Quantum Field Theory

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Objectives

The goal of this course is to develop a solid understanding of the formalism of Quantum Field Theory, namely the unification of classical field theory, special relativity, and quantum mechanics. The course begins with the quantisation of the free scalar field. This framework is then extended to include self-interactions, providing the basis for understanding how to derive Feynman rules and compute scattering amplitudes and cross sections starting from a given Lagrangian.

The quantisation of spin-1/2 and spin-1 fields is subsequently introduced, with particular emphasis on the Dirac equation. This leads naturally to the formulation of Quantum Electrodynamics and to the calculation of elementary processes.

The course concludes with a brief introduction to the construction of the Standard Model of particle physics.

Syllabus

1. Field theory and symmetries
The Poincaré Group. Variational principle in field theory.
Global symmetries and Noether theorem. Energy-momentum and angular momentum tensors.

2. The free scalar field
Canonical quantisation of the harmonic oscillator.
Quantisation of the real and complex scalar field; causality and propagators.

3. Spin 1 fields
Maxwell Equations. Gauge invariance and gauge fixing. Quantisation and the spin 1 boson propagator.

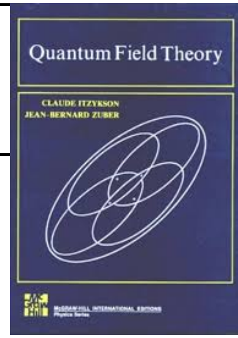
4. Dirac equation
From Schrödinger to Dirac, covariance and spin. Solutions of the Dirac equation.

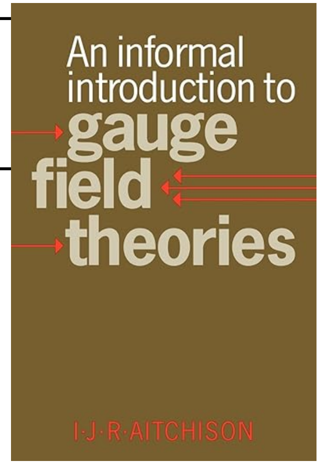
5. Scalar theory with interactions
The S matrix and perturbation theory, LSZ reduction and Wick's theorem. Feynman rules, scattering amplitudes and cross sections.

6. QED
Lagrangian, Feynman rules and elementary processes.

7. Non-abelian gauge theories
Classic theories. Quantisation, gauge fixing and Fadeev-Popov ghosts. Brief introduction to the Standard Model.

Bibliography





<u>Quantum and Particle Physics</u>

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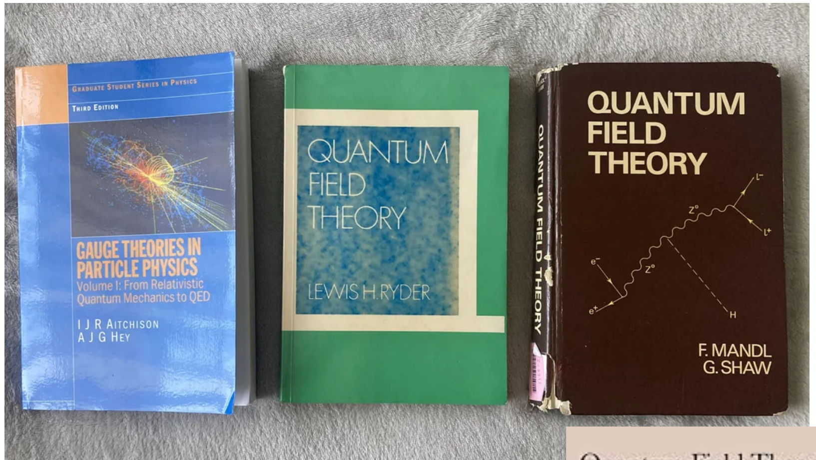

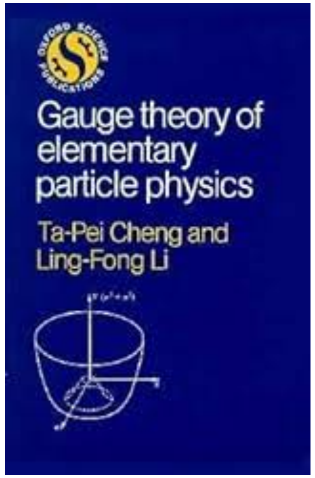

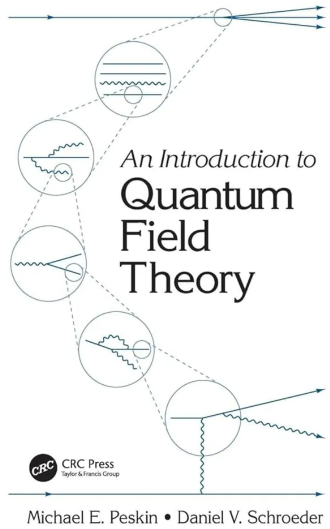

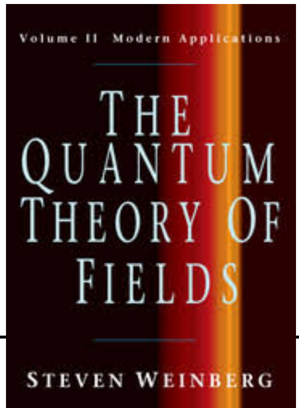

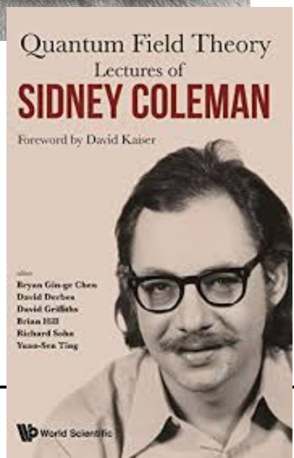

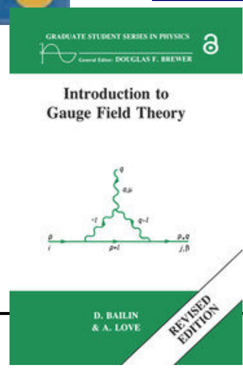

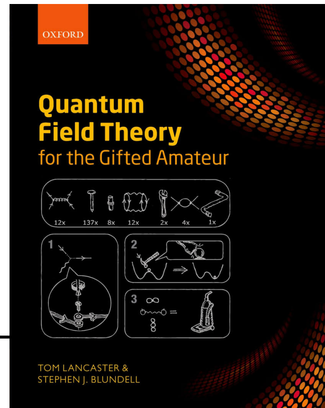

High Energy Codes

- FeynRules/LanHEP - model; FeynArts - shows Feynman diagrams and calculate amplitudes; FeynCalc - manipulates amplitudes

- MadGraph/CalcHEP - calculates cross sections and Branching ratios

- BSMPTv3 - Beyond the Standard Model Phase Transitions: The C++ program package BSMPT calculates the strength of the electroweak phase transition in extended Higgs sectors (KIT/CFTC-UL).

- MicrOMEGAs - a code for the calculation of Dark Matter Properties including the relic density, direct and indirect rates in a general supersymmetric model and other models of New PhysicsBeyond the Standard Model Phase Transitions.

- RelExt - specialized C++ software tool designed for high-energy physics, specifically for calculating DM relic density and scanning parameter spaces in BSM. (KIT/CFTC-UL)

- ScannerS - Beyond the Standard Model scans with interfaces with a number of other codes (KIT/CFTC-UL).

Evaluation

Assessment

The course assessment consists of two components:

- **Oral Presentation** – 30% of the final grade
- **Final Written Examination** – 70% of the final grade

A minimum grade of **10 out of 20** is required in **each component** in order to pass the course.

Oral Presentation

Each student must select one of the proposed topics and deliver an individual presentation on **22 April**. Presentations will have a maximum duration of **20 minutes**, including approximately **5 minutes for questions and discussion**.

A written abstract (maximum length: one page) summarising the main points of the presentation must be submitted on the day of the presentation.

The proposed topics involve the reading and critical analysis of a research article, as well as broader conceptual aspects of dark matter. Students may alternatively propose a dark matter paper of their choice, subject to the instructor's approval.

The deadline for topic selection is 4 **March**.

Students are encouraged to use AI tools; this reflects my personal view. Any use of AI must not replace your own critical thinking and analysis.

The presentation grade will be distributed as follows: 15% for the written abstract, 20% for the scientific content, 30% for the quality and clarity of the oral presentation, and 35% for the discussion and your ability to answer questions.

Groups of one

1. Path Integral vs. Canonical Quantisation

Scalar field quantisation
Derivation of propagators
Generating functionals
Connection to Feynman diagrams

2. Renormalisation in ϕ^4 Theory

Divergences and regularisation (cutoff vs. dimensional regularisation)
Renormalised mass and coupling
Beta function and running coupling
Physical interpretation of renormalisation

3. Spontaneous Symmetry Breaking & Goldstone's Theorem

Goldstone bosons
Higgs mechanism

4. Effective Field Theory (EFT)

Power counting
Decoupling of heavy fields
Matching and running

5. Anomalies in Quantum Field Theory

Classical vs. quantum symmetries
Triangle diagrams
Physical consequences

And before we start

Lectures will begin 10 minutes after the scheduled start time. I will be available during those 10 minutes to answer questions about the previous lecture. <u>Once the lecture has started, students will not be permitted to enter the classroom.</u>

- Listening to Radiolab - https://radiolab.org/
- Watch Veritasium https://www.youtube.com/veritasium