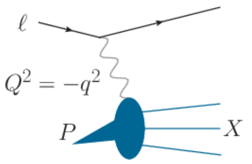
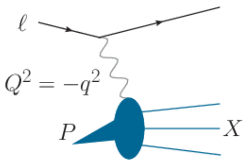


Quantum Field Theory I: PHYS 721
Autumn/Fall 2021
Preliminary syllabus



Chris Monahan
Department of Physics, William & Mary

Contact details

Course Instructor Prof. Chris Monahan. My pronouns are he/his/him. Email is the best way to contact me.

Contact email cjmonahan@wm.edu.

Course webpage is cjmonahan.net/qft721_2021.

Office hours Tuesdays 3–4 pm are currently set aside for office hours.

College dates Add/Drop deadline is Friday September 10 and the withdrawal deadline is Monday November 1, but be sure to contact the Registrar and Administrator of Graduate Student Services.

Course overview

Let's start by acknowledging that this could end up another strange and difficult semester. It is quite possible that the course will have to evolve as the semester progresses, and we'll have to try to adapt as best we can. We will have to work together with patience and understanding, because we will all be going through this for the first time together, but we will get through it! Please let me know if there is anything I can do to help you navigate the course, and the semester more generally.

Basics We will work in an in-person mode, with two in-person classes each week. Much of the material is based on Schwartz's textbook *Quantum Field Theory and the Standard Model*, although you will also find Peskin and Schroeder's textbook, Quantum Field Theory (the student edition is available online through the library here [log-in required]), and David Tong's lecture notes here extremely useful. I discuss further references towards the end of this syllabus. The material will **not** be presented in the order in which Schwartz presents it; I hope to weave a thread that ties together the majority of Schwartz's presentation with elements of Tong's notes and even some of Peskin and Schroeder.

Class schedule Classes take place in Small Hall 235, **Tuesday** and **Thursday 11:00–12:20**.

Prerequisites PHYS 622 (Quantum mechanics II)

Assessments Will consist of:

- Problem sets (60%);

- Take-home final exam (40%).

Problem sets will be posted on the webpage on Thursday mornings and are due **at the start of** the **following Thursday class**. I will drop the lowest grade on your weekly problem sets. There is no punishment for late work, but it helps everyone in the course (not least me) if you are able to submit on time.

Grade boundaries are approximate, and could change slightly, owing to the unusual nature of the semester. But you can reasonably expect that the letter grades will largely correspond to percentage grades as follows:

- A: 90% and above
- B+: 85–89.99%
- B: 80–84.99%
- B-: 75–79.99%
- C: 65–74.99%

Remember that this is a graduate class: learning and applying quantum field theory effectively is much more important than the (passing!) grade you earn. Even if you do not think that you'll be using QFT directly in your research, QFT incorporates many powerful concepts and techniques that are widely used in contemporary physics; building a good foundation in QFT will broaden your physics knowledge and strengthen your research toolkit.

Be aware This syllabus is subject to change during the semester. I will announce changes in class, but you are responsible for keeping up to date with the latest version on the course webpage[1].

Course description

What is the Universe really made of? Are there new fundamental particles we haven't found yet? Just how cool is the Large Hadron Collider (LHC)?

Quantum field theory is the mathematical framework that underpins our attempts to answer these questions. Except for the third, for which the answer is obviously: very. Grappling with quantum field theory is key to understanding particle and nuclear physics, and much of condensed matter physics, too.

In order, this course will:

- Motivate and introduce quantum field theory.
- Review special relativity and four vectors, Maxwell's equations, and classical field theory.
- Motivate the tools of QFT from scattering observables.
- Introduce group theory and representations of the Lorentz group.
- Identify particles as *unitary representations of the Poincaré* group.
- Develop the tools necessary to study bosons and fermions, focussing on spinor representations of the Lorentz group.

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[1] I will not use Blackboard in this course.

- Study the Dirac equation as the starting point for unifying quantum mechanics and special relativity.
- Study the role of propagators, Green functions and causality in quantum field theory.
- Prove Wick's theorem and demonstrate the need for Feynman diagrams.
- Introduce quantum electrodynamics, the quantised description of electromagnetism and a pillar of the Standard Model of particle physics.
- Study scattering processes in quantum electrodynamics.

By the end of the course, you will be able to:

- Describe why we need and use quantum field theory.
- Analyse the symmetries of bosonic and fermionic fields.
- Categorise quantities according to their behaviour under the Lorentz and Poincaré groups.
- Explain how to "embed" particles into fields.
- Write down the Lagrangians for common models or theories studied in quantum field theory, such as scalar field theory, Yukawa interactions and quantum electrodynamics.
- Derive Feynman rules from a given Lagrangian.
- Relate scattering observables to quantities calculable in quantum field theory.
- Apply Wick's theorem to derive correlation functions for that model, theory or action.
- Calculate scattering cross-sections for various processes at leading order.

We will cover:

1. Review of relativity and classical field theory.
2. Representations of the Lorentz group, including spin 0, spin 1/2, and spin 1 representations.
3. Spin and statistics.
4. Gauge symmetries and electromagnetism.
5. Quantisation of scalar, spinor and gauge fields.
6. Scattering cross-sections and decay rates.
7. First infinities and normal ordering.
8. S-matrix, time ordering, and the LSZ reduction.
9. Propagators, Green functions, and Feynman rules.
10. Scalar quantum electrodynamics.
11. Quantum electrodynamics.
12. Sample scattering processes in quantum electrodynamics.

Textbooks and resources

Strongly recommended

- *Quantum Field Theory and the Standard Model*, Schwarz, Cambridge.
  I really like this textbook: its presentation of the material is very modern and works through material in a very pedagogical manner. It covers a lot of material, with an emphasis on high energy physics applications, so sometimes its coverage is not as detailed as other works. This is the best accompaniment to the course.

- *Quantum Field Theory*, David Tong.
  The lecture notes we all aspire to write. A modern classic.
- *An Introduction to Quantum Field Theory*, Peskin and Shroeder, Westview Press.
  This has been the modern classic textbook for many people over the last two decades, although some of its presentation can be a bit disjointed and some of their discussions start off strong, only to trail off halfway through.

Highly recommended

- *Introduction to Quantum Field Theory*, Nastăse, Cambridge.
  This is another very good and very recent textbook, and the order of presentation is closely aligned to the course (certainly early on). It is a very accessible introduction, although it does not treat topics in great depth and it can be a little light on examples. It does, however, cover some very cool advanced topics that I have not seen in comparable textbooks. In particular, these advanced chapter do a great job drawing together a wide range of modern applications of QFT, from lattice field theory to amplitudes in twistor space.

Recommended

- *Quantum Field Theory*, Srednicki, Cambridge.
  This textbook emphasises the path integral formalism, and develops the material in a rather different order than Peskin and Shroeder. It is useful for an alternative perspective and for some detailed discussion of topics that are not covered in as much depth in Peskin and Shroeder. The notation is quite different, however.

- *Quantum Field Theory*, Mandl and Shaw, Wiley.
  The Peskin and Schroeder of the 80s. A venerable classic that has evolved since it was first published, but retains its character as one of the more introductory texts, emphasising QED.

Accommodations and Student Accessibility Services

William & Mary accommodates students with disabilities in accordance with federal laws and university policy. Any student who feels they may need an accommodation based on the impact of a learning, psychiatric, physical, or chronic health diagnosis should contact Student Accessibility Services staff at 757-221-2512 or at sas@wm.edu to determine if accommodations are warranted and to obtain an official letter of accommodation. For more information, please see the Student Accommodation Services website.

Course policies

The following policies are founded on three tenets:

1. You are responsible for your own learning.
2. You have agreed to abide by the Honor Code.
3. You have agreed to abide by the Healthy Together Community Commitment.

Some aspects or details of these policies are open for revision during the semester, if we, as a class, feel that they are not working. These tenets, however, are not.

Honor Code

As graduate students at William & Mary you have agreed to abide by the Honor Code. You are responsible for your behaviour in class and are expected to uphold the Honor Code.

Healthy Together

As members of the William & Mary community you have agreed to abide by the Healthy Together Community Commitment. You are responsible for your behaviour on campus and are expected to uphold the three keys to this commitment by: mitigating risk of transmitting COVID-19; demonstrating care and concern; and support the University's mission. During our in-person classes, you will wear a mask, wash your hands before and after entering the classroom, and try to maintain appropriate physical distancing as far as possible. You may not move the chairs.

Responsibility for learning

As graduate students you are responsible for your own understanding of the course material. We all learn in different ways, and I aim to foster an environment that allows us all to learn effectively. Taking responsibility for your own learning guides the following policies.

Working together You are welcome to work together on problem sets if you so choose, but you must write up your own solutions. Collaboration helps develop and cement understanding of the material, and is an important skill for your future careers. Your problem set, however, should represent your own understanding and we must strike a balance between working collaboratively and copying someone else's work. I cannot emphasise this enough: **Copying solutions will not help you understand quantum field theory**. Moreover, copying is cheating and a form of plagiarism. An example of appropriate collaboration is working together to sketch out the main steps in a derivation or in the solution to a problem, then going away to write up your solutions in detail separately. An example of cheating is taking someone else's solutions the night before the deadline and copying them line by line.

You **may not work together on the final (take-home) exam**. This must be your own work.

Attendance Attendance does not form part of the grade for this class, either online or in-person. After all, you are responsible for your own understanding of the course material. Attending class will, however, significantly improve your enjoyment of the course and will likely improve your satisfaction with both your own understanding and your grade.

Late work, extensions Problem sets are due at Wednesday on noon. You are strongly encouraged to submit your problem set by this time for three reasons. First, grading all questions at the same time ensures grading is fairer. Second, problem sets can be returned in a timely manner to all of you if all problem sets have been submitted on time, which will help you all reinforce your understanding. Third, keeping track of problem sets is much easier for me if they are all submitted on time.

There is no punishment for late work, but an early warning is appreciated. Reasons for late submissions are also appreciated, but not necessary, because sometimes you may not wish to share your reasons with me, for, you know, personal reasons. As with all these policies, I expect you to treat this responsibly–remember that this policy, like all of these, can be amended if necessary.

Laptops and mobile devices You are welcome to bring laptops and mobile devices to class and are responsible for their appropriate use. Please note, however, that there is significant evidence (see, for example, **here**, **here**, and **here**) that using your device for tasks that are not related to in-class activities will (significantly) impinge on your understanding of quantum field theory and perhaps even your grade. The notable exception to this rule is typewriters. Typewriters are forbidden in class; they are distracting.

Student resources

Useful resources (links in online PDF):

- The Path Forward.
- William & Mary's COVID-19 response.
- The Dean of Students and the Student Success office.
- Student Accessibility Services
- Writing Resource Center
- Equity program
- LGBTQ resources
- Neurodiversity Initiative
- Health and Wellness, mental health resources and the Counseling Center
- The Haven
- Lifeline
- Options for reporting Discrimination, Harassment, Retaliation and Sexual Misconduct.

The full policy of the College on Discrimination, Harassment and Retaliation is here.

Quantum field theory resources

Some useful quantum field theory textbooks

There is a very nice (and more detailed than mine) overview of quantum field theory textbooks by Flip Tanedo here.

- *Quantum Field Theory*, Banks, Cambridge.

The subtitle of this textbook is “A Concise Introduction” and the emphasis is on “concise”. Generally has more words and fewer equations than other textbooks in the list, but has a unique perspective and choice of topics for an introductory text, often slanted towards high energy theory rather than the particle phenomenology of Peskin and Schroeder.

- *Quantum Field Theory*, Brown, Cambridge.
  A fairly straightforward presentation, although the choice and order of topics is somewhat unusual. For example, this has a nice introductory treatment of resonant bound states, which is particularly useful for those of you interested in JLab physics.
- *A Pedestrian Approach to Quantum Field Theory*, Harris, Dover.
  An older textbook, reprinted recently. Useful as a primer for certain topics, it introduces many topics quite gradually, although it necessarily is less suitable for making contact with modern experiments at, for example, the very cool LHC.
- *Quantum Field Theory*, Itzykson and Zuber, Dover.
  Another advanced and venerable textbook. Covers topics that cannot be found elsewhere, with as much rigour as can be expected in quantum field theory, but, like Weinberg’s textbook, is not always the most accessible as an introductory text.
- *Quantum Field Theory: A Modern Introduction*, Kaku, Oxford.
  A useful general textbook covering many topics at an intermediate level, by a well-known physicist and science communicater. Perhaps a little more formal than Peskin and Schroeder.
- *A Modern Introduction to Quantum Field Theory*, Maggiore, Oxford.
  An elegant introduction, with an emphasis on particle physics and working through the details of calculations. Covers most of the usual topics, but in a slightly unusual order.
- *Quantum Field Theory for the Gifted Amateur*, Lancaster and Blundell, Oxford.
  A lively textbook that covers a wide variety of topics from particle to condensed matter theory, many not covered by more standard texts. Necessarily does not provide a detailed treatment of all topics, but gives a good overview of the basic aspects of QFT.
- *Field Theory: A Modern Primer*, Ramond, Addison-Wesley.
  An older work that has the rare attribute of working directly in Euclidean space, a valuable commodity for those of us working on lattice QCD. Includes a number of unusual, but useful, topics, such as applications to general relativity.
- *Quantum Field Theory*, Ryder, Cambridge.
  An older text that has been updated with a second edition and many reprintings. Generally focussed on particle and high energy theory, with some good chapters on topological effects in QFT, and generally somewhat formal. Fills in a number of holes left by Peskin and Schroeder’s treatment of Abelian and non-Abelian gauge theories.
- *The Quantum Theory of Fields*, Weinberg, Cambridge.
  An advanced textbook in three parts by one of the architects of the Standard Model of Particle Physics. Part I is most relevant to this course. The notation is particular to Weinberg and the treatment is generally both in-depth and wide-ranging, covering many topics excluded from other textbooks, and often quite formal.

- *Quantum Field Theory in a Nutshell*, Zee, Princeton.
  This is not exactly a textbook in the traditional sense, but provides an excellent and breezy introduction to the basic ideas, often framed in an imaginative approach. Emphasises the conceptual aspects of QFT, rather than calculational details. Covers some unusual topics, include subjects outside the usual particle theory applications of QFT.

Related textbooks

- *Gauge theories in particle physics*, Aitchison and Hey, CRC Press.
  A book that has been through several iterations, but starts with a nice overview of the Standard Model of particle physics, before moving on to a more standard introductory treatment of quantum field theory.
- *Particles and Nuclei: An Introduction to the Physical Concepts*, Povh *et al.*, Springer.
  This is not a quantum field theory textbook, but provides a nice introduction to the rich phenomena in particle and nuclear physics that helps set quantum field theory in context.
- *Quantum Field Theory of Many-Body Systems*, Wen, Oxford.
  A very nice introduction to quantum field theory in the context of condensed matter and statistical physics, which helps one to abstract the mathematical foundations from the physical applications. Particular useful for those interested in lattice field theory.

Lecture notes

There are many sets of lectures notes online, but here are a few to start with, in alphabetical order. Almost any lectures notes for a first course on quantum field theory will cover much of the same material (although Coleman's classic notes present a different approach to the topic).

- *Introduction to Relativistic Quantum Field Theory*, Hendrik van Hees.
- *Quantum Field Theory I*, Niklas Beisert.
- Introduction to Quantum Field Theory, John Cardy.
- Notes from Sidney Coleman's Physics 253a, Sidney Coleman.
- QFT Lecture Notes, Jared Kaplan.
- Fields, Warren Siegel
- *Quantum Field Theory I + II*, Timo Weigand.