Session R Abstracts

Energy scale of sphalerons
Pritvik Sinhadc
Mentor: Harvey B. Newman

Sphalerons are unstable, static, finite-energy solutions of classical field equations that facilitate baryon and lepton number-violating transitions, making them essential in the context of electroweak theory, symmetry breaking, and baryogenesis. These non-perturbative topological field configurations, if experimentally confirmed, could provide critical insights into the matter-antimatter asymmetry in the universe and offer direct phenomenological evidence for Beyond Standard Model (BSM) physics. Current estimates place the sphaleron energy barrier height between 9 and 20 TeV, but there remains uncertainty due to higher-order electroweak corrections, the influence of the Higgs potential, and thermal effects. This research refines these theoretical estimates, develops collider-search strategies, and assesses the feasibility of detecting sphalerons at high-energy colliders such as the Large Hadron Collider (LHC), High Luminosity LHC (HL-LHC), and the Future Circular Collider (FCC-hh). The project, therefore, integrates advanced Monte Carlo simulations, Bayesian inference methods, LHC Run 2 and Run 3 datasets to probe potential sphaleron-induced signatures, thereby setting upper limits on their production cross-section. The research also involves event reconstruction techniques using BaryoGEN, HERBVI, HERWIG, and Pythia to differentiate sphaleron-like events from Standard Model backgrounds, applying deep learning classifiers and jet substructure analysis. Further, sensitivity projections for next-generation colliders are generated, evaluating the required energy thresholds and luminosity constraints for sphaleron discovery. A novel aspect of this research is the exploration of sphaleron transitions in modified electroweak scenarios, including their connection to topological defects and gravitational waves from first-order phase transitions, which may be detectable by Laser Interferometer Space Antenna (LISA) and pulsar timing arrays. If sphalerons are confirmed experimentally, this would possibly be a landmark discovery in particle physics, showing evidence for electroweak baryogenesis and potential modifications to the Higgs field dynamics. In the absence of positive detection, the results from this research would still yield crucial constraints on sphaleron physics, shaping future experimental searches and theoretical refinements in high-energy physics. By integrating collider phenomenology with computational modeling as well as early-universe constraints, this research definitely establishes a comprehensive framework for sphaleron detection and characterization, guiding future searches for non-perturbative electroweak processes.

Developing photon reconstruction algorithm for the muon collider
Alyna X. Tang
Mentors: Harvey B. Newman and Kiley E. Kennedy

The discovery of the Higgs boson in 2012 confirmed the mechanism of spontaneous symmetry breaking in the Standard Model, but the detailed shape of the Higgs potential—particularly near its minimum—remains unknown, motivating the need for a future high-energy collider. One leading candidate is the muon collider, which offers clean collisions at multi-TeV energies. However, muons are unstable and decay into electrons and positrons that initiate electromagnetic showers upon interacting with collider materials, generating severe beam-induced background (BIB) that floods detectors with out-of-time noise. In this challenging environment, precision photon reconstruction is essential for measuring key Higgs decay channels and enabling searches for new physics involving photon-rich final states. Using simulated photon-gun samples with and without BIB, we analyzed energy deposition in the electromagnetic calorimeter by studying the longitudinal and transverse development of electromagnetic showers, as well as hit timing distributions across calorimeter cells from both signal and BIB. Based on these insights, we developed a photon reconstruction algorithm designed for the muon collider environment, combining spatial clustering, timing cuts, and additional mitigation strategies to suppress BIB and enhance reconstruction performance.

Search for long-lived particles with HCAL segmentation in CMS at the Large Hadron Collider
Katherine A. Avanesov
Mentors: Harvey B. Newman and Kiley E. Kennedy

A search for long-lived particles (LLPs) with lifetimes greater than 0.1 ns is presented, using data from the Compact Muon Solenoid (CMS) experiment. Such particles are predicted by various theories beyond the Standard Model (BSM) that address phenomena such as dark matter and supersymmetry. The search targets Higgs boson decays to a pair of massive LLPs (X), which subsequently decay to a final state with two bottom quark- antiquark pairs: H —> XX —> bbbb The analysis utilizes the depth segmentation of the CMS Hadronic Calorimeter (HCAL) to identify the distinct topology of LLPs decaying within its volume. Two neural network (NN) classifiers are employed: a "depth" tagger, which uses information on the jet's decay depth in the calorimeter, and an "inclusive" tagger, which does not. This paper optimizes the signal region for an "asymmetric double-tag" strategy that requires at least one LLP to decay in the HCAL. Thresholds on the depth and inclusive scores are chosen to maximize statistical significance. We find that signal events for different LLP mass points populate distinct regions of the score space, favoring either high depth and low inclusive scores, or vice versa. Further investigation focuses on defining a unified optimal signal region boundary.

Photon pointing at a muon collider using 3D ECAL segmentation and machine learning
Medha S. Ravi
Mentors: Harvey B. Newman and Kiley E. Kennedy

In high-energy muon colliders, precision reconstruction of final-state particles is essential for disentangling new physics from beam-induced background (BIB). One of the most critical and challenging final-state objects is the photon, especially in the context of precision Higgs boson measurements such as \(H ightarrow \gamma \gamma\). Unconverted photons do not leave tracks and must be reconstructed entirely from calorimeter information. In this project, we propose a machine learning-based algorithm to infer the production \(z\)-vertex of such photons using 3D spatial information from an electromagnetic calorimeter (ECAL). We employ 3D convolutional neural networks (CNNs) to regress the photon’s production vertex from segmented calorimeter energy depositions. We demonstrate initial performance on simulated data and validate the approach against a simple analytical method. We also discuss the broader scientific significance of this technique for future colliders and other fields.

Investigating methods for constraining cosmological parameters in the Pantheon+ analysis
Zilan Xiong
Mentors: Charles L. Steinhardt and Philip F. Hopkins

The Pantheon+ analysis constrained cosmological parameters from light curves of Type Ia (SNe Ia) supernovae from a variety of surveys spanning a wide range of redshifts (from z = 0.001 to 2.26). SNe Ia are imperfect standard candles, necessitating a standardization process. To determine cosmological parameters, the Pantheon+ analysis uses a general analysis package for supernova light curves called SNANA. SNANA is a complex software comprised of multiple independent pieces written in at least four different languages (Fortran, Python, C, and C++) that form a pipeline that has been in development for upwards of the past 25 years. The Pantheon+ analysis determined a dark energy equation of state parameter w = -1 and cosmological parameters that closely align with a LambdaCDM model. In this project, we recreate the Pantheon+ analysis using SNANA, and we show that the cosmological parameters determined by SNANA are sensitive to an assumed cosmology used in its standardization pipeline. Different cosmologies are found during cosmological analysis when different assumptions are provided to SNANA. This renders SNANA unfit for constraining cosmological parameters and points toward a need to rewrite its codes such that a cosmological model is not imposed.

Integration and testing of components for the ATLAS high luminosity upgrade to the Large Hadron Collider
Mitchell J. Agris
Mentors: Caterina Vernieri and Michele Papucci

The High-Luminosity LHC (HL-LHC) upgrade will significantly increase the luminosity of proton-proton collisions, requiring substantial upgrades to the ATLAS detector. By focusing on pre-production integration and testing, this project supports the development of the new all silicon Inner Tracker (ITk), which senses the products of colliding protons in the LHC. The objective was to develop a procedure to assemble detector support structures and testing boxes in addition to testing modules and connecting electrical services to testing boxes. Methods included assembling 3D-printed mechanical rings into carbon-fiber frames and installing them into a quarter shell, mounting the cable tray, and preparing a service box for high-voltage, low-voltage, and temperature-sensing connections. Additionally, we built a testing chamber to validate the electrical and mechanical properties of loaded supports. Over the course of the project, we observed improved dew point performance in the small testing boxes, successfully integrated rings into the first quarter shell, and identified procedure inconsistencies requiring a detailed updated procedure. Future goals include full shell integration and finalization of electrical service assembly. This work provides procedural insight for streamlining full-scale production and integration of the ATLAS ITk detector.

Phase space formulation of quantum optics for measurement-device-independent quantum key distribution
Ahaan Shetty
Mentors: Maria Spiropulu and Raju Valivarthi

Measurement-device-independent quantum key distribution (MDI-QKD) has proven to be an exciting and groundbreaking approach to develop secure, side-channel attack resistant quantum communication. A novel approach to theoretically modeling time-bin qubits in an experimental MDI-QKD setup is by using the phase space formulation of quantum optics to derive analytic results. In the setup, Alice and Bob's transmission of coherent state pulses to Charlie are modeled, including every physical component realized experimentally via symplectic transformations. Through the representation of a bucket-type photon detection as Gaussian, a two-fold detection probability has been calculated for the purpose of the Bell State Measurement (BSM). This has been used to derive data for key rate, error rate and gain for the generation of a shared secure key. Further, time-bin overlap between qubits, detector dead time and dark count probabilities have all been modeled and included in derivations. The exciting results have been successful and largely in agreement with other theoretical predictions and experimental realization of MDI-QKD setups. In addition, this theory is being extended to a setup with more than two parties involved, and including quantum teleportation using entangled TMSV states for secure long-distance communication.

Dispersion compensation for entanglement distribution in quantum networks
Shreyas Singh
Mentors: Maria Spiropulu, Prathwiraj Umesh, and Raju Valivarthi

Quantum Key Distribution (QKD) is a powerful scheme allowing communicating parties to create an encryption key whose security is guaranteed by the laws of quantum mechanics rather than the assumed difficulty of computational problems. QKD, along with other promising applications of quantum networks, requires the long-distance distribution of entangled qubits, often implemented using time-binned photons sent through optical fibers. However, the accuracy and rate of qubit transmission is hampered by chromatic dispersion (CD), an effect which increases the timing uncertainty of qubit detection and compounds over longer distances and higher photon bandwidths. We seek to experimentally mitigate the effects of CD on entanglement distribution by means of tunable dispersion compensators based on fiber Bragg gratings. We design an algorithmic protocol to minimize the time-spread of photons traveling through fiber spools with length varying up to 100 km, and demonstrate its efficacy using modulated laser pulses detected with SNSPDs. Additionally, we aim to reproduce Hong-Ou-Mandel (HOM) interference between two independent dispersion-compensated photons, demonstrating the viability of various QKD protocols over long distances.

Automating the measurement of high rate entanglement at INQNET

Karen I. Shekyan
Mentors: Maria Spiropulu and Raju Valivarthi

Entanglement is central to quantum information processing, with time-bin entangled photons being one of the primary mediums for protocols such as entanglement distribution and swapping. These methods can be realized for the purpose of quantum key distribution or long-distance communication but suffer from attenuation, causing a significant slowdown in the transmission of data for postprocessing. As such, we work to automate the generation of time-bin entangled photons by developing software to control the necessary laser, interferometers, and SNSPDs (superconducting nanowire single-photon detectors). To further counter the issues present in long-distance communication, we incorporate polarization stabilization, dispersion compensation, and clock synchronization modules. We particularly focus on polarization stabilization and demonstrate the automation of this process over a 150-km fiber, successfully maintaining a fidelity exceeding 96% with a polarization drift of 0.25° per second over 24 hours.