CAMBRIDGE

Cambridge University Press
052146840X - An Introduction to Gauge Theories and Modern Particle Physics,
Volume 1: Electroweak Interactions, the 'new particles' and the Parton Model
Elliot Leader and Enrico Predazzi
Table of Contents
More information

Contents: Volume 1
Electroweak interactions, the 'new particles' and the parton model

Preface xxi

Acknowledgements xxiv

Notational conventions xxv
Note added in proof: the discovery of the top quark (?) xxxi
Note added in proof: the demise of the SSC xxxiii

1 Field theory and pre-gauge theory of weak interactions 1
1.1 A brief introduction to field theory 1
1.2 Pre-gauge theory of weak interactions 6
1.3 The spin and isospin structure 15
1.3.1 The spin or helicity structure 16
1.3.2 Relation between particle and antiparticle matrix elements 17
1.3.3 The isospin structure 18
1.4 Tests of the $V-A$ structure and 'lepton universality' 20

2 The need for a gauge theory 23
2.1 The intermediate vector boson 23
2.2 Towards a renormalizable theory 27
2.3 Gauge symmetry 29
2.3.1 Global gauge invariance—the Abelian case 30
2.3.2 Local gauge invariance—the Abelian case 31
2.3.3 Global gauge invariance—the non-Abelian case 33
2.3.4 Non-Abelian local gauge invariance—Yang–Mills theories 35
2.4 Freedom to choose the gauge 38
2.5 Summary 39

3 Spontaneous symmetry breaking: the Goldstone theorem and the Higgs phenomenon 40
3.1 Spontaneously broken symmetries in field theory: Goldstone's theorem 41

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052146840X - An Introduction to Gauge Theories and Modern Particle Physics,
Volume 1: Electroweak Interactions, the 'new particles' and the Parton Model
Elliot Leader and Enrico Predazzi
Table of Contents
More information

3.2	The Higgs mechanism	45
3.3	Unitarity and renormalizability	47
3.4	Summary	48
4	**Construction of the standard model**	49
4.1	Model building (towards the standard model)	49
4.2	The standard model	50
4.2.1	Coupling of the gauge bosons to the Higgs scalars	52
4.2.2	Self-coupling of the gauge bosons	55
4.2.3	Coupling of the gauge bosons to the leptons	55
4.2.4	Coupling of the leptons to the Higgs	61
4.3	Discovery of W and Z^0	63
4.3.1	Discovery of the W boson(?)	63
5	**Lowest order tests of the SM in the leptonic sector**	67
5.1	Phenomenology of purely leptonic reactions	67
5.1.1	$\nu_e e$ and $\bar{\nu}_e e$ elastic scattering	69
5.1.2	$\nu_\mu e^-$ and $\bar{\nu}_\mu e$ elastic scattering	74
5.1.3	Inverse μ-decay	76
5.2	A check of the minimal Higgs mechanism	76
5.3	Support for the SM from hadronic collider data	77
5.3.1	W production and decay in $\bar{p}p$ collisions	78
5.3.2	$\bar{p}p$ collider data	82
5.4	Concluding remarks	87
6	**The Higgs boson**	90
6.1	Introductory remarks	90
6.2	Higgs decay	91
6.3	Higgs production at the Z^0 mass	95
6.3.1	$Z^0 \to Hf\bar{f}$	95
6.3.2	$Z^0 \to H\gamma$	96
6.4	Limits on the Higgs mass	97
6.5	Concluding comments	100
7	**The standard model beyond lowest order**	101
7.1	Radiative corrections	101
7.2	Renormalization and physical parameters	103
7.3	The effective fine structure constant	106
7.4	The muon lifetime revisited	107
7.5	Estimates of one loop corrections	109
7.6	Higher order corrections	110
7.7	Practical problems in testing radiative corrections	112
7.8	Strategies to overcome the imprecision in M_W	113
7.9	Testing the minimal Higgs mechanism	114
7.10	Beyond the standard model	115

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052146840X - An Introduction to Gauge Theories and Modern Particle Physics,
Volume 1: Electroweak Interactions, the 'new particles' and the Parton Model
Elliot Leader and Enrico Predazzi
Table of Contents
More information

8	**e^+e^- physics and the standard model**	118
8.1	Electron–positron storage rings	118
8.2	The new e^+e^- colliders: TRISTAN and LEP	121
8.3	e^+e^- physics at energies $\ll M_Z$	126
8.4	e^+e^- and the standard model	132
8.5	LEP data near the Z^0 peak	133
	8.5.1 e^+e^- angular distributions	134
8.6	Determination of the SM parameters of the Z^0	142
8.7	Neutrino counting	147
	8.7.1 The invisible width method	147
	8.7.2 The single photon method	148
8.8	Asymmetries and polarization measurements at the Z^0 peak	149
8.9	Conclusions	154
9	**Extension to the hadrons; quark–lepton universality**	157
9.1	Charm, bottom and top	157
9.2	Quark mixing	160
9.3	Electroweak interaction of the quarks	163
9.4	The GIM mechanism	164
9.5	Colour	166
	9.5.1 The quark statistics	166
	9.5.2 $\pi^0 \to 2\gamma$	168
	9.5.3 Triangle anomalies	170
	9.5.4 The cross-section for $e^+e^- \to$ *hadrons*	174
9.6	Summary of the quark sector of the standard model	176
9.7	Quark masses and the KM matrix	179
10	**Phenomenology of semi-leptonic reactions**	182
10.1	Model independent tests	184
10.2	Parity violation in electron–nucleus scattering	189
10.3	Optical rotation	193
10.4	Summary	201
11	**The discovery of the narrow vector resonances**	202
11.1	Introduction	202
11.2	The 'new' particles	204
11.3	Some qualitative features of QCD	206
11.4	Quark–lepton parallelism	208
11.5	Flavour classification of hadrons	209
11.6	The J/Ψ and the OZI rule	213
11.7	Experimental status of the J/Ψ spectroscopy	219
	11.7.1 Mass determination of the J/Ψ	224
11.8	Properties of the $J/\Psi(3097)$ and $\Psi'(3685)$	225
	11.8.1 J/Ψ and Ψ' widths	225
	11.8.2 J^{PC} assignments	228
	11.8.3 I^G assignment	229
11.9	Baryonic decay of J/Ψ	232

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052146840X - An Introduction to Gauge Theories and Modern Particle Physics,
Volume 1: Electroweak Interactions, the 'new particles' and the Parton Model
Elliot Leader and Enrico Predazzi
Table of Contents
More information

11.10 The Υ family and its experimental status 234

12 Hidden flavour bound states 240
12.1 Quarkonium 240
12.1.1 The positronium analogy 241
12.1.2 The QCD potential 242
12.1.3 The strength of the potential 245
12.1.4 Spin dependence of the potential 248
12.1.5 Comparison with the data 249
12.2 J/Ψ decays. Calculation of the widths 254
12.3 Determination of α_s 260
12.4 Leptonic widths 262
12.5 Exotics: glueballs, hybrids, etc. 264
12.6 $\Psi' \to \varrho\pi$: a puzzle 267
12.7 Conclusions 268

13 Open heavy flavours 269
13.1 Discovery and basic properties of charm and bottom particles 270
13.1.1 Detection of heavy flavours 276
13.1.2 Charge of the charm and bottom quarks 279
13.1.3 Heavy flavour masses 280
13.2 Charm decay 282
13.2.1 Heavy flavour lifetimes 284
13.2.2 Purely leptonic charm decays 286
13.2.3 Semi-leptonic and hadronic decays of charm mesons 287
13.3 B physics 290
13.3.1 The decay $\bar{B}^0 \to D^{+*}\ell^-\bar{\nu}$ 291
13.4 Production of heavy flavours 293
13.4.1 Theoretical estimates of heavy flavour production 293
13.5 Heavy flavours at LEP 295
13.5.1 Production of c and b quarks at the Z^0 pole 295
13.5.2 Production cross-section 296
13.5.3 Miscellaneous 297
13.6 Final comments 299

14 The heavy lepton τ 300
14.1 Introduction 300
14.2 Discovery of the τ lepton 301
14.3 Properties of the τ lepton 304
14.3.1 The τ mass 304
14.3.2 The τ lifetime 306
14.3.3 The spin of the τ 307
14.3.4 Point-like structure 308
14.3.5 $\tau - e - \mu$ universality 309
14.4 τ decay 309
14.4.1 Semi-leptonic τ decays 310
14.4.2 QCD tests from τ decay 311
14.5 The τ neutrino 312

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052146840X - An Introduction to Gauge Theories and Modern Particle Physics, Volume 1: Electroweak Interactions, the 'new particles' and the Parton Model
Elliot Leader and Enrico Predazzi
Table of Contents
More information

14.6	Rare τ decays	314
14.7	Miscellaneous and conclusions	314
15	**Towards the parton model—deep inelastic scattering**	316
15.1	Electron–muon scattering	317
15.2	Elastic electron–proton scattering	321
15.3	Inelastic electron–nucleon scattering	324
15.4	Inelastic neutrino–nucleon scattering	331
15.5	Deep inelastic scattering and scaling behaviour	335
15.6	Polarization effects in deep inelastic scattering	342
16	**The quark–parton model**	352
16.1	The introduction of partons	352
16.2	Antipartons	359
16.3	Partons as quarks	361
16.4	The detailed quark–parton model	364
16.4.1	The scaling functions for purely electromagnetic interactions	366
16.4.2	Charged current scaling functions	368
16.4.3	Neutrino and antineutrino neutral current scaling functions	373
16.5	Charged lepton induced reactions for Q^2 of order M_Z^2	374
16.6	Behaviour of the quark number densities as $x \to 0$	375
16.7	The missing constituents—gluons	377
16.8	The parton model in polarized deep inelastic scattering	378
16.9	Appendix to Chapter 16: The parton model as an impulse approximation	382
16.9.1	The parton model as an impulse approximation	382
16.9.2	The parton model including transverse motion	386
16.9.3	Current matrix elements in the quark–parton model	393
17	**Experimental tests of the quark–parton model**	396
17.1	Deep inelastic scaling functions for $Q^2 \ll M_Z^2$	396
17.1.1	Sum rules and their experimental tests	401
17.1.2	Polarized scattering sum rule and the 'spin crisis'	405
17.1.3	The nuclear EMC effect	409
17.1.4	Experimental status of the scaling functions	416
17.2	Neutrino cross-sections in the quark–parton model for $Q^2 \ll M_Z^2$	416
17.3	Cross-sections in the quark–parton model for Q^2 comparable with M_Z^2	425
17.4	Application of the parton model to related processes	426
17.4.1	e^+e^- annihilation into hadrons	427
17.4.2	The Drell–Yan process	428
17.4.3	Production of heavy mesons by Drell–Yan mechanism	440
	Note added in proof: polarized deep inelastic scattering	442

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052146840X - An Introduction to Gauge Theories and Modern Particle Physics,
Volume 1: Electroweak Interactions, the 'new particles' and the Parton Model
Elliot Leader and Enrico Predazzi
Table of Contents
More information

Appendix 1: Elements of field theory 443
A1.1 Fields and creation operators 443
A1.2 Parity, charge conjugation and G-parity 447
A1.2.1 Parity 447
A1.2.2 Charge conjugation 447
A1.2.3 G-parity 449
A1.3 The S-matrix 449

Appendix 2: Feynman rules for QED, QCD and the SM 451
A2.1 Relation between S-matrix and Feynman amplitude 451
A2.2 QCD and QED 452
A2.3 The SM 455
A2.4 Some examples of Feynman amplitudes 457
A2.5 Colour sums 459
A2.6 The Gell-Mann $SU(3)$ matrices 462
A2.7 The Fierz reshuffle theorem 463
A2.8 Dimension of matrix elements 464

Appendix 3: Conserved vector currents and their charges 465

References 470

Analytic subject index for vols. 1 and 2 482

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052146840X - An Introduction to Gauge Theories and Modern Particle Physics,
Volume 1: Electroweak Interactions, the 'new particles' and the Parton Model
Elliot Leader and Enrico Predazzi
Table of Contents
More information

Contents: Volume 2
CP Violation, QCD and hard processes

Preface xix

Acknowledgements xxii

Notational conventions xxiii
Note added in proof: the discovery of the top quark (?) xxix
Note added in proof: the demise of the SSC xxxi

18 Determination of the Kobayashi–Maskawa matrix 1
18.1 KM matrix elements from β-decay reactions 2
18.2 KM matrix elements from deep inelastic scattering 8
18.3 Summary 10

19 Mixing and CP violation 12
19.1 General phenomenology of mixing and CP violation 12
19.1.1 General formalism for mixing 12
19.1.2 General formalism for CP violation 15
19.1.3 Practical aspects of mixing and CP violation 17
19.2 Detailed phenomenology of CP violation in the K^0–$\bar{K}^0$ system 23
19.2.1 Formalism and summary of data 23
19.2.2 Relation between phenomenological parameters and the CP-violating Hamiltonian 28
19.3 Dynamics of mixing and CP violation 32
19.3.1 Connection with the SM (weak) Hamiltonian 32
19.3.2 Estimate for ϵ in the SM 35
19.3.3 Estimate of ϵ'/ϵ in the SM 40
19.3.4 Summary on ϵ and ϵ' in the K^0–$\bar{K}^0$ system 44
19.4 Dynamics of B^0–$\bar{B}^0$ mixing 45
19.4.1 Mixing ignoring CP violation 46
19.4.2 CP violation in the B^0–$\bar{B}^0$ system 48

20 Regularization, renormalization and introduction to the renormalization group 53
20.1 Introduction 53
20.2 Parameters and physical observables in a field theory 54

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052146840X - An Introduction to Gauge Theories and Modern Particle Physics, Volume 1: Electroweak Interactions, the 'new particles' and the Parton Model
Elliot Leader and Enrico Predazzi
Table of Contents
More information

20.3	The idea of renormalization	56
20.4	Choice of cut-off procedure—regularization	62
20.5	Choice of renormalization scheme	66
	20.5.1 The momentum point subtraction (MPS) scheme	67
	20.5.2 Renormalization schemes specifically linked to dimensional regularization (DR)	71
20.6	The renormalization group	73
20.7	A concrete example of different renormalization schemes	76
20.8	Consequences of the renormalization group equation	78
20.9	Scaling and asymptotic freedom	81
20.10	Appendix to Chapter 20	86
	20.10.1 Definition of a d-dimensional integral	86
	20.10.2 Questions of convergence and analytic continuation	87
	20.10.3 Some useful d-dimensional integrals	91
	20.10.4 Regularization of the 4-point vertex in ϕ^4 theory	93
21	**Gauge theories, QCD and the renormalization group**	97
21.1	Introduction	97
21.2	Gauge theories: QED	98
	21.2.1 Retaining Maxwell's equations for the field operators	101
	21.2.2 Modifying Maxwell's equations for the field operators	103
21.3	Gauge theories: QCD	104
	21.3.1 Differences between QCD and QED	107
21.4	Feynman rules for QCD	114
	21.4.1 The propagators	114
	21.4.2 The vertices	115
21.5	The renormalization group for QCD	116
	21.5.1 Specification of the renormalization scheme in QCD	117
	21.5.2 Consequences of the renormalization group in QCD	120
21.6	The effect of heavy quarks	121
21.7	The running coupling in QCD	124
	21.7.1 Renormalization scheme dependence of α and Λ	127
21.8	Conclusion	127
22	**Applications of the QCD renormalization group**	128
22.1	$e^+e^- \rightarrow$ hadrons	128
22.2	Deep inelastic lepton scattering	135
	22.2.1 The operator product expansion	136
	22.2.2 Relating coefficient functions to moments of structure functions	137
	22.2.3 Renormalization group analysis of coefficient functions	142
	22.2.4 q^2 dependence of the moments in leading order	144
	22.2.5 An interpretation of the Q^2 variation of parton distributions in leading logarithmic approximation	148
	22.2.6 q^2 dependence of the moments in higher order	151
	22.2.7 Conclusion	154
23	**The parton model in QCD**	155
23.1	Partons in a field theoretic context	155
	23.1.1 Heuristic reinterpretation of simple Feynman diagrams	157
	23.1.2 Application to QCD	160
	23.1.3 The parton model in field theory	163
23.2	QCD corrections to the parton model	168
	23.2.1 Redefinition of $f_{q/h}$	168

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052146840X - An Introduction to Gauge Theories and Modern Particle Physics, Volume 1: Electroweak Interactions, the 'new particles' and the Parton Model
Elliot Leader and Enrico Predazzi
Table of Contents
More information

	23.2.2 Collinear singularities—their physical origin	171
23.3	Structure of the leading logarithmic terms	174
23.4	Q^2-dependent distribution functions	180
23.5	Summary of the evolution equations in LLA	186
23.6	Small x behaviour of the Q^2-dependent gluon distribution in LLA	189
23.7	Behaviour of distributions as $x \to 1$ in LLA	192
23.8	Beyond the LLA	195
23.9	Comparison with experiment in deep inelastic scattering	202
23.10	General form of the QCD-improved parton model	206
23.11	QCD corrections to Drell–Yan and W production	209
	23.11.1 Drell–Yan production	210
	23.11.2 Transverse momentum distribution of Drell–Yan pairs	213
	23.11.3 Hadronic production of W and Z^0	216
	23.11.4 Transverse momentum distribution of W and Z^0	217
23.12	Summary	218
24	**Large p_T phenomena and jets in hadronic reactions**	219
24.1	Introduction	219
24.2	Historical survey. Hard qq scattering	221
24.3	From quarks to hadrons	225
	24.3.1 Inclusive reactions	225
	24.3.2 Exclusive reactions	228
24.4	Comments on the QCD interpretation of large p_T phenomena	232
	24.4.1 Evidence for jets	233
	24.4.2 Inclusive jet production	234
	24.4.3 Transverse momentum distribution with respect to the jet axis	239
24.5	Two-jet production at large p_T	239
	24.5.1 Jet angular distribution	241
	24.5.2 Tests of the Q^2 evolution	242
	24.5.3 Hadronic interactions at large p_T revisited	244
24.6	Prompt photons	245
24.7	Two and more jets in the final state	249
24.8	Jet fragmentation	249
24.9	Comments on $O(\alpha_s^3)$ corrections and conclusions	250
25	**Jets and hadrons in e^+e^- physics**	253
25.1	Introduction	253
25.2	General outline of e^+e^- jets	253
	25.2.1 Angular distribution of hadrons produced in e^+e^- collisions	255
25.3	SPEAR two-jet events	258
	25.3.1 Sphericity	259
	25.3.2 Jet axis	260
	25.3.3 Corrections to $e^+e^- \to$ hadrons: multijets	262
25.4	Planar events: evidence for three jets	265
25.5	Tests of QCD up to LEP energies	268
25.6	The total hadronic width at the Z^0	269
25.7	Basic Monte Carlo formulations	270
25.8	QCD Monte Carlo programs	272
	25.8.1 The perturbative phase	273
	25.8.2 The hadronization phase	276
25.9	Multiplicity	277
25.10	Global event-shape analysis	278

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052146840X - An Introduction to Gauge Theories and Modern Particle Physics, Volume 1: Electroweak Interactions, the 'new particles' and the Parton Model
Elliot Leader and Enrico Predazzi
Table of Contents
More information

25.11	Jet definition or recombination schemes	282
25.12	Particle flow patterns in 3-jet events	285
25.13	To what extent is QCD being tested?	285
26	**Low p_T or 'soft' hadronic physics**	289
26.1	The total and elastic cross-sections	289
26.2	The differential cross-section	292
26.3	The real to imaginary ratio	293
26.4	The inclusive p_T distribution	295
26.5	Diffractive dissociation	295
26.6	The average multiplicity	296
26.7	The multiplicity distribution of charged particles	297
26.8	Conclusions	298
	Note added in proof: the real to imaginary ratio, ϱ, in $p\bar{p}$ elastic scattering	300
27	**Some non-perturbative aspects of gauge theories**	301
27.1	QCD sum rules	302
27.2	Lattice approach to QCD	304
27.3	The vacuum in quantum mechanics and instantons	312
	27.3.1 An example in one-dimensional motion	313
27.4	The QCD vacuum and instantons	318
	27.4.1 Degenerate vacua in classical field theory	318
	27.4.2 The θ-vacuum in QCD	326
27.5	Strong CP violation and the $U(1)$ problem	328
27.6	Baryon and lepton non-conservations: sphalerons	332
	27.6.1 Degenerate vacua in the SM	333
	27.6.2 Baryon and lepton numbers of the vacua	334
	27.6.3 The sphaleron	336
28	**Beyond the standard model**	339
28.1	Introduction	339
28.2	The 'missing links' of the SM	340
28.3	Criticisms of the SM	340
	28.3.1 The $U(1)$ and θ problems	340
	28.3.2 Parameter counting	342
28.4	Grand unification theories (GUT)	342
28.5	Compositeness	347
28.6	Supersymmetry and supergravity	347
	Appendix 1: Elements of field theory	351
A1.1	Fields and creation operators	351
A1.2	Parity, charge conjugation and G-parity	355
	A1.2.1 Parity	355
	A1.2.2 Charge conjugation	355
	A1.2.3 G-parity	357
A1.3	The S-matrix	357

© Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
052146840X - An Introduction to Gauge Theories and Modern Particle Physics, Volume 1: Electroweak Interactions, the 'new particles' and the Parton Model
Elliot Leader and Enrico Predazzi
Table of Contents
More information

Appendix 2: Feynman rules for QED, QCD and the SM 359
A2.1 Relation between S-matrix and Feynman amplitude 359
A2.2 QCD and QED 360
A2.3 The SM 363
A2.4 Some examples of Feynman amplitudes 365
A2.5 Colour sums 367
A2.6 The Gell-Mann $SU(3)$ matrices 370
A2.7 The Fierz reshuffle theorem 371
A2.8 Dimension of matrix elements 372

Appendix 3: Conserved vector currents and their charges 373

Appendix 4: Operator form of Feynman amplitudes and effective Hamiltonians 378

Appendix 5: S-matrix, T-matrix and Feynman amplitude 382

Appendix 6: Consequences of CPT invariance for matrix elements 384

Appendix 7: Formulae for the basic partonic 2 $\longrightarrow$ 2 processes 387
A7.1 Reactions with only quarks and gluons 387
A7.1.1 Comparison of parton cross-section at 90° 391
A7.2 Reactions with one photon 391
A7.3 Reactions with two photons 393

Appendix 8: Euclidean space conventions 395

References 397

Analytic subject index for vols. 1 and 2 405

© Cambridge University Press www.cambridge.org