Fundamental Physics At

THE INTENSITY FRONTIER

2012 Report

U.S. DEPARTMENT OF ENERGY | Office of Science

ANL-HEP-TR-12-25
SLAC-R-991

Fundamental Physics at the Intensity Frontier

Report of the Workshop held December 2011 in Rockville, MD

Workshop Chairs: J.L. Hewett[117], and H. Weerts[3]

Conveners: R. Brock[76], J.N. Butler[38], B.C.K. Casey[38], J. Collar[23], A. de Govêa[93], R. Essig[122], Y. Grossman[30], W. Haxton[11], J.A. Jaros[117], C.K. Jung[122], Z.T. Lu[3], K. Pitts[51], Z. Ligeti[64], J.R. Patterson[30], M. Ramsey-Musolf[145], J.L. Ritchie[126], A. Roodman[117], K. Scholberg[36], C.E.M. Wagner[3,23], G.P. Zeller[38]

S. Aefsky[8], A. Afanasev[139], K. Agashe[70], C. Albright[38,92], J. Alonso[73], C. Ankenbrandt[82], M. Aoki[98], C.A. Argüelles[38,108], N. Arkani-Hamed[111], J.R. Armendariz[149], C. Armendariz-Picon[124], E. Arrieta Diaz[76], J. Asaadi[127], D.M. Asner[100], K.S. Babu[97], K. Bailey[3], O. Baker[148], B. Balantekin[145], B. Baller[132], M. Bass[27], B. Batell[23], J. Beacham[87], J. Behr[129], N. Berger[49], M. Bergevin[12], E. Berman[38], R. Bernstein[38], A.J. Bevan[112], M. Bishai[10], M. Blanke[30], S. Blessing[40], A. Blondel[42], T. Blum[29], G. Bock[38], A. Bodek[113], G. Bonvicini[140], F. Bossi[55], J. Boyce[59], R. Breedon[12], M. Breidenbach[117], S.J. Brice[38], R.A. Briere[20], S. Brodsky[117], C. Bromberg[76], A. Bross[38], T.E. Browder[48], D.A. Bryman[9,129], M. Buckley[38], R. Burnstein[52], E. Caden[35], P. Campana[22,55], R. Carlini[59,143], G. Carosi[65], C. Castromonte[21], R. Cenci[70], I. Chakaberia[61], M.C. Chen[13], C.H. Cheng[16], B. Choudhary[32], N.H. Christ[28], E. Christensen[136], M.E. Christy[45], T.E. Chupp[75], E. Church[148], D.B. Cline[14], T.E. Coan[120], P. Coloma[136], J. Comfort[4], L. Coney[15], J. Cooper[38], R.J. Cooper[95], R. Cowan[73], D.F. Cowen[105], D. Cronin-Hennessy[78], A. Datta[79], G.S. Davies[58], M. Demarteau[3], D.P. DeMille[148], A. Denig[69], R. Dermisek[54], A. Deshpande[122], M.S. Dewey[84], R. Dharmapalan[1], J. Dhooghe[12], M.R. Dietrich[3], M. Diwan[10], Z. Djurcic[3], S. Dobbs[93], M. Duraisamy[79], B. Dutta[127], H. Duyang[119], D.A. Dwyer[16], M. Eads[86], B. Echenard[16], S.R. Elliott[67], C. Escobar[38], J. Fajans[11], S. Farooq[61], C. Faroughy[122], J.E. Fast[100], B. Feinberg[64], J. Felde[12], G. Feldman[47], P. Fierlinger[81], P. Fileviez Perez[87], B. Filippone[16], P. Fisher[73], B.T. Flemming[148], K.T. Flood[16], R. Forty[22], M.J. Frank[135], A. Freyberger[59], A. Friedland[67], R. Gandhi[46], K.S. Ganezer[17], A. Garcia[138], F.G. Garcia[38], S. Gardner[63], L. Garrison[54], A. Gasparian[89], S. Geer[38], V.M. Gehman[64], T. Gershon[22,137], M. Gilchriese[64], C. Ginsberg[38], I. Gogoladze[6], M. Gonderinger[145], M. Goodman[3], H. Gould[64], M. Graham[117], P.W. Graham[121], R. Gran[77], J. Grange[39], G. Gratta[121], J.P. Green[3], H. Greenlee[38], R.C. Group[38,135], E. Guardincerri[67], V. Gudkov[119], R. Guenette[148], A. Haas[87], A. Hahn[38], T. Han[107], T. Handler[125], J.C. Hardy[127], R. Harnik[38], D.A. Harris[38], F.A. Harris[48], P.G. Harris[123], J. Hartnett[142], B. He[6], B.R. Heckel[138], K.M. Heeger[145], S. Henderson[38], D. Hertzog[138], R. Hill[23], E.A Hinds[53], D.G. Hitlin[16], R.J. Holt[3], N. Holtkamp[117], G. Horton-Smith[61], P. Huber[136], W. Huelsnitz[67], J. Imber[122], I. Irastorza[149], J. Jaeckel[37], I. Jaegle[48], C. James[38], A. Jawahery[70], D. Jensen[38], C.P. Jessop[94], B. Jones[73], H. Jostlein[38], T. Junk[38], A.L. Kagan[24], M. Kalita[63], Y. Kamyshkov[125], D.M. Kaplan[52], G. Karagiorgi[28], A. Karle[145], T. Katori[73], B. Kayser[38], R. Kephart[38], S. Kettell[10], Y.K. Kim[23,38], M. Kirby[38], K. Kirch[103], J. Klein[104], J. Kneller[90], A. Kobach[93], M. Kohl[45], J. Kopp[38], M. Kordosky[143], W. Korsch[63], I. Kourbanis[38], A.D. Krisch[75], P. Krizan[66], A.S. Kronfeld[38], S. Kulkarni[136], K.S. Kumar[72], Y. Kuno[98], T. Kutter[68], T. Lachenmaier[130], M. Lamm[38], J. Lancaster[83], M. Lancaster[25,38], C. Lane[35], K. Lang[126], P. Langacker[111], S. Lazarevic[48], T. Le[114], K. Lee[14], K.T. Lesko[11], Y. Li[10], M. Lindgren[38], A. Lindner[33], J. Link[136], D. Lissauer[10], L.S. Littenberg[10], B. Littlejohn[145], C.Y. Liu[54], W. Loinaz[2], W. Lorenzon[75], W.C. Louis[67], J. Lozier[36], L. Ludovici[56], L. Lueking[38], C. Lunardini[4,10], D.B. MacFarlane[117], P.A.N. Machado[115,116], P.B. Mackenzie[38], J. Maloney[92], W.J. Marciano[10], W. Marsh[38], M. Marshak[78], J.W. Martin[144], C. Mauger[67], K.S. McFarland[113], C. McGrew[122], G. McLaughlin[90], D. McKeen[133], R. McKeown[59], B.T. Meadows[24], R. Mehdiyev[126], D. Melconian[127], H. Merkel[69], M. Messier[54], J.P. Miller[7], G. Mills[67], U.K. Minamisono[76], S.R. Mishra[119], I. Mocioiu[105], S. Moed Sher[38], R.N. Mohapatra[70], B. Monreal[73], C.D. Moore[38], J.G. Morfin[38], J. Mousseau[39], L.A. Moustakas[60], G. Mueller[39], P. Mueller[3], M. Muether[38], H.P. Mumm[84], C. Munger[117], H. Murayama[11,57,64], P. Nath[91], O. Naviliat-Cuncin[76], J.K. Nelson[143], D. Neuffer[38], J.S. Nico[84], A. Norman[38], D. Nygren[64], Y. Obayashi[128], T.P. O'Connor[3], Y. Okada[62], J. Olsen[110], L. Orozco[70], J.L. Orrell[100], J. Osta[38], B. Pahlka[38], J. Paley[3], V. Papadimitriou[38],

M. Papucci[64], S. Parke[38], R.H. Parker[3,23], Z. Parsa[10], K. Partyka[148], A. Patch[140], J.C. Pati[117], R.B. Patterson[16], Z. Pavlovic[67], G. Paz[140], G.N. Perdue[113], D. Perevalov[38], G. Perez[22,141], R. Petti[119], W. Pettus[145], A. Piepke[1], M. Pivovaroff[65], R. Plunkett[38], C.C. Polly[38], M. Pospelov[106,133], R. Povey[142], A. Prakesh[73], M.V. Purohit[119], S. Raby[96], J.L. Raaf[38], R. Rajendran[38], S. Rajendran[121], G. Rameika[38], R. Ramsey[70], A. Rashed[79], B.N. Ratcliff[117], B. Rebel[38], J. Redondo[80], P. Reimer[3], D. Reitzner[38], F. Ringer[130], A. Ringwald[33], S. Riordan[72], B.L. Roberts[7], D.A. Roberts[70], R. Robertson[138], F. Robicheaux[5], M. Rominsky[38], R. Roser[38], J.L. Rosner[23], C. Rott[96], P. Rubin[71], N. Saito[62], M. Sanchez[3,58], S. Sarkar[99], H. Schellman[93], B. Schmidt[22], M. Schmitt[93], D.W. Schmitz[38], J. Schneps[131], A. Schopper[22], P. Schuster[106], A.J. Schwartz[24], M. Schwarz[44], J. Seeman[117], Y.K. Semertzidis[10], K.K. Seth[93], Q. Shafi[6], P. Shanahan[38], R. Sharma[38,101], S.R. Sharpe[138], M. Shiozawa[128], V. Shiltsev[38], K. Sigurdson[9], P. Sikivie[39], J. Singh[3], D. Sivers[75,109], T. Skwarnicki[124], N. Smith[118], J. Sobczyk[38,146], H. Sobel[13], M. Soderberg[124], Y.H. Song[119], A. Soni[10], P. Souder[124], A. Sousa[47], J. Spitz[73], M. Stancari[38], G.C. Stavenga[38], J.H. Steffen[38], S. Stepanyan[59], D. Stoeckinger[34], S. Stone[124], J. Strait[38], M. Strassler[114], I.A. Sulai[23], R. Sundrum[70], R. Svoboda[12], B. Szczerbinska[31], A. Szelc[148], T. Takeuchi[136], P. Tanedo[30], S. Taneja[122], J. Tang[147], D.B. Tanner[39], R. Tayloe[54], I. Taylor[122], J. Thomas[25], C. Thorn[10], X. Tian[119], B.G. Tice[114], M. Tobar[142], N. Tolich[138], N. Toro[106], I.S. Towner[127], Y. Tsai[30], R. Tschirhart[38], C.D. Tunnell[99], M. Tzanov[68], A. Upadhye[3], J. Urheim[54], S. Vahsen[48], A. Vainshtein[78], E. Valencia[43], R.G. Van de Water[67], R.S. Van de Water[10], M. Velasco[93], J. Vogel[65], P. Vogel[16], W. Vogelsang[10,130], Y.W. Wah[23], D. Walker[117], N. Weiner[87], A. Weltman[18], R. Wendell[36], W. Wester[38], M. Wetstein[3], C. White[52], L. Whitehead[50], J. Whitmore[85], E. Widmann[134], G. Wiedemann[44], J. Wilkerson[88,95], G. Wilkinson[99], P. Wilson[38], R.J. Wilson[27], W. Winter[147], M.B. Wise[16], J. Wodin[117], S. Wojcicki[121], B. Wojtsekhowski[59], T. Wongjirad[36], E. Worcester[10], J. Wurtele,[11,64], T. Xin[58], J. Xu[75], T. Yamanaka[98], Y. Yamazaki[76], I. Yavin[74,106], J. Yeck[11,145], M. Yeh[10], M. Yokoyama[128], J. Yoo[38], A. Young[90], E. Zimmerman[26], K. Zioutas[102], M. Zisman[132], J. Zupan[24], R. Zwaska[38]

[1]University of Alabama, Tuscaloosa, AL 35487, USA
[2]Amherst College, Amherst, MA 01002, USA
[3]Argonne National Laboratory, Argonne, IL 60439, USA
[4]Arizona State University, Tempe, AZ, 85287-1504, USA
[5]Auburn University, Auburn, AL36849, USA
[6]Bartol Research Institute, University of Delaware, Newark, DE, 19716-2593, USA
[7]Boston University, Boston, MA 02215, USA
[8]Brandeis University, Waltham, MA 02453, USA
[9]University of British Columbia, Vancouver, BC V5A 1S6 Canada
[10]Brookhaven National Lab, Upton, NY, 11973-5000, USA
[11]University of California, Berkeley, Berkeley, CA 94720, USA
[12]University of California, Davis, Davis, CA 95616, USA
[13]University of California, Irvine, Irvine, CA 92698, USA
[14]University of California, Los Angeles, Los Angeles, CA 90095, USA
[15]University of California, Riverside, Riverside, CA 92521, USA
[16]California Institute of Technology, Pasadena, CA 91125, USA
[17]California State University, Dominguez Hills, Carson, CA 90747-0005, USA
[18]Univeristy of Cape Town, Rondenbosch, South Africa
[19]Carleton University, Ottawa, ON, K1S 5B6 Canada
[20]Carnegie Mellon University, Pittsburgh, PA 15213, USA
[21]Centro Brasileiro de Pesquisas Fisicas, Rio de Janiero, RJ, 22290-180, Brazil
[22]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[23]University of Chicago, Enrico Fermi Institute, Chicago, IL 60637, USA
[24]University of Cincinnati, Cincinnati, OH 45221, USA

[25]University College London, London WC1E 6BT, United Kingdom
[26]University of Colorado, Boulder, CO 80309, USA
[27]Colorado State University, Fort Collins, CO 80523, USA
[28]Columbia University, New York, NY 10027, USA
[29]University of Connecticut, Storrs, CT 06269-3046, USA
[30]Cornell University, Laboratory for Elementary Particle Physics, Ithaca, NY 14853, USA
[31]Dakota State University, Madison, SD 57042-1799, USA
[32]University of Delhi, Delhi 110-007, India
[33]Deutsches Elektronen-Synchrotron, Hamburg, Germany
[34]Dresden University of Technology, Dresden, Germany
[35]Drexel University, Philadelphia, PA 19104-2816, USA
[36]Duke University, Durham, NC 27708-0754, USA
[37]Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, United Kingdom
[38]Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[39]University of Florida, Gainesville, FL 32611, USA
[40]Florida State University, Tallahassee, FL 32306, USA
[41]University of Freiburg, Freiburg, Germany
[42]Université de Genève, Geneva, Switzerland
[43]Universidad de Guanajuato, Guanajuato, Mexico
[44]University of Hamburg, Hamburg, Germany
[45]Hampton University, Hampton, VA 23668-0108, USA
[46]Harish Chandra Research Institute, Allahabad, India
[47]Harvard University, Cambridge, MA 02138, USA
[48]University of Hawaii, Honolulu, HI 96822 USA
[49]University of Heidelberg, Heidelberg, Germany
[50]University of Houston, Houston, TX 77004-2693, USA
[51]University of Illinois, Urbana, IL 61801, USA
[52]Illinois Institute of Technology, Chicago, IL, 60616-3793 USA
[53]Imperial College London, London, SW7 2AZ, United Kingdom
[54]University of Indiana, Bloomington, IN 47405-7105, USA
[55]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[56]INFN Sezione di Roma and Universitá di Roma, La Sapienza, Roma, Italy
[57]Institute for the Physics and Mathematics of the Universe, Tokyo, Japan
[58]Iowa State University, Ames, IA 50011, USA
[59]Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
[60]Jet Propulsion Laboratory, Pasadena, CA 91109, USA
[61]Kansas State University, Manhattan, KS 66506-2601, USA
[62]KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
[63]University of Kentucky, Lexington, KY 40506, USA
[64]Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[65]Lawrence Livermore National Laboratory, Livermore, CA, 94550, USA
[66]University of Ljubljana, Ljubljana, Slovenia
[67]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[68]Louisiana State University, Baton Rouge, LA 70803, USA
[69]University of Mainz, Mainz, Germany
[70]University of Maryland, College Park, MD 20742, USA
[71]George Mason University, Fairfax, VA 22030-4444, USA
[72]University of Massachusetts, Amherst, MA 01003, USA
[73]Massachusets Institute of Technology, Cambridge, MA 02139, USA

[74]McMaster University, Hamilton, ON, L8S4L8 Canada
[75]University of Michigan, Ann Arbor, MI 48109, USA
[76]Michigan State University, East Lansing, MI 48824-1045, USA
[77]University of Minnesota, Duluth, MN 55812, USA
[78]University of Minnesota, Minneapolis, MN 55455, USA
[79]University of Mississippi, University, MS 38677, USA
[80]Max-Planck-Institut, Munich, Germany
[81]Technical University of Munich, Munich, Germany
[82]Muons, Inc., Batavia, IL 60510, USA
[83]National Academies-National Research Council, Washington DC 20001, USA
[84]National Institute of Standards and Technology, Gaithersburg, MD 20899-1070, USA
[85]National Science Foundation, Arlington, VA 22230, USA
[86]University of Nebraska, Lincoln, NE 68588-0299, USA
[87]New York University, New York, NY 10012, USA
[88]University of North Carolina, Chapel Hill, NC 27599, USA
[89]North Carolina A&T State University, Greensboro, NC 27411, USA
[90]North Carolina State University, Raleigh NC 27603, USA
[91]Northeastern University, Boston, MA 02115, USA
[92]Northern Illinois University, Dekalb, IL 60115, USA
[93]Northwestern University, Evanston, IL 60208 USA
[94]University of Notre Dame, Notre Dame, IN 46556, USA
[95]Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[96]Ohio State University, Columbos, OH 43210, USA
[97]Oklahoma State University, Stillwater, OK 74078, USA
[98]Osaka University, Osaka, Japan
[99]University of Oxford, Oxford, OX1 3RH, United Kingdom
[100]Pacific Northwest National Laboratory, Richland, WA 99352, USA
[101]Panjab University, Chandigarh, India
[102]University of Patras, Patras, Greece
[103]Paul Scherrer Institut, Switzerland
[104]University of Pennsylvania, Philadelphia, PA 19104, USA
[105]Pennsylvania State University, University Park, PA 16802, USA
[106]Perimeter Institute for Theoretical Physics, Waterloo, ON N2L 2Y5, Canada
[107]University of Pittsburgh, Pittsburgh, PA 15260, USA
[108]Pontificia Universidad Católica del Perú, Lima, Perú
[109]Portland Physics Institute, Portland, OR 97201, USA
[110]Princeton University, Princeton, NJ 08544, USA
[111]Institute for Advanced Study, Princeton, NJ 08540, USA
[112]Queen Mary University of London, London, E1 4NS, United Kingdom
[113]University of Rochester, Rochester, NY, 14627, USA
[114]Rutgers University, New Brunswick, NJ 08901, USA
[115]CEA Saclay, Gif-sur-Yvette, France
[116]Universidade de São Paulo, São Paulo, Brazil
[117]SLAC National Accelerator Laboratory, Menlo Park CA 94025, USA
[118]SNOLAB, Lively, ON P3Y 1N2, Canada
[119]University of South Carolina, Columbia, SC 29208, USA
[120]Southern Methodists University, Dallas, TX, USA
[121]Stanford University, Stanford, CA 94305 USA
[122]Stony Brook University, Stony Brook, NY 11794, USA

[123]University of Sussex, Brighton, BN1 9RH, United Kingdom
[124]Syracuse University, Syracuse, NY, 13244-5040, USA
[125]University of Tennessee, Konxville, TN 37996-1200, USA
[126]University of Texas, Austin, TX 78712-0587, USA
[127]Texas A&M University, College Station, TX 77843-4242, USA
[128]University of Tokyo, Tokyo Japan
[129]TRIUMF, Vancouver, BC V6T 2A3, Canada
[130]Universitat Tübigen, Tübingen, 07071 29-0 Germany
[131]Tufts University, Medford, MA 02155, USA
[132]US Department of Energy, Office of High Energy Physics, Washington DC 20585, USA
[133]University of Victoria, Victoria, BC V8N 1M5, Canada
[134]University of Vienna, Vienna, 01 42770 Austria
[135]University of Virginia, Charlottesville, VA 22904-4714, USA
[136]Virginia Tech, Blacksburg, VA 24061, USA
[137]University of Warwick, Coventry, CV4 7AL United Kingdom
[138]University of Washington, Seattle, WA, 98195 USA
[139]George Washington University, Washington, DC 20052, USA
[140]Wayne State University, Detroit, MI, 48202, USA
[141]Weizmann Institute of Science, Rehovot 76100, Israel
[142]University of Western Australia, Crawley, Western Australia 6009, Australia
[143]College of William and Mary, Williamsburg, VA 23187-8795, USA
[144]University of Winnipeg, Winnipeg, MB R3B 2E9, Canada
[145]University of Wisconsin, Madison, WI 53706, USA
[146]Wroclaw University, Wroclaw Poland
[147]University Würzburg, Würzburg, Germany
[148]Yale University, New Haven, CT 06511-8962, USA
[149]Universidad de Zaragoza, Zaragoza, Spain

Executive Summary

Particle physics aims to understand the universe around us. The Standard Model of particle physics describes the basic structure of matter and forces, to the extent we have been able to probe thus far. However, it leaves some big questions unanswered. Some are within the Standard Model itself, such as why there are so many fundamental particles and why they have different masses. In other cases, the Standard Model simply fails to explain some phenomena, such as the observed matter-antimatter asymmetry in the universe, the existence of dark matter and dark energy, and the mechanism that reconciles gravity with quantum mechanics. These gaps lead us to conclude that the universe must contain new and unexplored elements of Nature. Most of particle and nuclear physics is directed towards discovering and understanding these new laws of physics.

These questions are best pursued with a variety of approaches, rather than with a single experiment or technique. Particle physics uses three basic approaches, often characterized as exploration along the cosmic, energy, and intensity frontiers. Each employs different tools and techniques, but they ultimately address the same fundamental questions. This allows a multi-pronged approach where attacking basic questions from different angles furthers knowledge and provides deeper answers, so that the whole is more than a sum of the parts. A coherent picture or underlying theoretical model can more easily emerge, to be proven correct or not.

The intensity frontier explores fundamental physics with intense sources and ultra-sensitive, sometimes massive detectors. It encompasses searches for extremely rare processes and for tiny deviations from Standard Model expectations. Intensity frontier experiments use precision measurements to probe quantum effects. They typically investigate new laws of physics, at energies higher than the kinematic reach of high energy particle accelerators. The science addresses basic questions, such as: Are there new sources of CP violation? Is there CP violation in the leptonic sector? Are neutrinos their own antiparticles? Do the forces unify? Is there a weakly coupled hidden sector that is related to dark matter? Are there undiscovered symmetries?

To identify the most compelling science opportunities in this area, the workshop *Fundamental Physics at the Intensity Frontier* was held in December 2011, sponsored by the Office of High Energy Physics in the US Department of Energy Office of Science. Participants investigated the most promising experiments to exploit these opportunities and described the knowledge that can be gained from such a program. The workshop generated much interest in the community, as witnessed by the large and energetic participation by a broad spectrum of scientists. This document chronicles the activities of the workshop, with contributions by more than 450 authors.

The workshop organized the intensity frontier science program along six topics that formed the basis for working groups: experiments that probe (*i*) heavy quarks, (*ii*) charged leptons, (*iii*) neutrinos, (*iv*) proton decay, (*v*) light, weakly interacting particles, and (*vi*) nucleons, nuclei, and atoms. The conveners for each working group included an experimenter and a theorist working in the field and an observer from the community at large. The working groups began their efforts well in advance of the workshop, holding regular meetings and soliciting written contributions.

Specific avenues of exploration were identified by each working group. Experiments that study rare strange, charm, and bottom meson decays provide a broad program of measurements that are sensitive to new laws of physics. Charged leptons, particularly muons and taus, provide a precise probe for new physics because the Standard Model predictions for their properties are very accurate. Research at the intensity frontier can reveal CP violation in the lepton sector, and elucidate whether neutrinos are their own antiparticles. A very weakly coupled hidden-sector that may comprise the dark matter in the universe could be discovered. The search for proton decay can probe the unification of the forces with unprecedented reach and test sacrosanct symmetries. Detecting an electric dipole moment for the neutron, or neutral atoms, could establish a clear signal for new physics, while limits on such a measurement would place severe constraints on many new theories.

This workshop marked the first instance where discussion of these diverse programs was held under one roof. As a result, it was realized that this broad effort has many connections; a large degree of synergy exists between the different areas and they address similar questions. Results from one area were found to be pertinent to experiments in another domain. For example, participants identified several avenues for exploring new physics that could account for the matter-antimatter asymmetry of the universe, and it is the combination of results that could provide the ultimate explanation. The workshop also revealed many synergies between the intensity frontier and the energy and cosmic frontiers. The three frontiers are closely linked, with much overlap in the physics they can discover and interpret. A clear conclusion of the workshop is that intensity frontier experiments constitute an integral and crucial part of a balanced experimental program in particle and nuclear physics. It is rich with outstanding science opportunities that have the potential to change paradigms.

The workshop identified the facilities required to do intensity frontier science. Experiments that can be performed this decade with current or planned facilities were described, as well as those proposed for the next decade that require new facilities or technology to reach their full potential. Some emphasis was placed on experiments that could produce data by the end of this decade. It is clear that the intensity frontier will move the field forward substantially this decade. For example, the recent determination that the remaining mixing angle in the neutrino sector is large, opens the possibility that detectors planned to start construction soon can make measurements that address fundamental questions about neutrinos and the universe. Likewise, several experiments searching for the neutron electric dipole moment will start this year and are expected to advance the field. Muon experiments planned for later this decade will allow for an improvement over current results by roughly four orders of magnitude. this decade, new heavy quark facilities have the potential to search beyond the reach of the Large Hadron Collider this decade. For the next decade, proposals for new experiments and facilities with more intense beams and more sensitive detectors are already under consideration, and will provide a large step forward. This document compares the science reach of these facilities to the reach of others around the globe, new and old, that propose to house similar programs. The result is a challenging, interconnected, and essential science program covered by the intensity frontier.

The vibrancy of the workshop reflected the enthusiasm of the community for intensity frontier physics. Since the workshop addressed all aspects of the intensity frontier, participants were forced to look across traditional boundaries and become aware of the intensity science program as a whole. It was realized that there is a strong intensity frontier community that has common physics interests and is addressing fundamental questions. It is important for the future of the field that broad workshops such as this continue. In this way members of the intensity frontier community can continue to learn from each other and see how their program contributes to our understanding of the universe.

We hope this report provides valuable input into strategic decision-making processes in the United States and elsewhere, and contributes to establishing a worldwide intensity frontier program to which the US contributes in a major and competitive way. The workshop confirmed that the proposed facilities and experiments will position the US as a global leader in intensity frontier science.

U.S. DEPARTMENT OF ENERGY | Office of Science

science.energy.gov