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Introduction to Particle and Astroparticle Physics

Multimessenger Astronomy and its Particle
Physics Foundations

Second Edition

 Springer

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Foreword

My generation of particle physicists has been incredibly fortunate. The first paper I ever read was George Zweig’s highly speculative CERN preprint on “aces,” now called quarks. After an exhilarating ride, from the chaos of particles and resonances of the sixties to the discovery of the Higgs boson that gives them mass, quarks are now routinely featured in standard physics texts along with the levers and pulleys of the first chapter.

My office was one floor below that of Monseigneur Lemaitre; strangely, I only knew of his existence because I used the computer that he had built. That was just before the discovery of the microwave background brought him fame and the juggernaut that is now precision cosmology changed cosmology from boutique science to a discipline pushing the intellectual frontier of physics today.

Over the same decades, the focus of particle physics shifted from cosmic rays to accelerators, returning in the disguise of particle astrophysics with the discovery of neutrino mass in the oscillating atmospheric neutrino beam, the first chink in the armor of the Standard Model.

This triptych of discoveries represents a masterpiece that is also strikingly incomplete—like a Titian painting, only the details are missing, to borrow Pauli’s description of Heisenberg’s early theory of strong interactions. The mechanism by which the Higgs endows the heaviest quark, the top, with its mass is unstable in the Standard Model. In fact, the nonvanishing neutrino mass directly and unequivocally exposes the incompleteness of the symmetries of the Standard Model of quarks and leptons. Precision cosmology has given birth to a strange Universe of some hydrogen and helium (with traces of the other chemical elements) but mostly dark energy and dark matter. The stars, neutrinos, microwave photons, and supermassive black holes that constitute the rest do not add up to very much. But this is business as usual—deeper insights reveal more fundamental questions whose resolution is more challenging. Their resolution has inspired a plethora of novel and ambitious instrumentation on all fronts.

After decades of development on the detectors, we recently inaugurated the era of multimessenger astronomy for both gravitational waves and high-energy neutrinos. On August 17, 2017, a gravitational wave detected by the LIGO-Virgo

interferometers pointed at the merger of a pair of neutron stars that was subsequently scrutinized by astronomical telescopes in all wavelengths of astronomy, from radio waves to gamma rays. Barely a month later, some of the same instruments traced the origin of an IceCube cosmic neutrino of 300 TeV energy to a distant flaring active galaxy.

At the close of the nineteenth century, many physicists believed that physics had been essentially settled—we do not live with that illusion today. Yet, the key is still to focus on the unresolved issues, as was the case then. Based on the size of the Sun and given the rate that it must be contracting to transform gravitational energy into its radiation, Lord Kelvin concluded that the Sun cannot be more than 20–40 million years old. His estimate was correct and directly in conflict with known geology. Moreover, it did not leave sufficient time for Darwin’s evolution to run its course. The puzzle was resolved after Becquerel accidentally discovered radioactivity, and Rutherford eventually identified nuclear fusion as the source of the Sun’s energy in 1907. The puzzling gap between some ten million and 4.5 billion for the age of the solar system provided the hint of new physics to be discovered at a time when many thought “only the details were missing.” Today we are blessed by an abundance of puzzles covering all aspects of particle physics, including the incompleteness of the Standard Model, the origin of neutrino mass, and the perplexing nature of dark matter and dark energy.

This book will inspire and prepare students for the next adventures. As always, the science will proceed with detours, dead ends, false alarms, missed opportunities, and unexpected surprises, but the journey will be exhilarating and progress is guaranteed, as before.

Francis Halzen

Francis Halzen is the principal investigator of the IceCube project, and Hilldale and Gregory Breit Professor in the department of physics at the University of Wisconsin–Madison.

Preface

This book introduces particle physics, astrophysics and cosmology starting from experiment. It provides a unified view of these fields, which is needed to answer our questions to the Universe—a unified view that has been lost somehow in recent years due to increasing specialization.

This is the second edition of a book we published only three years ago, a book which had a success beyond our expectations. We felt that the recent progress on gravitational waves, gamma ray and neutrino astrophysics deserved a new edition including all these new developments: multimessenger astronomy is now a reality. In addition, the properties of the Higgs particle are much better known now than three years ago. Thanks to this second edition we had the opportunity to fix some bugs, to extend the material related to exercises, and to change in a more logical form the order of some items. Last but not least, our editor encouraged us a lot to write a second edition.

Particle physics has recently seen the incredible success of the so-called standard model. A 50-year long search for the missing ingredient of the model, the Higgs particle, has been concluded successfully, and some scientists claim that we are close to the limit of the physics humans may know.

Also astrophysics and cosmology have shown an impressive evolution, driven by experiments and complemented by theories and models. We have nowadays a “standard model of cosmology” which successfully describes the evolution of the Universe from a tiny time after its birth to any foreseeable future. The experimental field of astroparticle physics is rapidly evolving, and its discovery potential appears still enormous: during the three years between the first and the second edition of this book gravitational waves have been detected, an event in which gravitational waves were associated to electromagnetic waves has been detected, and an extragalactic source of astrophysical neutrinos has been located and associated to a gamma-ray emitter.

The situation is similar to the one that physics lived at the end of the nineteenth century, after the formulation of Maxwell’s equations—and we know how the story went. As then, there are today some clouds which might hide a new revolution in physics. The main cloud is that experiments indicate that we are still missing the

description of the main ingredients of the Universe from the point of view of its energy budget. We believe one of these ingredients to be a new particle, of which we know very little, and the other to be a new form of energy. The same experiments indicating the need for these new ingredients are probably not powerful enough to unveil them, and we must invent new experiments to do it.

The scientists who solve this puzzle will base their project on a unified vision of physics, and this book helps to provide such a vision.

This book is addressed primarily to advanced undergraduate or beginning graduate students, since the reader is only assumed to know quantum physics and “classical” physics, in particular electromagnetism and analytical mechanics, at an introductory level, but it can also be useful for graduates and postgraduates, and postdoc researchers involved in high-energy physics or astrophysics research. It is also aimed at senior particle and astroparticle physicists as a consultation book. Exercises at the end of each chapter help the reader to review material from the chapter itself and synthesize concepts from several chapters. A “further reading” list is also provided for readers who want to explore in more detail particular topics.

Our experience is based on research both at artificial particle accelerators (in our younger years) and in astroparticle physics after the late 1990s. We have worked as professors since more than twenty years, teaching courses on particle and/or astroparticle physics at undergraduate and graduate levels. We spent a long time in several research institutions outside our countries, also teaching there and gaining experience with students with different backgrounds.

This book contains a broad and interdisciplinary material, which is appropriate for a consultation book, but it can be too much for a textbook. In order to give coherence to the material for a course, one can think of at least three paths through the manuscript:

- For an “old-style” one-semester course on particle physics for students with a good mathematical background, one could select chapters 1, 2, 3, 4, 5, 6, part of 7, and possibly (part of) 8 and 9.
- For a basic particle physics course centered in astroparticle physics one could instead use chapters 1, 2, 3, 4 (excluding 4.4), 5.1, 5.2, part of 5.4, part of 5.5, 5.6, 5.7, possibly 6.1, 8.1, 8.4, 8.5, part of 10, and if possible 11.
- A one-semester course in high-energy astroparticle physics for students who already know the foundations of particle physics could be based on chapters 1, 3, 4.3.2, 4.5, 4.6, 8, 10, 11; if needed, an introduction to experimental techniques could be given based on 4.1 and 4.2.
- A specialized half-semester course in high-energy astroparticle physics could be based on chapters 4.3.2, 4.5, 4.6, 8.1, 8.4, 8.5, 10; an introduction to experimental techniques could be given based on 4.1 and 4.2 if needed.

Unfortunately we know that several mistakes will affect also this second edition. Readers can find at the Web site

<http://ipap.uniud.it>

a “living” errata corrige, plus some extra material related in particular to the exercises. Please help us to improve the book by making suggestions and corrections: we shall answer all criticisms with gratitude.

Our work would have not been possible without the help of friends and colleagues; we acknowledge here (in alphabetical order) Pedro Abreu, Sofia Andringa, Stefano Ansoldi, Pedro Assis, Liliana Apolinario, Luca Baldini, Fernando Barão, Sandro Bettini, Giovanni Busetto, Per Carlson, Nuno Castro, Julian Chela-Flores, Stefano Ciprini, Ruben Conceição, Jim Cronin, Davide De Grandis, Barbara De Lotto, Michela De Maria, Ivan De Mitri, Pino di Sciascio, Tristano di Girolamo, Jorge Dias de Deus, Anna Driutti, Catarina Espírito Santo, Fernando Ferroni, Alberto Franceschini, Giorgio Galanti, Gianluca Gemme, Riccardo Giannitrapani, Antonella Incicchitti, Giovanni La Mura, Marco Laveder, Claudia Lazzaro, Andrea Longhin, Francesco Longo, Rubén Lopez, Manuela Mallamaci, José Maneira, Ioana Maris, Mauro Mezzetto, Teresa Montaruli, Luc Pape, Alessandro Pascolini, Gianni Pauletta, Elena Pavan, Massimo Persic, Giampaolo Piotto, Piero Rafanelli, Ignasi Reichardt, Jorge Romao, Marco Roncadelli, Sara Salvador, Pablo Saz Parkinson, Ron Shellard, Franco Simonetto, Radomir Smida, Vincent Tatischeff, Bernardo Tomé, Ezio Torassa, Andrea Turcati, Michael Unger, Robert Wagner, Scott Wakely, Alan Watson, Jeff Wyss, Jean-Pierre Zendri.

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About the Authors

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Mário Pimenta is a high-energy physicist and astrophysicist. Professor at the Instituto Superior Técnico of the University of Lisbon, he is currently the president of the Portuguese national organization for Particle and Astroparticle Physics, coordinator of the international Ph.D. doctoral network IDPASC, and the representative for Portugal at the Pierre Auger Observatory in Argentina. Formerly member of the WA72, WA74, NA38 and DELPHI experiments at CERN and of the EUSO collaboration at ESA, his main interest of research is on high-energy physics, especially cosmic rays of extremely high energy and development of detectors for astroparticle physics. He graduated from Lisbon and Paris VI, and was employed at CERN in the late 1980s. His original contributions have been mostly related to advanced trigger systems, search for new particles, hadronic interactions at extremely high energies, and recently to innovative particle detectors. He has taught general physics and particle physics in Portugal, has lectured at the University of Udine and has been visiting professor at SISSA/ISAS in Trieste.

Acronyms

a.s.l.	Above sea level (altitude)
ACE	Advanced composition explorer (astrophysical observatory orbiting the Earth)
AGASA	Akeno giant air shower array (experiment in Japan)
AGILE	Astro-rivelatore gamma a immagini leggero (gamma-ray telescope orbiting the Earth)
AGN	Active galactic nucleus
ALEPH	A LEP experiment (at CERN)
ALICE	A large ion collider experiment (at CERN)
ALLEGRO	A Louisiana low-temperature experimental gravitational radiation observatory (in the USA)
ALP	Axion-like particle
ALPHA	Antihydrogen experiment at CERN
AMS	Alpha magnetic spectrometer (particle detector onboard the ISS)
ANTARES	Astronomy with a neutrino telescope and abyss environmental research (experiment in the Mediterranean Sea)
APD	Avalanche photodiode (detector)
ARGO-YBJ	Cosmic-ray detector at the Yanbanjing Observatory (in Tibet)
ATIC	Advanced thin ionization calorimeter (balloon-borne experiment)
ATLAS	A toroidal LHC apparatus (experiment at CERN)
AU	Astronomical unit (a.u.)
AURIGA	An ultracryogenic gravitational waves detector
BaBar	B–anti-B experiment at SLAC
BATSE	Burst and transient source experiment (in the CGRO)
BBN	Big Bang nucleosynthesis
BEBC	Big European Bubble Chamber (experiment at CERN)
Belle	b physics experiment at KEK
BESS	Balloon-borne experiment with superconducting spectrometer
Bevatron	Billion electron volts synchrotron (accelerator in the USA)
BGO	$\text{Bi}_4 \text{Ge}_3 \text{O}_{12}$ (scintillating crystal)

BH	Black hole
BL Lac	Blazar Lacertae (an active galactic nucleus)
BNL	Brookhaven National Laboratory (in Long Island, NY)
Borexino	Boron solar neutrino experiment (at the LNGS)
BR	Branching ratio (in a decay process)
CANGAROO	Collaboration of Australia and Nippon (Japan) for a gamma-ray observatory in the outback (Cherenkov observatory)
CAST	CERN axion search telescope (experiment at CERN)
CDF	Collider detector at Fermilab (experiment)
Λ CDM	Lambda and cold dark matter (model with cosmological constant Λ)
CERN	European Organization for Nuclear Research, also European laboratory for particle physics
CGC	Colour glass condensate
CGRO	Compton gamma-ray observatory (orbiting the Earth)
cgs	centimeter, gram, second (system of units)
CKM	Cabibbo, Kobayasha, Maskawa (matrix mixing the quark flavors.)
CMB	Cosmic microwave background (radiation)
CMS	Compact Muon Solenoid (experiment at CERN)
COBE	Cosmic Background Explorer (satellite orbiting the Earth)
CoGeNT	Coherent germanium neutrino telescope (experiment in the USA)
COUPP	Chicagoland observatory for underground particle physics (experiment at Fermilab)
CP	Charge conjugation \times Parity (product of symmetry operators)
CPT	Charge conjugation \times Parity \times Time reversal (product of symmetry operators)
CR	Cosmic rays
CREAM	Cosmic-ray energetics and mass experiment (now on the ISS)
CRESST	Cryogenic rare event search with superconducting thermometers (experiment at LNGS)
CTA	Cherenkov Telescope Array (an international gamma-ray detector)
CUORE	Cryogenic underground observatory for rare events (experiment at LNGS)
D0	Experiment at Fermilab
DAMA	Dark matter experiment (at LNGS)
DAMPE	Dark matter particle explorer (astrophysical space observatory)
DAQ	Data acquisition (electronics system)
DARMa	De Angelis, Roncadelli, Mansutti (model of axion-photon mixing)
DAS	Data acquisition system
DASI	Degree angular scale interferometer
DELPHI	Detector with lepton, photon, and hadron identification (experiment at the CERN's LEP)

DESY	Deutsche synchrotron (laboratory in Germany)
DM	Dark matter
DNA	Desoxyribonucleic acid (the genetic base of life)
DONUT	Direct observation of the ν_τ (experiment at Fermilab)
DSA	Diffusive shock acceleration (of cosmic rays)
dSph	Dwarf spheroidal galaxy
EAS	Extensive air shower (cosmic rays)
EBL	Extragalactic background light
ECAL	Electromagnetic calorimeter (detector)
EGMF	Extragalactic magnetic field
EGO	European Gravitational Observatory (in Italy)
EGRET	Energetic gamma-ray experiment telescope (part of the CGRO)
EHE	Extremely high energy
EHS	European hybrid spectrometer (experiment at CERN)
EJSM/Laplace	European Jupiter space mission–Laplace (ESA/NASA Mission)
ESA	European Space Agency
EUSO	Extreme Universe Space Observatory
FCNC	Flavor-changing neutral currents (hypothetical electroweak process)
FD	Fluorescence detector
Fermilab	Fermi National Accelerator Laboratory (near Chicago, IL); also FNAL
FLRW	Friedmann, Lemaitre, Robertson, Walker (metric model in general relativity)
FNAL	Fermi National Accelerator Laboratory (near Chicago, IL); also Fermilab
FoV	Field of view
FPGA	Field-programmable gate array (processor)
FRI	Fanaroff and Riley class I (astrophysical sources)
FSRQ	Flat spectrum radio quasars
GALLEX	Gallium experiment (at LNGS)
GAMMA-400	gamma-ray space observatory (space astrophysical observatory)
Gargamelle	Experiment at CERN
GBM	Gamma Burst Monitor (detector)
GC	Galactic center
GERDA	Germanium detector array (experiment at the LNGS)
GIM	Glashow, Iliopoulos, Maiani (mechanism)
GLAST	Gamma-ray large area space telescope, renamed <i>Fermi</i> after positioning in orbit
GPM	Gaseous photomultipliers
GPS	Global positioning system
GRB	Gamma-ray burst (astrophysical event)
GSW	Glashow–Salam–Weinberg model of electroweak unification
GUT	Grand unified theory
GZK	Greisen, Zatsepin, Kuz'min (energy cutoff for cosmic rays)

H.E.S.S.	High-energy stereoscopic system (Cherenkov experiment in Namibia)
HAWC	High-altitude water Cherenkov (observatory in Mexico)
HBL	High-energy peaked BL Lac
HCAL	Hadron calorimeter (detector)
HE	High energy
HEGRA	High-energy gamma-ray astronomy (Cherenkov experiment in La Palma)
HERA	Hadron elektron ring anlage (particle accelerator at DESY)
HPD	Hybrid photon detector
HST	Hubble Space Telescope (orbiting the Earth)
IACT	Imaging Atmospheric Cherenkov Telescope
IBL	Intermediate energy peaked BL Lac
IC	Inverse Compton scattering (mechanism for the production of HE gamma rays)
IceCube	Neutrinos observatory in Antarctica
ICRR	Institute for Cosmic Ray Research (at the University of Tokyo, Japan)
IDPASC	International doctorate on particle and astroparticle physics, astrophysics, and cosmology (doctoral network)
IMB	Irvine, Michigan, Brookhaven (experiment in the US)
INFN	Istituto Nazionale di Fisica Nucleare (in Italy)
IR	Infrared (radiation)
IRB	Infrared background (photons)
ISS	International Space Station
IST	Instituto Superior Técnico (at the University of Lisboa, Portugal)
JEM	Japanese experimental module (onboard the ISS)
K2K	KEK to Kamioka experiment (Japan)
Kamiokande	Kamioka neutrino detector (experiment in Japan)
KamLAND	Kamioka liquid scintillator antineutrino detector (experiment in Japan)
KASCADE	Karlsruhe shower and cosmic array detector (experiment in Germany)
KATRIN	Karlsruhe tritium neutrino experiment (in Germany)
KEK	High-energy accelerator in Japan
Kepler	Mission to search for extraterrestrial planets (NASA)
KM	Parametrization of the CKM matrix in the original paper by Kobayasha and Maskawa
Km ³ NeT	kilometer cube neutrino telescope (experiment in the Mediterranean Sea)
kTeV	Experiment at Fermilab
L3	LEP third (experiment at CERN)
LAr	Liquid argon
LAT	Large Area Telescope (detector on the <i>Fermi</i> Satellite)
<i>Fermi</i> -LAT	Large Area Tracker, a gamma-ray telescope orbiting the Earth

LBL	Low-energy peaked BL Lac
LEBC	LExan Bubble Chamber (experiment at CERN)
LEP II	Second phase of operation of LEP, at energies above the Z mass
LEP	Large electron positron (collider at CERN)
LHC	Large hadron collider (at CERN)
LHCb	LHC beauty (experiment at CERN)
LHCf	LHC forward (experiment at CERN)
LIGO	Laser interferometer gravitational-wave observatory (in the USA)
LISA	Laser interferometer space antenna (project for gravitational wave's detection)
LIV	Lorentz invariance violation
LMC	Large Magellanic Cloud (dwarf galaxy satellite of the Milky Way)
LNGS	Laboratorio Nazionale del Gran Sasso (Laboratory for particle and astroparticle physics in Italy)
LO	Leading order in perturbative expansions
LPHD	Local parton hadron duality (approximation in QCD predictions)
LPM	Landau–Pomeranchuk–Migdal (effect)
LSND	Liquid scintillator neutrino detector (experiment in the USA)
LSP	Lightest supersymmetric particle
LST	Large-size telescope (Cherenkov telescope for CTA)
ly	light-year
MACE	Major atmospheric cherenkov experiment (Cherenkov experiment in India)
MACHO	Massive astronomical compact halo object
MAGIC	Major atmospheric gamma-ray imaging Cherenkov telescopes (Cherenkov experiment in Canary Islands)
MARE	Microcalorimeter arrays for a Rhenium experiment (in Italy)
MC	Monte Carlo (simulation technique)
MILAGRO	Cosmic-ray (gamma in particular) experiment in the USA
MINOS	Main injector neutrino oscillation search (experiment in Fermilab)
mip	minimum ionizing particle
MoEDAL	Monopole and exotics detector at the LHC (experiment at CERN)
MOND	Modified Newtonian dynamics
MSSM	Minimal supersymmetric model
MSW	Mikheyev, Smirnov, Wolfenstein (matter effect in neutrino oscillations)
NA#	North area # (experiment at CERN, # standing for its number)
NASA	National Aeronautics and Space Agency (in the USA)
NEMO	Neutrino Ettore Majorana Observatory (in France)
NESTOR	Neutrino Extended Submarine Telescope with Oceanographic Research (experiment in the Mediterranean Sea)
NFW	Navarro, Frenk and White (profile of dark matter distribution)
NIST	National Institute of Standards and Technology (US institute)

NKG	Nishimura Kamata Greisen (lateral density distribution function for showers)
NLO	Next-to-leading order in QCD perturbative expansions
NLSP	Next-to-lightest supersymmetric particle
NNLO	Next-to-next-to-leading order in perturbative expansions
NS	Neutron star
NT-200	Neutrino telescope (experiment in Russia)
NTP	Normal temperature and pressure
NU	Natural units (system of units)
OPAL	Omni-purpose apparatus for LEP (experiment at CERN)
OPERA	Oscillation project with emulsion-tracking apparatus (experiment at LNGS)
OZI	Okubo Zweig Iizuka (rule for transitions in particle processes)
PAMELA	Payload for antimatter–matter exploration and light-nuclei astrophysics (astrophysical observatory orbiting the Earth)
PAO	Pierre Auger Observatory (cosmic-ray observatory in Argentina)
PDF	Parton density function
PDG	Particle Data Group
PHENIX	A physics experiment at RHIC
Planck	ESA mission for precise measurement of CMB anisotropy and other properties
PLATO	Planet transits and oscillations of stars (ESA mission to search for extraterrestrial planets)
PMNS	Pontecorvo, Maki, Nakagawa, Sakata (neutrino mixing matrix)
PMT	Photomultiplier tube (detector)
PSF	Point spread function (space or angular resolution)
PVLAS	Polarizzazione del vuoto con laser (experiment in Italy)
PWN	Pulsar wind nebula (astrophysical object)
QCD	Quantum chromodynamics
QED	Quantum electrodynamics
QG	Quantum gravity
QGP	Quark gluon plasma (state of matter)
QPM	Quark parton model
RF	Radiofrequency
RHIC	Relativistic Heavy Ion Collider (at BNL)
RICH	Ring imaging Cherenkov (detector)
RMS	Root mean square
RPC	Resistive plate chamber (detector)
SAGE	Soviet–American gallium experiment (in Russia)
SCT	Semiconductor tracker (detector)
SDP	Shower detector plane (cosmic rays)
SED	Spectral energy distribution
SETI	Search for extraterrestrial intelligence
SI	International system (of units)
SiPM	Silicon photomultiplier (detector)

SK	Super-Kamiokande neutrino detector (experiment in Japan); also Super-K
SLAC	Stanford linear accelerator center (in the USA)
SLD	SLAC large detector
SM	Standard model (of particle physics)
SMBH	Supermassive black hole
SMC	Small Magellanic Cloud (dwarf galaxy satellite of the Milky Way)
SNO	Sudbury neutrino observatory (Canada)
SNR	Supernova remnant
SNU	Solar neutrino unit (of neutrino interactions)
SO(n)	Special orthogonal group of rank n
SPEAR	Stanford Positron Electron Asymmetric Rings (particle accelerator in the USA)
SPS	Super-proton synchrotron (particle accelerator at CERN)
$S\bar{p}\bar{p}S$	Super-proton–antiproton synchrotron (collider at CERN)
SSB	Spontaneous symmetry breaking
SSC	Self-synchrotron Compton (mechanism for production of HE gamma-rays)
SSM	Standard solar model (of physics reactions in the Sun’s core)
SU(n)	Special unitary group of rank n
Super-K	Super-Kamiokande neutrino detector (experiment in Japan); also SK
SUSY	Supersymmetry (model beyond the SM)
T2K	Tokai to Kamioka experiment (in Japan)
TA	Telescope Array (cosmic-ray observatory in the USA)
TDAQ	Trigger and data acquisition (electronics system)
Tevatron	Teraelectronvolt synchrotron (collider at Fermilab)
TeVCAT	Catalog of astrophysical VHE gamma-ray sources
TGC	Triple gauge coupling (coupling between the electroweak gauge bosons— Z , W bosons, and the photon)
Tibet-AS	Cosmic-ray experiment
TMAE	Tetra dimethyl-amine ethylene
TNT	Trinitrotoluene (2-Methyl-1,3,5-trinitrobenzene, chemical explosive)
TOTEM	Total cross section, elastic scattering and diffraction dissociation at the LHC (experiment at CERN)
TPC	Time projection chamber (detector)
TRD	Transition radiation detector
TRT	Transition radiation tracker (detector)
U(n)	Unitary group of rank n
UA#	Underground area # (experiment at CERN, # standing for its number)
UHE	Ultrahigh-energy (cosmic rays)
UHECR	Ultrahigh-energy cosmic rays

UV	Ultraviolet (radiation)
V–A	Vector minus axial-vector relational aspect of a theory
VCV	Véron-Cetty Véron (catalog of galaxies with active galactic nuclei)
VERITAS	Very energetic radiation imaging telescope array system (Cherenkov experiment in the USA)
VHE	Very high-energy (cosmic rays)
VIRGO	Italian-French laser interferometer collaboration at EGO (experiment in Italy)
VLBA	Very long baseline array (of radio telescopes, in the USA)
WA#	West area # (experiment at CERN, # standing for its number)
WBF	Weak boson fusion (electroweak process)
WHIPPLE	Cherenkov telescope (in Arizona)
WIMP	Weakly interactive massive particle
WMAP	Wilkinson microwave anisotropy probe (satellite orbiting the Earth)
XCOM	Photon cross sections database by NIST
XTR	X-ray transition radiation