

This book presents a thorough and detailed description of the very successful Lund model of the dynamics of particle physics. The Lund model, inspired by quantum chromodynamics, has provided a very promising and pictorial approach to the dynamics of quark and gluon interactions. Starting with a brief reprise of basic concepts in relativity, the quantum mechanics of fields and particle physics, this book goes on to discuss the dynamics of the massless relativistic string, confinement, causality and relativistic covariance, Lund fragmentation processes, QED and QCD bremsstrahlung, multiplicities and particle-parton distributions. The book also explores the relationships between the Lund model and other models based on field theory (the Schwinger model, S -matrix models, lightcone algebra physics and variations of the parton model) or on statistical mechanics (the Feynman-Wilson gas, scaling, iterative cascade models).

The book will be of interest to experimental and theoretical particle physicists, and also to those working in other branches of physics who would like to develop a feel for these basic interactions. This title, first published in 1998, has been reissued as an Open Access publication on Cambridge Core.

**CAMBRIDGE MONOGRAPHS ON PARTICLE PHYSICS,
NUCLEAR PHYSICS AND COSMOLOGY: 7**

General Editors: T. Ericson, P. V. Landshoff

THE LUND MODEL

**CAMBRIDGE MONOGRAPHS ON PARTICLE PHYSICS,
NUCLEAR PHYSICS AND COSMOLOGY**

1. K. Winter (ed.): **Neutrino Physics**
2. J. F. Donoghue, E. Golowich and B. R. Holstein: **Dynamics of the Standard Model**
3. E. Leader and E. Predazzi: **An Introduction to Gauge Theories and Modern Particle Physics, Volume 1: Electroweak Interactions, the 'New Particles' and the Parton Model**
4. E. Leader and E. Predazzi: **An Introduction to Gauge Theories and Modern Particle Physics, Volume 2: CP-Violation, QCD and Hard Processes**
5. C. Grupen: **Particle Detectors**
6. H. Grosse and A. Martin: **Particle Physics and the Schrödinger Equation**
7. B. Andersson: **The Lund Model**

The Lund Model

BO ANDERSSON
Lund University





Shaftesbury Road, Cambridge CB2 8EA, United Kingdom
One Liberty Plaza, 20th Floor, New York, NY 10006, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India
103 Penang Road, #05-06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment,
a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of
education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781009401258

DOI: 10.1017/9781009401296

© Cambridge University Press 1998, 2023

This work is in copyright. It is subject to statutory exceptions and to the provisions
of relevant licensing agreements; with the exception of the Creative Commons version the
link for which is provided below, no reproduction of any part of this work may take
place without the written permission of Cambridge University Press.

An online version of this work is published at doi.org/10.1017/9781009401296 under a
Creative Commons Open Access license CC-BY-NC-ND 4.0 which permits re-use,
distribution and reproduction in any medium for non-commercial purposes providing
appropriate credit to the original work is given. You may not distribute derivative works
without permission. To view a copy of this license, visit
<https://creativecommons.org/licenses/by-nc-nd/4.0>

All versions of this work may contain content reproduced under license from third parties.
Permission to reproduce this third-party content must be obtained from these third-parties directly.

When citing this work, please include a reference to the DOI 10.1017/9781009401296

First published 1998
Reissued as OA 2023

A catalogue record for this publication is available from the British Library.

ISBN 978-1-009-40125-8 Hardback
ISBN 978-1-009-40128-9 Paperback

Cambridge University Press & Assessment has no responsibility for the persistence or accuracy of
URLs for external or third-party internet websites referred to in this publication
and does not guarantee that any content on such websites is, or will remain,
accurate or appropriate.

Contents

	<i>Acknowledgements</i>	xi
1	Introduction	1
2	Relativistic kinematics, electromagnetic fields and the method of virtual quanta	6
2.1	The Lorentz boost	7
2.2	Particle kinematics	11
2.3	Timelike, lightlike and spacelike vectors in Minkowski space	14
2.4	The electromagnetic field equations and some of their consequences	18
2.5	The method of virtual quanta	22
3	The harmonic oscillator and the quantum field	27
3.1	Introduction	27
3.2	The quantum field as a sum of harmonic oscillators	28
3.3	Feynman's time-ordering prescription	40
3.4	The method for calculating the scattering cross sections	49
3.5	The propagators in lightcone physics in the infinite-momentum frame	52
4	The vacuum as a dielectric medium; renormalisation	57
4.1	Introduction	57
4.2	The Källén-Lehmann representation, the n -particle phase space	61
4.3	A scalar-field-theory propagator in the Källén-Lehmann representation	64
4.4	The photon propagator in QED and the gluon propagator in QCD	69
4.5	Two reasons why in QCD the polarisation tensor behaves differently; the introduction of cut diagrams	77
4.6	The Callan-Symanzik equations for the renormalisation group	85
5	Deep inelastic scattering and the parton model	90
5.1	The parton model: Feynman's proposal	93
5.2	Rutherford's formula from classical mechanics	95

5.3	Rutherford's formula in relativistic quantum mechanics	98
5.4	The target recoil and the general elastic cross section for the scattering of spin 1/2 particles	101
5.5	The extension to non-pointlike baryons, form factors	104
5.6	The inelastic scattering of electrons on baryons; lightcone physics	106
5.7	The parton model revisited	109
5.8	The partons as quarks	111
6	The classical motion of the massless relativistic string	114
6.1	Introduction	114
6.2	The MRS as a constant force field	115
6.3	The QCD vacuum as a color superconductor	126
7	The decay kinematics of the massless relativistic string	134
7.1	Introduction	134
7.2	The kinematics of the decay and its implications	136
7.3	Ordering of the decay process along the lightcones	139
7.4	Iterative cascade fragmentation models	141
7.5	The formation time and iterative cascade jets	144
8	A stochastic process for string decay	146
8.1	Introduction	146
8.2	The unique breakup distribution for a single hadron	148
8.3	The production of a finite-energy cluster of hadrons	154
8.4	The Artru-Menessier-Bowler model	159
9	The properties of the Lund model fragmentation formulas; the external-part formulas	163
9.1	Introduction	163
9.2	The production properties of a cluster	164
9.3	The properties of the distributions H and f	165
9.4	The particle density in a general iterative cascade model	168
9.5	The relationship between the vertex proper time and the momentum transfer across the vertex	172
10	The internal-part fragmentation formulas and their relations to the unitarity equations of a field theory; Regge theory	177
10.1	Introduction	177
10.2	The decay properties of a cluster	178
10.3	The relationship to the unitarity equations for the S -matrix in a quantum field theory	183
11	The dynamical analogues of the Lund model fragmentation formulas	192
11.1	Introduction	192
11.2	The decay of the vacuum in an external field	193
11.3	The Wilson loop exponential laws and gauge invariance	199

Contents

ix

11.4	The fragmentation formulas and the partition functions for the Feynman-Wilson gas in rapidity space	207
12	Flavor and transverse momentum generation and the vector meson to pseudoscalar meson ratio	213
12.1	Introduction	213
12.2	The classical transverse motion of a string	214
12.3	A general process for transverse momentum generation	219
12.4	The phenomenological implications of the tunnelling process	224
12.5	Vector meson suppression	228
13	Heavy quark fragmentation and baryon production	234
13.1	Introduction	234
13.2	Heavy quark fragmentation	235
13.3	Baryon-antibaryon production	241
13.4	A different use of the Lund model formulas, the UCLA model	247
14	The Hanbury-Brown-Twiss effect and the polarisation effects in the Lund model	249
14.1	Introduction	249
14.2	The Hanbury-Brown-Twiss effect	251
14.3	The polarisation effects in the Lund model	262
15	The Lund gluon model, its kinematics and decay properties	269
15.1	Introduction	269
15.2	The dance of the butterfly	270
15.3	The general description of string motion	276
15.4	Multigluon states and some complications	282
15.5	The breakup of a gluonic Lund string	286
15.6	The final-state particles in the breakup of a $qg\bar{q}$ -state	290
15.7	A measure of multigluon activity, the generalised phase-space rapidity	298
16	Gluon emission via the bremsstrahlung process	302
16.1	Introduction	302
16.2	The matrix element for dipole emission	303
16.3	The dipole cross section	307
16.4	The antenna pattern of dipole emission	314
17	Multigluon emission, the dipole cascade model and other coherent cascade models	318
17.1	Introduction	318
17.2	The consequences of the second-order matrix element	319
17.3	An aside on ordering and the Sudakov form factors	321
17.4	The generalisation of the λ -measure to multigluon situations	323
17.5	The phase-space triangles of DCM	325
17.6	The description of multigluon emission as a process on the directrix	328

x	<i>Contents</i>	
17.7	Single-parton emission compared to the DCM procedure	334
17.8	Some further comments	345
18	The λ-measure in the leading-log and modified leading-log approximations of perturbative QCD	349
18.1	Introduction	349
18.2	The L -method	352
18.3	The κ -method	363
18.4	The next-to-leading-order corrections	372
18.5	On the running coupling in QCD	374
18.6	Discrete QCD, another approximation method	376
18.7	The x -curve and an infrared-stable λ -measure	384
18.8	The fractal properties of the QCD cascades	390
19	The parton model and QCD	392
19.1	Introduction	392
19.2	The DIS cross sections, initial- and final-state bremsstrahlung	393
19.3	A bird's-eye view of the features of deep inelastic scattering	397
19.4	The moment method and the DGLAP mechanism	402
19.5	The Lipatov results and a critique on the stability	413
19.6	The CCMF model, interpolating between the DGLAP and the BFKL contributions	417
19.7	The GLR model of reinteraction of partons	421
20	Inelastic lepto-production in the Lund model, the soft radiation model and the linked dipole chain model	423
20.1	Introduction	423
20.2	The classical motion of a yoyo-string exposed to a large momentum transfer at an endpoint	425
20.3	The fragmentation of a final-state yoyo-string stemming from a DIS event	428
20.4	A model for baryon fragmentation	430
20.5	The soft radiation model	434
20.6	The relationship between the SRM and the non-local form factor of the CCMF model	437
20.7	The linked dipole chain model	440
20.8	The structure function behavior of the LDC model	455
	<i>References</i>	465
	<i>Index</i>	468

Acknowledgements

This book is dedicated to the memory of my teacher, Gunnar Källén, who died much too young. He was the greatest teacher any man could have had. Those of us who enjoyed the vision of physics according to the way he described it, as a great adventure, have often asked what he would have said about the greatest adventure my generation will ever have, i.e. the confined field theory of QCD (which is so different from what we talked about in Lund in the 1960s!).

I would also like to thank my collaborators over the years, in particular the past and present members of the Lund High-Energy Theory Group. I will firstly mention Gösta Gustafson, who kindly has read most parts of this book and provided many useful remarks. He has been my principal collaborator for very many years and there is no way to thank him for all the joy and insight he has provided. Further, one of our recent students, Jari Häkkinen, has helped me both with my sometimes very temperamental computer and also with the figures. As there are very few ‘free luncheons in life’, as my American friends tell me, his help has been something that I will savour for all times. I have also been teased, kicked around and during the process learned a lot from my copy-editor, Susan Parkinson.

But even if I have been endowed with the best advisers, with regard to any remaining errors and omissions the buck rests with me!