Quantum Field Theory Extension
MSc Physics and Astronomy (Joint Degree)
Theoretical Physics Track

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Study Guide 2019-2020

current version: **November 11, 2019**

Introduction

Quantum Field Theory (QFT) is the mathematical framework that describes the behaviour of subatomic elementary particles as well as quasi-particles in condensed matter systems. It is built upon the combination of classical field theory, quantum mechanics, and special relativity. In particular, QFT is the language of the Standard Model of particle physics, one of the most successful physical theories ever constructed by humankind, and whose predictions have been shown to reproduce experimental data to an astonishing level of precision.

This course is the natural continuation of the *Quantum Field Theory* course taught by Daniel Baumann in the preceding periods. In this extension, we discuss a number of additional important topics in Quantum Field Theory, therefore complementing the topics covered in Daniel's course. In particular, we study how infinities arises in QFTs and how they can be tamed using the renormalization procedure; we develop the mathematical framework required to construct Effective Field Theories; we present the quantization of the photon field in Abelian gauge theories; and study the consequences of the quantization of Abelian symmetry for the description of the interactions between matter and gauge fields; This way we can provide a natural bridge with to the two related, more advanced QFT courses that take place subsequently in the Theory Track of the master program: Advanced Quantum Field Theory and Field Theory in Particle Physics.

All the resources and teaching materials associated to the course, in particular the lecture notes, the exercises for the tutorials, and sample exams from previous years, can be found on the Canvas page of the course:

https://canvas.uva.nl/courses/10977

with further information, in particular concerning the scheduling and the lecture rooms, being available in the Datanose page of the course:

https://datanose.nl/#course[78133]

Embedding in the MSc program

This course is part of the joint UvA and VU Master course (MSc) in Physics and Astronomy, in particular within the *Theoretical Physics* track. More information about the Theoretical Physics track of the MSc program can be found here:

https://jvanwezel.com/Masters/

as well as in the Canvas page of the track

https://canvas.uva.nl/courses/6070

More general information about the Amsterdam MSc program in Physics and Astronomy can be found here

https://student.uva.nl/phys-astro

In this course we will assume that all participating students have followed the *Quantum Field Theory* course. The topics covered in the present extension should be of general interest for all theoretical physics students, irrespective of the specialization that they are considering. Further study of QFT topics after this course is provided by the *Field Theory for Particle Physics* and the *Advanced Quantum Field theory* courses. Both courses continue this exploration of the rich nature of QFTs from various points of view, the first more focused towards phenomenological applications in particle physics and the second concentrating on the more formal aspects of the theory.

Instructors

The course coordinator and main instructor of the course is:

Dr. Juan Rojo
Nikhef, Room H353
j.rojo@vu.nl

The tutorial sessions will be carried out by:

Dr. Jacob J. Ethier
Nikhef Room H225
j.j.ethier@vu.nl

Students are encouraged to contact the course instructors if they would like to further discuss any matters related to the course. Meetings with the instructors will take place at Nikhef and can be arranged via email or before/after the lectures or tutorials.

Course schedule

As indicated in the Datanose page for this course:

`https://datanose.nl/#course[78133]`

the course takes place during the first four teaching weeks of January. Each week there are four hours of lectures, following by two ours of tutorial sessions. The exceptions are the first week, where there will be a regular lecture on Friday, and the last (fourth) week, where on Friday we will have the exam of the course. In Table 1 we indicate for each class, the week, the date and time of the lecture, the type of lecture, and the name of the instructor. We also indicate the corresponding lecture room. In any case we always encourage students to check Datanose regularly for last-minute changes in the schedule.

Course assessment

The assessment of the course will be based on a **final exam**, to take place on Friday 31st of January 2019. This will be an open book exam, meaning that students are allowed to bring in their own learning materials, such as textbooks and lecture notes. They can also bring their laptops but wireless connection needs to be switched off during the exam. A minimum mark of 6 over 10 will be required in the exam to pass the course.

Week	Day	Date	Time	Type	Staff	[redacted]
2	Monday	06-01	09.00	Lecture 1	**JR**	**SP D1.111**
2	Tuesday	07-01	15.00	Lecture 2	**JR**	**SP C0.110**
2	Friday	10-01	09.00	Lecture 3	**JE**	**SP G2.10**
3	Monday	13-01	09:00	Lecture 4	**JR**	**SP D1.111**
3	Tuesday	14-01	15:00	Lecture 5	**JR**	**SP C0.110**
3	Friday	17-01	09:00	Tutorial 1	**JE**	**SP D1.111**
4	Monday	20-01	09:00	Lecture 6	**JR**	**SP D1.111**
4	Tuesday	21-01	15:00	Lecture 7	**JR**	**SP C0.110**
4	Friday	24-01	09.00	Tutorial 2	**JE**	**SP C1.112**
5	Monday	28-01	09.00	Lecture 8	**JR**	**SP C1.112**
5	Tuesday	29-01	15:00	Lecture 9	**JR**	**SP G2.10**
5	Friday	31-01	**09:00**	**Exam**	**JR**	**REC C1.03**

Figure 1. Course schedule. For each class, we indicate the week, the date and time of the lecture, the type of lecture, and the name of the instructor. We also provide the corresponding lecture room. This information is also available via the Datanose page of the course.

Course outline

In the first part of the course, we introduce calculations in quantum theory beyond the Born approximation, showing how ultraviolet divergences arise in loop diagrams for the specific case of $\lambda\phi^4$ theory. We also demonstrate how in renormalizable quantum field theories these divergences can be absorbed into a redefinition of the Lagrangian bare (unphysical) parameters. We will introduce a useful language to relate the behaviour of quantum field theories at energy different scales, called the renormalization group equation. We will then discuss the main concepts underlying the powerful Effective Field Theory paradigm, and discuss how one can construct towers of QFTs with different degrees of freedom relevant for different energy regimes.

In the second part of the course, we move to discuss of the quantization of Quantum Electrodynamics (QED), the quantum field theory of the electromagnetic interactions, deriving in particular in canonical quantization of the photon field and deriving the Feynman rules of the theory, both when the photon is coupled to scalars and to fermions. In this part we will also present for completeness a review of the classical symmetries of the Abelian gauge theory, and complete the discussion by performing calculations of a number of simple scattering processes in scalar QED. We will study in particular how the symmetries of Abelian gauge theory determine to a big extent the properties of scattering amplitudes both at the Born level and once loop corrections are included.

Teaching materials

The main resource for this course are the lecture notes, that will be available via the corresponding Canvas page of this course:

https://canvas.uva.nl/courses/10977

These lecture notes will be updated as the course goes on. These notes are however not meant to be the only study resource, but rather they represent a guide to help the student to navigate within the course material and when needed consult additional references. In addition, the lecture notes have not been completely proof-read or cross-checked, and students are encouraged to let the instructors know of mistakes and typos that they might find. These lecture notes are naturally complemented by the corresponding lecture notes of Daniel Baumann's *Quantum Field Theory* course, which for completeness have also been linked to the Canvas page of this course.

The topics covered in this course are inherited to different degrees from three main textbooks, namely:

- *Quantum Field Theory*, Mark Srednicki, Cambridge University Press.

  This textbook is freely accessible online as a .pdf file:

  https://www.physics.utoronto.ca/~luke/PHY2403F/References.html

- *Quantum Field Theory and the Standard Model*, Matthew D. Schwartz, Cambridge University Press.

  More information about this textbook can be found here:

  http://users.physics.harvard.edu/~schwartz/teaching

- *An introduction to Quantum Field Theory*, Michael E. Peskin and Daniel V. Schroeder, Westview Press. A classic QFT textbook. The solutions for the exercises in some of the earlier chapters of the book can be found here:

  http://homerreid.dyndns.org/physics/peskin/index.shtml

For the interested students, other related online lectures notes that they might consider to also study are the following ones:

- David Tong's lecture notes on Quantum Field Theory:

  http://www.damtp.cam.ac.uk/user/tong/qft.html

- Sidney Coleman's Harvard Quantum Field Theory course:

https://arxiv.org/pdf/1110.5013.pdf

- Michael Luke's QFT lecture notes

https://www.physics.utoronto.ca/~luke/PHY2403F/References.html

Finally, let me mention that a potentially useful overview of several QFT textbooks by Flip Tanedo can also be found here:

https://fliptomato.wordpress.com/2006/12/30/
from-griffiths-to-peskin-a-lit-review-for-beginners/

Course learning objectives.

At the end of the course, the students should be able to:

- Describe the physical origin of the infinities that arise in calculations of scattering processes in Quantum Field Theory beyond the Born approximation, and how to regularise them.
- Calculate finite one-loop processes in QFT by removing these infinities using the renormalization method in the case of the scalar $\lambda\phi^4$ theory, and demonstrate how physical predictions for scattering cross-sections are made finite this way.
- Demonstrate how physical phenomena in Quantum Field Theory taking place at different distance and energy scales by using the renormalization group.
- Construct related QFTs valid in different energy domains using the formalism of Effective Field Theories.
- Analyze the quantized version pf Maxwell's electromagnetism and perform tree-level calculations involving spin-one photon gauge fields and their interaction with fermions
- Demonstrate what are the implications of electromagnetism's classical symmetries at the QFT level, and explain how these symmetries allow predicting all-order results in the quantum theory.