonal lattices through the method of exact diagonalization and group convolutional neural networks, leveraging the symmetries of the model to significantly reduce the computational overhead associated with large-scale quantum many-body systems. In parallel, we implement truncation methods that selectively exclude states that minimally contribute to lowering the system's energy. While this truncation alters the structural integrity of the wavefunction, the energy remains relatively unaffected, owing to the stability granted by the variational principle. However, such approximations introduce subtle distortions in the wavefunction, which manifest in observables that are sensitive to the underlying structure, such as spin-spin correlations. By investigating these correlations, we assess the fidelity of our approximations and ensure that the physical properties of the system are preserved. This combination of symmetry exploitation and state truncation allows us to extend our analysis to larger lattice sizes, offering deeper insights into the behavior of quantum spin systems and the inherent correlations within the Heisenberg model.

Supersymmetric Wormhole Teleportation
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Mentors: Joseph Lykken and Maria Spiropulu

Our research extends previous work on simulating supersymmetric quantum mechanics to super- symmetric field theory. Beginning with a 1D Kitaev model as a warm-up, where we use Majorana fermions to perform an energy spectrum and entanglement power analysis, we further extend the Gao-Jafferis protocol for wormhole teleportation between copies of supersymmetric SYK models. We show in finite-N simulations that the supersymmetric SYKs exhibit signature holographic features of wormhole teleportation, including those related to size winding. In particular, the analysis indicates superior teleportation as compared to that of the non-supersymmetric original. This work represents a first step in incorporating supersymmetry into the "quantum gravity in the lab" program.

Increasing the Light Output of Extruded Polystyrene Scintillator Bars
Victor Gomez
Mentors: David Hitlin and James Oyang

The Light Dark Matter eXperiment (LDMX) is designed to probe the lower thermal mass range (~ MeV to GeV) for dark matter particles. Dark matter could present itself as missing momentum carried away by the non-interacting dark matter particle. In LDMX, high-energy electrons are fired at a target and scatter. The energy and angle of all the outgoing radiation products are measured to find a missing momentum caused by the non-interacting dark matter. One component necessary in doing so is a hadron calorimeter (HCal), composed of alternating layers of steel absorber and POPOP-doped polystyrene scintillator bars with a wavelength-shifting fiber passing through the center. The polystyrene bars are produced at Fermilab by co-extruding with a TiO_2 coating. However, measurements of the TiO_2 reflectance show a drop-off across the POPOP emission spectrum. This motivates using a $BaSO_4$ reflective coating which maintains a high reflectance throughout the POPOP emission spectrum. Furthermore, the transmission of the polystyrene pellets currently used at Fermilab has been measured to be poor when compared to polystyrene pellets produced by the Taita Chemical Company. From initial Monte-Carlo simulations, it has been shown that making these two changes promises a 4-times improvement in the photoelectron yield per scintillation event.

Understanding the Light Dark Matter eXperiment's Sensitivity to Visibly Decaying Axion-Like Particles
Nathan Jay
Mentors: David Hitlin and Sophie Middleton

The proposed Light Dark Matter eXperiment (LDMX) will probe the MeV to GeV range in the search for dark matter, using the missing momentum approach. LDMX is theorized to be sensitive to axion-like particles (ALPs), but it must be shown that these particles can be discriminated against from the background. This project simulates photon-coupled ALPs and a photo nuclear background that originates from the electromagnetic calorimeter. Then, we utilize LDMX simulation software to reconstruct the generated samples. After determination of features that can discriminate between signal and background, a boosted decision tree is trained to separate ALP decay events.

Optimizing the input variables will improve the model, working towards the eventual goal of obtaining a sensitivity estimate for these samples of ALPs.

Search for Long-Lived Particles With HCAL Segmentation in CMS at the Large Hadron Collider
Katherine Avanesov
Mentors: Harvey Newman and Kiley Kennedy

Long-Lived Particles (LLPs), defined as particles with lifetimes greater than 0.1 nanoseconds, are predicted by both the Standard Model (SM) and many Beyond the Standard Model (BSM) theories, including those addressing dark matter, the matter-antimatter asymmetry in the universe, and supersymmetry. We search for the Higgs boson decay to a pair of such hypothesized heavy particles which subsequently decay to two pairs of bottom quark-antiquark jets H —> ss —> $b\bar{b}b\bar{b}$. The analysis exploits the new depth segmentation upgrade of the Compact Muon Solenoid (CMS) Hadronic Calorimeter (HCAL) to target the characteristic topology of a jet-cluster from an LLP that decays inside the HCAL and therefore whose decay vertex is displaced from the central beam line. Using Monte Carlo-generated signal samples against a W+ jet background, we develop and compare the performances of various neural network (NN)-based classifiers. Among the explored architectures, we produce 3D convolutional neural networks (CNN) trained on images of the jet energy distribution across the HCAL depth-layers and in eta-phi space. This motivates the use of Gradient-weighted Class Activation Mapping (GradCAM) to gain insight into the features learned by the CNN and to evaluate the reliability of the model.

Optimization of Programmable Computer Networks Using Machine Learning
Pranit Gunjal
Mentors: Harvey Newman and Mariam Kiran

The largest scientific programs, such as the Large Hadron Collider, face the challenges of distributing exabytes of data per year among hundreds of sites throughout the world where it can be processed and collaboratively analyzed, on the road to the next round of discoveries. The challenges continue to grow as the data volumes generated and expand by an order of magnitude every few years and are projected to match and soon outstrip the available capacity of the world's research and education networks, which must also support the network traffic on which the at-large academic and research communities rely. There is therefore a clear need for low-latency networks that can distribute the data as effectively as possible, coordinating the use of the available network resources with the computing and storage resources at the various sites, and responding dynamically to a "river" of requests, taking priorities and policies, fair sharing among different programs, approaching deadlines and other constraints into account while seeking an effective operational optimum. With the advent of the P4 language and programmable networks, engineers can now control how networks respond, learn to intervene, and optimize their behavior to make them more efficient and responsive to the needs. The goal of this study is to determine if a reinforcement learning strategy can enable an agent to route flows through a complex network topology in the most optimal way. The methods developed will aim to deal with simulated traffic surges by delaying the queues on certain switches. To simulate the disabling of routes, manual intervention will be done to simulate a route being disabled.

Rotational Diffusion of Dipole Emitters: Improving Accuracy via Physical Theory and Computational Imaging
Erik Lindeman
Mentors: Matthew Lew and Sunil Golwala

Using fluorescent molecules, super-resolution fluorescence microscopy allows for nano-scale-precision measurements; it has invaluable applications in fields such as biophysics and material science. However, the precision of measurements is limited by the finite number of fluorescent photons emitted since observations are subject to Poisson shot noise. This issue can be mitigated by modifying the optical elements used to image the dipole (i.e., fluorescent molecule). One such optical element is the phase mask, which applies a position-dependent phase-shift to the collected fluorescence before it is focused onto a detector. Moving beyond fixed imaging systems, we propose an adaptive approach, whereby two different phase masks are used during a single image acquisition, to measure a dipole’s rotational diffusion during the acquisition. Monte Carlo simulations show that this two-mask technique (TMT) leads to 25% or higher improvement in measurement precision for some dipole orientations over standard fixed imaging systems. Our methods therefore improve precision of rotational mobility measurements where it is possible to image dipoles on an individual basis, allowing for more insight into the molecules or system being studied. We demonstrate the improved performance of the TMT by imaging fluorescent markers attached to glass in both air and within a polymer film.