0 Syllabus

Course: NYU PHYS-GA 2027 Particle Physics
Semester: Spring 2025
Instructor: Jesse Liu
Lectures: Tuesday and Thursdays, 11:00–12:15, 726 Broadway, Room 1025
Office hours: Wednesdays, 11:00–12:00, Room 852 or by appointment

0.1 Course overview

This is the New York University graduate introduction to the Standard Model of particle physics (PHYS-GA 2027). The semester comprises 14 weeks of classes with two 75-minute lectures per week, totalling 27 planned lectures slots. Like previous versions of this class, the finals week is devoted to student presentations. Below is a lecture plan, which is subject to change based on the pace of delivery (sections of lecture notes in parentheses):

Historical origins

1. Course overview, motivation and introduction to the Standard Model (1.1–1.3).
2. Radioactivity, evidence for neutrinos, ionisation and cloud chambers (2.1).
3. Proton and neutron, cosmic rays for positron and muon discoveries (2.2–2.3).
4. Relativity and quantum mechanics review, constructing Dirac equation (3.1–3.2).
5. Weyl equations, helicity and chirality, Dirac mass, antimatter (3.3).
6. Spinor rotation, non-relativistic limit to Pauli equation: gyromagnetic factor (3.4).

Quantum electrodynamics

7. Feynman diagrams, electromagnetic scattering, virtual particles, propagators (4.1–4.3).
8. Gauge theory of forces, local symmetry, gauge fixing, Feynman rules (4.4).
9. Accelerators, cross-sections, Fermi's golden rule, density of states (5.1–5.4).
10. Electron–positron annihilation, spinor–helicity analysis, resonances (6.1–6.3).
11. Loop effects: Lamb shift, anomalous magnetic moment, running coupling (7.1–7.3).

Strong force

12. Particle zoo: nuclear moments, emulsions, cyclotrons, bubble chambers (8.1–8.4).
13. Quark model, strangeness, meson and baryon multiplets, colour charge (9.1–9.4).
14. Nuclear form factors, deep inelastic scattering and evidence for partons (10.1–10.2).
15. Evidence for quarks and their quantum properties, charmonium J/ψ (10.3–10.4).

16. Yang–Mills theory, evidence for colour, gluons, asymptotic freedom (11.1–11.4).

Electroweak interactions

17. Low-energy beta decay: Fermi theory, neutrino detection, parity violation (12–12.3).
18. Helicity suppression, flavour mixing, charge-parity violation in kaons (12.3–12.5).
19. Collider experiments, particle–matter interactions, terascale detectors (13.1–13.3).
20. Collider kinematics and event reconstruction, particle identification (13.4–13.5).
21. Abelian Higgs model, Glashow–Salam–Weinberg model (14.1–14.2).
22. Generating gauge boson masses, electroweak unification (14.3).
23. W and Z boson discovery, evidence for three light neutrinos (14.4–14.5).
24. Higgs boson discovery, ATLAS and CMS measurements (15.1–15.2).
25. Higgs–Yukawa couplings, Cabbibo–Kobayashi–Maskawa matrix (15.3–15.4).
26. Evidence for massive neutrinos, solar and atmospheric oscillations (16.1–16.4).

Outlook

27. Open questions, motivation for physics beyond the Standard Model.

Structure and approach

This graduate class has been taught by many esteemed colleagues at NYU with various levels and approaches. In recent years, the class required Quantum Field Theory I (PHYS-GA 2058), but this version does not. I instead return to more conventional introductory particle physics textbooks for advanced undergraduates and beginning graduates. This course develops relativistic quantum mechanics and emphasises experimental discoveries, assuming a standard US undergraduate physics curriculum as pre-requisites. This enables the course to complement rather than overlap too much with the theoretical QFT classes.

Given the breadth of particle physics, the choice of topics can neither be an exhaustive nor encyclopedic list of all particles, processes, calculations, and experiments. The aim instead is to convey the foundations and build intuition using illustrative examples as a springboard for more specialised study. This includes the literature review presentations in this class and the start of your graduate careers.

The course is organised into four parts covering how the Standard Model was discovered: (i) historical origins discussing motivation alongside foundational discoveries, (ii) quantum electrodynamics as the prototypical gauge theory, (iii) strong force showing how quarks and gluons emerged from the particle zoo, (iv) electroweak interactions from parity violation in low-energy beta decay to the Higgs boson and neutrino oscillations. The ordering may appear superficially historical, but worry not, the structure largely charts increasing energy scales and decreasing interaction strengths. This unsurprisingly coincides with technological advances, with more powerful machines simply taking longer to develop.

The lectures endeavour to weave selected historical, phenomenological, and experimental perspectives that make particle physics such a fascinating subject. Indeed understanding the *process* of discovery is as interesting as the discovery itself, especially for aspiring researchers learning how to uncover new knowledge themselves. I anticipate a mix of board work for mathematical derivations supplemented by slides to show more detailed figures and data. As time permits, the last lecture(s) may introduce the motivation for physics beyond the Standard Model and/or special research topics.

Pre-requisites

Mathematics: linear algebra (matrix multiplication, eigenvalues), complex numbers, vector calculus (integration in spherical coordinates). Physics: special relativity (space-time metric, Lorentz boosts), electromagnetism (Maxwell's equations, electromagnetic waves), quantum mechanics (Schrödinger equation, Pauli matrices, perturbation theory).

Recommended but not required: Quantum Field Theory I (PHYS-GA 2058) and II (PHYS-GA 2077) covers similar topics with more theoretical emphasis.

Assessment

- Grade: 60%. Homework. There are 5 problem sets planned based on lecture content.
- Grade: 40%. Research review. 10–15 minute presentation with slides. Attendance is required. Usual class location and time during finals week.

Presentation topics

In lieu of a final exam, each student selects a historical discovery or ongoing experiment related to particle physics and prepares a 10–15 minute talk; I recommend 10 slides of content. The presentation comprises a research literature review using slides during the regular class times of finals week. The topic is mutually agreed upon with me in advance (to ensure breadth by not too many people choosing the same topic). Suggested topics include:

1. Discovery of tau-lepton and/or tau-neutrino.
2. Discovery of top quark at Tevatron, Fermilab.
3. Higgs potential shape and Higgs self-coupling probes at LHC.
4. Tetraquarks and pentaquarks at LHCb Experiment.

5. Charge-parity violation in B-mesons.
6. Laboratory neutrino oscillations and charge-parity violation e.g. MicroBOONE, DUNE.
7. Majorana vs. Dirac neutrinos and neutrinoless double beta decay e.g. SNO+.
8. Measuring the muon anomalous magnetic moment $(g-2)$ at Fermilab.
9. Physics of High-Luminosity LHC and detector upgrades.
10. Future high-energy colliders (e.g. FCC, Muon Collider) and their physics goals.
11. Searches for weak-scale dark matter at colliders and direct detection experiments.
12. Searches for axion dark matter and axion-like particles.
13. Cosmic-ray observatories in space and terrestrial e.g. AMS, IceCube, Auger.
14. Accelerators and detectors in medical physics for imaging and radiotherapy.
15. Cosmic-ray muography for imaging volcanoes and archaeology sites.

0.2 Literature

There is no required textbook and I encourage you to browse your library to find your preferred text. This list also represents a bibliography I consulted (or studied as a student) in preparing the lecture notes.

Open access books. It is a truth universally acknowledged that textbooks are expensive. So I was happy to see certain texts recently made open access funded by the SCOAP^3 initiative coordinated by CERN, which is worth supporting:

- Giles Barr, Robin Devenish, Roman Walczak, Tony Weidberg, *Particle Physics in the LHC era* [1] (OUP 2016, Open Access Library[1]). Based on Oxford Part C master's level course; I myself took the graduate lectures in particle physics as a PhD student.
- Alessandro Bettini, *Introduction to Elementary Particle Physics* (3rd Edition, CUP 2024, open access on Cambridge Core[2]. This recently-updated textbook has particularly lucid accounts of the history behind experimental discoveries of particle physics.

Online lecture materials. A quick Internet search of "particle physics lectures" reveals many high-quality materials online. I list some from my academic heritage:

- **Advanced undergraduate level**
  Tina Potter teaches the Cambridge *Part II Nuclear and Particle Physics*[3] course for

[1] https://library.oapen.org/handle/20.500.12657/59108
[2] https://doi.org/10.1017/9781009440745
[3] https://www.hep.phy.cam.ac.uk/~chpotter/particleandnuclearphysics/mainpage.html

final (third) year undergraduates, which also covers nuclear physics. This is a standard introductory course for third-year British undergraduates, where I myself took the analogous lectures at Oxford taught by Alan Barr in 2014. I still possess some notes from my studies that I recycle here.

- **Graduate level**
  Chris Lester has over 600 slides for the Cambridge Natural Sciences *Part III Particle Physics*[4] master's level course with an experimental emphasis and complements the Thomson textbook. Theory counterparts are written up by David Tong[5], alongside Fernando Quevedo and Andreas Schachner[6].

  My education followed the *Standard Model* course at the Perimeter Institute, taught by Stefania Gori and Gordan Krnjaic with Daniel Wohns and Gang Xu in 2015; video recordings remain online[7] and the most recent 2025 edition is lectured by Sydek Ipek[8]. I also took an advanced PSI classes by David Morrissey who has clear SM notes[9] and Brian Shuve who has SM lectures recorded[10].

Canonical textbooks. Here are a few much-loved particle physics textbooks that do not assume quantum field theory, where the publication year is suggestive of whether post-LHC updates are included:

- David Griffiths, *Introduction to Elementary Particles* (2nd Edition, Wiley 2004). An old favourite with good coverage of history and Feynman rule calculations.
- Andrew J. Larkoski. *Elementary Particle Physics: An Intuitive Introduction* (CUP 2019). This recent textbook provides pedagogical coverage of LHC-era analysis topics.
- Brian R. Martin and Graham Shaw, *Particle Physics* (4th Edition, Manchester Physics Series 2017). Discussions on the quark model and interactions are especially clear, with good introductory chapters about accelerator and detector techniques.
- Donald Perkins, *Introduction to High Energy Physics* (4th Edition, CUP 2000). Old but classic with good balance of experiment and phenomenology, which trained many generations of professionals before the Higgs discovery.

[4] https://www.hep.phy.cam.ac.uk/~lester/teaching/partIIIparticles/welcome.html
[5] https://www.damtp.cam.ac.uk/user/tong/standardmodel.html
[6] https://arxiv.org/abs/2409.09211
[7] https://pirsa.org/c15001
[8] https://pirsa.org/c25003
[9] https://particletheory.triumf.ca/PHYS528/
[10] https://brianshuvephysics.com/materials

- Mark Thomson, *Modern Particle Physics* (CUP 2013)[11]. Modern classic written for the Cambridge Natural Sciences Part III course by the new CERN Director General.

Further reading. More specialised reading and summer school materials for the aspiring particle physics researcher:

- Particle Data Group, *Review of Particle Physics* (PRD 2024)[12]. *The* standard reference compiling up-to-date values and reviews, regularly updated by the group.
- Theoretical Advanced Study Institute (2024)[13]. Colorado summer school lectures providing advanced training for aspiring theorists and phenomenologists.
- Fermilab–CERN Hadron Collider Physics School (2024)[14]. The summer school alternates between Fermilab and CERN with slides available for advanced training aimed at aspiring collider physicists.
- Robert Cahn and Gerson Goldhaber, *The Experimental Foundations of Particle Physics* (CUP 2009). Nice account of the experimental evidence with prints of original discovery papers that led to the Standard Model.
- Howard Georgi, *Lie Algebras In Particle Physics: from Isospin To Unified Theories* (CRC Press 2000). For those who want to study the more mathematical aspects of group and representation theory underpinning particle physics.
- Glenn Knoll, *Radiation Detection and Measurement* (Wiley 2010). The standard reference for instrumentation underpinning detector physics.
- Tom Lancaster and Stephen Blundell, *Quantum Field Theory for the Gifted Amateur*[15] (OUP 2014). An accessible and lucid quantum field theory text written by condensed matter experimentalists that I found very helpful as a student.

[11] https://www.hep.phy.cam.ac.uk/~thomson/MPP/ModernParticlePhysics.html
[12] https://pdg.lbl.gov/, https://doi.org/10.1103/PhysRevD.110.030001
[13] https://sites.google.com/colorado.edu/tasi-2024-hub/home
[14] https://indico.fnal.gov/event/63696/
[15] https://academic.oup.com/book/36442