Caltech
Student-Faculty Programs

Session N Abstracts

Reducibility and hardness of random quantum stabilizer codes
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Mentors: Vinod Vaikuntanathan and Hsin-Yuan Huang

The task of decoding random linear codes, termed Learning Parity with Noise (LPN), is a computational problem that is widely believed to be hard. It has served as a versatile post- quantum cryptographic assumption—recently, a quantum version of this problem was proposed, called Learning Stabilizers with Noise (LSN). LSN is the algorithmic task of decoding a random quantum stabilizer code. Very little was previously known about LSN, including its relationship to other computational problems like LPN, and whether it shares its nice properties. We show that LSN is harder than a particularly hard case of LPN, for which no subexponential algorithms are known. In doing so, we apply a new technique that relates LPN to a version of the problem for more structured linear codes. Furthermore, we extend the equivalence of LPN's search and decision formulations to LSN, showing that certain reducibility properties of LPN extend to LSN. These results show that generic quantum codes are harder to decode than classical codes— the cryptographic utility of LSN, however, remains open.

Fulton's intersection theory of Matroid
Guanxi Li
Mentor: Paolo Aluffi

A Matroid is a combinatorial abstraction of the notion of linear independence. It has many cryptomorphic definitions and relates to many other combinatorial structures, such as graphs and polytopes, in a natural way. In the past decade, many geometric models of matroids have been understood through algebraic and tropical geometry. One could recover combinatorial information by studying the Chow ring associated to the geometry. Many conjectures regarding the log-concavity of the various polynomials related to matroids have been proven by proving the Kahler package on the Chow ring. In the literature, the Chow ring of a matroid is studied through toric and tropical intersection theory. In this project, we study the intersection theory of matroids through Fulton's perspective. Specifically, we define a notion of Segre classes for matroids.

Groundwork for Hodge-refined Whitehead torsion
Samuel J. Moss
Mentors: Aravind Asok and Tom B. Graber

Given a manifold M of dimension $n \geq 5$, the s-cobordism theorem provides a bijective correspondence between h-cobordisms of M and elements of $\mathrm{Wh}\big(\pi_1(M)\big) \coloneqq K_1(\mathbb{Z}[\pi_1(M)])/\{\pm\pi_1(M)\}$ through a cobordism invariant known as Whitehead torsion. Let X be a smooth projective variety over $\mathbb{C}$, and let W be an algebraic deformation of X parameterized by the unit interval I such that the fibers of W have isomorphic (mixed) Hodge structures on their cohomology and quotients of $\mathbb{Q}[\pi_1(X)]$ by powers of its augmentation ideal. In this paper we lay some of the groundwork for defining a variation of Whitehead torsion which can detect whether an algebraic deformation of such a variety is trivial. Since we expect this invariant to make use of various Hodge structures present for smooth projective varieties, we refer to this invariant as "Hodge-refined Whitehead torsion." We first provide an explicit computation of the Hodge structures on the cohomology of a class of smooth projective varieties with fundamental group $\mathbb{Z}/5\mathbb{Z}$. In doing so, we develop a spectral sequence for calculating the Hodge structures and numbers of projective hypersurfaces and their quotients by free group actions, and we explore some of its consequences. Finally, we define a notion of "Hodge-refined" rings and modules, and we discuss how we expect these tools to be used in defining a Hodge-refined Whitehead torsion.

The Gaussian curvature of superminimal immersions in the round 4-sphere
Tisya C. Rawat
Mentor: Riccardo Caniato

Through this SURF project in Differential Geometry, we investigated the existence of negatively curved minimal surfaces in spheres, particularly in S^4. We studied the following problem: Is there a negatively curved, closed, minimal surface in a round sphere? The problem has remained open for decades, since there are serious obstructions, given by the positive curvature of the ambient space, to the existence of negatively curved minimal surfaces in spheres. Bryant and Hano have invented methods to generate minimal surfaces in spheres with semi-explicit twistorial constructions. We studied new methods to understand the Gaussian curvature of Bryant–Hano surfaces. We show that no smooth superminimal immersion in S^4 can have strictly negative Gaussian curvature, as any such immersion of genus $g \geq 2$ must have at least one umbilic point.

Irrationality proofs by arithmetic holonomy bounds
Eduardo H. Rodrigues do Nascimento
Mentor: Vesselin A. Dimitrov

We explore Calegari, Dimitrov and Tang's method of Arithmetic Holonomy Bounds for irrationality proofs, seeking both applications of the method to new irrationality proofs and improvements to the method, which would open the possibility for proofs of new irrationality results. Specifically, we show that 1, log(2) and $\pi^2/6 \log^2 2 /2 + \log^2(3) - 2Li_2(1/3)$ are $\mathbb{Q}$-linearly independent, which implies that the latter two numbers are irrational. We also show that if $\varphi = (1+\sqrt{5})/2$ is the golden ratio, the numbers 1, $5 \log^2(\varphi)$ and $\sqrt{5}(\pi^2/12 + \log(\varphi)\log(\varphi/5) + Li_2(-\varphi^{-2}))$ are $\mathbb{Q}$-linearly independent (and hence, the two last ones are irrational).

Furthermore, we use a related method involving Hermite-Padé approximants and the product formula from algebraic number theory to reprove Mahler’s theorem that the p-adic logarithm is transcendental when applied at algebraic numbers. Finally, we generalize a rationality result by Cantor and expand the key idea to generalize multiple other holonomy bounds in the literature.

On the absolute prismatic cohomology of number rings
Justin D. Lee
Mentor: Matthias Flach

Prismatic cohomology was introduced by Bhatt and Scholze as a new p-adic cohomology theory that admits specializations to well-known cohomology theories, such as crystalline cohomology, Etale cohomology, and de Rham cohomology. Despite having been studied extensively, the absolute prismatic cohomology has not been computed for the simplest cases of p-complete rings. It is known, by the Hodge-Tate comparison theorem, that the cohomology is concentrated in the zeroth and first degrees. In this project, we work towards computing the absolute prismatic cohomology of the ring of integers of local fields. To achieve this, we adapt and improve upon a method of relative to absolute descent developed by Antieau, Krause, and Nikolaus.

Modeling and shielding of mobile electron beam for increased asphalt durability
Maverick S. McKown
Mentors: Maria Spiropulu, Adi Bornheim, and Christopher J. Edwards

Improving the durability of road infrastructure presents a significant economic and engineering challenge. A novel solution is the use of a mobile 10 MeV, 20kW electron beam to irradiate and strengthen freshly paved asphalt. However, the deployment of such a high-power accelerator in a public environment creates a critical radiation safety hazard, which is a primary barrier to its industrial application. This research addresses this problem by designing and modeling an effective radiation shield for the mobile unit. Using the Monte Carlo code MARS15, complex primary and secondary radiation fields produced when the electron beam interacts with the road surface are simulated. The work involves first creating and validating a baseline simulation of the beam with a simple geometry, which will then be expanded to model the entire truck and road system to determine unshielded dose rates. This analysis will guide the design of a practical shield, evaluating materials such as tungsten composites and layered metals and addressing the engineering challenge of maintaining a shield flush with an uneven road surface. The development of a verified shielding solution is essential for the safe deployment of this technology, enabling its potential to deliver significant improvements to transportation infrastructure.

Quantum chaos and black holes in N = 2 SYK and D1-D5-P
Damian R. Musk
Mentors: Joseph D. Lykken, Maria Spiropulu, and Kyriakos Papadodimas

We explore the emergence of chaotic dynamics within the protected BPS sectors of the D1-D5-P system, with a particular focus on the fate of states with nonzero right-moving R-charge j_R. While the elliptic genus captures an index of BPS states immune to lifting under deformations, the full BPS partition function—refined by j_L and j_R—provides a more granular view of the spectrum and its potential sensitivity to moduli. We investigate whether states with j_R, associated with black hole "hair," survive deformations away from the orbifold point, and whether their degeneracies can grow parametrically to account for black hole entropy.

Investigating and improving Z-boson mass resolution for Higgs decay to dimuon searches
Jiahui Xie
Mentors: Maria Spiropulu, Christina Wang, Cristian Peňa, and Si Xie

The Higgs boson decaying to a dimuon pair is a rare Standard Model process with a branching ratio of ~0.02%. Detecting it with high statistical significance (5σ) requires precise mass resolution to distinguish the narrow Higgs peak from large Drell–Yan and Z-boson's decay to dimuon backgrounds. Because the same reconstruction pipeline simulation is used for both Z and Higgs events, improving Z-boson mass resolution, which is a well-established standard candle, would directly enhance Higgs sensitivity. Here, we evaluated the effect of Beam Spot Constrained (BSC) reconstruction on Z-boson and Higgs mass resolution in 2022–2024 CMS Monte Carlo simulations and collision data, across different production modes (ggH, VBF, ttH). Gaussian fits to invariant mass spectra were used to quantify resolution changes, revealing a consistent improvement after BSC, with the ttH category showing an improvement of up to ~10% in σ. To investigate the origin resolution differences between production modes, we examined the pseudorapidity distributions and muon momentum residuals of the Monte Carlo results, but the observed patterns were never fully explained. These results confirm that BSC improves resolution and provide the basis for future smearing algorithms to align simulation with data, supporting higher-precision H to μμ searches.

Improving Higgs boson decay classification into tau leptons via fine tuning of the Particle Transformer
Tuyen T. Nguyen
Mentors: Maria Spiropulu, Jennifer Ngadiuba, and Raghav Kansal

This project aims to develop a machine-learning framework that enhances the identification of Higgs boson decays into tau-lepton pairs in proton-proton collision data. We implement a two-stage pipeline in which a Particle Transformer network is first pretrained on one hundred million jets using constituent-level kinematic and interaction features. The resulting jet embeddings are then combined with high-level jet features and passed to a DeepSet classifier for event-level signal versus background discrimination. Training is conducted on a 45/5/50 split with Lookahead and RAdam optimizers, checkpointing epochs with the best validation accuracy and loss. As model training continues, we will assess the impact of joint optimization, and refine hyperparameters to maximize background rejection at fixed signal efficiency. These investigations will inform subsequent studies on real detector data.

Bootstrapping methods for matrix quantum mechanics and quantum field theory
Sophia M. Adams
Mentors: Xi Yin, David Simmons-Duffin, and Joshua Sandor

This project is aimed at improving bootstrapping methods for matrix quantum mechanics and quantum field theory. The bootstrap method is an analytic alternative to Monte Carlo simulation that produces rigorous bounds on the expectation values of observables. The large N limit of the two-matrix anharmonic oscillator is of particular interest since it is conjectured to be a minimal truncation of BFSS dual to a string theory of black holes. Energy eigenvalues of the single particle anharmonic oscillator, large N one-matrix case, and large N two-matrix case were bounded without logarithmic relaxation using the Quantum Information Conic Solver.

Probing correlated dark matter signals in pulsar timing arrays might lead to promising bounds on substructure
Abhiram Cherukupalli
Mentors: Kathryn M. Zurek, Kim V. Berghaus, and Vincent Lee

Dark matter models predict very different small-scale structure: WIMPs exhibit damping below $\sim 10^{-6} M_\odot$, while (post-inflationary) QCD axions can produce an enhanced microhalo abundance via isocurvature fluctuations. Conventional probes like microlensing rapidly lose sensitivity to extended subhalos because their low surface densities smear the lensing signature. We revisit the detection of this diffuse substructure with pulsar timing arrays by targeting the correlated stochastic signature of dark matter subhalo flybys. Projecting timing residuals onto the dipolar spatial mode isolates a dark-matter signal from the dominant stochastic gravitational-wave background and the intrinsic pulsar red noise. Using a gauge-invariant treatment of Doppler, Einstein, and Shapiro effects, we forecast constraints on the subhalo mass function in the $\sim 10^{-12} - 10^{-6} M_\odot$range. Such bounds could sharply discriminate between cold, axion-like, and warm/free-streaming dark matter scenarios.