Caltech
Student-Faculty Programs

Session U Abstracts

Machine learning-driven waveform reconstruction and split-off recovery for the Mu2e electromagnetic calorimeter

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Mentors: Bertrand Echenard and David G. Hitlin

The Mu2e experiment aims to observe the neutrinoless conversion of a muon to an electron. Its electromagnetic calorimeter is vital for isolating the 104.967 MeV signal from background events, but high-luminosity environments create spatial and temporal pile-ups that degrade energy resolution which current extraction methods struggle to resolve. In this project, I developed a dual-head Temporal Convolutional Network (TCN) to optimize waveform digitization and split-off cluster recovery. Optimized via a composite loss function, the model jointly predicts energy amplitudes and per-tick peak-probability heatmaps. During the peak extraction step, max-pool Non-Maximum Suppression was applied to isolate discrete signal hits by filtering out adjacent, non-maximum values. Results demonstrate that the TCN successfully deconvolves temporal pile-up, offering a robust, automated foundation for split-off reconstruction.

Timing information for background rejection in a muon missing-momentum search

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A muon-beam missing-momentum search for an invisibly decaying dark photon A′ must reject reducible backgrounds at the 10−7 level. We study what detector information that rejection requires in an idealized Geant4 simulation of a 5 GeV/c μ− beam on an active LYSO target read out with electromagnetic, downstream hadronic, and side hadronic calorimeters. A graph neural network over a 625-node representation of the four subdetectors, reading energy and position only, leaves a mean of 5.6 background events at 90% matched fired-signal efficiency in a 5.0×107-muon benchmark, with strong seed-to-seed variation. That residual is entirely muon-nuclear: 12 unique events, every one carrying a neutron at the target exit. Adding two per-node timing observables (the energy-weighted mean deposit delay and its temporal RMS) to an otherwise identical network lowers the residual in four of five seeds and ties in the fifth; the mean falls from 5.6 to 1.6 events, and ten of the twelve disappear entirely. Under Gaussian smearing of the deposit times from 100 ps to 50 ns the mean residual stays between 1.2 and 2.2 throughout, so the effect does not depend on exact simulation timestamps. Because a real channel does not resolve individual deposits, this demonstrates robustness of the temporal information, not a hardware requirement; a pulse-level detector-response model and hadronic-model validation remain necessary before any detector-performance reading.

Performance evaluation of a Kinetic Inductance Traveling Wave Parametric Amplifier

Clayton G. Bishop
Mentor: Sunil Golwala

For the continued search for dark matter (DM), low-temperature phonon detectors are a promising technology for probing the sub-GeV DM parameter space. Kinetic Inductance Detectors (KID) are sensitive to energy depositions in a substrate through athermal phonons generated by a potential interaction. Kinetic Inductance Traveling Wave Parametric Amplifiers (KI-TWPA) improve energy resolution through their high gain and nearly quantum-limited noise, thereby maximizing the signal-to-noise ratio. In this work, we outfitted a dilution refrigerator with proper components to operate a KID and KI-TWPA. After cooling down, we measured the gain and bandwidth of the parametric amplifier and determined its added noise using the Y-factor method.

Confirming functionality of a single pixel bolometer for use in shearing interferometry
Ian J. Chang
Mentor: Sunil Golwala

Over this presentation, I tested the functionality of a bolometer that would be used to measure the uniformity of the surface of the Leighton Chajnantor Telescope using a tactic called shearing interferometry. I first go over the background of the telescope and shearing interferometry, which requires a single pixel bolometer and mirrors. I then describe the structure of the bolometer and its surrounding dewar, which was built to use liquid helium to keep the bolometer at a temperature under 1 kelvin. I go over the tests that I ran on testing the functionality of the dewar and its ability to cool the bolometer for an extended period of time. I first start with testing the dewar's ability to hold vacuum, necessary to thermally isolate the bolometer and the cold liquid nitrogen and helium inside the dewar. I then test the behavior of the dewar under liquid nitrogen, and I finally go over the response of the dewar under operating conditions, with liquid nitrogen and helium in separate tanks to create a cryogenic environment to sufficiently cool the bolometer. I go over the results of the tests, and look ahead towards how the bolometer will be used to help the construction of the Leighton Chajnantor Telescope in Chile.

Improving the sensitivity of NEMS resonators for mass and optical sensing
Ron A. Freeman
Mentor: Michael L. Roukes

Nanomechanical (NEMS) resonators achieve ultra-high sensitivity sensing by translating small shifts in resonator parameters like mass or temperature to shifts in resonant frequency. These systems have been developed for well over a decade and offer promising applications from massively parallel proteomics with single molecule resolution to a new class of uncooled, optomechanical IR detectors. However, they suffer from anomalous phase noise (APN) that limits ultimate detector sensitivity to orders of magnitude higher than the thermomechanical limit. Here, we present a holistic full system approach to characterizing, understanding and designing around APN. On the device side, we use theoretical modeling, and simulation to develop design intuition resulting in novel device design and a planned test campaign to understand and bound APN sources in silicon doubly clamped beam resonators. On the hardware side, we construct a dark port interferometer to drive readout noise to a minimum and implement real-time computational techniques to dynamically cancel noise processes.

Engineering explosive synchronization in an 8-node NEMS oscillator network
Alice T. Wang
Mentors: Michael L. Roukes and Scott T. Habermehl

Explosive synchronization, which occurs when all nodes in a coupled oscillator network synchronize suddenly at a critical coupling strength, is theorized to be an important mechanism for neural communication. We aim to demonstrate explosive synchronization experimentally using an 8-node NEMS network. We first analyze phase transitions produced by uniform frequency distributions in numerical simulations and experiments on the NEMS network, and find that hysteresis reflects the presence of multi-stable states, with the presence of "cluster states" occurring as a finite size effect. Using numerical simulations, we further determine that explosive synchronization could be produced by frequency-weighting of coupling strength or correlating intrinsic frequencies with coupling topologies in sparse Erdos-Renyi random graphs. We find that although explosive synchronization is guaranteed only in the continuum limit, it could be implemented in a small-node experiment using specific network topologies in the low frequency limit. Our results represent a step forward towards improved analog reservoir computing with NEMS.

Study of signal response of SMSPDs exposed to high energy ionizing radiation
Cecilia I. Moxley
Mentors: Maria Spiropulu and Soham Bhattacharya

Superconductive nanowire single photon detectors (SNSPDs) are used to detect photons; they have very low noise and fast signals, which can be useful for precision timing detectors for high energy particles. However the exact mechanisms triggering the detection on the atomic scale have not been proven yet for high energy charged particles. The SNSPD is simulated in Geant4 to obtain data on the interactions. The simulation models a 3nm layer of WSi(the wire), a 0.2mm layer of SiO2 substrate and a 0.3mm layer of aSi substrate. A 120 GeV proton is shot at the WSi. Our preliminary results suggest the proton creates cerenkov photons in the substrates. The different variations of optical properties show that 20%-60% of the simulations will have photons reflected to the WSI and absorbed there, depositing 1-6eV. The proton deposits 2.27eV in the wire 99% of the time, suggesting that it alone is not the source of the signal. This project studies the sensitivity of the photon deposits to different properties of the materials which can differ at cryogenic temperatures, in comparison to reported values in literature at higher temperatures.

High-dimensional communication via continuous wave lasers
Elizabeth C. Ellison
Mentors: Maria Spiropulu and Raju Valivarthi

High-dimensional quantum entanglement allows for denser information storage in quantum communication by utilizing a larger Hilbert space. Experimental implementations are severely impacted by channel loss, detector limitations, and system noise, which result in loss of information. In our work, we demonstrate long-distance distribution of high-dimensional time-bin entanglement with a continuous-wave laser that creates entanglement via spontaneous parametric down-conversion (SPDC) and unbalanced interferometers. The entangled photons were transmitted up to 200 km. This transmission was then improved by optimizing pair generation rate, dimension measured, and detector settings. The optimization showed ideal operational regimes that varied based on system loss. The results demonstrate long-distance high-dimensional entanglement distribution that is effective in realistic high-loss systems.

Long-distance time-bin entanglement distribution using dispersion compensation
Raghava K. Kalidindi
Mentors: Maria Spiropulu and Raju Valivarthi

Quantum key distribution (QKD) relies on the faithful transmission of entangled photons over long distances, where chromatic dispersion in optical fiber degrades temporal indistinguishability, reduces quantum interference, and limits secure key generation. This work investigates dispersion compensation for high-rate time-bin entangled photon sources as a means of preserving entanglement quality over long fiber links. Building upon previous classical-light characterization of a tunable dispersion compensator, coherent pulses were first used to calibrate optimal compensation settings before extending the study to pulsed and continuous-wave time-bin entangled photon sources. Entanglement visibility, coincidence rates, and Hong-Ou-Mandel (HOM) interference measurements were used to quantify the effectiveness of both local and nonlocal dispersion compensation over fiber lengths ranging from 50 to 200 km. The performance of the two compensation strategies was compared to determine their ability to restore temporal indistinguishability and preserve quantum interference after long-distance transmission. The results provide insight into the relationship between chromatic dispersion, photon indistinguishability, and QKD performance, while identifying practical operating conditions for high-rate entanglement distribution in fiber-based quantum communication systems. These findings contribute toward the development of scalable long-distance quantum networks and represent an important step toward realizing a functional quantum internet.