Physics 686 – Phenomenology of Particle Physics – Fall 2016

Dr. S. Martin Office: 214 La Tourette spmartin@niu.edu

Office hours: M,Tu,W,F 10:00-11:30 (or whenever you can find me)

Home page: http://www.niu.edu/spmartin/phys686/

Class meetings: M,W,F 9:00-9:50 in 227 La Tourette.

Graduate Catalog Description: Advanced topics in the standard model of quarks, leptons, gauge bosons and their fundamental interactions. Particle production and decay phenomenology.

Textbook: There is no official textbook for this course. Instead, updated lecture notes that correspond very closely to the course material will be provided electronically. The lecture notes will feature a table of contents, an index, and appendices with useful references. You may make your own personal copies of the lecture notes. However, please do not distribute them to others, either electronically or in paper form. Comments, corrections, and missing index entries for the lecture notes will be greatly appreciated.

Another useful resource is the Particle Data Group's "Review of Particle Properties" and its on-line version at http://pdg.lbl.gov/. You can even order your own free hard copy there. The whole RPP is a very large file, but individual sections can also be downloaded.

In an Appendix of the lecture notes is a list of other books that you may find useful, although I will not closely follow any of these books.

Topics to be covered: We will treat modern particle physics, using some of the language of quantum field theory but without completely developing the formal ideas of quantum field theory. We will aim to understand the Standard Model of particle physics, and how to compute cross-sections and decay rates. For a detailed outline, see the table of contents of the lecture notes. I *strongly* urge you to take notes in class, even though I will very closely follow the lecture notes.

Grading: Homework sets assigned about once per week will account for 100% of your course grade. Neatness, organization, and clarity count! Homeworks should be submitted on single-sided paper. Electronic submission of homework is not allowed. Late penalty policy: 10% off for each day after the due date, up to 1 week; 100% off after 6 days. Late means after 4:30 PM. You are encouraged to consult with each other and/or with outside sources on the homework. However, do not turn in anything that you have simply copied, or anything that you do not completely understand.

Contents

1 Introduction **4**
- 1.1 Fundamental forces . . . 5
- 1.2 Resonances, widths, and lifetimes . . . 5
- 1.3 Leptons and quarks . . . 6
- 1.4 Hadrons . . . 8
- 1.5 Decays and branching ratios . . . 12

2 Special Relativity and Lorentz Transformations **15**
- 2.1 Lorentz transformations . . . 15
- 2.2 Relativistic kinematics . . . 18
- 2.3 Tensors and Lorentz invariant quantities . . . 22
- 2.4 Maxwell's equations and electromagnetism . . . 25

3 Relativistic Quantum Mechanics of Single Particles **28**
- 3.1 Klein-Gordon and Dirac equations . . . 28
- 3.2 Solutions of the Dirac equation . . . 35
- 3.3 The Weyl equation . . . 43
- 3.4 Majorana fermions . . . 45

4 Field Theory and Lagrangians **46**
- 4.1 The field concept and Lagrangian dynamics . . . 46
- 4.2 Quantization of free scalar field theory . . . 53
- 4.3 Quantization of free Dirac fermion field theory . . . 58
- 4.4 Scalar field with ϕ^4 coupling . . . 61
- 4.5 Scattering processes and cross-sections . . . 67
- 4.6 Scalar field with ϕ^3 coupling . . . 77
- 4.7 Feynman rules . . . 84

5 Quantum Electro-Dynamics (QED) **92**
- 5.1 QED Lagrangian and Feynman rules . . . 92
- 5.2 Electron-positron scattering . . . 100
  - 5.2.1 $e^-e^+ \to \mu^-\mu^+$ . . . 100
  - 5.2.2 $e^-e^+ \to f\overline{f}$. . . 105
  - 5.2.3 Helicities in $e^-e^+ \to \mu^-\mu^+$ . . . 110
  - 5.2.4 Bhabha scattering ($e^-e^+ \to e^-e^+$) . . . 118
- 5.3 Crossing symmetry . . . 123
  - 5.3.1 $e^-\mu^+ \to e^-\mu^+$ and $e^-\mu^- \to e^-\mu^-$ . . . 124
  - 5.3.2 Møller scattering ($e^-e^- \to e^-e^-$) . . . 126
- 5.4 Gauge invariance in Feynman diagrams . . . 128
- 5.5 External photon scattering . . . 130
  - 5.5.1 Compton scattering ($\gamma e^- \to \gamma e^-$) . . . 130
  - 5.5.2 $e^+e^- \to \gamma\gamma$ . . . 138

6 Decay Processes **140**
- 6.1 Decay rates and partial widths . . . 140
- 6.2 Two-body decays . . . 141
- 6.3 Scalar decays to fermion-antifermion pairs: Higgs decay . . . 143
- 6.4 Three-body decays . . . 147

7 Fermi Theory of Weak Interactions **150**
7.1 Weak nuclear decays . . . 150
7.2 Muon decay . . . 152
7.3 Corrections to muon decay . . . 162
7.4 Inverse muon decay ($e^-\nu_\mu \to \nu_e\mu^-$) . . . 164
7.5 $e^-\overline{\nu}_e \to \mu^-\overline{\nu}_\mu$ . . . 167
7.6 Charged currents and $\pi^\pm$ decay . . . 168
7.7 Unitarity, renormalizability, and the W boson . . . 175

8 Gauge theories **180**
8.1 Groups and representations . . . 180
8.2 The Yang-Mills Lagrangian and Feynman rules . . . 191

9 Quantum Chromo-Dynamics (QCD) **198**
9.1 QCD Lagrangian and Feynman rules . . . 198
9.2 Scattering of quarks and gluons . . . 200
9.2.1 Quark-quark scattering ($qq \to qq$) . . . 200
9.2.2 Gluon-gluon scattering ($gg \to gg$) . . . 203
9.3 Renormalization . . . 204
9.4 Parton distribution functions and hadron-hadron scattering . . . 215
9.5 Top-antitop production in $p\overline{p}$ and pp collisions . . . 224
9.6 Kinematics in hadron-hadron scattering . . . 228
9.7 Drell-Yan scattering ($\ell^+\ell^-$ production in hadron collisions) . . . 231

10 Spontaneous Symmetry Breaking **235**
10.1 Global symmetry breaking . . . 235
10.2 Local symmetry breaking and the Higgs mechanism . . . 239
10.3 Goldstone's Theorem and the Higgs mechanism in general . . . 242

11 The Standard Electroweak Model **245**
11.1 $SU(2)_L \times U(1)_Y$ representations and Lagrangian . . . 245
11.2 The Standard Model Higgs mechanism . . . 250
11.3 Fermion masses and Cabibbo-Kobayashi-Maskawa mixing . . . 255
11.4 Neutrino masses and the seesaw mechanism . . . 264
11.5 $gg \to h$ and the Higgs boson discovery . . . 266

Appendices **273**
A.1 Natural units and conversions . . . 273
A.2 Dirac Spinor Formulas . . . 274
A.3 Further reading . . . 276

Index **278**

Accessibility Statement: Northern Illinois University is committed to providing an accessible educational environment in collaboration with the Disability Resource Center (DRC). Any student requiring an academic accommodation due to a disability should let his or her faculty member know as soon as possible. Students who need academic accommodations based on the impact of a disability will be encouraged to contact the DRC if they have not done so already. The DRC is located on the 4th floor of the Health Services Building, and can be reached at 815-753-1303 (V) or drc@niu.edu.