From Quarks and Gluons to Nuclear Forces and Structure

Monday 15 July 2019 - Friday 02 August 2019

ECT* - Villa Tambosi

Scientific Programme

The TALENT summer school would be run by leading experts in these research fields, and we have commitments from **Z. Davoudi, E. Epelbaum, D. Lee, T. Luu,** and **A. Shindler** to serve as the main lecturers. A. Shindler will be the student coordinator during the whole duration of the School. We will have a single lecture from a guest lecturer, F. Pederiva from University of Trento (tbc). The aim is to prepare graduate students to master key ideas and methods in LQCD, χEFT, and NLEFT and how to determine physical properties of multi-nucleon systems from the fundamental theory of the strong interactions. We would like to address specific theoretical and computational challenges that must be overcome: signal-to-noise problems, ultraviolet cutoff effects, finite size effects, systematic errors, and effective field theory convergence are a few examples.

Week 1

Expectations: Students will understand formal aspects of functional formalism in quantum field theory and the basic ideas of the lattice formulation of QCD. They will understand numerical techniques for LQCD calculations together with their homework projects and they will also be exposed to nuclear-specific computational advances.

• Background: Path integral formalism for quantum mechanics. Solution of a quantum field theory with the functional formalism. Rotation to Euclidean space. Spectral decomposition. Scalar, fermion and gauge fields.
• Lattice QCD: QCD and lattice regulator. The approach to the continuum and renormal- ization. Improvement. Observables in LQCD. Static potential. Hadron spectroscopy. Spon- taneous chiral symmetry breaking. Chiral condensate and chiral Lagrangian. Low energy constants and their determination in LQCD.
• Computational techniques 1: How a lattice QCD computation proceeds. Computation of quark propagators. Krylov-space solvers and deflation. Simulation algorithms. Importance sampling. Markov chains. Hybrid Monte Carlo (HMC).
• Computational techniques 2: Lattice QCD with several quark flavors. Variance reduc- tion methods. Random sources and source constructions. Multilevel simulations. Nuclear contraction algorithms. Statistical error analysis. Resampling: bootstrap and jackknife. Autocorrelation analysis. Recent developments: machine learning.

Week 2

Expectations: Students will be introduced to LQCD applications for two- and multi-hadron systems. Students will start learning about the consequences of pions and pion-nucleon interactions.

• Finite-volume systems: Scattering parameters from finite volume energy eigenvalues. Resonances and bound systems. Reaction and transition amplitudes.
• Meson systems: Lattice QCD calculations of a single meson and multi-meson systems
• Baryon systems and light nuclei: Lattice QCD calculations of a single baryon. Lat- tice QCD calculations of two-baryon systems. Lattice QCD calculations of light nuclei and hypernuclei.
• Chiral perturbation theory: Consequences of chiral symmetry on the interactions of pions and pion-nucleon interactions.

Week 3

Expectations: Students will understand the derivation of chiral two-and three-nucleon interactions, χEFT interactions in the continuum and on a lattice, and nuclear lattice simulations. Students will then be introduced to the research priorities in the field.

• Two-nucleon and three-nucleon interactions: Derivation of chiral two-nucleon and three-nucleon interactions using the method of unitary transformations.
• Auxiliary fields: Introduction of auxiliary field methods and their implementation.
• χEFT interactions and scattering on the lattice: Implementation of χEFT on the lattice and two-nucleon scattering on the lattice.
• Nuclear matrix elements: Gluonic structure, neutrinoless double beta decay, neutrino- nucleus scattering: recent progress and control of uncertainties with LQCD and EFT.

During the school theoretical and numerical exercises will be proposed. They will be stand- alone exercises that also serve for a succesful completion of a research project proposed and to be handed in later. The homework will closely follow and complement the daily lectures. Potential final projects include:

• Analytical and numerical calculation of the tree-level fermion propagator in lattice QCD

• Data analysis with resampling and autocorrelation techniques of real lattice QCD data

• Implementation of heatbath and overrelaxation algorithms for simple statistical systems (Ising model) or quantum mechanical systems (harmonic oscillator) or simpler field theo- ries such as scalar field theory or U(1) gauge theory

• Calculations of nucleon-nucleon phase shifts using the Lippmann-Schwinger equation and χEFT interactions.

• Lattice simulations of fermions with pointlike interactions
• Obtaining two-baryon scattering phase-shifts from LQCD correlators using Luescher methodology. A sample of two-baryon correlators will be provided to students.