THE HEPAP LHC/ILC REPORT

JOSEPH LYKKEN

DOE/NSF HIGH ENERGY PHYSICS ADVISORY PANEL

American Linear Collider Physics Group

2005 International Linear Collider Physics and Detector Workshop and Second ILC Accelerator Workshop

Snowmass, Colorado, August 14-27, 2005

WHO WE ARE

- Jim Siegrist (co-chair): LBNL, ATLAS and CDF
- Joe Lykken (co-chair): Fermilab
- Jonathan Bagger: Johns Hopkins, EPP2010 NRC
- Barry Barish: Caltech, GDE
- Neil Calder: SLAC, ILC communications
- Albert de Roeck: CERN, co-coordinator of CMS physics analysis
- Jonathan L. Feng: UC Irvine, co-chair ILC Cosmology study
- Fred Gilman: Carnegie-Mellon, chair of HEPAP
- JoAnne Hewett: SLAC, ALCPG, editor of LHC/ILC study
- John Huth: Harvard, head of US ATLAS physics and computing
- Judy Jackson: Fermilab, ILC communications
- Young-Kee Kim: Univ. of Chicago, ALCPG, CDF
- Rocky Kolb: Fermilab Astro Center
- Konstantin Matchev: Univ. of Florida, CMS
- Hitoshi Murayama: Berkeley, ALCPG
- Rainer Weiss: MIT, LIGO

WHAT WE HAVE DONE

DESCRIBED THE DISCOVERY OPPORTUNITIES FOR THE LARGE HADRON COLLIDER AND THE PROPOSED INTERNATIONAL LINEAR COLLIDER.

WE HAVE DRAWN FROM THOUSANDS OF PAGES OF TECHNICAL REPORTS, PRODUCED BY HUNDREDS OF PHYSICISTS AROUND THE WORLD.

- LHC/ILC STUDY GROUP REPORT
- LINEAR COLLIDER PHYSICS RESOURCE BOOK
- ATLAS PHYSICS TECHNICAL DESIGN REPORT
- CMS PHYSICS TECHNICAL DESIGN REPORT (IN PROGRESS)
- LINEAR COLLIDER CONNECTIONS TO ASTROPHYSICS AND COSMOLOGY WORKING GROUP
- TESLA TECHNICAL DESIGN REPORT

WHO WE HAVE CONSULTED

LHC COMMUNITY:

- FABIOLA GIANOTTI, ALBERT DE ROECK, JOHN HUTH, ...

ILC COMMUNITY:

- BARRY BARISH, JIM BRAU, HARRY WEERTS, MARK OREGLIA, GEORG WEIGLEIN, GUDRID MOORTGAT-PICK, JOANNE HEWETT, RITCHIE PATTERSON, ANDREAS KRONFELD, YOUNG-KEE KIM, HITOSHI MURAYAMA, ...

THE BROADER PARTICLE PHYSICS AND ASTROPHYSICS COMMUNITIES

+ WASHINGTON POLICYMAKERS, LAB DIRECTORS, ...

TIMELINE

- 25 March: first meeting at LCWS Palo Alto
- 22 April: meeting in Washington with J. Marburger, M. Turner, R. Staffin, P. Looney, M. Holland, J. Parriott, K. Carroll
- 23 April: writing begins
- 19 May: HEPAP meeting
- 26 May: meeting at Fermilab
- 15 June: meeting at SLAC
- 24 June: first complete pre-draft sent to R. Staffin and M. Turner
- 1-31 July: drafts circulated to members of the community
- 8 July: draft report sent to HEPAP
- 2 August: unveiling to EPP2010 National Academy committee at their Cornell meeting
- 10 September: version 2 (for broader audience) goes to printer

- Our guidance from the EPP2010 committee was that they were looking for a whitepaper on the physics related to the LHC and linear collider
- This also fulfilled a significant part (but not all) of our charge from HEPAP
- Version one of our report is a 25 page whitepaper with a 15 page introduction and a summary table
- This was transmitted to EPP2010 along with a cover letter from Fred Gilman that addressed the specific EPP2010 questions to HEPAP
- The feedback from the EPP2010 committee was that we had delivered what they were hoping for, and had answered all of their questions

LET'S HAVE A LOOK AT THE REPORT:

DISCOVERING THE QUANTUM UNIVERSE

THE ROLE OF PARTICLE COLLIDERS

JOSEPH LYKKEN

DOE/NSF HIGH ENERGY PHYSICS ADVISORY PANEL

NRC EPP2010 COMMITTEE MEETING, CORNELL, 2-3 AUGUST 2005

CONTENTS

PHYSICS FIRST

- The report is organized around the physics
- Chapter I begins with the 9 great questions from the *Quantum Universe* report
- Note these correspond to questions 1, 5, 26, 27, 32, 33, 34, 36, and 37 of the top 125 questions in all of science, according to *Science*.

PHYSICS FIRST

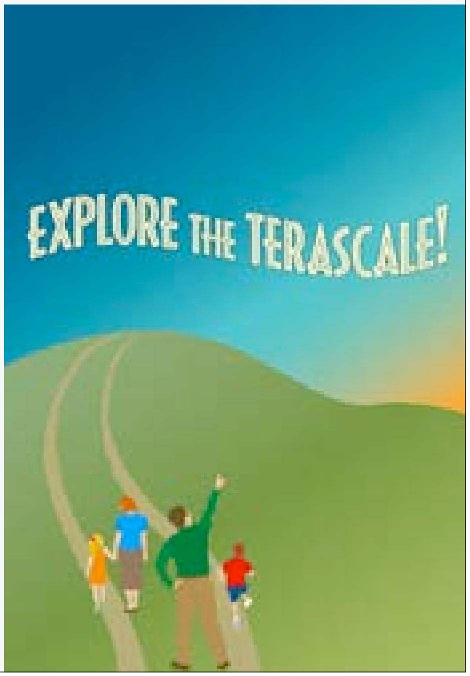
- The great questions are mapped into the three main physics themes that are most relevant for the LHC and ILC colliders
- Chapter II explains the three physics themes

DISCOVERY SCENARIOS

- Chapter III describes 10 of the most likely and robust discovery scenarios for LHC and ILC
- Each scenario begins with a specific LHC discovery (because LHC will turn on first!)
- Each scenario ends with an ILC discovery triggered by the LHC discovery
- Typically there are other discoveries for which the relative contributions of LHC and ILC depend on details of the physics, and on uncertainties in the reach of LHC analyses

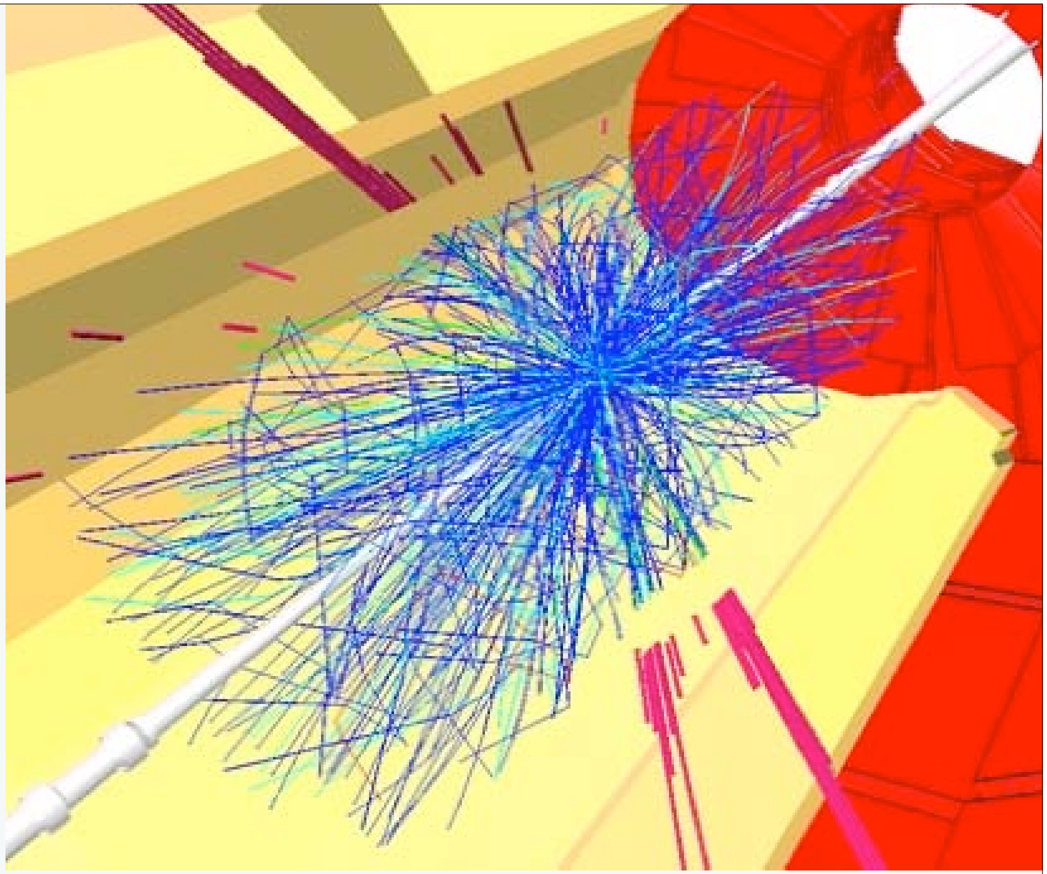
LA TERASCALA

- The report shows how a variety of evidence points to the TeV energy regime as a gateway to revolutionary discoveries
- This is why we are so excited about the LHC
- However “TeV scale” is a lousy name
- So we borrowed “Terascale” from our friends in high-performance computing



LHC

ACCELERATING TO THE TERASCALE



- 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.

DISPELLING MISCONCEPTIONS

- There is a misconception that if LHC discovers more and measures more, then there is less motivation for the ILC

- Our report makes it clear that the opposite is true

- The more that researchers discover at the LHC, the greater the discovery potential of the linear collider

DISPELLING MISCONCEPTIONS

- There is a misconception that the only thing colliders do is discover particles
- Our report explains how particles are the tools that we use to resolve mysteries and discover new laws of nature

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.

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.

THE THREE
PHYSICS 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.

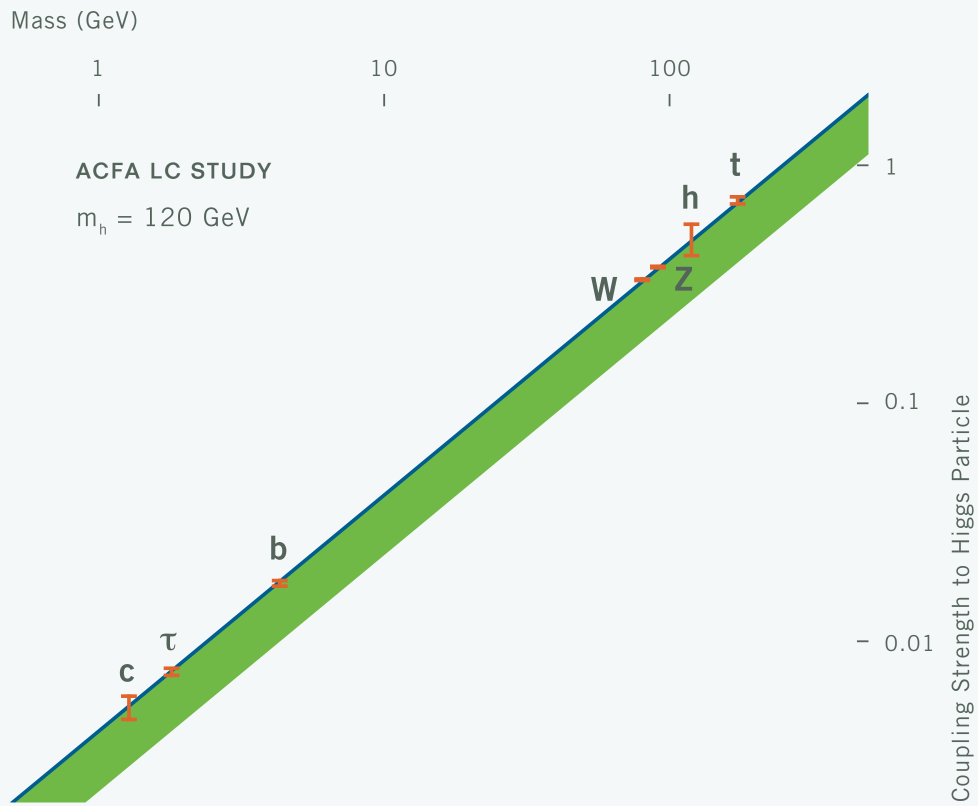
2. **DETERMINING WHAT DARK MATTER PARTICLES CAN BE PRODUCED IN THE LABORATORY AND DISCOVERING THEIR IDENTITY.** Most theories of Terascale physics contain new massive particles with the right properties to contribute to dark matter. Such particles would first be produced at the LHC. Experiments at the 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.

DISPELLING MISCONCEPTIONS

- There is a misconception that once LHC discovers a Higgs particle, the rest is details
- Our report shows that the discovery of a Higgs particle will raise compelling questions leading to even greater discoveries

ILC experiments will have the unique ability to make model-independent tests of Higgs couplings to other particles, at the percent level of accuracy



This is right sensitivity to discover extra dimensions, a new source of CP violation, or other novel phenomena

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 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.

LIGHT ON DARK MATTER

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

- There is no reason to think that dark matter should be any simpler than visible matter
- 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
- Together with direct searches, this could tell us both the what and the why of this dark matter

SEEING THE INVISIBLE – A TALE OF TWO COLLIDERS

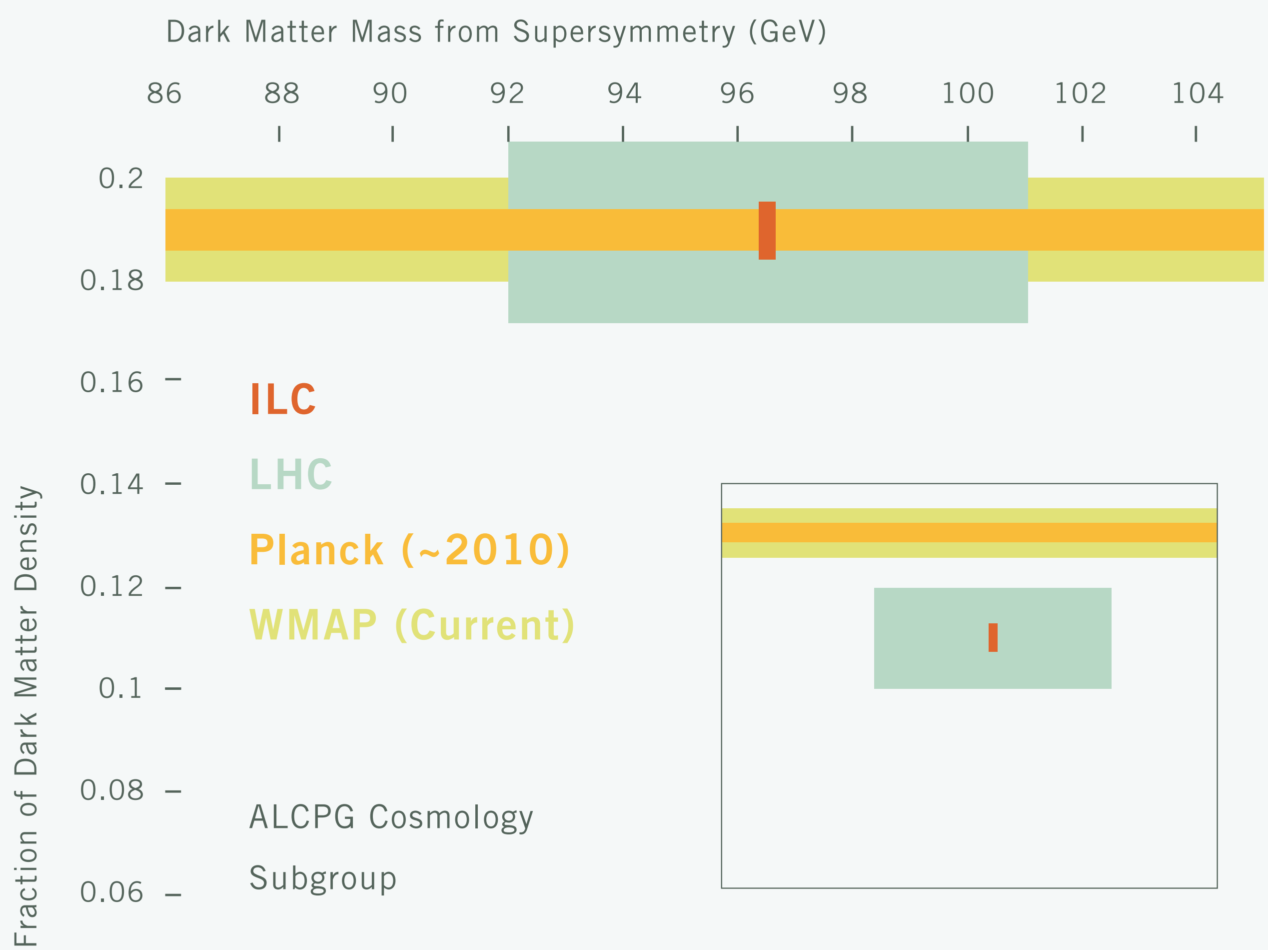
In particle physics, discovery often depends on meticulous bookkeeping. The fundamental forces in high energy collisions can do their work in a septillionth of a second, creating new particles that are highly unstable, decaying almost immediately into many “daughter” particles. Computers write an elaborate 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.

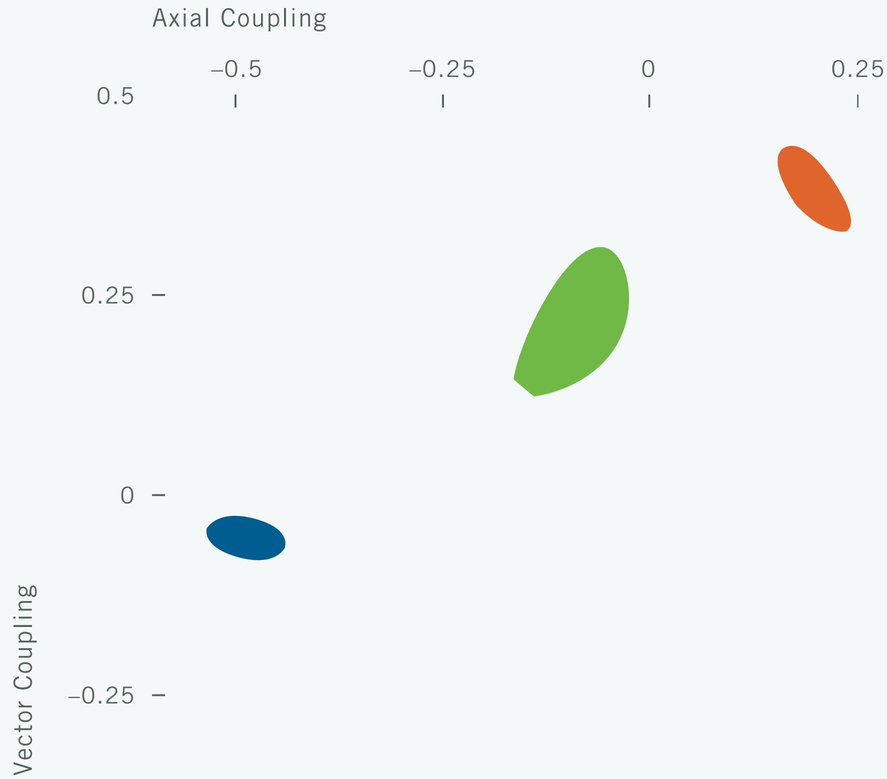


THIS IS WHY THE ILC HAS AN ESSENTIAL ROLE IN DISCOVERING THE IDENTITIES OF DARK MATTER

EINSTEIN'S TELESCOPE

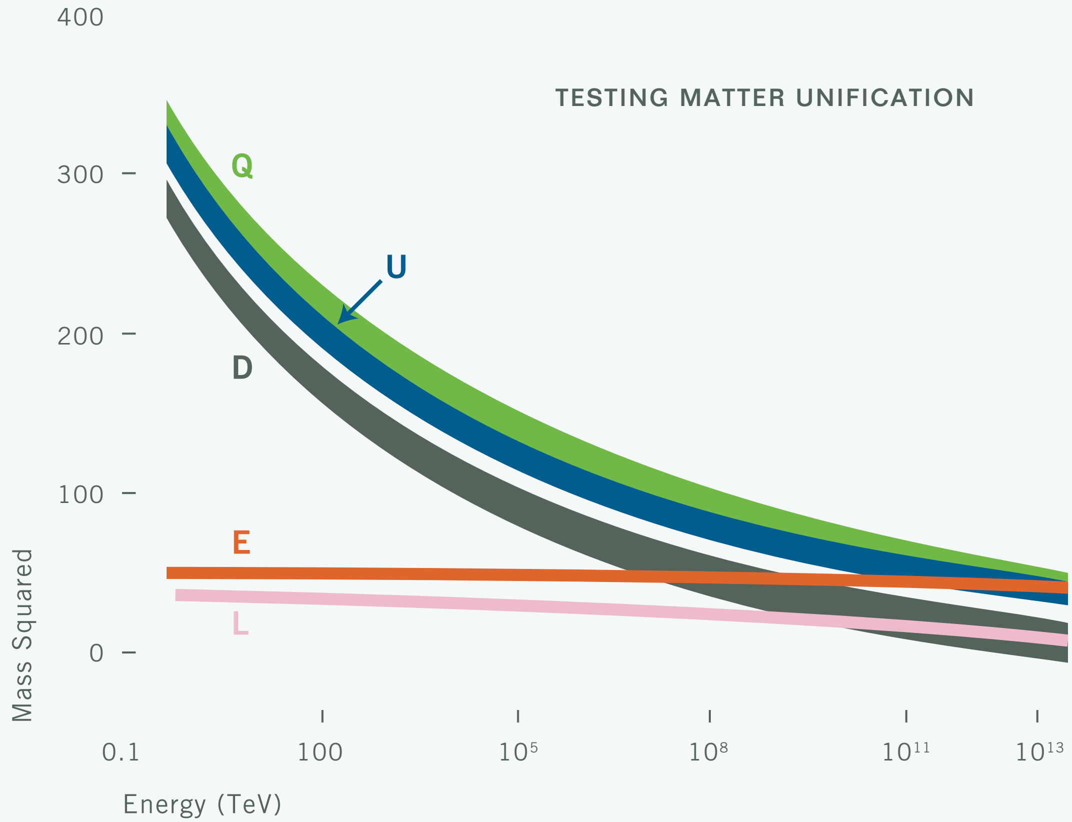
- Virtual particles are the phenomena that make particle collisions work as a telescope
- They swarm around all particles, affecting how those particles interact with each other
- They change the strength of particle interactions and give rise to an energy dependence called the "running' of the particle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

Observing the quantum effects of heavy virtual particles



example: discovery of a Z-prime

Extrapolating running couplings to higher energies



example: discovery of matter unification in supersymmetry

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

MORE LESSONS LEARNED

- “Concurrency” is not an issue
- Success of LHC initial running will be a big help in green-lighting the ILC
- But avoid confusing LHC initial signals with clear discoveries, e.g. the LHC cannot discover a “Standard Model Higgs” in initial running

WHAT NEEDS TO BE DONE

- We are only just beginning to make the physics case for the ILC
- We will have to make a strong, compelling case to multiple audiences who aren't familiar with any of our jargon
- The Discovery report is only the first step towards reaching those audiences