The Linear Collider Project

- Physics

- Technology

- International Progress

ICEPP Symposium, Hakuba, Feb. 2004
R.-D. Heuer, Univ. of Hamburg
The physical world is composed of Quarks and Leptons interacting via force carriers (Gauge Bosons).

Last entries: top-quark 1995
tau-neutrino 2000
Standard Model

\[ e^+e^- \rightarrow Z^0 \rightarrow f \bar{f} \]
where \( f = q, l, \nu \)

\( \sigma_Z \) and \( \Gamma_Z \) depend on number of (light) neutrinos

during of families:

\[ N = 2.994 \pm 0.012 \]
Standard Model:
Testing Quantum Fluctuations

LEP:
Indirect determination of the top mass
possible due to
• precision measurements
• known higher order electroweak corrections

\[ \propto \left( \frac{M_t}{M_W} \right)^2, \ln \left( \frac{M_h}{M_W} \right) \]
Standard Model today enormously successful:

- tested at quantum level
- (sub)permille accuracy

precise and quantitative description of subatomic physics, valid to the 0.1% level
Success of the Standard Model:
Describes matter and interactions of observed particles consistently up to the Planck scale
But:
Origin of Electro-Weak Symmetry Breaking (EWSB) not revealed, Higgs-Boson not found yet

The SM is unstable:
Higgs mass not protected against very large corrections
$200^2 = (10^{19})^2 - (10^{19})^2$ strange…

The SM is incomplete:
95% of the total energy of the Universe does not appear in the SM
Key Questions of Particle Physics and Cosmology

- What is the origin of mass
- Are there more than four space-time dimensions
- What is the quantum theory of gravity
- Do the forces unify, at what scale
- Are there new forces
- What is dark matter
- What is dark energy
- What happened to antimatter
Towards the Answers

To find answers to these questions at the frontiers of the very complex, very large, and the very small, there is a variety of very different experimental approaches:

- Astrophysics (SN, CMB, cosmic rays, WIMP searches)
- Neutrino Physics (cosmic, solar, atmospheric, reactors, accelerators)
- High precision experiments at low energy (B-Factories, g-2, $\mu \rightarrow e\gamma$, …)

and

- Colliders at the energy frontier
There are two distinct and complementary strategies for gaining new understanding of matter, space and time at future particle accelerators:

Towards highest energies

**Hadron Colliders**
- LHC under construction at CERN

Towards precision measurements

**Electron-Positron Colliders**
- e.g. GLC, NLC, TESLA

Physics and experience teach us that we need these different tools to answer the open questions and that they complement each other

**prime example:** LEP / Tevatron
The next steps

We know enough now to predict with great certainty that fundamental new understanding of how forces are related, and the way that mass is given to all particles, will be found with the LHC and a Linear Collider operating at an energy of at least 500 GeV.

Experimental limits on the Higgs boson mass

$M_H$ between 114 and ~210 GeV
Electron-Positron Linear Collider offers

- well defined initial state
  \( \sqrt{s} \) well defined and tuneable
  quantum numbers known
  polarisation of e\(^+\) and e\(^-\) possible

- clean environment
  collision of pointlike particles
  \( \rightarrow \) low backgrounds

- precise knowledge of cross sections

Machine for Discoveries and Precision Measurements
An Analogy: What precision does for you ...
# The Role of Electron Positron Colliders

Explore new Physics through **high precision at high energy**

<table>
<thead>
<tr>
<th>microscopic</th>
<th>telescopic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+ e^- \rightarrow X_{new} (+Y_{SM})$</td>
<td>$e^+ e^- \rightarrow SM$</td>
</tr>
</tbody>
</table>

- Study the properties of new particles (cross sections, BR’s, quantum numbers)
- Study known SM processes to look for tiny deviations through virtual effects (needs ultimate precision of measurements and theoretical predictions)

Reason: low experimental backgrounds, weakly interacting initial state $\rightarrow$ high precision predictions
Linear Collider Parameters
international consensus (30/9/2003)

(1) baseline machine
   200 GeV < \(\sqrt{s}\) < 500 GeV
   integrated luminosity \(\sim\) 500 fb\(^{-1}\) in 4 years
   electron polarisation \(\sim\) 80%

(2) energy upgrade
   to \(\sqrt{s}\) \(\sim\) 1 TeV
   integrated luminosity \(\sim\) 1 ab\(^{-1}\) in 3 years

(3) options
   positron polarisation of \(\sim\) 50%
   high luminosity running at \(M_Z\) and W-pair threshold
   e\(^-\)e\(^+\), e\(\gamma\), \(\gamma\gamma\) collisions


! Times quoted for data taking cover only part of program !
Physics

Comprehensive and high precision coverage of energy range from $M_Z$ to $\sim 1$ TeV

cross sections few fb to few pb → e.g. $O(10,000)$ Hz/yr
1. Electroweak symmetry breaking
   light Higgs
   no Higgs
   ← and many(!) new models in between
2. Hierarchy and Unification
   SUSY
   Extra Dimensions
   and much more…
3. Flavour physics
The Higgs-Boson is a new form of matter
    a fundamental scalar
    a new force coupling to mass

Discovery and first measurements at LHC

Task at the Linear Collider:
Establish Higgs mechanism as the mechanism responsible
for electro-weak symmetry breaking

- Is it a Higgs-Boson ?
- Is it responsible for mass generation ?
- Does the Higgs field have a non-zero v.e.v. ?
- Structure of Higgs sector !
EWSB: Precision physics of Higgs bosons

Dominant production processes at LC:

\[
\begin{align*}
\text{Task at the LC:} \\
&\text{determine properties} \\
&\text{of the Higgs-boson} \\
&\text{establish Higgs mechanism} \\
&\text{responsible for the origin} \\
&\text{of mass}
\end{align*}
\]
EWSB: Precision physics of Higgs bosons

“seeing it without looking at it”: decay-mode independent observation

Recoil mass spectrum $ee \rightarrow HZ$ with $Z \rightarrow l^+l^-$

$\Delta \sigma \sim 3\%$

model independent measurement

$\Delta m \sim 50 \text{ MeV}$

sub-permille precision
ee $\rightarrow$ HZ
Z $\rightarrow$ ll
H $\rightarrow$ qq
EWSB: Precision physics of Higgs bosons

$\Delta m_H = 40 \text{ MeV}$

$\Delta m_H = 70 \text{ MeV}$

$m_H = 120 \text{ GeV}$

$\rightarrow bbqq$

$ee \rightarrow HZ$

diff. decay channels

$m_H = 150 \text{ GeV}$

$\rightarrow WW^{-}qq$

$\rightarrow q\bar{q}\ell^{+}\ell^{-}$

$\rightarrow W^{+}W^{-}\ell^{+}\ell^{-}$
EWSB: Precision physics of Higgs bosons

Higgs field responsible for particle masses
→ couplings proportional to masses

Precision analysis of Higgs decays

$\Delta BR/BR$

- bb 2.4%
- cc 8.3%
- gg 5.5%
- tt 6.0%
- gg 23.0%
- WW 5.4%

For 500 fb$^{-1}$
$M_H = 120$ GeV
EWSB: Precision physics of Higgs bosons

High precision measurement of Higgs branching ratios allows sensitivity to new effects, e.g. additional heavy Higgs bosons.

Global fit to measured cross sections and BRs yields Higgs couplings, e.g. $g(H_{bb})$ and $g(H_{\tau\tau})$.

Example: Standard Model Higgs vs MSSM Higgs.
Heavy SUSY Higgs bosons:
observation and mass/BR/width(?) measurements
depth into the LHC wedge region at 800-1000 GeV LC

EWSB: Heavy SUSY-Higgs

\[ \sqrt{s} = 800 \text{ GeV} \]
\[ m_A = 300 \text{ GeV} \]
\[ m_H = 250 \text{ GeV} \]

HA → bbbb and HA → bbττ/ττbb observable

HA: 5σ discovery possible
up to \( \Sigma m = \sqrt{s} - 30 \text{ GeV} \)
EWSB: Reconstruction of the Higgs-potential

\[ \Phi(H) = \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4 \]

SM: \( g_{HHH} = 6\lambda v \), fixed by \( M_H \)

\( \Delta \lambda / \lambda \approx 20\% \) (1 ab\(^{-1}\))
EWSB: No Higgs boson(s) found….

→ divergent $W^+_L W^-_L \rightarrow W^+_L W^-_L$ amplitude in SM at $\Lambda^2 = \mathcal{O} \left( \frac{4\pi\sqrt{2}}{G_F} \right) \approx (1.2 \text{TeV})^2$

→ SM becomes inconsistent unless a new strong QCD-like interaction sets on
→ Goldstone bosons (“Pions”) = $W$ states (“technicolor”)
→ no calculable theory until today in agreement with precision data

**Experimental consequences:** deviations in

- **triple gauge couplings**

  ![Diagram of triple gauge couplings]

  LC (800 GeV): sensitivity to energy scale $\Lambda$:
  - triple gauge couplings: $\sim 8 \text{ TeV}$
  - quartic gauge couplings: $\sim 3 \text{ TeV}$  ⇒ complete threshold region covered
Detector Challenges

- high statistical power of LC has to be met by excellent detector performance
- detector design challenging
  unprecedented resolution and systematics

Detector R&D needed now
• Goal: distinguish W and Z in their hadronic decay modes
• Example: Jet energy resolution (Particle Flow)

\[ e^+ e^- \rightarrow WW\nu\bar{\nu} \quad , \quad e^+ e^- \rightarrow ZZ\nu\bar{\nu} \]

Detector Challenges

Detector R&D ongoing in international proto-collaborations

LEP-like resolution

LC goal

Detector R&D ongoing in international proto-collaborations
Summary: EWSB

All(?) models of EWSB require study of Higgs Bosons or longitudinal Gauge Bosons

• precision measurements at the Linear Collider together with the results from LHC are crucial to establish the Higgs mechanism responsible for the origin of mass and for revealing the character of the Higgs boson

• if the electroweak symmetry is broken differently or in a more complicated way then foreseen in the Standard Model, the LC measurements strongly constrain the alternative model
Beyond the Higgs

Why are electroweak scale \((10^2 \text{ GeV})\) and the Planck scale \((10^{19} \text{ GeV})\) so disparate?

Are there

- new particles? \(\rightarrow\) supersymmetry
- hidden dimensions?
Supersymmetry

- unifies matter with forces
  for each particle a
  supersymmetric partner
  \((sparticle)\) of opposite
  statistics is introduced

- allows to unify strong
  and
  electroweak forces

- provides a link
  to string theories
Supersymmetry

- **Predicts**
  - light Higgs boson (+ additional heavier Higgs bosons)
  - spectrum of sparticles (→doubling number of particles)
- **Contains**
  - many new parameters connected to SUSY breaking
- **Provides**
  - dark matter candidate

**LC task for SUSY**

High precision measurements of
- masses
- couplings
- quantum numbers

needed to
- extract fundamental parameters (few)
- determine the way Supersymmetry is broken
  i.e the underlying supersymmetric model
Supersymmetry

Mass spectra depend on choice of models and parameters...

well measureable at LHC

precise spectroscopy at the Linear Collider
Supersymmetry

Production and decay of supersymmetric particles at $e^+e^-$ colliders

$e^+e^- \rightarrow \tilde{\chi}^\pm\tilde{\chi}^\mp$

$e^+e^- \rightarrow \mu^+\mu^-$

Charginos

S-muons

Lightest supersymmetric particle stable in most models

Candidate for dark matter

Experimental signature: missing energy
Supersymmetry

Measurement of sparticle masses

*ex:* Sleptons

lepton energy spectrum in continuum

*ex:* Charginos

threshold scan

achievable accuracy: $\delta m/m \sim 10^{-3}$
Extrapolation of SUSY parameters from weak to GUT scale (within mSUGRA)

Gauge couplings unify at high energies,
Gaugino masses unify at same scale

Precision provided by LC for slepton, charginos and neutralinos will allow to test if masses unify at same scale as forces

If there is a line of sight from EW to GUT/Planck scale physics in Nature, the LC has precise enough focus and sufficient aperture to observe the signals!
Summary: Supersymmetry

The Linear Collider will be a unique tool for high precision measurements

- model independent determination of SUSY parameters
- learn about SUSY breaking mechanism
- extrapolation to GUT scale possible

but what if ……
Extra Dimensions

Effects from real graviton emission:

measures the number of extra dimensions!
polarisation important to reduce background!
Extra Dimensions

Effects from virtual graviton exchange:

...can prove Spin-2 exchange!

angular distribution

left-right asymmetry (beam polarisation!)
Top Quark – the Key to Flavour Physics?

scan of the threshold for $e^+e^- \rightarrow t\bar{t}$

precise mass measurement
(100 MeV)

very important ingredient to
for precise theoretical predictions

(need to know SM parameters
if we want to see beyond-SM
physics!)
Precision electroweak tests

high luminosity running at the Z-pole
Giga Z ($10^9$ Z/year) $\approx 1000 \times \text{“LEP” in 3 months}$
with $e^-$ and $e^+$ polarisation

$\Delta\sin\Theta_W = 0.000013$

together with

$\Delta M_W = 7 \text{ MeV}$
(threshold scan)

And

$\Delta M_{\text{top}} = 100 \text{ MeV}$
Physics Conclusion

LC with $\sqrt{s} \leq 1$ TeV and high luminosity allows

- most stringent test of electroweak Standard Model
- to establish Higgs mechanism in its essential elements
- to explore SUSY sector with high accuracy, model independent
- extrapolations beyond kinematically accessible region
- ....

World-wide consensus on physics case:
http://sbhep1.physics.sunysb.edu/~grannis/lc_consenus.html
The challenges:

**Luminosity:**
- high charge density \(10^{10}\), > 10,000 bunches/s
- very small vertical emittance (damping rings, linac)
- tiny beam size \((5\times500 \text{ nm})\) (final focus)

**Energy:**
- high accelerating gradient (> 25 MV/m, 500 - 1000 GeV)

To meet these challenges:
- A lot of R&D on LC’s world-wide
- different technologies: GLC/NLC.....TESLA......(CLIC)

For \(E > 200\) GeV need to build linear colliders

Proof of principle:
- SLC
Warm RF, 11.4 GHz
Loaded gradient 50 MV/m
For site length 33 km: $E_{cm} = 1.1-1.3$ TeV
The Technical Design Report incl. cost was published in March 2001.

Superconducting RF, 1.3 GHz
Loaded gradient up to 35 MV/m
For site length 33 km: $E_{cm} = 800 \text{ GeV}$
some design parameters at 500 GeV c.m.

<table>
<thead>
<tr>
<th></th>
<th>JLC/NLC</th>
<th>TESLA</th>
<th>SLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L \times 10^{33}$ (cm$^{-2}$s$^{-1}$)</td>
<td>25</td>
<td>34</td>
<td>3x10$^{-3}$</td>
</tr>
<tr>
<td>$P_{AC}$ (MW)</td>
<td>195</td>
<td>140</td>
<td>500</td>
</tr>
<tr>
<td>$\sigma_y^*$ (nm)</td>
<td>3</td>
<td>5</td>
<td>500</td>
</tr>
<tr>
<td>bunch separation (ns)</td>
<td>1.4</td>
<td>337</td>
<td>500</td>
</tr>
<tr>
<td>$G_{acc}$ (MV/m), 500GeV</td>
<td>50</td>
<td>23.5</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>35</td>
<td>800</td>
</tr>
</tbody>
</table>
TESLA Test Facility at DESY

Operation for >13,000 h

Base for Project Proposal TDR (March 2001)

Technical readiness demonstrated
New surface treatment, gradients of > 40 MV/m (single cells) -> clear energy upgrade

 Routine production of cavities exceeding 25 MV/m (TESLA goal for 500 GeV)
High Power Test of a Complete EP nine-cell Cavity

Several single cell cavities reached > 40 MV/m

- 1/8th of a TESLA cryomodule
- 5 Hz, 500 ms fill, 800 ms flat-top
- 33-> >35 MV/m with no interruption related to cavity-coupler-klystron for more than 1000 hours
- > 50 h at 36 MV/m
- No field emission

Two cavities tested
Collaboration of interested accelerator laboratories and institutes world-wide with the goal to design, build, operate and utilise a large new accelerator:

Global Accelerator Network

Global Organisation

New large scale accelerators need to be global efforts

Need to go new ways in international collaborations in order to advance science

Collaboration of interested accelerator laboratories and institutes world-wide with the goal to design, build, operate and utilise a large new accelerator:

Global Accelerator Network
How to arrive at a **Linear Collider** as a **World-Project**

**ICFA Initiative for an international Coordination:**

- **Asian SG**
- **US SG**
- **European SG**
  - **Reg**
  - **Reg**
  - **Reg**
- **ECFA**

**International Linear Collider Steering Committee**

active since Aug. 2002
What has Happened recently?

• OECD Global Science Forum (2002 and continuing)
• ILCSC and regional steering group
• WG’s on organisational matters
• International LC Technical Review Committee
  (established R&D list for both technologies)
• Parameter list has been established
• US: Facilities for the Future of Science
• International technology recommendation panel (ITRP)
• Technology progress
• Discussion among funding agencies
• OECD science ministers’ statement

…a lot
Next Milestones towards a Linear Collider as a World-Project

2004  Selection of Collider Technology (warm or cold)
setting up of an international project team with branches in America, Asia and Europe
Continuation of discussion between funding agencies
Further studies of organisational structures

2005  Start of work of project teams

2006  Completion of the project layout including costing

2007  Decision in principle by governments to go ahead with LC

2015  Start of commissioning
Summary + Outlook

• Linear Electron Positron Collider in the range 500-1000 GeV has excellent scientific potential

• Worldwide consensus: LC next large HEP project – soon

• HEP community wants to build the LC as truly global project – choice of technology by end 2004

• Activities on political level started – Think global
Supersymmetry

- best motivated extension of SM
  - grand unification – connection to gravity – light Higgs – $\sin^2\Theta_W$
  - dark matter candidate – …. 

- mass spectrum depends on the unknown breaking scheme

- LC task for SUSY
  - reconstruction of kinematically accessible sparticle spectrum
  - i.e. measure sparticle properties (masses, Xsections, spin-parity)

  extract fundamental parameters (mass parameters, mixings, couplings)
  at the weak scale

  extrapolate to GUT scale using RGEs

  → determine underlying supersymmetric model
Global Accelerator Network

- make best use of world-wide competence, ideas, resources

- Well defined roles and obligations of all partners

- make projects part of the national programs of the participating countries

- create a visible presence of activities in all participating countries

- keep culture of accelerator development (scientific and technical) alive in laboratories and universities and be attractive for young scientists

- not an international permanent institution but an international project of limited duration
Global Accelerator Network

- Follows major detector collaboration in particle physics
- Partners contribute in full responsibility through components or subsystems
- Facility is common property
- Responsibility, cost are shared
- Remote operation
Remote Operation: Social Aspects

• how much manpower is needed in host lab to operate accelerator etc.
• how much manpower is needed as user support
• how much manpower is needed in home labs
• which are the necessary qualifications of the staff
• how to achieve the desired 'corporate identity', i.e. the common identification with the project
• how to maintain the 'scientific social life'
Towards a global project

International Linear Collider Technical Review Committee
ILC-TRC (chair Greg Loew)

- To assess the present technology status of the LC designs at hand, and their potential for meeting the advertised parameters at 500 GeV c.m.
- Use common criteria, definitions, computer codes, etc., for the assessments
- To assess the potential of each design for reaching energies above 500 GeV c.m.
- To establish, for each design, the R&D work that remains to be done in the next few years
- Categorise (rank) the R&D items
- To suggest future areas of collaboration
# ILC-TRC Rankings Score Sheet

<table>
<thead>
<tr>
<th>E&lt;sub&gt;cm&lt;/sub&gt;</th>
<th>TESLA</th>
<th></th>
<th>JLC/NLC</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
<td>800</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>R1</td>
<td>0</td>
<td>+1</td>
<td>2</td>
<td>+0</td>
</tr>
<tr>
<td>R2</td>
<td>7</td>
<td>+4</td>
<td>3</td>
<td>+0</td>
</tr>
<tr>
<td>R3</td>
<td>10</td>
<td>+3</td>
<td>11</td>
<td>+0</td>
</tr>
<tr>
<td>R4</td>
<td>1</td>
<td>+0</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Report by the ILC-TRC (420 pages) endorsed by ICFA in February 2003
### ILC-TRC The Rankings for R&D

<table>
<thead>
<tr>
<th>Rank</th>
<th>R&amp;D Needed Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>R&amp;D needed for feasibility demonstration of the machine</td>
</tr>
<tr>
<td>TESLA 800 GeV</td>
<td>Building and testing of a cryomodule (8 cavities) at 35 MV/m and measurements of dark current</td>
</tr>
<tr>
<td>JLC/NLC 500 GeV</td>
<td>Test of complete accelerator structure at design gradient with detuning and damping, including study of breakdown and dark current&lt;br&gt;Demonstration of SLED-II pulse compressor at full power</td>
</tr>
<tr>
<td>R2</td>
<td>R&amp;D needed to finalize design choices and ensure reliability</td>
</tr>
<tr>
<td>R3</td>
<td>R&amp;D needed before starting production of systems and components</td>
</tr>
<tr>
<td>R4</td>
<td>R&amp;D desirable for technical or cost optimisation</td>
</tr>
</tbody>
</table>
“TESLA has essentially demonstrated its main linac rf performance specifications for 500 GeV c.m. In 2004, one will hopefully know if TESLA can reach 800 GeV c.m. by testing of the cryomodules at 35 MV/m.”

{ Note: cms-energy above 800 GeV achievable by appropriate choice of length and site of the interaction region }
Dr. H. Schunck, EPS HEP conference in Aachen, July 2003:

“The TESLA linear collider has been one of the proposals evaluated by the Wissenschaftsrat. The judgement of the Wissenschaftsrat on the scientific perspectives of the project has indeed been very positive. The Wissenschaftsrat has strongly suggested that the linear collider should be realized as a genuine global project.

The German government has decided to follow this and as a consequence not to proceed nationally and at this moment not to propose a German site for TESLA. We have to wait for the international development. But we will continue our efforts to be able to participate in a global linear collider project. Let me underline: my government is the first one to have announced to be principally committed to participating in the project.”
US 20-Year Outlook
Facilities for the Future of Science

Near Term
Readiness for construction

HEPAP: “The intrinsic science potential of the Linear Collider and the capability of the facility to achieve that science are absolutely central. Presently in an advanced R&D phase on an international basis, with the formation of an international design team it would enter the project engineering and design phase in 2006.”
The DoE Advisory Committees recommended 53 major facilities for construction, and assessed each according to two criteria:

- **scientific importance**
- **readiness for construction**

Of the 53 facilities initially proposed by the Advisory Committees, 28 made the list of **most important facilities** that will be needed over the next 20 years to support the Nation’s research needs in areas that have been the traditional responsibility of the DOE.

Prioritisation process:

Two different concepts for a 500-1000 GeV LC:

**NLC/GLC**
- normal-conducting resonators

**TESLA**
- super-conducting resonators

Final choice still to be made
Linear Collider Challenges

Challenge of a tiny beam size:

intense R&D program on beam delivery system including final focus

Strong involvement of UK machine and particle physicists
LHC+LC: SUSY Higgs parameter determination

⇒ Comparison of MSSM prediction based on assumed inputs with BR’s measured at the LC yields very sensitive test of the model
LHC+LC: SUSY Higgs parameter determination

⇒ Indirect determination of trilinear coupling $A_t$:

Precise measurement of $m_t$ at the LC crucial, $\delta m_t \lesssim 100$ MeV

$\Delta m_t^{LC}$ vs. $\Delta m_t^{LHC}$ ⇒ accuracy of $A_t$ determination improved by factor 3
Physics: Join Forces: LHC + LC

Example: SUSY

Cascade decays of squarks: if heavy, only accessible at LHC hard to measure properties, if masses and BR's of lower members of decay chain unknown.

Example:

only accessible at LHC if these are known from LC

Improvement of squark mass by ~factor 3-4!

ongoing work... LHC/LC study group

www.ippp.dur.ac.uk/~georg/lhclc
Physics: Join Forces LHC + LC

Worldwide LHC/LC working group to explore the synergy between both machines, in general, and in particular when overlapping in time.

Work out cases where LC input improves LHC analyses

Example: absolute top Yukawa coupling from
\[ gg,qq \rightarrow t\bar{t}H \ (H \rightarrow bb,WW) \ (@LHC) \ (\text{rate } \sim (g_t g_{b/W})^2) \quad \text{and} \quad \text{BR}(H \rightarrow bb,WW) \ (@LC) \ (\text{absolute measurement of } g_{b/W}) \]
LHC+LC: SUSY Higgs parameter determination

Combination of LHC data on heavy Higgs states with LC data on the light CP-even Higgs

[K. Desch, S. Heinemeyer, G.W.]

Assume: LHC information on $M_A$, $\tan \beta$ $\oplus$ (LHC $\otimes$ LC) information on stop/sbottom masses $\oplus$ LHC / LC measurement of $m_h$:

$M_A$: 15% accuracy, $m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$: 5% accuracy, $\tan \beta > 15$

BR($h \to b\bar{b}$): 2.5% accuracy, BR($h \to WW^*$): 5% accuracy
The International Linear Collider Steering Committee (ILCSC) has successfully completed the selection of the twelve members of the International Technology Recommendation Panel (ITRP):

**Asia:**
- G.S. Lee
- A. Masaike
- K. Oide
- H. Sugaware

**Europe:**
- J-E Augustin
- G. Bellettini
- G. Kalmus
- V. Soergel

**North America:**
- J. Bagger
- B. Barish (Chair)
- P. Grannis
- N. Holtkamp

Recommendation of one technology before end of 2004
Global Design Organisation

The task force is preparing a Global Design Organisation. Main thrust of present thinking:

- The ILC Global Design Organization (GDO) to be established as an inter-regional entity as soon as the International Technical Recommendation Committee establishes their choice of the basic technology.
- The first mission of the GDO is to turn the technology choice to conceptual design of the machine (parameters, layout, roadmap, R&D).
- The GDO will consist of a Central Team and three Regional Teams, representing Asia, Europe and North America. (EU Design Study)
- project should have a **minimal administrative structure**, with mainly management oversight functions

- well defined roles and obligations of all partners

- coherent and **transparent process for reaching decisions** (consensus) inside collaboration

- **financial stability** combined with necessary flexibility

- not an international permanent institution but an **international project of limited duration**
Remote Operation: Technical Aspects

- remote controls and access, multiple control rooms
- protection against un-authorised access
- communication (speech, visual, computer)
- standardisation of systems & software, common documentation
- the role of GRID
- modular components and good spare parts

Plans for testing the remote operation concept are being pursued in the framework of existing facilities (TTF,...)
Outlook

- Strong world enthusiasm for a LC continues and grows
- The HEP community has demonstrated the will to join behind one technology and to build the LC jointly. It has the capability of getting organised
- The reason: „The next discoveries will have a disproportionate impact of our understanding of Nature“.
- We have convinced many people outside our community, but we need to get our own community more on board
- Need to go new ways in international collaborations in order to advance science and to maintain the strong existing centres
- Most important: we need to keep focused on reaching the next milestones while looking at the same time further ahead
High Gradients

2. cavity with similar performance

Very important for choice of technology
The path to higher energies….

High power test of electropolished nine-cell Cavity
> 1100 hrs at 35 MV/m

April 2003: 38 MV/m
High Power Test of a Complete EP nine-cell Cavity

Several single cell cavities reached > 40 MV/m

- 1/8th of a TESLA cryomodule
- 5 Hz, 500 µs fill, 800 µs flat-top
- 33-35 MV/m with no interruption related to cavity-coupler-klystron for more than 1000 hours
- > 50 h at 36 MV/m
- No field emission
measurement of cross sections at different energies allows to determine number and scale of extra dimensions (500 fb-1 at 500 GeV, 1000 fb-1 at 800 GeV)

cross section for anomalous single photon production

Hidden dimensions

$\delta = \# \text{ of extra dimensions}$

$e^+e^- \rightarrow \gamma G$
No Higgs boson(s) found….

$W_LW_L$ scattering:

Standard Model mathematically inconsistent unless new physics at about 1.3 TeV

Experimental consequence: New strong interaction measurable in triple and quartic gauge boson couplings

Sensitivity at a 800-1000 Gev Linear Collider: ~ 8 TeV (TGC)
~ 3 TeV (QGC)

complete threshold region covered
No Higgs boson(s) found….

Analysis of $ee \rightarrow WW$ within technicolour models:

Linear Collider sensitive to masses up to $\sim 2.5$ TeV and can distinguish LET from SM.
Reconstructed Higgs Mass (GeV)

Precision physics of Higgs bosons

$m_H = 240$ GeV

$e^+e^- \rightarrow ZH \rightarrow \ell^+\ell^- q\bar{q} q\bar{q}$

$\Delta m_H = 400$ MeV (0.2%)

$\Delta \sigma (HZ) = 4$

Results available for $M_H$ up to 320 GeV
Precision physics of Higgs bosons

Determination of quantum numbers

Spin from threshold measurement

CP-quantum numbers from H, Z angular distributions or polarisation analysis of Higgs decays to taus
Standard Model today enormously successful:

- tested at quantum level
- (sub)permille accuracy

precise and quantitative description of subatomic physics, valid to the 0.1% level

But:
many key questions open
Particle Physics and Cosmology both point to New Physics at the TeV scale

- Electroweak unification
- Dark Matter
- Dark Energy
- Inflation
- Neutrino Masses
- CP Violation
There are two distinct and complementary strategies for gaining new understanding of matter, space and time at future particle accelerators.

**HIGH ENERGY**
- direct discovery of new phenomena
- i.e. accelerators operating at the energy scale of the new particle

**HIGH PRECISION**
- interference of new physics at high energies through the precision measurement of phenomena at lower scales

Both strategies have worked well together → much more complete understanding than from either one alone

prime example: LEP / Tevatron
Warm RF, 11.4 GHz
Loaded gradient 50 MV/m
For site length 33 km: $E_{cm} = 1.1-1.3$ TeV