UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

COURSE SYLLABUS

Theory and Phenomenology of Fundamental Interations

2223-1-F1701Q128

Aims

- 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.

Contents

Introduction to the Standard Model of the electroweak and strong interactions: the SU(3)xSU(2)xU(1) model. Electroweak symmetry breaking, the Higgs boson, and the phenomenology of the strong and electroweak interactions.

Detailed program

Review of various topics:

- representations of the Lorentz group (in particular spinors and their transformation properties)
- kinematics and phase space (in 4 and in d dimensions)
- rules to compute cross sections and decay widths
- Feynman parameterization and (scalar and tensorial) 1-loop integrals in dimensional regularization
- optical theorem

Lagrangian of the Standard Model:

- SU(N) algebra. Comments on SU(2) and SU(3).
- Abelian gauge theories.
- Non-abelian gauge theories.
- The electroweak sector of the Standard Model:
  - Experimental evidences
  - Spontaneous Symmetry Breaking, Higgs potential, masses 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,...)
  - Neutrino masses, Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, Dirac and Majorana fermions (+)
- 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 (confinement,...)

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 Fermi theory and in longitudinal vector boson scattering
- from LEP to Higgs phenomenology at the LHC

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

Final-state soft and collinear singularities:

- Eikonal approximation
- 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), Bjorken scaling and the "naive" parton model
- Factorization theorem and partonic distribution functions (PDF)
- Initial-state soft and collinear singularities
- Altarelli-Parisi splitting functions
- "Improved" parton model, factorization scale
- The Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations

LHC phenomenology:

- kinematics at hadron colliders (+)
- examples of SM/BSM studies (+)

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

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,...)

Teaching form

Frontal lectures.

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 teacher)

QCD part: main references:

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

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*

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 a written test, followed by an oral one. Normally the oral test takes place few days after the written one.

- Written test: exercises similar to those of previous years and of complexity similar to the cases discussed during lectures. In practice, the requirements are
  - being able to compute a cross section (or decay rate) in all its parts (going from the Feynman rules to the squared amplitude, compute the phase space, express the kinematics using relativistic invariants, e.g. Mandelstam variables)
  - being able to comment on the properties of the result obtained.
- Oral test: questions on the topics discussed during the course.

During the academic year, there will be at least 5 exam sessions, typically in January, February, June, July, Spetember.

Office hours

By appointment.

Sustainable Development Goals

QUALITY EDUCATION