Scientific Opportunities at a Linear Collider: Making the Case

JoAnne Hewett, SLAC
The LHC is Becoming a Reality!

And the excitement is building...
Major Discoveries are Expected

BSM Physics at the LHC: pp @ 14 TeV

New Gauge Bosons?

ZZ/WW resonances?

Technicolor?

Supersymmetry?

Extra Dimensions?

Black Holes???

Little Higgs?

Split Susy?

LHC 14 TeV $10^{33}$ cm$^{-2}$s$^{-1}$ $10^{34}$ cm$^{-2}$s$^{-1}$
SLHC 14 TeV $10^{35}$ cm$^{-2}$s$^{-1}$ 28 TeV $10^{34}$ cm$^{-2}$s$^{-1}$ (42 TeV??)

SLHC: 2015(+)

hep-ph/0204087

- A. De Roeck, Snowmass 2005
2 Steps to Discovery:
1) Discovery of a new particle
2) Discovery of the theory behind the new particle

Particles Tell Stories: New particles are not produced at accelerators merely to be catalogued. Rather, particles are the messengers that reveal the story of the nature of matter, energy, space, and time.

Measurements at the ILC, together with results from the LHC, will identify the full nature of the Physics at the TeV scale
The more discoveries that are made at the LHC, the greater the discovery potential at the ILC.
HEPAP LHC/ILC Subpanel Report(s):

- 43 page semi-technical version, submitted to EPP2010 panel in late July

- 35 page non-technical version, in press.
The Authors:

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- Hitoshi Murayama: UC Berkeley theorist, American LC Physics Group
- Rainer Weiss: MIT, LIGO gravity waves
The tools of the ILC:

- Well defined initial energy
- Ability to vary the center of mass energy
- Well defined angular momentum (polarization) of initial beams
- Knowledge of initial quantum state
- Clean environment due to elementary initial states

The report emphasizes:

- the synergy between the LHC and ILC
- differences in how measurements are made at ILC and LHC
- unique physics to ILC
The report centers on 3 physics themes:

1. **Mysteries of the Terascale**: Solving the mysteries of matter at the Terascale

2. **Light on Dark Matter**: Determining what Dark Matter particles can be produced in the laboratory and discovering their identity

3. **Einstein’s Telescope**: Connecting the laws of the large to the laws of the small

Now for some highlights of physics unique to the ILC
Higgs at the Terascale

• An important Higgs production process is $e^+e^- \rightarrow Z + \text{Higgs}$

• There are many possible final states, depending on how the Z and Higgs decay

Recoil Technique:  

In $e^+e^- \rightarrow Z + \text{Anything}$

• ‘Anything’ corresponds to a system recoiling against the Z

• The mass of this system is determined solely by kinematics and conservation of energy

• because we see everything else, we know what is escaping

Peak in Recoil Mass corresponds to 120 GeV Higgs!
ILC Simulation for $e^+e^- \rightarrow Z + \text{Higgs}$
with $Z \rightarrow 2 \text{b–quarks}$ and $\text{Higgs} \rightarrow \text{invisible}$

N. Graf
Recoil technique gives precise determination of Higgs properties *Independent* of its decay mode.

Provides accurate, direct, and *Model Independent* measurements of the Higgs couplings.

- The strength of the Higgs couplings to fermions and bosons is given by the mass of the particle.
- Within the Standard Model this is a direct proportionality.

\[
\text{Higgs} \rightarrow f, \bar{f} \quad \sim m_f
\]

This is a crucial test of whether a particle’s mass is generated by the Higgs boson!
ILC will have unique ability to make model independent tests of Higgs couplings at the percent level of accuracy.
Possible deviations in models with Extra Dimensions

This is the right sensitivity to discover extra dimensions, new sources of CP violation, or other novel phenomena.
ILC Detector Simulation of Chargino Production
Supersymmetry at the Terascale

ILC Studies superpartners individually via $e^+e^- \rightarrow S\bar{S}$

Determines
- Quantum numbers (spin!)
- Supersymmetric relation of couplings

Proof that it IS Supersymmetry!

fine structure constant
$\alpha = e^2 / 4\pi$
Selectron pair production @ ILC

2% accuracy in determination of Supersymmetric coupling strength
Precision Mass Measurements of Superpartners

Example: $\tilde{e} \rightarrow e + \gamma$

Fixed center of mass energy gives flat energy distribution in the laboratory for final state electron.

Endpoints can be used to determine superpartner masses to part-per-mil accuracy
A realistic simulation:

Determines: Superpartner masses of the electron and photon to 0.05%!
A complicated Table with lots of details that illustrates how ILC results improve upon Superpartner mass measurements at the LHC

<table>
<thead>
<tr>
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<th>(m_{\text{SPS1a}})</th>
<th>LHC</th>
<th>LC</th>
<th>LHC+LC</th>
<th>(m_{\text{SPS1a}})</th>
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<th>LC</th>
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Shows accuracy of mass determinations at LHC and ILC alone and combined
Extra Dimensions at the Terascale

- Kaluza–Klein modes in a detector

Number of Events in $e^+e^- \rightarrow \mu^+\mu^-$

For a conventional braneworld model with a single curved extra dimension of size $\sim 10^{-17}$ cm

Davoudiasl, Hewett, Rizzo

For this same model embedded in a string theory
Detailed measurements of the properties of KK modes can determine:

- That we really have discovered additional spatial dimensions
- Size of the extra dimensions
- Number of extra dimensions
- Shape of the extra dimensions
- Which particles feel the extra dimensions
- If the branes in the Braneworld have fixed tension
- Underlying geometry of the extra dimensional space
Example: Production of Graviton Kaluza–Klein modes in flat extra dimensions, probes gravity at distances of $\sim 10^{-18}$ cm

Production rate for $e^+e^- \rightarrow \gamma + \text{Graviton}$

![Graph showing production rate vs. center of mass energy](image)

- Size of Measurement error

With

- Extra Dimensions
- Measurement possible due to well-defined initial state & energy plus clean environment
Where particles live in extra dimensions

Polarized Bhabha Scattering

Determines location of left- and right-handed electron in extra dimension of size $4 \text{ TeV}^{-1}$

T. Rizzo
Telescope to Very High Energy Scales

ILC can probe presence of Heavy Objects with Mass > Center of Mass Energy in $e^+e^- \rightarrow \bar{f}f$

Many tools to detect existence of heavy object ‘X’:  
• Deviations in production rates  
• Deviations in production properties such as distribution of angle from beam-line  
• Deviations in distributions of angular momentum

For all types of final state fermions!

⇒ Indirect search for New Physics
Example: New Heavy Z–like Boson from Unification Theories

Collider Sensitivity

Various Unification Models

95% (=2σ) direct discovery at LHC

For ILC Sensitivity:
Solid = 5σ = standard discovery criteria
Dashed = 2σ
ILC can probe masses many times the machine energy!

S. Godfrey
Heavy Z–like Bosons appear as resonance peak at LHC

Number of Events in \( pp \rightarrow \mu^+\mu^- \)

LHC determines mass of new Z–like boson to few percent
Indirect sensitivity at ILC determines $Z$–like boson couplings to fermions

3 Scenarios:
- SO(10) $Z'$: origin of $\nu$ mass
- $E_6$ $Z'$: Higgs unified with fermions
- Kaluza–Klein $Z'$

LHC determines mass
ILC determines interactions

95% contours for couplings to leptons

S. Riemann
Accurate superpartner mass determinations necessary for unification tests

Evolution of superpartner masses to high scale:
- Force unification
- Matter Unification

Blair, Porod, Zerwas
Light on Dark Matter

- Dark Matter comprises 23% of the universe
- No reason to think Dark Matter should be simpler than the visible universe ⇒ likely to have many different components
- Dream: Identify one or components and study it in the laboratory
One Possibility: Dark Matter in Supersymmetry

- A component of Dark Matter could be the Lightest Neutralino of Supersymmetry
  - stable and neutral with mass $\sim 0.1 - 1$ TeV
- In this case, electroweak strength annihilation gives relic density of

$$\Omega_{\text{CDM}} h^2 \sim \frac{m^2}{(1 \ \text{TeV})^2}$$
Comparative precision of ILC measurements (within SUSY)

ILC and Astro measurements

ILC and direct detection
## 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.

<table>
<thead>
<tr>
<th>Mysteries of the Terascale</th>
<th>If LHC discovers</th>
<th>What ILC could do</th>
<th>Qu</th>
</tr>
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<tbody>
<tr>
<td>A single Higgs boson, similar to that predicted by the standard model</td>
<td>Discover the effects of extra dimensions or other new phenomena by measuring Higgs couplings to other particles.</td>
<td></td>
<td>1.3</td>
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<tr>
<td>More than one Higgs-like particle</td>
<td>Discover a new source of matter-antimatter asymmetry by observing angular distributions in Higgs decays.</td>
<td></td>
<td>9</td>
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<tr>
<td>Superpartner particles</td>
<td>Confirm the symmetry of supersymmetry, or detect inconsistencies in the theoretical framework.</td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>A complicated spectrum of superpartner particles</td>
<td>Feed data on lighter superpartners back into LHC analyses and observe those superpartners that LHC cannot detect. Discover what kind of supersymmetry is operating.</td>
<td></td>
<td>1</td>
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<tr>
<td>Evidence for extra dimensions</td>
<td>Discover the number and shape of the extra dimensions, and discover the locations of particles within them.</td>
<td></td>
<td>3</td>
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</tbody>
</table>

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<td>Missing energy from a weakly interacting heavy particle</td>
<td>Measure the particle’s mass, spin and couplings; and determine the thermal relic density of this particle. Discover its identity as dark matter.</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Heavy charged particles that appear to be stable</td>
<td>Discover that these particles eventually decay to very weakly interacting particles. Identify these “superWIMPs” as dark matter.</td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

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<th>Einstein’s Telescope</th>
<th>If LHC discovers</th>
<th>What ILC could do</th>
<th>Qu</th>
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<tr>
<td>Superpartner particles</td>
<td>Extrapolate supersymmetry parameters to reveal force unification and matter unification at ultra-high energies.</td>
<td></td>
<td>4.5</td>
</tr>
<tr>
<td>A Z-prime boson, representing a new force at short distances.</td>
<td>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.</td>
<td></td>
<td>4.7</td>
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<tr>
<td>Superpartner particles matching predictions of supergravity</td>
<td>Use extrapolated supersymmetry parameters to discover features of string theory and extra dimensions.</td>
<td></td>
<td>3.8</td>
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</table>