Quantum Chromodynamics

High Energy Experiments and Theory

GÜNTHER DISSERTORI

Institute for Particle Physics, ETH Zürich, Switzerland

IAN G. KNOWLES

Formerly University of Edinburgh, Scotland, U.K.

MICHAEL SCHMELLING

Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany

CLARENDON PRESS • OXFORD

2003

CONTENTS

Notation	x
1 Introduction	1
2 The development of QCD	6
2.1 Experimental evidence	6
2.1.1 The quark model	6
2.1.2 The quark parton model	8
2.1.3 Colour	15
2.1.4 Other puzzles	19
2.2 The QCD Lagrangian	21
3 The theory of QCD	25
3.1 QCD as an SU(3) gauge theory	25
3.2 The QCD description of basic reactions	31
3.2.1 Electron–positron annihilation	34
3.2.2 Lepton–hadron scattering	38
3.2.3 Hadron–hadron scattering	52
3.3 Born level calculations of QCD cross sections	62
3.3.1 e^+e^- annihilation to quarks at $\mathcal{O}(\alpha_s^0)$	62
3.3.2 e^+e^- annihilation to quarks at $\mathcal{O}(\alpha_s^1)$	70
3.3.3 Gauge invariance of the QCD Lagrangian	74
3.3.4 The evaluation of colour factors	79
3.4 Ultraviolet divergences and renormalization	80
3.4.1 Self-energy and vertex corrections	81
3.4.2 Renormalization	87
3.4.3 The renormalization group equations	93
3.4.4 Calculating the RGE coefficient functions	96
3.4.5 The running coupling and quark masses	98
3.4.6 An explicit example	103
3.5 Infrared safety	106
3.5.1 Infrared cancellations	106
3.5.2 e^+e^- annihilation to hadrons at NLO	108
3.5.3 Infrared safe observables	114
3.6 The QCD improved parton model	117
3.6.1 DIS at the parton level	118
3.6.2 DIS at leading order	120
3.6.3 A heuristic treatment of factorization	121

3.6.4	DIS at next-to-leading order	128
3.6.5	The evolution of the parton density functions	135
3.6.6	Leading logarithms	139
3.6.7	The analysis of ladder diagrams	144
3.6.8	The Drell-Yan process	149
3.7	The treatment of soft gluons	153
3.8	Hadronization models	157
3.8.1	Space-time structure of multi-hadron events	158
3.8.2	Independent hadronization	161
3.8.3	String hadronization	162
3.8.4	Cluster hadronization	168
3.8.5	A comparison of the main hadronization models	171
4	Monte Carlo models	179
4.1	Fixed-order Monte Carlos	179
4.2	All-orders Monte Carlos	181
4.2.1	The parton evolution equations	182
4.2.2	Branching kinematics	184
4.2.3	Time-like Monte Carlo algorithm	185
4.2.4	Space-like Monte Carlo algorithm	187
4.2.5	Soft gluon logarithms	190
4.2.6	The colour dipole model	196
4.2.7	The soft underlying event model	200
4.3	Multi-purpose event generators	202
4.3.1	Using event generators	202
5	Experimental set-up	206
5.1	Accelerators	206
5.1.1	Accelerator systems	208
5.1.2	Beam optics	211
5.2	Detectors at high energy colliders	213
5.2.1	Tracking detectors	215
5.2.2	Calorimeters	216
5.2.3	Passage of particles through matter	220
5.2.4	Particle identification	221
5.2.5	ALEPH: an example of a LEP detector	223
6	QCD analyses	228
6.1	General concepts	228
6.1.1	Event selection	230
6.2	Observables	235
6.3	Corrections	240
6.3.1	Detector corrections	240
6.3.2	Hadronization corrections	241
6.4	Systematic uncertainties	243

6.5	Examples	244
6.5.1	Structure function measurement at HERA	244
6.5.2	Inclusive jet production at the TEVATRON	250
6.5.3	Jet rates at LEP	255
7	Structure functions and parton distributions	258
7.1	Charged lepton–nucleon scattering	260
7.1.1	Neutral current interactions	260
7.1.2	Charged current interactions	264
7.1.3	The low- x and low- Q^2 region	269
7.1.4	The gluon density in the proton	273
7.2	Neutrino–nucleon scattering	277
7.2.1	Experimental issues	279
7.2.2	Measurements of F_2 and xF_3	280
7.2.3	The gluon distribution	285
7.2.4	The strange quark distribution	285
7.3	Sum rules	288
7.3.1	The Adler sum rule	288
7.3.2	The Gross–Llewellyn Smith sum rule	289
7.3.3	The Gottfried sum rule	290
7.3.4	The momentum sum rule	290
7.3.5	Sum rules for polarized structure functions	291
7.4	Hadron–hadron scattering	292
7.4.1	The Drell–Yan process	292
7.4.2	The W rapidity asymmetry	294
7.4.3	Direct-photon production	295
7.4.4	Inclusive jet production	297
7.5	Global QCD analyses	299
8	The strong coupling constant	305
8.1	Theoretical predictions	306
8.2	Comparison and combination of results	307
8.3	Inclusive measurements	309
8.3.1	The ratios R_γ and R_l	309
8.3.2	Measurement of α_s from R_τ	310
8.3.3	α_s from sum rules	312
8.4	Measurements of α_s from heavy flavours	313
8.4.1	Decays of heavy quarkonia	314
8.4.2	Lattice calculations	315
8.5	Scaling violations	316
8.5.1	Scaling violations in fragmentation functions	316
8.5.2	Scaling violations in structure functions	320
8.6	Measurements at hadron colliders	320
8.7	Global event shape variables	321
8.7.1	Theoretical predictions	321

8.7.2	Event shape variables	322
8.8	Analytical approaches to power law corrections	326
8.9	Jets in deep inelastic scattering	329
8.10	Summary of α_s measurements	329
9	Tests of the structure of QCD	334
9.1	Parton spins	334
9.1.1	The quark spin	334
9.1.2	The gluon spin	336
9.2	Flavour independence of strong interactions	340
10	Tests of the gauge structure of QCD: colour factors	344
10.1	Three-jet variables	346
10.2	Four-jet variables	351
10.3	Combination of three- and four-jet variables	358
10.4	Information from the running of α_s	359
10.5	Information from jet fragmentation	362
10.6	Limits on new physics	363
11	Leading-log QCD	365
11.1	The structure of the parton shower	365
11.2	Momentum spectra	366
11.3	Particle multiplicities	369
11.4	Isolated hard photons	372
11.5	Subjet multiplicities	373
11.6	Breit frame analyses	375
12	Differences between quark and gluon jets	376
12.1	Theoretical expectations	376
12.2	Extracting quark and gluon jet properties	377
12.3	Experimental properties of quark and gluon jets	380
12.3.1	Topology dependence of jet properties	380
12.3.2	Multiplicities	381
12.3.3	Jet profiles	387
12.3.4	Fragmentation functions	388
12.3.5	Particle content	389
13	Fragmentation	392
13.1	Identified particles	394
13.1.1	Multiplicities	394
13.1.2	Momentum spectra	397
13.2	Inter-jet soft gluons and colour coherence	398
13.2.1	The string effect	399
13.2.2	Colour coherence in hadron-hadron collisions	400
13.3	Two-particle correlations	402
13.3.1	Proton-antiproton correlations	402

13.3.2 Strangeness correlations	404
13.3.3 Bose–Einstein correlations	406
13.4 Colour reconnection	410
14 Summary	413
Appendices	415
A Elements of group theory	415
A.1 Basics of Lie groups	415
A.2 The $U(N)$ and $SU(N)$ groups	421
A.3 Colour factors	423
B Building blocks of theoretical predictions	425
B.1 The Feynman rules of QCD	425
B.2 Phase space and cross section formulae	427
C Dimensional regularization	429
C.1 Integration in non-integer dimensions	429
C.2 D -dimensional γ -matrix algebra	433
C.3 D -dimensional phase space	433
C.4 Useful mathematical formulae	435
D R_γ, R_l and R_τ for arbitrary colour factors	436
D.1 The running coupling constant and masses	436
D.2 Theoretical predictions for R_γ	438
D.3 The theoretical prediction for R_l	439
D.4 The theoretical prediction for R_τ	440
E Scaling violations in fragmentation functions	442
E.1 Definitions	442
E.2 The flavour non-singlet case	443
E.3 The flavour-singlet case	444
E.4 Fragmentation functions and hadron spectra	445
E.5 Electroweak weight functions	446
F Solutions	447
References	506
Index	524