Lepton Collider

- The case for a lepton collider will be built at the CERN LHC
  - Starting at 7 TeV, continuing at 14 TeV …

- We will soon know what that case might be
  - Hallelujah!
    - The long wait is over …
  - It’s exciting – and frightening – to finally have the tools we need!
High-energy electron colliders are linear. Why?

Circular machines suffer synchrotron radiation

- Power loss: \[ \frac{dP}{dt} \propto \frac{E^4}{m^4 R^2} \]
- Electrons are much lighter than protons (and muons), so synchrotron radiation is a real show stopper for circular machines at high energies
- Three times the energy \( \Rightarrow \) nine times the radius!
What are the advantages of a linear collider?

A linear collider annihilates electrons and positrons at well-defined CM energies.

It allows a clean look at the underlying physics.

- LHC: Broadband initial state
- LC: Precise, well-controlled initial state

History shows that both have their place.
- Both are discovery machines …
At present, there are two options:

- **ILC (International Linear Collider)**
  - 1.3 GHz superconducting RF
  - 500 GeV – 1 TeV in the CM

- **CLIC (Compact Linear Collider)**
  - 12 GHz warm copper RF, powered by drive beam
  - 500 GeV – 1 TeV – 3 TeV (?) in the CM

Many common subsystems, with the ultimate energy limited by cost and wall plug power …
ILC vs CLIC

- The ILC will be ready to propose in 2013
  - The GDE produced an RDR in 2008, and is preparing a TDR for late 2012

- CLIC will be ready at some point in the future
  - The CLIC Collaboration is preparing a CDR for late 2011, and is aiming for a TDR later in the decade, perhaps 2016

- The physics case is the same!
ILC vs CLIC

- The eventual decision will be made on grounds of technical maturity, cost, and upgrade potential
  - Informed by LHC physics
- In this talk I’ll focus on physics
  - I will only discuss first-stage linear colliders …
  - With CM energies below 1 TeV
- That is all we can expect in the foreseeable future …
### CLIC Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CLIC 500 GeV</th>
<th>CLIC 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerating structure</td>
<td>Relaxed 502</td>
<td>6</td>
</tr>
<tr>
<td>Total (Peak 1%) luminosity</td>
<td>8.8(5.8)(10^{33})</td>
<td>7.3(3.5)(10^{33})</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>50</td>
<td></td>
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<tr>
<td>Loaded accel. gradient MV/m</td>
<td>80</td>
<td>100</td>
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<tr>
<td>Main linac RF frequency GHz</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Bunch charge (10^9)</td>
<td>6.8</td>
<td>3.72</td>
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<tr>
<td>Bunch separation (ns)</td>
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<tr>
<td>Beam pulse duration (ns)</td>
<td>177</td>
<td>156</td>
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<tr>
<td>Beam power/beam MWatts</td>
<td>4.9</td>
<td>14</td>
</tr>
<tr>
<td>Hor./vert. norm. emitt((10^{-6}/10^{-9}))</td>
<td>7.5/40</td>
<td>0.66/20</td>
</tr>
<tr>
<td>Hor./vert. FF focusing (mm)</td>
<td>4/0.4</td>
<td>4 / 0.1</td>
</tr>
<tr>
<td>Hor./vert. IP beam size (nm)</td>
<td>248 / 5.7</td>
<td>101/3.3</td>
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<tr>
<td>Hadronic events/crossing at IP</td>
<td>0.07</td>
<td>0.28</td>
</tr>
<tr>
<td>Coherent pairs at IP</td>
<td>10</td>
<td>3.8 (10^8)</td>
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<td>BDS length (km)</td>
<td>1.87</td>
<td>2.75</td>
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<tr>
<td>Total site length km</td>
<td>13.0</td>
<td>48.3</td>
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<tr>
<td>Wall plug to beam transfert eff</td>
<td>7.5%</td>
<td>6.8%</td>
</tr>
<tr>
<td>Total power consumption MW</td>
<td>241</td>
<td>568</td>
</tr>
</tbody>
</table>
Linear Collider

- ILC requirements
  - Physics between 200 and 500 GeV
  - Calibration at 91 GeV
  - Luminosity of 500 fb\(^{-1}\) in four years
  - Electron polarization > 80%
  - Stable at the 0.1% level

- The requirements are physics driven, so they should apply to CLIC as well
ILC options

- Upgradeable for physics up to 1 TeV
- Positron polarization > 50%
- GigaZ
- e⁻e⁻
- e⁻γ and γγ

And likewise for CLIC ...
As of now, the physics case for a 500 GeV linear collider rests primarily on the Higgs.

- There may be other new physics in range, especially electroweak physics.
- But we are unlikely to know for sure based on results from the 7 TeV LHC.

We need to argue based on what we know we will accomplish:
- Discoveries beyond that are an added bonus.
But that’s OK: The Higgs is different!

- It’s a fundamental spin-zero boson that fills the vacuum
  - Bose-Einstein condensate…
  - Which implies that space itself is a superconductor!

It is a radically new kind of particle

- Not seen since the earliest moments of the Universe!
To be *the* Higgs, a Higgs must obey some very special relations …

\[ M_V \propto g v \]

\[ M_F \propto \lambda v \]

\[ \Gamma_V \propto g^2 M_H \]

\[ \Gamma_F \propto \lambda^2 M_H \]

Masses and decay rates are related!
Great claims demand great evidence …

- To separate fact from fiction. That’s the basis of science!

Therefore, given a candidate Higgs, we need to determine its properties – to figure out what it is – and to see how it works

- Is a Higgs is the Higgs, or is it an imposter?
- To answer the question, we need to measure
  - Its mass, spin, couplings …
Higgs Boson

- At a linear collider, the Higgs can’t hide!

\[ e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^-X \]

![Graph showing the distribution of missing mass](image)

\( \sqrt{s} = 300\text{GeV} \)

500 fb\(^{-1}\)

From Z recoil!
Higgs Boson

- Higgs decays depend on the Higgs mass

Allowed region: $115 < M_H < 150$ GeV
Higgs Boson

- Measure Higgs mass
  \[ \Delta M_H \approx \pm 40 \text{ MeV} \]

This plot:
\[ e^+e^- \rightarrow b\bar{b}q\bar{q} \]
\[ \sqrt{s} = 350 \text{ GeV} \]
\[ L = 500 \text{ fb}^{-1} \]

\[ m_H = 120 \text{ GeV} \]
Higgs Boson

- Determine Higgs spin
  Threshold energy scan
  Spin 0!

This plot:
  \( L = 20 \text{ fb}^{-1} \) per point
Higgs Boson

- Measure Higgs branching ratios

This plot: $\sqrt{s} = 350$ GeV, $L = 500$ fb$^{-1}$

![Higgs branching ratio graph](image)
Higgs Boson

- Determine Higgs couplings
  \[ g_{HWW} \text{ and } g_{HZZ} \]
  to 1 – 2 %

Sensitive test!

Tops too:
  \[ \lambda_{Htt} \]
  to < 10%

\[ \Delta g_{Htt}/g_{Htt} \text{ (\%)} \]

\[ m_H (\text{GeV/c}^2) \]

- L = 1000 fb\(^{-1}\)
- \( E_{\text{cms}} = 800 \text{ GeV} \)
Higgs Boson

- Measure Higgs trilinear self-coupling

\[ \lambda_{HHH} \]

to 12%

for \( M_H = 120 \) GeV, \( \sqrt{s} = 1000 \) GeV, \( L = 1000 \) fb\(^{-1}\)

Test of Higgs potential

\[ \lambda_{HHH} = \sqrt{2} \, M_H \]

\[ V(H) = \frac{1}{2} M_H^2 H^2 + \sqrt{2} M_H H^3 + \cdots \]
Higgs Boson

- Is a Higgs the Higgs? The ultimate test …

This plot is even more interesting if the Higgs is not “standard”
A threshold scan can determine the top quark mass to 100 – 200 MeV
Top Quark

- Top quark couplings are an excellent place to search for new physics.
New Force

- The LC can search for Z' bosons up to very high energies

This plot:

\[ e^+e^- \rightarrow \text{hadrons} \]

\[ \sqrt{s} = 500 \text{ GeV} \]

\[ L = 1000 \text{ fb}^{-1} \]

\[ P(e^-) = 0.8 \]

\[ P(e^+) = 0.6 \]
New Force

- The LC can search for Z’ bosons up to very high energies

This plot:

\[ e^+e^- \rightarrow \mu^+\mu^- \]

\[ \sqrt{s} = 500 \text{ GeV} \]

\[ L = 1000 \text{ fb}^{-1} \]

\[ P(e^-) = 0.8 \]

\[ P(e^+) = 0.0, 0.6 \]
New Force

- The LC can distinguish one \( Z' \) from another …

This plot:

- 3 TeV \( Z' \)
- \( e^+e^- \rightarrow \) fermions
- \( \sqrt{s} = 500 \) GeV
- \( L = 1000 \) fb\(^{-1} \)
- \( P(e^-) = 0.8 \)
- \( P(e^+) = 0.6 \)
Other Possibilities

- Of course, the story continues. The linear collider is versatile. So no matter what the new physics, it has a role to play – if the physics is within its reach …

  - Supersymmetry: charginos, neutralinos, sleptons
  - Extra dimensions: KK gravitons, photons, leptons
  - Little Higgs: New tops, Higgs particles, gauge bosons
  - Dark Matter: WIMPS …
Conclusions

- With its polarized beams, adjustable energy, and clean collisions, the LC is well-suited to probing the Higgs – and to disentangling any other new physics that the LHC finds.

- The catch is that the LC’s reach is limited to CM energies less than of order 1 TeV.
  - We might or might not be lucky …

- But we cannot count on luck.
  - We must base the physics case on what we know.
Conclusions

• Fortunately, the Higgs provides an excellent place to start
  ♦ With it, we can do pathbreaking physics while we aggressively pursue higher energies – by developing a higher gradient linear collider, a muon collider, or other advanced accelerator techniques

• But first, we must find the Higgs – or whatever takes its place!
Information

- For more information, visit
  - www.interactions.org/
    quantumuniverse
  - www.linear collider.org
  - clic-study.org

All unattributed plots are taken from the ILC RDR, available at interactions.org