UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

COURSE SYLLABUS

Theory and Phenomenology of Fundamental Interations

2425-1-F1701Q128

Aims

Contents:

- Study of the theoretical aspects at the core of the Standard Model of Particle Physics (electroweak and strong sectors).
- Learning of techniques to compute cross-sections and decay widths.
- Deepening the knowledge of the phenomenology of fundamental interactions.

Aims:
At the end of the course, the student will have completed the knowledge of the EW sector of the standard model acquired in previous courses (in particular with regard to the theory and phenomenology of the Yukawa sector of the Lagrangian). Furthermore, they will know the theoretical framework and the calculation techniques of perturbative QCD at lepton and hadron colliders.

In more detail, the student

1. will know the Yukawa term of the electroweak Lagrangian and the respective theoretical and phenomenological implications (quark mixing, CP violation)
2. will be able to discuss in a semi-quantitative way aspects of electroweak phenomenology at e+e- colliders and of the Higgs boson at hadronic colliders
3. will know the problems and physical concepts that emerge from soft and collinear limits in the calculation of radiative corrections in perturbative QCD, also making reference to the use of dimensional regularization
4. starting from experimental evidence, he will know the foundations of the parton model and the physical concepts that emerge when calculating radiative corrections
5. will be able to calculate cross sections (or decay widths) in all steps (go from Feynman rules to the calculation of the squared amplitude, calculate the phase space, express the kinematics using relativistic invariants) and comment the results obtained.

Contents

Theoretical aspects of the Standard Model of electroweak and strong interactions (SU(3)xSU(2)xU(1)) and its applications, mainly for the phenomenology of (past, present and future) lepton and hadron colliders.

Detailed program

Review of various topics:

- representations of the Lorentz group (in particular spinors and their transformation properties)
- Abelian gauge theories.
- Non-abelian gauge theories.
- kinematics and phase space (in 4 and in d dimensions)
- rules to compute cross sections and decay widths
- optical theorem

Lagrangian of the Standard Model:

- SU(N) algebra. Comments on SU(2) and SU(3).
- The electroweak sector of the Standard Model:
    - Quick review of the experimental evidences leading to the SU(2)xU(1) model, and of the concepts of Spontaneous Symmetry Breaking, Higgs potential and masses and couplings of the W and Z vector bosons
    - Yukawa potential and masses of quarks and charged leptons; Cabibbo-Kobayashi-Maskawa (CKM) matrix, CP violation, unitary triangle (+)
    - EW vertexes
    - various comments (Landau-Yang theorem, propagator of a massive vector boson and Breit-Wigner distribution,...)
- The strong sector (Quantum Chromodynamics - QCD)
    - Experimental evidences (quark model, naive parton model, need of colour: R-ratio, Delta++,..)
    - Lagrangian and vertexes of the strong sector
    - color algebra
    - Sum over polarizations (qqbar->gamma gamma vs qqbar -> gluon gluon), gauge choice
    - various comments

Computation of cross sections and decay widths:

- Z, W, H decay widths
- e+ e- -> mu+ mu-: forward-backward asymmetry
- unitarity bounds: examples of unitarity violation in longitudinal vector boson scattering
- from LEP to Higgs phenomenology at the LHC
- Higgs production through gluon fusion (+)

Review of the renormalization procedure:

- The renormalization of the electromagnetic and of the strong coupling constant
- The renormalization scale and the ?-function in QED and QCD
- The asymptotic freedom in QCD
- The renormalization group equations (+)

Electron-positron annhilation into hadrons at Next-to-Leading Order (NLO):

- Preliminary analysis of potential divergences
- Computation of the Born term, and of the real and virtual contributions in dimensional regularization (+)
- Phase space
- Total cross section and cancellation of divergences (KLN theorem)

Final-state soft and collinear singularities:

- Eikonal approximation and soft factorization
- Final state collinear factorization (FSR)
- Sterman-Weinberg jets as an example of an infrared-safe observable
- General properties of infrade-safe observables, brief discussion on event shapes

Hadrons in the initial state:

- Deep-Inelastic Scattering (DIS) and structure functions, Bjorken scaling and the "naive" parton model
- Factorization theorem and partonic distribution functions (PDF)
- Initial-state soft and collinear singularities (ISR)
- Altarelli-Parisi splitting functions
- "Improved" parton model, factorization scale
- The Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations: interpretation and phenomenological consequences.
- Approaches to all-order resummed computations (+)

(+) = some of these topics might be skipped or discussed only briefly, depending on the time available and on the students' interest.

Depending on the students' interest, some supplementar topics might be discussed, as for example:

- Neutrino masses, Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, Dirac and Majorana fermions
- Kinematics and phenomenology at hadron colliders
- Physics Beyond the Standard Model (BSM)

Prerequisites

Basics knowledge of Quantum Field Theory.
Familiarity with basic techniques to compute amplitudes and cross sections for simple processes in QED (Dirac matrices, sum over polarizations and traces,...)
(content of the "Fisica Teorica 1+2" class: essentially necessary, content of the Mathematical Methods for Physics class: recommended)

Teaching form

Frontal teaching (lessons at the blackboard/tablet)

Textbook and teaching resource

Notes and lectures can be found at the web page: https://virgilio.mib.infn.it/~re

EW part: main references:

- C. Becchi and G. Ridolfi: *An Introduction to Relativistic Processes and the Standard Model of Electroweak Interactions*
- lecture notes / reviews (available on elearing and/or on the webpage of the lecturer)

QCD part: main references:

- lectures by P. Nason, by M. Mangano and others (available on elearning and/or on the webpage of the lecturer)
- lecture notes from previous years course (available on elearning and/or on the webpage of the lecturer)

Very useful textbooks:

- Peskin, Schroeder: *An Introduction To Quantum Field Theory*
- Schwartz: *Quantum Field Theory and the Standard Model*
- Ellis, Stirling, Webber: *QCD and collider Physics*
- Cheng, Li: *Gauge theory of elementary particle physics*
- Dissertori, Knowles, Schmelling: *Quantum Chromodynamics. High Energy Experiments and Theory*

Other references:

- T. Muta: *Foundations of Quantum Chromodynamics*
- R. D. Field: *Applications of Perturbative QCD*

Exam sheets from previous years can be found here: https://virgilio.mib.infn.it/~re

Semester

Second term.

Assessment method

The exam consists of an oral test structured as follows:

- the lecturer will assign a series of exercises at the end of the course. The exercises will mainly probe the ability to calculate cross sections (or widths) or parts thereof in all steps (go from the Feynman rules to the squared amplitude, compute the phase space, express the kinematics using relativistic invariants, e.g. Mandelstam variables, etc)

- students will have to solve all the exercises (as homework) autonomously and in a written form before taking the exam. In the first part of the oral exam, a part of the problems (chosen by the teacher) will be discussed. The discussion will take place by examining the written solutions presented and commenting on the crucial points. In this phase, the actual knowledge of the techniques used to solve the exercises and the ability to comment on the results obtained will be verified.

- the second part of the oral test consists of open questions on the theoretical topics discussed during the course.

At least five exam sessions are scheduled during the year, typically in the following periods: January, February, June, July, September.

NB: this assessment method will apply starting from June 2025

Office hours

By appointment.

Sustainable Development Goals

QUALITY EDUCATION