Interplay Between the LHC and a Linear Collider

Albert De Roeck  CERN
Ecole de Gif  2004
Le Future de la Physique des Hautes Energies
Contents

• Introduction: LHC↔ LC
• Examples of complimentarity
  - Supersymmetry
  - Higgs
  - Z’ bosons
  - Extra dimensions
• Conclusion
Next projects on the HEP roadmap

- **Large Hadron Collider (LHC) at CERN** → G. Unal
  - Approved, budget in place and under construction
  - Expected turn on in middle of 2007
- **Linear Collider (LC)?** → H. Videau
  - Strong world-wide effort to start construction around 2009/2010, if approved and budget established
  - Expected turn on 2015(+)
  - Study groups in Europe, Americas and Asia (+World Wide Study)
- Physics case for both machines separately is well established
- In Europe: up to LHC/LC study little contact between - experimental- the two communities (→"miss understandings"...)
  ⇒Initiative to form a LHC/LC common study group in 2002
The LHC/LC study group

Aim of the LHC/LC Study group: investigate how the analyses at the LHC could profit from results obtained at the LC and vice versa - maybe even affect LHC running or triggers --

• Started in summer 2002 as a world wide effort
• Collaborative effort of the LHC and linear collider community.
• Study group which has been officially recognized by international linear collider steering committee (ILCSC)
• Current about 190 (interested) working group members from ATLAS, CMS, LC working groups + Tevatron contact person
• Working group coordinators: R. Godbole, G. Weiglein
• Web page  www.ippp.dur.ac.uk/~georg/lhocl
LHC / LC Study Group Working Document

Contains work discussed at ~ 5 meetings, in particular around/during Les Houches 2003 (May 2003)

⇒ Over 500 Pages already !?!
⇒ Mostly comparison studies between the two machines
But a number of true complementarity studies...several are still ongoing
⇒ Not the final word

Expect to finalize by fall 2004

Abstract
The LHC / LC Study Group investigates the possible interplay between the LHC and a future $e^+e^-$ Linear Collider in testing the Standard Model and in searches for new physics. It is studied in particular to what extent analyses carried out at one of the machines can profit from results obtained at the other machine. Mutual benefits can occur both at the level of a combined interpretation of Hadron Collider and Linear Collider data and at the level of combined analyses of the data, where results obtained at one machine can directly influence the way analyses are carried out at the other machine. Topics under study comprise the physics of weak and strong electroweak symmetry breaking, Supersymmetric models, new gauge theories, models with extra dimensions, and electroweak and QCD precision physics. The present report summarizes the status of the work that has been carried out within the LHC / LC Study Group so far. Possible topics for future studies are outlined.
LHC/LC studies

• Electroweak Symmetry breaking (weakly)
  H. Haber, R. Godbole, G. Weiglein, ADR (*)

• Strong Electroweak Symmetry breaking
  T. Barklow, K. Moenig

• Supersymmetric Models

• New Gauge Theories
  S. Riemann

• Models with Extra Dimensions
  J. Hewett

• Exotics
  J. Gunion

• Electroweak and QCD precision tests
  E. Boos, S. Heinemeyer, J. Stirling, ADR

(*) = main chapter editors/organizers
Different characteristics of the two machines ⇒ Different capabilities & virtues

LHC pp collisions $\sqrt{s} = 14$ TeV
⇒ Strong point: larger mass reach for direct discoveries
• Kinematics: can use conservation of $p$
• Composite nature of colliding protons ⇒ underlying event
• $\sqrt{s}$ of the hard interaction not fixed
• Strongly interacting particles ⇒ huge QCD cross sec. (background)

e+e- collisions at $\sqrt{s} = 0.5-1.0$ TeV
⇒ Strong point: high precision physics
• Kinematics: mom. conservation used to analyze the decays,…
• Well defined initial state, beam polarization, $\sqrt{s}$,…
• Backgrounds smaller than LHC
• Options: $\gamma \gamma$, $e \gamma$, e-e- colliders.
The LHC/LC study

• Physics case well established for the LHC and LC
  - Not the aim to see who is better (always tempting of course...)
  - One of the purposes is to make both communities aware when designing there analyses on what kind of additional information they might get when a LC kicks in

• Interplay between LHC and a LC can happen at different levels
  - Combined interpretation of LHC/LC data
    ⇒ In particular to reduce possible model dependencies
    \[ \text{LHC} \oplus \text{LC} > \text{LHC} + \text{LC} \]
  - Combined analyses of LHC and LC (simultaneous running)
    \[ \text{LHC} \otimes \text{LC} > \text{LHC} \oplus \text{LC} \]

• If a LC gets into operation in time, could even influence detector/trigger choices at LHC upgrades (time-of-flight, softer scales, particle ID,...)
  ⇒ Can help to make the case for concurrent running of LHC and a LC
ILCSC Road Map

2004 technology recommendation (confirmed by ITRP)
Establish Global Design Initiative / Effort (GDI/E)
2005 CDR for Collider (incl. first cost estimate)
2007 TDR for Collider
2008 site selection
2009/2010 construction could start (if budget approved)

First collisions in 2015? Certainly a challenge
LC the first real “global machine” in HEP?
International LC scope document

- 500 GeV, and upgradeable to ~1 TeV,
- 500 fb\(^{-1}\) in 4 years at 500 GeV
- 2 interaction regions,
- 80% electron polarization
- Energy flexibility between \(\sqrt{s} = 90\text{-}500\) GeV
- Future: possibility of \(\gamma\gamma\), e-e-, e+ polarization, Giga -Z

⇒ TeV e+e- Linear Collider
**LHC Status/plans**

- Date for first beams/collisions: ⇒ *Spring 2007*
- Initial physics run starts in summer/fall 2007
  ⇒ collect \( \sim 10 \text{ fb}^{-1}/\text{exp} \) \( 2.10^{33} \text{cm}^{-2} \text{s}^{-1} \) by early 2008
- Depending on the evolution of the machine...
  ⇒ collect 200-300 \( \text{fb}^{-1}/\text{exp} \) \( 3.4-10.10^{33} \text{cm}^{-2} \text{s}^{-1} \) in 5-6 years time

> **Already time to think of upgrading the machine**

**Two options presently discussed/studied**

- Higher luminosity \( \sim 10^{35} \text{cm}^{-2} \text{s}^{-1} \) (SLHC)
  - Needs changes in machine and and particularly in the detectors
  ⇒ Start change to SLHC mode some time 2013-2016
  ⇒ Collect \( \sim 3000 \text{ fb}^{-1}/\text{experiment} \) in 3-4 years data taking.

- Higher energy?
  - LHC can reach \( \sqrt{s} = 15 \text{ TeV} \) with present magnets (9T field)
  - \( \sqrt{s} \) of 28 (25) TeV needs \( \sim 17 \) (15) T magnets ⇒ R&D needed!
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Upgrades of the LHC

J. Strait exercise:
Not an “official” LHC plot

Possible lumi scenario

If startup is as smooth as assumed here:
⇒ Around 2013: simple continuation becomes less exciting
⇒ Time for an upgrade?
By the Time the LC Turns on...

- The LHC luminosity upgrade complete or nearing completion
  ⇒ ~ 300 fb\(^{-1}\)/experiment accumulated
  ⇒ LHC luminosity = \(10^{35}/\text{cm}^{-2}\text{s}^{-1}\)
- Physics is focused on
  - Improvements in determination of SM parameters
    (Higgs & gauge boson couplings)
  - Improvements of accuracy of new physics parameters
    (sparticle spectroscopy, \(\tan\beta\) measurements)
  - Extension of the high mass discovery reach
  - Extension of the sensitivity to rare processes
    (FCNC top decays, Higgs pair production...)

The hard stuff

Discovery Physics → Spectroscopy
1. Supersymmetry
Supersymmetry

Supersymmetry (SUSY) → assumes a new hidden symmetry between the bosons (particles with integer spin) and fermions (particles with half integer spin) to stabilize the Higgs mass up to the Planck scale

⇒ Lots of new particles (squarks, sleptons,...) predicted with masses in the range from 10's of GeV's up to several TeV range

Should SUSY be realized, we have a lot to do

• Is it really SUSY?
• How is it realized? (particle content) MSSM NMSSM,...
• How is it broken?
  Measure as many of the ~100 low energy parameters as possible
  Measure them precisely as possible
  → Extrapolation to high scale

Lightest SUSY particle stable: dark matter candidate?
Discovery should be 'easy' for squark masses < ~2 TeV

E.G. 900 GeV squarks
E_{\text{miss}} > 300 GeV
+ 4 jets
SUSY at the LHC

3 isolated leptons
+ 2 b-jets
+ 4 jets
+ $E_t^{\text{miss}}$

But exclusive reconstruction often difficult
Sparticle discoveries

- A number of SUSY (msugra) benchmark points to study LHC/LC sensitivity (Battaglia, ADR, Ellis, Gianotti, Olive, Pape)
- Take into account direct searches at LEP and Tevatron, BR \( b \to s \gamma \), \( g_\mu - 2 \) (E821), Cosmology: \( 0.09 \leq \Omega \chi h^2 \leq 0.13 \)

Allowed regions in the \( M_0 - M_{1/2} \) plane

Complementarity in sparticle reach
LHC: mostly squarks/gluinos
LC: mostly gauginos, sleptons

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For several of these scenarios (almost) all particles can be detected.

Just an example... there are many more (also non-msugra) scenarios in use.

For the LHC/LC study: Choose point B (SPS1a)
Favorable point for LHC/LC!! Maybe Nature will be less kind...
1. Measurement of Sparticle Masses

To understand SUSY breaking we will need to measure as many parameters as possible, e.g. sparticle masses

LHC: complicated by decay chains for squarks and gluons

Examples worked out for SPS1a (point B) in ATLAS/CMS

LHC will see all squarks, H, A and may see most gauginos

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**LHC Sparticle Reconstruction**

Example

\[ p \rightarrow b \bar{b} \tilde{\chi}^0_2 \tilde{\chi}^0_1 \ell^+ \ell^- \]

Problem $\tilde{\chi}^0_1$ measurement!
It escapes detection like a neutrino!
Use kinematic formulae...

\[ M_{\ell^+\ell^-}^{\text{max}} = \sqrt{M_{\tilde{\chi}^0_2}^2 - M_{\ell}^2} (M_{\ell}^2 - M_{\tilde{\chi}^0_1}^2) / M_{\ell} \]

**Strategy:**
- Study many decay modes & fit "kinematic end points"
- Assume 'model' for $\tilde{\chi}^0_1$ & reconstruct masses

$M(e^+e^-) + M(\mu^+\mu^-)$

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Mass Correlations

Masses of the measured particles are strongly correlated with the mass of the lightest neutralino.

However LHC can do better analyzing many edges simultaneously ...

... but correlations between masses will remain
Analyse many edges of distributions:

\[
\begin{align*}
(m_{ll}^2)_{\text{edge}} &= \frac{(m_{\chi_0^2}^2 - m_{l_R}^2)(m_{l_R}^2 - m_{\chi_1^0}^2)}{m_{l_R}^2} \\
(m_{qll}^2)_{\text{edge}} &= \frac{(m_{q_L}^2 - m_{\chi_0^2}^2)(m_{\chi_0^2}^2 - m_{l_R}^2)}{m_{\chi_0^2}^2} \\
(m_{qL}^2)_{\text{min}} &= \frac{(m_{q_L}^2 - m_{\chi_0^2}^2)(m_{\chi_0^2}^2 - m_{l_R}^2)}{m_{\chi_0^2}^2} \\
(m_{qL}^2)_{\text{max}} &= \frac{(m_{q_L}^2 - m_{\chi_0^2}^2)(m_{l_R}^2 - m_{\chi_1^0}^2)}{m_{l_R}^2} \\
(m_{qll}^2)_{\text{thres}} &= [(m_{q_L}^2 + m_{\chi_0^2}^2)(m_{\chi_0^2}^2 - m_{l_R}^2) - (m_{l_R}^2 - m_{\chi_1^0}^2) \sqrt{(m_{\chi_0^2}^2 + m_{l_R}^2)^2 - 16m_{\chi_0^2}^2m_{l_R}^2m_{\chi_1^0}^2} \\
&+ 2m_{l_R}^2(m_{q_L}^2 - m_{\chi_0^2}^2)(m_{\chi_0^2}^2 - m_{l_R}^2)]/(4m_{l_R}^2m_{\chi_0^2}^2)
\end{align*}
\]

Min, max refer to choice of lepton

Solve numerically equations ⇒ derive masses
# Extracted Edge Values

**SPS1a 300 fb⁻¹**  
**Includes 1% energy-scale systematics**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value (GeV)</th>
<th>Stat. (GeV)</th>
<th>Errors Scale (GeV)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\ell\ell}^{\text{max}}$</td>
<td>77.07</td>
<td>0.03</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>$m_{\ell\ell q}^{\text{max}}$</td>
<td>428.5</td>
<td>1.4</td>
<td>4.3</td>
<td>4.5</td>
</tr>
<tr>
<td>$m_{\ell q}^{\text{low}}$</td>
<td>300.3</td>
<td>0.9</td>
<td>3.0</td>
<td>3.1</td>
</tr>
<tr>
<td>$m_{\ell q}^{\text{high}}$</td>
<td>378.0</td>
<td>1.0</td>
<td>3.8</td>
<td>3.9</td>
</tr>
<tr>
<td>$m_{\ell q}^{\text{min}}$</td>
<td>201.9</td>
<td>1.6</td>
<td>2.0</td>
<td>2.6</td>
</tr>
<tr>
<td>$m_{\ell q}^{\text{max}}$</td>
<td>183.1</td>
<td>3.6</td>
<td>1.8</td>
<td>4.1</td>
</tr>
<tr>
<td>$m_{\ell q}^{\ell \ell}$</td>
<td>106.1</td>
<td>1.6</td>
<td>0.1</td>
<td>1.6</td>
</tr>
<tr>
<td>$m(\ell_L) - m(\tilde{\chi}_1^0)$</td>
<td>280.9</td>
<td>2.3</td>
<td>0.3</td>
<td>2.3</td>
</tr>
<tr>
<td>$m_{\ell \ell}^{\text{max}}(\tilde{\chi}_4^0)$</td>
<td>80.6</td>
<td>5.0</td>
<td>0.8</td>
<td>5.1</td>
</tr>
<tr>
<td>$m(\tilde{g}) - 0.99 \times m(\tilde{\chi}_1^0)$</td>
<td>500.0</td>
<td>2.3</td>
<td>6.0</td>
<td>6.4</td>
</tr>
<tr>
<td>$m(\tilde{q}_R) - m(\tilde{\chi}_1^0)$</td>
<td>424.2</td>
<td>10.0</td>
<td>4.2</td>
<td>10.9</td>
</tr>
<tr>
<td>$m(\tilde{g}) - m(\tilde{b}_1)$</td>
<td>103.3</td>
<td>1.5</td>
<td>1.0</td>
<td>1.8</td>
</tr>
<tr>
<td>$m(\tilde{g}) - m(\tilde{b}_2)$</td>
<td>70.6</td>
<td>2.5</td>
<td>0.7</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Supersymmetry at a LC

Kinematics: end-points allows to measure sparticle masses precisely

$$E_{\text{max/min}} = \frac{M_{\mu}}{2} \left( 1 - \frac{M_{\tilde{\chi}_2^0}^2}{M_{\mu}^2} \right) \times \left( 1 \pm \sqrt{1 - \frac{M_{\mu}^2}{E_{\text{beam}}^2}} \right)$$

Measure single muons

$$e^- e^+ \rightarrow \tilde{\mu}_L \tilde{\mu}_R \rightarrow \mu \tilde{\chi}_2^0$$

$$e^- e^+ \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow \mu \mu \tilde{\chi}_1^0$$

Precision on masses of order 0.5-0.1%
### SUSY Sparticle Mass Precision at a LC

<table>
<thead>
<tr>
<th>$\tilde{\chi}_1^{\pm}$</th>
<th>176.4</th>
<th>0.55</th>
<th>simulation threshold scan, 100 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}_2^{\pm}$</td>
<td>378.2</td>
<td>3</td>
<td>estimate $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$, spectra $\tilde{\chi}_2^{\pm} \to Z\tilde{\chi}_1^{\pm}$, $W\tilde{\chi}_1^0$</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0$</td>
<td>96.1</td>
<td>0.05</td>
<td>combination of all methods</td>
</tr>
<tr>
<td>$\tilde{\chi}_2^0$</td>
<td>176.8</td>
<td>1.2</td>
<td>simulation threshold scan $\tilde{\chi}_2^0\tilde{\chi}_2^0$, 100 fb$^{-1}$</td>
</tr>
<tr>
<td>$\tilde{\chi}_3^0$</td>
<td>358.8</td>
<td>3 – 5</td>
<td>spectra $\tilde{\chi}<em>3^0 \to Z\tilde{\chi}</em>{1,2}^0$, $\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_3^0\tilde{\chi}_4^0$, 750 GeV, $&gt; 1000$ fb$^{-1}$</td>
</tr>
<tr>
<td>$\tilde{\chi}_4^0$</td>
<td>377.8</td>
<td>3 – 5</td>
<td>spectra $\tilde{\chi}<em>4^0 \to W\tilde{\chi}</em>{1,2}^\pm$, $\tilde{\chi}_2^0\tilde{\chi}_4^0$, $\tilde{\chi}_3^0\tilde{\chi}_4^0$, 750 GeV, $&gt; 1000$ fb$^{-1}$</td>
</tr>
<tr>
<td>$\tilde{e}_R$</td>
<td>143.0</td>
<td>0.05</td>
<td>$e^-e^-$ threshold scan, 10 fb$^{-1}$</td>
</tr>
<tr>
<td>$\tilde{e}_L$</td>
<td>202.1</td>
<td>0.2</td>
<td>$e^-e^-$ threshold scan 20 fb$^{-1}$</td>
</tr>
<tr>
<td>$\tilde{\nu}_e$</td>
<td>186.0</td>
<td>1.2</td>
<td>simulation energy spectrum, 500 GeV, 500 fb$^{-1}$</td>
</tr>
<tr>
<td>$\tilde{\mu}_R$</td>
<td>143.0</td>
<td>0.2</td>
<td>simulation energy spectrum, 400 GeV, 200 fb$^{-1}$</td>
</tr>
<tr>
<td>$\tilde{\mu}_L$</td>
<td>202.1</td>
<td>0.5</td>
<td>estimate threshold scan, 100 fb$^{-1}$ [36]</td>
</tr>
<tr>
<td>$\tilde{\tau}_1$</td>
<td>133.2</td>
<td>0.3</td>
<td>simulation energy spectra, 400 GeV, 200 fb$^{-1}$</td>
</tr>
<tr>
<td>$\tilde{\tau}_2$</td>
<td>206.1</td>
<td>1.1</td>
<td>estimate threshold scan, 60 fb$^{-1}$ [36]</td>
</tr>
<tr>
<td>$\tilde{t}_1$</td>
<td>379.1</td>
<td>2</td>
<td>estimate $b$-jet spectrum, $m_{\text{min}}(t)$, 1 TeV, 1000 fb$^{-1}$</td>
</tr>
</tbody>
</table>

Table 5.12: Sparticle masses and their expected precisions in Linear Collider experiments, SPS 1a mSUGRA scenario

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Mass Determinations including LC data

Improvement of measured particle masses at LHC when the mass of the lightest neutralino is known from the LC

slepтон → χ₁ precision from the LC

squark

sbottom

Significant improvements & reduction of correlations

... but correlations between masses will remain
Combining the LC/LHC Data

300 fb$^{-1}$@LHC

Takes into account 1% energy scale uncertainties

$\Delta M$ values in GeV

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>LHC+LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{\tilde{\chi}_1^0}$</td>
<td>4.8</td>
<td>0.05 (LC input)</td>
</tr>
<tr>
<td>$\Delta m_{\tilde{\chi}_2^0}$</td>
<td>4.7</td>
<td>0.08</td>
</tr>
<tr>
<td>$\Delta m_{\tilde{\chi}_4^0}$</td>
<td>5.1</td>
<td>2.23</td>
</tr>
<tr>
<td>$\Delta m_{\tilde{t}_R}$</td>
<td>4.8</td>
<td>0.05 (LC input)</td>
</tr>
<tr>
<td>$\Delta m_{\tilde{\ell}_L}$</td>
<td>5.0</td>
<td>0.2 (LC input)</td>
</tr>
<tr>
<td>$\Delta m_{\tau_1}$</td>
<td>5-8</td>
<td>0.3 (LC input)</td>
</tr>
<tr>
<td>$\Delta m_{\tilde{q}_L}$</td>
<td>8.7</td>
<td>4.9</td>
</tr>
<tr>
<td>$\Delta m_{\tilde{q}_R}$</td>
<td>7-12</td>
<td>5-11</td>
</tr>
<tr>
<td>$\Delta m_{b_1}$</td>
<td>7.5</td>
<td>5.7</td>
</tr>
<tr>
<td>$\Delta m_{b_2}$</td>
<td>7.9</td>
<td>6.2</td>
</tr>
<tr>
<td>$\Delta m_{\tilde{g}}$</td>
<td>8.0</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Significant improvements with an LC/LHC combined data
Why do we want % precision on masses?

Discrimination between different SUSY-breaking scenarios

Need information of both the squark and slepton sector
Need % level accuracy to distinguish between different models
2. Predict Sparticle Masses from LC → LHC

A step further: predicting sparticles masses from LC data.
LC can measure neutral $\chi_1$, $\chi_2$ and charged $\chi_1$ precisely

⇒ Measurements of masses, cross sections and the mixing angles (using polarized beams)
⇒ Determine the SUSY parameters $M_1$, $M_2$ ($U(2)$ and $SU(2)$ gaugino masses)
   $\mu$ (higgsino mixing parameter) and $\tan \beta$

<table>
<thead>
<tr>
<th>SUSY Parameters</th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$\mu$</th>
<th>$\tan \beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>99.1 ± 0.2</td>
<td>192.7 ± 0.5</td>
<td>352.4 ± 4.5</td>
<td>10.2 ± 0.9</td>
</tr>
</tbody>
</table>

Predicts: $m(\chi_4) = 378.3 ± 8.8$ GeV
Finding $\chi_4$ in the LHC Data...

⇒ This helps to interpret the LHC data
⇒ Marginal edge for $\chi_4$ at the LHC found with LC input!

Di-lepton spectrum

\[ 100 \text{ fb}^{-1} \]

ATLAS

$\chi_4$ (Not $\chi_2^{\pm}$)

With a tailored analysis can measure $\Rightarrow m(\chi_4)$ to $\sim 5$ GeV
When $m(\chi_1)$ is known from the LC then $\Rightarrow m(\chi_4)$ to 2.2 GeV

Requires machines to run at the same time
Not a precedent...

2003: Belle (e+e-) finds \(X(3872) \rightarrow D0\) and CDF search and find it
...and now.. ⇒ use $\chi_4$ for LC data!

**LC information alone**

$\Delta \chi^2 = 6$ curves

**LHC+LC information**

<table>
<thead>
<tr>
<th>SUSY Parameters</th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$\mu$</th>
<th>$\tan \beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$99.1 \pm 0.1$</td>
<td>$192.7 \pm 0.3$</td>
<td>$352.4 \pm 2.1$</td>
<td>$10.2 \pm 0.6$</td>
</tr>
</tbody>
</table>

Significant improvement of the precision

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Some Comments

• LC prediction for $M(\chi_4)$ increases the statistical significance of the LHC: testing only one mass hypothesis rather than many hypotheses.

• A mismatch between LC prediction and LHC measurement can imply (N)MSSM or something entirely different. So it will be important anyway.

• Prototype example of LHC/LC synergy:
  - A signal with small statistical significance seen at the LHC after LC predicts it, calls for higher luminosity, improved analyses, cuts, perhaps trigger upgrades etc.
  - In such case overlap in LHC/LC running will be very important.
3. Full Reconstruction of the stop/bottom Parameters with LHC ⊗ LC

Hisano, Kawagoe, Nojiri

- Take the set of electroweak SUSY parameters determined by the LC and LHC data.
- Take branching ratios of bottom (stop) measured by the LHC.
- Take $m_{b_1}$ and $m_{b_2}$ from edge study (+ neutralino from the LC).

- Measure
  - $tb$ invariant mass distribution
  - Rate of “edge events” in $m_{tb}$ distribution (chargino chain)
  - Rate of events in the 2 lepton+b distribution (neutralino-2 chain)

⇒ extract sbottom and stop mixing parameters
Determination of \( \theta_b \) from \( \frac{\text{BR}(\tilde{g} \rightarrow \tilde{b}_2 \rightarrow bb\tilde{\chi}_2^0)}{\text{BR}(\tilde{g} \rightarrow \tilde{b}_1 \rightarrow bb\tilde{\chi}_2^0)} \) with/without exp systematics

Determination of \( \theta_{\text{stop}}, m_{\text{stop}} \) when \( \theta_b \) is known

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4. Determine the Pattern of SUSY Breaking

With all LC/LHC information ⇒ Determine the SUSY Parameters

<table>
<thead>
<tr>
<th>Parameter, ideal</th>
<th>“LHC+LC” errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_1$</td>
<td>101.66</td>
</tr>
<tr>
<td>$M_2$</td>
<td>191.76</td>
</tr>
<tr>
<td>$M_3$</td>
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<tr>
<td>$\mu$</td>
<td>357.4</td>
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<tr>
<td>$M_{\tilde{E}_3}^2$</td>
<td>3.8191 \cdot 10^4</td>
</tr>
<tr>
<td>$M_{\tilde{E}_3}^2$</td>
<td>1.8441 \cdot 10^4</td>
</tr>
<tr>
<td>$M_{\tilde{Q}_3}^2$</td>
<td>29.67 \cdot 10^4</td>
</tr>
<tr>
<td>$M_{\tilde{U}_3}^2$</td>
<td>27.67 \cdot 10^4</td>
</tr>
<tr>
<td>$M_{\tilde{D}_3}^2$</td>
<td>27.45 \cdot 10^4</td>
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<tr>
<td>$M_{\tilde{L}_3}^2$</td>
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<td>$M_{\tilde{E}_3}^2$</td>
<td>1.7788 \cdot 10^4</td>
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<tr>
<td>$M_{\tilde{Q}_3}^2$</td>
<td>24.60 \cdot 10^4</td>
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<tr>
<td>$M_{\tilde{U}_3}^2$</td>
<td>17.61 \cdot 10^4</td>
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<tr>
<td>$M_{\tilde{D}_3}^2$</td>
<td>27.11 \cdot 10^4</td>
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<tr>
<td>$M_{\tilde{H}_3}^2$</td>
<td>3.25 \cdot 10^4</td>
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<tr>
<td>$M_{\tilde{H}_2}^2$</td>
<td>−12.78 \cdot 10^4</td>
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<tr>
<td>$A_t$</td>
<td>−497.</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>10.0</td>
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</table>

Low energy SUSY parameters

<table>
<thead>
<tr>
<th>Mass, ideal</th>
<th>“LHC”</th>
<th>“LC”</th>
<th>“LHC+LC”</th>
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<tbody>
<tr>
<td>$\tilde{\chi}^+_i$</td>
<td>179.7</td>
<td>0.55</td>
<td>0.55</td>
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<tr>
<td>$\tilde{\chi}^0_2$</td>
<td>382.3</td>
<td>3.0</td>
<td>3.0</td>
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<tr>
<td>$\tilde{\chi}^0_1$</td>
<td>97.2</td>
<td>4.8</td>
<td>0.05</td>
</tr>
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<td>180.7</td>
<td>4.7</td>
<td>1.2</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1$</td>
<td>364.7</td>
<td>3-5</td>
<td>3-5</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1$</td>
<td>381.9</td>
<td>5.1</td>
<td>3-5</td>
</tr>
<tr>
<td>$\tilde{\tau}_R$</td>
<td>143.9</td>
<td>4.8</td>
<td>0.05</td>
</tr>
<tr>
<td>$\tilde{\tau}_L$</td>
<td>207.1</td>
<td>5.0</td>
<td>0.2</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>191.3</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>$\tilde{\mu}_R$</td>
<td>143.9</td>
<td>4.8</td>
<td>0.2</td>
</tr>
<tr>
<td>$\tilde{\mu}_L$</td>
<td>207.1</td>
<td>5.0</td>
<td>0.5</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>191.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{\tau}_1$</td>
<td>134.8</td>
<td>5-8</td>
<td>0.3</td>
</tr>
<tr>
<td>$\tilde{\tau}_2$</td>
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<td>-</td>
<td>1.1</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>190.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{q}_R$</td>
<td>547.6</td>
<td>7-12</td>
<td>5-11</td>
</tr>
<tr>
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<td>570.6</td>
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<td>2.0</td>
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<td>$\tilde{t}_2$</td>
<td>586.3</td>
<td>-</td>
<td>-</td>
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<tr>
<td>$\tilde{b}_1$</td>
<td>515.1</td>
<td>7.5</td>
<td>5.7</td>
</tr>
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<td>$\tilde{b}_2$</td>
<td>547.1</td>
<td>7.9</td>
<td>6.2</td>
</tr>
<tr>
<td>$g$</td>
<td>604.0</td>
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<td>6.5</td>
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<td>$h^0$</td>
<td>110.8</td>
<td>0.25</td>
<td>0.05</td>
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<td>$H^0$</td>
<td>399.8</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>$A^0$</td>
<td>399.4</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>$H^\pm$</td>
<td>407.7</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Check the Unification of the Couplings

Input SUSY spectrum parameters and present data on $\alpha, \alpha_s, \sin^2 \theta$...

Renormalization Group Equations

![Diagram showing renormalization group equations and LHC results.](image)
Extrapolation to Physics at High Scales

From a combination of LHC and LC results, precise measurements of masses of SUSY particles, couplings: Evolution of gaugino mass parameters

Model independent bottom-up approach: combined information on low-energy SUSY parameters as input to the Renormalization Group Equation evolution
From a combination of LHC and LC results, precise measurements of masses of SUSY particles, couplings: Evolution of sfermion mass parameters.
Precision on MSUGRA Parameters

$M_0, M_{1/2}, \tan \beta, A_0, \text{sign}(\mu)$ are the MSUGRA parameters

<table>
<thead>
<tr>
<th></th>
<th>&quot;LHC&quot;</th>
<th>&quot;LC&quot;</th>
<th>&quot;LHC+LC&quot;</th>
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</thead>
<tbody>
<tr>
<td>$M_{1/2}$</td>
<td>250.0 ± 2.1</td>
<td>250.0 ± 0.4</td>
<td>250.0 ± 0.2</td>
</tr>
<tr>
<td>$M_0$</td>
<td>100.0 ± 2.8</td>
<td>100.0 ± 0.2</td>
<td>100.0 ± 0.2</td>
</tr>
<tr>
<td>$A_0$</td>
<td>-100.0 ± 34</td>
<td>-100.0 ± 27</td>
<td>-100.0 ± 14</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>10.0 ± 1.8</td>
<td>10.0 ± 0.6</td>
<td>10.0 ± 0.4</td>
</tr>
</tbody>
</table>
Few Remarks on these SUSY Studies

- All studies done (coherently) for SPS1a!
- In future we need to study also less favorable points.

⇒ The impact of a LC/LHC synergy may be even larger for “less favorable” SUSY points, e.g. points at large tan β
- lots of decays into τ leptons
- more difficult at the LHC
2. Higgs Physics
Higgs Measurement Prospects

Discovery in full range with 10 fb\(^{-1}\)

**LHC**
- \(\Delta M/M = 0.1-1\%\) large region
- \(\Delta \Gamma/\Gamma = 5-8\% \ (M_H > 2M_Z)\)
  \(= \sim 20\% \ (M_H < 2M_Z)\)
- Ratios of couplings: 10-20%

**LC**
- \(\Delta M/M = 0.03\%\)
- Total width
- Invisible width (ee→ZH)
- Absolute couplings: few %
- Higgs self coupling 20 %
- ...

**Signal significance**

\[ \begin{align*}
\int L \, dt &= 10 \text{ fb}^{-1} \\
\int L \, dt &= 30 \text{ fb}^{-1}
\end{align*} \]

ATLAS + CMS (no K-factors)

\[ \begin{align*}
\text{Signal significance} \\
L \&( \text{fb}^{-1})
\end{align*} \]

\[ \begin{align*}
10^2 \\
10 \\
1
\end{align*} \]

\[ \begin{align*}
m_H \ (\text{GeV}) \\
10^2 \\
10^3
\end{align*} \]

\[ 5 \sigma \]

Albert De Roeck (CERN)
1. Combine LHC Data on Heavy Higgs with LC Data on the Light Higgs

Desch, Gross, Heinemeyer, Weiglein

Assume:
LHC information on $M_A$ and $\tan \beta$

⊕ (LHC×LC) information on stop/bottom masses

⊕ LHC/LC measurement of $m_H$

⊕ LC information on $m_{top} \sim 0.1$ GeV

Comparison of MSSM predictions based on LHC data with BR’s measured at the LC leads to very sensitive tests.
Trilinear Coupling $A_t$

If $m_{\text{stop}}$ and $m_{\text{bottom}}$ measured
$\Rightarrow m_H$ allows for an indirect determination of $A_t$ (up to a sign)

Precise measurement of $m_t$ at the LC crucial: $\Delta m_t \sim 100$ MeV
$\Rightarrow \Delta m_t^{\text{LC}}$ vs $\Delta m_t^{\text{LHC}}$ $\Rightarrow$ accuracy of $A_t$ determination improved by factor 3
2. Heavy MSSM Higgs

At low $\tan \beta$, we may exploit the sparticle decay modes:

$$A, H \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4l + E_T^{\text{miss}}$$

Plot for $5\sigma$ discovery

September 2001

ATLAS + CMS
$\int dt = 300 \text{ fb}^{-1}$
Maximal mixing

CMS, 100 fb$^{-1}$
Maximal stop mixing

$A, H \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4 \text{ lept}$
$\tau \tau \rightarrow l + \tau - \text{jet} + X$, 30 fb$^{-1}$

Excluded by LEP

Albert De Roeck (CERN)
Reconstruct $M_A$

Moortgat

$H, A \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$ \rightarrow 4 leptons and missing $E_T$

Get mass from sensitivity to the four lepton invariant mass

$LHC: \text{Sensitivity dominated by uncertainty at the LSP mass knowledge}\n
LHC \otimes LC: \text{Sensitive to } M_A \sim 3\% \text{ if mass of LSP known to better than 1\%}$
3. Constraining $M_A$ from LHC and LC Measurements

- Suppose LHC sees only one Higgs and some SUSY particles, but not the $A/H$ Higgses (SPS1a, but $M_A$ as a free parameter)
- Use information from the measured SUSY spectrum at LC & LHC and from measured BR of the Higgs measured at LC to predict mass of $M_A$ (mass of the gluino, sbottom quarks, light stop, Higgs and tan $\beta$)
- Compare:

$$r \equiv \frac{[BR(h \to b\bar{b})/BR(h \to WW^*)]_{MSSM}}{[BR(h \to b\bar{b})/BR(h \to WW^*)]_{SM}}$$

Determine $M_A$ with 20-30% for $M_A$ 600-800 GeV
MSSM Higgs search with a LHC upgrade

In the green region only SM-like $h$ observable with $300 \text{ fb}^{-1}/\text{exp}$
- Red line: extension with $3000 \text{ fb}^{-1}/\text{exp}$
- Blue line: 95% excl. with $3000 \text{ fb}^{-1}/\text{exp}$

Factor 10 increase in luminosity:
Heavy Higgs observable region increases by $\sim 100 \text{ GeV}$.

If LC predicts e.g. $M_A \sim 600 \text{ GeV}$ (for $\tan\beta = 15$) then the $A$ boson within reach of the LHC with sufficient luminosity.
4. Top Yukawa Coupling

Dawson, Desch, Juste, Rainwater, Reina, Schumacher, Wackeroth

Assume a light Higgs < 2m_t

Production processes
LC: e+e- → ttH  No precise measurement at 350-500 GeV LC
LHC: gg → ttH  measures σ•BR

studied for ttbb and tt WW final states
depends on g^2_{ttH} g^2_{bbH} and g^2_{ttH} g^2_{WWH}

$g^2_{bbH}$ and $g^2_{WWH}$ can be measured precisely in a model
independent way at a LC (few %)

$\begin{array}{|c|c|c|}
\hline
m_H \text{ (GeV)} & \Delta \text{BR}(bb)/\text{BR}(bb) & \Delta \text{BR}(WW)/\text{BR}(WW) \\
\hline
100 & 0.024 & \\
120 & 0.024 & 0.051 \\
140 & 0.026 & 0.025 \\
160 & 0.065 & 0.021 \\
200 & & 0.021 \\
\hline
\end{array}$

⇒ can determine $g^2_{ttH}$ without any model assumptions

LC
350 GeV
500 fb⁻¹

Albert De Roeck (CERN)  51
**Top Yukawa Coupling**

![Graphs showing precision in the top Yukawa coupling](image)

**Precision of the top Yukawa coupling**

<table>
<thead>
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<th>$m_H$ (GeV)</th>
<th>$30 \text{ fb}^{-1}$</th>
<th>$300 \text{ fb}^{-1}$</th>
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<tbody>
<tr>
<td></td>
<td>bb</td>
<td>WW</td>
</tr>
<tr>
<td>100</td>
<td>0.22(0.12)</td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>0.25(0.15)</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>0.31(0.19)</td>
<td>0.52(0.49)</td>
</tr>
<tr>
<td>130</td>
<td>0.43(0.28)</td>
<td>0.28(0.25)</td>
</tr>
<tr>
<td>140</td>
<td>0.72(0.50)</td>
<td>0.20(0.17)</td>
</tr>
<tr>
<td>150</td>
<td>0.18(0.14)</td>
<td></td>
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<tr>
<td>160</td>
<td>0.16(0.13)</td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>0.17(0.13)</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>0.18(0.15)</td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>0.22(0.19)</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>0.26(0.23)</td>
<td></td>
</tr>
</tbody>
</table>

**~15%**
3. New Gauge Theories

![Graph depicting new gauge theories with different values of $\Gamma$.]
New Gauge Theories

Discover of an extra gauge boson at the LHC ⇒ measure the mass

LC is sensitive to $g/M_Z$. Mass at LHC + precision LC measurements allows to determine the couplings and distinguish between different scenarios.
Assume no Z' etc. detected directly at the LHC
Revisit the Z with a Z- factory (Giga-Z: $10^9$ Zs!)

Example interplay scenarios

**Little Higgs:** assume LHC sees Higgs at 300 GeV
⇒ Giga-Z can estimate the mass of the Z' (U(1) singlet), say 5 GeV

**Universal extra dimensions:** assume LHC sees a light Higgs only.
⇒ Giga-Z demonstrates that direct and indirect Higgs mass meas. disagree
   Improve search strategy or increase energy of LHC (a little)
4. Extra Dimensions
Curved Space: RS Extra Dimensions

Randall, Sundrum, PRL 83, 3370 (1999)

\[ ds^2 = e^{-2ky} \eta_{\mu\nu} \, dx^\mu \, dx^\nu - dy^2 \]

- Gravity strong at \( y=0 \) and falls like \( \exp(-ky) \)
- Gravity scale \( \Lambda_\pi = M_{\text{Planck}} \exp(-k\pi r_c) \sim \text{TeV} \) — no hierarchy
- Graviton resonances \( m_n = x_n \, k \, \exp(-k\pi r_c) \), \( J_1(x_n)=0 \)
- \( M_{\text{Planck}}/M_{\text{electroweak}} \Rightarrow kr_c \sim 11-12 \)
- Newton’s law \( \Rightarrow |R_5| < M_{5D}^2 \Rightarrow \text{coupling } c < 0.1 \)
Radions!

- Models with 3-branes in extra dimensions predict radions
- Quantum excitations of brane distance in RS theories

- Radion Couplings to Gauge Bosons and Fermions similar to SM $H^0$;

- $\phi$ Mixing to $H, \xi$ cause shift in $g_{HVV}$ and $g_{Hff}$ couplings

Three Fundamental Parameters:

$$m_r, \xi, \frac{v}{\Lambda}$$

Can change things a lot for the LHC
Higgs and Radion Searches

Detectability at the LHC versus mixing $\xi$ and mass of the radion $M_\phi$

LHC has regions from the parameters space where it cannot find the Higgs. However in most of these regions LHC will observe a Radion. $\Rightarrow$ LHC will essentially always see a scalar particle.
Higgs or Radion?

- At LHC mostly ratios of couplings are determined
- Radions: same fermions/WW,ZZ coupling ratio as for SM Higgs
- Couplings to $\gamma\gamma$ and gg receive anomalous contributions $\rightarrow$ e.g. $g_{h\gamma\gamma}/g_{hWW}$

Figure 4: Ratio of couplings $g_{H\gamma\gamma}^{\text{effective}}/g_{HWW}$ normalised to the SM prediction as function of $\xi$. Results are obtained for $M_H=120$ GeV and $\Lambda=2.5$ TeV (left), 5.0 TeV (center) and 7.5 TeV (right). The darker (blue) curves refer to $M_\phi = 150$ GeV and the lighter (red) to $M_\phi = 300$ GeV.

Effects are $\sim$1-5%: Difficult to establish at LHC
Some absolute rates go down up to factor 2 for $m_\phi > 2m_H$ and $\xi \neq 0$
• Nature (h or φ) can be determined at LC since it measures absolute coupling strengths with a few % accuracy: e.g. using couplings to bb and WW

If mixing is strong enough the LC can easily distinguish a Higgs from a Radion
• Lots more on
  - Electroweak physics
  - QCD
  - Top physics
  - ADD extra dimensions
  - CP studies in the Higgs sector
  - Higgs potential
  - NMSSM studies
  - Little Higgs studies
  - ‘Invisible’ Higgs
  - Contact interactions
  - etc... etc.
Summary

• Topics covered here just a small survey. Expect the first document to be a basis for future work, summarize where we are and give guidance for future studies.
  - Several studies still need to be worked out quantitatively
  - Certainly more ideas will come when we think a bit harder.
    If you have any, please do join us.

• Combined information from LHC & LC better than the sum of both separately. Not surprising, but quantified in coherent examples.

• Need to Run the machines at the same time:
  A few concrete examples studies.

• Impact of LC data on analyses strategy, luminosity/detector upgrades, triggering etc. at LHC started but needs more work.
  Ideas exist, e.g. stable gluinos in split SUSY, metastable Staus in models with gravitino LSP, decays of massive particles in many soft particles...

Positive outcome is good synergy between LHC and LC enthusiasts.