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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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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To all these individuals and organizations, without whose contributions we could not have held this Symposium, we extend our deepest thanks.

Photographs of the Symposium on the following pages are by Joe Faust, and provided courtesy of SLAC.
Burton Richter helps Steven Weinberg with the microphone before his opening talk.

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

Gross, Sam Schweber, and Harry Lipkin.
Michael Riordan and Sidney Bludman discussing the sequence of speakers.

John Heilbron and Laurie Brown.
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.
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.
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.
Abbreviations and Acronyms

Acta Phys. Pol
Am. J. Phys.
Dokl. Akad. Nauk SSR
JETP Lett.
J. Phys.
Lett. Nuovo Cimento
Natl. Acad. Sci. USA
Nucl. Phys.
Phys. Lett.
Phys. Rev.

Acta Physica Polonica
American Journal of Physics
Annals of Physics
Annual Reviews of Nuclear and Particle Science
Communications in Mathematical Physics
Doklady Akademii Nauk SSR
Helvetica Physica Acta
Historical Studies in the Physical and Biological Sciences
Historical Studies in the Physical Sciences
Journal of Experimental and Theoretical Physics Letters
Journal of Mathematical Physics
Journal de Physique
Lettres al Nuovo Cimento
Proceedings of the National Academy of Sciences (USA)
Nuclear Physics
Physics Letters
Physics Reports
Physical Review
### Abbreviations and Acronyms

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<td>Prog. Theor. Phys.</td>
<td>Progress of Theoretical Physics</td>
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<tr>
<td>Rev. Mod. Phys.</td>
<td>Reviews of Modern Physics</td>
</tr>
<tr>
<td>Z. Phys.</td>
<td>Zeitschrift für Physik</td>
</tr>
<tr>
<td>AdA</td>
<td>Anello di Accumulatione (i.e., storage ring)</td>
</tr>
<tr>
<td>ADONE</td>
<td>“big AdA”</td>
</tr>
<tr>
<td>AEC</td>
<td>Atomic Energy Commission</td>
</tr>
<tr>
<td>AGS</td>
<td>Alternating Gradient Synchrotron (at Brookhaven)</td>
</tr>
<tr>
<td>ARGUS</td>
<td>third-generation particle detector built at DORIS; also the collaboration</td>
</tr>
<tr>
<td>BCS</td>
<td>Bardeen–Cooper–Schrieffer (theory)</td>
</tr>
<tr>
<td>BEPC</td>
<td>Beijing Electron–Positron Collider</td>
</tr>
<tr>
<td>BES</td>
<td>Beijing Spectrometer at BEPC</td>
</tr>
<tr>
<td>BNL</td>
<td>Brookhaven National Laboratory</td>
</tr>
<tr>
<td>BRS</td>
<td>Becci–Rouet–Stora (invariance or transformation)</td>
</tr>
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<td>CDF</td>
<td>Collider Detector at Fermilab; also the experimental collaboration</td>
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<tr>
<td>CEA</td>
<td>Cambridge Electron Accelerator</td>
</tr>
<tr>
<td>CELLO</td>
<td>solenoidal particle detector at PETRA; also the collaboration</td>
</tr>
<tr>
<td>CERN</td>
<td>Centre European pour la Recherche Nucléaire (now known as the European Center for Particle Physics)</td>
</tr>
<tr>
<td>CESR</td>
<td>Cornell Electron Storage Ring</td>
</tr>
<tr>
<td>CKM</td>
<td>Cabibbo–Kobayashi–Maskawa (matrix)</td>
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<td>solenoidal particle detector and experimental collaboration at CESR</td>
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<td>CRT</td>
<td>cathode-ray tube</td>
</tr>
<tr>
<td>CUSB</td>
<td>Columbia University/Stony Brook detector and collaboration at CESR</td>
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<td>CVC</td>
<td>conserved vector current (hypothesis)</td>
</tr>
<tr>
<td>DASP</td>
<td>Double-Arm Spectrometer (DESY); also the experimental collaboration</td>
</tr>
<tr>
<td>DELCO</td>
<td>Direct Electron Counter detector built at SPEAR</td>
</tr>
<tr>
<td>DESY</td>
<td>Deutsches Elektronen Synchrotron</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
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<td>D0</td>
<td>large particle detector (at Fermilab); also the experimental collaboration</td>
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<td>DORIS</td>
<td>Double-Ring Storage electron–positron collider at DESY</td>
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<tr>
<td>ERDA</td>
<td>Energy Research and Development Administration</td>
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<tr>
<td>FNAL</td>
<td>Fermi National Accelerator Laboratory (a.k.a. Fermilab)</td>
</tr>
<tr>
<td>GIM</td>
<td>Glashow–Iliopolous–Maiani (mechanism)</td>
</tr>
<tr>
<td>GWS</td>
<td>Glashow–Weinberg–Salam (model or theory)</td>
</tr>
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<td>HRS</td>
<td>large particle detector at PEP; also the experimental collaboration</td>
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<tr>
<td>ISABELLE</td>
<td>unfinished proton collider (at Brookhaven)</td>
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<td>ISR</td>
<td>Intersecting Storage Rings (CERN)</td>
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<td>JADE</td>
<td>solenoidal particle detector at PETRA; also the collaboration</td>
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<tr>
<td>LBL</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>LEP</td>
<td>Large Electron–Positron collider (CERN)</td>
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<tr>
<td>MAC</td>
<td>solenoidal particle detector and experimental collaboration at PEP</td>
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<td>MARK I</td>
<td>The first SLAC–LBL particle detector at the SPEAR $e^+e^-$ collider (SLAC)</td>
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<td>MARK II</td>
<td>solenoidal particle detector built at SPEAR and moved to PEP (SLAC)</td>
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<td>MARK-J</td>
<td>large particle detector at PETRA; also the collaboration</td>
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<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
</tr>
<tr>
<td>MURA</td>
<td>Midwestern Universities Research Association</td>
</tr>
<tr>
<td>NAL</td>
<td>National Accelerator Laboratory (renamed Fermilab)</td>
</tr>
<tr>
<td>PCAC</td>
<td>partially conserved axial current</td>
</tr>
<tr>
<td>PEP</td>
<td>Positron Electron Project (at SLAC)</td>
</tr>
<tr>
<td>PETRA</td>
<td>Positron–Electron Tandem Ring Accelerator (at DESY)</td>
</tr>
<tr>
<td>PLUTO</td>
<td>detector built at DORIS and moved to PETRA; also the collaboration</td>
</tr>
<tr>
<td>QCD</td>
<td>quantum chromodynamics</td>
</tr>
<tr>
<td>QED</td>
<td>quantum electrodynamics</td>
</tr>
<tr>
<td>SALT</td>
<td>Strategic Arms Limitations Talks</td>
</tr>
<tr>
<td>SLAC</td>
<td>Stanford Linear Accelerator Center</td>
</tr>
<tr>
<td>SPEAR</td>
<td>Stanford Positron–Electron Asymmetric Ring (at SLAC)</td>
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<tr>
<td>TASSO</td>
<td>Two-Armed Solenoidal Spectrometer at PETRA; also the collaboration</td>
</tr>
<tr>
<td>TPC</td>
<td>solenoidal particle detector at PEP; also the experimental collaboration</td>
</tr>
<tr>
<td>UA1</td>
<td>magnetic particle detector and collaboration at CERN pp collider</td>
</tr>
<tr>
<td>UA2</td>
<td>major particle detector and collaboration at CERN pp collider</td>
</tr>
<tr>
<td>URA</td>
<td>Universities Research Association</td>
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## Mathematical Notation

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

\[ e^+ \]
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

\[ \text{GeV} \]
billions of electron volts, or gigaelectronvolts

\[ g, g' \]
generalized coupling constants

\[ I \]
isospin quantum number

\[ I, I_1, I_2, I_3 \]
isospin operator

\[ J \]
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^-, \ldots) 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

\[ K^0, K^0_L, K^0_S \]
neutral K mesons

\[ K^0_1, K^0_2 \]
neutral K mesons (now more commonly written as \( K^0_S, K^0_L \))

\[ L^- (L^+) \]
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)

\[ \text{MeV} \]
million electron volts, or megar electron 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 \( l = 1 \)

\[ P_{\epsilon} \]
spin-1 particle (also known as \( \chi \)) produced in \( \psi \) decays
Mathematical Notation

\( P_{\mu}, P_{\nu} \)  
four-momentum components of a particle

\( \vec{P}_0, \vec{P}_1, \vec{P}_2 \)  
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

\( R = \sigma_{\text{had}} / \sigma_{\mu\mu} \)  
ratio of hadron to muon-pair production in \( \text{e}^+\text{e}^- \) collisions

\( R = \sigma_L / \sigma_T \)  
ratio of longitudinal to transverse photoabsorption in \( \text{e}^-\text{N} \) scattering

\( S \)  
strangeness operator or quantum number

\( S, 1S, 2S, \ldots \)  
\( S \) states of a particle system – having orbital angular momentum \( l = 0 \)

\( S \)-matrix  
scattering matrix

\( \text{SU(N)} \)  
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

\( \text{TeV} \)  
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

\( \alpha \)  
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 gamma 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

\( \eta^{+}, \eta^{0} \)  
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
Mathematical Notation

\( \sigma(X \rightarrow Y) \) \hspace{1cm} \text{cross section for a scattering or decay process } X \rightarrow Y

\( \sigma_{\text{had}} \) \hspace{1cm} \text{cross section for hadron production (especially in } e^+ e^- \text{ collisions)}

\( \sigma_{\mu\mu} \) \hspace{1cm} \text{cross section for muon-pair production (especially in } e^+ e^- \text{ collisions)}

\( \sigma_L \) \hspace{1cm} \text{cross section for absorption of longitudinal virtual photons}

\( \sigma_T \) \hspace{1cm} \text{cross section for absorption of transverse virtual photons}

\( \tau, \tau^- (\tau^+) \) \hspace{1cm} \text{tau (antitau) lepton; also used for particle lifetimes, tau mesons}

\( \tau_x \) \hspace{1cm} \text{mean lifetime of a subatomic particle } x

\( \Upsilon, \Upsilon', \Upsilon'' \ldots \) \hspace{1cm} \text{upsilon particles – composed of a bottom quark and its antiquark}

\( \phi \) \hspace{1cm} \text{phi meson – composed of a strange quark and its antiquark}

\( \chi \) \hspace{1cm} \text{chi particles – neutral spin-1 particles produced in decays of } \psi \text{ particles}

\( \psi, \psi' \) \hspace{1cm} \text{wave function or spinor}

\( \psi, \psi', \psi'' \) \hspace{1cm} \text{psi particles – composed of a charm quark and its antiquark}

\( \psi_1, \psi_2 \) \hspace{1cm} \text{components of a wave function or spinor}

\( \Omega^- \) \hspace{1cm} \text{omega-minus baryon – composed of three strange quarks}

\( \omega, \omega^0 \) \hspace{1cm} \text{omega meson – neutral, composed of up and down quarks}