Physics @ CLIC

Albert De Roeck CERN

Introduction
Experimenting at a Multi-TeV e+e- Collider
Physics Studies and Physics Potential
Outlook

Web Site http://clicphysics.web.cern.ch/CLICphysics/
Linear e+e- Colliders

Since end of 2001 there seems to be a worldwide consensus (ECFA/HEPAP/Snowmass 2001...)

The machine which will complement and extend the LHC best, and is closest to be realized is a Linear e+e- Collider with a collision energy of at least 500 GeV

PROJECTS:

⇒TeV Colliders (cms energy up to 1 TeV) → ~Technology ready
  NLC (US)               Warm technology (X band)
  GLC (Japan)            Warm technology (X and C band)
  TESLA (DESY/Europe)    Superconducting technology

⇒Multi-TeV Collider (cms energy up to 1 TeV) → R&D
  CLIC (CERN/Europe)     Two beam acceleration
Linear e+e- Colliders

- To reach high energies with electron beams in future, linear accelerators are the only possibility (due to the sync. radiation)

**Advantages w.r.t. hadron machines**
- Electron are pointlike particles: all beam energy used in the collision i.e. beam energy in the collision is very monochromatic and tunable
- Beams can be polarised to a high degree (e-: 80%; e+ 60%)
- Beams are used once, so can be converted e.g. via Compton scattering (photon collider)

**Disadvantages:**
- Lower energy reach than pp (ppbar) machines
- Beams are used only once: more effort to make enough luminosity

An e+e- linear collider will be a precision machine!
R&D at CERN: CLIC

- An $e^+e^-$ linear collider optimized for a c.m. energy of 3 TeV with $\mathcal{L} \approx 10^{35} \text{cm}^{-2} \text{s}^{-1}$

- Construction can be staged without major modifications, starting an experimental program at lower energies, if useful.

- Aim: 3 TeV collisions, complementing LHC/TeV class LC and breaking new ground, with a final stage up to 5 (10?)TeV

To achieve this within reasonable cost (length $\sim$ 35-40 km), and not too many active elements:

→ Accelerating gradient $\sim 150 \text{ MV/m}$: Two Beam Acceleration (TBA)

→ High beamstrahlungs regime to reach luminosity

→ Challenging beam parameters and machine requirements (nm stability, strong final focus, 30 GHz accelerating structures, ...)

- Status CTF2: 150-193 MV/m (15 ns pulses)
  
  CTF3: Under construction: 2002-2006 (drive beam test)
FAQs (frequently asked questions)

• Q: CLIC still in R&D state. How far is CLIC behind w.r.t. a TeV collider?
  • A: O(5 years)

• Q: When will CLIC demonstrate its readiness as a technology for a LC?
  • A: By 2009/2010 (if additional funding will be in place)

• Q: Can CLIC run at lower energies?
  • A: Yes you can run in the energy range from 90 GeV-3TeV

• Q: What can we gain on physics reach with CLIC?
  • A: → This lecture
Building CLIC at CERN?

It is possible!

Geological analyses show that there is a continuous stretch of 40 km parallel to the Jura and the lake, with good geological conditions.
1. Experimenting at CLIC
Physics case for CLIC documented in a new CERN yellow report CERN-2004-005
CLIC Backgrounds

CLIC 3 TeV e+e- collider with a luminosity $\sim 10^{35}\text{cm}^{-2}\text{s}^{-1}$ (1 ab$^{-1}$/year)

<table>
<thead>
<tr>
<th>$E_{cm}$ [TeV]</th>
<th>$L$ $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$</th>
<th>$L_{0.99}$ $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>2.1</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>10.0</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>8.0</td>
<td>3.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$f_T$ [Hz]</th>
<th>$N_b$</th>
<th>$\Delta_b$ [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>154</td>
<td>0.67</td>
</tr>
<tr>
<td>100</td>
<td>154</td>
<td>0.67</td>
</tr>
<tr>
<td>100</td>
<td>154</td>
<td>0.67</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$N$ $[10^{10}]$</th>
<th>$\sigma_z$ [$\mu$m]</th>
<th>$\epsilon_z$ [$\mu$m]</th>
<th>$\epsilon_y$ [$\mu$m]</th>
<th>$\sigma_x^*$ [nm]</th>
<th>$\sigma_y^*$ [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>35</td>
<td>2</td>
<td>0.01</td>
<td>202</td>
<td>$\approx 1.2$</td>
</tr>
<tr>
<td>0.4</td>
<td>30</td>
<td>0.68</td>
<td>0.02</td>
<td>43</td>
<td>$\approx 0.7$</td>
</tr>
<tr>
<td>0.4</td>
<td>35</td>
<td>0.68</td>
<td>0.01</td>
<td>$\approx 60$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\delta$ [%]</th>
<th>$n_{\gamma}$</th>
<th>$N_\perp$</th>
<th>$N_{\text{Hadr}}$</th>
<th>$N_{\text{MJ}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4</td>
<td>0.7</td>
<td>7.2</td>
<td>0.07</td>
<td>0.003</td>
</tr>
<tr>
<td>31</td>
<td>2.3</td>
<td>60</td>
<td>4.05</td>
<td>3.40</td>
</tr>
<tr>
<td>21</td>
<td>1.5</td>
<td>43</td>
<td>2.3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

To reach this high luminosity: CLIC has to operate in a regime of high beamstrahlung.

- Expect large backgrounds
- # of photons/beam particle
  - e+e- pair production
  - $\gamma \gamma$ events
  - Muon backgrounds
  - Neutrons
  - Synchrotron radiation
- Expect distorted lumi spectrum

**CLIC**

Albert De Roeck (CERN) 10
Time Structure of the Beams

Train repetition rate: 100 Hz

CLIC

1 train = 154 bunches
0.67 nsec apart
~ 20 cm

Sub-TeV colliders

Warm technology
⇒ 120 Hz 1 train = 192 bunches 1.4 nsec apart

Cold technology
⇒ 5 Hz 1 train = 2820 bunches 336 ns apart

Experimenting at CLIC similar to the NLC
Luminosity Spectrum

Spectra for CLIC studies (sharper $\leftrightarrow$ high lumi)

**CLIC.01:** $\mathcal{L} = 1.05 \times 10^{35}$

**CLIC.02:** $\mathcal{L} = 0.40 \times 10^{35}$

Energy loss due to beam-beam interactions

Luminosity within 1% & 5% of c.m. energy

<table>
<thead>
<tr>
<th>Energy (TeV)</th>
<th>0.5</th>
<th>1</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{L}$ in 1% $\sqrt{s}$</td>
<td>71%</td>
<td>56%</td>
<td>30%</td>
<td>25%</td>
</tr>
<tr>
<td>$\mathcal{L}$ in 5% $\sqrt{s}$</td>
<td>87%</td>
<td>71%</td>
<td>42%</td>
<td>34%</td>
</tr>
</tbody>
</table>

Preliminary Results: expect accuracy $\frac{\delta \sqrt{s}}{\sqrt{s}} \approx 10^{-4}$ for 100 fb$^{-1}$

Luminosity spectrum not as sharply peaked as e.g. at LEP

Albert De Roeck (CERN)
\( \gamma \gamma \) Background

\( \gamma \gamma \rightarrow \text{hadrons}: \text{4 interactions/bx with } W>5 \text{ GeV} \)

Neutral and charged energy as function of \( \cos \theta \) per bx

Particles accepted within \( \theta > 120 \text{ mrad} \)

For studies: take 20 bx and overlay events

CLIC

Most activity at small angles
Muon Background

Muon pairs produced in electromagnetic interactions upstream of the IP e.g. beam halo scraping on the collimators

GEANT3 simulation, taking into account the full CLIC beam delivery system

# of muons expected in the detector ~ few thousand/bunch train (150 bunches/100ns)

⇒ OK for (silicon like) tracker
⇒ Calorimeter?
CLIC Tools for Background/Detector

Physics generators (COMPHEP, PYTHIA6, ...)
+ CLIC lumi spectrum (CALYPSO)

+ γγ → hadrons background
e.g. overlay 20 bunch crossings
(+ e+e- pair background files...)

Detector simulation
• SIMDET (fast simulation)
• GEANT3 based program
⇒ Study benchmark processes
A Detector for a LC

TESLA TDR Detector

Background at the IP enforces use of a mask

CLIC: Mask covers region up to 120 mrad
Energy flow measurement possible down to 40 mrad

~TESLA/NLC detector qualities: good tracking resolution, jet flavour tagging, energy flow, hermeticity,...
### Detector Parameters

<table>
<thead>
<tr>
<th>Detector</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vertexing</strong></td>
<td>$15 \mu m \oplus \frac{35 \mu m \cdot GeV/c}{\rho \sin^{3/2} \theta}$</td>
</tr>
<tr>
<td></td>
<td>$15 \mu m \oplus \frac{35 \mu m \cdot GeV/c}{\rho \sin^{5/2} \theta}$</td>
</tr>
<tr>
<td><strong>Solenoidal Field</strong></td>
<td>$B = 4 \ T$</td>
</tr>
<tr>
<td><strong>Tracking</strong></td>
<td>$\frac{\delta p_t}{p_t} = 5 \times 10^{-5}$</td>
</tr>
<tr>
<td><strong>E.m. Calorimeter</strong></td>
<td>$\frac{\delta E}{E(GeV)} = 0.10 \frac{1}{\sqrt{E}} \oplus 0.01$</td>
</tr>
<tr>
<td><strong>Had. Calorimeter</strong></td>
<td>$\frac{\delta E}{E(GeV)} = 0.40 \frac{1}{\sqrt{E}} \oplus 0.04$</td>
</tr>
<tr>
<td><strong>$\mu$ Detector</strong></td>
<td>Instrumented Fe yoke $\frac{\delta p}{p} \simeq 30%$ at 100 GeV/c</td>
</tr>
<tr>
<td><strong>Energy Flow</strong></td>
<td>$\frac{\delta E}{E(GeV)} \simeq 0.3 \frac{1}{\sqrt{E}}$</td>
</tr>
<tr>
<td><strong>Acceptance</strong></td>
<td>$</td>
</tr>
<tr>
<td>mask</td>
<td>120 mrad</td>
</tr>
<tr>
<td>beampipe</td>
<td>3 cm</td>
</tr>
<tr>
<td>small angle tagger</td>
<td>$\theta_{min} = 40$ mrad</td>
</tr>
</tbody>
</table>

**Starting point: the TESLA TDR detector**  
Adapted to CLIC environment

**First ideas:**

- 3–15 cm
- 15–80 cm
- 80–240 cm
- 240–280 cm
- 280–400 cm
- 400–450 cm
- 450–800 cm

<table>
<thead>
<tr>
<th>VDET</th>
<th>Silicon/forward disks</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPC</td>
<td></td>
</tr>
<tr>
<td>ECAL (30 X₀)</td>
<td></td>
</tr>
<tr>
<td>HCAL (6λ)</td>
<td></td>
</tr>
<tr>
<td>Coil (4T)</td>
<td></td>
</tr>
<tr>
<td>Fe/muon</td>
<td></td>
</tr>
</tbody>
</table>

..or all silicon (15-120 cm) more compact...
Example B-tagging

\[ B \rightarrow X \text{ Decay Length} \]

<table>
<thead>
<tr>
<th>( \sqrt{s} ) (TeV)</th>
<th>0.09</th>
<th>0.2</th>
<th>0.35</th>
<th>0.5</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z^0 )</td>
<td>( HZ )</td>
<td>( HZ )</td>
<td>( HZ )</td>
<td>( H^+ H^- )</td>
<td>( bb )</td>
</tr>
<tr>
<td>( d_{space} ) (cm)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.7</td>
<td>0.85</td>
<td>2.5</td>
</tr>
</tbody>
</table>

B-Decay length is long!

- Define Area of Interest by \( \pm 0.04 \) rad cone around the jet axis
- Count hit multiplicity (or pulse height) in Vertex Track layers
- Tag heavy hadron decay by step in detected multiplicity
- Can reach 50% eff./\( \sim 80\% \) purity
Physics Menu at CLIC

- **Higgs sector**: light and heavy Higgses, Higgs potential
- **Supersymmetry**: if exists, will be discovered at a hadron collider

**Role of CLIC**: completing the particle spectra with precision measurements (masses < \(\sqrt{s}/2\))

- **Particle Factory**: if new particles have been detected/predicted at the LHC/LC-500 in the range of 1-5 TeV (New Gauge bosons, Kaluza-Klein resonances, resonances in WW scattering...): CLIC will produce them directly, provide an accurate determination of their couplings and establish their Nature. Also exotic decays (such as \(Z'\rightarrow\) heavy Majorana Neutrinos) can be detected.

- If **NO** new particles are observed directly, probe scales up to the \(O(100-800)\) TeV indirectly via precision measurements
- **QCD measurements**: BFKL, photon structure, \(\alpha_s\),...
- **The unexpected???:**

\[ e^+e^- \text{ at } \sqrt{s} \approx 3-5 \text{ TeV}: \text{ Expect to break new grounds} \]
Cross Sections at CLIC

\[
\sigma \propto \frac{1}{s}
\]

\[
\sigma \propto \log(s)
\]

### Event Rates/Year (1000 fb\(^{-1}\))

<table>
<thead>
<tr>
<th></th>
<th>3 TeV 10(^3) events</th>
<th>5 TeV 10(^3) events</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e^+e^- \rightarrow t\bar{t})</td>
<td>20</td>
<td>7.3</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow b\bar{b})</td>
<td>11</td>
<td>3.8</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow ZZ)</td>
<td>27</td>
<td>11</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow WW)</td>
<td>490</td>
<td>205</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow hZ/h\nu (120 GeV))</td>
<td>1.4/530</td>
<td>0.5/690</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow H^+H^- (1 TeV))</td>
<td>1.5</td>
<td>0.95</td>
</tr>
<tr>
<td>(e^+e^- \rightarrow \bar{\mu}^+\bar{\mu}^- (1 TeV))</td>
<td>1.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>
2. Higgs Physics
The Higgs Mechanism

The Higgs Field

Particles acquire mass through interaction with the Higgs field

At least one scalar Higgs boson should be discovered
We do not know its mass!!!
Except \( \rightarrow \) Theory \( M_H < \sim 1 \text{ TeV} \)

The Higgs coupling to particles is proportional to their mass
\( \Rightarrow \) Needs to be checked

Reconstruct the Higgs potential (depends on the new physics)

\[ V(\phi) = \mu^2 |\phi(x)|^2 + \lambda |\phi(x)|^4 \]

Potential energy density of the Higgs field: lowest value is not at zero!

Vacuum expectation value of the Higgs field:

\[ \left( \sqrt{2} G_F \right)^{-1/2} \approx 246 \text{ GeV} \]

\[ g_{HVV} = \frac{2M_V^2}{\langle \phi \rangle} / \langle \phi \rangle \]

\[ g_{Hff} = \frac{m_f}{\langle \phi \rangle} \]
Higgs Production at a e+e- Linear Collider

Dominant production processes at LC:

$$\sigma(e^+e^- \rightarrow \text{Higgs}) \, [\text{fb}]$$

- $\sigma \sim 1/s$
- $\sigma \sim \ln(s)$
- $\sigma \sim 1/s$

500 GeV, 500 fb$^{-1}$

TeV LC: statistics drop for high masses
Higgs Production

Cross section at 3 TeV:
- Large cross section at low masses
- Large CLIC luminosity → Large events statistics
- Keep large statistics also for highest Higgs masses

- Low mass Higgs: 400 000 Higgses/year
- 45K/100K for 0.5/1 TeV LC

\[ \sigma_{ZH+H\gamma} \]
Rare Higgs Decays: $H \rightarrow \mu^+ \mu^-$

$H \rightarrow \mu^+ \mu^-$: Branching Ratio $\sim 10^{-4}$

Not easy to access at a 500 GeV collider

Result for $\sqrt{s} = 3.0$ TeV with $f \mathcal{L} = 5 \text{ ab}^{-1}$

<table>
<thead>
<tr>
<th>$M_H$ (GeV)</th>
<th>$\delta \text{BR}/\text{BR}$</th>
<th>$\Rightarrow$ Precision on $g_{H\mu\mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>0.072</td>
<td>CLIC $3.5% \rightarrow 10%$</td>
</tr>
<tr>
<td>140</td>
<td>0.121</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>0.210</td>
<td></td>
</tr>
</tbody>
</table>
Rare Higgs Decays

Higgs→ BB decays for higher Higgs masses, e.g. 180 GeV

<table>
<thead>
<tr>
<th>$M_H$ (GeV)</th>
<th>$S/\sqrt{B}$</th>
<th>$\delta g_{Hbb}/g_{Hbb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>40.5</td>
<td>0.016</td>
</tr>
<tr>
<td>200</td>
<td>25.0</td>
<td>0.025</td>
</tr>
<tr>
<td>220</td>
<td>18.0</td>
<td>0.034</td>
</tr>
</tbody>
</table>
Reconstruct shape of the Higgs potential to complete the study of the Higgs profile and to obtain a direct proof of the EW symmetry breaking mechanism

⇒ Measure the triple (quartic) couplings

\[ V_H = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v} H^3 + \frac{m_H^4}{8v^2} H^4 \]

\[ \lambda_{HHH} = 3m_H^2/v \]

process \[ e^+e^- \rightarrow (WW)\nu\bar{\nu} \rightarrow hh\nu\bar{\nu} \].

\[ H H \rightarrow b\bar{b}b\bar{b}, \ W^+W^-W^+W^- \]

Albert De Roeck (CERN)
Results: $e^+e^- \rightarrow HH\nu\nu$

Precision on $\lambda_{HHH}$ for $5 \text{ ab}^{-1}$ for Higgs masses in the range:

- $m_H = 120 \text{ GeV}$
- $m_H = 140 \text{ GeV}$
- $m_H = 180 \text{ GeV}$
- $m_H = 240 \text{ GeV}$

Can improve by factor 1.7 if both beams are polarized.

<table>
<thead>
<tr>
<th>$M_H$ (GeV)</th>
<th>$\sigma_{HHH\nu\nu}$ Only</th>
<th>$\cos \theta^*$ Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>± 0.094 (stat)</td>
<td>± 0.070 (stat)</td>
</tr>
<tr>
<td>180</td>
<td>± 0.140 (stat)</td>
<td>± 0.080 (stat)</td>
</tr>
</tbody>
</table>

3 TeV
Heavy Higgs (MSSM)

Cross section as function of Higgs mass

Study the channel $H^\pm \rightarrow tb \rightarrow Wb \rightarrow qqbb$

Example for $M_H = 880$ GeV (15 BC background)
Tag 4 $b$ jets / reconstruct $W$'s from 4 'light' jets / reconstruct $t$ jet $\rightarrow$ events with 8 jets

$e^+e^- \rightarrow H^+H^- M_H = 900$ GeV

$O(20)$ events/ ab$^{-1}$, with negligible background
Increase statistics by factor 10 for 'single' H tags

Mass measurement $\Delta m/m \sim 1\%$ (3 ab$^{-1}$)
Discovery potential $M_H < 1.2$ TeV (3 TeV/3 ab$^{-1}$)
Higgs: Strength of a multi-TeV collider

- Precision measurements of the quantum numbers and properties of Higgs particles, for large Higgs mass range
- Study of Heavy Higgses (e.g. MSSM $H, A, H^\pm$)
- Rare Higgs decays
- Higgs self coupling over a wide range of Higgs masses
- Study of the CP properties of the Higgs...

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$M_H$ (GeV)</th>
<th>$\delta X/X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta g_{Htt}/g_{Htt}$</td>
<td>120–180</td>
<td>0.05–0.10</td>
</tr>
<tr>
<td>$\delta g_{Hbb}/g_{Hbb}$</td>
<td>180–220</td>
<td>0.01–0.03</td>
</tr>
<tr>
<td>$\delta g_{H\mu\mu}/g_{H\mu\mu}$</td>
<td>120–150</td>
<td>0.03–0.10</td>
</tr>
<tr>
<td>$\delta g_{HNN}/g_{HNN}$</td>
<td>120–180</td>
<td>0.07–0.09</td>
</tr>
<tr>
<td>$g_{HHHH}$</td>
<td>120</td>
<td>$\neq 0$ (?)</td>
</tr>
</tbody>
</table>
3. Supersymmetry

\[ e^+e^- \rightarrow e_L e_R \]

missing \( E_T = 0.8 \text{ TeV} \)

\( h^0 \rightarrow b\bar{b} \)
Masses of Sparticles

Depend on SUSY parameters, SUSY breaking mechanism…

We don’t really know…

Examples: Scenarios in Constrained MSSM
Sparticle Discoveries

- A number of SUSY (mSUGRA) benchmark points to study LHC/LC sensitivity (Battaglia et al hep-ph/0306219)
- Take into account direct searches at LEP and Tevatron, BR (b → sγ), g-2 (E821), Cosmology: 0.09 ≤ Ωχh² ≤ 0.13

Allowed regions in the M₀-M₁/₂ plane

- 'WMAP' lines

sleptons and gauginos often difficult to detect at a LHC
Sparticle Discoveries

LHC+LC 1 TeV

CLIC 3 TeV

CLIC 5 TeV

Note: LHC mass precision ~5%

CLIC can help to complete the sparticle spectra

Albert De Roeck (CERN)
Sparticle Discoveries

Particle discovery scan along a WMAP line

Observe all sparticles & measure properties more precisely than at LHC
Selectron and Smuon Measurements

E.G. $m_{1/2} = 300$ GeV, $m_0 = 1450$ GeV, $\tan \beta = 10$, $A = 0$ GeV, $\text{sign}(\mu) > 0$ (mSUGRA) (point E)

CLIC beamstrahlung ($10^{35}$)

E.G. $m_{1/2} = 1500$ GeV, $m_0 = 420$ GeV, $\tan \beta = 20$, $A = 0$ GeV, $\text{sign}(\mu) > 0$ (mSUGRA) (point H)

$\Rightarrow M_{\tilde{\mu}} = 1150$ GeV

Measure inclusive muon spectrum in $\tilde{\mu} \rightarrow \mu \chi^0$

$\Rightarrow E_{\text{max/min}} = \frac{M_{\tilde{\mu}}}{2} \left(1 - \frac{M_{\chi_1^0}^2}{M_{\tilde{\mu}}^2}\right) \times \left(1 \pm \sqrt{1 - \frac{M_{\tilde{\mu}}^2}{E_{\text{beam}}}}\right)$

Signal $\tilde{\nu}_e \tilde{\nu}_e \rightarrow e^+ \chi^- e^- \chi^+_1 (180)$

Typical 'box' shape of the signal preserved in CLIC environment

Typical 'box' shape of the signal preserved in CLIC environment (1 ab$^{-1}$)
**Smuon Mass Precision**

Point E: $m_\mu \approx 1500$ GeV  
Point H: $m_\mu \approx 1000$ GeV

<table>
<thead>
<tr>
<th>Point</th>
<th>Beamstrahlung</th>
<th>Pol.</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\int L$ (ab$^{-1}$)</th>
<th>$\delta M$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>$\tilde{\mu}_L$</td>
<td>none</td>
<td>0/0</td>
<td>3.0-3.5</td>
<td>1</td>
</tr>
<tr>
<td>H</td>
<td>$\tilde{\mu}_L$</td>
<td>Std.</td>
<td>0/0</td>
<td>3.0-3.5</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>$\tilde{\mu}_L$</td>
<td>none</td>
<td>0/0</td>
<td>3.8-4.2</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>$\tilde{\mu}_L$</td>
<td>Std.</td>
<td>0/0</td>
<td>3.8-4.2</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>$\tilde{\mu}_L$</td>
<td>none</td>
<td>80/60</td>
<td>3.8-4.2</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>$\tilde{\mu}_L$</td>
<td>Std.</td>
<td>80/60</td>
<td>3.8-4.2</td>
<td>1</td>
</tr>
</tbody>
</table>

Mass measurements to $O(1\%)$ possible
Sensitivity to $\chi_2 \rightarrow \chi_1 + 2$ leptons

Case study: $\chi_2$

Sensitivity (5$\sigma$) for LHC and LC

$\tan \beta = 10$

Mass measurement precision
$m_{\chi_2} = 540$ GeV, $m_{\chi_1} = 290$ GeV

$\sim 1.5\%$ precision on $\chi_2$ mass
Importance of Precision Measurements

Reconstruct the theory at the high scale from measured masses and cross sections, evolve with Renormalization Group Equations. Do the masses unify at a higher GUT scale?

⇒ Precision measurements are crucial!

(a) $M_i$ [GeV]

(b) $M_i^2$ [GeV$^2$]

Gaugino mass parameters

1st generation sfermion parameters

CLIC

Albert De Roeck (CERN)
Complete the SUSY spectrum further (extended reach w.r.t. LC and LHC)

Measure properties of sparticles with linear collider type of precisions in the high mass range (e.g. masses up to 1%, spin, mixing angles, tanβ, gaugino couplings, slepton quantum numbers...) → see CLIC Report for details

<table>
<thead>
<tr>
<th>$\delta p/p^2$</th>
<th>Beamstrahlung</th>
<th>Fit Result (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.</td>
<td>none</td>
<td>1150 ± 10</td>
</tr>
<tr>
<td>$3.0 \times 10^{-5}$</td>
<td>none</td>
<td>1150 ± 12</td>
</tr>
<tr>
<td>$4.5 \times 10^{-5}$</td>
<td>none</td>
<td>1151 ± 12</td>
</tr>
<tr>
<td>$4.5 \times 10^{-5}$</td>
<td>Std.</td>
<td>1143 ± 18</td>
</tr>
</tbody>
</table>
4. Extra Dimensions
Large Extra Dimensions

ADD: Arkani–Ahmed, Dimopolous, Dvali

Problem:

\[ m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^2} = 246 \text{ GeV} \]

\[ M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19} \text{ GeV} \]

Idea of from String Theory (assumes 11 space-time dimensions)
Assume the world we see is in 4 dimensions but that gravity can expand in 4+δ dimensions. Extra dimensions have size R (mm to fm)

\[ V(r) \sim \frac{m_1 m_2}{M_{Pl}^2} \frac{1}{r} \]

\[ V(r) \sim \frac{m_1 m_2}{M_D^{\delta+2}} \frac{1}{r^{\delta+1}}, \quad (r \ll R) \]

\[ V(r) \sim \frac{m_1 m_2}{M_D^{\delta+2} R^\delta} \frac{1}{r}, \quad (r \gg R) \]
Large Extra Dimensions

Large Extra dimensions (ADD)
Gravity in bulk / flat space
Missing energy/interference/black holes
\[ ds^2 = G_{ij} dx^i dx^j = \eta_{\mu\nu} dx^\mu dx^\nu + h_{ij}(y) dy^i dy^j, \]

Warped Extra Dimensions (Randal-Sundrum)
Gravity in bulk / curved space
Spin 2 resonances > TeV range
\[ ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2, \] \[ k = \text{warp factor} \]

TeV Scale Extra Dimensions (Antoniadis et al.)
Gauge bosons/Higgs in the bulk
Spin 1 resonances > TeV range
Interference with Drell-Yan

Universal Extra Dimensions (Appelquist et al.)
Everybody in the bulk!
Fake SUSY spectrum of KK states
+ many combinations/variations
Extra Dimension Reach

Example: Deviations from SM due to virtual Kaluza Klein Graviton effects

Discovery reach (T. Rizzo)

Scale of extra longitudinal dimension

<table>
<thead>
<tr>
<th>Collider</th>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
<th>Gluon</th>
<th>$W^\pm$</th>
<th>$\gamma + Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC500</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>15</td>
</tr>
<tr>
<td>LC1000</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>22</td>
</tr>
<tr>
<td>LC3000</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>42</td>
</tr>
<tr>
<td>LHC</td>
<td>10</td>
<td>15</td>
<td>8.2</td>
<td>6.7</td>
</tr>
<tr>
<td>LHC</td>
<td>100</td>
<td>20</td>
<td>14</td>
<td>12</td>
</tr>
</tbody>
</table>

T. Han, T. Rizzo et al. (Moriond '00/debated...)

<table>
<thead>
<tr>
<th>Collider</th>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
<th>Reaction</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC</td>
<td>100</td>
<td>$e^+e^- \rightarrow ff$</td>
<td>$6.5\sqrt{s}$</td>
</tr>
<tr>
<td>$\gamma\gamma$ Collider</td>
<td>100</td>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>$11\sqrt{s}$</td>
</tr>
<tr>
<td>LHC</td>
<td>100</td>
<td>$p\bar{p} \rightarrow tt$</td>
<td>6.0</td>
</tr>
</tbody>
</table>
Extra Dimensions  Randall-Sundrum phenomenology  (curves by T. Rizzo)

SM fields on brane and graviton in bulk

Observe KK resonances in e.g. \( e^+e^- \rightarrow \mu\mu \) cross sections

LC is like a KK factory

Allows to measure properties of KKs (spin, BRs...)

Can determine parameters \( c \) up to 0.2\%, \( M \) better than 0.1\%
Extra Dimensions

TeV scale extra dimensions
⇒ SM gauge field in the bulk
⇒ May lead to complicated spectra in e.g. $e^+e^- \rightarrow \mu\mu$
   (interference effects/spin-1 states)

Different models
ADD Models

Rigid brane: Coupling of massive KK towers is exactly the same for less massive towers

Soft branes: Coupling of higher mass KK towers reduced

\[ g_n^2 \rightarrow g_n^2 e^{-(m/\Delta)^2} \]

\( \Delta = \text{wall tension} \)

could have any value but expected \( \sim O(\text{TeV}) \)

\[ \delta = 7 \]

\( \Delta = 4 \text{ TeV} \)

\( \delta = 2 \)

\( M_D \)'s fixed to agree with \( M_D = 5 \text{ TeV}, n=2 \)

Discover deviations \( \Rightarrow \) Energy lever arm important!!
• All particles can go into the bulk KK-partners for all particles!
• Resulting spectrum looks very similar to a SUSY spectrum (there are subtle differences)
  ⇒ ? Did we discover SUSY or UEDs?
• Important difference: spin of the KK same as SM partner, while it differs by $\frac{1}{2}$ from SUSY sparticles → measure spin
• Not easy at the LHC but doable at a LC
• Compare SUSY/UED for 500 GeV (s)muons

$$e^+ e^- \rightarrow \mu^+_1 \mu^-_1 \quad \iff \quad e^+ e^- \rightarrow \tilde{\mu}^+ \tilde{\mu}^-$$

$\mathbf{CLIC}$

Albert De Roeck (CERN)
Black Holes

If $M_{\text{planck}} \sim O(1 \text{ TeV}) \Rightarrow$ Black Hole production at Multi-TeV Scale

- $\sigma = \pi R_s^2 \sim 1 \text{ TeV}^{-2} \sim O(100) \text{ pb}$
  - $R_s =$ Schwarzschild Radius
- If $\sqrt{s}_{e^+e^-} > M_{\text{BH}} > M_{\text{planck}} \rightarrow$ BH factory
- BH lifetime $\sim 10^{-25}$-$10^{-27} \text{ sec}$
- Decay via 'Democratic' Hawking Radiation

Many jets, 2% hard photons leptons, 10% leptons

Study Quantum Gravity in the lab?
Large cross sections!
EDs: Strength of a multi-TeV collider

- Extended sensitivity to Extra Dimensions into several tens of TeV range
- Can observe directly/study KK resonances in the few TeV range. Measure quantum numbers and properties precisely. Distinguish between models.
- Large lever arm in energy to study more complicated ED scenarios such as soft branes
- If the Planck scale is $O(1 \text{ TeV}) \rightarrow$ micro black hole production. Study quantum gravity in the lab

| ED (ADD) | 30 TeV ($e^+e^-$) |
| ED (RS)  | 55 TeV ($\gamma\gamma$) |
| ED (TeV$^{-1}$) | 18 TeV (c=0.2) |
| Black Holes | 80 TeV |
|           | 5 TeV |
5. New Gauge Theories
Contact Interactions etc.
Z Profile Measured at LEP

One of the most important measurements at LEP
Uncanny precision!

\[ \frac{\delta M_Z}{M_Z} \sim 2.5 \cdot 10^{-5}; \frac{\delta \Gamma_Z}{\Gamma_Z} \sim 1 \cdot 10^{-3} \]
\( \sqrt{s} \) Scan (\( Z^0 \)-like Lineshape Scan) \( e^+e^- \rightarrow Z' \rightarrow f\bar{f} \)

Assume \( M_{Z'} = 3.0 \) TeV and \( \Gamma(Z')/M_{Z'} \approx \Gamma(Z^0)/M_{Z^0} (\Gamma_{SM}) \);

Compute \( \sigma(e^+e^- \rightarrow Z') \) vs. \( \sqrt{s} \) including ISR and beamstrahlung for a range of mass and \( \Gamma(Z')/\Gamma_{SM} \) values;

Assume \( \int L = 1000 \text{ fb}^{-1} \) (CLIC.01) or 400 \( \text{ fb}^{-1} \) (CLIC.02) shared in 3-7 points scan and extract \( M_{Z'}/\Gamma_{SM} \) and \( \sigma_{peak} \) from \( \chi^2 \) fit:

**Fit Accuracy**

<table>
<thead>
<tr>
<th>Observable</th>
<th>Breit Wigner</th>
<th>CLIC.01</th>
<th>CLIC.02</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_{Z'} ) (GeV)</td>
<td>3000 ± .12</td>
<td>± .15</td>
<td>± .21</td>
</tr>
<tr>
<td>( \Gamma(Z')/\Gamma_{SM} )</td>
<td>1. ± .001</td>
<td>± .003</td>
<td>± .004</td>
</tr>
<tr>
<td>( \sigma_{peak}^{eff} ) (fb)</td>
<td>1493 ± 2.0</td>
<td>564 ± 1.7</td>
<td>669 ± 2.9</td>
</tr>
</tbody>
</table>

**Precision will be comparable to LEP (factor 2-3 worse)**
Degenerate Resonances

Smearing due to the lumi spectrum of CLIC

E.G. Degenerate BESS Model (Strong EWSB)
D. Dominici, De Curtis, M. Battaglia

Two (almost) degenerate Triples $L_3, L_3^\pm, R_3, R_3^\pm$

Sensitivity to $L_3$ and $R_3$ with $M = 3$ TeV for $L = 500$ fb$^{-1}$ at LHC and $L = 1000$ fb$^{-1}$ at CLIC

<table>
<thead>
<tr>
<th>$g/g''$</th>
<th>$M$ (GeV)</th>
<th>$\Gamma_{L_3}/\Gamma_{R_3}$</th>
<th>$S/\sqrt{S+B}$ LHC $(e+\mu)$</th>
<th>$S/\sqrt{S+B}$ CLIC (had)</th>
<th>$\Delta M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>3000</td>
<td>2.0 / 0.3</td>
<td>(3.4)</td>
<td>62</td>
<td>23.20 ± 0.06</td>
</tr>
<tr>
<td>0.2</td>
<td>3000</td>
<td>8.2 / 1.2</td>
<td>(6.6)</td>
<td>152</td>
<td>83.50 ± 0.02</td>
</tr>
</tbody>
</table>

Energy Scan of Narrow Resonances $(g/g'' = 0.15)$

CLIC: can measure $\Delta M$ down to 13 GeV $(g/g'' > 0.08)$
Precision Measurements

Measure $\sigma_{b\bar{b}}$, $A_{FB}^{\mu^+\mu^-}$ and $A_{FB}^{b\bar{b}}$

<table>
<thead>
<tr>
<th>Observable</th>
<th>Relative Stat. Accuracy $\delta\mathcal{O}/\mathcal{O}$ for 1 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\mu^+\mu^-}$</td>
<td>$\pm 0.010$</td>
</tr>
<tr>
<td>$\sigma_{b\bar{b}}$</td>
<td>$\pm 0.012$</td>
</tr>
<tr>
<td>$\sigma_{t\bar{t}}$</td>
<td>$\pm 0.014$</td>
</tr>
<tr>
<td>$A_{FB}^{\mu\mu}$</td>
<td>$\pm 0.018$</td>
</tr>
<tr>
<td>$A_{FB}^{b\bar{b}}$</td>
<td>$\pm 0.055$</td>
</tr>
<tr>
<td>$A_{FB}^{t\bar{t}}$</td>
<td>$\pm 0.040$</td>
</tr>
</tbody>
</table>

$\Rightarrow$ Sensitivity to $M_{Z'}$ to 30-40 TeV
In case that there is no Higgs:
WW scattering will show effects of strong dynamics in the TeV region
⇒ Study $W_L W_L \rightarrow W_L W_L$ scattering

Resonances can form in the TeV range that can be observed directly (difficult at the LHC)
Little Higgs Models

- Stabilizing the Higgs with new weakly coupled fermions and Gauge bosons
  $\implies$ Expect ‘new top’ quark and new $W_H, Z_H$ around 1 TeV.
  $\implies$ Expect the new gauge bosons to be copiously be produced at a LC, e.g. via the associated production $e^+e^-\to WW_H$

**Cross section: Large!**

![Cross section graph](image)

**$W_H$ decay modes**

![Decay modes graph](image)

Allow for detailed studies of $W_H$ (and other new particles) properties
Triple Gauge Couplings

High precision analysis of the self coupling of the EW gauge bosons

Expectation of the precision for $\Delta \lambda_\gamma$ and $\Delta \kappa_\gamma \sim 10^{-4}$

Measurements for one year of high luminosity for the future colliders
Reach to Probe New Physics

$1 \text{ ab}^{-1}, P=0.8, \quad e^+e^{-}\rightarrow \mu^+\mu^-$

Ultimate: $5 \text{ ab}^{-1}$ at $5 \ (10) \ \text{TeV} \rightarrow 400-800 \ (500-1000) \ \text{TeV}$

Contact Interactions: sensitivity to scales up to 100-400 TeV

Remember: If Higgs light $\rightarrow$ something new must happen before 1000 TeV

CLIC

Albert De Roeck (CERN)
A light Higgs implies that the Standard Model cannot be stable up to the GUT or Planck scale ($10^{19}$ GeV).

The effective potential blows up, due to heavy top quark mass.

The electroweak vacuum is unstable to corrections from scales $\Lambda \gg v = 246$ GeV.

New physics expected in TeV range.
Alternative Theories

- Excited lepton production

- Production of 4\textsuperscript{th} family quarks and leptons

- Leptoquarks

- Effects of non-commutative interactions on physical observables

- Transplanckian effects when the centre of mass system energy is above the fundamental gravity mass scale

- Lepton size measurements

\begin{tabular}{|c|c|}
\hline
Radius cm & \sqrt{s} \text{ (TeV)} \\
\hline
3.0 \cdot 10^{-18} & 1 \\
1.2 \cdot 10^{-18} & 3 \\
0.9 \cdot 10^{-18} & 5 \\
\hline
\end{tabular}
## Summary: CLIC vs Hadron Colliders

ADR, F. Gianotti, J. Ellis hep-ph/0112004  
U. Bauer et al. hep-ph/0201227

+ updates

<table>
<thead>
<tr>
<th>Process</th>
<th>LHC 14 TeV 100 fb(^{-1})</th>
<th>SLHC 14 TeV 1000 fb(^{-1})</th>
<th>VLHC* 200 TeV 100 fb(^{-1})</th>
<th>CLIC 3-5 TeV 1000 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>squarks (TeV)</td>
<td>2.5</td>
<td>3</td>
<td>20.</td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>sleptons (TeV)</td>
<td>0.34</td>
<td></td>
<td></td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>Z' (TeV)</td>
<td>5.4</td>
<td>6.5</td>
<td>30-40</td>
<td>20-30</td>
</tr>
<tr>
<td>q^* (TeV)</td>
<td>6.5</td>
<td>7.5</td>
<td>70-75</td>
<td>3-5</td>
</tr>
<tr>
<td>l^* (TeV)</td>
<td>3.4</td>
<td></td>
<td></td>
<td>3-5</td>
</tr>
<tr>
<td>ED (ADD/2D/TeV)</td>
<td>9</td>
<td>12</td>
<td>65</td>
<td>30-55</td>
</tr>
<tr>
<td>W_L W_L</td>
<td>3.4 (\sigma)</td>
<td>(\geq 4.0 \sigma)</td>
<td>30 (\sigma)</td>
<td>70-90 (\sigma)</td>
</tr>
<tr>
<td>TGC (95%)</td>
<td>0.0014</td>
<td>0.0006</td>
<td>0.0003</td>
<td>0.00013- 0.00008</td>
</tr>
<tr>
<td>(\Lambda) Compos (TeV)</td>
<td>30</td>
<td>40</td>
<td>100</td>
<td>300-400</td>
</tr>
</tbody>
</table>

**CLIC Comparable to VLHC**

* Very Large Hadron Collider: 233 km Circumference

---

Albert De Roeck (CERN) 63
Summary: CLIC Physics Potential

Experimental conditions at CLIC are more challenging than e.g. at LEP, or even a TeV collider.

Physics studies for CLIC have included the effects of the detector, and backgrounds such as e+e- pairs and γγ events.

Benchmark studies show that CLIC will allow for precision measurements in the TeV range.

Very large physics potential, reach beyond that of the LHC.

Measurements at CLIC (5 TeV / 1 ab⁻¹)

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs (Light)</td>
<td>λ_{HHH} to ~ 5 - 10% (5 ab⁻¹)</td>
</tr>
<tr>
<td></td>
<td>g_{Hμμ} to ~ 3.5 - 10% (5 ab⁻¹)</td>
</tr>
<tr>
<td>Higgs (Light)</td>
<td>2.0 TeV (e⁺e⁻)</td>
</tr>
<tr>
<td>Higgs (Heavy)</td>
<td>3.5 TeV (γγ)</td>
</tr>
<tr>
<td>Squarks</td>
<td>2.5 TeV</td>
</tr>
<tr>
<td>Sleptons</td>
<td>2.5 TeV</td>
</tr>
<tr>
<td>Z' (direct)</td>
<td>5 TeV</td>
</tr>
<tr>
<td>Z' (indirect)</td>
<td>30 TeV</td>
</tr>
<tr>
<td>l*, q*</td>
<td>5 TeV</td>
</tr>
<tr>
<td>TGC (95%)</td>
<td>0.00008</td>
</tr>
<tr>
<td>Δ compos.</td>
<td>400 TeV</td>
</tr>
<tr>
<td>W_L W_L</td>
<td>&gt; 5 TeV</td>
</tr>
<tr>
<td>ED (ADD)</td>
<td>30 TeV (e⁺e⁻)</td>
</tr>
<tr>
<td>ED (RS)</td>
<td>55 TeV (γγ)</td>
</tr>
<tr>
<td>ED (TeV⁻¹)</td>
<td>18 TeV (c=0.2)</td>
</tr>
<tr>
<td>Resonances</td>
<td>80 TeV</td>
</tr>
<tr>
<td>Black Holes</td>
<td>5 TeV</td>
</tr>
</tbody>
</table>