Experimental Challenges and Techniques for Future Accelerators

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DESY
Outline

> Lecture 1
  - Future particle physics at the energy frontier: case for a Linear Collider
  - Linear Collider Concepts
  - Experimental Challenges
  - Detector Concepts

> Lecture 2
  - R&D for detector components
  - Vertex detector
  - Tracking detectors
  - Calorimeters
> **Particle Physics entering Terascale**
>   - Start of the Large Hadron Collider (LHC) at CERN

> **Expect answers to fundamental questions**
>   - Origin of mass (Higgs)
>   - Mystery of Dark Matter
>   - Supersymmetry
>   - Extra space dimensions
>   - Grand Unification
Future of Particle Physics at the Energy Frontier

> LHC and its upgrades
  - Luminosity
  - Energy (?)

> Electron-Positron Linear Collider
  - ILC (supra-conducting technology)
  - CLIC (two-beam acceleration)
  - Muon collider (?)

> Here: emphasis on detector challenges for Linear Collider
Comparison Proton and Electron Colliders

- Proton (anti-) proton colliders:
  - Energy range higher (limited by magnet bending power)
  - Composite particles, different initial state constituents and energies in each collision
  - Hadronic final states difficult
- Discovery machines
- Excellent for some precision measurements

- Electron positron colliders:
  - Energy range limited (by RF power)
  - Point-like particles, exactly defined initial state quantum numbers and energies
  - Hadronic final states easy
- Precision machines
- Discovery potential

- Precision is main motivation for a new electron positron collider
- Complementarity to proton machines, e.g. SppS/Tevatron and LEP
Comparison Proton and Electron Colliders

\[ pp \rightarrow H + X \]

\[ e^+e^- \rightarrow HZ \]
Electron Positron Collider

- The $e^+e^-$ cross section drops $\sim 1/\sqrt{s}$

- The key parameters for a competitive $e^+e^-$ machine are
  - energy reach
  - luminosity

strive for few $10^{34}/\text{cm}^2/\text{s}$
(comparable to LHC)

Recall: $10^{34}/\text{cm}^2/\text{s}$ corresponds to 100 fb$^{-1}$ per year
Linear Collider Concepts

- **International Linear Collider ILC**
  - superconducting acceleration
  - 31.5 MeV/m, 1.3 GHz
  - advanced design (c.f. XFEL)
  - 500 GeV → 1 TeV
  - Luminosity: $2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

- **Compact Linear Collider CLIC**
  - normalconducting acceleration
  - 100 MeV/m, 12 GHz
  - two-beam acceleration principle
  - up to several TeV
  - still in fundamental R&D phase

- **Summary:**
  - ILC ready to go ahead, but limited in energy reach (≤ 1 TeV)
  - CLIC in very early state, but may pave the way for higher energy
● Dominant production mechanisms: Higgsstrahlung and WW-fusion
Higgs

- Model independent Higgs measurement
Higgs Couplings

- Measuring the couplings of the Higgs to massive particle
  - The smoking gun!

Introduction
Verification of the Higgs Potential

\[ V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 \quad \mu^2 < 0 \quad \lambda > 0 \]

Vacuum expectation value \( v = \sqrt{-\mu^2/\lambda} \)

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

\[ m_H = \sqrt{2\lambda v} \]

- Measurement of double Higgs-strahlung: \( e^+ e^- \rightarrow \) HHZ

\( \Delta g_{HHH}/g_{HHH} = 0.22 \)

- Measurement of \( g_{HHHH} \) not possible
• Production of $10^9$ Z-Bosonen at $\sqrt{s} = 91$ GeV
  • 100-fold LEP I statistics
  • polarisation (as SLC)
  • $30 \text{ fb}^{-1} = 1/2$ year

<table>
<thead>
<tr>
<th></th>
<th>LEP/SLC/Tevatron</th>
<th>Giga-Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$</td>
<td>$91\ 187,5 \pm 2,1 \text{ MeV}$</td>
<td>---</td>
</tr>
<tr>
<td>$\sin^2 \theta_W$</td>
<td>$0,23153 \pm 0,00016$</td>
<td>$\pm 0,000013$</td>
</tr>
<tr>
<td>$A_b$</td>
<td>$0,899 \pm 0,013$</td>
<td>$\pm 0,001$</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$0,21629 \pm 0,00066$</td>
<td>$\pm 0,00014$</td>
</tr>
<tr>
<td>$m_W$</td>
<td>$80\ 392 \pm 29 \text{ MeV}$</td>
<td>$\pm 6 \text{ MeV}$</td>
</tr>
</tbody>
</table>

Comparison to direct Higgs mass measurement
Supersymmetry

- If $m_{\text{SUSY}} < 2$ TeV $\Rightarrow$ Discovery at the LHC

SUSY will be the New Standard Model

- Scalar partners of fermions
  $\tilde{e}_R, \tilde{e}_L, \tilde{\mu}_R, \tilde{\mu}_L, \ldots, \tilde{t}_1, \tilde{t}_2$

- Fermionic partners of bosons
  $\tilde{\chi}^\pm, \tilde{\chi}^0, \ldots, \tilde{\chi}_4^0, \tilde{g}$

- $\geq 2$ Higgs-doublets
  $h, H, A, H^\pm$

Advantages of an electron positron collider:
- tune cms energy: turn on SUSY particles one-by one
- mass measurement at the kinematic threshold
- polarisation of electrons and positrons
  separation of SUSY partners, e.g.:
  $$e^+_L e^-_L \rightarrow \tilde{e}^+_L \tilde{e}^-_L \quad e^+_R e^-_R \rightarrow \tilde{e}^+_R \tilde{e}^-_R$$
The Cosmological Connection

- Could SUSY particles be the Cold Dark Matter?
- Astrophysics experiments measure just densities
- ILC could close the loop
- Electron-positron collider
  - centre-of-mass energy up to 1 TeV centre-of-mass energy
  - luminosities $> 10^{34}/\text{cm}^2/\text{s}$

- Designed in a global effort

- Accelerator technology: supra-conducting RF cavities

- Elements of a linear collider:
International Linear Collider (ILC)

- $E_{cm}$ adjustable from 200 – 500 GeV
- Luminosity $\int L dt = 500 \text{ fb}^{-1}$ in 4 years (corresponds to $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with a start-up profile)
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarisation of at least 80%
  
  **Positron polarisation**

- The machine must be upgradeable to 1 TeV!
ILC Time Schedule

- 2006: Baseline Configuration Document

![ILC Time Schedule Diagram]
Challenges

- Quest for the highest possible accelerator gradient
- ILC goal: 35 MV/m

- Huge progress over the last 15 years
- 25-fold improvement in performance/cost

- Major impact on next generation light sources:
  - XFEL designed for $\geq 25$ MV/m
  - 10% prototype for ILC

- Recall: LEP II used 7 MV/m
FLASH: Prototype for XFEL and ILC

- 1 GeV electron LINAC based on SCRF
- used for ILC studies and as light source (free electron laser)
Challenges

- Getting to 35 MV/m:
  - Acceleration gradient goal:
    - 35 MV/m in 9-cell cavities with production yield >80%
    - 50 MV/m have been reached with single cavities
    - Mass production reliability is the key problem
Cavity Quality (Q value)

- Superconducting cavity: $Q > 10^{10}$

- A church bell (300 Hz) with $Q = 5 \times 10^{10}$ would ring - once excited - longer than one year!
**Challenges**

- **Luminosity:**

\[
L = \frac{n_b N_e^2 f_{\text{rep}}}{4\pi \sigma_x^* \sigma_y^*} \times H_D
\]

- \(n_b\): number of bunches per pulse
- \(N_e\): number of electrons (positrons) per bunch
- \(f_{\text{rep}}\): pulse repetition frequency
- \(H_D\): disruption enhancement factor (\(\approx 2\))
- \(\sigma_{x(y)}^*\): beam dimensions at interaction point

- make beams as small as possible at IP
  6 nm \(\times\) 600 nm

- and make them collide!!!
Simulation of two LC bunches as they meet each other
Challenges

Beamstrahlung

- Energy loss in collision due to Beamstrahlung:

\[ \delta_{BS} = \frac{\Delta E}{E} = \frac{E_{CM}}{\sigma_Z} \left( \frac{N}{\sigma_x + \sigma_y} \right)^2 \]

- But: \( \mathcal{L} \sim 1/\sigma_x\sigma_y \Rightarrow \) choose flat beams
- 1.5% energy loss on average
- \( \approx 100,000 \gamma\gamma \) pairs per BX!
- Intense backgrounds in the forward direction, need high \( B \) field to control \( e^+e^- \) pairs
## Comparison LHC and ILC

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>total energy</td>
<td>14 TeV</td>
<td>0.5-1 TeV</td>
</tr>
<tr>
<td>usable energy</td>
<td>a fraction</td>
<td>full</td>
</tr>
<tr>
<td>beam</td>
<td>composite</td>
<td>point-like</td>
</tr>
<tr>
<td>signal rate</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>background</td>
<td>very high</td>
<td>low</td>
</tr>
<tr>
<td>analysis</td>
<td>specific modes</td>
<td>nearly all modes</td>
</tr>
<tr>
<td>reconstruction</td>
<td>loose along beam</td>
<td>full event</td>
</tr>
<tr>
<td>status</td>
<td>soon to start</td>
<td>design to be completed</td>
</tr>
</tbody>
</table>
ILC Physics Motivation

- ILC will complement LHC discoveries by precision measurements

- Here just two examples:

1) There is a Higgs, observed at the LHC
   - $e^+e^-$ experiments can detect Higgs bosons without assumption on decay properties
   - Higgs-Strahlungs process (à la LEP)

   - identify Higgs events in $e^+e^- \rightarrowZH$ from $Z \rightarrow \mu\mu$ decay

   - count Higgs decay products to measure Higgs BRs
   - and hence (Yukawa)-couplings

\[ e^- \rightarrow Z^* \rightarrow H \]
\[ e^+ \rightarrow Z \rightarrow Z \]

\[ e^+e^- \rightarrow \rightarrow \]
Measure Higgs self-couplings
$e^+e^- \rightarrow ZHH$ to establish Higgs potential
Note: small signal above large QCD background

2) There is NO Higgs (definite answer from LHC!)
   - something else must prevent e.g. WW scattering from violating unitarity at O(1 TeV)
   - strong electroweak symmetry breaking?
     → study $e^+ e^- \rightarrow WW\nu\nu, Wze\nu$ and $ZZee$ events

   - need to select and distinguish W and Z bosons in their hadronic decays!
     $BR (W/Z \rightarrow \text{hadrons}) = 68\% / 70\%$

- Many other physics cases: SM, SUSY, new phenomena, …
  Need ultimate detector performance to meet the ILC physics case
Impact on Detector Design

- **Vertex detector:**
  - e.g. distinguish c- from b-quarks
    - goal impact parameter resolution
      \[ \sigma_{r\phi} \approx \sigma_z \approx 5 \oplus \frac{10}{p \sin \frac{\Theta}{2}} \mu m \]
      3 times better than SLD
  - small, low mass pixel detectors, various technologies under study
    \( O(20 \times 20 \mu m^2) \)

- **Tracking:**
  - superb momentum resolution
    to select clean Higgs samples
  - ideally limited only by \( \Gamma_Z \)

  \[ \Delta (1/p_T) = 5 \times 10^{-5} /GeV \]
  (whole tracking system)
  3 times better than CMS

Options considered:
- Large silicon trackers (à la ATLAS/CMS)
- Time Projection Chamber with \( \approx 100 \mu m \) point resolution
  (complemented by Si–strip devices)
Tracker Resolution

Tracker resolution matters

\[ a = 2.0 \times 10^{-5} \]
\[ b = 1.0 \times 10^{-3} \]
\[ \Delta M_h = 103 \text{ MeV} \]

\[ a = 8.0 \times 10^{-5} \]
\[ b = 1.0 \times 10^{-3} \]
\[ \Delta M_h = 273 \text{ MeV} \]
Impact on Detector Design

- **Calorimeter:**
  - distinguish W- and Z-bosons in their hadronic decays
  - $30\%/\sqrt{E}$ jet resolution!

- **WW/ZZ → 4 jets:**
  - $60\%/\sqrt{E}$ jet resolution
  - $30\%/\sqrt{E}$ jet resolution

→ Particle Flow or Dual Readout calorimeter

2 times better than ZEUS
Detector Challenges at the ILC

- Bunch timing:
  - 5 trains per second
  - 2820 bunches per train separated by 307 ns
    - no trigger
    - power pulsing
    - readout speed

- 14 mrad crossing angle

- Background:
  - small bunches
  - create beamstrahlung → pairs

background not as severe as at LHC but much more relevant than at LEP
Two Detectors

Additional complication:

One interaction region, but two detectors:
Additional complication:

One interaction region, but two detectors:

push pull operation anticipated
Detector Push-Pull

The concept is evolving and details are being worked out.

accessible during run

Platform for electronics and services (~10x8x8m³). Shielded (~0.5m of concrete) from five sides. Moves with detector. Also provide vibration isolation.
The CLIC Two Beam Scheme

Two Beam Scheme

Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics
- high energy (9 GeV – 1.5 TeV)
- current 1.2 A

Drive beam - 100 A from 2.4 GeV -> 240 MeV (deceleration by extraction of RF power)

Main beam - 1.2 A from 9 GeV -> 1.5 TeV

No individual RF power sources -> CLIC itself is basically a ~50 km long klystron...
### Comparison ILC and CLIC

<table>
<thead>
<tr>
<th></th>
<th>ILC 500 GeV</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>
<td></td>
</tr>
<tr>
<td>Total (Peak 1%) luminosity [10^{34}]</td>
<td>2,(1.5)</td>
<td>2.3,(1.4)</td>
<td>5.9,(2.0)</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>5</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Loaded accel. gradient MV/m</td>
<td>32</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Main linac RF frequency GHz</td>
<td>1.3</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Bunch charge ([10^9])</td>
<td>20</td>
<td>6.8</td>
<td>3.7</td>
</tr>
<tr>
<td>Bunch separation (ns)</td>
<td>370</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Beam pulse duration (ns)</td>
<td>950,\mu s</td>
<td>177</td>
<td>156</td>
</tr>
<tr>
<td>Beam power/beam (MWatts)</td>
<td>4.9</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Hor./vert. IP beam size (nm)</td>
<td>600 / 6</td>
<td>200 / 2.3</td>
<td>40 / 1.0</td>
</tr>
<tr>
<td>Hadronic events/crossing at IP</td>
<td>0.12</td>
<td>0.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Incoherent pairs at IP</td>
<td>1\cdot10^5</td>
<td>1.7\cdot10^5</td>
<td>3\cdot10^5</td>
</tr>
<tr>
<td>BDS length (km)</td>
<td>1.87</td>
<td>2.75</td>
<td></td>
</tr>
<tr>
<td>Total site length km</td>
<td>31</td>
<td>13</td>
<td>48</td>
</tr>
<tr>
<td>Total power consumption MW</td>
<td>230</td>
<td>130</td>
<td>415</td>
</tr>
</tbody>
</table>

Crossing Angle 20 mrad (ILC 14 mrad)
CLIC Time Structure

- Bunch Spacing
  - ILC: 337 ns, enough time to identify events from individual BX
  - CLIC: 0.5 ns, extremely difficult to identify events from individual BX
  - Need short shaping time of pulses
  - Power cycling with 50 Hz instead 5 Hz at ILC
  - Larger power dissipation? Does silicon tracker need to be cooled? (not cooled in SiD)
Why Time Stamping?

> Overlay of physics events with background events from several bunch crossings
  - degradation of physics performance

> Main background sources from beamstrahlung
  - $e^+e^-$ pairs from beamstrahlung photons
    - low pT, can be kept inside beam pipe with high magnetic field, $B > 3$ T
  - hadrons from 2-photon collisions (beamstrahlung photons)
    - can have high pT, reach main tracker and confuses jet reconstruction
    - typically $\sim O(1)$ hadronic background event per BX with $p_T > 5$ GeV tracks

Higgs mass reconstruction from $HZ \rightarrow bbqq$
Summary of CLIC Challenges + R&D

> Time stamping
  - most challenging in inner tracker/vertex region
  - trade-off between pixel size, amount of material and timing resolution

> Power pulsing and other electronics developments
  - in view of CLIC time structure

> Hadron calorimetry
  - dense absorbers to limit radial size (e.g. tungsten)
  - PFA studies at high energy
  - alternative techniques, like dual/triple readout

> Background
  - innermost radius of first vertex detector layer
  - shielding against muon background more difficult at higher E

> Alignment and stability
Main Differences CLIC as compared to ILC

> Higher energy results in more dense particle jets
  ▪ Improved double track resolution
  ▪ Calorimeters with larger thickness and higher granularity

> Much shorter bunch spacing
  ▪ CLIC 0.5 ns wrt. ILC 337 ns
  ▪ Requires time stamping
  ▪ Impact on pulsed power electronics

> Smaller beam sizes and higher energy
  ▪ Result in more severe background
Time Lines

ILC Timeline

- 2005: Baseline Configuration
- 2006: Reference Design
- 2007: Engineering
- 2008: International Management
- 2009: ILC R&D Programme
- 2010: PROJECT

GLOBAL DESIGN EFFORT

LHC Results

CLIC Feasibility Study

Technical Design Report 2012
End of Lecture 1