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978-0-521-57816-5 - The Rise of the Standard Model: Particle Physics in the 1960s and 1970s

Edited by Lillian Hoddeson, Laurie Brown, Michael Riordan and Max Dresden

Frontmatter

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## THE RISE OF THE STANDARD MODEL

Editors Lillian Hoddeson, Laurie Brown, Michael Riordan, and Max Dresden have brought together a distinguished group of elementary particle physicists and historians of science to explore the recent history of particle physics. Based on a conference held at Stanford University, this is the third volume of a series recounting the history of particle physics and offers the most up-to-date account of the rise of the Standard Model, which explains the microstructure of the world in terms of quarks and leptons and their interactions

Major contributors include Murray Gell-Mann, John Heilbron, Leon Lederman, Michael Redhead, Silvan Schweber, and Steven Weinberg. The wide-ranging articles explore the detailed scientific experiments, the institutional settings in which they took place, and the ways in which the many details of the puzzle fit together to account for the Standard Model.

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# THE RISE OF THE STANDARD MODEL

Particle Physics in the 1960s and 1970s

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Contents

<i>Contributors</i>	<i>page</i> ix
<i>Editors' Acknowledgments</i>	xiii
<i>Photographs of the Symposium</i>	xvi
<i>Abbreviations and Acronyms</i>	xxii
<i>Mathematical Notation</i>	xxvi
 <b>Part One: Introduction</b>	
1 The Rise of the Standard Model: 1964–1979 <i>Laurie M. Brown, Michael Riordan, Max Dresden, and Lillian Hoddeson</i>	3
2 Changing Attitudes and the Standard Model <i>Steven Weinberg</i>	36
3 Two Previous Standard Models <i>J. L. Heilbron</i>	45
 <b>Part Two: Quarks and Leptons</b>	
4 From the Psi to Charmed Mesons: Three Years with the SLAC–LBL Detector at SPEAR <i>Gerson Goldhaber</i>	57
5 The Discovery of the Tau Lepton <i>Martin Perl</i>	79
6 The Discovery of the Upsilon, Bottom Quark, and <i>B</i> Mesons <i>Leon M. Lederman</i>	101

Cambridge University Press  
978-0-521-57816-5 - The Rise of the Standard Model: Particle Physics in the 1960s and 1970s  
Edited by Lillian Hoddeson, Laurie Brown, Michael Riordan and Max Dresden  
Frontmatter  
[More information](#)

vi	<i>Contents</i>	
7	The Discovery of <i>CP</i> Violation <i>James Cronin</i>	114
8	Flavor Mixing and <i>CP</i> Violation <i>Makoto Kobayashi</i>	137
<b>Part Three: Toward Gauge Theories</b>		
9	The Path to Renormalizability <i>Martinus Veltman</i>	145
10	Renormalization of Gauge Theories <i>Gerard 't Hooft</i>	179
11	Asymptotic Freedom and the Emergence of QCD <i>David Gross</i>	199
12	Quark Confinement <i>Leonard Susskind</i>	233
13	A View from the Island <i>Alexander Polyakov</i>	243
14	On the Early Days of the Renormalization Group <i>Dmitrij V. Shirkov</i>	250
<b>Part Four: Accelerators, Detectors, and Laboratories</b>		
15	The Rise of Colliding Beams <i>Burton Richter</i>	261
16	The CERN Intersecting Storage Rings: The Leap into the Hadron Collider Era <i>Kjell Johnsen</i>	285
17	Development of Large Detectors for Colliding-Beam Experiments <i>Roy Schwitters</i>	299
18	Pure and Hybrid Detectors: Mark I and the Psi <i>Peter Galison</i>	308
19	Building Fermilab: A User's Paradise <i>Robert R. Wilson and Adrienne Kolb</i>	338
20	Panel Session: Science Policy and the Social Structure of Big Laboratories <i>Catherine Westfall</i>	364
21	Some Sociological Consequences of High-Energy Physicists' Development of the Standard Model <i>Mark Bodnarczuk</i>	384

	<i>Contents</i>	vii
22	Comments on Accelerators, Detectors, and Laboratories <i>John Krige</i>	394
<b>Part Five: Electroweak Unification</b>		
23	The First Gauge Theory of the Weak Interactions <i>Sidney Bludman</i>	403
24	The Early History of High-Energy Neutrino Physics <i>Melvin Schwartz</i>	411
25	Gargamelle and the Discovery of Neutral Currents <i>Donald Perkins</i>	428
26	What a Fourth Quark Can Do <i>John Iliopoulos</i>	447
27	Weak-Electromagnetic Interference in Polarized Electron–Deuteron Scattering <i>Charles Prescott</i>	459
28	Panel Session: Spontaneous Breaking of Symmetry <i>Laurie M. Brown, Robert Brout, Tian Yu Cao, Peter Higgs, and Yoichiro Nambu</i>	478
<b>Part Six: The Discovery of Quarks and Gluons</b>		
29	Early Baryon and Meson Spectroscopy Culminating in the Discovery of the Omega-Minus and Charmed Baryons <i>Nicholas Samios</i>	525
30	Quark Models and Quark Phenomenology <i>Harry Lipkin</i>	542
31	From the Nonrelativistic Quark Model to QCD and Back <i>Giacomo Morpurgo</i>	561
32	Deep-Inelastic Scattering and the Discovery of Quarks <i>Jerome Friedman</i>	566
33	Deep-Inelastic Scattering: From Current Algebra to Partons <i>James Bjorken</i>	589
34	Hadron Jets and the Discovery of the Gluon <i>Sau Lan Wu</i>	600
<b>Part Seven: Personal Overviews</b>		
35	Quarks, Color, and QCD <i>Murray Gell-Mann</i>	625

Cambridge University Press  
978-0-521-57816-5 - The Rise of the Standard Model: Particle Physics in the 1960s and 1970s  
Edited by Lillian Hoddeson, Laurie Brown, Michael Riordan and Max Dresden  
Frontmatter  
[More information](#)

viii	<i>Contents</i>	
36	The Philosopher Problem <i>Paul Teller</i>	634
37	Should We Believe in Quarks and QCD? <i>Michael Redhead</i>	637
38	A Historical Perspective on the Rise of the Standard Model <i>Silvan Schweber</i>	645
	<i>Index</i>	685

Cambridge University Press

978-0-521-57816-5 - The Rise of the Standard Model: Particle Physics in the 1960s and 1970s

Edited by Lillian Hoddeson, Laurie Brown, Michael Riordan and Max Dresden

Frontmatter

[More information](#)

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Cambridge University Press

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Frontmatter

[More information](#)

x

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Edited by Lillian Hoddeson, Laurie Brown, Michael Riordan and Max Dresden

Frontmatter

[More information](#)

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xi

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Cambridge University Press

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Frontmatter

[More information](#)

xii

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Edited by Lillian Hoddeson, Laurie Brown, Michael Riordan and Max Dresden

Frontmatter

[More information](#)

## Editors' Acknowledgments

We are deeply grateful to all the people who contributed to the success of the Third International Symposium on the History of Particle Physics. Without their efforts it would have been a much smaller and far less enjoyable gathering. Limits of space prevent us from thanking each and every one of them by name, but certain individuals deserve special recognition.

We thank laboratory directors Burton Richter and John Peoples for their strong support of this Symposium. In assembling the program, we benefited extensively from the sage advice of Barry Barish, James Bjorken, Peter Galison, Gerson Goldhaber, Sam Schweber, and Lenny Susskind, who served with us as members of the Program Committee.

In hosting the Symposium and attending to the myriad details that contributed to making it an enjoyable and successful gathering, the untiring efforts of Nina Adelman Stolar stand out from all the rest. She arranged lodging and transportation for speakers and participants, distributed the invitations and registration forms, and supervised a small army of SLAC and Fermilab staff members who supported us for the four-day event; the Symposium would not have been such a success without her contributions. Nina was ably assisted in these tasks by Juanita O'Malley, who handled communications with speakers and participants. Herbert McIntyre coordinated all the audio-visual services, while Bernie Lighthouse took care of the specific needs of individual speakers. Rene Donaldson designed and produced the Symposium program, based on period photographs of leading physicists located by Robin Chandler;

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Edited by Lillian Hoddeson, Laurie Brown, Michael Riordan and Max Dresden

Frontmatter

[More information](#)

xiv

*Editors' Acknowledgments*

blow-ups of these photos also graced the walls of the auditorium lobby. In addition, we wish to thank the following people for their help:

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Jeff Machado, for catering the Symposium banquet and other social events;

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Frontmatter

[More information](#)

*Editors' Acknowledgments*

xv

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Frontmatter

[More information](#)



Burton Richter helps Steven Weinberg with the microphone before his opening talk.



Peter Higgs and Donald Perkins.

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Frontmatter

[More information](#)



David Gross, Alexander Polyakov, Gerhard 't Hooft, and Lenny Susskind chat during a coffee break.



Gross, Sam Schweber, and Harry Lipkin.



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Frontmatter

[More information](#)



Michael Riordan and Sidney Bludman discussing the sequence of speakers.



John Heilbron and Laurie Brown.

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Frontmatter

[More information](#)



Maurice Goldhaber, Pief Panofsky, and Bill Wallenmeyer during the panel session on Science Policy and the Sociology of Big Laboratories.



John Krige speaking during the panel session, while Mark Bodnarczuk and Robert Seidel listen.

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Frontmatter

[More information](#)



Fermilab's first Director, Robert R. Wilson, talks with Norman Ramsey, the first President of Universities Research Association.



Jim Cronin, Nick Samios, Maurice Goldhaber, and Alan Wattenberg.

Cambridge University Press

978-0-521-57816-5 - The Rise of the Standard Model: Particle Physics in the 1960s and 1970s

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Frontmatter

[More information](#)



Maurice Goldhaber greets Murray Gell-Mann at the Symposium banquet, while Lillian Hoddeson and Matt Sands look on.



Gell-Mann, Gosta Ekspong, and Nina Adelman Stolar.

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Frontmatter

[More information](#)

## Abbreviations and Acronyms

<i>Acta Phys. Pol</i>	<i>Acta Physica Polonica</i>
<i>Am. J. Phys.</i>	<i>American Journal of Physics</i>
<i>Ann. Phys.</i>	<i>Annals of Physics</i>
<i>Ann. Rev. Nucl. Part. Sci.</i>	<i>Annual Reviews of Nuclear and Particle Science</i>
<i>Comm. Math. Phys.</i>	<i>Communications in Mathematical Physics</i>
<i>Dokl. Akad. Nauk SSR</i>	<i>Doklady Akademii Nauk SSR</i>
<i>Helv. Phys. Acta</i>	<i>Helvetica Physica Acta</i>
<i>Hist. Stud. Phys. Biol. Sci.</i>	<i>Historical Studies in the Physical and Biological Sciences</i>
<i>Hist. Stud. Phys. Sci.</i>	<i>Historical Studies in the Physical Sciences</i>
<i>JETP Lett.</i>	<i>Journal of Experimental and Theoretical Physics Letters</i>
<i>J. Math. Phys.</i>	<i>Journal of Mathematical Physics</i>
<i>J. Phys.</i>	<i>Journal de Physique</i>
<i>Lett. Nuovo Cimento</i>	<i>Lettres al Nuovo Cimento</i>
<i>Natl. Acad. Sci. USA</i>	<i>Proceedings of the National Academy of Sciences (USA)</i>
<i>Nucl. Phys.</i>	<i>Nuclear Physics</i>
<i>Phys. Lett.</i>	<i>Physics Letters</i>
<i>Phys. Rep.</i>	<i>Physics Reports</i>
<i>Phys. Rev.</i>	<i>Physical Review</i>

*Abbreviations and Acronyms* xxiii

<i>Phys. Rev. Lett.</i>	<i>Physical Review Letters</i>
<i>Proc. Roy. Soc.</i>	<i>Proceedings of the Royal Society (London)</i>
<i>Prog. Theor. Phys.</i>	<i>Progress of Theoretical Physics</i>
<i>Prog. Theor. Phys. Supp.</i>	<i>Progress of Theoretical Physics Supplement</i>
<i>Rep. Prog. Phys.</i>	<i>Reports on Progress in Physics</i>
<i>Rev. Mod. Phys.</i>	<i>Reviews of Modern Physics</i>
<i>Sov. J. Part. Nucl.</i>	<i>Soviet Journal of Particles and Nuclei</i>
<i>Sov. Phys. Dokl.</i>	<i>Soviet Physics – Doklady</i>
<i>Sov. Phys. JETP</i>	<i>Soviet Physics – Journal of Experimental and Theoretical Physics</i>
<i>Stud. Hist. Phil. Sci.</i>	<i>Studies in the History and Philosophy of Science</i>
<i>Supp. Nuovo Cimento</i>	<i>Supplemento al Nuovo Cimento</i>
<i>Z. Phys.</i>	<i>Zeitschrift für Physik</i>
AdA	Anello di Accumulatione (i.e., storage ring)
ADONE	“big AdA”
AEC	Atomic Energy Commission
AGS	Alternating Gradient Synchrotron (at Brookhaven)
ARGUS	third-generation particle detector built at DORIS; also the collaboration
BCS	Bardeen–Cooper–Schrieffer (theory)
BEPC	Beijing Electron–Positron Collider
BES	Beijing Spectrometer at BEPC
BNL	Brookhaven National Laboratory
BRS	Becci–Rouet–Stora (invariance or transformation)
CDF	Collider Detector at Fermilab; also the experimental collaboration
CEA	Cambridge Electron Accelerator
CELLO	solenoidal particle detector at PETRA; also the collaboration
CERN	Centre European pour la Recherche Nucléaire (now known as the European Center for Particle Physics)
CESR	Cornell Electron Storage Ring
CKM	Cabibbo–Kobayashi–Maskawa (matrix)

xxiv	<i>Abbreviations and Acronyms</i>
CLEO	solenoidal particle detector and experimental collaboration at CESR
CRT	cathode-ray tube
CUSB	Columbia University/Stony Brook detector and collaboration at CESR
CVC	conserved vector current (hypothesis)
DASP	Double-Arm Spectrometer (DESY); also the experimental collaboration
DELCO	Direct Electron Counter detector built at SPEAR
DESY	Deutsches Elektronen Synchrotron
DOE	Department of Energy
D0	large particle detector (at Fermilab); also the experimental collaboration
DORIS	Double-Ring Storage electron-positron collider at DESY
ERDA	Energy Research and Development Administration
FNAL	Fermi National Accelerator Laboratory (a.k.a. Fermilab)
GIM	Glashow–Iliopolous–Maiani (mechanism)
GWS	Glashow–Weinberg–Salam (model or theory)
HRS	large particle detector at PEP; also the experimental collaboration
ISABELLE	unfinished proton collider (at Brookhaven)
ISR	Intersecting Storage Rings (CERN)
JADE	solenoidal particle detector at PETRA; also the collaboration
LBL	Lawrence Berkeley Laboratory
LEP	Large Electron–Positron collider (CERN)
MAC	solenoidal particle detector and experimental collaboration at PEP
MARK I	The first SLAC–LBL particle detector at the SPEAR $e^+e^-$ collider (SLAC)
MARK II	solenoidal particle detector built at SPEAR and moved to PEP (SLAC)



MARK III	third-generation detector built at SPEAR; also the collaboration
MARK-J	large particle detector at PETRA; also the collaboration
MIT	Massachusetts Institute of Technology
MURA	Midwestern Universities Research Association
NAL	National Accelerator Laboratory (renamed Fermilab)
PCAC	partially conserved axial current
PEP	Positron Electron Project (at SLAC)
PETRA	Positron–Electron Tandem Ring Accelerator (at DESY)
PLUTO	detector built at DORIS and moved to PETRA; also the collaboration
QCD	quantum chromodynamics
QED	quantum electrodynamics
SALT	Strategic Arms Limitations Talks
SLAC	Stanford Linear Accelerator Center
SPEAR	Stanford Positron–Electron Asymmetric Ring (at SLAC)
TASSO	Two-Armed Solenoidal Spectrometer at PETRA; also the collaboration
TPC	solenoidal particle detector at PEP; also the experimental collaboration
UA1	magnetic particle detector and collaboration at CERN $p\bar{p}$ collider
UA2	major particle detector and collaboration at CERN $p\bar{p}$ collider
URA	Universities Research Association



Mathematical Notation

$A$	axial-vector interaction (or current); also a scattering amplitude
$A_\mu$	four-vector electromagnetic potential
$B(X \rightarrow Y)$	branching ratio for interaction $X \rightarrow Y$
$B, B^0, B_u, B_d$	$B$ mesons – heavy mesons containing a bottom quark
$B^+$	baryon-matter field (in the Nagoya model); also used for $B$ meson
BeV	billion electron volts (old usage, now written as GeV)
$b(\bar{b})$	bottom quark (antiquark); also the Yang–Mills field
$C$	charge-conjugation operator or quantum number
$CP$	charge-conjugation–parity operator or quantum number
$CPT$	charge-conjugation–parity–time-reversal operator; also a theorem
$c(\bar{c})$	charm quark (antiquark); also the speed of light in vacuum
$D^0, D^+, D^-$	charmed mesons – containing a charm quark and an up or down quark
$D^{0*}, D^{+*}$	charmed meson resonances
$d(\bar{d})$	down quark (antiquark)
$E$	energy
$E^-(E^+)$	hypothetical electron-like heavy lepton (antilepton)
$E_{cm}$	center-of-mass energy
$e, e^-$	electron; $e$ is also the magnitude of the electron charge

*Mathematical Notation* xxvii

$e^+$	positron – the antiparticle of the electron
$e^+e^-$	electron-positron (as in electron-positron collisions)
$F, F^+, F^*$	F mesons – composed of a charm quark and a strange antiquark
$F_{\mu\nu}$	electromagnetic tensor
$G_F$	Fermi coupling constant
$G$	G-parity operator or quantum number
GeV	billion electron volts, or gigaelectronvolts
$g, g'$	generalized coupling constants
$I$	isospin quantum number
$I$	isospin operator
$I_1, I_2, I_3$	isospin components
$J$	total angular momentum operator or quantum number
$J$	angular momentum operator
$J, J/\psi$	J or J-psi particle – a heavy neutral meson of mass 3.1 GeV
$J^P$	spin-parity quantum numbers (e.g., $0^+, 1^-, \dots$ ) of a particle
$J^{PC}$	spin, parity and charge-conjugation quantum numbers of a particle
$K, K^+, K^-$	K mesons, or kaons – mesons that contain a strange quark
$K^*$	kaon resonance
$K^0, K_L^0, K_S^0$	neutral K mesons
$K_1^0, K_2^0$	neutral $K$ mesons (now more commonly written as $K_S^0, K_L^0$ )
$L^-(L^+)$	hypothetical heavy lepton (antilepton)
$\mathcal{L}$	Lagrangian (of a system)
$l, l^-(l^+)$	lepton (antilepton); $l$ is also used to denote orbital angular momentum
$M$	generalized mass of a subatomic particle
$M^-(M^+)$	hypothetical muon-like heavy lepton (antilepton)
MeV	million electron volts, or megaelectron volts
$m_x$	mass of a subatomic particle $x$
$N^*$	nucleon resonance
$n(\bar{n})$	neutron (antineutron); also the neutron current
$P$	parity operation or quantum number
$P$	quantum state with orbital angular momentum $l = 1$
$P_c$	spin-1 particle (also known as $\chi$ ) produced in $\psi$ decays

xxviii	<i>Mathematical Notation</i>
$P_\mu, P_\nu$	four-momentum components of a particle
$^3P_0, ^3P_1, ^3P_2$	P states with third component of angular momentum $m = 0, 1, 2$
$p_T$ or $P_t$	transverse momentum
$p(\bar{p})$	proton (antiproton); also the proton current
$p$ or $P$	particle four-momentum; $P$ also used for probability
$\vec{p}$	three-vector momentum of a particle
$Q$	charge quantum number; also decay energy in $K$ decays
$q(\bar{q})$	generalized quark (antiquark); $q$ also generalized charge on a particle
$R = \sigma_{had} / \sigma_{\mu\mu}$	ratio of hadron to muon-pair production in $e^+e^-$ collisions
$R = \sigma_L / \sigma_T$	ratio of longitudinal to transverse photoabsorption in $e-N$ scattering
$S$	strangeness operator or quantum number
$S, 1S, 2S, \dots$	$S$ states of a particle system – having orbital angular momentum $l = 0$
$S$ -matrix	scattering matrix
$SU(N)$	special unitary group in $N$ dimensions
$s(\bar{s})$	strange quark (antiquark); also the center-of-mass energy squared
$T$	time-reversal operator or quantum number
TeV	trillion electron volts, or teraelectronvolts
$t(\bar{t})$	top quark (antiquark)
$U$	“unknown” particle (e.g., the particle later called the tau lepton)
$u(\bar{u})$	up quark (antiquark)
$V$	vector interaction (or current)
$V$	Cabibbo–Kobayashi–Maskawa matrix; $V$ also used for $V$ particle
$V-A$	vector minus axial-vector interaction (or current)
$V_{ij}(V_{ij}^*)$	$ij$ th element (or its hermitian conjugate) of CKM matrix
$W, W^+, W^-$	charged vector bosons
$W_\mu$	charged vector-boson field
$Z, Z^0$	neutral vector boson
$Z_3, Z_S$	transverse, longitudinal components of the neutral vector boson field

*Mathematical Notation* xxix

$\alpha$	fine-structure constant; also $g^2/4\pi$ , where $g$ = general coupling constant
$\beta$	beta particle – an electron or positron emitted in nuclear beta decay; also a parameter in Callan–Symanzik equation
$\beta$ decay	nuclear decay by emission of a beta particle (plus a neutrino)
$\Gamma$	width of a resonance or interaction strength; also scattering amplitude
$\gamma$	photon, or gammy ray
$\gamma_\mu, \gamma_5$	Dirac matrices
$\delta$	$CP$ -violating phase in the Cabibbo–Kobayashi–Maskawa matrix
$\varepsilon$	dielectric constant (of a medium)
$\varepsilon, \varepsilon'$	$CP$ -violating parameters measured in neutral kaon decays
$\eta, \eta^0$	eta meson – neutral, composed of up and down quarks
$\eta_{+-}, \eta_{00}$	eta plus-minus, eta zero zero – neutral kaon decay parameters
$\theta, \theta^0$	theta mesons (now known as kaons); $\theta$ also used for polar angle
$\theta_c$	Cabibbo angle
$\theta_W$	weak mixing angle (or Weinberg angle)
$\theta_1, \theta_2, \theta_3$	mixing angles in the Cabibbo–Kobayashi–Maskawa matrix
$\Lambda(\bar{\Lambda})$	lambda baryon (antibaryon); also used for QCD scaling parameter
$\Lambda_c(\bar{\Lambda}_c)$	charmed lambda baryon (antibaryon)
$\mu, \mu^-(\mu^+)$	muon (antimuon); $\mu$ also the magnetic permeability
$\nu(\bar{\nu})$	neutrino (antineutrino), of any type
$\nu_e(\bar{\nu}_e)$	electron neutrino (antineutrino)
$\nu_l(\bar{\nu}_l)$	neutrino (antineutrino) of type or lepton “flavor” $l$
$\nu_\mu(\bar{\nu}_\mu)$	muon neutrino (antineutrino)
$\nu_\tau(\bar{\nu}_\tau)$	tau neutrino (antineutrino)
$\pi, \pi^+, \pi^-, \pi^0$	pi mesons, or pions – spin-0 mesons composed of up and down quarks
$\rho$	rho parameter (in deep-inelastic $\nu$ – $N$ scattering)
$\rho, \rho^0, \rho^+, \rho^-$	rho mesons – neutral and charged, composed of up and down quarks
$\sigma$	generalized cross section; also used for sigma model

xxx	<i>Mathematical Notation</i>
$\sigma(X \rightarrow Y)$	cross section for a scattering or decay process $X \rightarrow Y$
$\sigma_{had}$	cross section for hadron production (especially in $e^+e^-$ collisions)
$\sigma_{\mu\mu}$	cross section for muon-pair production (especially in $e^+e^-$ collisions)
$\sigma_L$	cross section for absorption of longitudinal virtual photons
$\sigma_T$	cross section for absorption of transverse virtual photons
$\tau, \tau^-(\tau^+)$	tau (antitau) lepton; also used for particle lifetimes, tau mesons
$\tau_x$	mean lifetime of a subatomic particle $x$
$\Upsilon, \Upsilon', \Upsilon'' \dots$	upsilon particles – composed of a bottom quark and its antiquark
$\phi$	phi meson – composed of a strange quark and its antiquark
$\chi$	chi particles – neutral spin-1 particles produced in decays of $\psi$ particles
$\psi, \psi'$	wave function or spinor
$\psi, \psi', \psi''$	psi particles – composed of a charm quark and its antiquark
$\psi_1, \psi_2$	components of a wave function or spinor
$\Omega^-$	omega-minus baryon – composed of three strange quarks
$\omega, \omega^0$	omega meson – neutral, composed of up and down quarks