UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

COURSE SYLLABUS

Effective Field Theories and Non-Perturbative Methods for Particle Physics

2627-1-F1703Q067

Aims

The objective of this course is to introduce students to the modern methodology of quantum Effective Field Theories (EFTs) and selected non-perturbative methods in particle physics. Upon completion, students will be able to construct and apply EFTs, and will understand their ubiquitous role in contemporary theoretical physics through concrete examples rooted in the Standard Model and beyond.

At the end of the course, the student will be able to:

1. **(Knowledge and understanding)**
   Understand the fundamental concepts of EFTs within the formalism of quantum field theory, including power counting, matching, and renormalization group evolution.

2. **(Applying knowledge and understanding)**
   Apply EFT techniques to concrete problems in theoretical particle physics, including the electroweak sector, flavor physics, and low-energy QCD, and appreciate how non-perturbative methods such as lattice QCD complement perturbative EFT calculations.

3. **(Making judgments)**
   Critically assess the validity and limitations of a given EFT description, evaluate the consistency of theoretical models against experimental constraints, and recognize when non-perturbative input is needed.

4. **(Communication skills)**
   Clearly communicate the concepts and implications of EFTs and non-perturbative methods using appropriate technical language, in both specialized research and broader scientific contexts.

5. **(Learning skills)**
   Independently pursue advanced study of EFTs and their applications, using specialized scientific literature and keeping pace with theoretical and experimental developments.

Contents

Quantum Effective Field Theories (EFTs) are a cornerstone of modern theoretical physics, providing a systematic framework to describe physical phenomena across widely separated energy scales.
The course introduces the conceptual foundations of EFTs — power counting, matching, and renormalization group evolution — and demonstrates their potential through a series of concrete examples spanning different sectors of the Standard Model of particle physics.
These include the Standard Model itself viewed as an EFT, the weak effective Hamiltonian and its applications to flavor physics, Chiral Perturbation Theory as the low-energy EFT of QCD, and Heavy Quark Effective Theory for systems containing heavy quarks. The course concludes with an introduction to lattice QCD as a non-perturbative approach to strongly interacting systems, where the Symanzik effective theory provides the EFT framework for understanding and systematically improving lattice discretization effects.

Detailed program

The program of the course will cover the following topics:

- **Introduction & Philosophy of EFTs** — scales, degrees of freedom, decoupling theorem, Wilsonian renormalization group, non-perturbative renormalization, matching and running, warm-up examples;
- **The Standard Model as an EFT** — Fermi theory as a paradigmatic example; SMEFT framework, dimension-5 Weinberg operator, seesaw mechanism and neutrino mass generation, dimension-6 operators, precision electroweak constraints;
- **Weak Effective Hamiltonian & Flavor EFTs** — operator basis for weak decays, matching at the W/Z scale and RG evolution, applications to K and B decays, meson mixing;
- **Chiral Perturbation Theory** — chiral symmetry breaking in QCD, Goldstone theorem, chiral Lagrangian, loops and renormalization, LECs, pion and kaon physics;
- **Heavy Quark Effective Theory** — heavy quark limit, spin-flavour symmetry, 1/m expansion, applications to B and D meson decays;
- **Non-Perturbative Methods & Lattice QCD** — path integral discretization, fermion doubling, Symanzik effective theory and lattice improvement, non-perturbative renormalization on the lattice, hadronic matrix elements on the lattice.

Prerequisites

Knowledge of the topics covered in the courses:

- Theoretical Physics I
- Theoretical Physics II
- Mathematical Methods for Physics

Teaching form

Frontal lectures with blackboard

Textbook and teaching resource

- Matthew D. Schwartz, Quantum Field Theory and The Standard Model;
- Steven Weinberg, The Quantum Theory of Fields, Volume 1: Foundations and Volume 2: Modern Applications;
- Antonio Pich, Effective Field Theory, arXiv:9806303;
- Riccardo Barbieri, Lectures on the Electroweak Interactions, arXiv:0706.0684v1;
- Additional lecture notes will be made available during the course.

Semester

Second semester, first year

Assessment method

The exam consists of an oral in-person examination.
The final evaluation will take into account the understanding of the topics covered, the ability to construct theoretical arguments, and the solving of specific problems.

Office hours

By appointment, by writing an email (marco.ce@unimib.it) to the course teacher.

Sustainable Development Goals

QUALITY EDUCATION