DISCOVERING THE QUANTUM UNIVERSE

THE ROLE OF PARTICLE COLLIDERS

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INTRODUCTION

To discover what the universe is made of and how it works is the challenge of particle physics. "Quantum Universe," the 2004 report from the High Energy Physics Advisory Panel, identified nine key questions that define the field of particle physics today. The opportunity is at hand to address these great questions through astrophysical observations, in underground experiments and at particle accelerators.

This report explores in successively greater depth the role that accelerators will play in discovering the quantum universe. CHAPTER I introduces three discovery themes. CHAPTER II elucidates the meaning of the three themes in the context of the Large Hadron Collider and the International Linear Collider. CHAPTER III presents a discussion in depth of the physics of the Higgs particle and supersymmetry; the search for dark matter; and the quest for ultimate unification.

EINSTEIN'S DREAM OF UNIFIED FORCES

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

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THE TERASCALE: GATEWAY TO A QUANTUM REVOLUTION

Around the world, a broad research program is underway to address the key questions of particle physics. In the years just ahead, physicists expect that data from astrophysical observatories, from detectors underground and from accelerator experiments will result in a fundamental shift in the understanding of the universe and its physical laws.

Both theory and experiment suggest that discoveries will come in a range of very high energies called the Terascale, for the Teravolts, or TeV, of energy that define it. Indeed, since the time of Fermi in the 1930s, physicists have known that new forces of nature come into play in this energy region. In the intervening years, further advances, from precision measurements at particle colliders to astrophysical observations of dark matter, have strengthened the case for exploring Terascale energies.

At the Terascale, physicists expect to make discoveries that range from finding new forces of nature to detecting new dimensions of space. By resolving fundamental contradictions inherent in today's theories of particle physics, these discoveries will change the current picture with new theoretical constructs, such as supersymmetry and string theory. The result will be a radically new understanding of what the universe is made of and how it works.

LHC: ACCELERATING TO THE TERASCALE

Particle accelerators will play a special role in these discoveries. They have the unique ability to probe nature at the highest energies and smallest distances, and to reproduce in controlled laboratory environments forms of matter and energy last seen in the earliest moments of the universe.

Later in this decade, the Large Hadron Collider, a new proton-proton accelerator now under construction at CERN, will provide the first clear look at the Terascale. The LHC will provide a wealth of data from a region of energy beyond the reach of today's accelerators. By analyzing billions of collisions, physicists expect that LHC experiments will find new particles never before observed. They have already given names to hypothetical particles that they may find: the Higgs, superpartners, WIMPs, Z-primes. The largest and most sensitive particle detectors ever built will be in place to catch the traces of these proposed new forms of matter.

Whatever particles are found, their existence and the way they interact will shed light on the mysteries of the quantum universe. The LHC experiments could make a number of discoveries. Among the possibilities:

- The mass of ordinary matter arises entirely from particle interactions.
- All elementary particles have "superpartners."
- Invisible particles make up dark matter.
- Space has extra dimensions.
- New forces of nature appear at the Terascale.

Such discoveries will raise compelling questions – compelling because they will signal a sharply changed perspective on the universe. Responding to these Terascale discoveries will call for tools of still greater sensitivity.

THE LHC, THE LINEAR COLLIDER, AND THE QUANTUM UNIVERSE

As we enter the 21st century, we view accelerators not simply as producing new particles to be catalogued, nor merely as discerning the intricate workings of a cosmic clockwork. Rather, particles are messengers telling a profound story about the nature of matter, energy, space and time. The role of physicists is to listen to the story and translate it into the language of human knowledge.

Historically, the most striking progress in particle physics has come from combining results from proton accelerators, like the LHC, with results from electron accelerators, like the International Linear Collider, an electron-positron collider proposed by the global particle physics community. Physicists are designing the ILC to extend LHC discoveries and answer the questions that they will raise.

This report discusses the relationship between LHC discoveries and ILC discovery opportunities, using what physicists expect to be the most likely physics scenarios.

The discovery scenarios follow three themes.

1. **SOLVING THE MYSTERIES OF MATTER AT 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. **DETERMINING WHAT DARK MATTER PARTICLES CAN BE PRODUCED IN THE LABORATORY AND DISCOVERING THEIR IDENTITY.** 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. **CONNECTING THE LAWS OF THE LARGE TO THE LAWS OF THE SMALL.** 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.

DISCOVERING THE QUANTUM UNIVERSE

A summary of the relationship between discoveries at the LHC and the ILC in answering the nine fundamental questions of particle physics. 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
MYSTERIES OF THE TERASCALE	A single Higgs boson, similar to that predicted by the standard model	Discover the effects of extra dimensions or other new phenomena by measuring Higgs couplings to other particles.	1,3
	More than one Higgs-like particle	Discover a new source of matter-antimatter asymmetry by observing angular distributions in Higgs decays.	9
	Superpartner particles	Confirm the symmetry of supersymmetry, or detect inconsistencies in the theoretical framework.	1,2
	A complicated spectrum of superpartner particles	Feed data on lighter superpartners back into LHC analyses and observe those superpartners that LHC cannot detect. Discover what kind of supersymmetry is operating.	1
	Evidence for extra dimensions	Discover the number and shape of the extra dimensions, and discover the locations of particles within them.	3
LIGHT ON DARK MATTER	Missing energy from a weakly interacting heavy particle	Measure the particle's mass, spin and couplings; and determine the thermal relic density of this particle. Discover its identity as dark matter.	6
	Heavy charged particles that appear to be stable	Discover that these particles eventually decay to very weakly interacting particles. Identify these "superWIMPs" as dark matter.	6
EINSTEIN'S TELESCOPE	Superpartner particles	Extrapolate supersymmetry parameters to reveal force unification and matter unification at ultra-high energies.	4,5
	A Z-prime boson, representing a new force at short distances.	Discover the origin of the Z-prime by measuring its couplings to lighter particles. Connect it to the unification of quarks with neutrinos, of quarks with Higgs, or with extra dimensions.	4,7
	Superpartner particles matching predictions of supergravity	Use extrapolated supersymmetry parameters to discover features of string theory and extra dimensions.	3,8

LEGEND: THE QUESTIONS

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?

5 Why are there so many kinds of particles?

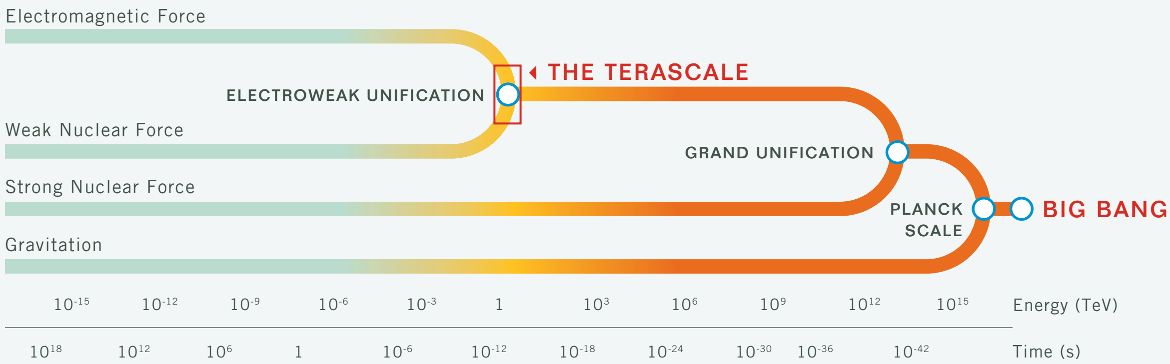
6 What is dark matter? How can we make it in the laboratory?

7 What are neutrinos telling us?

8 How did the universe come to be?

9 What happened to the antimatter?

From "Quantum Universe"



BACK TO THE BIG BANG

Particle accelerators allow physicists to look farther and farther back in time, to revisit the high energies of the early universe after the Big Bang. Do the four forces we observe today – gravity, the electromagnetic force, and the weak and strong forces – converge to a single unified force at ultrahigh energy? Particle collisions may provide the first evidence for such unification of forces.

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 matter 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 connects 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 take us 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.

CHAPTER II
DISCOVERING THE QUANTUM UNIVERSE: AN OVERVIEW

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

A

MYSTERIES OF THE TERASCALE

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?

Later in this decade, experiments at the LHC 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 supersymmetry, extra dimensions of space, parallel universes – or something completely unexpected.

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, the Higgs 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 the Higgs field, all matter would crumble; atoms would fly apart at the speed of light.

So far, no one has ever seen the Higgs field. To definitively detect it, particle accelerators must first create Higgs particles – the particles responsible for the Higgs field. By measuring their properties, physicists will probe the Higgs field itself. 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 the hallmark of linear collider physics. The 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? The linear collider would be able to make clean determinations of critical Higgs properties at the percent level of accuracy.

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. Every particle tells a story. The discovery of a new particle is often the opening chapter of an entirely new story revealing unexpected features of our universe.

When the positron, the brother of the electron, was first detected, the discovery was not just 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, telling 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. Within a few years, particle accelerators had produced myriad cousins of the pion: etas, deltas, rhos, omegas. Soon physicists were running out of Greek letters to name them all. Finally the story became clear. These were not elementary particles after all, but tiny bags of quarks, held together by a new force so strong that no quark could ever escape it.

Other aspects of the universe may 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 and interactions, physicists could discover the shape of the extra dimensions.

Using the LHC and the 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 unified story of the dark and the visible worlds.

A Higgs discovery, however, will raise a perplexing new question: According to our present understanding, if the Higgs exists, it should have a mass a billion billion times beyond the Terascale. Although a Terascale Higgs is necessary to give mass to particles, its own mass should be much, much greater. Why does the Higgs have a mass at the Terascale?

For many years, theorists have tried to explain this mystery, devising myriad possibilities, including supersymmetry, extra dimensions and new interactions. Most of these theories bring with them dark matter particles and other new phenomena, all at the Terascale.

Which, if any, of these theories is correct? Sorting that out is a primary task for the LHC and the linear collider. The LHC will have enough energy to survey the Terascale landscape. Then the linear collider could zoom in to distinguish one theory from another.

For example, theories of supersymmetry and extra dimensions predict new particles that are close relatives of the Higgs. Some of these particles are difficult to detect or identify at the LHC; others are difficult to distinguish from the Higgs itself. Linear collider experiments would have unique capabilities, including polarized beams, to allow physicists to identify these particles and pinpoint how they relate to their standard model partners – through supersymmetry, extra dimensions or something as yet unimagined.

The Terascale may hold the answers to still more 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 differently – that is, in undiscovered sources of 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 these new sources of matter-antimatter asymmetry.

A map of the Terascale will take physicists far into new scientific territory as 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

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.

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 familiar baryonic matter. 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 suggests a possible connection. Supersymmetry provides a natural context for the Higgs field and a possible explanation for the small but finite value of dark energy.

Definitive evidence for dark matter has come from many sources, including astrophysical observations of clusters of galaxies that would have flown apart if held together only by visible matter. As close to home as the Milky Way, visible matter alone would not keep the stars within 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.

There is no reason to think that dark matter should be any simpler than visible matter, with its multiple quarks and leptons. Historically, new particles have not appeared 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 it in the laboratory.

LARGE HADRON COLLIDER

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

The LHC accelerates two beams of particles in opposite directions, smashing them together to create showers of new particles via Einstein's famous equation $E=mc^2$. The beams of protons or lead ions 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 TeV to give a proton-proton collision energy of 14 TeV. Proton collisions have the advantage of very high energy, but they also have drawbacks. The protons themselves contain quarks and gluons, each carrying a fraction of the proton's 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.

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 B meson decays. ALICE, using LHC's ability to accelerate lead ion beams, 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 that will link thousands of computers worldwide and create a global computing resource to store and process the deluge of data from the LHC.

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 linear collider. Is this Terascale conjunction a coincidence? Most theories of Terascale physics, although developed with entirely 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 linear collider have the potential to produce massive 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. 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. The linear collider would then zero in to determine its mass and interaction strength – to take its fingerprints and make a positive identification. By a fine-tuned energy scan, the linear collider would also catch any dark matter candidates that might be hiding in the multitude of background events in LHC collisions.

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

INTERNATIONAL LINEAR COLLIDER

The International Linear Collider is a proposed new accelerator designed to work in concert with the LHC to discover the hidden mechanisms of the microphysical world. The ILC would consist of two linear accelerators, each some 20 kilometers long, hurling beams of electrons and their antimatter twins, 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 stuffed into beams approximately 3 nanometers thick. Positrons start from one end of the collider, electrons from the other. As the particles speed down the accelerator, superconducting accelerating cavities give them more and more energy. They meet in an intense crossfire that ensures a high rate of collisions. The energy of the ILC's beam can be adjusted to home in on processes of interest. ILC beams would also be polarized, adding power to the subsequent 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 North America, Europe and Asia. The ILC will be designed, funded, managed and operated as a fully international scientific project. An international effort will define the administrative and financial model for the project.

C

EINSTEIN'S TELESCOPE

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?

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. A century after Einstein, the combined capabilities of the LHC and the linear collider promise to open the Terascale for discovery and lead the way toward that ultimate theory.

The precision of its electron-positron collisions would give the 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, the linear collider would have the potential to 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.

The linear collider's capability as a telescope to ultra-high energies rests on the in-depth knowledge of the nature of matter that particle physicists have achieved in the past few decades. This hard-won understanding gives physicists a way to measure the effects of phenomena occurring at energies beyond those that accelerators can reach.

For now, however, the telescopic view is clouded by physicists' ignorance of Terascale physics. Data from the LHC and the ILC would clear the view of the Terascale to allow the 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)? Physicists believe that there was just one force 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 concepts including supersymmetry, which predicts superpartners for all of the known particles and forces; and the presence of extra dimensions of space. Among the most exciting possibilities for the LHC is its very real potential to discover superpartners.

Theorists cannot yet predict at what energy the evidence for extra dimensions – if they exist – will emerge. For that reason, the linear collider's sensitivity makes 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 the 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.

CHAPTER III
DISCOVERING THE QUANTUM UNIVERSE: DETAILED SCENARIOS

A discussion in depth of the physics underlying the most likely scenarios for discovery at the Large Hadron Collider and the International Linear Collider

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

HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY?

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A MYSTERIES OF THE TERASCALE

Both theoretical calculations and data from experiments indicate that the mass of standard model particles is generated at the Teravolt energy scale. Calculations within the standard model itself show that, without a Higgs particle or some other new phenomenon, the theory becomes inconsistent at energies near 1 TeV. Physicists designed the Large Hadron Collider with more than enough energy to observe whatever resolves this inconsistency and to explore the Terascale.

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 without revealing the structure of the proton itself. Finally experiments with electron beams discovered that protons are made of quarks and gluons. Later experiments cleanly measured 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 their detectors. Shortly afterwards, physicists discovered such jets in collisions at the new CERN proton-antiproton collider. Jets are now a tool for all analyses that search for new particles whose decays involve quarks and gluons.
- The discovery of the J/psi 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 the detectors was set for different phenomena and missed the J/psi. A different trigger and redesigned detectors allowed observation of the J/psi and showed how it is produced by the strong interactions in high-energy proton-proton collisions.
- After the discovery at Fermilab of the Upsilon, containing the bottom quark, electron-positron machines soon found a whole spectroscopy 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.
- Detectors at electron-positron colliders that could measure sub-millimeter 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. Detectors that could spot the telltale displaced vertex of the bottom quark in top quark decays were important to the discovery of the top at the Tevatron collider.

Higgs particles have mass, and can only be directly produced by particle collisions with high enough energy. Below this energy, the effects of the Higgs can be felt through virtual particles – particles that exploit quantum uncertainty to wink in and out of existence at microscopic scales. For example, a Z boson produced in a collider can emit and reabsorb a virtual Higgs particle in the instant before the Z boson itself decays. Precision measurements of the decays of many thousands of Z bosons can detect this effect. Data collected during the last 20 years at LEP, SLC and the Tevatron reveal several such small effects consistent with a Higgs particle with mass in the range 0.1 to 0.25 TeV. These effects may offer a glimpse of what lies ahead at the Terascale.

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 the Higgs presents mysteries of its own that will be even more challenging to solve. For example, Higgs particles have mass, like matter particles, but in most respects Higgs particles behave more like force particles. How can this be? In truth, the Higgs is neither matter nor force; the Higgs is just different.

FIGURE 1

The discovery window for the Higgs. Direct searches at the LEP collider put a lower limit on the Higgs mass. The Higgs mass also has an upper limit, if quantum fluctuations seen in precision data are caused by a standard model Higgs. LHC experiments will be sensitive to both standard and nonstandard Higgs, over a mass range larger than the colored region shown here.

The biggest mystery of a Terascale Higgs is how it manages to exist at all. When the Higgs gives mass to other particles, quantum theory says that swarms of virtual particles will drag the particle masses toward higher and higher values. In the standard model, this quantum instability is forbidden by fundamental symmetries of nature. Ironically, these symmetries stabilize the mass of every particle except that of the Higgs itself. Absent a breakdown of quantum theory or a gigantic cosmic coincidence, some new fundamental principle or interaction must stabilize the mass of the Higgs. This could be supersymmetry, new forces, extra dimensions of space or something else. Whatever it is, it should be observable at the Terascale.

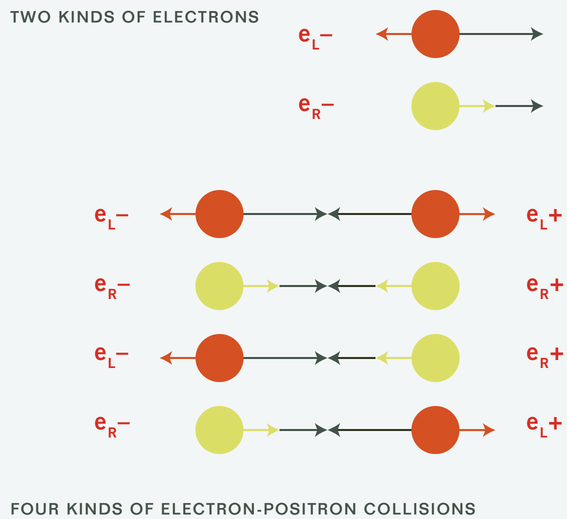
Physicists suspect that there may be many Higgs-like particles: Why should the Higgs be the only one of its kind? Supersymmetry requires at least five Higgs particles; other models of Terascale physics predict even more. Theorists have hypothesized Higgs-like particles for many reasons seemingly unrelated to the origin of mass: the "radions" of extra dimensions; the "moduli" of string theory; the "inflatons" of cosmic inflation. There are even proposed Higgs particles related to dark energy.

If many Higgs-like particles exist, they may interact directly with each other, as well as with other new particles such as the superpartners of supersymmetry. Physicists call this collection of particles and interactions "the Higgs sector." Even if the Higgs does not interact directly with its Higgs-like cousins, virtual particles mix them together. Thanks to quantum theory, when a Higgs particle is produced, it contains a bit of its Higgs-like cousins. The Higgs sector is fertile ground for Terascale discovery.

EXPLORING THE HIGGS SECTOR

Physicists expect experiments at the LHC to discover a Higgs particle. This landmark discovery will represent the culmination of decades of resolute experimental and theoretical effort. However, new questions about the Higgs will emerge. The LHC experiments will answer some of them, but the rest are likely to require precision measurements at the linear collider.

The LHC experiments can observe a Higgs particle in a variety of production channels. They will be able to measure its mass to 0.1 percent, as well as ratios of Higgs branching fractions (the fractional rate of decay to specific final states) to some of the standard model particles to 10 to 20 percent accuracy. For example, the ratio of the Higgs decay rate into W bosons to the decay



POLARIZED BEAMS

An electron is an electron is an electron is an electron. Well, not quite: by studying properties of the weak force, physicists have discovered that there are two different kinds of electron. One kind, called e_L^-, interacts with W bosons, the other kind, called e_R^-, does not. They both interact with Z bosons, but with different charges.

These two kinds of electron also differ in their polarizations. We are all familiar with the two polarizations of light: polarized sunglasses block the horizontally polarized light, which contains most of the glare, and let through the vertically polarized light. Electrons also have two polarizations, which physicists call left-handed and right-handed. This refers to the "spin," a quantum bit of angular momentum always carried by the particle. An e_L has a left-handed spin, denoted in the figure by a colored arrow pointing opposite to the direction that the electron is moving; an e_R has a right-handed spin, denoted by a colored arrow pointing in the same direction that the electron is moving.

With two kinds of electrons, and the corresponding positrons e_L^+ and e_R^+, four different kinds of collisions can occur in a linear collider. When both spin arrows are pointing in the same direction, collisions have the right amount of angular momentum to make a Z boson or a photon; otherwise they do not. Similarly, only one of the four kinds of collision can produce a pair of W bosons.

The linear collider is designed to produce an almost completely polarized electron beam, either all e_L or all e_R. The positron beam could also be polarized. This would allow linear collider experiments to switch among four different kinds of collisions for making a variety of discoveries, including the mechanisms of supersymmetry breaking and the identity of dark matter.

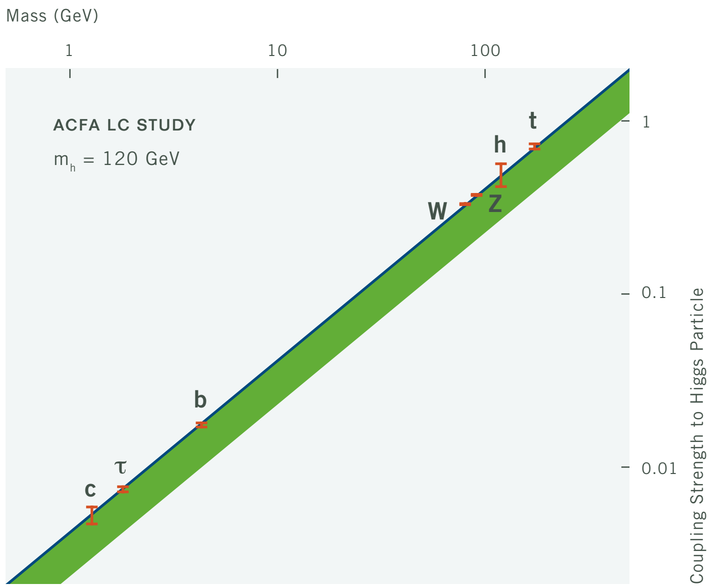


FIGURE 2

Higgs interactions reveal extra dimensions. The linear collider would precisely measure the interaction strength of the Higgs with standard model particles. The straight blue line gives the standard model predictions. The range of predictions in a class of models with extra dimensions is indicated by the green band, which ranges at most 30% below the standard model. The models predict that the effect on each particle would be exactly the same size. The red error bars indicate the level of precision attainable at the linear collider for each particle, including couplings to tau leptons, three kinds of quarks (c,b,t), W and Z bosons, and the Higgs self-coupling. These measurements could discover and explore the extra dimensional physics.

rate into Z bosons can be directly determined at the LHC at 15 percent accuracy for a 150 GeV Higgs. Absolute branching fractions to individual final states can only be determined if the analysis includes specific assumptions about the structure of the theory.

Experiments at a 0.5 TeV linear collider could produce the Higgs in association with a Z boson, e^+e^- to Z + Higgs. Since the initial beam energy is known and the final-state Z boson is directly observed and reconstructed from its decay products, simple kinematics and conservation of energy would allow the linear collider to observe the Higgs no matter how it decays. This fact allows the linear collider experiments to measure the properties of the Higgs, including its branching fractions and spin, to the accuracy of a few percent. The standard model predicts that the strength of the Higgs interactions with particles is directly proportional to the mass of the particle; this precision measurement would provide a critical test. Determining whether the observed Higgs is from the standard model and is responsible for mass, or whether it arises from a more complex theory is likely to require the accuracy achievable at the linear collider. (For an example, see Figure 2.)

The observed Higgs will have modified properties at the detailed level if it mixes with additional Higgs-like particles present in supersymmetry or arising from extra dimensions of space, or even from theories of dark energy.

These cousins of the Higgs may be produced directly at the LHC, or they may be too heavy or interact too weakly to be observed. In the latter case, physicists will only know of their existence by detecting their influence on the properties of the Higgs with the precision measurements available at the linear collider. The pattern in which the Higgs properties are altered reveals the origin of the extra Higgs particles, and the magnitude of the deviations points to their mass.

For example, quantum fluctuations of the size of extra dimensions give rise to a Higgs-like cousin, the radion. Higgs-radion mixing modifies the strength with which the Higgs interacts with standard model particles. In particular, this mixing reduces the strength compared to standard model expectations. The Higgs interaction strength with the quarks, leptons, W and Z bosons is suppressed by at most 30 percent, spanning the full parameter space of extradimensional models allowed by present experiments. Extra dimensions predict that the effect on each quark, lepton and heavy gauge boson would have exactly the same size. Detecting deviations of this magnitude requires the linear collider's precision. If such deviations appear, experiments at the linear collider

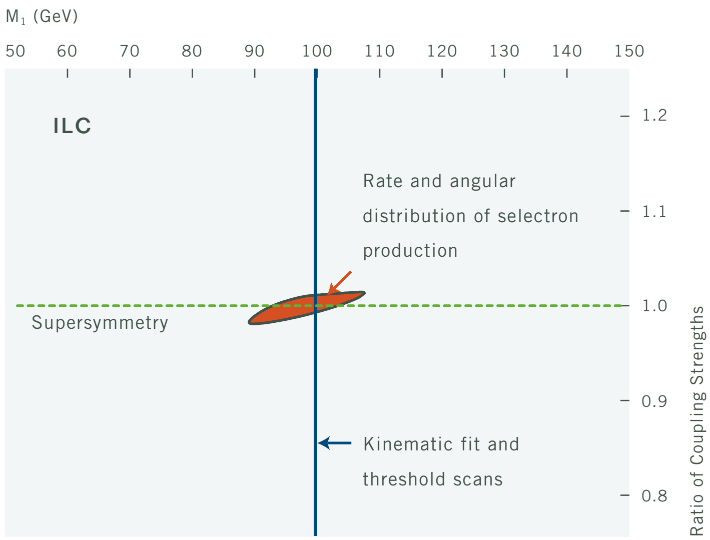


FIGURE 3
Discovering the symmetry of supersymmetry. The ratio of coupling strengths for two different superpartner interactions could be determined with a precision of 2% from measuring the properties of the supersymmetric partner of the electron at the ILC. The gaugino mass parameter M_1 could be separately determined to lie within the blue band from threshold energy scans. Supersymmetry predicts that the intersection of the colored regions should be at a ratio of one. This is a stringent test of the symmetry of supersymmetry.

could accurately measure their magnitude and in turn determine the size of the extra dimensions.

REVEALING NEW SOURCES OF CP VIOLATION

The dominance of matter over antimatter in the universe remains a mystery, not explained by the standard model. A complex Higgs sector 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. This moment is called the electroweak phase transition. With just the physics of the standard model present in the universe, this phase transition has almost, but not quite, enough ingredients to produce an imbalance of matter over antimatter. What appears to be missing is a stronger source of CP violation and some additional interactions of the Higgs with other Higgs-like particles.

A complex Higgs sector is a promising source for both these ingredients and is predicted by many theories. Supersymmetry, for example, allows for several new sources of CP violation and requires an extended Higgs sector.

The LHC can take the first step in investigating this scenario by discovering multiple Higgs particles or other evidence for an extended Higgs sector, such as superpartners. Then the question will be whether new sources of CP violation exist at the Terascale. In principle, they could be observed from the decays of Higgs-like particles, superpartners or other Terascale relatives of the Higgs. However it is extremely difficult to extract CP information from particle decays without precise control and knowledge of the initial collisions that create the particles, making it a challenge for LHC experiments.

Linear collider experiments could detect CP violation much more readily. For example, LHC experiments might discover two neutral Higgs-like particles, H1 and H2, and determine that they have roughly opposite properties under the CP symmetry. If the linear collider then produced both particles in association with a Z boson, i.e. e^+e^- to Z+H1 and e^+e^- to Z+H2, it would signal the discovery of a new source of CP violation. This production would show that both particles are mixtures of different CP properties. The precise mixture could be determined by measuring details of their decays. A simulation of a light Higgs decaying to tau leptons used angular distributions of the decays to estimate that the linear collider running at 0.35 TeV could determine

CP mixtures with an accuracy of 3 percent. This degree of precision is in the right range for explaining matter domination in the universe. At higher energies, the linear collider would also be sensitive to CP violation in the decays of superpartners.

DISCOVERING SUPERSYMMETRY

Supersymmetry is a proposed symmetry of nature that doubles the number of fundamental particles. Every particle in the standard model would have a heavier partner with a different spin. The superpartners that feel the strong interactions, the partners of the standard model quarks and gluons, would be copiously produced at the LHC. They decay in several steps to the lightest superpartner and a rash of standard model particles, making the final state quite complicated. This decay chain will likely obscure many of the properties of the superpartners and may make them difficult to study at the LHC.

The linear collider is best-suited for producing the superpartners of the leptons and weak gauge bosons. The beam energies could be tuned to scan the thresholds for superpartner production, allowing the linear collider experiments to focus on one type of superpartner at a time, with a clean and simple final state. These scans and the precise knowledge of the beam energy would result in measurements of the partner masses to the precision of a percent or better.

The mass spectrum of the partners yields information on the type of supersymmetric model nature has chosen; this in turn tells us why the superpartners are heavy. Precision measurements enable accurate extrapolation to higher energy scales, exploring the physics responsible for the unification of the forces. Precision measurements of the lightest superpartner properties can be used to refine calculations of the supersymmetric component of the dark matter relic density and facilitate comparison with astrophysical data.

Precise mass determinations of the lightest superpartners at the ILC would feed back into the analyses of the LHC experiments, clarifying decay chains and perhaps discovering new ones for the superpartners previously found at the LHC. Detailed studies have shown that this cross-input would lead to significant improvements in the LHC analyses, especially the detection of heavier gauginos, and the determination of the masses of quark and gluon superpartners. This would improve the ability to characterize the underlying supersymmetric theory.

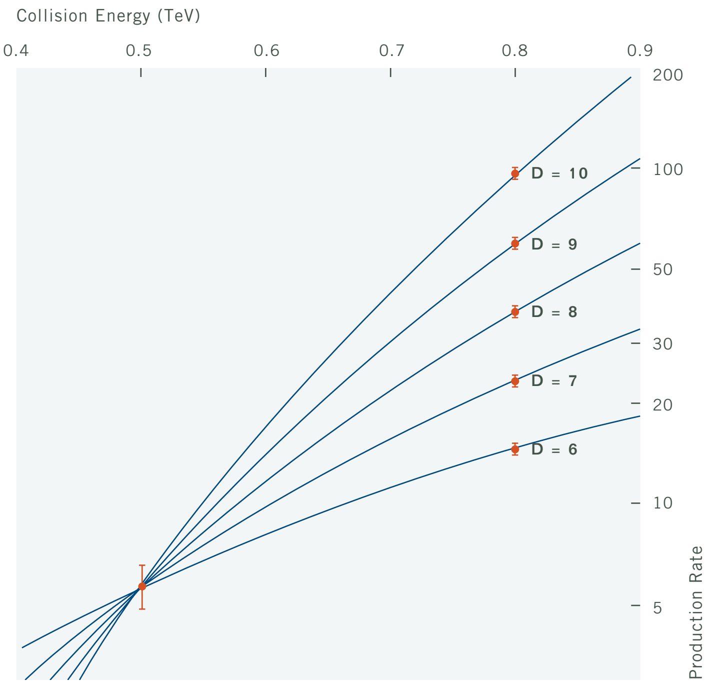


FIGURE 4

Determination of the number of extra dimensions. The LHC may discover evidence for extra dimensions of space. For a large class of models, this implies that the linear collider could produce, in association with a high-energy photon, particles that disappear into the extra dimensions. The production rate for this process varies with both energy and the number of extra dimensions, as shown. By operating the linear collider at two different collision energies, the number of extra dimensions could be measured in a straightforward way.

Such a synergy between proton and electron accelerators follows a historical pattern where discoveries at one type of machine have enriched the science of the other. While this report focuses on how LHC discoveries will lead to ILC discoveries, this supersymmetry scenario shows how ILC discoveries could also affect the science coming from LHC experiments.

Supersymmetry is a broad framework that could well encompass unexpected phenomena that would be challenging to capture and archive in the complex LHC environment. The selection of events to be written to the LHC data set might then need to be reoptimized to increase the "catch" of these phenomena. The ILC, if running concurrently, could guide this process.

The theory of supersymmetry entails more than just a suite of new particles; it is a new symmetry, or principle of nature. Physicists must observe the predictions of this symmetry in order to know that supersymmetry is present in nature and is responsible for the partner particles. A primary consequence of this symmetry is a specific relation between the strength of interactions of the standard model particles and the corresponding interactions of their partners. The LHC lacks the resolving power to measure the superpartner interactions at the level required to test the symmetry of supersymmetry.

Linear collider experiments could measure the strength of superpartner interactions by making use of the known scattering energy, polarization of the electron beams, and the clean experimental environment. For example, they could study superpartner interactions in the pair production of supersymmetric electrons. Beam polarization isolates the desired coupling from other interactions that also contribute to this production. The known kinematics and clean environment allow for the reconstruction of the production angle of the supersymmetric electron. This, together with the precise partner mass determination discussed above, determines the superpartner interaction strength to a level of 2 percent precision. At this level of accuracy experimenters could expect to see violations of the supersymmetry relations due to quantum effects from other kinds of new phenomena, if they exist.

Thus linear collider experiments could discover the symmetry of supersymmetry, verify that the new particles at the LHC are indeed superpartners, and, with the LHC, establish the validity of supersymmetry as a theory of nature.

EXPLORING EXTRA DIMENSIONS

Extra dimensions of space are a prediction of string theory, whose discovery would dramatically change our view of space and time. Each point in space-time would have additional spatial dimensions attached to it. The extra dimensions might be too tiny to see. Yet the particles of the standard model could already live in the additional dimensions and feel their effects. As a particle moves in an extra dimension, its extra kinetic energy is converted to a tower of massive particles in our four-dimensional world. The mass of each partner state in this tower is related to the size of the tiny dimension. The characteristics of the extra dimensions are encoded in the behavior of this tower of partners; measurement of their properties would reveal what the additional dimensions look like.

THE TAU LEPTON – AN UNEXPECTED DISCOVERY

With the discovery of the fourth, or charm, quark, particle physicists had a tidy and symmetrical theory of nature with four quarks and four leptons as the constituents of all matter. This picture did not last long, however. An even more surprising discovery was waiting in the same energy region as charm.

In 1975, evidence came from the SPEAR electron-positron collider at SLAC for a third charged lepton, in addition to the electron and the muon. Clean particle events, without the debris of the initial beam, along with knowledge of the total energy and momentum that is characteristic of electron-positron colliders, were crucial to the discovery. They allowed isolation of events that could come from no other source than a new lepton, the tau. Without an electron-positron collider, the discovery of the tau would have been impossible in that era.

Just as the muon acted like a heavier electron, the data indicated that the tau did too, only it was 17 times heavier yet. Experimental evidence soon showed that, like the electron and muon, the tau had a neutrino partner. I.I. Rabi's "Who ordered that?" about the muon gave way to the bigger mystery of why nature had chosen the pattern of three charged leptons and their three neutrino partners.

Without knowledge of the tau, other measurements, such as those at hadron colliders of the decay patterns of the W and Z bosons (which have important decay modes involving the tau and the tau neutrino), would have been misinterpreted, mistakenly contradicting the predictions of the standard model and sending physicists down a false trail.

Uncovering the tau had led to the proposal of a new theoretical construct of six leptons and six quarks. Would nature follow the six-quark paradigm? The focus turned to experiments at proton accelerators, which could produce particles with much higher masses. The Upsilon, containing the bottom quark, was discovered at Fermilab in 1977. Two decades later, experimenters found the top quark at the Tevatron collider. The quarks and leptons of the standard model were in place.

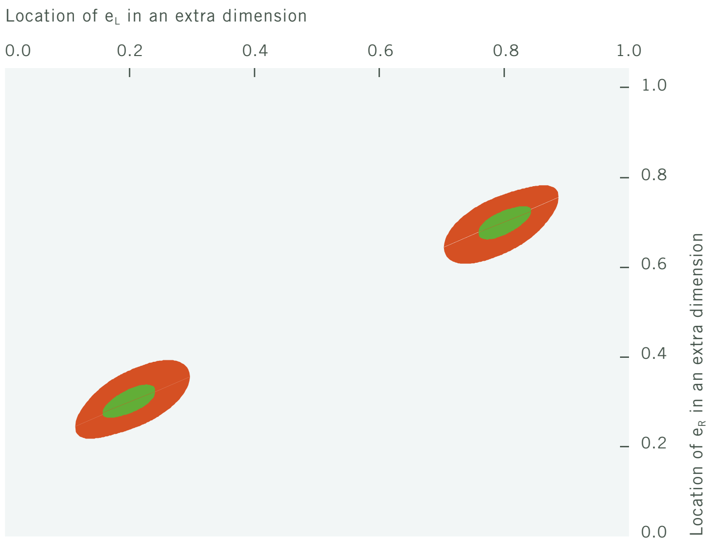


FIGURE 5
Where particles live in extra dimensions. The locations of the two kinds of electron (left- and right-handed) in an extra dimension could be measured with the polarized beams of the linear collider. In this figure, the horizontal and vertical scales represent distance along the extra dimension, in units of hbar c / 4 TeV (1/20,000th the diameter of a proton).The red and green curves correspond to estimated experimental errors of a 0.5 and 1.0 TeV ILC, respectively. ILC observations would place particles in one of these two colored regions.

If extra dimensions exist at the Terascale, then the LHC will discover partner towers. The LHC and ILC would then study these partner towers and determine the number of dimensions, their size and shape, and which particles live inside them. For example, the linear collider experiments could measure the number of extra dimensions in a simple way. The production rate for the graviton partner tower in association with a photon depends on the number of dimensions. Measuring this rate at two different center-of-mass energies at the linear collider cleanly gives the number of additional spatial dimensions.

The identification of the partner tower provides an illustration of how the LHC and ILC would span the range of possibilities. For example, if a partner tower state were produced singly at the LHC and appeared as a resonance peak, then LHC experiments could determine which standard model particle it is associated with. However, if the partner state were produced in pairs at the LHC, the techniques for identification would be lost, and threshold scans at the linear collider could cleanly detect the partner's standard-model counterpart. If the partner is only detected via its virtual effects, then precise measurements of cross sections and angular distributions at the linear collider could pinpoint the partner's identity. In particular, these virtual effects could uniquely disclose whether gravity resides in the additional dimensions.

An intriguing example of how nature could operate is given by a possibility known as split quarks and leptons. In this scenario, each quark and lepton in the standard model has two components, e_L and e_R. These two components could sit at different locations in the extra dimensions; this would explain why matter particles have their particular masses. Polarized beams at the linear collider could probe such a scenario by detecting differences in the way the two components of the electron behave. Experimenters would then observe deviations in the polarized scattering of electrons, $e^+e^-_{L,R}$ to e^+e^-. The attainable level of precision is more than enough to resolve the locations of the two components of the electron. In this way, the linear collider could map the geography of the standard model particles in the extra dimensions. Such a discovery would require the capability of beam polarization, unique to the linear collider.

THE COSMOLOGICAL COUSINS OF THE HIGGS

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

Moreover, theorists have predicted other Higgs-like particles without spin as essential components of cosmology. The Higgs particle will be the first step towards understanding such 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 the vast size it has today. To power inflation, physicists postulate one or more Higgs like particles called inflatons.

Why is the universe speeding up? Cosmological observations have confirmed that the expansion of the universe is accelerating. Dark energy, which makes up a staggering 70 percent of the 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 involve other Higgs-like particles.

Why are there particles that don't spin? One possible explanation is supersymmetry, which says that particles that 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 hope to find out why and how the Higgs exists. This knowledge could yield insights into the mechanisms for inflation or dark energy.

B LIGHT ON DARK MATTER

WHAT IS DARK MATTER? HOW CAN WE MAKE IT 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.

Proposed candidates for dark matter particles include neutralinos, axions, Kaluza-Klein particles, gravitinos, WIMPzillas, Q balls, and a roster of other particles with equally exotic names and properties to match. These candidates are not all mutually exclusive. For simplicity, most theoretical studies assume that all of dark matter is composed of a single kind of particle, but if the dark universe is as rich and varied as the visible world, this assumption may appear as simplistic to future generations as ancient theories of earth, air, fire and water appear to us today.

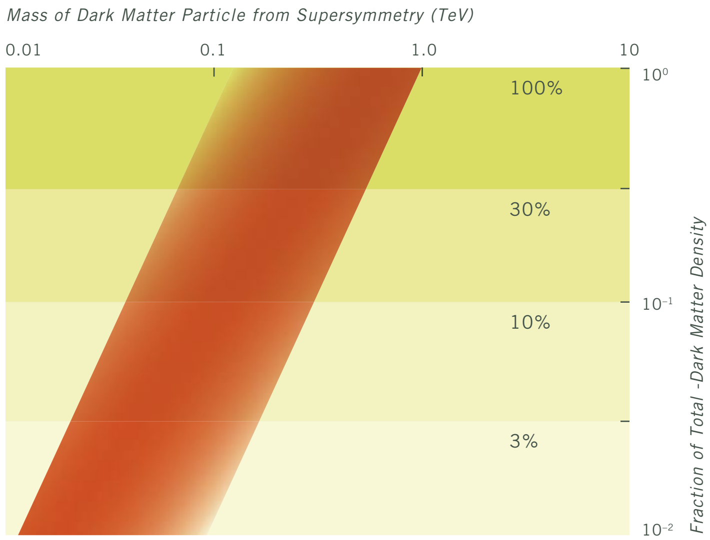


FIGURE 6

Terascale dark matter. Theories of Terascale physics often predict new heavy particles with weak interactions. Assuming, for example, that there is a new particle that feels only one of the weak interactions of the standard model, we can compute its thermal relic density as a function of its mass. The band roughly indicates the expected amount of dark matter left over from the Big Bang as a fraction of the experimentally observed dark matter abundance in the universe.

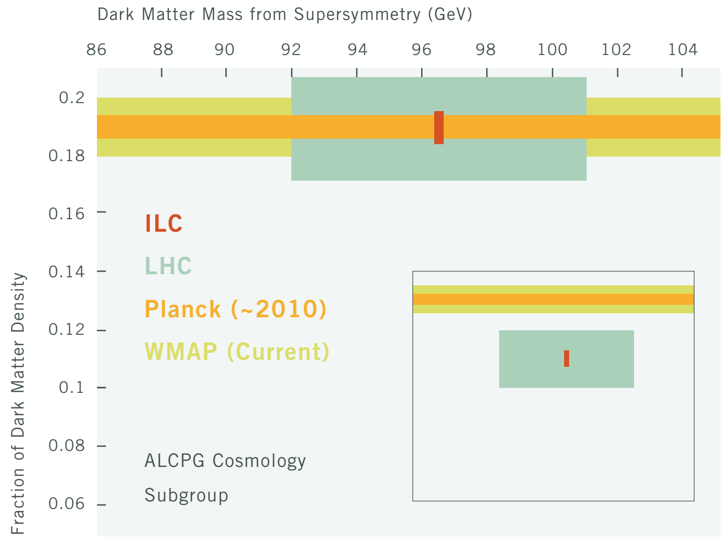
DARK MATTER IN THE LAB

A major goal of the LHC and ILC is to identify one or more components of dark matter by producing it in the laboratory and studying its properties. High-energy colliders are the tools of choice for this exploration. In the past, every large advance in collider energy has produced new forms of matter: tau leptons, bottom quarks, top quarks and many others. The LHC and ILC build on this tradition, with particle collisions at energies almost an order of magnitude beyond current colliders – a golden opportunity to create and study new particles and distill the resulting data into new laws of nature.

What evidence suggests that dark matter will show up at the next jump in collision energy? In fact, the Terascale is a promising hunting ground. The current understanding of particle physics and cosmology allows physicists to extrapolate back to early times in the history of the universe. Shortly after the Big Bang, the universe was dense and hot. Particles annihilated with antiparticles to form pairs of dark matter particles, which in turn annihilated to form particle-antiparticle pairs. As the universe expanded and cooled, however, meetings between particles and their antiparticles became rarer, until ultimately the number of dark matter particles approached a constant value. The resulting density of dark matter particles, the thermal relic density, depends primarily on the interaction strength of dark matter, which, in turn, is naturally related to the mass of the dark matter particle. Detailed calculations in many different theoretical frameworks show that for the thermal relic density to be in the range of the observed dark matter density, the mass of the dark matter particle should be at the Terascale.

This simple explanation of the observed amount of dark matter strongly suggests new particles within the energy reach of the LHC and the ILC. It is independent of other indications from particle physics, but the various strands are intertwined. In fact, many of the most appealing ideas in particle physics predict the existence of Terascale particles that are ideal candidates for dark matter. This confluence of motivations, all pointing to the Terascale, suggests a synergy between studies of the very small and the very large. There is no guarantee that all of dark matter is in the form of Terascale particles, but because Terascale particles naturally are present in cosmologically significant densities, a careful search for dark matter candidates at Terascale colliders is an essential step toward understanding dark matter.

FIGURE 7
Relic density and mass determinations for neutralino dark matter. The WMAP and Planck satellites determine the amount of dark matter in the universe. The LHC and ILC colliders determine the neutralino's thermal relic density and mass. Agreement between satellite and collider relic densities would imply that neutralinos are the dark matter. Disagreement, as shown in the inset, would establish the identity of some of the dark matter as neutralinos and provide evidence for additional components.



DARK MATTER UNDER THE MICROSCOPE

The identification of dark matter candidates is the first step toward discovering dark matter. The candidate particles' properties must then be precisely determined and compared with those required for dark matter. These measurements are challenging, because dark matter interacts so weakly that it leaves no trace in collider detectors. However, careful studies of missing momentum and missing energy can determine dark matter properties. Such search strategies have been honed for years and have been very successful in the study of neutrinos. With this experience, physicists working at the LHC are likely to find the first evidence for Terascale dark matter.

But is it really dark matter? How much does it contribute to the dark matter total? The linear collider, with its flexibility to select collision energies and well-defined states of polarization, provides the ideal environment for detailed studies. By exploiting all of these properties, the linear collider would conduct an extremely thorough search for dark matter candidates and could determine candidate masses and interaction strengths without the need for theoretical assumptions.

Through such measurements, the LHC and ILC would determine the thermal relic densities of dark matter candidates at the percent level. (See Figure 7) Three of the many possibilities:

1. *The LHC discovers a host of new particles, some revealed through missing momentum.* Experiments at the LHC and ILC show that the new particles are supersymmetric and that the missing particles are neutralinos, quantum mechanical mixtures of several supersymmetric states. Precision studies determine the neutralino's mass and composition, as well as the properties of other supersymmetric particles required to establish the strength of neutralino interactions. With this data, the linear collider then determines the neutralino thermal relic density at the percent level. The thermal relic density is found to be three-fourths of what is required to explain all of dark matter, showing that supersymmetry accounts for much of the dark matter, but providing strong motivation for searches for other forms of dark matter that make up the remaining one-fourth.

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 new particles that are highly unstable, decaying 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 to be detected directly but 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 already employed to deduce the role of neutrinos in high energy collisions.

With 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 the bookkeeping at any proton collider.

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

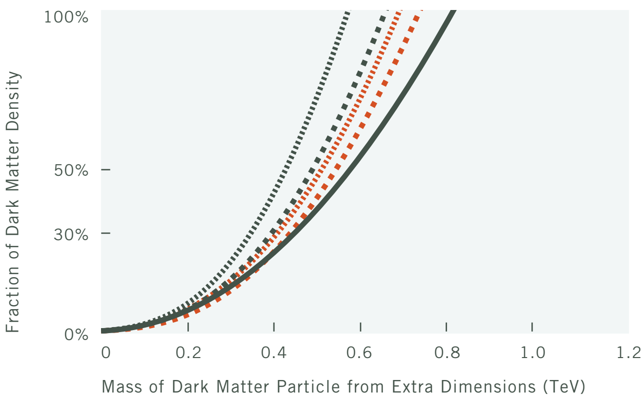


FIGURE 8

The relic density of Kaluza-Klein photons as a function of their mass. The different curves are for a variety of extra dimensional models. These particles are natural candidates for dark matter, with mass less than about 1 TeV.

2. *The LHC discovers a host of new particles, some revealed through missing energy and missing momentum.* LHC mass measurements indicate that the new particles are beyond the reach of a 500 GeV linear collider, but well within reach of an 800 GeV machine. Follow-up studies at the LHC and the ILC show that the new particles are similar to those predicted by supersymmetry, but with the wrong spins. Precision studies determine that the new particles are in fact not supersymmetric, but are particles called Kaluza-Klein particles, predicted by extra spatial dimensions. The missing particles are the lightest new states, which are found to be Kaluza-Klein photons. Further detailed studies of extradimensional particles measure the interaction strengths of Kaluza-Klein photons. The studies determine the thermal relic density of Kaluza-Klein photons to be only one-tenth of the required amount, requiring another form of matter to make up the dominant component of dark matter.

3. *The LHC discovers heavy, charged, apparently stable particles.* Because they are charged, they cannot be dark matter. Together the LHC and ILC determine that the new particles are staus, predicted by supersymmetry. If these staus were absolutely stable, calculations show that the stau relics of the Big Bang would today have a total mass greater than that of the entire universe! This paradox is resolved by further studies, which show that, on time scales of a month, staus decay to gravitinos, uncharged, extremely weakly interacting particles called superWIMPs, predicted by supersymmetry. Careful studies of the decays determine that the amount of gravitinos in the universe is exactly that required to be dark matter, providing strong quantitative evidence that dark matter is entirely in the form of gravitinos.

In all of these cases, results from the linear collider are essential in determining the identity of at least some fraction of the dark matter. By creating particle collisions at energies last seen in the very early universe, colliders play the role of time machines, opening windows on the universe as it existed when the dark matter density was established, a mere one nanosecond after the Big Bang.

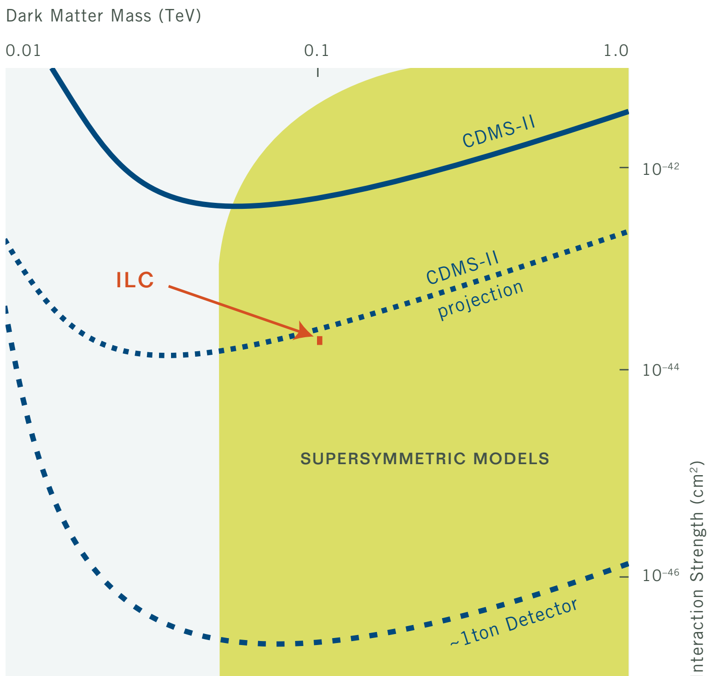


FIGURE 9
The linear collider and direct searches for dark matter at the Cryogenic Dark Matter Search experiment. Present and future dark matter search experiments can see signals if the interaction strength of dark matter with ordinary matter is above the contours indicated. Precision measurements at the ILC will constrain the mass and interaction strength to the region indicated with uncertainties smaller than the size of the red dot. The shaded region shows the range of predictions of supersymmetric models.

MAPPING THE DARK UNIVERSE

Dark matter may also be detected in other ways. The CDMS II experiment deep underground in a Minnesota iron mine is searching for the recoil of dark matter particles as they pass through highly sensitive detectors. Astrophysics experiments are searching for cosmic particles that are remnants of dark matter annihilation. A signal in any of these dark matter detection experiments will constrain some dark matter properties. These experiments will not be able to determine the identity of the dark matter, nor will they be sufficient to determine thermal relic densities with useful precision. However, an unambiguous signal will provide strong motivation for producing dark matter at the LHC and ILC, where experimenters can perform detailed studies of the kind outlined above.

In fact, physicists are already reporting tentative hints of signals in dark matter search experiments. Unfortunately, the expected signals and detection rates in these experiments are uncertain, because they are clouded by two unknowns: particle physics uncertainties, such as the mass and interaction strengths of the dark matter; and astrophysical uncertainties, such as the spatial distributions and velocities of dark matter particles in the galaxy. These significant unknowns make signals difficult to interpret.

If supplemented by collider data, however, these experiments will prove invaluable. In the process of unveiling dark matter, the linear collider will also determine its particle properties, removing this source of uncertainty. Dark matter detection rates then provide unambiguous probes of dark matter distributions. In this way, just as traditional telescopes have mapped the luminous universe, the linear collider and other experiments will determine what the dark universe is made of and help map the dark universe, shedding light on the structure of the cosmos.

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?

C EINSTEIN'S TELESCOPE

Experiments at the LHC and ILC will climb the high ground of Terascale physics to get a clear view of quantum processes at high energies. From this vantage point, physicists will gain a telescopic view to even higher energies.

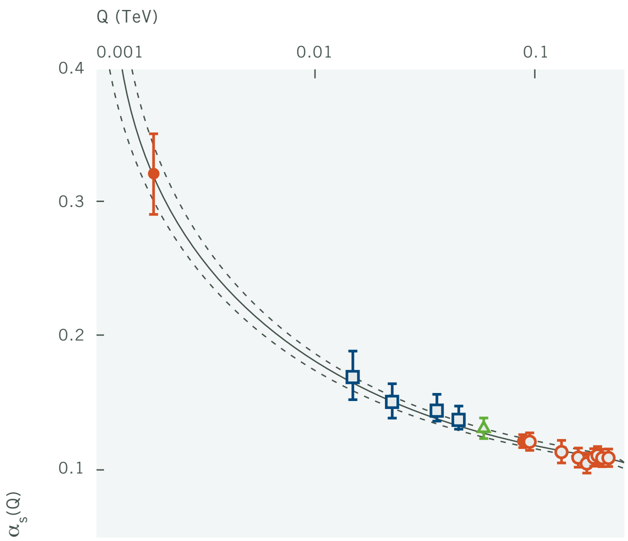


FIGURE 10

The strength of the strong QCD force between quarks is expressed as a parameter called α_s. Due to the quantum effects of virtual particles, α_s depends on the energy exchanged in the quark collisions. As the energy gets larger, the QCD force gets weaker. The data points are from several electron-positron colliders, varying over a wide range of energy.

Virtual particles are the phenomena that make particle collisions work as a telescope. They are the continual quantum fluctuations that swarm around all particles, affecting how those particles interact with each other. They change the strength of particle interactions and give rise to an energy dependence called the "running" of the particle coupling strengths.

Particle physicists have developed techniques to exploit virtual particles as a telescope to higher energies:

- *Extrapolating running couplings to higher energies.* For example, the strong force of quantum chromodynamics, or QCD, becomes weaker in higher-energy collisions, allowing quarks to move more freely. Theory first predicted this quantum effect as the running of the QCD coupling α_s, which has since been verified by data from many experiments spanning three orders of magnitude in energy. The QCD coupling varies as the logarithm of the energy; as a result, a thousand-fold increase in energy weakens the strength of the force by only a factor of four. Physicists need this extrapolation to make precise predictions of particle interaction rates at the LHC.
- *Observing the quantum effects of heavy virtual particles.* Electron-positron collider experiments at CERN's LEP and SLAC's SLC detected clear evidence of virtual top quarks from their small effects on the decays of Z bosons. From this data physicists were able to predict the existence, charges and approximate mass of the top, despite the fact that the LEP collider was operating at about one-fourth the energy required to produce top quarks directly. After physicists discovered the top at the Tevatron, they obtained a more accurate value for its mass. They then fed this value into the analysis of LEP and SLC data, showing that Z boson decays are affected by smaller effects of at least one more unknown particle. This data is most simply explained in terms of the virtual effects of a Higgs particle, with a mass close to the experimental lower bound as determined from direct searches.

UNIFIED FORCES, EINSTEIN'S DREAM

If LHC experiments detect superpartners, Einstein's dream of a theory of unified forces will at last be within reach. The running couplings of the three known gauge forces do not unify when extrapolated to higher energies.

Assuming the existence of superpartners changes this result dramatically, giving an apparent unification of the three forces to a common strength. This force unification occurs at an energy 20 trillion times that of the Terascale. The probability that such an extrapolation would produce this result by accident is very small. It is remarkable that this ultrahigh energy is close to the energy realm where many physicists believe that quantum gravity and strings should appear.

This extrapolation in energy can be computed with great confidence, because the force couplings are measured very precisely at lower energies. Since the force strengths vary as the logarithm of the energy, an extrapolation by 20 trillion times in energy is less daring than it sounds: the logarithm of 20 trillion is about four times larger than the logarithm of 1000, the energy range over which these quantum effects have already been observed.

Even so, it will be an experimental challenge to reveal the existence of force unification. LHC and ILC experiments will need not only to verify the existence of supersymmetry, but also to determine the properties of the superpartner particles. They must do this in order to look for signs of other exotic particles or new interactions occurring anywhere between the Terascale and the unification scale. The presence of any such phenomena could either spoil unification or change our understanding of how it works.

For example, the LHC may show superpartners with decays and masses characteristic of models that are "gauge-mediated." In such models there are heavy "messenger" particles, with masses at least 100 times that of the Terascale. The quantum effects of these messengers may or may not upset the unification of the force couplings. While these particles would be too heavy to produce directly, linear collider measurements of the masses of superpartners would be sensitive to their charges and mass differences.

Another scenario, supersymmetry with an extended Higgs sector, is likely to be a signal of new strong forces, appearing at energies intermediate between the Terascale and the putative unification scale. Again, their effects may or may not upset unification. The LHC experiments could get the first indication of such a scenario by discovering that the Higgs particle is heavier than predicted by minimal supersymmetry, possibly with nonstandard decays. The linear collider would then be essential to discover the nature of the extended Higgs sector. Experiments at a 0.5 TeV linear collider would be sensitive to small variations in the production of the

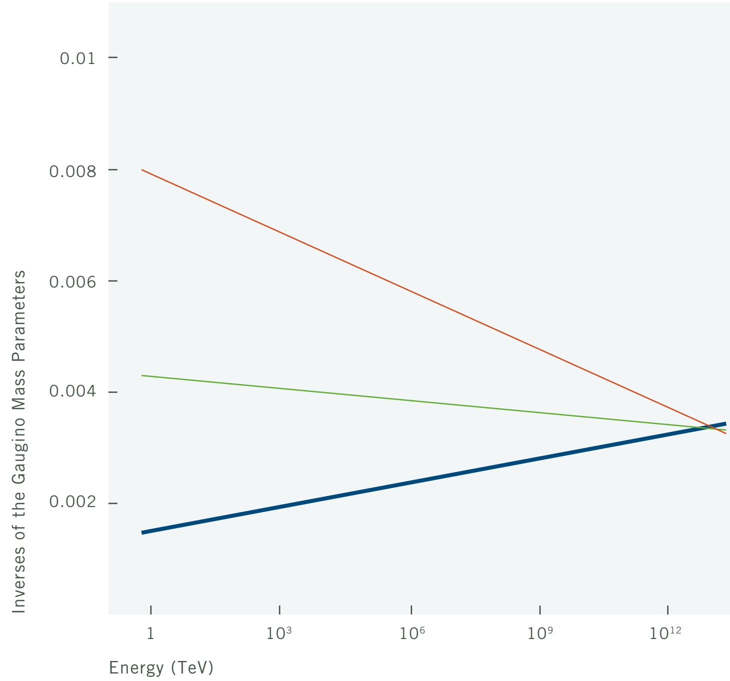


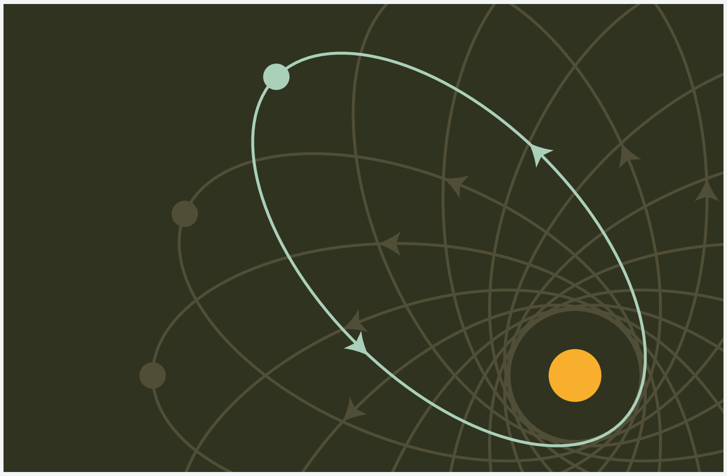
FIGURE 11
Gaugino mass unification. Gauginos are the superpartners of the force particles. The gaugino mass parameters M_1, M_2 and M_3 should vary with energy, as do the strengths of the forces. They may also unify at high energies, like the forces.

Higgs in association with Z bosons – variations that are characteristic of extended Higgs models. If charginos and neutralinos are also produced, they would provide an independent probe, since quantum effects mix neutralinos with the superpartners of the extra Higgs particles. Using polarized beams to get one percent measurements of key parameters, linear collider experiments would reveal many features of the extended Higgs sector, including its impact on unification.

DOES MATTER UNIFY?

The discovery of the Higgs at the LHC would mean that mass originates entirely from particle interactions and is not an innate property of the particles themselves. This would imply that particle masses also "run" with energy, in the sense that the strengths of the particle interactions that produce mass vary with energy. One of the deepest questions in physics is whether some or all of the interactions that produce mass also unify at very high energies. If so, this could mean that a top quark and an electron are really different low-energy manifestations of the same particle, their apparently different charges and masses merely artifacts of the running of various interactions. Physicists have constructed "grand unified" theories, in which matter unification of quarks and leptons occurs at the same energy as force unification. Grand unification makes dramatic predictions, such as the ultimate instability of all matter through proton decay.

If LHC experiments discover superpartners, a key question will be whether superpartners exhibit matter unification and, if they do, how it compares with force unification in the underlying framework of supersymmetry. The first step will be to measure the masses of the gauginos, the superpartners of the gauge force particles. Gauginos can be extracted from the production of gluinos at the LHC, of charginos at the ILC, and from detailed studies at the LHC and the ILC of neutralinos, particles that are mixtures of the superpartners of the photon, Z, and Higgs particles. In the simplest models of grand unification, the gauginos are represented by three running masses M_1, M_2 and M_3. Linear collider precision will be essential to make a compelling extrapolation of these parameters. Small deviations from gaugino unification, if observed, could be a signal of string theory or other new phenomena at ultrahigh energies. To obtain the required precision, physicists would use both polarized beams and their ability to scan the linear collider beam energies over the minimum threshold value required to produce pairs



The orbit of Mercury is an elongated ellipse. At the end of each orbit it does not come back to exactly where it was before, but slightly ahead of itself.

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 we cannot observe directly.

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 solve 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 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 general relativity.

of charginos. In a study of a benchmark supersymmetry model, it was estimated that linear collider experiments could determine M_2 to 0.3 percent accuracy, and M_1 to 0.1 percent accuracy. LHC determines M_3 to an accuracy of 3 percent, improving to 2 percent if linear collider results are used as inputs to the LHC analysis.

The next step in exploring matter unification is to measure the masses and couplings of the superpartners of quarks and leptons. Once these matter superpartner parameters are extracted with precision, they can also be extrapolated to the unification scale. If the matter superpartners unify five or 10 at a time into multiplets of related particles, this signals matter unification as predicted in models of supersymmetric grand unification. Moreover, the consistency or inconsistency of this unification, compared to gaugino and force unification, provides a powerful probe of new particles and forces appearing anywhere between the Terascale and the unification scale. This is of crucial

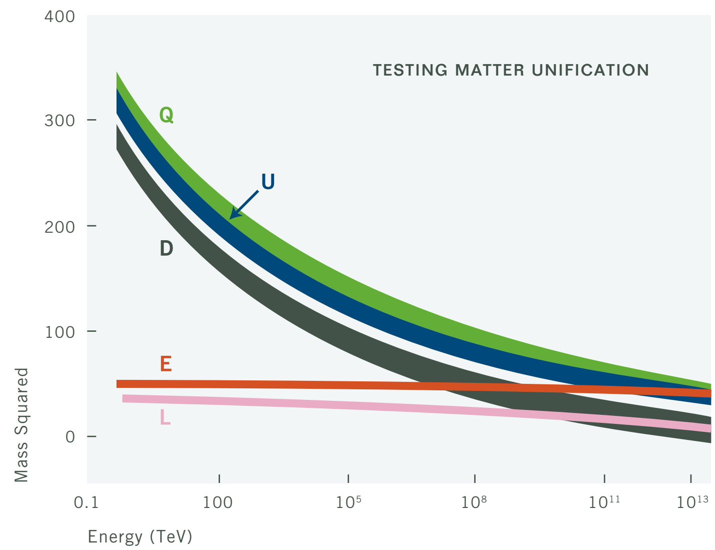


FIGURE 12

Matter unification at high energies: The strengths of the interactions that produce masses for the matter superpartners vary with energy. Using precision measurements of the superpartner masses, this "running" can be extrapolated to ultra-high energies. If the lines converge, it is evidence for matter unification. Shown are simulated data for the masses of the squarks (D, Q, U) measured at LHC, and sleptons (E, L) measured at ILC. The width of the bands is the estimated experimental accuracy.

importance for understanding the origin of neutrino masses and the possibility of leptonic CP violation, both mysteries that are probably beyond the direct reach of any accelerator. These discoveries will require both the LHC and the ILC to produce enough superpartners. For the linear collider, this means high enough beam energies to produce sleptons, the superpartners of the leptons. The ability of linear collider experiments to measure precise couplings will be key to untangling superpartner mixtures and to extracting the running mass parameters from the measured superpartner properties.

DISCOVERY OF A Z-PRIME

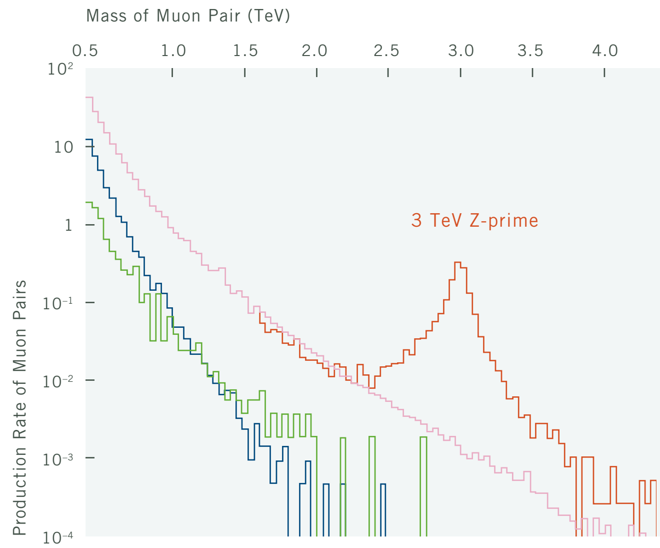
One of the most likely discovery scenarios for the LHC is detection of a new heavy particle called a Z-prime. Such particles are predicted in a wide variety of theoretical frameworks, including grand unification, extra dimensions, string theory, and various models of supersymmetry. Z-prime particles are associated with a new force of nature that, like the weak force, would only operate at very short distances. In grand unification or string theory, this new force would be unified with the other known forces at ultra-high energies. In the framework of extra dimensions, the Z-prime particle is nothing more than a Z boson moving in one or more extra spatial dimensions.

The LHC experiments can detect Z-prime particles as a deviation, usually in the form of a resonance peak, in the production of pairs of muons or electrons. This is a basic process at the LHC, and, if it exists, a Z-prime discovery is assured even if the mass is in the multi-TeV range. However, for a Z-prime heavier than about 2 TeV, the LHC experiments will have limited ability to determine properties of the Z-prime other than its mass.

Linear collider experiments have the ability to detect a multi-TeV Z-prime, not through direct production but rather by using the ILC as a telescope. The experiments would detect the contribution of virtual Z-prime particles to the production of pairs of muons or tau leptons. This could be done with great precision at the linear collider, where such events would be copiously produced in a clean, controlled environment. Using polarized beams and the angular distributions of the particle produced, there are enough separately measurable quantities to extract the couplings of the Z-prime to leptons. Since the linear collider does not independently measure the mass of the Z-prime, this would require input from LHC data.

FIGURE 13

Discovery of a Z-prime particle at the LHC. Simulated data showing the discovery of a Z-prime particle, with mass 3 TeV, in the CMS detector at the LHC. The Z-prime is seen as an excess, called a "resonance peak," in the number of collisions that produce pairs of high energy muons, as a function of Mμμ, which measures the energy of the muon pair. The red bars are the excess events due to the Z-prime, the other bars are background from standard processes involving photons, Z bosons and W's.



A 1 TeV linear collider would have sufficient reach to allow precise measurements of the couplings of a 3 TeV Z-prime to lighter particles. As seen in figure 14, the linear collider data could clearly discriminate among different origins of the Z-prime particle. For example:

- The Z-prime arises from an SO(10) grand unification framework. This is the simplest unification scenario that naturally explains the origin of neutrino masses. (Red region in Figure 14)
- The Z-prime arises from an E6 unification framework. This is the simplest unification scenario in which the Higgs is unified with quarks and leptons. (Green region in Figure 14)
- The Z-prime is an exact but heavier copy of the Z boson. This is a likely indicator of the existence of an extra dimension. Further analysis could confirm this by finding effects of a heavy copy of the photon at the linear collider, or a heavy copy of the gluon at the LHC. (Blue region in Figure 14)

STRINGS

One of the ultimate goals of particle physics is to understand the nature of quantum gravity and its connection both to the other forces of nature and to the cosmos. Perhaps the most promising way to connect gravity to particle physics is through its effects on supersymmetry-breaking. If supersymmetry is discovered at the LHC and ILC, physicists will confront the mystery of why supersymmetry is not an exact symmetry of the world around us: why aren't we made of superatoms? Gravity may hold the key.

The best-developed theoretical models for supersymmetry breaking invoke gravity and postulate new interactions that occur at ultra-high energy – at the Planck scale, where gravity becomes a strong force and should play an essential role in particle interactions. The Planck scale is thought to be somewhat above the unification scale. It is also the energy scale where strings should become manifest. These "supergravity" models make predictions for the patterns of superpartner masses and mixings, which will be tested starting with experiments at the LHC. If LHC results are consistent with supergravity models, physicists will use this remarkable discovery as a window to the Planck scale.

String theory predicts the existence of new particles called "moduli," associated with extra dimensions and other exotic features of string interactions. The fields associated with moduli determine the size and shape of the extra dimensions that string theory requires.

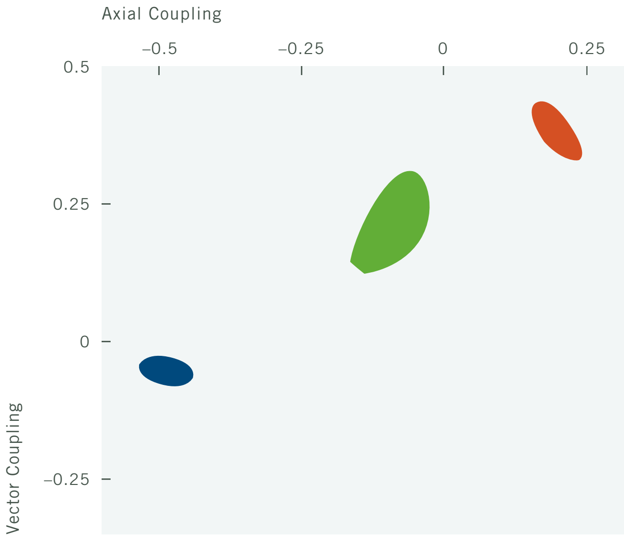


FIGURE 14

Revealing the origin of a Z-prime: At a 1 TeV linear collider, a 3 TeV Z-prime could be detected via its quantum effects on the production of pairs of muons or tau leptons. Precision measurements of the lepton decays, taking advantage of the linear collider beam polarization, could allow the determination of the coupling parameters of the Z-prime to leptons. The experimental accuracy, shown by the colored contours, is more than enough to discriminate among three possible origins of the Z-prime particle, described in the text.

They may also control the amount of dark energy in the universe. Some of these same fields play a role in supersymmetry breaking at the Planck scale, analogous to the role played by the Higgs at the Terascale. Instead of giving mass to quarks and leptons, these fields would give mass to superpartners.

This is physics at the ragged edge of our current understanding, but preliminary studies have looked at the ability of LHC and ILC experiments to detect characteristic effects of string moduli on superpartner masses and mixings, extrapolating from a long list of experimental inputs at the Terascale. Here linear collider precision, maximum beam energy and maximum integrated luminosity are essential, since the string effects appear as small differences in the extrapolated values of the superpartner parameters. The results of these studies are encouraging: in one study a combined analysis of simulated LHC and ILC data matched the fundamental parameters of the underlying string dynamics to percent level accuracy. This includes determining the overall size of the extra dimensions, as well as the overall strength of string interactions. While not a direct discovery of strings *per se*, such an achievement would truly be the realization of Einstein's boldest aspirations.