DAEC2026

TATA INSTITUTE OF FUNDAMENTAL RESEARCH
DEPARTMENT OF THEORETICAL PHYSICS
PARTICLE PHYSICS GROUP

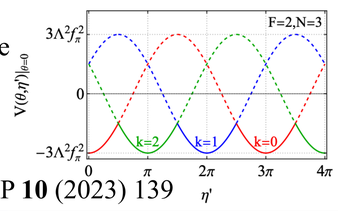
Our Research Program

The high energy group at TIFR studies the laws of nature at the most fundamental scales that can be experimentally probed. We develop theoretical frameworks whose predictions can be tested by a wide array of experiments such as proton-proton and heavy ion collisions at the LHC, neutrino and flavour experiments as well as low energy experiments sensitive to new particles. The group also focuses on open problems in particle physics such as understanding the QCD phase diagram, the spectrum of QCD resonances, the origin of neutrino masses, beyond Standard Model physics etc. The group currently comprises 6 faculty members, and many postdoctoral researchers and graduate students. This poster highlights recent developments made by the group.

Supersymmetric QCD

We employ Supersymmetric (SUSY) QCD to derive the chiral Lagrangian of QCD upto next-to-leading order accuracy and compute the dynamically generated up-quark mass in presence of anomaly-mediated SUSY breaking. The dynamically generated up-quark mass, testable by lattice QCD results, vanishes at large number of colors, but becomes order one when number of colours equal number of flavors. [SQ1]

We study the origin of the η′ potential in QCD, showing that number of flavors drastically modify the branched vacuum structure of the Yang–Mills theory. The same strong dynamics is responsible for generating both the non-zero η′ and axion masses, for which a general formula is derived. [SQ2]



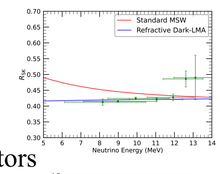
We are deriving a low energy Lagrangian of QCD in presence of ultralight scalar and pseudoscalars using SUSY.

• [SQ1] 2505.07953 (2025) •[SQ2] JHEP **10** (2023) 139

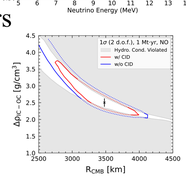
Neutrino and Dark Matter

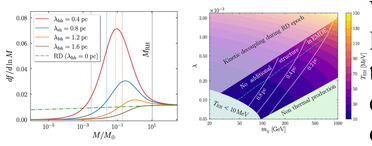
We studied how neutrino oscillations and their non-standard interactions—involving sterile states, matter effects, and atmospheric neutrinos—can reveal fundamental properties and mass ordering of neutrinos.

We showed that interactions between neutrinos and an ultralight dark-matter halo can give neutrinos effective "refractive masses" that modify their solar oscillation behavior and might revive the dark-LMA solution in active-sterile models. [ND1]



We further studied atmospheric neutrino oscillations to probe Earth's internal structure, illustrating how neutrino matter effects can constrain core-mantle density features in detectors like iron calorimeter detector (ICAL). [ND2]





We have studied how an early matter-dominated era before BBN can cause dark matter to decouple and cool earlier than usual, reducing its free-streaming length and enhancing small-scale structure and annihilation signals, offering a potential probe of non-standard pre-BBN cosmology. [ND3]

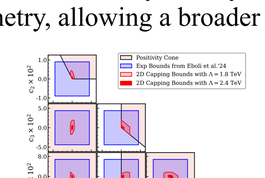
• [ND3] JCAP **03** (2025) 030

• [ND1] 2511.19420 (2025)
• [ND2] 2405.04986 (2024)

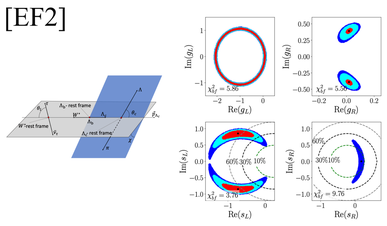
Effective Field Theory

Effective field theory (EFT) is an important tool to explore physics beyond the Standard Model. In this context two major frameworks, namely SMEFT and HEFT are most well-studied. SMEFT describes new physics by extending the Standard Model with higher-dimensional operators that linearly realize electroweak symmetry, whereas HEFT is a more general framework with a non-linear realization of the symmetry, allowing a broader range of Higgs dynamics and deviations from SMEFT.

We derive strong theoretical constraints on HEFT parameters using unitarity and positivity criteria of quantum field theoretic S-matrices, which significantly exceed current experimental limits. [EF1]



We perform an EFT analysis of top quark pair production process in association with a Z-boson at future colliders like FCC-hh, probing the fundamental SMEFT interactions. [EF2]



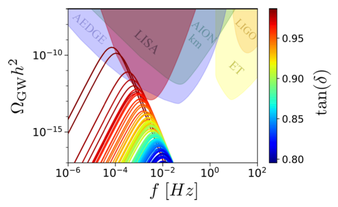
We show that angular observables in the rare meson decays can probe HEFT-specific scalar and vector operators—offering a way to distinguish between HEFT and SMEFT. [EF3, EF4]

With increasing experimental sensitivities, and progress in the computation of higher-order quantum corrections—it is crucial to go beyond the lowest-order EFT description. We are developing a systematic framework to study higher-order EFT effects on differential observables in the Higgs-strahlung process by establishing an all-orders mapping between the partial-wave and EFT expansions. [EF5]

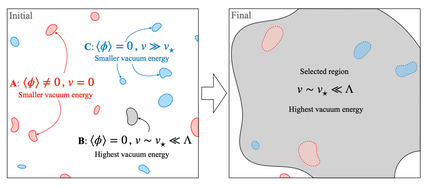
• [EF1] 2412.14155 (2024)
• [EF2] 2509.10449 (2025)
• [EF3] PRD **110** (2024) 015010
• [EF4] PRD **110** (2024) 115041 • [EF5] 2601.88821 (2026)

Hierarchy Problem and Higgs Physics

The hierarchy problem refers to the key question: why the Higgs mass (or the electroweak scale) is stable under quantum mechanical corrections, and remains so much lighter than the Planck scale? Well-studied solutions of this problem include invoking supersymmetry, considering the Higgs boson as composite particle, and selecting the correct vacuum cosmologically.



We show that a composite Higgs in presence of an additional light pseudoscalar boson can trigger a strong first-order electroweak phase transition in the early universe, potentially generating observable gravitational waves at the future detectors like LISA, providing a new way to test such models beyond collider experiments. [H1]



We propose a minimal inflationary landscape with a light pseudoscalar and an extra Higgs doublet that dynamically selects a small, nonzero electroweak vacuum, thus offering a novel solution to the hierarchy problem, and predicts testable signatures for precision Higgs-studies. [H2]

• [H1] JHEP **10** (2024) 106 • [H2] PRL **134** (2025) 241803

The group has access to extensive DTP computational resources, with further expansion planned, supporting large-scale numerical simulations. It previously had access to resources from the Indian Lattice Gauge Theory Initiative (ILGTI). The group regularly hosts international visitors and runs the Free Meson seminar series, a weekly theory seminar active for nearly five decades, along with a regular journal club. It collaborates extensively with researchers across the globe and continuously adopts new theoretical and computational tools to pursue cutting-edge research and remain competitive with international peers. For further information, please contact any of the following email addresses:

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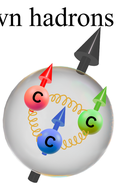
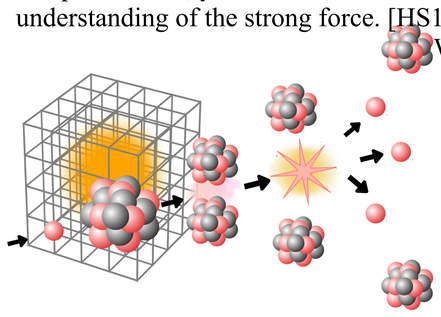
Hadron Spectroscopy

Using lattice QCD, we perform hadron spectroscopy to precisely determine the properties of known hadrons and predict new, yet-to-be-discovered hadrons, guiding experimental searches and deepening our understanding of the strong force. [HS1, H2]

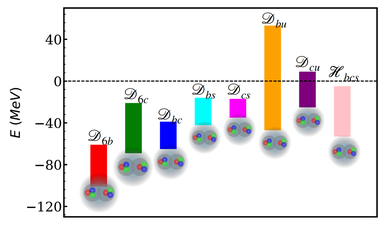


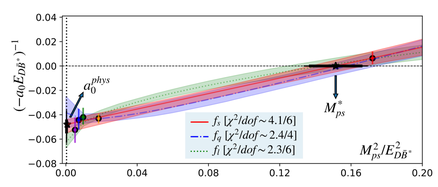


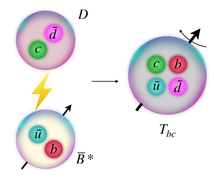
We have worked recently on the following ideas:

• Understanding nucleon properties and interactions from lattice QCD. [HS3]

• Predicting exotic heavy hadrons: Bound states of doubly-heavy tetraquarks, the most sought-after hadrons of this decade, and precise calculations of triply-charmed baryons. [HS4, HS5, HS6, HS7]





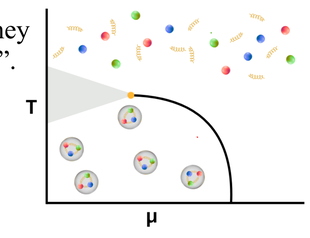


• Heavy dibaryons: to explore how baryons interact and uncover the dynamics of the strong force. [HS8,HS9,HS10,HS11, HS12]

• [HS1] PRL **121** (2018) 202002
• [HS2] PRL **119** (2017) 042001
• [HS3] PRD **112** (2025) 114505
• [HS4] PRL **132** (2024) 201902
• [HS5] PRD **110** (2024) 034506
• [HS6] PRD **111** (2025) 114504
• [HS7] PRD **112** (2025) L111501
• [HS8] PRD **112** (2025) 054501
• [HS9] PRL **123** (2019) 162003
• [HS10] PRL **130** (2023) 111901
• [HS11] PRD **111** (2025) 014512
• [HS12] PRD **106** (2022) 054511

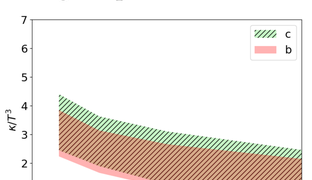
Quark–Gluon Plasma and QCD

While the quarks and gluons are confined into color neutral hadrons because of the confining nature of strong interactions, at high temperatures and baryon densities, they form a deconfining, chiral symmetry restoring medium, called "quark gluon plasma". Indian scientists are at the core of the experimental investigations of this phase.

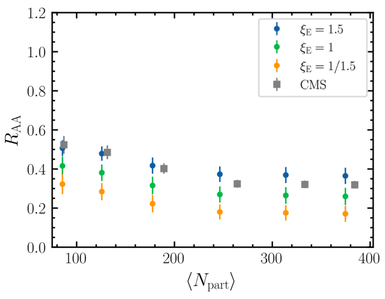


• We can learn about the phases of strongly interacting matter by analyzing the dynamical properties of various observables.

• In the QGP phase, significant changes to the evolution of energetic probes of the medium, for example jets. [QG1]

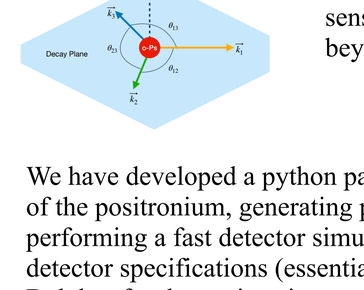


• Heavy quarks lose their momenta by interacting with the quark-gluon plasma. We have calculated the momentum diffusion coefficient (κ) and the relaxation time of the charm and bottom quarks in the plasma, and their temperature and quark mass dependence. [QG2, QG3]



• Yields of quarkonia, bounds states of heavy quarks (for example ϒ) are suppressed in the QGP. We have studied the suppression of bottomonia, taking into account the non-Markovian nature of the quantum evolution, and compared with the CMS observations. [QG4]

• Nonperturbative evaluation of the parameters for such quantum evolution are also underway. [QG5]

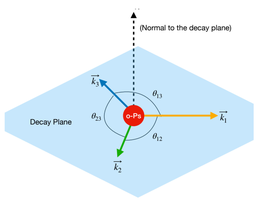


• Dynamical information about light quark observables are more difficult to obtain theoretically. Using effective field theory techniques, we can learn about dynamical properties like the velocity of the pions, μ_π, from the static properties that are easier to calculate using Lattice QCD. Such an effective theory can also be used to learn about the phase structure at high baryon number densities. [QG6, QG7]

• At low temperatures and high baryon number densities, the transition to the deconfined phase is first order. As temperature increases, the transition becomes weaker, finally ending at a critical point. The search for this critical point is a major ongoing experimental program. We studied this transition line, in particular, how the location of the transition line can shift with the volume of the system. [QG8]

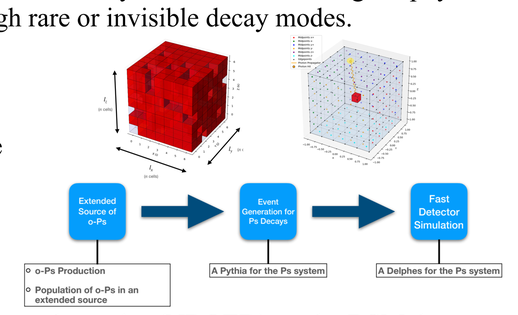
• [QG1] PRD **112** (2025) 034017
• [QG2] JHEP **08** (2022) 128
• [QG3] Nucl. Phys. A **1038** (2023) 122721
• [QG4] PRD **112** (2025) 114038
• [QG5] PRD **112** (2025) 074509
• [QG6] PRD **97** (2018) 036025
• [QG7] 2511.00409 (2025)
• [QG8] Nucl. Phys. A **1054** (2025) 122981

Positronium Physics



Positronium is a unique, purely leptonic bound state of an electron and a positron whose precisely calculable properties make it an exceptionally clean and sensitive system for testing quantum electrodynamics and searching for physics beyond the Standard Model through rare or invisible decay modes.

We have developed a python package for modeling the source of the positronium, generating positronium decay events, and performing a fast detector simulation with user-provided detector specifications (essentially developing a Pythia and Delphes for the positronium system).



We are studying the applications of nonrelativistic quantum electrodynamics (NRQED) on the BSM decays of positronium. Specifically, we are constructing an EFT to study the different spin states of positronium in the presence of BSM physics, such as an axion or milli-charged particles.