The Linear $e^+e^-$ Collider

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Outline

- What is a linear collider?
  - Why build a linear collider?
  - How can a linear collider be built?
  - What will the detectors be like?
  - Prospects
What is a linear collider?

- Next in the line of high energy $e^+e^-$ colliders
$e^+e^-$ colliders at the frontier

![Graph showing the evolution of centre-of-mass energy (GeV) for different e+e- colliders from 1980 to 2020. The graph includes the years 1980, 1990, 2000, and 2010, with corresponding centre-of-mass energy values. The graph also highlights PETRA, PEP, TRISTAN, SLC, LEP - I, LEP - II, and LC.]
why linear?

Centre-of-mass Energy (GeV)

Circumference / Length (km)

$ R \propto E^2 $

$L \propto E$

circular colliders

linear colliders

$\$
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Why build a Linear Collider?

- Just as LEP/SLC studied *electroweak symmetry* to high precision, the LC will study *electroweak symmetry breaking* to high precision:
  - LEP/SLC firmly established the electroweak theory
    - likewise, LEP/SLC could have shown the Standard Model to be incorrect
    - the large variety of measurements would have pointed to the new theory
  - The LC will either firmly establish the mechanism of EWSB & mass generation,
    - or it will provide critical data to point to the new theory
Legacy of LEP/SLC:

- A large number of precise measurements testing the SM at the level of quantum fluctuations...
Higgs appears to be within grasp

- From these precision measurements:
  \[ m_H < 193 \text{ GeV} \]
  @ 95% CL

- Direct searches at LEP:
  \[ m_H > 114.4 \text{ GeV} \]
  @ 95% CL
The golden processes

- At LEP the golden processes for studying the electroweak sector were:

  \[ e^+ e^- \rightarrow Z^0 \quad e^+ e^- \rightarrow W^+ W^- \]

- At the LC the golden processes for studying the Higgs sector are:

  \[ e^+ e^- \rightarrow Z^0 H \quad e^+ e^- \rightarrow H \nu \overline{\nu} \]

- LEP beam energies were not sufficiently high enough for these process to occur
The golden processes

- Cross section vs. Higgs mass
Higgs production at a LC
Recoil mass

\[ e^+ e^- \rightarrow Z^0 H^0 \rightarrow \mu^+ \mu^- X \]

\[ e^+ e^- \rightarrow Z^0 H^0 \rightarrow q\bar{q}b\bar{b} \]

\( E_{cm} = 350 \text{ GeV} \)
\( L = 500 \text{ fb}^{-1} \)

\( m_H = 140 \text{ GeV} \)

with 5C fit
\( \delta m_H \sim 50 \text{ MeV} \)
Higgs couplings

- Branching fractions to fermions & bosons:
  - confirm(?) its role in mass generation
  - distinguish SM from SUSY Higgs (?)
Other Higgs properties

- Confirm (?) fundamental properties:
  - spin & parity
  - total width
  - its couplings to Gauge bosons and to itself
    - confirm its role in EWSB

\[
\Gamma_H^{Total} = \frac{\Gamma(H \rightarrow WW)}{BR(H \rightarrow WW)}
\]
Other precision measurements

- Fermion pair production
  - sensitive to $Z^{'}$, $W^{'}$, R-parity violation, leptoquarks
  - sensitivity reaches beyond $\sqrt{s}$
    - for example, LC is sensitive to $Z^{'}$ if $m_{Z^{'}} < 5 - 10 \sqrt{s}$
- Top mass measurement: $\delta m_{\text{top}} \approx 100$ MeV
- W pair production
  - a gain by 2 orders in magnitude in the sensitivity to anomalous couplings in the gauge sector
- Return to the $Z^0$ peak and $W W$ threshold
  - 30 fb$^{-1}$ at $Z^0$ peak $\rightarrow 10^{9} Z^0$ in a few months
  - with 80% (60%) $e^-$ ($e^+$) pol. $\rightarrow \delta \sin^2 \theta_{\text{eff}} \approx 0.00001$
<table>
<thead>
<tr>
<th></th>
<th>Now</th>
<th>+LHC</th>
<th>+LC</th>
<th>+\text{Z}^0,\text{W}^+</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta M_W$</td>
<td>30 MeV</td>
<td>15 MeV</td>
<td>15 MeV</td>
<td>6 MeV</td>
</tr>
<tr>
<td>$\delta \sin^2 \theta_{\text{eff}}$</td>
<td>0.00017</td>
<td>0.00017</td>
<td>0.00017</td>
<td>0.00001</td>
</tr>
<tr>
<td>$\delta m_t$</td>
<td>5 GeV</td>
<td>2 GeV</td>
<td>0.2 GeV</td>
<td>0.2 GeV</td>
</tr>
</tbody>
</table>

$\sin^2 \theta_{\text{eff}}$ vs. $m_{\text{top}}$ (GeV)

68% C.L.
Consensus: Europe

- ECFA statement:
  - “…the realisation, in as timely a fashion as possible, of a world-wide collaboration to construct a high-luminosity e+e- linear collider with an energy range up to at least 400 GeV as the next accelerator project in particle physics; decisions concerning the chosen technology and the construction site for such a machine should be made soon”
Consensus: U.S.

- HEPAP statement:
  - “We recommend that the highest priority of the U.S. program be a high-energy, high-luminosity, electron-positron linear collider, wherever it is built in the world.... We recommend that the United States prepare to bid to host the linear collider, in a facility that is international from the inception.”
Consensus: Asia

- ACFA statement:
  - “ACFA urges the Japanese Government to arrange a preparatory budget for KEK to pursue an engineering design of the collider, to study site and civil engineering, as well as to investigate the process for the globalization.”
Consensus: OECD

OECD GSF report:

- “The Consultative Group concurs with the world-wide consensus of the scientific community that a high-energy electron-positron linear collider is the next facility on the Road Map.”
- “There should be a significant period of concurrent running of the LHC and the LC, requiring the LC to start operating before 2015. Given the long lead times for decision making and for construction, consultations among interested countries should begin at a suitably-chosen time in the near future.”
- The cost of the LC will be broadly comparable to that of the LHC, and can be accommodated if the historical pattern of expenditure on particle physics is maintained, taking into account the additional resources that the host country (or countries) will need to provide.
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How can a linear collider be built?

- Two designs for a linear collider exist:
  - TESLA: led by DESY (Germany)
    - lower frequency (1.3 GHz) superconducting cavities
    - Initially: $E_{cm} = 500$ GeV $\quad L = 3 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
    - Later: $E_{cm} = 800$ GeV $\quad L = 5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
    - Lower wakefields, looser tolerances, higher luminosity
  - NLC/JLC: led by SLAC & KEK (US & Japan)
    - higher frequency (11.4 and 5.7 GHz) warm cavities
    - Initially: $E_{cm} = 500$ GeV $\quad L = 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
    - Later: $E_{cm} = 1 – 1.5$ TeV $\quad L = 4 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
    - highest gradients
Accelerator structures

- The heart of the linear collider:
Accelerator physics challenges

- technical challenges for a linear collider:
  - high gradients
    - TESLA: TTF has performed according to design gradient
    - higher gradient cavities now routinely constructed
    - NLC: gradients achieved in NLCTA, but damage observed
    - redesign completed, tests are underway
  - low emittance
    - damping ring test facility (ATF at KEK) successful
  - small beam spot size (high luminosity)
    - final focus test facility shows required demagnification
Beam spot sizes:

- SLC (500 nm)
- FFTB (50 nm)
- TESLA/NLC (2-5 nm)
Vibration control system

- The small vertical beam sizes (few nm) necessitate an accurate vibration control system for the linear collider magnets near the interaction point.
- Tom Mattison (UBC) is studying the feasibility of a 10 m baseline laser interferometer to monitor and control the vibration of heavy objects at the nanometer scale.
The costs...

- **TESLA** completed an accurate costing:
  - 3.1 Billion Euro, European costing
    - does not include lab personnel
    - does not include contingency
  - Particle physics detector: 0.2-0.3 Billion
  - Free electron laser laboratory: 0.3 Billion

- **NLC cost estimate, without contingency:**
  - $3.5 Billion

- **JLC estimate**
  - $4.5 Billion

Only one Linear Collider can be built: it will be an International Laboratory.
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A linear collider detector
Vertex detector

- charm tagging (light Higgs, W) is a challenge
  - prime motivator for bringing in vertex detector as close as possible
- leading candidate: CCDs (success at SLD)
Central tracker
Central tracking designs

- Leading candidate: Time projection chamber
TPC readout technology choices

- Gas Electron Multiplier (GEM)
  - negligible E x B distortions: improved resolution
  - narrower and faster signals: improved 2 particle separation
  - reduced ion feedback
Example Events

- Outer 6 rows are used to define track
  - Inner two rows: resolution studies
  - 2 mm x 6 mm / 3 mm x 5 mm pads
Tracking resolution

- Ar CO₂ (90:10)
- \(d < 2 \text{ cm}\)
- \(|\phi| < 0.05 \text{ rad}\)
- pad width: 2 mm
- \(\langle \sigma \rangle = 0.5 \text{ mm}\)
- \(w/\langle \sigma \rangle = 4\)
- resolution: 130 \(\mu\text{m}\)
Calorimeter concepts
Jet Energy Resolution Requirements

- Goal: distinguish W and Z in their hadronic modes
- requires: jet energy resolution, $\sigma_E \approx 30\% \sqrt{E}$

example: $e^+ e^- \rightarrow WW \nu \bar{\nu}$, $e^+ e^- \rightarrow ZZ \nu \bar{\nu}$
Moliere radius (Iron vs. Tungsten)

Iron

Tungsten

(many images courtesy H. Videau)
Si/W ECAL: Si

Silicon Area (m²)

Total amount of Si required: 1-3 x 10³ m²

DATA From H.F-W. Sadrozinski, UC-Santa Cruz
Si/W ECAL: Si cost

Si/W ECAL costs dominated by Si cost: will it become affordable?

DATA From H.F-W. Sadrozinski, UC-Santa Cruz

Blank wafer price 6" $2/\text{cm}^2$

Used in the TDR
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Where will it be built?

US: California and Illinois sites under consideration

DE: site selected in Hamburg

Japan: beginning site selection process
Status of proposals

- **TESLA:**
  - Technical Design Report submitted to German Science Council in March 2001
  - Response from Council (July 2002) very positive
  - Initial German government response (Feb 2003) also very positive

- **NLC/JLC:**
  - US working to complete proof of concept by 2003
  - Japan has released its Project Report (Feb 2003)
Summary

- $e^+e^-$ colliders have firmly established the Standard Model of Particle Physics:
- However, the Standard Model has its problems:
  - It fails to answer many “deep” questions
  - Mass generation is on shaky ground
- Important to bring a linear collider online soon to investigate these issues in detail
- The linear collider is entering the political phase... once approval comes to begin this project, the real excitement starts!