

DISCOVERING THE QUANTUM UNIVERSE

THE ROLE OF PARTICLE COLLIDERS

DOE / NSF

HIGH ENERGY PHYSICS ADVISORY PANEL



Nine key questions define the field of particle physics.

EINSTEIN'S DREAM OF

UNIFIED FORCES

1 ARE THERE UNDISCOVERED PRINCIPLES OF NATURE: NEW SYMMETRIES, NEW PHYSICAL LAWS?

2 HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY?

3 ARE THERE EXTRA DIMENSIONS OF SPACE?

4 DO ALL THE FORCES BECOME ONE?

THE PARTICLE WORLD

5 WHY ARE THERE SO MANY KINDS OF PARTICLES?

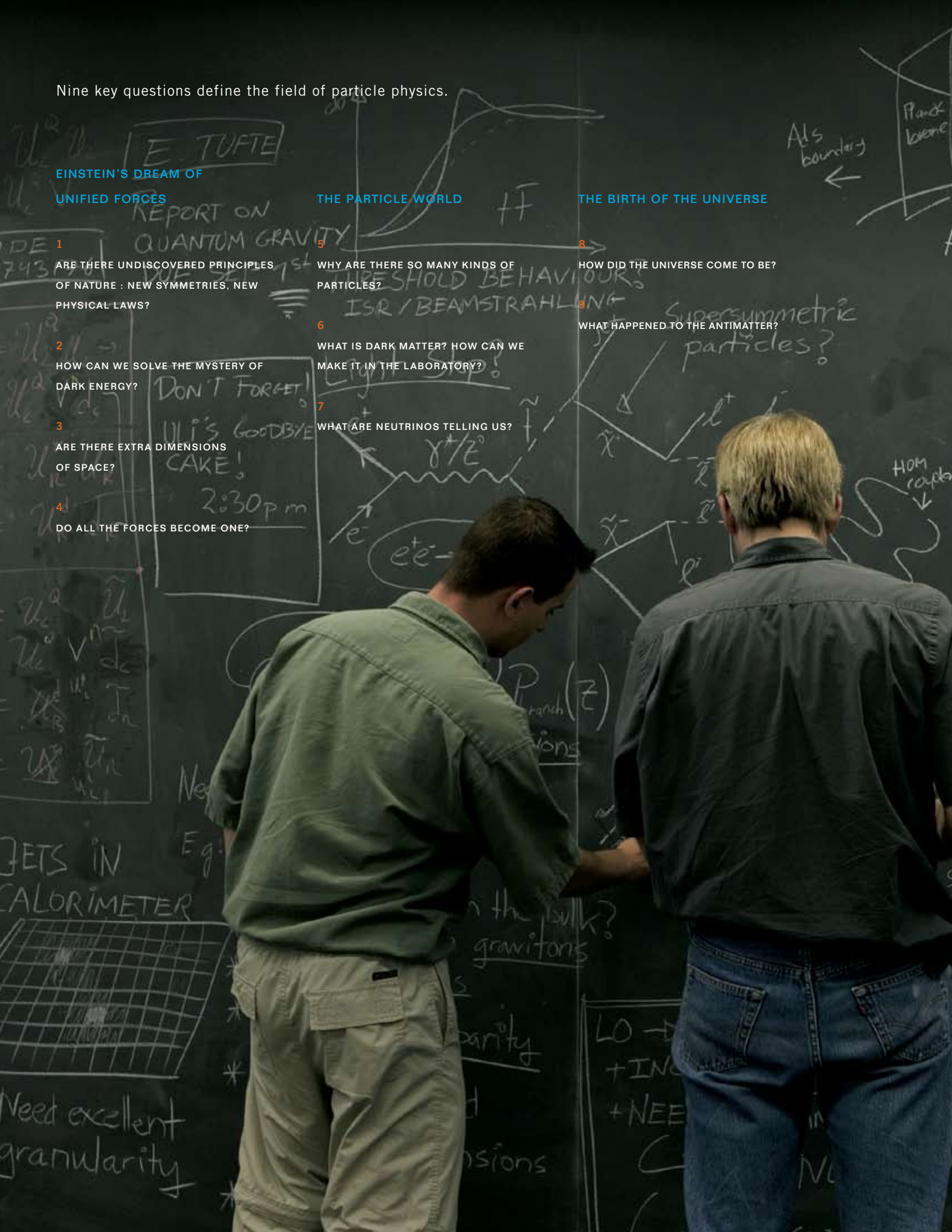
6 WHAT IS DARK MATTER? HOW CAN WE MAKE IT IN THE LABORATORY?

7 WHAT ARE NEUTRINOS TELLING US?

THE BIRTH OF THE UNIVERSE

8 HOW DID THE UNIVERSE COME TO BE?

9 WHAT HAPPENED TO THE ANTIMATTER?

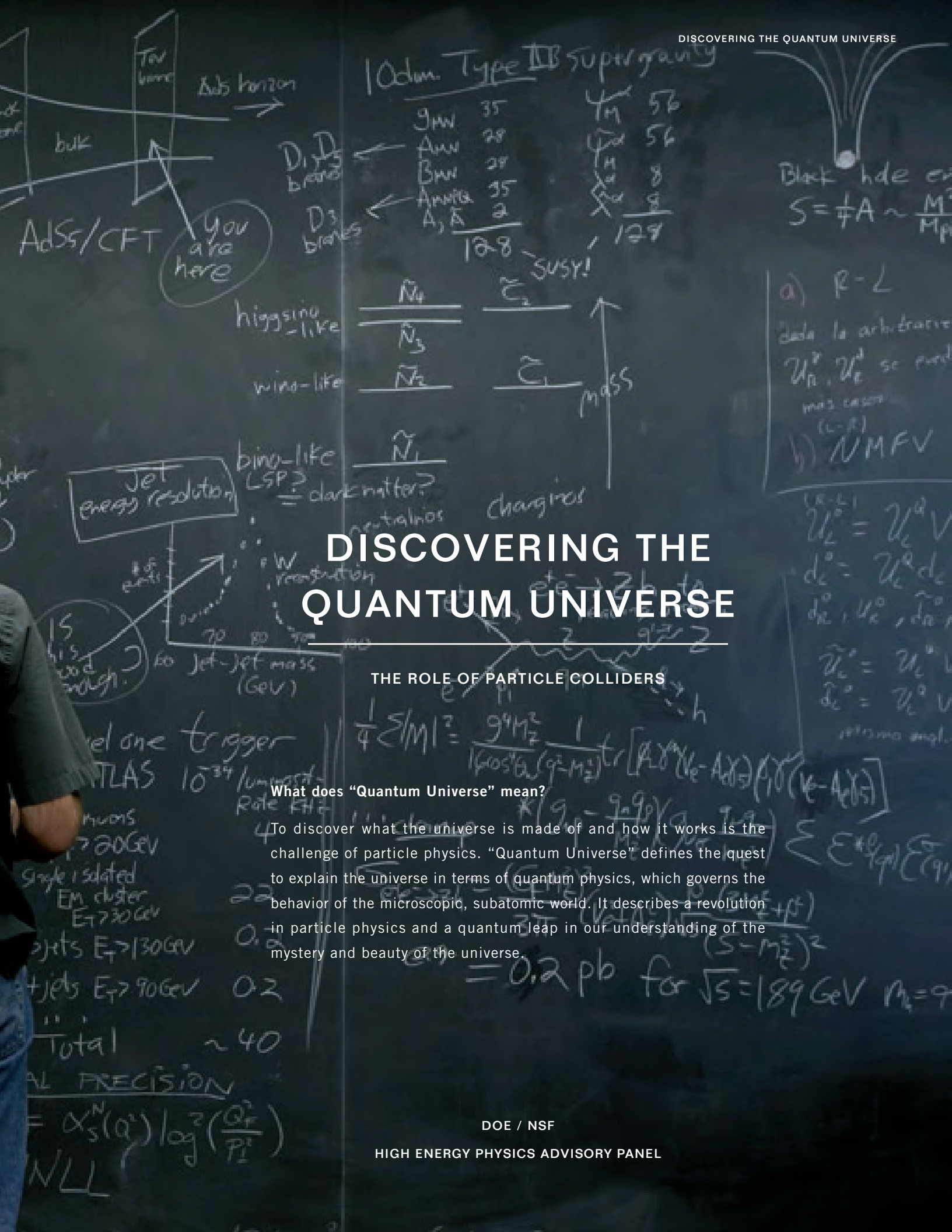


DISCOVERING THE QUANTUM UNIVERSE

THE ROLE OF PARTICLE COLLIDERS

What does "Quantum Universe" mean?

To discover what the universe is made of and how it works is the challenge of particle physics. "Quantum Universe" defines the quest to explain the universe in terms of quantum physics, which governs the behavior of the microscopic, subatomic world. It describes a revolution in particle physics and a quantum leap in our understanding of the mystery and beauty of the universe.



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LINEAR
COLLIDER
WORKSHOP

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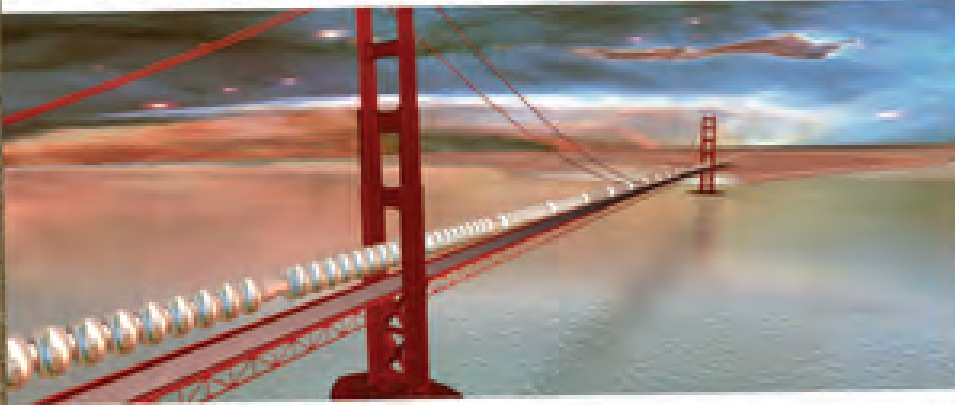
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2005 INTERNATIONAL LINEAR COLLIDER WORKSHOP



LCWS 05

Stanford, California, USA 19-22 March 2005



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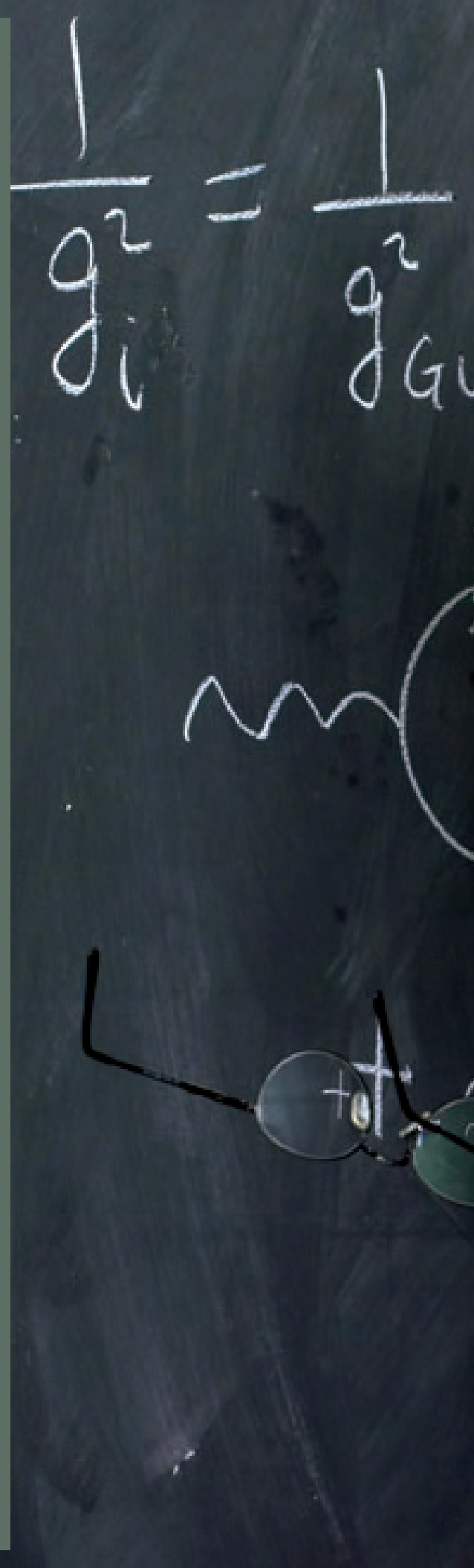
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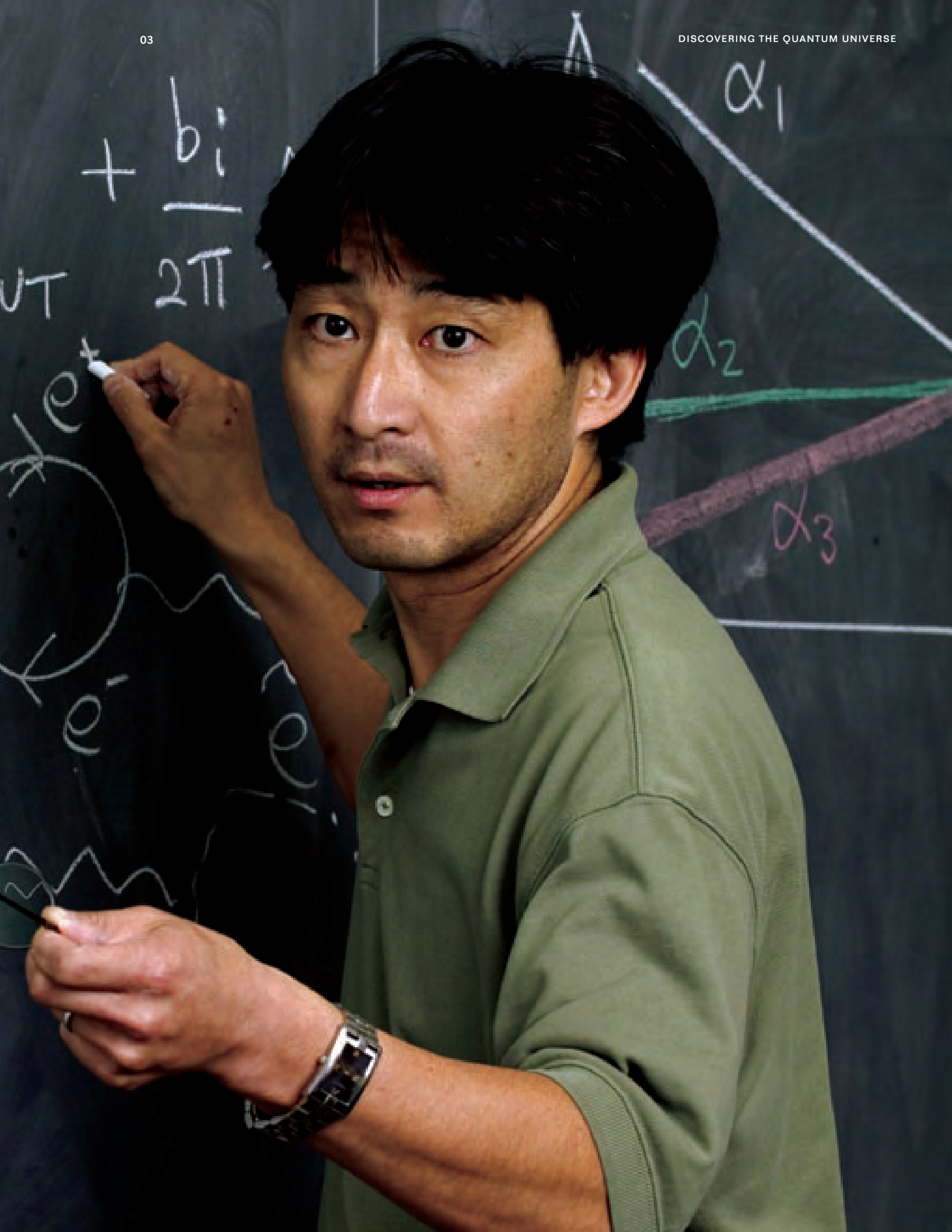
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INTRODUCTION

DISCOVERING THE QUANTUM UNIVERSE

Right now is a time of radical change in particle physics. Recent experimental evidence demands a revolutionary new vision of the universe. Discoveries are at hand that will stretch the imagination with new forms of matter, new forces of nature, new dimensions of space and time. Breakthroughs will come from the next generation of particle accelerators – the Large Hadron Collider, now under construction in Europe, and the proposed International Linear Collider. Experiments at these accelerators will revolutionize your concept of the universe.





EXECUTIVE SUMMARY

LIGHTING OUT FOR THE TERASCALE

*“I reckon I got to light out for
the territory ahead of the rest...”*

Mark Twain, Huckleberry Finn

Particle physicists are about to light out for a vast new scientific *terra incognita*. When they do, later in this decade, they will encounter a territory of discovery that many of them have theorized and dreamed about all their lives. This unexplored country is the Terascale, named for the Teravolts of particle accelerator energy that will open it up for scientific discovery. The next generation of particle accelerators are physicists’ tickets to the Terascale and the mysteries that it harbors about the nature of the physical laws that govern the universe. Once they’ve seen the Terascale, physicists believe, the universe will never look the same.

Although physicists have yet to explore the Terascale, they have ideas of what they may find. The past 30 years of experiment and theory have produced many clues and predictions of its features and contours – a detailed travel guide to a country that no one has yet visited. Experiments at the Large Hadron Collider at CERN in Europe will soon show what relation the theorists’ guidebook bears to Terascale reality. Real data from these experiments will rewrite the theorists’ *Guide to the Quantum Universe*.

About certain features of the Terascale, most predictions agree. Most physicists expect to find the Higgs boson – or, if

not the Higgs, whatever it is that does Higgs’s job of giving mass to the particles of matter. Experiment and theory so far all seem to say that SOMETHING like the Higgs exists at the energy of the Terascale to keep the universe and everything in it from flying apart at the speed of light. The LHC experiments will very likely discover it. When they do, the discovery will be a triumph of technology and human understanding. Less certain, but also distinctly likely, are discoveries of dark matter, extra dimensions of space, “superpartners” for all the familiar particles of matter, parallel universes – and completely unexpected phenomena.

Like the discovery of an uncharted continent, the exploration of the Terascale at the LHC will transform forever the geography of the universe. But there will be limits to the LHC’s view. A true grasp of Terascale physics will require a source of comprehensive and nuanced information of a different kind. Along with the LHC, physicists propose a second particle accelerator for Terascale discoveries, one that would use different particles – electrons instead of the LHC’s protons – and different technology. With LHC pointing the way, this linear collider would make a whole new round of discoveries about the quantum universe.

If, for example, the LHC experiments were to spot a Higgs particle, or something that looks like a Higgs, a linear collider would move in for a close-up. Is it in fact the Higgs? Is it all alone, or does it have relatives? How does it interact with the particles around it?

The LHC experiments may well identify candidates for dark matter, the unseen mystery substance that outweighs visible matter in the universe five to one. A dark matter sighting by the LHC would be an extraordinary discovery; and again, a linear collider could discover the information physicists need: Is it really dark matter? Does it have all the characteristics that dark matter must have? Does it make up all of dark matter, or only a fraction? If LHC experiments see evidence for supersymmetry, extra dimensions or parallel universes, a linear collider would have the ability to discover their true nature.

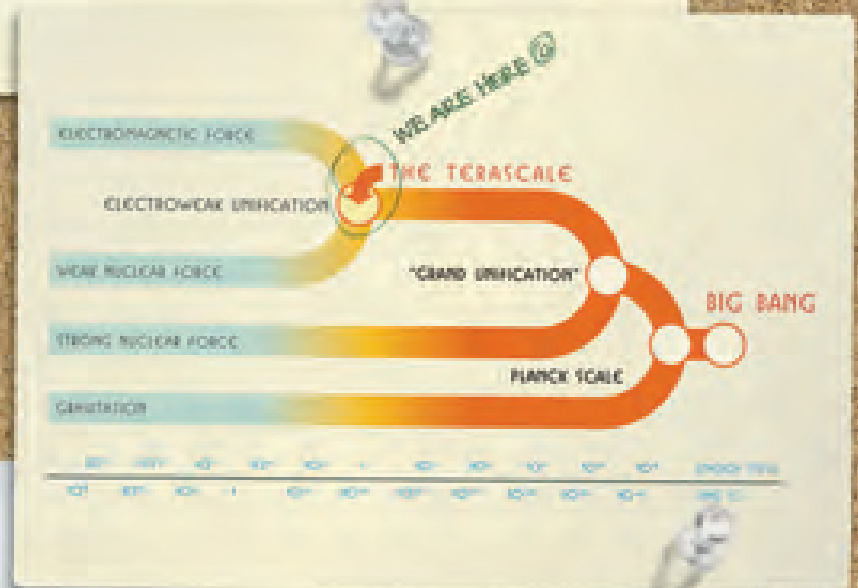
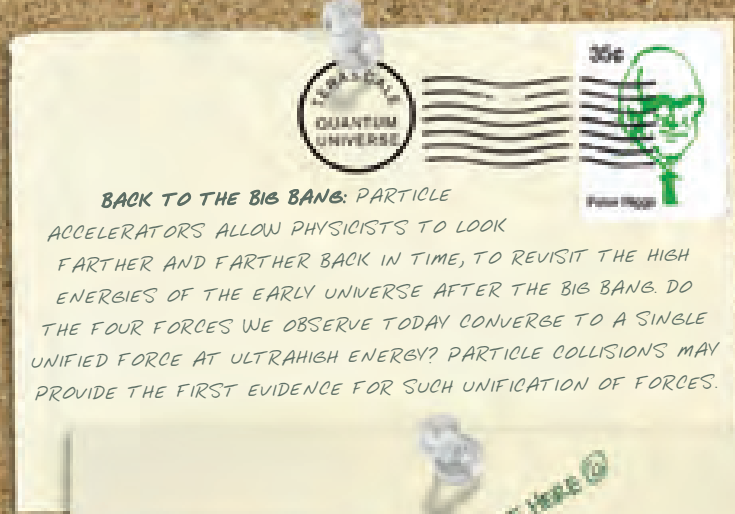
With the perspective from the LHC experiments, a linear collider could range across the physics of the Terascale. It would also offer another unique capability. Using coordinates from LHC discoveries, it could detect the quantum effects of phenomena occurring at energies far beyond the Terascale, acting as a telescope from the Terascale to the energy regions Einstein dreamed of, where all of nature's different forces may become one single force.

A linear collider's design would allow it to function as an all-terrain explorer of the Terascale, adaptable to investigate in depth what the LHC discovers. The more information the LHC uncovers about the Terascale, the more discoveries a linear collider would make.

The definitive map of the Terascale must await the results of experiments at these next-generation accelerators – the LHC a soon-to-be reality, the linear collider now at the stage of a proposal. *Discovering the Quantum Universe* gives a best estimate of the questions the experiments will answer about this new scientific territory, following three themes: Mysteries of the Terascale; Light on Dark Matter; and Einstein's Telescope.

THE DISCOVERY SCENARIOS FOLLOW THREE THEMES.

1. **MYSTERIES OF THE TERASCALE.** The LHC should discover the Higgs and other new particles. Experiments at the linear collider would then zoom in on these phenomena to discover their secrets. Properties of the Higgs may signal extra dimensions of space or explain the dominance of matter over antimatter. Particle interactions could unveil a universe shaped by supersymmetry.
2. **LIGHT ON DARK MATTER.** Most theories of Terascale physics contain new massive particles with the right properties to contribute to dark matter. Such particles would first be produced at the LHC. Experiments at the linear collider, in conjunction with dedicated dark matter searches, would then discover whether they actually are dark matter.
3. **EINSTEIN'S TELESCOPE.** From a vantage point at the Terascale, the linear collider could function as a telescope to probe far higher energies. This capability offers the potential for discoveries beyond the direct reach of any accelerator that could ever be built. In this way, the linear collider could bring into focus Einstein's vision of an ultimate unified theory.



POSTCARDS FROM THE TERASCALE

The sun warms planet Earth, but we live in a universe where the temperature of space is only three degrees above absolute zero. Its energy is so low that we can no longer see what space contained in the inferno of its birth. As the universe cooled from the Big Bang, it passed through a series of phases, each at a lower energy and each with its own set of particles and forces acting according to its own physical laws.

Particle accelerators give us the opportunity to go back and revisit the higher energies of our ancestral universe, to observe phenomena no longer visible in our own era. These high-energy phenomena are important to us, because our universe today still feels their imprint. The order behind what appears arbitrary in our own universe becomes clear at higher energies.

For example, many theories predict that at the extreme energy just after the Big Bang, all of nature's forces were combined in one single unified force, splitting as the universe cooled into the four forces that we know today. Reconnecting to the early universe may reveal how gravity relates to electromagnetism as different aspects of a single principle of nature.

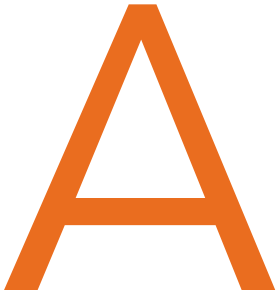
Since the early cyclotrons of the 1950s, particle accelerators have served as the passports to higher and higher energies. The entire standard model of the structure of matter, with its fundamental particles and forces, has emerged from the increasing energies of particle collisions. Each generation of accelerators has built on the discoveries of previous generations to venture deeper into the history of the universe. Now, a new generation of accelerators with the highest energies yet will open up for exploration a region of energy – the Terascale – that has ten thousand trillion times the energy of space today. Postcards from the Terascale will answer basic questions about the universe.

Moreover, the Terascale is not the end of the story. Discoveries there may reveal phenomena occurring at energies so high that no particle accelerator will ever achieve them directly. Such postcards from the Planck scale once seemed an unreachable fantasy. Forwarded from an address in the Terascale, they may one day arrive.

- A MYSTERIES OF THE TERASCALE
- B LIGHT ON DARK MATTER
- C EINSTEIN'S TELESCOPE

DISCOVERING THE QUANTUM UNIVERSE : AN OVERVIEW

Starting with the discovery of the electron, particle physicists have ventured successively deeper into the unseen world within the atom. They have discovered a structure and simplicity neither expected nor predicted, even by Einstein. Their discoveries have redefined the human conception of the physical world, connecting the smallest elements of the universe to the largest, and to the earliest moments of its birth.



MYSTERIES OF THE TERASCALE

Later in this decade, experiments at the Large Hadron Collider at CERN will break through to the Terascale, a region of energy at the limit of today's particle accelerators where physicists believe they will find answers to questions at the heart of modern particle physics.

The LHC will expose the Terascale to direct experimental investigation. Present-day experiments suggest that it harbors an entirely new form of matter, the Higgs boson, that gives particles their mass. Beyond that, physicists believe that the Terascale may also hold evidence for such exotic phenomena as dark matter, extra dimensions of space, and an entire new roster of elementary superparticles.

The first target is the Higgs. Over the past few decades, theoretical breakthroughs and precision experiments have led to the construction of the standard model of particle physics, which predicts that an omnipresent energy field permeates the cosmos, touching everything in it. Like an invisible quantum liquid, it fills the vacuum of space, slowing motion and giving mass to matter. Without this Higgs field, all matter would crumble; atoms would fly apart at the speed of light.

RELATED QUESTIONS

ARE THERE UNDISCOVERED PRINCIPLES OF NATURE :
NEW SYMMETRIES, NEW PHYSICAL LAWS?

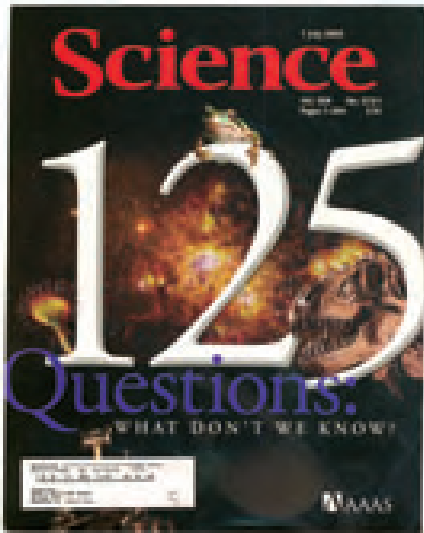
HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY?

ARE THERE EXTRA DIMENSIONS OF SPACE?

WHAT HAPPENED TO THE ANTIMATTER?

So far, no one has ever seen the Higgs field. To detect it, particle accelerators must first create Higgs particles and then measure their properties. The LHC is designed with enough energy to create Higgs particles and launch the process of discovery.

To determine how the Higgs really works, though, experimenters must precisely measure the properties of Higgs particles without invoking theoretical assumptions. Such precise and model-independent experiments are a hallmark of linear collider physics, not available in the complex experimental environment of the LHC. A linear collider could determine if the Higgs discovered at the LHC is the one-and-only Higgs. Does it have precisely the right properties to give mass to the elementary particles? Or does it contain admixtures of other new particles, heralding further discoveries? A linear collider would be able to make clean and precise determinations of critical Higgs properties at the percent level of accuracy.



Science Magazine's 125 Questions.

Question #1: "What is the Universe made of?"



Installation of the ATLAS detector at CERN. Courtesy of CERN

A Higgs discovery, however, will raise a perplexing new question: According to our present understanding, the Higgs particle itself should have a mass a trillion times beyond the Terascale. Although the Higgs gives mass to Terascale particles, its own mass should be much, much greater. Why does the Higgs have a mass at the Terascale?

For years, theorists have tried to explain this mystery, devising multiple possibilities including supersymmetry, extra dimensions and new particle interactions. Which, if any, of the theories is correct? Sorting that out is a task for the LHC and a linear collider. The LHC will have enough energy to survey the Terascale landscape. Then a linear collider could zoom in to distinguish one theory from another.

Theories of supersymmetry and extra dimensions, for example, predict new particles that are close relatives of the Higgs. Some of these particles would be difficult to detect or identify at the LHC, and difficult to distinguish from the Higgs itself. Linear collider experiments would have unique capabilities to allow physicists to identify these particles and pinpoint how they are related to ordinary matter.

The Terascale may hold the answers to still more of particle physics' most basic questions. The dominance of matter over antimatter in the universe remains a mystery, but part of the answer could lie in undiscovered interactions that treat matter and antimatter slightly differently – that is, in undiscovered sources of the matter-antimatter asymmetry physicists call CP violation. At the LHC, it will be difficult to extract CP information about Terascale physics. Experiments at a linear collider, however, could detect and measure new sources of matter-antimatter asymmetry.

Mapping the Terascale will take physicists far into new scientific territory, as complex theoretical frameworks come face to face with experimental data. From this clash of theory with data will arise a profoundly changed picture of the quantum universe.

B

LIGHT ON DARK MATTER

The past decade has witnessed the startling discovery that over 95 percent of the universe is not made of ordinary matter, but instead consists of unknown dark matter and dark energy. Astrophysical observations have demonstrated that only four percent of the universe is made of matter like that here on Earth. Seventy-three percent is dark energy, and 23 percent is dark matter.

Dark energy is a mysterious force that fills the vacuum of empty space, accelerating the expansion of the universe. Physicists don't know what dark energy is, how it works, or why it exists. They do know that it must ultimately have an explanation in terms of particle physics. Are dark energy and the Higgs field related? The discovery of supersymmetry would provide a possible connection. Supersymmetry provides a natural context for both the Higgs field and dark energy.

Definitive evidence for the dark universe has come from many sources, including astrophysical observations of clusters of galaxies that would have flown apart if visible

RELATED QUESTIONS

WHAT IS DARK MATTER?

HOW CAN WE MAKE IT IN THE LABORATORY?

Dark, *adj.* 1a. Lacking or having very little light. b. Lacking brightness...8. Difficult to understand; obscure. 9. Concealed or secret; mysterious.

matter were the only thing holding them together. As close to home as the Milky Way, visible matter alone would not hold the stars in their orbits. Dark matter holds the universe together.

What is this dark matter that binds the galaxies and keeps the universe from flying apart? Although dark matter is not made of the same stuff as the rest of the world, physicists have clues to its identity. Cosmological measurements favor "cold" dark matter – heavy particles moving at low speeds – as a major component. For now, though, the dark side of the universe remains a mystery.

Moreover, there is no reason to think that dark matter should be any simpler than visible matter, with its multiple quarks and leptons. New particles do not normally appear in isolation. The 1932 discovery of the positron, for example, signaled a new world of antimatter particles. Today, the challenge is to explore the world of dark matter by creating dark matter particles in the laboratory.



There are many possible candidates for the particles that make up dark matter. When particle physicists suspect that the underlying theory for something is complex, they call it a “moose”.

Illustration: Michael S. Turner

If dark matter is made up of weakly interacting massive particles (something like heavy versions of the neutrinos), cosmological calculations suggest that they would have Terascale masses, in the energy region of the LHC and the ILC. Is this Terascale conjunction a coincidence? Most theories of Terascale physics, although developed with different motivations, posit particles that may contribute to dark matter. For example, an oft-invoked dark-matter candidate is the lowest-mass supersymmetric particle, the neutralino, theorized to reside at the Terascale. The LHC and the ILC have the potential to produce dark matter particles identical to the dark matter present in the universe.

Besides accelerator experiments, other experiments are watching for individual dark matter particles in highly sensitive detectors deep underground. Astrophysics experiments, in turn, are seeking the cosmic remnants of dark matter annihilation in space. However, none of these experiments can positively identify dark matter without help from accelerator experiments.

Accelerator experiments will be able to place dark matter particles into context. For example, the LHC may identify a dark matter candidate in particle collisions. A linear collider could then zero in to determine its mass and interaction strength – to take its fingerprints and make a positive identification. By a fine-tuned scan of the energy scale, a linear collider could also flush out any potential dark matter candidates that might be hiding in the multitude of LHC collisions.

A linear collider’s measurements would allow calculation of a dark matter candidate’s density in the universe. In parallel, increasingly sophisticated cosmological observations will measure dark matter’s density to a corresponding accuracy. A match between the collider and cosmological measurements would provide overwhelming evidence that the candidate particle really is dark matter.



EINSTEIN'S TELESCOPE

On his death bed, Einstein asked for a pen and paper, to work on his calculations of a unified field theory. “I am optimistic,” he told a friend, “I think that I am getting close.”

The dream of today’s particle physicists, like that of Einstein, is to find a theory that describes a single unified force of nature. A century after Einstein, the combined capabilities of the LHC and the ILC promise to lead the way toward that ultimate theory.

The precision of its electron–positron collisions would give a linear collider the potential to act as a telescope to see into energies far beyond those that any particle accelerator could ever directly achieve. As a telescope to the beyond, a linear collider could explore energies a trillion times that of the accelerator itself, in the ultrahigh-energy realm where physicists believe all of nature’s forces become one.

A linear collider’s capability as a telescope to ultrahigh energies rests on the quantum properties of matter discovered in the past few decades. This hard-won understanding gives physicists a means to measure the effects of phenomena occurring at energies beyond those that accelerators can reach.

RELATED QUESTIONS

[ARE THERE EXTRA DIMENSIONS OF SPACE?](#)

[DO ALL THE FORCES BECOME ONE?](#)

[WHY ARE THERE SO MANY KINDS OF PARTICLES?](#)

[WHAT ARE NEUTRINOS TELLING US?](#)

[HOW DID THE UNIVERSE COME TO BE?](#)

For now, though, the telescopic view to the beyond is obscured by lack of knowledge of Terascale physics. Data from the LHC and the ILC would part the clouds of physicists’ ignorance of the Terascale and allow a linear collider to act as a telescope to the unknown.

In the current understanding of the universe, the laws of the large and the laws of the small do not agree. Is it possible to reconcile gravity (the laws of the large) with quantum theory (the laws of the small) and thereby address this central question of modern physics?

Physicists believe that just one force existed after the Big Bang. As the universe cooled, that single force split into the four forces we know today: gravity, electromagnetism, and the strong and weak nuclear forces. Physicists have already discovered that remarkably similar mathematical laws and principles describe three of the four forces. However, at the final step of bringing gravity into the fold, ideas fail; some key element is missing.

String theory is the most promising candidate to unify the laws of the large and the small. The theory holds that all particles and forces are tiny vibrating strings. One vibration of the string makes it a quark, while another makes it a photon. String theory brings with it a number of dramatic

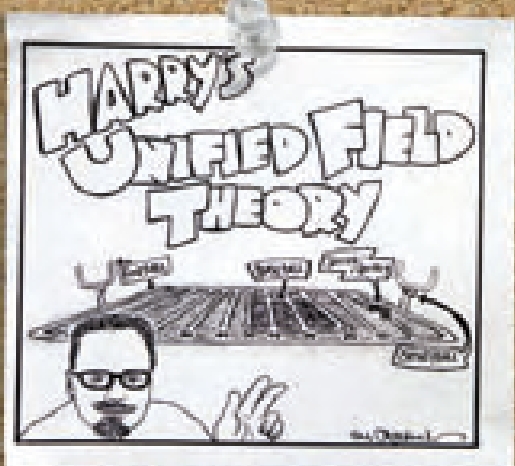


Albert Einstein, Edwin Hubble, and Walter Adams (L-R) in 1931 at the Mount Wilson Observatory 100" telescope, in the San Gabriel Mountains of southern California. It was here in 1929 that Hubble discovered the cosmic expansion of the universe. *Courtesy of the Archives, California Institute of Technology*

concepts including supersymmetry and extra dimensions of space. Among the most exciting possibilities for the LHC is its very real potential to discover the superpartners of the known particles.

Theorists cannot yet predict at what energy the evidence for extra dimensions – if they exist – will emerge. A linear collider's sensitivity would make it the best window on quantum gravity, extra dimensions and the physics of strings that physicists are likely to have for a long time – perhaps ever.

Physicists could use a linear collider to focus on the point where both forces and masses may unify, linked by supersymmetry into one theory that encompasses the laws of the large and the laws of the small.



DISCOVERING THE QUANTUM UNIVERSE

This chapter presents nine scenarios illustrating discovery scenarios at the Large Hadron Collider (LHC) and International Linear Collider (ILC). The exact scenario will depend upon what nature has chosen, but the connection is clear. The more that researchers discover at the LHC, the greater the discovery potential of the linear collider.

IF LHC DISCOVERS:	WHAT ILC COULD DO:	QU	LEGEND: THE QUESTIONS
A Higgs particle	Discover why the Higgs exists and who its cousins are. Discover effects of extra dimensions or a new source of matter-antimatter asymmetry.	1,3,9	1 ARE THERE UNDISCOVERED PRINCIPLES OF NATURE : NEW SYMMETRIES, NEW PHYSICAL LAWS?
Superpartner particles	Detect the symmetry of supersymmetry. Reveal the supersymmetric nature of dark matter. Discover force unification and matter unification at ultra-high energies.	1,2,4,5	2 HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY? 3 ARE THERE EXTRA DIMENSIONS OF SPACE?
Evidence for extra dimensions	Discover the number and shape of the extra dimensions. Discover which particles are travelers in extra dimensions, and determine their locations within them.	3	4 DO ALL THE FORCES BECOME ONE? 5 WHY ARE THERE SO MANY KINDS OF PARTICLES?
Missing energy from a weakly interacting heavy particle	Discover its identity as dark matter. Determine what fraction of the total dark matter it accounts for.	6	6 WHAT IS DARK MATTER? HOW CAN WE MAKE IT IN THE LABORATORY?
Heavy charged particles that appear to be stable	Discover that these eventually decay into very weakly interacting particles. Identify these “super-WIMPs” as dark matter.	6	7 WHAT ARE NEUTRINOS TELLING US? 8 HOW DID THE UNIVERSE COME TO BE?
A Z-prime particle, representing a previously unknown force of nature	Discover the origin of the Z-prime. Connect this new force to the unification of quarks with neutrinos, of quarks with the Higgs, or with extra dimensions.	4,7	9 WHAT HAPPENED TO THE ANTIMATTER?
Superpartner particles matching the predictions of supergravity	Discover telltale effects from the vibrations of superstrings.	3,8	From “Quantum Universe”



LARGE HADRON COLLIDER

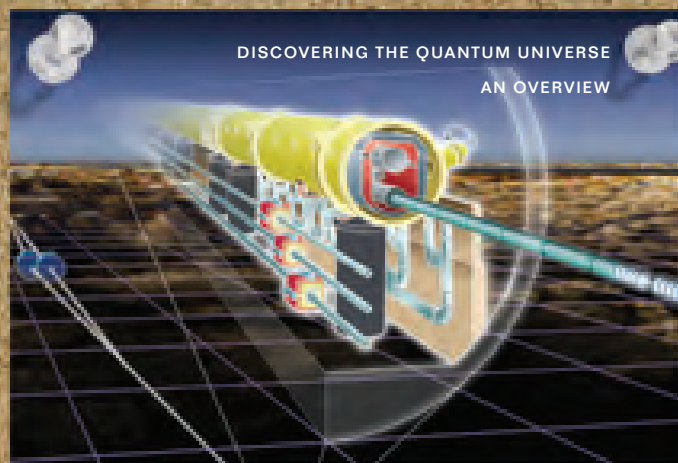
The Large Hadron Collider at CERN, the European Organization for Nuclear Research, will be the biggest and most powerful particle accelerator ever built when it turns on in 2007. It will operate in a circular tunnel 27 km in circumference, between France's Jura mountains and Switzerland's Lake Geneva. Experiments at the LHC will give scientists their first view of the Terascale energy region.

The LHC will accelerate two beams of particles in opposite directions, smashing them together to create showers of new particles via Einstein's famous equation, $E=mc^2$. Colliding beams of protons will generate some 800 million collisions per second.

Superconducting magnets will guide the beams around the ring. Each proton flying around the LHC will have an energy of 7 Tera electron volts to give a proton-proton collision energy of 14 TeV. The protons contain quarks and gluons, each carrying a fraction of the proton's total energy. A typical collision involves a quark or gluon from each proton colliding at lower energy, accompanied by debris from the remaining parts of the protons. The composite nature of the proton complicates the detection of the collision products.

Four major particle detectors – ALICE, ATLAS, CMS and LHCb – will observe the collisions. ATLAS and CMS, each with over 2000 collaborators, will survey all aspects of the Terascale. LHCb will concentrate on precise measurement of matter-antimatter asymmetry. ALICE, using LHC's ability to accelerate lead ion beams in addition to protons, will study matter at extreme energy densities.

The LHC experiments will record about 1000 Gigabytes of data every day. Particle physicists are working with computer scientists around the world to develop new grid networking technology. This will link thousands of computers worldwide to create a global computing resource to store and process the deluge of data from the LHC.



INTERNATIONAL LINEAR COLLIDER

The International Linear Collider is a proposed new accelerator designed to work in concert with the LHC to discover the physics of the Terascale and beyond. The ILC would consist of two linear accelerators, each some 20 kilometers long, aimed at each other, hurling beams of electrons and positrons toward each other at nearly the speed of light.

When electrons and positrons accelerate in a circle, they lose energy. The higher the acceleration energy, the more energy the electrons lose. At very high energies, a circular electron accelerator is no longer an option; too much energy is wasted. The solution is a straight-line collider.

In the design for the ILC, some 10 billion electrons and positrons are crammed into beams approximately 3 nanometers thick. Positrons start from one end of the collider, electrons from the other. As the particles speed along the length of the accelerator, superconducting accelerating cavities give them more and more energy, until they meet in an intense crossfire of collisions. The energy of the ILC's beam could be adjusted to home in on phenomena of interest. ILC beams would also be polarized, adding power to the subsequent data analysis.

The ILC Global Design Effort will establish the design of the ILC, focusing the efforts of hundreds of accelerator scientists and particle physicists in the Americas, Europe and Asia. The ILC will be designed, funded, managed and operated as a fully international scientific project.

THE HIGGS IS DIFFERENT
A SHORTAGE OF ANTIMATTER
MAPPING THE DARK UNIVERSE
EXPLORING EXTRA DIMENSIONS
DARK MATTER IN THE LABORATORY
SUPERSYMMETRY
MATTER UNIFICATION
UNKNOWN FORCES
CONCERTO FOR STRINGS

DISCOVERING THE QUANTUM UNIVERSE : DISCOVERY SCENARIOS

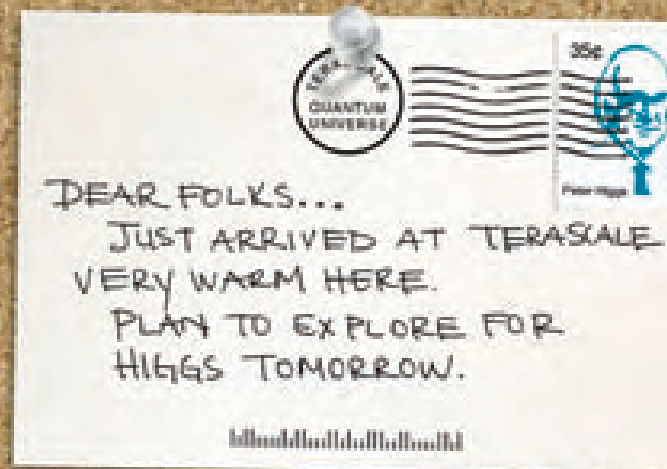
This chapter presents nine scenarios illustrating the LHC and linear collider discoveries listed in the table on page 14. Each individual case study shows how experiments at the next generation of particle accelerators will address the fundamental questions of particle physics.

DISCOVERY SCENARIOS :

THE HIGGS IS DIFFERENT

Discovery of a Higgs particle at the LHC would mark a giant step toward resolving the contradictions of Terascale physics. But a Higgs discovery would present mysteries of its own that would be even more challenging to solve than detecting the Higgs particle. For example, theory says that Higgs particles are matter particles, but in most respects the Higgs behaves more like a new force than like a particle. How can this be? In truth, the Higgs is neither matter nor force; the Higgs is just different.

Physicists suspect the existence of many Higgs-like particles: Why, after all, should the Higgs be the only one of its kind? They predict that new particles related to the Higgs play essential roles in cosmology, giving the universe the shape it has today. If many Higgs-like particles exist, they should interact with each other. Thanks to quantum theory, when a Higgs particle is produced, it contains a bit of its Higgs-like cousins. Experiments at a linear collider would zoom in on the Higgs to discover these innermost secrets.

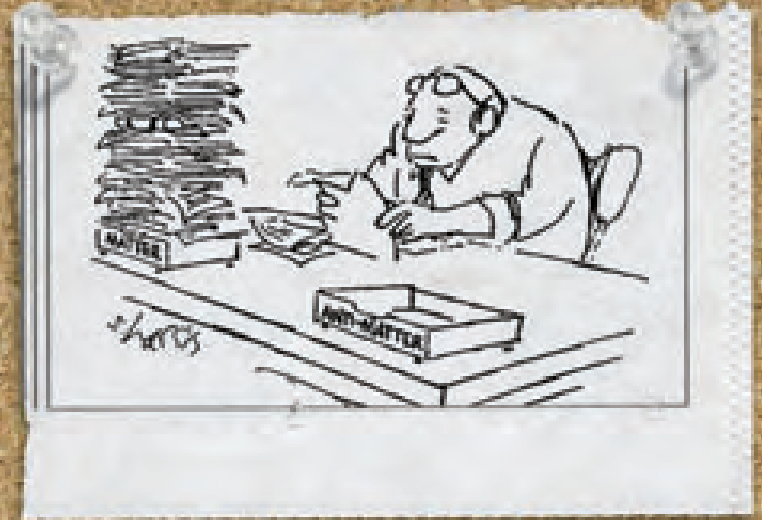


DISCOVERY SCENARIOS : A SHORTAGE OF ANTIMATTER

The dominance of matter over antimatter in the universe remains a mystery. The family of Higgs particles may have deep connections with this question.

In the instant after the Big Bang, physicists believe that the universe was too hot for the Higgs to do its job of dispensing mass. A short time later, the universe cooled enough for the Higgs to go to work. Within the known laws of physics, this explanation provides almost, but not quite, enough ingredients to produce an imbalance of matter over antimatter. What appear to be missing are a stronger source for this matter-antimatter imbalance and some additional interactions, such as interactions of the Higgs with other Higgs-like particles.

The LHC can take the first step in investigating this scenario by discovering multiple Higgs particles or uncovering other evidence, such as superpartners. Then linear collider experiments could discover a new source for the dominance of matter over antimatter.



Our Lopsided Universe:
The Matter with Anti-Matter

Public Lecture by
Steve Dimock (MIT)
Stanford Linear Accelerator Center

June 28th
7:30-8:30 pm

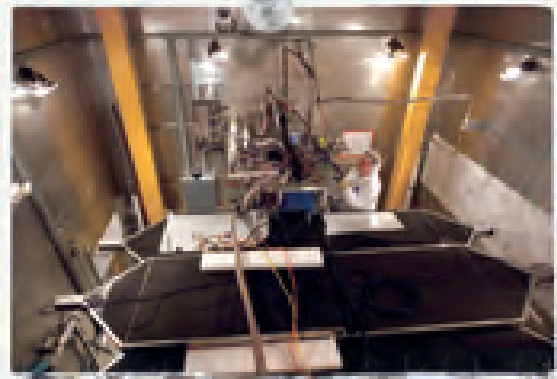
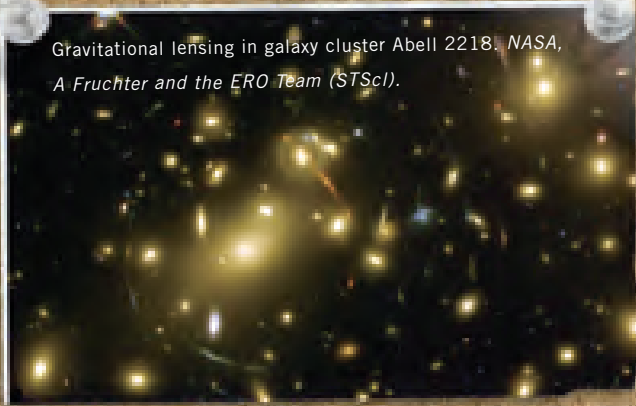
SLAC Campus/Panofsky Auditorium
2575 Sand Hill Road
Menlo Park, CA

Free Admission
No scientific knowledge needed to attend

Following the event, stay for refreshments
and chat with physicists.

For More Information:
Phone: (650) 924-6500
www.slac.stanford.edu/education/lectures

Gravitational lensing in galaxy cluster Abell 2218. NASA,
A Fruchter and the ERO Team (STScI).



COLD DARK MATTER SEARCH (CDMS)
SOUDAN MINE, MN.



Artist's conception of the GLAST spacecraft in orbit
above the Earth. Credit: Spectrum Astro

NOT JUST COLLIDERS

Discovering the Quantum Universe describes the role of the next generation of particle accelerators, the LHC and the ILC, in discovering laws of physics that will radically transform the human conception of the universe. While their role will be crucial, however, accelerators will not be the only tools that scientists use to answer the most compelling questions about the nature of matter and energy, space and time. Astrophysical and cosmological observations, in space and from the ground, are also exploring the fundamental parameters of the universe. Underground experiments are watching for the subtle signals of dark matter passing through ultrasensitive detectors.

No single scientific approach will suffice. For example, it took results from astrophysical and cosmological observations to reveal that most of the universe is made of dark matter and dark energy. It will take discoveries at accelerators to show exactly what they are and how they work.

To answer the most challenging questions about the nature of the universe, all the approaches must converge. Results from accelerator experiments must agree with astrophysical observations and results from underground. Discovering the quantum universe requires combining the most powerful and insightful observations in each of these different scientific approaches, in a synthesis far more powerful than any of them could achieve alone.



INSIDE THE CMS DETECTOR AT CERN



SEEING THE INVISIBLE – A TALE OF TWO COLLIDERS

In particle physics, discovery often depends on meticulous bookkeeping. The fundamental forces in high energy collisions can do their work in a septillionth of a second, creating highly unstable new particles that decay almost immediately into many “daughter” particles. Computers write an elaborate record for each collision event, determining as completely as possible what particles went in, what particles came out, how fast and in what direction each particle was moving. Physicists then reconstruct the most likely explanation for what happened in the collision.

In some events, the numbers don’t add up, and the books don’t balance. For example, the total energy of all the particles produced may be less than the total energy of the original collision; this is a missing energy problem. Another example is a new heavy particle that moves off at right angles to the colliding beams, with nothing to balance it in the opposite direction; this is a missing momentum problem. Missing energy and momentum can be signals of missing particles: particles that interact too weakly for direct detection but that betray their existence by carrying off energy and momentum.

If dark matter particles are produced at colliders, they will pass through the detectors without a trace. To document their fleeting presence, physicists will look for signs of missing energy or momentum. By detecting the other particles produced in the same collisions, physicists can then infer the properties of the dark matter particles. These are the same techniques now employed to deduce the role of neutrinos in high energy collisions.

In proton collisions at the LHC, the composite nature of protons creates an additional challenge for particle bookkeeping. A proton is like a tiny bag of quarks and gluons. In any individual collision, the identities and energies of the particular colliding quarks or gluons are not known. While it is still possible to observe missing momentum, there is a fundamental gap in particle bookkeeping at any proton collider.

In electron-positron collisions, though, experimenters know the identities, energies and momenta of the colliding particles, allowing for simple and complete particle bookkeeping and making a linear collider an incisive tool for identifying dark matter.


DISCOVERY SCENARIOS :

MAPPING THE DARK UNIVERSE

Deep underground in an old Minnesota iron mine, the CDMS II experiment is using highly sensitive detectors to search for the tiny wake left by dark matter particles streaming in from space. Astrophysics experiments, meanwhile, are searching for cosmic radiation produced by the annihilation of dark matter particles elsewhere in the universe. A signal from any of these dark matter detection experiments would give insight into dark matter properties, and strongly motivate the search for dark matter at the LHC and ILC.

In fact, physicists are already reporting tentative hints of signals in dark matter search experiments. Unfortunately, the interpretation of these experiments is uncertain, because two unknowns cloud them. Uncertainties about the properties of dark matter particles cannot be disentangled from astrophysical uncertainties, such as the spatial distributions and velocities of dark matter particles in the galaxy.

Maps



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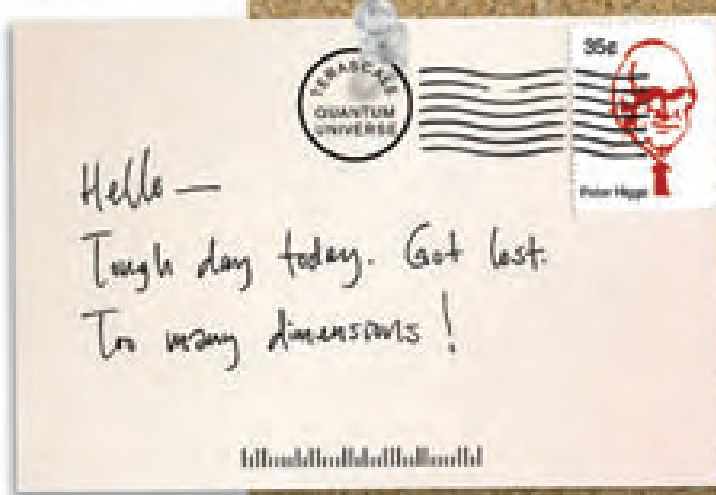
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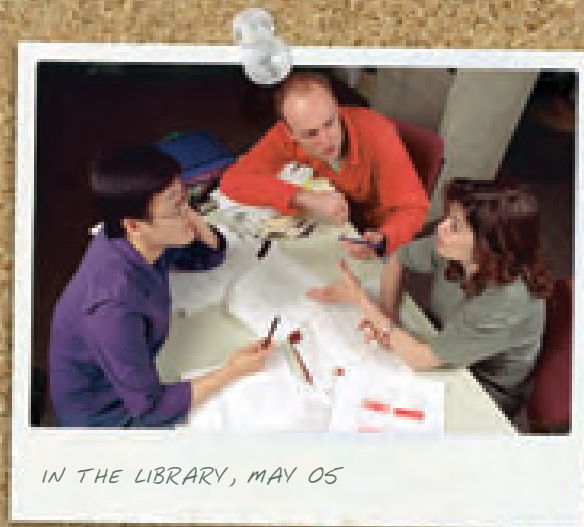
The ILC is essential for resolving these uncertainties, by discovering the precise properties of dark matter particles. Dark matter detection rates could then provide unambiguous probes of dark matter distributions. Just as traditional telescopes have mapped the luminous universe, the combination of linear collider data with other experiments and observations would map the dark universe, shedding light on the structure of the cosmos.

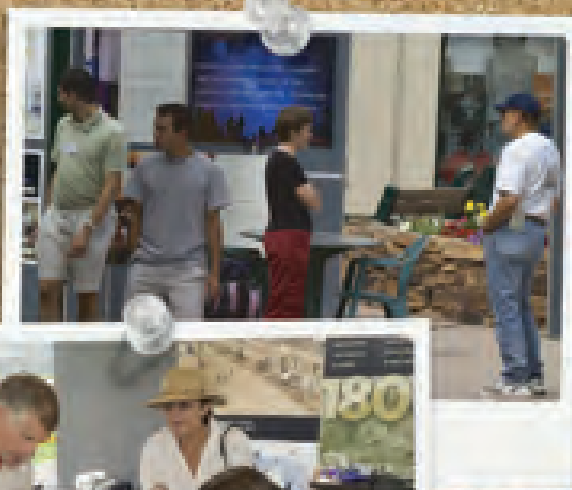
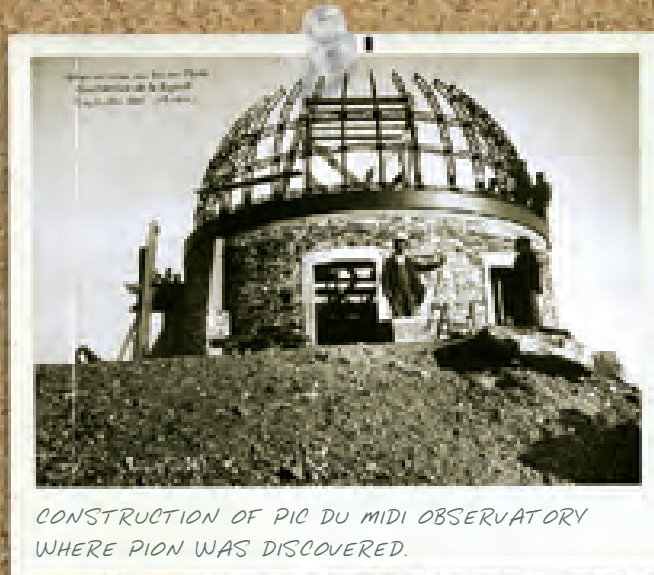
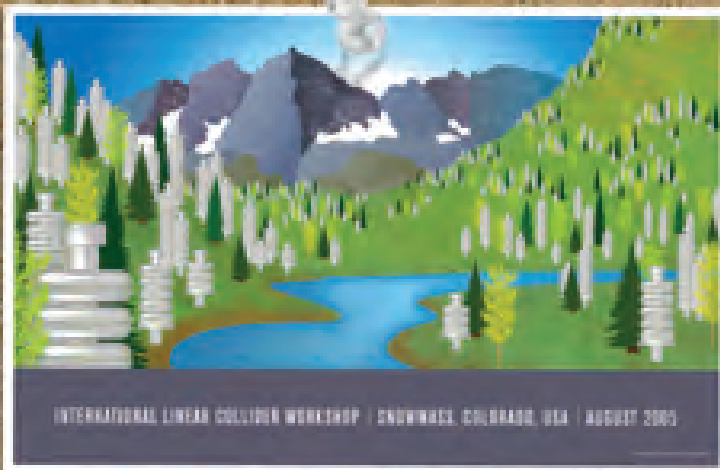


DISCOVERY SCENARIOS : EXPLORING EXTRA DIMENSIONS

The discovery of extra dimensions of space, a prediction of string theory, would dramatically change the concept of space and time. Each point in space would have additional spatial dimensions attached to it. The extra dimensions might be very tiny or otherwise hidden from view. Matter might be made of particles that already live in extra dimensions and feel their effects. A particle moving in an extra dimension would have extra energy, making it look like a heavier version of itself. Measurement of the mass and other properties of these travelers would show what the additional dimensions look like.

If new dimensions exist at the Terascale, then the LHC will discover them; experiments will look for high-energy collisions in which particles literally disappear into an extra dimension. Linear collider experiments could discover still tinier extra dimensions by detecting small disturbances in the behavior of ordinary particles. A linear collider could determine the number of dimensions, their size and shape, and which particles live inside them.





PARTICLES TELL STORIES

For Newton, it was apples. For Einstein, it was trains and Swiss clocks. Today, physicists use particles to discover new laws of nature in the microscopic world. The discovery of a new particle is often the opening chapter of an entirely new story revealing unsuspected features of the universe.

When the positron, the brother of the electron, was first detected, the discovery went beyond the identification of a particle. The positron revealed a hidden half of the universe: the world of antimatter. The positron showed how to reconcile the laws of relativity with the laws of quantum mechanics. The positron told a brand-new story about the structure of space and time.

When physicists first observed the pion in cosmic ray detectors atop the Pyrénées, they were puzzled. Soon, particle accelerators began producing myriad cousins of the pion: etas, deltas, rhos, omegas. Physicists were running out of Greek letters to name them all. Finally the story became clear. These were not elementary particles at all, but tiny bags of quarks, held together by a new force, a force so strong that no quark could ever escape it.

Other aspects of the universe may also unveil themselves in the form of new particles – extra dimensions of space, for example. An electron moving in tiny extra dimensions would not look like an electron to us; it would appear as a much heavier new particle, “heavier” because it is whirling around the extra dimensions. In fact, the tiny extra dimensions imply whole “towers” of new heavy particles. Producing some of these particles with an accelerator would be a great discovery; an equal challenge will be to pin down their identities as travelers in extra dimensions. How much we learn from these particles depends on how well we determine their properties. For example, by measuring their masses, physicists could discover the shape of the extra dimensions.

Using the LHC and a linear collider, physicists hope to produce particles of dark matter in the laboratory. They may well discover an entire dark world, with other new particles that tell a brand-new story of the dark and the visible universe.



JELLY BEAN UNIVERSE

Like the jelly beans in this jar, the universe is mostly dark: 95 percent consists of dark matter and dark energy. Only about five percent (the same proportion as the colored jelly beans) of the universe – including the stars, planets and us – is made of familiar atomic matter.

DISCOVERY SCENARIOS :

DARK MATTER IN THE LABORATORY

Four percent of the universe is familiar matter; 23 percent is dark matter, and the rest is dark energy. Although the amount of dark matter in the universe is now well known, its identity is a complete mystery.

Physicists have proposed many exotically named dark matter candidates: neutralinos, axions, gravitinos, Q balls, and WIMPzillas. For simplicity, most theoretical studies assume that all of dark matter is composed of a single kind of new particle. But if the dark universe is as rich and varied as the visible world, this assumption may someday appear as simplistic as ancient theories of earth, air, fire and water.

A major goal of the LHC and ILC is to identify one or more components of dark matter by producing particles of dark matter in the laboratory and studying their properties. Astrophysical evidence suggests that dark matter particles will show up at the Terascale. The current

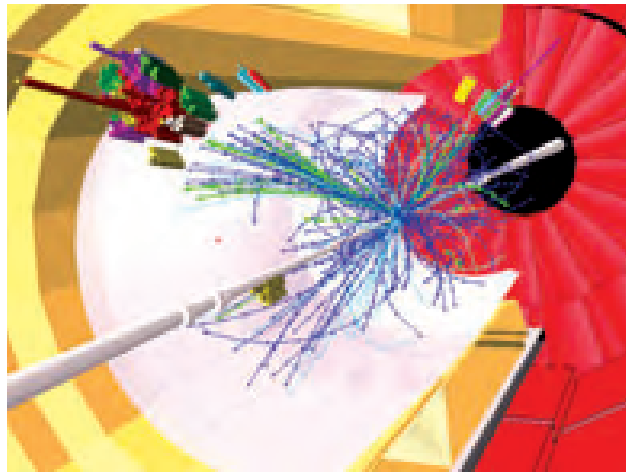
understanding of particle physics and cosmology allows physicists to extrapolate back to early times in the history of the universe. Assuming that dark matter particles are weakly interacting relics of the Big Bang, physicists can use the observed dark matter density to estimate the particles' mass. Detailed calculations in many different theoretical frameworks show that the mass of the dark matter particles place them at the Terascale.

Physicists working at the LHC are likely to find the first evidence for Terascale dark matter. But is it really dark matter? Is it all of the dark matter? Why is it there? A linear collider would be essential for answering these questions, making precise measurements of the dark matter particles and their interactions with other particles. Linear collider experiments could establish both the what and the why for this chapter of the dark matter story.

DISCOVERY SCENARIOS : SUPERSYMMETRY

A major obstacle to Einstein's dream of a unified theory is the clash of the laws of the large with the laws of the small. Quantum mechanics reveals an unruly subatomic world, bubbling with particles that pop into existence out of nowhere and then disappear. On the scale of the universe, we see stars and galaxies that proceed smoothly according to immutable laws of gravity. To reconcile the apparent contradiction, new principles must exist that bring order to the quantum universe. Supersymmetry, a prediction of string theory, could be the key.

Supersymmetry says that all known particles have heavier superpartners, new particles that bring order to the subatomic world. The lightest superpartner is a likely candidate for dark matter, thus perhaps also explaining the structure of the cosmos. Supersymmetry could even explain the existence of the Higgs particle, and be responsible for many Higgs-like cousins.



Simulation of the creation of superpartner particles at the LHC, as seen in the CMS detector at CERN.

Some of the heaviest superpartners may be copiously produced at the LHC. They would then decay to the lightest superpartner and dozens of ordinary particles, leaving spectacular but complicated signals in particle detectors. A linear collider would be best suited for producing the lighter superpartners. Linear collider experiments could focus on one type of superpartner at a time, measuring their properties cleanly enough to detect the symmetry of supersymmetry, and to reveal the supersymmetric nature of dark matter. In this way, linear collider physicists could discover how supersymmetry shapes both the inner workings and the grand designs of the universe.



Dark matter distribution in the galaxy cluster CL0152-1357 detected by gravitational weak-lensing from the Hubble Advanced Camera for Surveys (ACS) observations. The intensity of the purplish color is proportional to the density of dark matter.



THE COSMOLOGICAL COUSINS OF THE HIGGS

The discovery of the Higgs particle would open a new chapter in particle physics, because it would be the first of new breed of particle. Every elementary particle discovered so far spins like an eternal top. The Higgs particle would be the first elementary particle without spin.

Moreover, theorists predict that other Higgs-like particles without spin as essential elements of cosmology. The Higgs particle will be the first step toward understanding such spinless particles and how they might give the universe the shape it has today.

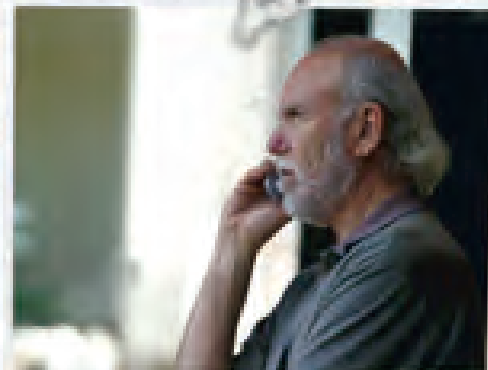
Why is the universe so big? Theory suggests that the universe underwent a cosmic inflation from its microscopic beginnings to its current vast size. To power inflation, physicists postulate one or more Higgs-like particles called inflatons.

Why is the universe speeding up? Cosmological observations confirm that the expansion of the universe is accelerating. Dark energy, which makes up a staggering 70 percent of the universe today, is thought to be responsible for cosmic acceleration. Because dark energy is very similar to cosmic inflation, many physicists believe that dark energy may also involve Higgs-like particles.

Why are there particles that don't spin? One possible explanation is supersymmetry, which says that particles that do spin have partners that don't. Or, if there are extra spatial dimensions, particles spinning in the extra dimensions may appear not to spin in our dimensions. Once physicists discover the Higgs, they plan to find out why and how the Higgs exists and thus gain insights into the mechanisms for inflation and dark energy.



1977 - DETECTOR USED TO DISCOVER THE UPSILON AT FERMILAB.



ILC GLOBAL DESIGN EFFORT DIRECTOR
BARRY BARISH

SYNERGY

Throughout the course of particle physics, results from one accelerator have stimulated discoveries at another. Early experiments smashing protons on protons produced new particles but did not reveal the structure of the proton itself. Finally experiments with electron beams discovered that protons are made of quarks and gluons. Later experiments showed clearly how quarks and gluons are distributed inside the proton – a requirement for understanding collisions at proton colliders. Experiments at electron-positron colliders discovered that high-energy quarks and gluons produce “jets” of particles inside detectors. Soon, physicists discovered such jets in collisions at a new CERN proton-antiproton collider. Jets are now a tool in all searches for new particles whose decays involve quarks and gluons.

The discovery of the J/ψ particle at SLAC and Brookhaven in 1974 revealed the charm quark and antiquark. The proton-proton Intersecting Storage Rings were in operation at CERN, but the “trigger” for ISR detectors was set to detect different phenomena and missed the J/ψ . Redesigning the detectors with different triggers allowed observation of the J/ψ and showed how it is produced by the strong interactions in proton-proton collisions.

After the discovery at Fermilab of the Upsilon, containing the bottom quark, electron-positron machines soon found a whole spectrum of related particles. They led to an understanding of the strong force that binds quarks to antiquarks and to measurements of the properties of the bottom quark.

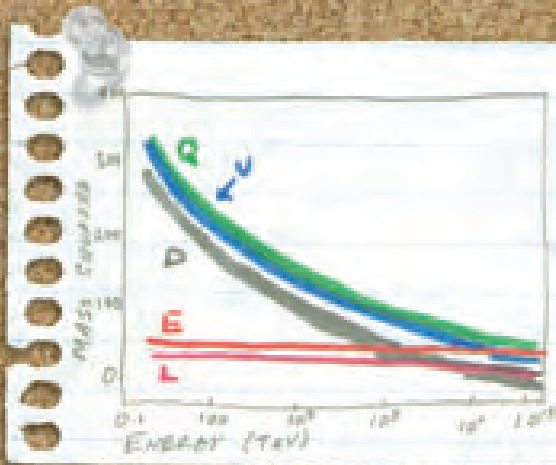
Electron-positron collider detectors equipped to measure submillimeter distances around a collision point allowed physicists to separate the point where the b quark is produced from the vertex of tracks at the point where it decays. Using this telltale “displaced vertex” of the b quark in top quark decays, experimenters discovered the top at the Tevatron collider.



SNOWMASS, AUGUST 05



COFFEE BREAK



The discovery of superpartner particles would allow definitive tests of matter unification. The converging bands would indicate that all of the superpartners started out as the same kind of particle in the first instant of the Big Bang.

DISCOVERY SCENARIOS :

MATTER UNIFICATION

In the everyday world, forces move things around and break things apart. In the subatomic world, forces can also transform one kind of elementary particle into another. These transmutations suggest that the particles that make up matter are related in fundamental but mysterious ways. One possibility is that there was only one kind of matter particle at the time of the Big Bang, which then took on many seemingly different forms as the universe cooled down. This would mean that the 45 different kinds of matter particles that are known today are really the same particle in different guises. This idea is called matter unification.

If superpartner particles are discovered at the LHC, physicists will be able to make definitive tests of matter unification. The orderly patterns of particle masses and interactions enforced by supersymmetry would provide new ways of structuring matter. In particular, these patterns would relate measurements at the Terascale to the much higher energies where matter unification may be manifest. Experiments at a linear collider would have the precision to exploit this relationship, focusing like a telescope on the first instant of the Big Bang.

The discovery of matter unification would have profound implications. It would mean that all ordinary matter eventually falls apart, sealing the ultimate fate of the universe. It would also require the existence of new fundamental forces of nature, forces that would produce a strange particle alchemy beyond anything yet observed.

DISCOVERY SCENARIOS : UNKNOWN FORCES

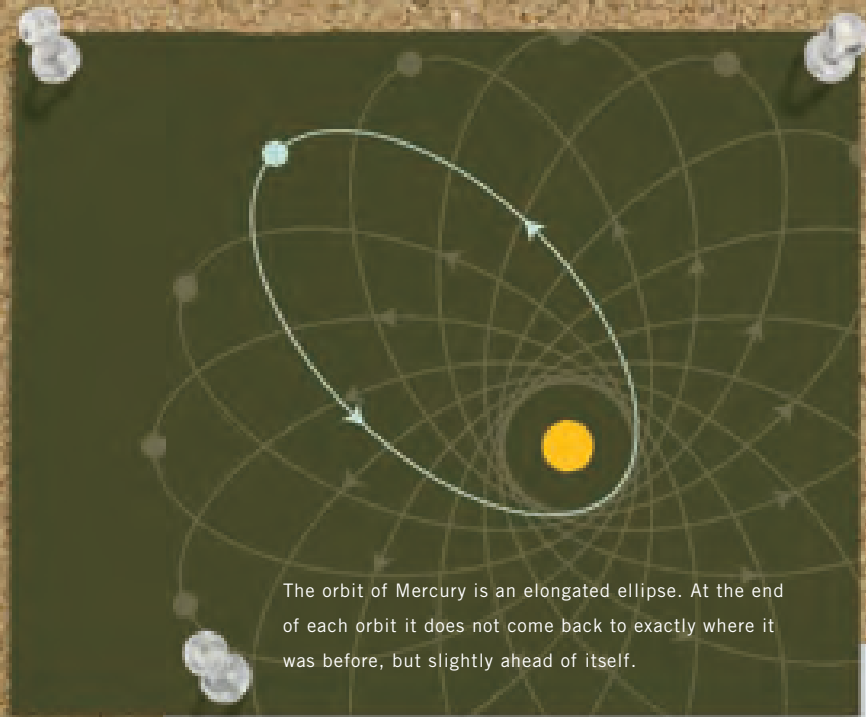
Unification, extra dimensions and string theory all imply the existence of new forces of nature. The detection at the LHC of a new heavy particle called a Z-prime would mean the discovery of just such a new force. This would raise compelling questions: What kind of force is this? Why is it there? Does the new force unify with the other known forces at ultrahigh energies? Is the Z-prime particle a traveler in one or more extra spatial dimensions?

Linear collider experiments would have the ability to detect a very heavy Z-prime by using the accelerator as a telescope. The experiments would detect the quantum effects of heavy Z-prime particles on the production of pairs of light matter particles. Linear collider data could clearly discriminate among different origins of the Z-prime particle. For example:

- The Z-prime arises from a unification framework that naturally explains the origin of neutrino masses.
- The Z-prime arises from a framework that unifies Higgs particles with matter particles.
- The Z-prime is moving in one or more extra dimensions. Further analysis could confirm this by finding other particles that move in these dimensions.

" THERE ARE UNKNOWN FORCES
IN NATURE; WHEN WE GIVE
OURSELVES WHOLLY TO HER,
WITHOUT RESERVE, SHE LENDS
THEM TO US; SHE SHOWS US
THESE FORMS, WHICH OUR
WATCHING EYES DO NOT SEE,
WHICH OUR INTELLIGENCE DOES
NOT UNDERSTAND OR SUSPECT."
- AUGUSTE RODIN





BRITISH PHYSICIST PHIL BURROWS DEMONSTRATES HOW NANOMETER BEAMS WOULD COLLIDE IN THE ILC.

PRECISION

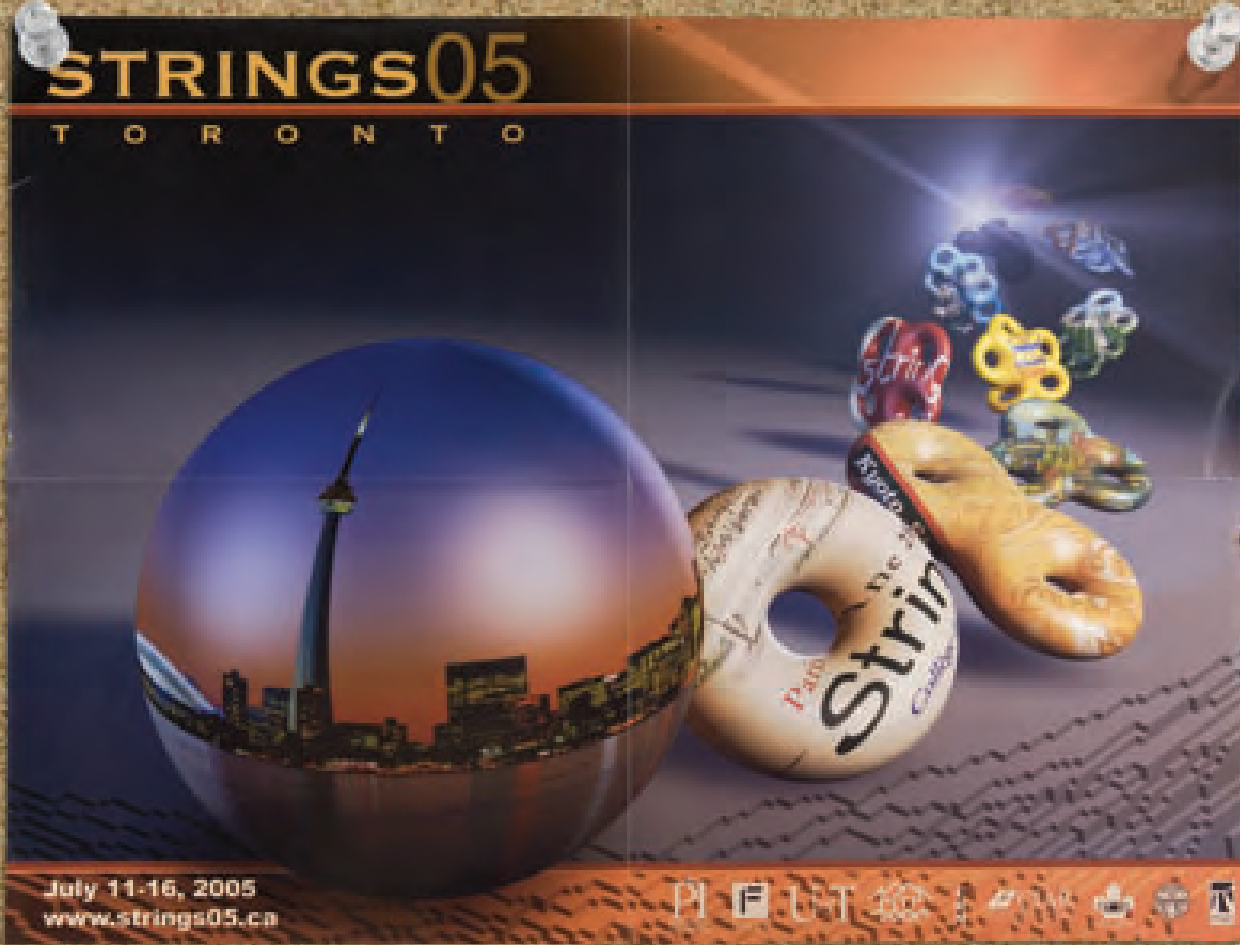
The role of precision measurements in discoveries runs through the history of physics. Precision measurements provide exacting confirmation that a proposed law of physics is correct; they exclude wrong guesses; and, most important, they can provide an opening to understanding aspects of the universe that not accessible to direct observation.

Precision measurement played a key role in one of the greatest discoveries in 20th-century physics. Einstein's relativity theory says that no information travels faster than the speed of light. On the other hand, Newton's familiar law of gravity says the force of gravity acts instantaneously on distant bodies. To resolve this paradox, Einstein proposed that matter bends and warps space and time, giving rise to gravity.

It was not easy to test Einstein's new theory of gravity, called the general theory of relativity. A precision measurement was required.

Mercury, the innermost planet in our solar system moves in an elliptical orbit. Astronomers had found that the ellipse of Mercury's path doesn't quite come back to the same point; each time Mercury revolves around the sun, it always comes back very slightly ahead of the ellipse. The effect is extremely small: only 43 arcseconds per century. Scientists had noted this effect before Einstein, but could not account for all of it with Newton's theory of gravity.

Einstein's theory of gravity predicts that Mercury's orbit should come back slightly ahead of itself, just as observed. With this precision measurement came verification of a profound insight into nature's workings, Einstein's theory of gravity.



BRIAN GREENE EXPLAINS STRINGS

DISCOVERY SCENARIOS :

CONCERTO FOR STRINGS

String theory is the most promising candidate to unify the laws of the large and the small. Its goal is to understand the nature of quantum gravity and its connection both to the other forces of nature and to the cosmos. In string theory, gravity is connected to particle physics through its effects on supersymmetry. If supersymmetry is discovered at the LHC and ILC, physicists will be able to test string-motivated predictions for the properties of superpartner particles. Precise measurements of these superpartner properties could then be mapped to properties of gravity and strings at ultrahigh energies.

This is physics at the ragged edge of our current understanding, but preliminary studies have looked at the ability of linear collider experiments to detect the telltale harmonies of strings. Here linear collider precision is essential, since the string effects appear as small differences in the extrapolated values of the superpartner parameters. A combined analysis of simulated LHC and ILC data shows that it may be possible to match the fundamental parameters of the underlying string vibrations. While not a direct discovery of strings *per se*, such an achievement would truly be the realization of Einstein's boldest aspirations.





CONCLUSION

DISCOVERING THE QUANTUM UNIVERSE

In graduate school at the University of Rochester, I decided to study particle physics, because to me it seemed the most exciting field I could imagine, and the most rewarding way to spend my life. But back then I never realized just how exciting it would be. In the past decade, we have understood that the beautiful and orderly universe we thought we knew so well, with its quarks and leptons and fundamental forces, is only a tiny fraction of what's out there. Ninety-five percent of the universe is a complete mystery: dark matter and dark energy. That's paradise for a particle physicist: a universe of unknown particles and forces to discover. I tell my students they are taking part in a revolution, not just in particle physics but in the way human beings see the universe. Every day brings us closer to the most amazing discoveries. That's what keeps me working late at night.

Young-Kee Kim
Physicist, University of Chicago

CHARGE TO THE COMMITTEE

Professor Frederick Gilman
 Chair, HEPAP
 Carnegie-Mellon University
 5000 Forbes Avenue
 Pittsburgh, PA 15213



Dear Professor Gilman:

We wish to congratulate you on the widely successful *Quantum Universe* report that with clarity and elegance expresses the great discovery opportunities in particle physics today. It has made a positive impact in Washington, DC, in the Nation, and abroad in conveying the drivers of the coming scientific revolution. As funding agencies and advisors of the Nation's research portfolio in this field, our ability to bring clarity and focus to outstanding scientific issues is an important responsibility. You have succeeded well with *Quantum Universe*.

This brings us to the following. The successful outcome of the International Technology Recommendation Panel, in coming to a clear technology recommendation, was a significant step toward a future Linear Collider. We now ask for your help in addressing another important issue in program planning and public communication. We need to explain clearly to the broad non-scientific community the need for a second large particle accelerator in addition to the Large Hadron Collider (LHC). Inevitably, the question arises as to how a less energetic electron accelerator would work in tandem with a higher energy proton machine

in exploring the energy frontier. How would these two accelerators complement one another? What crucial scientific discoveries might not be made without the LC?

To educate us and the public, and to clarify the matter more generally, we would like HEPAP to form a committee to write a document that addresses the following:

- In the context of already known physics, i.e. our current understanding of the electroweak symmetry breaking sector, what are the synergies and complementarities of these two machines? How would an LC be utilized in understanding a Standard Model Higgs, or whatever fulfills its role in the electroweak interaction?
- In the context of physics discoveries beyond the Standard Model (supersymmetry, extra dimensions or other new physics) that are assumed to be made at the Tevatron or early at the LHC, what would be the role of a TeV Linear Collider in making additional and unique contributions to these discoveries, in distinguishing between models, and in establishing connections to cosmological observations?

You may assume that the LHC will be operating over a 15-20 year timeframe with likely upgrades.

We are not asking for any new physics or simulation studies. As you know, there is by now a rather large body of work on this subject. Rather, we are asking for your help in distilling this body of work into a crisp, accessible, and persuasive case. The deliverable should be a short document (10 pages), accessible to knowledgeable non-experts (e.g., members of the EPP2010 Study, OSTP/OMB staff and ourselves). We ask that the report be completed as soon as practical but no later than summer 2005.

Finally, to further educate us as well as giving us an opportunity to refine the charge in conjunction with the committee that you appoint, we would suggest a half-day session at an upcoming HEPAP meeting devoted to this topic.

With best regards,



Robin Staffin
Associate Director
Office of High Energy Physics
Office of Science
U.S. Department of Energy



Michael Turner
Assistant Director
Mathematical and Physical Sciences
National Science Foundation

cc: Joseph Dehmer, NSF
Bruce Strauss, DOE SC-20

Discovering the Quantum Universe was prepared in response to a charge to the High Energy Physics Advisory Panel by Dr. Robin Staffin, Director of the Office of Science of U.S. Department of Energy and Dr. Michael Turner, Assistant Director for Mathematics and Physical Science of the National Science Foundation.



HEPAP

The High Energy Physics Advisory Panel has advised the federal government on the national program in experimental and theoretical high-energy physics research since 1967. HEPAP reports directly to the director of the U.S. Department of Energy's Office of Science and to the assistant director, Mathematical and Physical Sciences, of the National Science Foundation.

THE OFFICE OF SCIENCE

The Office of Science of the U.S. Department of Energy is the single largest supporter of basic research in the physical sciences in the United States, providing more than 40 percent of total funding for this vital area of national importance. It oversees—and is the principal federal funding agency for—the nation's research programs in high-energy physics, nuclear physics and fusion energy sciences.

The Office of Science manages fundamental research programs in basic energy sciences, biological and environmental sciences and computational science. In addition, the Office of Science is the federal government's largest single funder of materials and chemical sciences, and it supports unique and vital parts of U.S. research in climate change, geophysics, genomics, life sciences, and science education. The Office of Science continues to strengthen partnerships with other science agencies, including NSF and NASA, in support of basic research in the physical sciences.



THE NATIONAL SCIENCE FOUNDATION

Mathematical and Physical Sciences Directorate

The Mathematical and Physical Sciences Directorate (MPS) supports a strong and diverse portfolio of research and education in mathematics, astronomical science, physics, chemistry and materials research. The purpose of this work is both to deepen our understanding of the physical universe and to use this understanding in service to society. MPS is involved in many long-standing, very valuable partnerships with its sister US agencies, including DOE, NASA and NIH, as well as with international consortia. This mode of operation is sure to be augmented in the coming years.

DESIGN AND PRODUCTION

End Communications

Chicago, Illinois

PHOTOGRAPHY

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Fermilab Visual Media Services

ADDITIONAL GRAPHICS

Juna Kurihara, SLAC

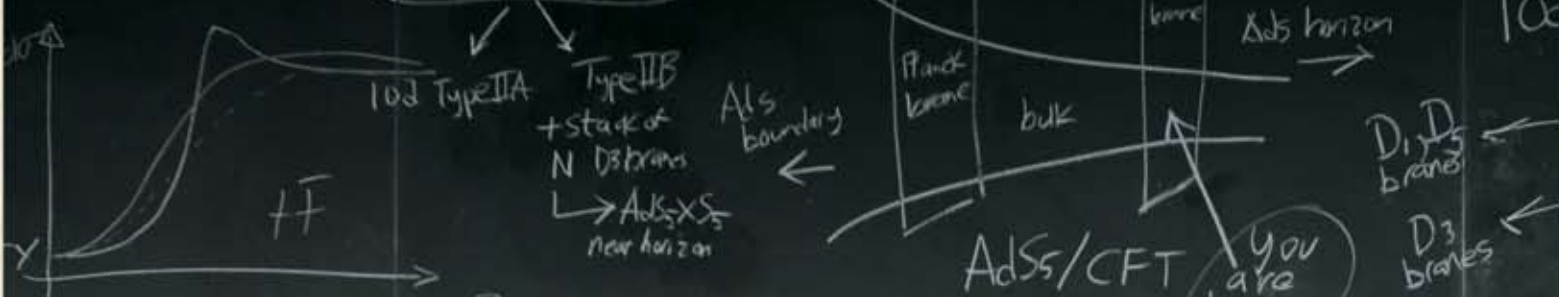
Terry Anderson, SLAC

Sandbox Studio

Filip Moortgat, CERN

Ianna Osborne, CERN

11d M theory



THRESHOLD BEHAVIOUR?
ISR / BEAMSTRAHLUNG

Right Stop?



$$D_{branch} = \frac{dQ^2}{Q^2} \frac{\alpha_s(Q^2)}{2\pi} P_{branch}(z)$$

Final-state emissions

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Supersymmetric particles?



Jet energy resolution



BASELINE

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st Barry)

Level one trigger

ATLAS	10^{34} luminosity	Rate kHz
Single muons	$p_T > 20 \text{ GeV}$	4
Single isolated EM cluster	$E_T > 30 \text{ GeV}$	22
3 jets	$E_T > 130 \text{ GeV}$	0.2
4 jets	$E_T > 90 \text{ GeV}$	0.2
Total		~ 40

VLO -> NNLO

DECREASED THEORETICAL PRECISION

RESUMMATION OF $\alpha_s^N(Q^2) \log^2(\frac{Q_F^2}{\mu_F^2})$

LL -> NLL -> NNLL

REDUCED DEPENDENCE ON

