UNIVERSITY OF DURHAM

Centre for Particle Theory

M.Sc. in Particles, Strings and Cosmology

2022–2023

DEPARTMENT OF MATHEMATICAL SCIENCES
AND
DEPARTMENT OF PHYSICS

Contents

1 Introduction

Welcome to the MSc in Particles, Strings and Cosmology!

The aim of the course is to bring students in twelve months to the frontier of theoretical high-energy physics. You can look forward to an enjoyable year with exciting and demanding lectures given by leading experts in the field.

This booklet contains information specific to the MSc in Particles, Strings and Cosmology. For information concerning general University regulations, examination procedures etc. you should consult the Faculty Handbooks and the University Calendar, which provide the definitive versions of University policy.

If at any time you would like to discuss aspects of your course, or if there are any questions about the Department which this booklet leaves unanswered, please contact the Course Director. This is Dr. Nabil Iqbal (MCS 3003, nabil.iqbal@durham.ac.uk) for the fall term and Dr. Martin Bauer, (OC323, martin.m.bauer@durham.ac.uk) for the remainder of the year. You may also contact your supervisor. For administrative queries, please contact the Maths Learning and Teaching Team, maths-teaching@durham.ac.uk (MCS 2093).

Much information about the Department and, in particular, about the Centre for Particle Theory can be found on the web at

http://www.dur.ac.uk/mathematical.sciences (Mathematics Department Homepage)

http://www.dur.ac.uk/physics (Physics Department Homepage)

http://www.cpt.dur.ac.uk/ (Centre for Particle Theory Homepage)

http://www.ippp.dur.ac.uk/ (Institute for Particle Physics Phenomenology Homepage)

This particular year will be the second that is affected by the presence of Covid-19. We encourage everyone to be aware of university and government guidelines related to the virus. The Durham University Covid Response web page is here.

https://www.dur.ac.uk/coronavirus/ (Durham University Covid Response)

We will operate according to university guidelines; as of this writing this permits (some) face-to-face teaching. If you have concerns about attending face-to-face teaching, please contact the course director. More details about how the course will be affected by Covid-19 are described below.

Ph.D. students please note:

Although you are not registered for the MSc course, it is important that you take the lectures seriously, as they will be the basis for your further study. In particular, the Centre expects all students registered for the PhD to achieve an average mark on the four end-of-term exams of at least 70%. If you miss this target, you will be required to demonstrate satisfactory progress by completing a small project during the summer term, and this together with your exam results will be used to decide your progression into the second year.

2 The Centre for Particle Theory

The Durham research group in theoretical high energy physics has members in both of the departments of Mathematical Sciences and Physics. It is one of the largest and most active groups in the United Kingdom, with interests which range over a wide spectrum of topics associated with the field of elementary particles. This is reflected in the variety of lecture courses and dissertation topics available in the MSc programme. Durham also hosts the Institute for Particle Physics Phenomenology (IPPP). The Institute is located in the Ogden Centre for Fundamental Physics, which will also be the location for all graduate lectures.

Whether members of Physics, Mathematics or the IPPP, all researchers/students in high energy theory belong to the Centre for Particle Theory (CPT) which is a close-knit group. Besides lectures together there is a series of CPT colloquia. In addition there are several series of weekly seminars with external and internal speakers organised around more specialised topics. You are strongly encouraged to go to as many of these as possible as a useful way of acquainting yourself with areas of current research. More information about the seminar schedules can be found on the following web page at

http://www.dur.ac.uk/cpt/seminars/

Other events in the IPPP and Mathematics department can be found at

http://www.ippp.dur.ac.uk/workshops

http://www.dur.ac.uk/mathematical.sciences/events/

3 Getting started

There will be an induction and welcoming event on Tuesday, Sept 27th; you will receive more specific information by email. This will be a chance to meet members of the CPT and to pick up information on the postgraduate lecture courses and other matters.

There are several administrative matters that must be seen to at the beginning of the academic year. It would be wise to complete them before lectures begin on Monday October 3rd.

New postgraduate students will need to obtain their campus cards. They are necessary to gain access to the main Library and a to number of other University buildings. They are also needed to loan books from the Main Library. At the same time you should be given your user name and password for a **computer account** with the University's IT Service.

Libraries

The Main University Library is located on the Science site close to the Department of Physics. It contains a large selection of books and journals of interest to particle physicists. To loan books you will require a Campus Card.

Computing Facilities

The main university computing facilities are run by the Computing and Information Services (CIS). You should have been registered automatically for an CIS account when completing your University Registration and obtaining your Campus Card (see above). In case of any problems or if you need any further information about the University's computing facilities, you should visit the IT Help-Desk which is situated on the ground floor of the University Library. The University maintains a number of clusters of PC's and Unix machines.

4 Prerequisites

Students entering the MSc course are supposed to be familar with a number of topics, which would normally be covered in an undergraduate degree. They fall into two categories, namely elementary mathematics and elementary physics. It would be a very good idea to recapitulate these topics before starting the course, because familiarity with these concepts will be assumed.

1. **Elementary Mathematics:**

   - **Linear algebra:** Scalar products of vectors, vector products. Matrices, multiplication, inversion, determinants, eigenvalues and eigenvectors diagonalisation by change of basis, orthogonal and unitary matrices, diagonalisation of symmetric matrices by orthogonal matrices.
   - **Complex numbers:** addition, multiplication, complex conjugate. Complex functions, differentiation, Cauchy-Riemann equations. Elementary functions: exp(z), log(z), cos(z), cosh(z), etc. Cuts and branches. Cauchy's integral formula. Evaluation of integrals (and series) by calculus of residues. Analytic continuation.
   - **Elementary group theory:** axioms of groups, examples: GL(n), SL(n), O(n).
   - **Functions of several variables:** Continuity. Partial differentiation. Chain rule. Taylor polynomial in two variables. The gradient and directional derivatives of a function. Line integrals of functions and vector fields. The divergence and the curl of a vector field. Index notation, summation convention. Epsilon(ijk) and delta(ij). Local and global extrema of functions. Extrema of functions with constraints.
   - **Multiple Integration:** iterated sums, double and triple integrals by repeated integration, volume enclosed by surface, Jacobians and change of variables. Line, surface and volume integrals. Stokes' and divergence theorems.
   - **PDEs:** Solution of Poisson's and Laplace's Equations: Uniqueness of solution of Laplace's and Poisson's equations. General solution of Poisson's equation. Green's function. Simple examples of solution of Laplace's equation by separation of variables.
   - **Fourier Series:** Orthogonal functions and Fourier series. Convergence, periodic extension, sine and cosine series, half-range expansion. Fourier transform and inverse, convolution theorem. Solution of heat equation on n-dimensional Euclidean space using Fourier transform and construction of heat kernel. Connection between heat kernel and Green's function. Laplace transform.

2. **Elementary physics:**

   - **Mechanics:** Frames of reference, Newton's laws in vector form, forces, mass, momentum, gravitational force, projectiles, Lorentz force and charged particles inconstant electromagnetic fields. Concepts of energy and angular momentum. Simple harmonic motion and oscillations about a stable equilibrium. Damped oscillations and resonance. Central forces and the use of energy and angular momentum to study planetary motion. Waves and strings, including the derivation of the wave equation for small amplitude vibrations and its solution by separation of variables. Energy, energy density, energy carried by wave.

- **Lagrangian Mechanics:** Lagrangian and Hamiltonian Dynamics: Hamilton's principle in dynamics. Generalised coordinates and momenta. Derivation of Lagrange's equations. Generalised forces. Conservative forces. Ignorable coordinates and conservation laws. Noether's theorem. Systems with constraints Hamilton's equations. Formulation in terms of Poisson brackets. Small oscillations of systems of particles: Positions of equilibrium and stability. Normal modes of oscillation and normal coordinates. Stationary properties of frequencies of systems with constraints. Basic variational calculus.
- **Special Relativity:** Inertial frames. Speed of light. Events. Spacetime. Time dilation and length contraction. Lorentz transformations. Standard Lorentz boosts. Composition of velocities. Doppler effect. Group structure of standard Lorentz boosts. Four vectors: Minkowski spacetime. Lorentz and Poincare groups. Worldline and light cone. Causality. Proper time, velocity, acceleration. Space-time vectors and tensors. Mass-energy equivalence. Einstein's relation. Zero-mass particles. Systems of free particles: Conservation of 4-momentum. Centre-of-mass frame. Collision processes.
- **Classical Electromagnetism:** Maxwell's equations with sources. Potentials and gauge invariance. Wave equation. Energy and momentum conservation (including energy density, Poynting vector, stress tensor). Plane waves. Polarisation. Retarded potentials. Special Relativistic Formulation of Electromagnetism: invariances of Maxwell's equations, the equations with microscopic sources expressed as tensor equations in Minkowski spacetime. Relativistic equation of motion for a charged particle in an external electromagnetic field.
- **Quantum Mechanics:** Photo-electric effect, atomic spectra, wave-particle duality, uncertainty principle.Vectors in Hilbert space, linear operators, hermitian operators, eigenvalues, complete sets, expectation values, commutation relations, observables and commuting operators, symmetries and spectra. Dirac notation. Schroedinger and Heisenberg pictures. Position operator, Harmonic Oscillator, creation-annihilation operators. Angular momentum, spin representations. Time–dependent and time–independent Schroedinger equation. Probability interpretation. Currents. Plane-waves, spreading of a wave-packet. Perturbation theory, interaction picture.

In addition, there are a number of things which you may have studied, but if you haven't it would be a good idea to read about before you come because these will be developed in greater depth at the beginning of the course:

3. <u>**Advanced topics:**</u>

   - **General Relativity:** gravity as geometry, equivalence principle. Differential Manifolds: spacetime as a manifold, coordinates and coordinate transformations, tangent vectors, tensors under general co-ordinate transformations.

Metric: distance relationships, light cones. Covariant Derivative: parallel transport, connection coefficients, differentiating tensors, metric connection, geodesics. Curvature: Riemann tensor, characterisation of flat space, parallel transport around closed curves, commutation formulae, Bianchi identity, Einstein tensor, geodesic deviation. Einstein's equations, linearized theory and Newtonian limit, Einstein–Hilbert action.

- **Quantum Field Theory:** Quantisation of free scalar fields: Multi-particle quantum mechanics, canonical quantisation of free scalar fields, Fock space, anti-particles, propagators, causality. Evolution operators, perturbative expansion, Wick's theorem, Feynman diagrams in position and momentum space, LSZ reduction, scattering matrix, cross sections.
- **Statistical Mechanics:** Thermodynamics: Thermal equlibrium, the laws of thermodynamics. Equations of state, ideal gas law. Classical statistical mechanics: Statistical basis of thermodynamics: microstates, macrostates and the thermodynamics limit. Ideal gas. Gibbs paradox and entropy. Microcanonical, canonical and grand-canonical ensembles. Distributions and identical particles: Maxwell-Boltzmann distribution. Bose and Fermi distributions.

5 The MSc Degree

Overview

The MSc course is organised into five *modules*: two modules of lecture courses in the fall term, two modules of lecture courses in the spring term, and a dissertation counting as the fifth module. You should aim to pass each module in order to successfully complete the course.

The first two lecture courses take place from October-December, followed by two examinations in January; the second two spans January-March, followed by another two examinations in April.

The remaining six-month period (April-September) is occupied with the preparation of the dissertation. The dissertation is not normally expected to be the report of publishable, original research you have done yourself; rather, it is an independent investigation, guided by your supervisor, of the literature surrounding a special topic. The purpose of this part of the programme is to assist you to develop creative and critical thinking, the ability to assemble material from several sources and to write an extended report. The dissertation should give a coherent account of the topic, presented in an original, well organised and appropriate manner.

Please note that you will be required to submit a signed plagiarism form, without which your dissertation will not be assessed. It is attached to this document as an appendix.

In addition to the official lecture modules we will organize a set of advanced lectures in the Easter term (May-June) which you can attend voluntarily and which will not be examined.

Details of the lecture courses and guidelines and regulations for the preparation of the dissertation are given below.

This year lectures will take place in person.

The Courses

Most of the instruction will take place in the form of **lectures** that take place in two-hour blocks, and will be held face-to-face in OC218. The course also has **tutorials** taught by our teaching assistants.

Overall Structure

The exact timetable for the course can be found on Blackboard Ultra. In our timetables we often use a peculiar week numbering scheme, where for example week 1 refers to the first teaching week of the academic year. The precise translation to Gregorian calendar dates can be found at

https://www.dur.ac.uk/dates/

We also often refer to the two terms using the nomenclature of the university: the fall term is thus called *Michaelmas*, and the spring term is *Epiphany.*

As you can see from the timetable, the lectures are split into two teaching blocks of four weeks each. Each teaching block is filled up by one of the main lecture modules[1], and are each worth 30 credits. The modules are split up into different teaching courses which are described later on in the handbook.

- Elementary Particle Theory I A (**PHYS52230**), Michaelmas weeks 1-4. Covers QFT1, IFT, GRP and GR).
- Elementary Particle Theory I B (**PHYS52330**), Michalemas weeks 6-9. Covers QFT2, SM, QED, and COS 1).
- Elementary Particle Theory II A (**MATH52430**), Epiphany weeks 11-14. Covers CFT, QCD, SUSY, ASTRO, NU, and RG.
- Elementary Particle Theory II B (**MATH52530**), Epiphany weeks 16-19. Covers FLAV, STRINGS, AMPL, NPP, COS II, and HIGGS.

The dissertation – described further below – also counts as a 60 credit module.

In more detail:

- **Michaelmas Term (Monday 5th October - Friday 10th December)** is *ten weeks* long, and there will be teaching in weeks 1-4 (starting on Mondays) and weeks 6-9. There will be a break from lectures in week 5, during which students will be expected to try to revise material from the first four weeks, and to complete any homework assignments set by the lecturers. Michaelmas term's courses will be assessed in two examinations tentatively scheduled on

  Wednesday January 4th, 2022 and Friday January 6th, 2022.

- **Epiphany Term: Monday 9th January - Friday 10th March** is *nine weeks* long, and there will be teaching in weeks 11-14 and 16-19. There will be a revision break in week 15. The two exams on the second term's courses are tentatively scheduled on

  Wednesday April 19th, 2022 and Friday April 21st, 2022.

[1]Some of these courses are in the Physics department and some in Mathematics; this is purely for administrative reasons and doesn't have any bearing on the content.

Each module spans multiple *courses* or topics. These individual lecture courses vary in length. Typically they contain *16 lectures* but there are a few cases with either *8 lectures* or *24 lectures.*

Details about all the individual courses are given later in this booklet, in particular information about useful books and other reading materials.

It is expected that students will attend **all the lecture courses in the Michaelmas Term**. Furthermore, the students are expected to choose **six courses from the courses in Epiphany term**, with approximately three from the first half and three from the second. Please refer to the structure of the exams described later on when making your choices.

All students are required to 'keep term' in accordance with University General Regulations. This means that they are expected to undertake work and be in attendance as required by their lecturers. There is an account of the possible consequences of not keeping term in the Graduate School's publication, Guidelines for Postgraduate Research Students and Supervisors.

From time to time lecturers will set problems for you to do. These are a valuable exercise as they test your understanding of the material. At least one set of homework should be marked by the lecturer, see below.

The Dissertation

MSc. students are expected to work on their dissertation during the Easter term and over the summer. The length of a dissertation must be around 20,000 words (in the range 40-60 pages). It must be typed (normally using TEX or LATEX) and loosely bound. More precise details concerning the format of the thesis are available in a document titled "Advice on the production of a Thesis", which can be found in the University Library. Two copies of the thesis must be handed to the Course Director (Dr. Martin Bauer) by

1st September 2023.

A list of topics which members of staff are willing to supervise will be circulated early in the Epiphany term. With many members of staff providing one or two titles, the list provides a wide choice. However, if you wish to investigate something different you will have to find a member of staff willing to supervise you. Your decision on a preferred topic and the agreement from the respective supervisor is due at

the end of week 16 (after the reading week of Epiphany).

You are encouraged to start talking to potential supervisors early in Epiphany term. The dissertations topics/supervisors will be finally assigned in week 17.

Once you have chosen your topic/supervisor, your supervisor will provide you with information concerning the preparation of the dissertation itself and with advise on how to work towards its preparation. Even where there is frequent contact during the course of the research work, it is good practice for supervisors to arrange to have regular sessions with their students at fixed times to review the progress.

All dissertations should have an introductory chapter describing the background to the work and the structure of the following chapters, a concluding chapter bringing together the themes of your dissertation, and a list of references and acknowledgements. The content of the other chapters will be very topic-dependent and the task may seem at first extremely daunting. The following advice is sometimes found to be helpful. Think of your task, at least to begin with, in terms of having to prepare a set of around six lectures on your chosen topic. These 'lectures' should be informative and interesting and explain the topic(s) at a level your MSc. colleagues would appreciate. Once you have explored the literature and determined the items you will want to 'explain', you will probably find you have your chapter headings and the material will be organised rationally. Your supervisor will be able to help you with this and assure you that you are developing in a sensible direction. Once you have the material organised you should be aiming to produce a draft of the dissertation by the end of August and give it to your supervisor for comments. After that you have a few weeks to finalise the thesis.

Commonly, students become fascinated by their topics and are tempted to write too much. Thinking in terms of the six 'lectures' and what can be achieved in an hour helps to keep the dissertation within sensible bounds.

As was mentioned before, dissertations are not expected to contain original publishable research, but there should be evidence of creativity in the way in which you deal with the material.

Feedback and Monitoring

Much of the contact between students and their adviser (for MSc students this is initially the Course Director) or later, at the dissertation stage, with their supervisor, is informal. The postgraduate students in each department have a representative on that department's Board of Studies (to whom the Management Committee of the MSc reports); but any urgent problems requiring official attention should be reported in the first instance to the Director for the degree, (Dr. Martin Bauer, OC323), or the adviser to postgraduate students in the relevant department (Prof. Simon Ross in Mathematics, and Dr. Michael Spannowsky in Physics).

In addition an MSc student representative will be on the Mathematics Department Postgraduate Studies Committee. At least twice a year students are invited to complete (anonymously) questionnaires about courses and other matters. Lecturers are generally available to answer queries on their courses and students are encouraged to approach them informally or to raise questions during lectures. Student progress is monitored through the first two terms by informal sessions with their adviser, and at the end of each term by that term's examination. In addition, each lecturer will set problems for students to try and will collect and mark work on a single occasion. Indicative results are available after each exam from the Chair of the BoE or the course director.

Assessment of the Degree

The MSc in Elementary Particle Theory consists of three compulsory modules. Your final mark for the course is averaged from the marks achieved on the individual modules, each of which carries the same weight.

- In order to **PASS the MSc** it is **necessary** to **pass each individual module**. To pass a module you must score **at least 50%**.
- In order to be awarded a **MERIT** you must pass each module and your **average mark over must be at least 60%**.
- In order to be awarded a **DISTINCTION** you must pass each module and **your average mark must be at least 70%**. In addition you must score at least **70% for your dissertation**.

Let us now discuss the assessment of each module separately.

The examination of the **Michaelmas modules** is based on the lecture courses given in the first term. There are two *two* examination papers, each accounting for together 90% of the module mark, plus an element of continuous assessment, realised through marked homework which will contribute 10% of the submodule mark. The first exam paper will examine PHYS52230, i.e. the four courses lectured in the first four weeks of term (QFT1, IFT, GRP and GR), and the second paper will examine PHYS52330, i.e. the courses given in the last four weeks (QFT2, SM, QED, COS). Each paper will contain a section A, containing one "fundamental" question for each of the four courses, and a section B which contains one more detailed harder question for each of the four courses. The rubric of these papers will be that full marks can be obtained by answering **any three** of the questions in Section A and **any two** questions from Section B[2]. In addition, the homework marks will be computed as the *average* homework mark for each of the Michaelmas courses.

The examination of the **Epiphany modules** is based on the lecture courses given in the second term. There are *two* examination papers, each accounting for together 80% of the module mark, plus an element of continuous assessment, realised through marked homework which will contribute 20% of the total module mark. The first exam paper will examine MATH52430, i.e. the material from the courses lectured in the first four weeks of Epiphany term (CFT, QCD, SUSY, ASTRO, NU, and RG) and the second paper will examine MATH52530, i.e. the material in the second four weeks (FLAV, STRINGS, AMPL, NPP, COS II, and HIGGS). In both cases the exam will contain one question for each 8 hours of lectures on a given topic. The rubric of these papers will be that the **best four** (for MSc students) or **best five** (for PhD students) of your answers to these questions will constitue the overall mark for the exam. For this term the homework mark will be computed as the *average of the best three* homeworks handed in for each four-week submodule, so six altogether over the whole term.

[2]Note that only the best three Section A and best two Section B marks will be taken to calculate your overall mark; marks for any additional questions will *not* be taken into account.

We are currently planning on having exams in person, with each exam taking place over three hours. However this remains subject to change due to Covid-19, and we will inform you about the precise procedure in due course.

If you fail an exam then you may be granted the permission to take resit exams (the mark on which will however be capped off at 50%). The resit exams, if any are needed, would take place near the end of the Easter term 2022, **tentatively** scheduled on Wednesday, June 14th for January Paper I; Friday, June 16th for January Paper II, Wednesday, June 21th for April Paper III; and Friday, June 23rd for April Paper IV. Note that the Core Regulations stipulate that you cannot resit more than 60 credits. If you have failed a module it is important to discuss the situation with the Course Director to understand carefully your options.

To proceed to write a dissertation you must pass both the Michaelmas and the Epiphany terms.

The final module (51360) consists of the dissertation. The dissertation *must* be 40-60 pages in length ($\sim 20,000$ words), and **two** copies of it have to be submitted by email to the Course Director by 1st September 2023.

The thesis is examined internally by two members of staff, and marks are moderated by the External Examiner. They will be looking for a good understanding of your topic, evidence that you have read and digested several sources, evidence that you have tackled the material critically and that you are able to explain it to them; they will also check that you have given proper acknowledgements and references. Please pay heed that you present your work in your own words – if your dissertation has too close a similarity to an existing article, your dissertation may be assessed as plagiarised. It is expected that the internal and external assessments will have been completed within six weeks.

Recommendations for the award of degrees are made by the Board of Examiners when all the marks are available. The Board of Examiners may exercise discretion and take account of special or exceptional circumstances which may have affected a candidate's performance and for which there is evidence. The views of the External Examiner are particularly influential in the case of disagreement on the mark to be awarded for a particular unit of assessment or on the final award.

Plagiarism

Along with your dissertation, you will be required to hand in a signed Plagiarism form, which has been provided as an appendix to this handbook.

This is a serious matter, and if you're not fully sure what might constitute plagiarism, you are urged to consult your supervisor. In particular, note that even if you paraphrase a given text (whether printed or on-line), you need to make sure you give the proper reference. The safest method is to present the material fully in your own words, and organise it in your own way as if you were giving a lecture to your peers.Ê

Plagiarism is referred to in the General Regulations of the University:

In formal examinations and all assessed work prescribed in degree, diploma and certificate regulations, candidates should take care to acknowledge the work and opinions of others and avoid any appearance of representing them as their own. (For example, you should say Einstein's theory of relativity, to avoid the possible implication that you are claiming to have invented it yourself.)

Unacknowledged quotation or close paraphrasing of other people's writing, amounting to the presentation of other person's thoughts or writings as their own, is plagiarism and will be penalised. In extreme cases, plagiarism may be classed as a dishonest practice under Section IV,2.(a)(viii) of the General Regulations and can lead to expulsion.

For more information on this, see the Graduate School's publication, *Guidelines for Postgraduate Research Students and Supervisors.*

Core Regulations

The Core Regulations provide a basic regulatory framework for the courses offered by the University. For our MSc they can be found at:

`https://www.dur.ac.uk/resources/university.calendar/volumeii/2022.2023/coreregsmtmd.pdf`

The practical consequences of these regulations have been described in the above, but it might be worth having a look at the details in exceptional circumstances.

6 Description of Courses & Recommended Books

The following pages contain a brief description of the courses. They are structured in five subject areas, namely

- Quantum Field Theory (QFT, 80 hours)
  containing Introductory Field Theory (IFT), Quantum Field Theory I and II (QFTI & QFTII), Quantum Electrodynamics (QED), and Supersymmetry (SUSY);
- General Relativity and Cosmology (GR/COS, 56 hours)
  containing General Relativity (GR), Cosmology I and II (COSI & COSII), Neutrinos (NU), and Astroparticle Physics (ASTRO);
- Gauge Field Theory (GAUGE, 64 hours)
  containing Group Theory (GRP), Standard Model (SM), Renormalisation Group (RG), Amplitudes (AMPL), and Non–Perturbative Physics (NPP)
- Superstring Theory (STRINGS, 32 hours)
  containing Conformal Field Theory (CFT), and Strings and D-branes (STRINGS)
- Phenomenology (PHENO, 40 hours)
  containing Strong Interactions (QCD), Higgs Phenomenology (HIGGS), and Flavour Physics and Effective Field Theories (FLAV)

Below, the individual courses and their interplay is described, including an approximate outline of the material and the learning outcomes. In addition, for each of these subject areas a list of recommended books is provided.

This information together with other useful lecture materials can be found on the web at
http://www.cpt.dur.ac.uk/GraduateStudies/

There will also be some voluntary advanced topic courses in the Easter Term which are not examined. Further details of the content of these additional courses will be published later.

Some books that are used in a number of lectures are

- M. E. Peskin and D. V. Schroeder, "*An Introduction to QFT*" (Addison Wesley,1984)
- C. Itzykson and J.-B. Zuber, "*Quantum Field Theory*" (McGraw-Hill,1980)
- T. P. Cheng and L. F. Li, "*Gauge Theory of Elementary Particles*" (Oxford University Press, 1984)
- P. Di Francesco, P. Mathieu and D. Sénéchal, "*Conformal Field Theory*", Springer (1997)
- J. Zinn-Justin, "*Quantum field theory and critical phenomena*" (Oxford University Press)

- R. D'Inverno, "*Introducing Einstein's Relativity*" (Oxford University Press, 2003)
- J. B. Hartle, "*Gravity; An Introduction to Einstein's General Relativity*" (Addison-Wesley,2003)

Students are encouraged to try to have them on long-term loan or to buy them.

QUANTUM FIELD THEORY

INTRODUCTORY FIELD THEORY (24 lectures)

Dr. R. Alonso

This course presents the foundations of quantum field theory (QFT) building on classical and quantum mechanics and special relativity. It is designed to provide the student with: a critical comprehension of QFT, the skills to derive results for operators in Fock space, transition matrix elements, cross sections and decay rates, and the background knowledge to undertake the subsequent QFT modules and explore more advanced topics. The content of this module as outlined below covers the opening chapters of introductory QFT books (e.g. chapters 1-4 of Peskin & Schroeder).

- **Classical mechanics and classical field mechanics**
  Lagrangian formulation. Legendre transform and Hamiltonian formulation. Poisson bracket.
- **Second quantization**
  Canonical commutation relations. Creation and annihilation operators. Fock Space and operators. Causality.
- **Symmetry in QFT**
  Infinitesimal transformations and generators. Lorentz and internal groups. Noether theorem. Conserved currents.
- **The Scattering matrix**
  Evolution operator. Dyson's formula. Transition matrix elements. Fermi's Golden rule. Decay rates. Cross sections.
- **Perturbation theory**
  Wick Theorem. Feynman diagrams. Correlation functions. LSZ reduction formula.
- **Fermions**
  Lorentz group representations. Dirac equation. Dirac field quantization. Spin-statistics. Elements of QED.

Additional material for the Course

- M. E. Peskin and D. V. Schroeder, "*An Introduction to QFT*" (Addison Wesley, 1995)
- C. Itzykson and J.-B. Zuber, "*Quantum Field Theory*" (McGraw-Hill,1980)
- P. Ramond, "*Field Theory, A Modern Primer*" (Benjamin, 1994)
- S. Weinberg, "*Quantum Theory of Fields*", vol I and II (Cambridge University Press, 1996)

- A. Zee, "*Quantum Field Theory in a Nutshell*" (Princeton University Press, 2010)
- D. Tong, "*Lectures on Quantum Field Theory*" (http://www.damtp.cam.ac.uk/user/tong/qft.html)
- F. Mandl and G. Shaw, "*Quantum Field Theory*" (Wiley, 1984)
- L. H. Ryder, "*Quantum Field Theory*" (Cambridge University Press, 1996)

QUANTUM FIELD THEORY I & II (8+16 lectures)

Dr. M. Lemos and Dr. A. Braun

This course will describe some of the basic ingredients of quantum field theories in the language of path integrals, and as such is complementary to the canonical quantisation approach in the Introductory Field Theory course. Path integrals are first introduced in the familiar context of quantum mechanics, before being applied to field theory where techniques are developed to allow the calculation of scattering amplitudes in gauge theories. Most of the content of this course can be found in Peskin and Schroeder, particularly in chapters 9, 10 and 16, although other textbooks are also useful, especially Feynman and Hibbs for an introduction to path integral quantum mechanics.

Outline of the Course

- **Path Integral Quantum Mechanics:**
  Derivation of path-integal formulation of quantum mechanics. Examples including the simple harmonic oscillator. Formulation of perturbation theory, and Feynman diagram representation. Extension to field theory.

- **Green functions:**
  LSZ reduction formulae for scalar and Dirac fields. Green functions. Perturbation theory and derivation of Feynman rules. Generating functionals for disconnected and connected Green functions. Introduction to Grassmann numbers. Path integrals for fermions. Global symmetries and Ward identities in the functional formalism.

- **Renormalisation:**
  One-loop renormalisation of ϕ^4 theory. General discussions of perturbative renormalisability. Brief discussion of regulators.

- **Gauge theory:**
  Abelian and non-Abelian gauge invariance, Yang-Mills action. Gauge fixing by Faddeev-Popov method, ghosts, Feynman rules.

Additional material for the Course

- R.P. Feynman and A.R. Hibbs, "*Quantum Mechanics and Path Integrals*" (Dover Books on Physics, 2010)
- M.E. Peskin and D.V. Schroeder "*An Introduction to QFT*" (Addison Wesley, 1984)
- A. Zee, "*Quantum Field Theory in a Nutshell*" (Princeton University Press, 2010)
- M. Srednicki, "*Quantum Field Theory*" (Cambridge University Press, 2007)

QUANTUM ELECTRODYNAMICS (16 lectures)

Dr. M. Schönherr

The course will develop techniques for computing scattering processes at tree level and one-loop.

The first part of the course builds on the Introduction to Quantum Field Theory course and is concerned with the application of Feynman rules to elementary scattering processes. The second part introduces Bremsstrahlung and loop corrections and describes how to handle the infrared and ultraviolet divergences that are present.

Outline of the Course

- **QED at tree level**: Application of Feynman rules for tree-level processes in QED, Dirac-algebra, polarisation sums, unpolarised cross sections, crossing symmetry.
- **QED at one loop**: UV singularities, dimensional regularisation, techniques for evaluation of one-loop integrals, renormalisation, IR singularities.

Additional material for the Course

- M. E. Peskin and D. V. Schroeder, "*An Introduction to QFT*" (Addison Wesley, 1994)
- I. J. R. Aitchison and A. J. G. Hey, "*Gauge theories in particle physics: A practical introduction*" (CRC Press, 1982)
- M. Kaku, "*Quantum Field Theory: A Modern Introduction*" (Oxford University Press Inc. 1994)
- C. Itzykson and J. B. Zuber, "*Quantum Field Theory*" (McGraw-Hill, 1980)

GENERAL RELATIVITY AND COSMOLOGY

GENERAL RELATIVITY (16 lectures)

Prof. S. Ross

General Relativity, Einstein's theory of gravity, is one of the most self-contained and elegant theories on the market; it has sometimes been viewed as somewhat disconnected from "real physics". However, with the rise in popularity of the superstring as a quantum theory of the interactions of nature including gravity, the importance of its classical limit, GR, has re-emerged. This course introduces many of the essential features of modern gravity theory, the notion of a space-time manifold and differential geometry, and black holes.

Outline of the Course

- **Setting up differential geometry**:
  manifolds, vectors and tensors, abstract index notation.
- **Differentiation on manifolds**:
  forms, Lie and covariant derivative; geodesics. The connection and curvature.
- **Structure on the manifold**:
  fields and energy momentum. The Einstein equations.
- **Solving the Einstein equations**:
  Black holes, gravitational waves and cosmology - exact and approximate solutions.
- **Frontiers**:
  Gravity in higher dimensions, outlook

Additional material for the Course

- R. M. Wald, "*General Relativty*" (University of Chicago Press, 1984)
- S. Carroll, "*Spacetime and Geometry: An Introduction to General Relativity*" (Addison-Wesley 2003)
- J. B. Hartle, "*Gravity; An Introduction to Einstein's General Relativity*" (Addison-Wesley,2003)
- C. W. Misner, K. S. Thorne, and J. A. Wheeler, "*Gravitation*" (Freeman, 1973)

COSMOLOGY I (16 lectures)

Dr. R. Alonso

This graduate course aims to give an introduction to modern cosmology. Starting from the traditional Friedmann-Robertson-Walker cosmological solutions, we will go on to discuss present-day cosmological models for the evolution of the universe. Observational constraints will be discussed and the inflationary scenario will be considered. Finally, an introduction will be given to current research in particle cosmology.

Outline of the Course

- **The Observed Universe**: Friedmann-Robertson-Walker cosmology (radiation, matter and de Sitter/ accelerating universe solutions).
- **Thermal history of the Universe**: The standard cosmological model and its successes.
- **Confronting observation**: The inflationary paradigm; late time acceleration.

Additional material for the Course

- Andrew Liddle, *An Introduction to Modern Cosmology* (Wiley-Blackwell 2015)
- R. D'Inverno, "*Introducing Einstein's Relativity*" (Oxford University Press, 2003)
- Scott Dodelson, "*Modern Cosmology*" (Amsterdam: Academic Press, 2003)
- Steven Weinberg, "*Cosmology* " (Oxford University Press, 2008)
- M. Trodden and S. Carroll, "*TASI Lectures: Introduction to Cosmology*" [astro-ph/0401547]

COSMOLOGY II (8 lectures)

Dr. D. Croon

This graduate course will discuss the latest discoveries in cosmology and how modern observations have shaped our understanding of the Universe (evolution, content, object formation).

Outline of the Course

Cosmological perturbation theory: perturbations of the Inflaton in the early universe will be studied in detail. The relation to observations of inhomogeneities in the cosmic microwave background and observations of large scale structure will be sketched.

Additional material for the Course

- Dodelson & Schmidt, *Modern Cosmology* (2nd ed), (Academic Press)
- Weinberg, *Cosmology*, (Oxford)
- Carroll, *Spacetime and Geometry*, (Cambridge)

NEUTRINO PHYSICS (8 lectures)

Dr. J. Turner

The aim of the course is to introduce the ideas and concepts of modern neutrino physics and astroparticle physics. The recent observation of neutrino oscillations implies that neutrinos are massive and mix. This constitutes the first evidence of new Physics beyond the Standard Model. The course will review i) the theoretical aspects of neutrino oscillations and the present knowledge of the oscillation parameters, ii) the non–oscillation searches for neutrinos, including neutrino less double beta decay and the issue of Majorana neutrinos. It will then move on to consider extensions of the Standard Model which can explain neutrino masses and their smallness. It will also briefly cover the role of neutrinos in the Early Universe, focusing on e.g. neutrinos as dark matter, baryogenesis and leptogenesis.

Outline of the Course

- **Neutrino oscillations**:
  Theory, experiments, present knowledge of neutrinos and questions for the future;
- **Nature of neutrinos and Neutrino masses**:
  Majorana versus Dirac particles, Dirac and Majorana masses, origin of neutrino masses beyond the Standard Model;
- **Neutrinos as Dark Matter**:
  light neutrinos as hot dark matter, sterile neutrinos as warm dark matter;
- **Baryogenesis and Leptogenesis**:
  Big Bang Nucleosynthesis, neutrinos and the Early Universe.

Additional material for the Course

- C. Giunti and C. W. Kim, "*Fundamentals of Neutrino Physics and Astrophysics*" (Oxford University Press, USA, 2007);
- A. Strumia and F. Vissani, "*Neutrino masses and mixings and...*", arXiv:hep-ph/0606054;
- J. Lesgourgues and S. Pastor, "*Massive neutrinos and cosmology*", Phys. Rept. 429 (2006) 307 [astro-ph/0603494].

ASTROPARTICLE PHYSICS (8 lectures)

Dr. J. Turner

In this course we will concentrate in the problem of dark matter in the Universe, one of the clearest hints for new Physics beyond the Standard Model. We will begin by summarising the astrophysical and cosmological observations that evidence the need for a new (and abundant) type of matter in the Universe that does not emit or absorb light. Then, the production of dark matter in the Early Universe will be studied, computing its relic abundance. We will observe that a generic massive particle with Electroweak interactions (WIMP) can reproduce the observed dark matter density. We will then investigate various particle physics models that can accommodate dark matter candidates. Finally, the detection of dark matter particles will be addressed. We will describe the main detection strategies (direct, indirect and in colliders), review the current experimental situation and future prospects.

Outline of the Course

- **Motivation for dark matter**:
  Rotation curves of spiral galaxies, Virial Theorem in Galaxy Clusters, Cosmological Evidence;
- **Dark matter production**:
  Thermal equilibrium and freeze out in the Early Universe, relic density of dark matter, hot and cold dark matter, the WIMP paradigm;
- **Dark Matter Candidates**:
  candidates in extensions of the Standard Model, non-WIMP candidates;
- **Dark Matter Searches**:
  Direct detection experiments, indirect searches, dark matter in colliders.

Additional material for the Course

- E.W. Kolb and M.S. Turner "*The Early Universe*", Westview Press (1994).
- G. Bertone, D. Hooper and J. Silk, "*Particle dark matter: Evidence, candidates and constraints*", Phys. Rept. 405 (2005) 279 [hep-ph/0404175].
- "*Particle Dark Matter: Observations, Models and Searches*", Cambridge University Press, Ed. G. Bertone (2010).

GAUGE FIELD THEORY

GROUP THEORY (12 lectures)

Prof. A. Taormina

This course concerns various aspects of the continuous groups which appear in High Energy Physics and Conformal Field Theory. After reviewing some general properties of abstract groups, Lie groups and Lie algebras will be introduced with relevant examples. This will be followed by the general classification of semi-simple Lie algebras provided by Dynkin diagrams.

Outline of the Course

- Basic notions of group theory
- Lie groups and Lie algebras
- U(n), SO(n) and their representations
- The classification of semi-simple Lie algebras
- Representations: roots and weights

Additional material for the Course

- H. Georgi, "*Lie Algebras in Particle Physics*" (Perseus Books 1999)
- R. Cahn, "*Semi Simple Lie Algebras and their Representations*" (Frontiers in Physics Series Volume 59 or http://www-physics.lbl.gov/~rncahn/book.html)
- H. Samelson, "*Notes on Lie Algebras*" (Springer, 1990)
- W. Fulton and J. Harris, "*Representation Theory: A First Course*" (Springer Science & Business Media, 1991)
- J. Fuchs and C. Schweigert, "*Symmetries, Lie Algebras and Representations*" (Cam. Monographs in Math. Physics)

THE STANDARD MODEL (16 lectures)

Prof. V.V. Khoze

The course constructs and studies the Lagrangian of the Standard Model of Glashow, Weinberg and Salam, starting from the basic ideas of Lorentz and local gauge invariance, building on the field and group theory courses.

Outline of Course

- **Space-Time symmetries**: The Lorentz and Poincaré Groups are presented concentrating on the representations of the groups, the existence of chiral fermions and the construction of Lorentz invariant actions.
- **Gauge theories** The QED Lagrangian is extended to the case of local gauge invariance under non-Abelian gauge groups such as $SU(2)$ and $SU(3)$. A chiral gauge theory, Glashow's model, based on the gauge group $SU(3) \times SU(2) \times U(1)$ is constructed.
- **Spontaneous symmetry breaking, Higgs particles, Salam-Weinberg model** Local gauge invariance requires massless gauge bosons. The idea of spontaneous symmetry breaking, giving massive vector bosons, is therefore introduced, leading to a discussion of the Higgs mechanism. The generation of fermion masses, by introducing Yukawa terms into the Lagrangian, is also considered.
- **Beyond the Standard Model**: The extension beyond the Standard Model to Grand Unified theories (GUTs) is motivated, and the hierarchy problem which unfortunately results is illustrated with the minimal $SU(5)$ GUT. The way in which supersymmetry avoids the hierarchy problem is finally sketched.

Additional material for the Course

- M. E. Peskin and D. V. Schroeder, "*An Introduction to QFT*" (Addison Wesley, 1994)
- T. P. Cheng and L. F. Li, "*Gauge Theory of Elementary Particles*" (Oxford University Press, 1984)
- F. Halzen and A. D. Martin, "*Quarks and Leptons*" (Wiley, 1984)
- A. Signer, "*Abc of SUSY* (arXiv:0905.4630)

RENORMALISATION GROUP (8 lectures)

Dr. M. Anber

The course introduces the concept of renormalisation group flow in quantum field theory building on previous lessons about renormalisation in other lectures on QFT. Applications to different field theories, including gauge theories, will be described.

Outline of the Course

- Wilson's renormalization group. Brief review of regularisation/renormalization in continuum QFT with examples. Introduction of Wilson's renormalization group using the path integral formulation of QFT. Implementation in scalar ϕ^4 theory.
- Callan-Symanzik equation. Renormalisation conditions. Callan-Symanzik equations. Introduction of β and γ functions. Renormalisation group equations.
- Renormalisation group flow in renormalised perturbation theory. Examples in scalar ϕ^4 theory in different dimensions, QED, non-abelian gauge theories. Asymptotic freedom in gauge theories.

Additional material for the Course

- M. E. Peskin and D. V. Schroeder, *"An introduction to QFT"* (Addison Wesley, 1994)
- J. Zinn-Justin, *"Quantum field theory and critical phenomena"*, (Oxford University Press, 2002)
- K. G. Wilson and J. B. Kogut, " *The Renormalization group and the epsilon expansion*", Phys. Rept.12:75-200, 1974.

AMPLITUDES (8 lectures)

Dr. A. Lipstein

Scattering amplitudes are the basic quantities that we need to compute to be able to predict the outcome of scattering experiments. Feynman diagrams provide an intuitive understanding of their structure but are exceedingly cumbersome to calculate with. Often there can be many cancellations between the diagrams that contribute to any given amplitude, resulting in simple final expressions. Understanding the mathematics that underlies this simplicity has recently led to remarkable advances in our ability to compute the amplitudes themselves. The course aims to provide an introduction to these techniques.

Outline of the Course

- **Spinor variables:** massless Dirac equation, dotted and undotted indices, helicity, conjugation, spinor products
- **Gauge theories:** polarization vectors and spinors, helicity, self-duality, LSZ, gauge fixing, colour ordering, fermions
- **Gauge invariance and tree amplitudes:** 3-point, 4-point, n-point all+, n-point one
- **BCFW** in general, and applied to MHV amplitudes
- **N=4 Super-Yang-Mills amplitudes, Gravity amplitudes** (If time permits)

Additional material for the Course

- Herbi K. Dreiner, Howard E. Haber and Stephen P. Martin, "*Two-component spinor techniques and Feynman rules for quantum field theory and supersymmetry*", hep-ph/0812.1594;
- G. 't Hooft, "*A planar diagram theory for strong interactions*, Nucl. Phys. **B72** (1974) 461 - 473;
- R. Britto, F. Cachazo, B. Feng and E. Witten, "*Direct proof of tree-level recursion relation in Yang-Mills theory*", Phys. Rev. Lett. **94** (2005) 181602 [hep-th/0501052];
- Lars Brink, John H. Schwarz, J. Scherk, Nucl. Phys. **B121** (1977) 77-92
- Edward Witten, "*Perturbative Gauge Theory As A String Theory In Twistor Space*", hep-th/0312171

NON-PERTURBATIVE PHYSICS (16 lectures)

Dr. T. Sulejmanpasic

This course is meant to be an introduction to some non-perturbative aspects of quantum field theory. The main focus of this course will be the focus on some non-perturbative aspects of quantum field theories, in particular gauge theories. The central theme will be instantons and solitons which arise as classical solutions of field equations. We will discuss topological aspects of these solutions, and classification, as well as their importance for the physics of such theories. We will make contact with anomalies and anomaly matching – a powerful method by which one can put constraints on low energy physics of quantum field theories. Time permitting, we will discuss dualities in quantum field theories, and some more advanced applications of symmetries in non-perturbative analysis of quantum field theories.

Outline of the course.

- **Non-perturbative aspects of quantum mechanics**: uniqueness of ground states, instantons and semiclassical analysis in quantum mechanics
- **Soliton and instanton basics**: Topology, Derrick?s theorem, Bogomolny bounds, examples of solitons (kinks, vortices,...).
- **Monopoles and instantons in gauge theories:** Chern number, topology of gauge theory instantons, θ-angle, Dirac monopoles, dyons and the Witten effect
- **Anomalies and anomaly matching:** meaning of anomalies, distinction between anomalous symmetries and 't Hooft anomalies. Descent formalism.
- **Advanced topics:** Use of symmetries in low-energy effective theories, Wess-Zumino-Witten terms, Chern-Simons theory, nonlinear sigma models and large N.

  Additional material for the course. Several online resources are made available to the students during the lectures, suitably tuned to the level of the class. Some good textbooks that covers most of the material of the course are:

  – S. Coleman, *Aspects of Symmetry*, Cambridge University Press 1985
  – N.S. Manton and P.M. Sutcliffe, *Topological Solitons*, Cambridge University Press 2004
  – R. Rajaraman, *Solitons and instantons. An introduction to solitons and instantons in quantum field theory*, North-Holland, 1982
  – E. Witten, Lecture on *Dynamics of Quantum Field Theory* from *Quantum Fields and Strings: A Course for Mathematicians* edited by Deligne, P. and Etingof, P. and Freed, D.S. and Jeffrey, L.C. and Kazhdan, D. and Morgan, J.W. and Morrison, D.R. and Witten, Edward, The American Mathematical Society 1999
  – S. Weinberg, *The Quantum Theory of Fields II*, Cambridge University Press 1996

FORMAL THEORY

SUPERSYMMETRY (16 lectures)

Dr. B. Hoare

This course provides a basic introduction to the main motivations and ideas in Supersymmetry (SUSY). Main topics include the SUSY algebra and its representations, superspace and superfields, the construction of supersymmetric actions, nonrenormalization theorems, supersymmetric gauge theories, and SUSY breaking.

Outline of the Course

- What is SUSY and why? Poincare and Lorentz group, spinors
- Supersymmetry algebra and on-shell representations (supermultiplets)
- 4d N=1 superspace and superfields
- SUSY field theories of chiral superfields. Holomorphy and non-renormalization theorems
- Vector superfields and supersymmetric gauge theories
- Spontaneous SUSY breaking

Additional material for the Course

- A. Bilal, *"Introduction to supersymmetry"*, arXiv:hep-th/0101055
- M. F. Sohnius, *"Introducing Supersymmetry"*, Phys. Rep. 128 (1985)
- M. Bertolini, *"Lectures on Supersymmetry"*, `http://people.sissa.it/~bertmat/susycourse.pdf`
- R. Argurio, *"Introduction to Supersymmetry"*, `http://homepages.ulb.ac.be/~rargurio/susycourse.pdf`
- P. Argyres, *"An Introduction to Global Supersymmetry"*, `http://homepages.uc.edu/~argyrepc/cu661-gr-SUSY/index.html`
- M. J. Strassler, "An Unorthodox Introduction to Supersymmetric Gauge Theory", arXiv:hep-th/0309149

CONFORMAL FIELD THEORY (16 lectures)

Dr. M. Lemos

This course will introduce the basic concepts and methods of conformal field theory in a pedestrian fashion, mostly focusing in theories in more than two space-time dimensions, and then covering the special two-dimensional case.

Outline of the Course

- Conformal transformations, conserved charges and the conformal algebra.
- Operators and representations of the conformal algebra, conformal constraints on correlation functions.
- Radial quantization, the state-operator correspondence, the operator product expansion, unitarity constraints
- Two-dimensional conformal field theories: the Witt algebra, Möbius transformations, Virasoro algebra and the vacuum module, mode expansions.

Additional material for the Course

- D. Simmons-Duffin, "*The Conformal Bootstrap, in Theoretical Advanced Study Institute in Elementary Particle Physics: New Frontiers in Fields and Strings*", pp. 1–74, 2017. arXiv:1602.07982.
- S. Rychkov, "*EPFL Lectures on Conformal Field Theory in D¿= 3 Dimensions*". Springer Briefs in Physics. 1, 2016. arXiv:1601.05000
- P. Di Francesco, P. Mathieu and D. Sénéchal, "*Conformal Field Theory*", Springer (1997)
- J. Polchinski, "*String Theory (Vols. 1 and 2)*" (Cambridge University Press 1998)

STRING THEORY (16 lectures)

Dr. M. Bullimore

String theory is the most promising candidate for a consistent theory of quantum gravity and fundamental particle physics. It has provided tremendous insights into many areas of theoretical physics and pure mathematics. This course will cover foundational aspects of string theory, including quantisation of the bosonic string, T-duality, D-branes, and an introduction to superstrings. This will provide a solid foundation for the study of more advanced topics.

Outline of the Course

- **Bosonic string:**
  Quantization of the bosonic string, physical state conditions, spectrum of physical states. Chan-Paton factors for open strings.

  Interactions and vertex operators.

  Compactification and T-duality for the bosonic string.

  D-branes, Dirac-Born-Infeld action.

- **Superstrings:**
  Fermions, R and NS sectors. Physical state conditions, GSO projection. Spectrum of physical states, construction of IIA, IIB, type I superstrings.

  T-duality and D-branes for the superstring.

Additional material for the Course

- J. Polchinski, "*String Theory (Vols. 1 and 2)*" (Cambridge University Press 1998)
  This will be the primary text
- M. Green, J. Schwarz and E. Witten, "*Superstring theory (Vols. 1 and 2)*" (Cambridge University Press 1986)
- K. Becker, M. Becker and J. Schwarz, "*String theory and M-theory*" (Cambridge University Press 2007)

Other Books/articles which may be of interest

- D. Tong,"*String Theory*", `arXiv:0908.0333`

PHENOMENOLOGY

QUANTUM CHROMODYNAMICS (16 lectures)

Dr. S. Jones

Quantum Chromodynamics (QCD) is the theory of the strong interaction, one of the four fundamental forces of nature. It describes the interactions between quarks and gluons, and in particular how they bind together to form hadrons. In this 'long-distance' regime the effective coupling is large and non-perturbative methods are appropriate. In contrast, at short distances the coupling between quarks and gluons is small, and perturbation theory can be used to make quantitative predictions that can be tested directly in experiment.

The course focuses on perturbative QCD and its applications in modern high-energy physics. The course covers various phenomenological applications: e^+e^- physics, which leads to the theory of quark and gluon jets; deep inelastic scattering, where perturbative QCD extends and refines the ideas of the original 'naive' parton model; and finally hadron colliders, where QCD provides many important backgrounds to new physics and where the ability to make precision predictions is paramount.

Outline of the Course

- Gauge invariance, Feynman rules, colour algebra, IR and UV divergences.
- Applications in high-energy collider physics: perturbative corrections and jet physics in e^+e^- annihilation;
- The parton model; hard scattering processes at present and future hadron-hadron colliders.

Additional material for the Course

- M. E. Peskin and D. V. Schroeder, "*An Introduction to Quantum Field Theory*" (Addison Wesley 1995)
- F. Halzen and A. D. Martin, "*Quarks and Leptons*" (Wiley, 1984)
- R. K. Ellis, W. J. Stirling, B. R. Webber, "*QCD and Collider Physics*", Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol. 8 (1996)
- J. M. Campbell, J. W. Huston and W. J. Stirling, "*Hard Interactions of Quarks and Gluons: A Primer for LHC Physics*", Rept. Prog. Phys. **70** (2007) 89 [hep-ph/0611148].

HIGGS PHENOMENOLOGY (8 lectures)

TBC

The aim of the course is to introduce the ideas and concepts associated with the phenomenology of the electroweak symmetry breaking post Higgs discovery, building on the foundations given in the SM course. The course starts with a detailed pedagogical introduction to electroweak symmetry breaking in the Standard Model, including gauge boson and fermion mass generation and the resulting predictions for Higgs boson interactions. The theoretical constraints on the Higgs sector coming from unitarity, and ideas of triviality, vacuum stability and fine tuning will be reviewed.

We then survey Higgs boson decays and production mechanisms at hadron colliders. The dominant production mechanism is gluon fusion and we will study this in depth, building on the foundations of the QCD course.

We finish with a discussion of Naturalness to motivate Higgs physics beyond the Standard Model. We will study two different types of extension - an effective theory that introduces the effects of new physics at high scales through higher dimensional operators, and a model with an additional Higgs-doublet (which is the foundation of the Minimal Supersymmetric Standard Model).

Outline of the Course

1. The Higgs Sector in the Standard Model
2. Theoretical Constraints on the Higgs Sector – Equivalence Theorem, Unitarity, Triviality, Vacuum Stability, Electroweak Precision Observables, Fine tuning
3. Higgs Decays
4. Higgs Production – Gluon Fusion at LO, Low energy effective theorem, Gluon Fusion at NLO, Vector boson fusion
5. Beyond the Standard Model Higgs – Naturalness, Higgs boson effective theory, Two Higgs doublet model, Supersymmetry, The Higgs portal

Additional material for the Course

1. H. E. Logan,
   "TASI 2013 lectures on Higgs physics within and beyond the Standard Model,"
   arXiv:1406.1786 [hep-ph].
2. L. Reina,
   "TASI 2011: lectures on Higgs-Boson Physics,"
   arXiv:1208.5504 [hep-ph].

3. S. Dittmaier *et al.* [LHCHXSWG],
"Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables,"
arXiv:1101.0593 [hep-ph].

4. S. Dittmaier, *et al.* [LHCHXSWG],
"Handbook of LHC Higgs Cross Sections: 2. Differential Distributions,"
arXiv:1201.3084 [hep-ph].

5. S. Heinemeyer *et al.* [LHCHXSWG],
"Handbook of LHC Higgs Cross Sections: 3. Higgs Properties,"
arXiv:1307.1347 [hep-ph].

FLAVOUR PHYSICS AND EFFECTIVE FIELD THEORIES (16 lectures)

Dr. B. Pecjak

Flavour physics observables can provide crucial constraints on extensions of the standard model (SM). Moreover the phenomenon of CP violation, which is supposed to be the key for the understanding of the existence of matter in the universe, was until now only observed in flavour transitions. For any meaningful interpretation of flavour data an understanding of the corresponding SM contribution is mandatory. The general concept of effective theories is also the basis of the theoretical framework for describing hadron decays. The essential premise of effective theories is that dynamics at low energies (or large distances) does not depend on the details of the dynamics at high energies (or short distances). As a result, low energy physics can be described using an effective Lagrangian that contains only a few degrees of freedom, ignoring additional degrees of freedom present at higher energies. In this lecture course several examples of effective theories relevant for flavour physics will be discussed in detail.

Outline of Course

- **Flavour phenomenology**
- **Fermi theory of weak interactions**
- **The effective Hamiltonian**
- **The heavy quark expansion (HQE)**
- **The heavy quark effective theory (HQET)**

Additional material for the Course

- A. Manohar, M. Wise, "*Heavy Quark Physics*" (Cambridge, 2000)
- H. Georgi, "*Weak Interactions and Modern Particle Theory*" (Dover Pubn Inc, 2009)
- A. Buras, "*Weak Hamiltonian, CP violation and rare decays*" arXiv: hep-ph/9806471
- A. Pich, "*Effective field theory: Course*" arXiv: hep-ph/9806303

OPTIONAL COURSE

INTRODUCTION TO SCIENTIFIC COMPUTING (8 lectures)

Dr. B. Pecjak

Computers are the tool of choice when solving highly complex problems as well as presenting results of the latter. The aim of this course is to give an overview of basic computing concepts commonly used in the scientific community that enable an efficient use of resources as well as automation of repetitive tasks.

Outline of Course

- **Linux and Bash (working with a terminal)**
- **Python (numerical tasks and data presentation)**
- **Latex (efficient type setting for publication quality)**
- **Working remotely and in groups (ssh and repositories)**

A Plagiarism form

Durham University

Shaped by the past, creating the future

Department of Mathematical Sciences

Plagiarism

The General Regulations of the University, Section VIII(D), state that "In formal examinations and all assessed work prescribed in degree, diploma and certificate regulations, candidates should take care to acknowledge the work and opinions of others and avoid any appearance of representing them as their own. Unacknowledged quotations or close paraphrasing of other people's writing, amounting to the presentation of other persons' thoughts or writings as one's own, is plagiarism and will be penalised. In extreme cases, plagiarism may be classed as a dishonest practice under Section IV, 5(a)(x) of the General Regulations and may lead to expulsion."

I .... (name) undertake that all assessed work to be submitted for my degree will be a result of my own work except where group project work is involved. In the case of a group project, the work will be prepared in collaboration with other members of the group. In all other cases material from the work of others not involved in the assessment will be acknowledged and quotations and paraphrases suitably indicated. I authorise the uploading of my work onto a plagiarism detection system, at the discretion of the Department of Mathematical Sciences/Physics, if plagiarism is suspected or for routine screening of work for plagiarised text.

I also undertake not to submit the same piece of work (or two substantially similar pieces of work) for assessment in two different modules, whether both modules are in the Department of Mathematical Sciences/Physics or one module is in another department.

Departmental IT Facilities

The University Regulations for the Use of University IT Facilities are contained in Section XIII of the General Regulations of the University. These University Regulations allow for additional regulations to be specified by academic departments. I understand that the Department of Mathematical Sciences/Physics will treat unauthorised attempts by students to gain access (by 'hacking' or otherwise) to departmental IT systems (including, but not limited to, departmental administrative and teaching-related databases) as an infringement of the University's IT and Discipline regulations and therefore might ultimately result in expulsion from the University, if the matter were referred to Senate Discipline Committee.

Attendance Requirements

The General Regulations of the University, Section V, state that "students shall, as required by the regulations governing the degree or other programme or module for which they are registered:

(i) attend courses of instruction in the University in each of the subjects required to the satisfaction of the Heads of Departments or Schools responsible for those subjects;

(ii) fulfil all academic obligations, including registration and those obligations defined (in the relevant module outline as published in either the Faculty Handbook or Postgraduate Module catalogue as appropriate) as being required to demonstrate academic progress in the modules for which they are registered to a standard satisfactory to the Heads of Departments or Schools responsible for the subjects."

I undertake to abide by the above regulation. I understand that specific information about the attendance requirements of my Mathematical Sciences/Physics modules, and the potential consequences of not meeting my compulsory obligations, are stated for my information on the departmental web site and that it is my responsibility to make myself aware of them.

Signed:.. Date:..................................