BEACONS OF DISCOVERY

THE WORLDWIDE SCIENCE OF PARTICLE PHYSICS
The Worldwide Science of Particle Physics

The Super Kamiokande neutrino detector in Kamioka, Japan. Photo courtesy of Kamioka Observatory, ICRR, University of Tokyo
To discover what our world is made of and how it works at the most fundamental level is the challenge of particle physics. The tools of particle physics—experiments at particle accelerators and underground laboratories, together with observations of space—bring opportunities for discovery never before within reach. Thousands of scientists from universities and laboratories around the world collaborate to design, build and use unique detectors and accelerators to explore the fundamental physics of matter, energy, space and time. Together, in a common world-wide program of discovery, they provide a deep understanding of the world around us and countless benefits to society. *Beacons of Discovery* presents a vision of the global science of particle physics at the dawn of a new light on the mystery and beauty of the universe.
BEACONS OF DISCOVERY

The Globe at CERN. Photo: Maximilien Brice, Claudia Marcelloni, CERN
A global vision

Deep in our human nature is the drive to understand the world around us. From stone tools to powerful computers, from the simplest observations of the natural world to today’s advanced science and technology, the exploration and creation of knowledge have drawn us forward and transformed our existence.

Yet even now, with all the advances we have made, we have a dramatic lack of understanding of the basic physical laws that govern our universe. Profound questions, sounding almost theological in nature, both bedevil and inspire us. The answers to at least some of these questions now appear to be on the horizon, as the world of particle physics comes together to make use of the most powerful set of scientific tools ever assembled. Will a grand synthesis emerge, as in the case of quantum mechanics in the early 20th century, to resolve all these mysteries in a revolutionary new framework? Or will we encounter yet more fundamental questions behind the ones we know today, beacons to more distant horizons?

The precision operations of the hugely complex detectors built for CERN’s Large Hadron Collider in Switzerland seem almost miraculous when we remember that scientists from institutes in dozens of countries designed, built and contributed the thousands of different detector components. The pieces must fit together perfectly to operate flawlessly, recording the data from tens of millions of particle collisions every second. How can over one hundred institutes and three thousand physicists, spread across the globe, achieve such precision on such a grand scale? How can physicists make the hard-fought decisions that determine design and technology choices and then move forward together? Ultimately, a shared and passionate vision is the beacon that draws collaborators together in a common purpose to create a scientific instrument of unprecedented power and precision.

Beacons of Discovery takes the next step in articulating just such a global vision for the future of particle physics. Reaching a grand synthesis or discovering the next set of mysteries will require a spectrum of research approaches in nations around the world. To take us beyond the horizon that we see today, physicists will use accelerators that reach the highest energies and produce new particles directly. They will design accelerators with the most intense beams to study the rare interactions that carry the imprints of worlds beyond our direct reach. And they will use observatories of natural processes deep underground, on the earth’s surface and in space. Achieving a grand synthesis will require all of these technologies. Our worldwide physics community has reached remarkable consensus on how to proceed. Just as a passionate and shared scientific vision brings the detector components together in a beautifully functioning whole, Beacons of Discovery shows how that same passion and vision draw us together in a shared global journey to discover the fundamental nature of matter, energy, space and time.

Pier Oddone
Chair elect, ICFA
Chair, ICFA writing committee

Autumn 2011
WHAT DO WE KNOW?
This much we know.

That the universe is vast and bounded only by the limitless confines of space and time. That particles of matter fill this space and time, and that forces bring structure to it all. This much we know.

The science of particle physics explores the relationship between space, time, matter and forces. Its ambition is no less than to illuminate our world and the universe we inhabit at the most fundamental level. Particle physics, the science of the very small, teams up with cosmology, the science of the very large, using observation and experiment to navigate the undiscovered universe from the vast extremes of space to the tiniest particles.

Looking out into space, we observe that at the largest scales, matter is organized into structures like galaxies. Studying the world around us, we find that at smaller scales, it is organized into stars, planets, people and atoms. And using the tools of particle physics to look deep into inner space, we discover the nuclei of atoms and the fundamental particles and forces that are the building blocks of everything.

Particle physics experiments have shown that, at the most basic level, all the variety of matter that we see around us, from the flowers in the field to the stars in the sky, consists of just a handful of fundamental particles and four forces acting among them. It’s a simple and elegant picture. At the largest scales, the force of gravity is master, corralling matter into beautiful swirling galaxies. Stars, planets, people and atoms dance to the tune of electromagnetism, which holds electrons in orbit around atomic nuclei and gives structure to everything we see. At the smallest scales, nuclear forces, strong and weak, take over. The strong force binds nuclei together, while the weak force drives the stellar furnaces that bring light and energy to us all.

A centuries-long journey of discovery has shown us that the Earth is round, that apples fall from trees for the same reason that Earth orbits the sun, that we can master natural phenomena like electricity and magnetism to the benefit of all. Particle physics and cosmology beckon us onward in the next phase of our journey.

Advances in these fields have let us voyage back in time to the point when the universe became transparent. We have witnessed the birth of the first galaxies and the ignition of the first stars. By studying fundamental particles, we have pieced together a detailed understanding of particles and forces. Along the way we have fostered new technologies in fields as diverse as medicine and information technology.

This much we know. But there’s one more thing our research has told us: we have much more to learn.
TWENTY-FIRST CENTURY QUESTIONS

Theory and experiment combine to address the fundamental questions of particle physics. Photo: Reidar Hahn, Fermilab
What message do neutrinos bring from the beginning of time?

When matter and antimatter meet, they annihilate in a puff of energy. At the birth of the universe, such puffs of energy should have produced particles and antiparticles in equal numbers. Yet somehow we live in a universe made entirely of matter. Could neutrinos, tiny particles permeating the universe, be responsible? Are neutrinos the reason we exist? The race is on to find out, using neutrino beams as well as neutrinos from reactors, the atmosphere and the sun.

Bonnie Fleming, Yale University/Fermilab, USA

What’s the matter with antimatter?

Matter consists of elementary particles such as the electron and proton. Every particle has its antiparticle. Together, the antiparticles compose antimatter. Strikingly, the observable universe is exclusively dominated by matter rather than antimatter, posing one of the greatest puzzles in physics: where’s the antimatter? Experimentalists at CERN, Fermilab, KEK and SLAC are producing antimatter in accelerators and studying its subtle differences from matter to illuminate the startling absence of antimatter in the universe.

Hong-Jian He, Tsinghua University, China

How can we solve the mystery of dark energy?

Observations of light emitted near the horizon of the universe reveal that everything seems to be flying apart with increasing velocity. Big Bang cosmology attributes this to “dark energy” that fills the entire universe—an amazing phenomenon! Is the Big Bang model too simple? Should Einstein’s equations be modified? Is there an unknown fundamental force? As the answers emerge, I expect that in the next decade physicists will solve the mystery of dark energy.

Wilfried Buchmueller, DESY, Germany
Are we on the threshold of a whole new understanding of nature’s particles and forces?

Is there an invisible force that swarms around matter to give it mass? Finding Higgs particles and studying their properties can tell us the answer. The Higgs holds secrets about how the forces of nature are related to each other, how matter became matter, and what is the origin of the atomic scale that makes life possible.

Joe Lykken, Fermilab, USA

What is the trajectory of our universe? How did it evolve?

Einstein’s theory tells us the universe must expand. We believe that everything started with the big bang from a single point, and indeed, we can observe that the distance between the galaxies is increasing. How did energy, matter and forces in the early universe influence how our universe is expanding today? Experiments at the Large Hadron Collider and observations of particles around us will help to solve the mystery of the evolution of the universe.

Mihoko Nojiri, KEK, Japan

Do invisible processes leave their imprint on the world we can observe?

Besides directly seeing new particles, physicists look for traces of exotic phenomena that may lurk unseen in experiments. These rare but crucial processes can leave traces of their existence in seemingly ordinary data and observations. For example, physicists inferred the W boson’s existence from observations of radioactive nuclear decay that heralded the particle’s existence 80 years before experimenters observed it directly. What patterns in today’s experiments will herald the next breakthrough?

Doug Bryman, University of British Columbia/TRIUMF Laboratory, Canada
What is dark matter?

Ordinary matter accounts for only five percent of the total inventory of the universe. From observing the rotational velocities of visible objects in the galaxies, cosmologists have “weighed” about 21 to 23 percent of the total energy of the universe as formed by invisible matter, called dark matter. The most attractive explanation postulates that dark matter is made of yet-undiscovered massive particles interacting very weakly with ordinary matter.

Lucia Votano, Laboratori Nazionali del Gran Sasso, Italy

Are there extra dimensions of space?

We all thought we lived in a universe with three dimensions of space. But to come up with a unified theory of all forces, a feat that even Einstein couldn’t accomplish, some modern-day physicists propose a whopping six more dimensions to the universe, curled up in such small sizes that so far we can’t see them.

Hitoshi Murayama, Institute for the Physics and Mathematics of the Universe, Japan

Is there a simple explanation for it all?

Probably not. “It all” should include the origin of space and time, as well as the basic properties of all known elementary constituents of matter, all emerging out of a more basic conceptual substratum. If there are large extra dimensions accessible to the LHC, today’s experiments could address these questions. Perhaps the ultimate reductionist dream can be realized.

Luis Alvarez-Gaume, CERN, Switzerland
The intricate tracking chamber of a particle detector at the research center DESY in Germany. Photo: Satoru Yoshioka, Japan
What does it take to know?

At laboratories around the world, experiments bring physicists together to address 21st-century questions.

To study nature’s smallest, simplest particles, physicists use the largest, most complex scientific instruments on earth. Accelerators, measured in miles or kilometers, create intense, high-energy particle beams. Detectors the size of cathedrals track particle interactions by the billions and trillions. Vast computing power records, stores and distributes the data from these interactions to thousands of physicists in experiment collaborations that span the globe.

Particle astrophysics uses the cosmos as a laboratory to probe the fundamental laws of physics in ways that complement accelerator-based experiments. The deep and beautiful connection between inner space and outer space enables us to uncover new particle physics through astrophysical observations.

These unique technologies, breathtaking in their scale and complexity, combine their complementary strengths and capabilities to form a single scientific enterprise. The tools of particle physics are beacons that draw scientists together in laboratories around the world in a common search for answers to the defining questions of 21st-century particle physics.
High energy

At the energy frontier, particle beams accelerated to ultra-high energy collide inside giant particle detectors. From the collision energy emerge particles that have not existed since the earliest moments of the universe. The detectors record the results of millions of collisions each second, and powerful computing grids distribute the collision data to collaborating physicists around the world for analysis—and for discoveries that illuminate the fundamental nature of the world around us.
Above: Seen during construction, the toroidal magnet system of the ATLAS particle detector dwarfs the person standing in the foreground. ATLAS was built and is operated by a global collaboration of around 3000 scientists working at universities and institutes in 38 countries. One of the most complex scientific instruments ever built, its 100 million readout channels record data that physicists are analyzing in search of new physics.

Above: At KEK in Japan, accelerator experts test advanced superconducting radiofrequency technology, under development for the proposed International Linear Collider. The technology combines efforts and components from DESY (Germany), INFN Milano-LASA (Italy), KEK (Japan), Fermilab and SLAC (US).

• Right: Particle collisions in CERN’s Large Hadron Collider produce beautiful images such as this one, recorded in the CMS particle detector. The initial collision gave rise to new particles, which in turn left these tracks in the detector. By analyzing millions of collisions like these, CMS’s global community of scientists are seeking out new phenomena.

TO STUDY NATURE’S SMALLEST, SIMPLEST PARTICLES, PHYSICISTS USE THE LARGEST, MOST COMPLEX SCIENTIFIC INSTRUMENTS ON EARTH.
High intensity

Physicists use intense accelerated beams, packed with the highest possible number of particles, to explore neutrino interactions and search for nature’s rarest processes. Neutrino mysteries lie at the heart of 21st-century particle physics. Ultra-rare processes open doorways to realms of energy far beyond those that we can reach directly in colliders, putting us further along the path to where physicists theorize that all of nature’s forces become one.

Cosmic laboratory

Astrophysicists use the cosmos as a laboratory to complement experiments at particle accelerators. Astrophysical observations reveal a universe made mostly of dark matter and dark energy. A combination of underground experiments and ground- and space-based telescopes explores these dark phenomena.
The Tools of Particle Physics are Beacons That Draw Scientists Together in a Common Quest to Discover the Fundamental Nature of Matter and Energy, Space and Time.

Far left: To discover the fundamental properties of neutrinos, the proposed Long Baseline Neutrino Experiment would send a beam of neutrinos from Fermilab to a detector some 800 miles away. Left: A bird’s eye view of KEK, a particle physics laboratory in Japan. KEK plans to upgrade its existing KEKB accelerator to SuperKEKB, aiming for a 40-fold increase in particle collisions.

Directly below: Italy’s Istituto Nazionale di Fisica Nucleare will construct the SuperB Factory at the University of Rome “Tor Vergata” to cast light on central questions of contemporary physics, including the disappearance of antimatter. Below, right: J-PARC’s main ring, a synchrotron accelerator in Japan with a maximum energy of 50 GeV.

The near detector for the NOvA experiment, beginning in 2013, NOvA will explore the strange properties of neutrinos using a particle beam that travels from Fermilab to a detector 500 miles away.
From the earliest days of high-energy physics in the 1930s to the latest 21st-century experiments, the bold and innovative ideas and technologies of particle physics have entered the mainstream of society to transform the way we live.

CASE STUDY

Particle physics and medical imaging

The time is the mid-1970s, and the medical profession has come up with a new concept for imaging brain metabolism. The idea sounds like science fiction: by arranging for antimatter to annihilate harmlessly in the body, producing photons detectable outside the body, doctors could trace brain function with a precision never before imaginable. How to turn this dream into reality? Step forward the particle physics community.

Detecting photons is all in a day’s work for particle physicists, so it was natural for the two communities to team up to produce some of the first positron emission tomography, or PET, scanners. A collaboration between CERN and Geneva’s University Hospital did just that, delivering a new diagnostic tool to the hospital while also developing powerful research techniques.

Fast forward one decade. A new generation of particle physics experiments develops a new generation of photon detectors, building on the work of academia and industry. These “scintillating crystals” have spurred advances in particle physics. And a new generation of PET scanners.

Take another 10-year leap. Scintillating crystal technology is still advancing, but more importantly a big collaboration preparing for physics at the LHC decides to use crystals inside a powerful magnetic field. The requisite electronics do not exist, so the collaboration teams up with industry to make it. Result: a yet-more-powerful tool for basic research and an opportunity for the medical imaging industry to develop a scanner combining the complementary techniques of PET and magnetic resonance imaging, MRI. Our final leap forward through time brings us to the present day, when clinical trials of such a device are now under way.

This case study, one of many, illuminates the circle linking basic research and society. The needs of science drive innovation, which fuels industry, which delivers more powerful tools to basic research. This long-term relationship, nurtured over decades, has a proven track record of delivering knowledge and innovation.

PET imaging uses accelerator-produced isotopes to provide information about dopamine’s function in the brain. The images show the concentration of living dopamine-producing cells; warmer colors represent a higher concentration of these cells. Comparing images of a healthy subject (left) and a subject with Parkinson’s disease (right), shows a decrease in PET signal (red color) in the diseased brain. This non-invasive, real-time functional brain imaging arose from particle physics and brings together physicists, chemists and biologists. Images courtesy of TRIUMF and the Pacific Parkinson’s Research Centre.
“I need highly automated, reliable, and efficient synchrotron beamlines for the fast 3-D atomic structure determinations of candidate pharmaceuticals in order to design effective drugs.”

Lisa Keefe, Industrial Macromolecular Crystallography Association

Ultra-brilliant x-rays from particle accelerators called synchrotron light sources illuminate every aspect of the material world, from the inner workings of cells to the molecular structure of new and more effective drugs to prevent and treat disease. Particle accelerators as imaging tools have sped the development of next-generation antibiotics as well as pharmaceuticals to fight HIV virus, cancer and diabetes.

“I need a battery that will store energy more efficiently.”

Jun Sugiyama, Toyota Central R&D Labs, Inc.

In high-performance batteries, the key issue is to study and control the movement of ions in materials, particularly at the interface between the electrode and electrolyte. Techniques from particle physics, including muon-spin spectroscopy and magnetic-resonance imaging using implanted isotopes, provide unique information on ion diffusion in solids and at interfaces.
“I need talented and motivated young people that thrive in a globally competitive environment.”
Richard Eppich, President, ACSI, Inc.

The fascinating questions at the heart of particle physics, along with its scientific and technical challenge, attract talented young people to science. The intense competition and close collaboration that characterize the field develop a talent for teamwork that is critical for success in a globally competitive environment. By its nature as a multinational field that combines fundamental physics, engineering and computer science, particle physics trains students to think across disciplines and work in creative and unorthodox ways to pursue the science that drives and inspires them.

“I can go from 1 to 1000—what I need is help in going from 0 to 1.”
Hideaki Omiya, President of Mitsubishi Heavy Industry

The passion to discover the secrets of the universe opens eyes and minds to revolutionary ideas and transformative technologies. The drive for discovery pushes science and technology past conventional limits and in uncharted directions, challenging us to look beyond incremental improvements to breakthroughs that open the pathway from zero to one.

“I need a safe and secure method to treat radioactive waste.”
Dame Sue Ion, Fellow, Royal Academy of Engineering/ Visiting Professor, Imperial College London

Containment, storage and safeguarding of long-lived radioactive components from spent nuclear fuel and nuclear waste present a major challenge. New technologies from particle accelerators and nuclear physics may have an answer: treating the materials with particle beams to literally transform them into safer substances with shorter lives for easier disposal and even recycling.

“Where does all the matter in the universe come from?”
Antoine, 14, student from Prevessin, France

The truth of the matter is we don’t know, but it’s vitally important that humankind continues to ask questions like these, and that young people the world over continue to be inspired by them. It is through seeking the answers that we progress, and it is through attracting young people to science that we ensure the means to progress.
“We need globally coordinated investment in basic science for globally applicable return.”

Massimo Marino, former director, World Economic Forum

Science emerged as a truly global human endeavor well before economic globalization, and particle physics has always been in the vanguard. Today’s basic research in the field would be impossible without deep-rooted collaboration on a global scale. This globally coordinated investment in basic science brings returns in terms of science, innovation and knowledge that are globally applicable. By working together, we generate solutions that work for all of us.

“I need sharp, clear images of the cancer activity in the body.”

Rene Laugier, MD, La Timone Hospital, Marseilles/project coordinator, EndoTOFPET_US

Our understanding of quarks, proton, neutrons, and nuclei has given physicists the ability to use unstable atoms to trace, identify, and increasingly implement therapy inside the human body. Biology tells us what is happening within the body and particle physics helps us develop new combinations of nuclear physics and radiochemistry to make pharmaceuticals that can diagnose and treat cancer inside the body.

“We need to inspect the inside of cultural properties nondestructively.”

Makoto Ozaki, Conservator, Gangoji Institute for Research of Cultural Property

Sometimes we need to see something without touching it. Particle physics provides a range of solutions to this challenge. Intense x-rays from light sources and intense beams of neutrons have allowed cultural anthropologists to study the chemistry, physical structure and detailed aging of cultural relics without destroying them, and with results that change our understanding of history.

“We need to improve the safety of artificial heart valves.”

Gwyn Jenkins, MD, Alabama A&M University

The interface of any material with its environment consists of particles, whether atoms, ions or molecules. Particle beams can modify the surface of a material to alter its interactions with the environment. Modifying the material for artificial heart valves by bombardment with silver ions from a particle accelerator makes them better tolerated by the body and therefore safer and longer lasting.
“What science will my grandchildren learn at school that the smartest physicists in the world don’t know today? If we don’t encourage discovery, they will use the same book I had.”

Tim Klaus, Fermilab Community Task Force

A bright future for our grandchildren depends on scientific progress across the spectrum from the most basic discoveries to the application of advanced technologies. Advances in science and technology have the potential to transform the future of our planet by addressing critical challenges: energy, the environment, health care and a strong and sustainable global economy. Scientists and engineers trained in the most modern science and technologies and with access to the best research tools will rewrite the science books, not only revolutionizing our understanding of nature’s laws but changing the world our grandchildren inherit.

“I need exciting science that inspires and motivates my students.”

Becky Parker, physics teacher, Simon Langton School, UK

Particle physics research is a journey of exploration into the mystery and beauty of the universe, asking fascinating questions that inspire wonder and dreams. Involving science teachers directly in the programs of major physics laboratories connects them with the excitement of research and helps them catalyze the interest of young people in today’s revolutionary science of particle physics.

“Particle accelerators will soon become important tools to lower the barriers to the growth of nuclear energy and expand its potential through the use of thorium in addition to uranium.”

Anil Kakodkar, former Secretary of the Department of Atomic Energy in India, now chairman of IIT Mumbai

To meet rapidly growing demand for energy and preserve the environment for coming generations, future energy sources must be abundant, safe, clean and economical. Incorporating innovative accelerator technologies into tomorrow’s nuclear energy supply has the potential to make nuclear power safer and cleaner with far less nuclear waste. Accelerators can drive next-generation reactors that burn non-fissile fuel, such as thorium, that can be burned with the use of particle beams.

“I need a device to understand the structure and properties of the Earth’s deep interior.”

Takehiko Yagi, Professor, Department of Earth and Material Science, University of Tokyo

Particles can carry secrets over distances—secrets of the atom, secrets of the universe or secrets of how the Earth is geologically evolving. Japan’s Super-Kamiokande experiment recently used neutrinos to look at the structure of the earth in a whole new “light.” Cosmic rays—particles from space—provide another new means to visualize the Earth’s interior.
BEACONS OF INTERNATIONAL COLLABORATION
Across all borders

The unique scientific opportunities and challenges of particle physics inspire and motivate men and women of science from every corner of the globe. A shared scientific vision draws particle physicists of hundreds of nationalities and cultures together in large collaborations to work together on experiments and projects at the horizons of discovery. Because the scale and complexity of the tools of particle physics put them beyond the reach of any single nation or region, particle physics projects now take shape as international collaborations from the outset.

A simultaneous spirit of lively competition and true collaboration characterizes the worldwide particle physics community. Physicists devote intense effort, over many years, to making their experiment, their laboratory, their nation the first to announce a key discovery. At the same time, they team up with colleagues in competing experiments, at other laboratories in other nations, contributing their best efforts to success in advancing the science that is their common passion.

For decades, strong international collaborations have designed and built particle detectors for experiments in laboratories worldwide. Today, accelerator design and construction increasingly proceed as joint efforts as well.

These scientific collaborations take on added significance as beacons for free and open interaction among scientists of all nations. They offer an enduring model for international cooperation from a field long known for its leadership in peaceful collaboration across all borders.

THESE SCIENTIFIC COLLABORATIONS TAKE ON ADDED SIGNIFICANCE AS BEACONS FOR FREE AND OPEN INTERACTION AMONG SCIENTISTS OF ALL NATIONS. THEY OFFER AN ENDURING MODEL FOR INTERNATIONAL COOPERATION.
INTERNATIONAL COMMITTEE FOR FUTURE ACCELERATORS
ICFA

The International Committee for Future Accelerators was created to facilitate international collaboration in the construction and use of accelerators for high energy physics. It was created in 1976 by the International Union of Pure and Applied Physics. Its purposes, as stated in 1985, are as follows:

• To promote international collaboration in all phases of the construction and exploitation of very high energy accelerators.
• To organize regular world-inclusive meetings for the exchange of information on future plans for regional facilities and for the formulation of advice on joint studies and uses.
• To organize workshops for the study of problems related to super high-energy accelerator complexes and their international exploitation and to foster research and development of necessary technology.

The Committee has sixteen members, selected primarily from the regions most deeply involved in high energy physics.

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Atsuto Suzuki, director of KEK Laboratory, ICFA chair. Photo: Cindy Arnold, Fermilab
Tim Berners-Lee, a scientist at CERN, invented the World Wide Web in 1989. The Web was originally conceived and developed to meet the demand for automatic information sharing among particle physicists working in different universities and institutes all over the world.