The ideas covered in this course are subtle, and their implementation can get technically complicated. It is well worth consulting textbooks to get other viewpoints on them, as well as details which may have been skipped in the lectures, not to mention additional examples. The books and chapters highlighted in **bold** are recommended.

Complete course

Gro **F. Gross, Relativistic quantum mechanics and field theory (Wiley, 1993)**
Probably the best single book available for a course at this level. Clear and readable. Covers essentially the whole course (except for deep-inelastic scattering). Also contains an introduction to gauge theories.

AH3 **I. J. R. Aitchison and A. J. G. Hey, Gauge theories in particle physics, Volume 1: From relativistic quantum mechanics to QED, 3rd edition (IOP, 2003)**
Also a very good book at this level, with a particularly clear introduction to scattering processes in particle physics and how to calculate them. Takes a slightly more advanced approach to field theory than Gross. Covers essentially the whole course (except for relativistic particles in potentials). Volume 2 provides an introduction to gauge theories at a similar level and so it could be useful for Symmetries in physics (PC4702).

GW K. Gottfried and V. Weisskopf, Concepts of Particle Physics, Vol. II (Oxford, 1986)
Similar in scope to Aitchison & Hey (2nd ed.). Idiosyncratic in places but the only book apart from Gross to treat the MIT bag model (which Weisskopf helped to invent). Also contains a good treatment of deep-inelastic scattering.

Sak **J. J. Sakurai, Advanced quantum mechanics (Addison-Wesley, 1967)**
Advanced level, but a classic with much physical insight. Even though the perverse choice of metric can make the formulae difficult to follow, the text around them is well worth reading.

Sca M. D. Scadron, Advanced quantum theory (Springer, 1991)
Rather terse and dull, but does cover nearly all of the material for this course.

Sch F. Schwabl, Advanced quantum mechanics (Springer, 1998)
Similar in scope to Scadron. Has a clear treatment of field theory.

Ynd F. J. Yndurain, Relativistic quantum mechanics and introduction to field theory (Springer, 1996)
Similar in scope to Scadron and Schwabl, but even more dull and formal.

Wave equations

Gre W. Greiner, Relativistic quantum mechanics: wave equations (Springer, 2000)
Lots of helpful examples and exercises, but generally too many equations and not enough words. No field theory or scattering.

Hol B. R. Holstein, Topics in advanced quantum mechanics (Addison-Wesley, 1992)
Messy presentation, but some interesting examples. Very little on field theory or scattering.

Lan R. H. Landau, Quantum mechanics II (Wiley, 1996)
Contains a good discussion of relativistic wave equations (Chapters 13–16). Also has the rudiments of field theory and its applications to scattering.

Str P. Strange, Relativistic quantum mechanics (Cambridge, 1998)
Good on relativistic wave equations, with interesting examples, but no field theory or scattering processes in particle physics. (By a condensed matter physicist.)

Field theory

BLP V. B. Berestetskii, E. M. Lifshitz and L. P. Pitaevskii, Quantum Electrodynamics (Pergamon, 1982)
Part of the classic course on theoretical physics by Landau and Lifshitz. Very advanced level, but with a lot of interesting physics.

BS N. N. Bogoliubov and D. V. Shirkov, Quantum fields (Benjamin/Cummings, 1983)
A good introduction to quantum field theory, but at a more advanced level than this course. (Not to be confused with the same authors' intimidating monograph, "Introduction to the theory of quantized fields".)

GR W. Greiner and J. Reinhardt, Field quantization (Springer, 1996)
An introduction to quantum fields at the right level for part 2 of this course.

IZ C. Itzykson and J.-B. Zuber, Quantum field theory (McGraw-Hill, 1980)
Very advanced level, but one of the best reference books on field theory. Chapters 2 to 5 contain material relevant to this course.

Kak M. Kaku, Quantum field theory (Oxford, 1993)
Advanced level, but a good qualitative introduction to field theory and many interesting applications.

MS F. Mandl and G. Shaw, Quantum field theory (Wiley, 1984)
A straightforward introduction to the basic calculational techniques in field theory.

PS M. E. Peskin and D. V. Schroeder, An introduction to quantum field theory (Perseus, 1995)
Now the standard text for graduate-level courses on field theory. A good introduction to many advanced topics and techniques, but probably not the best place to start.

Wei S. Weinberg, The quantum theory of fields, Volume 1: Foundations (Cambridge, 1995)
The first part of Weinberg's *magnum opus* is now perhaps the best reference book on the subject. Very advanced, but much more readable than many books at this level.

Applications to scattering

AH2 I. J. R. Aitchison and A. J. G. Hey, Gauge theories in particle physics, 2nd edition (IOP, 1989)
Older version of this book with much less on field theory but the same good coverage of scattering processes.

BD J. D. Bjorken and S. D. Drell, Relativistic quantum mechanics (McGraw-Hill, 1964)
Old and therefore regarded by some people as a classic. Deliberately avoids using field theory!

HM F. Halzen and A. D. Martin, Quarks and leptons (Wiley, 1984)
Like Bjorken and Drell, gets relativistic scattering amplitudes without quantising fields. Apart from the lack of field theory, similar in scope to Aitchison & Hey (2nd ed.) and Gottfried & Weisskopf.

Quantum mechanics

Gas S. Gasiorowicz, Quantum physics (Wiley, 1974)
Covers the background material on nonrelativistic quantum mechanics needed for this course. In particular, you should have met the following ideas: probability flux conservation for the Schrödinger equation, the Schrödinger and Heisenberg pictures, raising and lowering operators for the harmonic oscillator, interactions of charged particles and spins with magnetic fields, and basic ideas of scattering theory, such as cross sections. These are contained in Chapters 3, 4, 7, 13, 14 and 24.

Special relativity

Rin W. Rindler, Introduction to special relativity, 2nd edition (Oxford, 1991)
Most of the books above contain brief summaries of 4-vector notation for relativity. More details can be found here in Chapter IV and the Appendix. Chapter V treats relativistic kinematics and Chapter VI electromagnetism.

Background reading

A. Pais, Inward bound: Of matter and forces in the physical world (OUP, 1986)
A wonderful account of the development of the important ideas in quantum mechanics and particle physics. By someone who was either there at the time, or knew the people who were.

R. P. Feynman and S. Weinberg, Elementary particles and the laws of physics (Cambridge, 1987)

J. Gleick, Genius: Richard Feynman and modern physics (Pantheon, 1992)

G. Johnson, Strange beauty: Murray Gell-Mann and the revolution in 20th-century physics (Knopf, 1999)

COURSE SECTIONS

1 Relativistic wave equations

1.1 Natural units

AH3 Appendix B; **Sak 4.1**; AH2 Appendix B; Lan Appendix A.1; HM 1.4; MS 6.1

1.2 Some relativity

Gro 2.1; AH3 Appendix D; Sca 3.A; Gre 1.1; Lan Appendix C; AH2 Appendix A.2; HM 3.2; MS 2.1; **Rin IV, Appendix**

1.3 Some quantum mechanics

AH3 Appendix A; Sca 1.A; AH2 Appendix A.1; HM 3.1; **Gas 3**

1.4 Klein-Gordon equation

Gro 4.1; AH3 4.1; Sak pp. 6–7; Sca 4.A; Sch 5.2.1; Ynd 2.1; Gre 1.2; Hol VI.1; Lan 13.4; Str 3.1; IZ 2.1.1; MS 3.1; AH2 3.2; BD 1.2; HM 3.3

1.5 Negative energies

Gro 4.3; AH3 4.1.1; Sca 4.A; Sch 5.2.3; Gre 1.2; Lan pp. 206–207; Str 3.5; AH2 3.2.1; HM 3.3

1.6 Conserved current

Gro 4.2, 4.3; **Sak 3.1**; AH3 4.1.2; Sca 4.A; Sch 5.2.2; Ynd 2.3; Gre 1.2, 1.4; Hol pp. 260–261; Lan pp. 207–208; Str 3.2; IZ 2.1.1; AH2 3.2.2; BD 1.2; HM 3.3

(Schrödinger equation: **Gas pp. 47–48**)

1.7 Interaction with EM fields

Gro 4.1; Sca pp. 52–53; Ynd 2.4; Gre 1.9; Lan pp. 208–210; Str 3.1; AH2 3.6; HM 4.1

(Schrödinger equation: **AH3 3.4**; AH2 2.4, 2.5; **Gas 13**)

1.8 Klein-Gordon Hydrogen atom

Gro Problems 4.1, 4.2; Sca pp. 53–55; Sch 8.1; Ynd 2.5; Gre Exercise 1.11; Lan pp. 212–213, Problems 13.6.4; Hol VI.3; Str 3.7–3.8; **IZ 2.3.1**

1.9 Klein paradox

Gro 4.4; **Gre 13**; Lan pp. 213–216; Hol VI.2; **Str 3.6**

(Dirac version: **Sak pp. 120–121**; Sch 10.1.4; IZ pp. 62–63; BD pp. 40-42)

1.10 Dirac equation

Gro 5.1; **AH3 4.2**; GW II.A.3; Sak 3.2; Sca 5.A; Sch 5.3.1; Ynd 2.5; Gre 2; Hol VII.1; Lan 14.1; Str 4.1; IZ 2.1.2; MS 4.2; AH2 3.3; BD 1.3; HM pp. 100–101

(Pauli matrices: Gas pp. 232–239)

1.11 Conserved current

Gro 5.2; AH3 4.2.2; GW p. 203; Sak pp. 82–83; Sca 5.A; Sch 5.3.2; Ynd 3.3; Gre pp. 79–80; Hol p. 287; Lan 14.4; Str 4.6; IZ 2.1.2; AH2 3.3.2; BD 1.3; HM 5.2

1.12 Constants of motion

Gro pp. 164–165; **Sak pp. 113–114**; Sca p. 83; Sch 6.7; Ynd 3.2.1; Gre Exercise 9.4; Lan pp. 251–252; HM Exercise 5.4

1.13 Covariant notation

Gro 5.1; AH3 Problem 4.11; GW pp. 203–204; Sak 3.2; Sca 5.B; Sch 5.3.4; Ynd 3.1; Gre pp. 99–102; Hol VII.1; Lan 14.3; Str 4.2; IZ 2.1.2; MS 4.2; PS 3.2; AH2 6.1; BD 2.1; HM 5.1, 5.2

1.14 Plane-wave solutions

Gro 5.3, 5.4; **AH3 4.2.1**; Sak pp. 89–94; Sca 5.C; Sch 6.3.1; Ynd 3.5; Gre 2.1; Hol VII.5; Lan 15.2; Str 5.2; IZ 2.2.1; MS 4.2; PS 3.3; AH2 3.3.1; BD 3.1; HM 5.3

1.15 Dirac hole theory

Gro 5.4; **AH3 4.5.3, 4.5.4**; **Sak 3.9**; Sch 10.2; Ynd 3.7; **Gre 2.1, 12**; Hol VII.6; Lan 15.1; Str 5.4; IZ 2.4.1; AH2 3.4, 3.5; BD 5.1; HM 3.4, 3.5, 5.4

1.16 Helicity and chirality

Gro 5.11; AH3 4.3; **Sak pp. 167–170**; Sca 3.9; Sch 11.6; Gre pp. 94–95; Hol Problem VII.5.2; IZ 2.4.3; MS Appendix A.6; **AH2 10.4**; **HM 5.7**

1.17 Continuous symmetries

Gro 5.8–5.9; **AH3 4.4**; GW Appendix III.1; **Sak 3.4**; Sca 2.C, 3.B, pp. 71-72; Sch 6.2.1–6.2.2; Ynd 3.2; Gre 3; Hol pp. 283–286; Lan 14.5; IZ 2.1.3; Kak 2, pp. 78–79; MS Appendix A.7; AH2 Appendix A.2; BD 2.2

1.18 Parity

Gro p. 151; AH3 p. 91; **GW p. 210**; **Sak pp. 99-100, 103–104**; Sca pp. 104–105; Sch 6.2.2.4; Ynd 3.2.3; Gre 4; Lan p. 231; Str 6.5; IZ pp. 53–54; AH2 10.3; BD 2.3; HM p. 113

1.19 Interaction with fields

Gro 5.1, 5.7; **AH3 4.6**; **Sak pp. 85–86, 115**; Sca pp. 66–67; Sch 5.3.5; Ynd 3.4; Gre pp. 94–98; Lan 15.5; Str 4.4; IZ 2.2.3; MS 4.5; AH2 3.6; BD 1.4, 2.1; HM Exercise 5.5

1.20 Particle in a spherical well

Gro 6.1; Sca p. 84; Str 8.1; Ynd 3.6, 4.1; Gre Exercises 9.3, 9.5, 9.8; Lan 16.1

(Dirac H atom: Gro 6.3; Sak 3.8; Sca pp. 85–86; Sch 8.2; Ynd 4.2, 4.4; Gre Exercises 9.6, 9.7; Hol VII.4; Lan 16.2; Str 8.3; **IZ 2.3.2**; BD 4.4)

1.21 The MIT bag model

Gro 6.2; GW IV.D.1, Appendix VII

2 Quantum fields and their dynamics

2.1 Why do we need field theory?

AH3 2.1–2.2; **BLP 1**

(*Zitterbewegung*: **Sak pp. 117–119**; Sch 10.1.2; Hol pp. 324–326; Str 7.3; BD pp. 38–40; IZ 2.2.2)

2.2 Quantum mechanics of string

Gro 1.1–1.4; AH3 5.1; Sch 12.1; GR 1; IZ 3.1.1 Wei 1.2

(Analogous ideas for EM field: **Sak 2.1–2.2**; Ynd 8.2.1; BLP 2; MS 1.2)

2.3 Phonons

Gro 1.5–1.8; AH3 5.2; Sch 12.1; IZ 3.1.2

(Analogous ideas for photons: GW II.A.4; **Sak 2.2–2.3**; Sca 4.D; Ynd 8.2.1; Lan 20.1; BLP 2–3)

2.4 Klein-Gordon field

Gro 7.3; AH3 5.3; GW Appendix II; Sak p. 77; Sch 13.1.1, 13.2; Ynd 7.4.1; AH2 4.4; BLP 10; BS 3.1–3.2; 6.1–6.3 GR 4.1; IZ 3.1.2–3.1.3; Kak 3.2; MS 3.1–3.2; PS 2.3

2.5 Antiparticles

Gro 7.3; AH3 7.1; GW pp. 553–556; Sak p. 77; Sch p. 287; Ynd pp. 194–197; AH2 pp. 115–118; BLP 11–12; BS 7.1; GR 4.2; Kak 3.3; MS 3.2

2.6 Fermions

Gro 7.2; Sak pp. 28–29; Sch 1.4; Ynd 6.5; BS 7.3; GR 3.3; MS 4.1

2.7 Dirac field

Gro 7.4; AH3 7.2; GW Appendix III; **Sak pp. 144–154**; Sch 13.3.3–13.3.4; Ynd 9.5; Lan 22.1; AH2 4.5; BLP 25; BS 5; GR 5.3; IZ 3.3; Kak 3.5; MS 4.3; PS 3.5

2.8 Spin and statistics

Gro pp. 196–200; AH3 7.2; GW Appendix IV.2; Sak p. 152; Sch 13.4; AH2 4.5; BLP 11, 25; BS 7.5; GR pp. 129–130; IZ 3.3.3; Kak pp. 89–90; MS pp. 72–73; PS pp. 52–58

2.9 Causality

GW Appendix IV.1; AH3 pp. 157–158; Ynd 8.6; BS 8.1; GR 4.4; IZ pp. 117–118; Kak p. 74; MS 3.3; PS pp. 27–29

2.10 Feynman propagator

Gro pp. 113–116, 245–247, 249–252; AH3 pp. 157–163, 179–180, **Appendix G**; GW Appendix IV.1; **Sak 4.5**; Sca pp. 128–130, 10.D; Sch 13.1.2; Ynd 9.7; AH2 3.4, 3.5.3, 5.8.1; BD 6; HM 3.5, 6.16; Hol 7.8; BLP 75; BS 18; GR 4.5; IZ 1.3.1, 3.1.4; Kak 3.4; **MS 3.4**; PS 2.4

2.11 Virtual particles

GR p. 115; See also references for Section 3.1

(Mixed representation of propagator: BLP pp. 303–304)

2.12 The reason for antiparticles

Gro 8.7; **GW Appendix IV.3**; Sca 6.D; **BLP 13**; BS 9.4; GR 10.6; IZ 3.4.4

2.13 Interaction picture

Gro 1.8, 3.1; **AH3 6.2.1**; **Sak pp. 181–183**; Sca 1.D; Sch 15.2.1; Ynd pp. 150–151; BS 14.1–14.2; GR 8.2; MS 1.5; PS 4.2

2.14 The S-matrix

Gro pp. 63–64; AH3 pp. 147–148; **Sak 4.2**; Sca 7.D–7.E; Sch 15.2.2, 15.3.1; Ynd 7.3, 7.8.1; BS 14.3–14.4; GR 8.4; IZ 4.1.4; MS 6.2

2.15 Covariant perturbation theory

Gro 3.1; AH3 6.2.2, Problem 6.1; **Sak pp. 183–188**; Sca 10.C; Sch 15.3; Ynd pp. 152–153; GR 8.3–8.4; Kak 5.5

2.16 Decay amplitude

Gro 9.10; AH3 pp. 151–152; Sak pp. 200–201

2.17 Decay rate

Gro 9.2, pp. 277–279; AH3 6.3.1; Sak pp. 201–203; BS 21.5; HM 4.4

3 Scattering processes

3.1 Particle exchange

Gro 9.3–9.4; AH3 6.3.3; Sak pp. 242–250; Sca 10.D, 12.A; AH2 5.6

3.2 Feynman diagrams and Feynman rules

Gro 9.4, p. 270, pp. 299–301; AH3 pp. 162–163; pp. 221–223, Appendix L; GW II.B.1, II.B.4; Sak pp. 210–212, 215–216, 246–247, 256; Sca 10.C, 10.E; Sch 15.3.2, 15.5.4; Ynd pp. 268–269, 10.2.1; BS 19–20; GR 8.6; Kak 5.7; MS 7.1–7.3; PS 4.4, 4.6–4.8; AH2 Appendix F; HM p. 149

3.3 Nonrelativistic potential

Gro 9.6; AH3 2.3; Sak pp. 258–259, 264–266; Sca 12.A; Ynd 10.1, 10.5; Lan 22; AH2 5.8.2; BD pp. 211-212; Gas 24.C

3.4 Photon propagator

Gro pp. 286–289; AH3 3.3, 7.3, 7.4; Sak pp. 250–256; Sca 10.D; Sch 14.5; Ynd 9.7; BLP 76; GR 6.2, 7.5; MS 5.3; AH2 5.1–5.3; BD p. 109; HM 4.1–4.2, 6.11

3.5 Cross sections

Gro 9.5; **AH3 6.3.4**; Sca 10.A–10.B; Sch 15.5.3.2; Ynd 7.4; Hol pp. 54–58, II.5; BLP 64; BS 21.4; IZ 5.1.1; Kak 5.1; MS 8.1; PS 4.5; AH2 5.4–5.5; BD 7.1, 7.4; HM 4.3

3.6 Spin-$\frac{1}{2}$–spin-0 scattering

AH3 8.3.1–8.3.2; AH2 6.3–6.5

(Spin-0–spin-0: AH2 5.4–5.5; HM 4.2–4.3)

3.7 Nonrelativistic limits

Gro 5.5; AH3 8.1, 8.2.1; Sak pp. 188–193, **195–196**; Sca 11.A; Sch 15.5.2; Hol pp. 344–347; BLP 80; IZ 2.5.3; Kak 5.2; **MS 8.7**; BD 7.1–7.2; HM 8.1

3.8 Form factor

AH3 8.4.1; **GW pp. 240–242**; **Sak p. 194**; Hol pp. 359–360; AH2 6.6; HM 8.1

3.9 Spin-$\frac{1}{2}$–spin-$\frac{1}{2}$ scattering

Gro 10.2; AH3 8.7; GW II.C.1; Ynd 10.3.2; PS 5.4; AH2 6.7; BD 7.4; HM 6.5

3.10 Identical particles

Sak pp. 250–258; Sca 11.B; Sch 15.5.3.1; Ynd 10.3.2; BLP 81; BD 7.9; HM 6.2

3.11 High-energy scattering

AH3 Problem 8.18; GW p. 233; HM 6.5

(Mandelstam variables: AH3 p. 164; Sca p. 185; Ynd 7.2; BLP 66; PS pp. 156–158; AH2 pp. 147–148; HM 4.7)

3.12 Proton form factors

Gro pp. 294–296; **AH3 8.8**; GW II.A.1; Sca 5.D, 11.F; BLP 138–139; MS Problem 8.3; AH2 6.8; HM 8.2

3.13 Deep-inelastic scattering

AH3 9.1; **GW V.1–V.3**; Kak 14.1; AH2 7.1; HM 8.3, **9.1**

3.14 Partons

AH3 9.2; **GW V.4**; Kak 14.2; AH2 7.2; **HM 9.2**

3.15 e^-e^+ annihilation

Gro 10.3; **AH3 8.5**, Problem 8.19; GW II.C.2; MS 8.4; PS 5.1–5.2; AH2 Problem 6.7; HM 6.5–6.6

(e^-e^+ scattering: GW II.C.2; HM 6.7; Sak pp. 261–262; Sca 11.C; Ynd 10.4; BLP 81; MS 8.5; BD 7.9)

3.16 e^-e^+ annihilation into hadrons

Gro 10.4; **AH3 9.5**; AH2 7.5; HM 11.1

3.17 Renormalisation

AH3 10.1.1, 11.8

Mike Birse (January 2010)