HIGH P_T PHYSICS AT HADRON COLLIDERS

This book provides a comprehensive introduction to high transverse momentum reactions at hadron (proton–proton or proton–antiproton) colliders. It begins by introducing the Standard Model of high energy physics and describes the specialized detectors used. It then gives a general treatment of the reactions to be studied and summarizes the state of the art in hadron collider physics, defined by Tevatron results. The experimental program at the detectors being built for the Large Hadron Collider at CERN is described, with details of the search program and the general strategy to find the postulated Higgs particle. Speculations of physics beyond the Standard Model are also discussed. The book includes links to online freeware programs, freeware utilities, and high energy physics library resources. This book is suitable for graduate students and researchers in high energy physics.

DAN GREEN received his Ph.D. from the University of Rochester in 1969. He held a post-doctoral position at Stony Brook from 1969 to 1972 and worked for a time at the Intersecting Storage Rings (ISR) at CERN. His next appointment was as an Assistant Professor at Carnegie Mellon University from 1972 to 1978 during which time he was also Spokesperson of a BNL Baryonium Experiment. He has been a Staff Scientist at Fermilab from 1979 to the present, and has worked in a wide variety of roles on experiments both at Fermilab and elsewhere. He participated in the D0 Experiment as Muon Group Leader from 1982 to 1990 and as B Physics Group Co-Convener from 1990 to 1994. He led the US Compact Muon Solenoid (CMS) Collaboration as Spokesperson and then was Project Manager for the US groups working at the Large Hadron Collider (LHC) at CERN. At Fermilab, he was Physics Department Deputy Head from 1984 to 1986 and Head from 1986 to 1990. From 1993 to the present he has served as the CMS Department Head in the Particle Physics Division.

CAMBRIDGE MONOGRAPHS ON PARTICLE PHYSICS NUCLEAR PHYSICS AND COSMOLOGY
22

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

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. Anderson: *The Lund Model*
8. R. K. Ellis, W. J. Stirling and B. R. Webber: *QCD and Collider Physics*
9. I. I. Bigi and A. I. Sanda: *CP Violation*
10. A. V. Manohar and M. B. Wise: *Heavy Quark Physics*
11. R. K. Bock, H. Grote, R. Frühwirth and M. Regler: *Data Analysis Techniques for High-Energy Physics. Second edition*
12. D. Green: *The Physics of Particle Detectors*
13. V. N. Gribov and J. Nyiri: *Quantum Electrodynamics*
14. K. Winter (ed.): *Neutrino Physics, Second edition*
15. E. Leader: *Spin in Particle Physics*
16. J. D. Walecka: *Electron Scattering for Nuclear and Nucleon Structure*
17. S. Narison: *QCD as a Theory of Hadrons*
18. J. F. Letessier and J. Rafelski: *Hadrons and Quark–Gluon Plasma*
19. A. Donnachie, H. G. Dosch, P. V. landshoff and O. Nachtmann: *Pomeron Physics and QCD*
20. A. Hofmann: *The Physics of Synchrotron Radiation*
21. J. B. Kogut and M. A. Stephanov: *The Phases of Quantum Chromodynamics*
22. D. Green: *High P_T Physics at Hadron Colliders*

HIGH P_T PHYSICS AT HADRON COLLIDERS

DAN GREEN

Fermi National Accelerator Laboratory
Batavia, Illinois

CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge, CB2 2RU, UK
40 West 20th Street, New York, NY 10011–4211, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

http://www.cambridge.org

First published 2005

Printed in the United Kingdom at the University Press, Cambridge

Typeface Times 10/13 pt. *System* LaTeX 2$_\varepsilon$ [TB]

A catalog record for this book is available from the British Library

Library of Congress Cataloging in Publication data
Green, Dan.
High P_T physics at hadron colliders / Dan Green.
p. cm. – (Cambridge monographs on particle physics, nuclear physics, and cosmology; 22)
Includes bibliographical references and index.
ISBN 0 521 83509 7
1. Hadron colliders. 2. Proton–proton interactions. 3. Proton–antiproton interactions.
I. Title. II. Series.
QC787.C59G74 2004
539.7′3723 – dc22 2004045198

ISBN 0 521 83509 7 hardback

Science is an integral part of culture. It's not this foreign thing, done by an arcane priesthood. It's one of the glories of the human intellectual tradition.

Stephen Jay Gould (1990)

. . . some of our thinking should reveal the true structure of atoms and the true movements of the stars. Nature, in the form of Man, begins to recognize itself.

Victor Weisskopf (1962)

Contents

Acknowledgments

This text began as a series of lectures given to graduate students in Brazil and then later in expanded form to students at Fermilab. The comments and questions of the students have proved to be invaluable in improving this book. The secretarial work of Ms T. Grozis has made it possible to go smoothly from chaotic lecture notes to a complete and polished text. Finally, the many high energy physicists working on D0 and CMS as collaborators have shared their knowledge and insights countless times.

Acronyms

ALEPH One of the four experiments at the electron–positron collider (LEP) at CERN.

ATLAS One of the two general purpose experiments at the Large Hadron Collider (LHC) at CERN.

BaBar The experiment running at the electron–positron collider (PEP-II) at SLAC.

Belle The experiment running at the electron–positron collider at KEK, Japan.

Bose–Einstein The statistics obeyed by integral spin particles.

Breit–Wigner The mass distribution for resonant (unstable) particles, characterized by a central mass, M_o, and a decay width, Γ.

CDF One of the two general purpose experiments at the Tevatron proton–antiproton collider at Fermilab (FNAL).

CERN The European Centre for Nuclear Research located in Geneva, Switzerland.

CKM The unitary 3×3 matrix which describes the mixing of the strong interaction eigenstates (quarks) appropriate to the weak eigenstates active in decays.

CM The center of momentum frame, where the total momentum of the system is zero.

CMS One of the two general purpose experiments at the LHC at CERN.

COMPHEP A program to do calculations in high energy physics.

CP The combined operation of charge conjugation (C) and parity inversion (P).

CTEQ One of the sets of distribution functions of quarks and gluons available in COMPHEP.

D(z) The fragmentation function describing how a jet fragments into a collection of particles which carry a fraction z of the jet momentum.

DELPHI One of the four experiments at the electron–positron collider (LEP) at CERN.

Dirac Equation	The equation which describes the motion of spin ½ particles.
D0	One of the two general purpose experiments at the Tevatron proton–antiproton collider at Fermilab (FNAL).
Drell–Yan	A process in which a quark from one hadron annihilates with an antiquark from another hadron to create a boson.
EM	The electromagnetic compartment of a calorimeter.
EW	The electroweak theory which unifies electromagnetic and weak interactions.
Fermi–Dirac	The statistics obeyed by half integral spin particles. Such particles obey the Fermi Exclusion principle where two fermions cannot be in the same quantum state.
Fermilab (FNAL)	A national laboratory in the USA with a proton accelerator, located in Illinois.
Feynman diagram	A diagrammatic representation of a fundamental interaction as it occurs in space and time.
Γ	The decay width for a specific process. The inverse of the decay width is the lifetime for that process.
G	The effective coupling constant for a four fermion weak interaction.
GUT	A Grand Unified Theory, which proposes to unify the electroweak and strong interaction theories at a high mass scale.
HAD	The hadronic compartment of a calorimeter.
Higgs	The proposed particle in the Standard Model which has spin zero and whose field takes on a non-zero expectation value in the vacuum.
Jet	A collection of "stable" particles which is the result of the fragmentation of a quark or gluon. The jet has a parent quark or gluon.
KEK	The Japanese center for high energy physics located in Tskuba, Japan.
Klein–Gordon	The equation which describes a relativistic particle that has no intrinsic spin.
Λ	A parameter that is defined to "cutoff" the mass scale for a theory, which is badly behaved outside that mass range.
L3	One of the four experiments at the electron–positron collider (LEP) at CERN.
LC	Linear Collider. This is a proposed electron–positron collider which will have sufficient energy to directly form the Higgs boson.
LEP	The Large Electron Positron collider which operated at CERN prior to the LHC construction.

LHC The Large Hadron Collider is a proton–proton collider with a total CM energy of 14 TeV, which will begin operations at CERN in 2007.

Λ_{QCD} The cutoff energy in QCD below which the strong interactions become very strong. The strong interactions approach zero strength at very high energy scales.

LSP Lightest supersymmetric particle. In SUSY models the LSP is usually assumed to be absolutely stable. Therefore, the LSP is a candidate for the dark matter.

Luminosity The quantity which when multiplied by the cross section gives the reaction rate for a particular process.

Monte Carlo A numerical technique to simulate processes by choosing various quantities from specified distribution functions.

MMSM Minimal SUSY model. The SUSY hypothesis has many possible realizations. The minimal model allows for specific predictions by making assumptions having minimal extensions to the SM.

MRS One of the sets of distribution functions of quarks and gluons available in COMPHEP.

OPAL One of the four experiments at the electron–positron collider (LEP) at CERN.

Pseudorapidity A variable which approaches rapidity for particles with mass less than transverse momentum and which is a function only of polar angle.

P_T Transverse momentum. The transverse direction is perpendicular to the incident hadrons in a p–p collision. Therefore, a large value of this parameter indicates a violent collision probing small distance scales.

PYTHIA A Monte Carlo program which has a model for the fragmentation of quarks and gluons and also models the "underlying event" caused by the fragments of the fractured hadrons.

QED Quantum electrodynamics. The relativistic theory of the interaction of photons with fundamental, point like fermions.

QCD Quantum chromodynamics. The relativistic theory of the interaction of colored gluons with fundamental point like colored quarks.

R, G, B The color labels, red, green, and blue. The assignments are arbitrary and simply label the three distinct color charges contained in SU(3).

Rapidity A variable used in high energy physics because it is additive under "boost" or Lorentz transformation. It is the relativistic

	analog of velocity. One particle phase space implies a uniform rapidity distribution.
SLAC	The Stanford Linear Accelerator Center located in California and operating an electron–positron collider.
SLD	The detector operating at the SLAC Linear Collider (SLC) which studied the properties of the Z by resonant formation.
SM	Standard Model. The model of high energy physics which describes fermions, quarks and leptons, interacting by electroweak interactions and strong interactions. Gravity is not included in the SM.
SUGRA	A simplified SUSY model which has only five free parameters, thus giving predictive power.
SUSY	Supersymmetry. The postulated symmetry relates fermions to bosons. Therefore, each particle in the SM has a partner, all as yet undiscovered.
Tevatron	The proton–antiproton collider operated at Fermilab at a CM energy of 2 TeV.
UA1, UA2	The underground area experiments using the proton–antiproton collider operated at CERN at 0.27 TeV.
V-A	The coupling of weak currents to fermions is by way of vector and axial vector interactions. Parity and charge conjugation violation are an immediate consequence of the V-A form.
Weinberg angle	The angle that specifies the unitary rotation of the basic neutral gauge bosons into the physically realized Z and photon.
***WW* fusion**	The process whereby a quark emits a W from both initial state hadrons, thereby initiating W–W scattering or fusion into a variety of final states.
Yukawa interaction	A linear interaction between two fermions and a boson. If the boson has a mass, the range of the interaction is limited in space.
Z* (W*)	"Off shell" gauge bosons which are out on the allowed, but improbable, "tail" of the Breit–Wigner mass distribution.