# Elementary Particle Physics
# (Physics 225a)

**Syllabus**
Fall 2014

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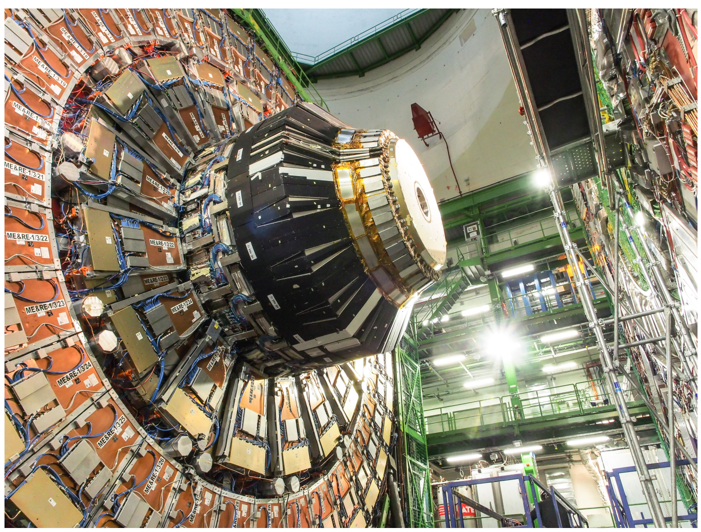

View of one of the CMS endcap detectors at the Large Hadron Collider.

## A new era in particle physics

With the discovery of the/a Higgs boson in July 2012, particle physics has entered a new era. Our expectation that the TeV energy scale is critical for understanding the fundamental structure of matter is being confirmed.

The exploration of this energy scale is just beginning. We have also confirmed the idea that the properties of the vacuum play a critical role in particle physics. The Higgs boson is a manifestation of electroweak symmetry breaking, which endows space with a non-zero vacuum expectation value of the Higgs field. What we think of as the "laws of physics" (e.g., the photon is a massless gauge boson, while the W and Z bosons are heavy) are partly determined by the properties of the vacuum.

We are also seeing an ever-closer connection between particle physics, particle astrophysics, and cosmology. It should be humbling that, in spite of the successes of the standard model of particle physics, we do not know what most of the matter in the universe is. (But we do know that it *does not* consist of any known type of particle!) In the best-case scenario, direct-detection experiments would finally observe astrophysical dark matter, while accelerator experiments would enable us to produce it and study its properties in detail. Maybe there will be an entirely new spectrum of supersymmetric particles – or maybe not!

There are many other profound mysteries, for example, those associated with the three generations of quarks and leptons. Why are there three generations? Why are neutrino masses so tiny? Are neutrinos their own antiparticles (Majorana fermions)? Why is there vastly more matter than antimatter in the universe? Do protons ever decay (baryon number violating interactions)?

Answering these questions presents huge challenges, but the next decade should be one of the most interesting in the history of our field. To make progress in the study of elementary particles, one needs sophisticated experimental and theoretical tools. We use accelerators of monumental size to produce particle collisions at energies that are equal to those a billionth of a second after the big bang. We routinely create and annihilate matter, transforming energy into new particles. The detectors that we use to study these collisions are nearly as impressive. At Fermilab, preparations are underway to create neutrino beams of unprecedented intensity, providing new tools for studying these objects. We are also searching for dark matter particles, which, presumably, are zipping through your body as you read this. Here at UCSB, the high-energy physics group is very active in constructing such detectors and in analyzing the results of experiments that we perform at various laboratories.

Ph 225 is a graduate-level course in elementary particle physics. We will survey the current understanding of particle properties and interactions, and we will explore the areas that seem most promising for yielding new discoveries and insights. I hope to present particle physics in a way that integrates a careful theoretical analysis with a physical and intuitive approach. In addition to our textbooks, I will provide extensive lecture notes, as well as many other reading materials, including papers from the research literature. Learning how to read research papers is one of the goals of this course.

## On Learning Particle Physics

Particle physics is an enormous subject, and in spite of its remarkable coherence, it is quite difficult to learn. Like quantum mechanics, it requires at least "two coats of paint" for many people. As you progress through the subject, I urge you to go back and review earlier material; you may well find that some of the earlier results will make much more sense when viewed in a broader context. I strongly encourage questions in class--they make things much livelier for all of us! It is well worth consulting a variety of different textbooks, which will offer a range of insights.

Please note that **reading the textbook** is extremely important. I will not have time in class to cover all of the relevant points. I will assume that you have read the relevant chapters. I will also expect you to read my lecture notes posted online. They will often contain details that I do not have time to cover in the lecture.

One aspect of this material that some students aren't used to is that it is extremely helpful for you to remember (i.e., to memorize) the qualitative/order-of-magnitude results of many of the calculations that we do. Or, in many cases, you don't need to remember any numerical results, but you need to know the key results in a conceptual or qualitative sense. These can be critical ingredients for addressing other questions**. Try to remember why things are the way they are**: what explains the most conspicuous features of each process we study? These are the sorts of questions that turn up on **oral candidacy exams**.

Finally, let me repeat a sentiment of a physicist I know. She said that doing particle physics is like climbing a mountain: the journey up can be a struggle, but the view from the top is worth it!

## The Transition from Classes to Research

The transition from classes to research is almost universally found by students to be difficult and even disorienting. A key ingredient of research is **asking a series of questions** as you make progress, in fact, **as a way of making progress**. So, in Ph225, we will constantly be asking, **"Given this new piece of information, what questions does it raise?"** I think that you will find this to be a great way to understand new information in a broader context and to prepare yourself for the type of mental attitude that goes with research.

## Grades, homework, tests, and all that stuff

- Homework will be assigned on Thursdays and is due in class on the following Wednesday.
- Grading policy:

1. Homework: 50%
2. Class participation: 15%
3. Final exam: 35%

- Textbooks: *Modern Particle Physics,* Mark Thomson (Cambridge U. Press, 2013) and *Gauge Theories in Particle Physics: A Practical Introduction*, Fourth Edition (2 volume set), Ian J. R. Aitchison and Anthony J. G. Hey (CRC Press, 2012). The book by Thomson will be the primary text, but I also strongly recommend Aitchison and Hey.
- Class time: Tues and Thurs, 2:00 to 3:15 PM
- Class location: Phelps 1444
- Class materials will be available on GauchoSpace
- Office hours: I will start with an office hour on Mondays at 2:00-3:00 PM. You are also free to contact me at any time to set up a meeting time, or to just stop by and see if I am available. I am often busy with LHC-related meetings in the morning, but I am usually available in the afternoon.
- Discussion section: I am hoping that we can find a time to have a class discussion section. This will allow us to discuss HW problems and many more examples than I will have time for in class.

## Some books on particle physics

- Collider Physics, V. Barger and R.J.N. Phillips, Addison-Wesley.
- The Higgs Hunter's Guide, J.F. Gunion, H.E. Haber, G. Kane, S. Dawson, Perseus Publishing.
- An Introduction to Gauge Theories and Modern Particle Physics (two volumes), E. Leader and E. Predazzi (Cambridge U. Press).
- Introduction to Elementary Particles, D. Griffiths, Wiley-VCH.
- Gauge Theory of Weak Interactions, W. Greiner and B. Muller, Springer-Verlag.
- Quantum Electrodynamics, W. Greiner, and J. Reinhardt, Springer-Verlag.
- Elementary Particle Physics, O. Nachtmann, Springe-Verlag.
- Concepts of Particle Physics (two volumes), K. Gottfried and V.F. Weisskopf
- Particle Physics: a Comprehensive Introduction, A. Seiden, Pearson.
- Particle Physics and Introduction to Field Theory, T.D. Lee, Harwood Academic Publishers.
- Neutrino Physics, K. Winter, Cambridge U. Press.
- Massive Neutrinos in Physics and Astrophysics, World Scientific.
- The Physics of Particle Detectors, D. Green, Cambridge U. Press.
- Particle Detectors, C. Grupen, Cambridge U. Press.
- Particle Physics, D. Carlsmith, Pearson.
- Gauge Theories in Particle Physics, I.J.R. Aitchison and A.J.G. Hey, Institute of Physics Publishers.
- Gauge Theories of Strong, Weak, and Electromagnetic Interactions, C. Quigg, Benjamin Cummings.
- Quantum Field Theory in a Nutshell, A. Zee, Princeton U. Press.

- Quantum Field Theory, M. Srednicki, Cambridge U. Press.
- Cosmology and Particle Physics, Bergstrom and Goodbar, Wiley.
- Experimental Foundations of Particle Physics, R.N. Cahn and G. Goldhaber, Cambridge U. Press.
- Quantum Chromodynamics, G. Dissertori, I. Knowles, M. Schmelling, Oxford Science Publications.
- Theory and Phenomenology of Sparticles, M. Drees, R.M. Godbole, P. Roy, World Scientific.
- Quarks and Leptons, F. Halzen and A.D. Martin, Wiley.
- Particle Physics in a Nutshell, C. Tully, Princeton U. Press.
- Perspectives on LHC Physics, G. Kane and A. Pierce, World Scientific.
- QCD and Collider Physics, R.K. Ellis, W.J. Stirling, and B.R. Webber, Cambridge U. Press.
- At the Leading Edge: The ATLAS and CMS LHC Experiments, D. Green, ed., World Scientific.
- Weak Scale Supersymmetry: From Superfields to Scattering Events, H. Baer, X. Tata, Cambridge U. Press.
- Gauge Theory of Elementary Particle Physics, T.-P. Cheng and L.-F. Li, Oxford U. Press.
- Supersymmetry: Theory, Experiment, and Cosmology, P. Binetruy. Oxford U. Press.
- Supersymmetry in Particle Physics, I. Aitchison, Cambridge U. Press.
- Particle and Astroparticle Physics, U. Sarker, Taylor & Francis.
- Neutrino Physics, K. Zuber, Institute of Physics Publishers.
- A Modern Introduction to Quantum Field Theory, M. Maggiore, Oxford U. Press.

# Physics 225a: preliminary schedule

| Class | Date | Topics | Reading (Thomson) |
|---|---|---|---|
| 1 | Thurs, 2 Oct | **Questions and puzzles in particle physics**. Surprises in particle physics. What is particle physics? What is an elementary particle? Particles, fields, and forces. The Standard Model. Quarks, leptons, and gauge bosons. Strong, electromagnetic, and weak interactions. Particle content of the room. Particles in the universe. Big questions in particle physics. | T.1 |
| 2 | Tues, 7 Oct | **Energy and length scales of particle physics**. Overview of mass scales in particle physics. Dimensions and units, hbar and c. Scales related to quantum gravity. Bound states vs. elementary particles. Compton wavelength. Scales associated with atoms and nuclei; the meaning of binding energy. Quarks, hadrons and the origin of familiar mass. Natural units. | T.2 |
| 3 | Thurs, 9 Oct | **Special relativity (SR) and applications in particle physics.** A physics story: relativity and the cyclotron. Events, spacetime coordinates, and reference frames. Postulates of SR. A first application of SR postulates. Lorentz transformation. Lorentz invariant quantities. Four vectors and the covariant derivative. SR applications: space-time. Applications of four-momentum conservation: two-body decay, scattering, fixed-target vs. colliding beam experiments. Effect of a Lorentz boost on kinematic observables. The $q^2$ variable and the scattering angle. Kinematically forbidden processes. | T.2 |
| 4 | Tues, 14 Oct | **Processes and observables.** Observables associated with scattering: cross section and differential cross section. Observables associated with decay: decay rate, differential decay rate, lifetime. Exponential decay and the Breit-Wigner line shape. Random variables: discrete vs. continuous. Parent distributions and samples. Particle oscillations. The particle spectrum. Strong interactions and the hadron spectrum. | T.3 |
| 5 | Thurs, 16 Oct | **Amplitudes and fundamental vertices of the Standard Model: concepts** Feynman diagrams, their ingredients, and their behavior. Fundamental vertex for quantum electrodynamics and QED processes: pair production, Bremsstrahlung, Compton scattering. Fundamental SM processes involving fermions. Comparison of strong, electromagnetic, and weak interactions. | T.3 |
| 6 | Tues, 21 Oct | **Amplitudes and fundamental vertices of the Standard Model: examples.** Examples from strong, electromagnetic and weak interactions. Conserved quantum numbers. The special case of the top quark. Two-body vs. three-body decays. Spin and helicity. Helicity-dependent amplitudes. Calculating angular distributions. | T.3 |
| 7 | Thurs, 23 Oct | **Principles of particle detection and experiment design.** Categories | T.4 |

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| | | of detectable and non-detectable particles. Geometries for different types of experiments. Accelerator issues. Luminosity and beam characteristics. Event rates and cross-section measurement. Triggering. Consequences of particle lifetimes. Particle tracking devices. Magnets. Multiple Coulomb scattering. Electromagnetic and hadronic calorimeters and shower development. Particle “identification” methods (time-of-flight, dE/dx, Cerenkov radiation, transition radiation). Correlating information within an experiment. Reconstruction of decay chains. Analysis design. Background determination. Non-accelerator experiments and cosmic rays. Low backround experiments. | |
| 8 | Tues, 28 Oct | **Relativistic wave equations: Klein-Gordon and the Dirac equation.** Klein-Gordon equation. Relativistic and non-relativistic behavior. Properties of the Dirac equation. Free-particle solutions. Probability currents and normalization of Dirac spinors. Structure of the solutions to the Dirac equation. | T4 |
| 9 | Thurs, 30 Oct | **Properties of the Dirac equation.** Lorentz covariance, charge conjugation (C), and parity operators (P). Structure of Dirac and Majorana spinors. Remarks on supersymmetry. Quantum number of hadrons. | T.4 |
| 10 | Tues, 4 Nov | **U(1) gauge symmetry and electromagnetic interactions; magnetic moments.** Review of group theory. Symmetry transformations and representations of groups. Properties of SU(n). Imposing gauge invariance. The gauge field (abelian case). Magnetic moments of the electron, muon, proton, and neutron and their implications. | T.4 |
| 11 | Thurs, 6 Nov | **Perturbation theory: review and summary of results.** Time dependent perturbation theory. Feynman diagrams. | T.5 |
| - | Tues, 11 Nov | HOLIDAY | |
| 12 | Thurs, 13 Nov | **Scattering from a fixed potential.** Amplitudes and currents. Phase space. Helicity behavior. The role of $q^2$. Rutherford scattering. | T5, T.6 |
| 13 | Tues, 18 Nov | **Quantum electrodynamics (QED): processes involving leptons and photons.** Moller scattering, Bhabha scattering, Compton scattering, Delbruck scattering. Polarization and helicity effects. | T.6 |
| 14 | Thurs, 20 Nov | **Quantum electrodynamics (QED): production of quarks.** Light hadron production, heavy-quark production, charmonium, bottomonium, jets. The R quantity. Z boson production. | T.6, T10.6 |
| 15 | Tues, 25 Nov | **Electron-proton scattering.** Rutherford scattering, Mott scattering, form factors, elastic scattering with proton recoil, Rosenbluth formula. | T.7 |
| - | Thurs, 27 Nov | THANKSGIVING HOLIDAY | |
| 16 | Tues, 2 Dec | **Deep inelastic scattering.** Kinematic variables, Bjorken x variable and structure functions, the parton model. | T.8 |
| 17 | Thurs, Dec 4 | **Quantum chromodynamics (I).** Color and SU(3) gauge invariance. Quark-gluon vertex, hadrons and color, jets, running of alpha_s | T.10 |
| 18 | Tues, Dec 9 | **Quantum chromodynamics (II).** Color factors, hadronic collisions, rapidlity and pseudorapidity. | T.10 |

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| 19 | Thurs, Dec 11 | **Quantum chromodynamics (III).** QCD processes at the LHC. | T.10 |
| **Final exam** | Tues, Dec 16<br>4—7 PM | | |

T = *Modern Particle Physics*, by Mark Thomson