# PHYS 575 (Particle Physics I), Fall 2023

## Contact Information

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**Course website:** http://courses.physics.illinois.edu/phys575/fa2023

## Course Description

Basic calculations in elementary particle theory. Quantum electrodynamics, quantum chromodynamics, and the Glashow-Weinberg-Salam theory of weak and electromagnetic interactions as applied to the phenomenology of particle decays and high energy reactions.

## Pre-requisites

None, but credit or concurrent registration in PHYS 582 recommended.

## Credit hours

4 graduate credit hours; 2.66 hours/week in class

## Overview

PHYS 575, "Particle Physics I," is a quantitative introduction to the Standard Model of Particle Physics. No background in quantum field theory will be assumed, but prior exposure to the topics in PHYS 582 and/or PHYS 583 will be extremely helpful in understanding the justification and context for many of the calculations we will do. By the end of the course, students will be familiar with the particles, forces, and interactions of the Standard Model, and will be able to perform basic calculations which can be directly compared with experimental results to justify our understanding of the Standard Model as the correct description of elementary particle processes at energies up to 1 TeV.

The language of high-energy physics in general, and the Standard Model in particular, is mathematics. After a review of the particle zoo, units, and relativistic kinematics, the first part of the course will be devoted to group theory and understanding how the observed symmetries of nature impose themselves on the structure of fundamental particle interactions. As a reward for this mathematical introduction, we will be able to write down the complete Lagrangian for the Standard Model by Week 5. Following an interlude devoted to the experimental details of elementary particle detection, the remaining weeks of the course will be devoted to pulling apart this Lagrangian, term by term, and comparing its predictions with concrete experimental results. The focus of this course will be on quantum electrodynamics (QED) and electroweak interactions, leaving a detailed study of quantum chromodynamics (QCD) for PHYS 576. In the final weeks of the course, we will take stock of the Standard Model and see where old and new experimental results might point to physics beyond the Standard Model.

# Textbooks

We will primarily use the following textbooks for this course, all of which are required. All three are available from the Illini Union bookstore. In particular, the books by Larkoski and Peskin do not require any knowledge of quantum field theory, and perform many of the same calculations as Schwartz using reasoning motivated by quantum mechanics.

Schwartz, **Quantum Field Theory and the Standard Model**
Larkoski, **Elementary Particle Physics: An Intuitive Introduction**
Peskin, **Concepts of Elementary Particle Physics**

For additional reading, you many find the following books useful. They are both available for checkout from the library; if unavailable, the instructor and/or TA will provide scans of the suggested reading.

Peskin and Schroeder, **An Introduction to Quantum Field Theory**
Chen (ed.), **Quantum Field Theory Lectures of Sidney Coleman**

# Grading

Grading will be based on a combination of homework, class participation, and a take-home problem set which will serve as the final exam. Most homework will be assigned weekly, but occasional problem sets will cover multiple weeks and will be longer (and worth more points) – see schedule below. The final exam will be due to my mailbox on the 2nd floor of Loomis, or via `my.physics` upload, on 12/14 at 5pm, More details on grading and point values can be found on the course webpage. **Please note: Unless a valid, verifiable excuse is given, homework sets which are submitted late will receive a 10% penalty per day (between Friday and Monday a 20% penalty applies). Homework sets which are turned in more than a week late will receive no credit.**

Your final grade for Physics 575 will be based upon your total score on all the components of the course. The total possible score is 2000 points. Homework will count for 1100 points, attendance and participation for 600 points, and the take-home final for 300 points. Letter grade cutoff values can be found on the course website.

# Absence Policy

Students are expected to come to class when they are healthy, but no penalties will be incurred for students who miss class due to illness or a verified excuse. The class participation grade is holistic and students can receive credit for interactions outside of class hours, for example during office hours or over the class Slack channel or email.

# Disability Access Statement

To obtain disability-related academic adjustments and/or auxiliary aids, students with disabilities must contact the course instructor and the as soon as possible. To ensure that disability-related concerns are properly addressed from the beginning, students with disabilities who require assistance to participate in this class should contact Disability Resources and Educational Services (DRES) and see the instructor as soon as possible. If you need accommodations for any sort of disability, please speak to the instructor after class, or make an appointment during office hours. DRES provides students with academic accommodations, access, and support services. To contact DRES you may visit 1207 S. Oak St., Champaign, call 333-4603 (V/TDD), or e-mail disability@illinois.edu. `http://www.disability.illinois.edu/`.

# Schedule

- **Week 1** (8/21, 8/23) – The particle zoo, matter and forces-carrying particles, natural units; review of relativistic kinematics and index notation; introduction to group theory and representations of the Lorentz group. **Objectives: perform basic calculations in relativistic kinematics, understand the naming conventions for Standard Model particles.**

- **Week 2** (8/28, 8/30) – Representations of the Poincaré group; classification of elementary particles by mass and spin, unitary representations. **Objectives: classify irreducible representations of the Poincaré group and construct its two Casimir operators.**

  – HW #1 due 8/30

- **Week 3** (9/6) – Relativistic Lagrangians for spin-0 particles with space-time and internal symmetries. **Objectives: construct a relativistic Lagrangian for spin-0 particles. NOTE:** no class on Monday 9/4 (Labor Day).

- **Week 4** (9/11, 9/13) – spin-1 Lagrangians; Lagrangians for spin-1/2 particles and Noether's Theorem. **Objectives: construct relativistic Lagrangians for spin-1/2 and spin-1 particles; identify their symmetries and verify invariance under these symmetries; promote global symmetries to local symmetries by introducing a gauge field.**

  – HW #2 due 9/11

- **Week 5** (9/18, 9/20) – Lagrangian for the Standard Model; particle detectors, cross sections and luminosity, phase space. **Objectives: identify the gauge and global symmetries of the Standard Model, as well as all component fields; explain how elementary particles are detected and how to convert a luminosity into an event rate for a given process.**

- **Week 6** (9/27) – QED Lagrangian, spinor and vector wavefunctions. **Objectives: solve the Dirac and Maxwell equations to identify momentum-dependent spinor and vector polarizations. NOTE:** no class on Monday 9/25 (Yom Kippur).

  – HW #3 due 9/27

- **Week 7** (10/2, 10/4) – Quantum electrodynamics (QED) at $e^+e^-$ colliders: cross sections, Feynman rules, angular dependence and helicity amplitudes. **Objectives: compute the angular dependence of the $e^+e^- \to \mu^+\mu^-$ cross section and explain in terms of helicity states.**

- **Week 8** (10/9, 10/11) – Quantum corrections in QED: electron and muon $g-2$, soft and collinear singularities. **Objectives: compute a finite 1-loop diagram**

**in QED, identify regions of phase space where matrix elements involving massless photons become singular.**

  - HW #4 due 10/9

- **Week 9** (10/16, 10/18) – Quantum chromodynamics (QCD): R-ratio, parton distribution functions, discovery of the top quark Quarks and quantum chromodynamics (QCD): R-ratio, parton distribution functions, discovery of the top quark. **Objectives: explain how $e^+e^- \to \text{hadrons}$ gives quantitative experimental evidence for the SU(3) gauge symmetry of QCD, estimate top quark production cross sections at colliders using parton distribution functions.**
  - HW #5 due 10/18
- **Week 10** (10/23, 10/25) – Chiral symmetry breaking and pions as pseudo-Goldstone bosons; intro to spontaneous gauge symmetry breaking and Abelian Higgs model. **Objectives: construct the chiral Lagrangian and identify possible pion interactions based on the principle of spontaneous chiral symmetry breaking; describe the degree-of-freedom counting that gives rise to massive vectors in a spontaneously broken gauge theory.**
- **Week 11** (10/30, 11/1) – Higgs mechanism in the Standard Model; 3 generations and flavor (CKM and PMNS matrices), Feynman rules for electroweak interactions. **Objectives: determine charged-current flavor-changing interactions and Standard Model particle masses from spontaneous breaking of SU(2) $\times$ U(1).**
  - HW #6 due 10/30
- **Week 12** (11/6, 11/8) – Basic electroweak processes and neutrino oscillations; Discovery of the $W$, $Z$, and Higgs. **Objectives: compute $W$, $Z$, and $H$ production and decay rates using electroweak Feynman rules.**
- **Week 13** (11/13, 11/15) – P and CP violation; weak interactions at low energies. **Objectives: identify physical processes which can probe P and CP violation in the Standard Model; explain the dominance of the muon decay mode in $\pi^\pm$ decay using helicity suppression arguments.**
  - HW #7 due 11/13
- **Week 14** (11/20, 11/22) – **FALL BREAK**
- **Week 15** (11/27, 11/29) – Beyond the Standard Model: introduction to effective field theories; introduction to dark matter. **Objectives: integrate out a heavy particle to generate effective operators; construct a simple model of dark matter and identify testable observables at direct detection experiments and colliders.**

- **Week 16** (12/4, 12/6) – Open for requests! Some possibilities: GR as an effective field theory, quantum anomalies
  - HW #8 due 12/4