The International Linear Collider – a precision probe for physics in the post-LHC era

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Quebec City, 11 June 2008
The ILC - the next high energy physics accelerator after the LHC

• LHC starts this summer - p+p at 14 TeV
• New Physics discoveries appear imminent
• ILC will be the next world facility for particle physics after the LHC.
• The ILC physics case & its experiments
• Canadian R&D toward building the detector for the ILC
• Outlook
e^+ e^- Linear Collider $E_{cm}$ adjustable from 200 – 500 GeV
Two experiments, complementary & contrasting technologies
Single interaction region, 14 mrad crossing angle
Luminosity $\rightarrow \int Ldt = 500 \text{ fb}^{-1}$ in 4 years
Ability to scan between 200 and 500 GeV
Energy stability and precision below 0.1%
Electron polarization at least 80%
The machine upgradeable to 1 TeV
ILC Global Design Effort & World Wide Study

V1: EXECUTIVE SUMMARY

V2: PHYSICS

V3: ACCELERATOR

V4: DETECTORS

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The GDE Plan and Schedule

Global Design Effort

- Baseline configuration
- Reference Design

LHC Physics

- Engineering Design
- ILC R&D Program
- Expression of Interest to Host
- International Mgmt

Including Detectors

Project

2005 2006 2007 2008 2009 2010
December, 2007

- UK: STFC cuts ILC funding
- US: The Congress cuts ILC budget by 75% three months into the new fiscal year. Money already spent.

Aftermath:
- Revised schedule
- Maintain momentum
- Focus on critical R&D items
- Prepare for LHC results
- Scientific case for ILC still valid
The Standard Model (SM)

Building Blocks of Matter

Symmetry

$SU(3)_C \times SU(2)_L \times U(1)_Y$

QCD  Electroweak theory

• EW symmetry spontaneously broken through Higgs mechanism
• SM highly successful, internally consistent in agreement with experiments within $\sim 0.1\%$.

The neutral scalar Higgs particle responsible for EW symmetry breaking remains undiscovered.
Higgs constrains from precision SM fits

114.4 < $M_{H_i}$ < 144 GeV
from LEP exclusion & SM fits

$M_t$ & $M_W$ from CDF & D0
Telltale signs for New Physics

- The predicted Higgs mass unexpectedly low $\sim 100 \text{ GeV}$
  $M_H \sim 10^{19} \text{ GeV}$ near Planck mass from large radiative corrections
- Low Higgs mass requires term by term cancellation of divergences

- Fine-tuning to cancel divergences is unnatural
- With Supersymmetry at $\sim 1 \text{ TeV}$, sparticle loops naturally cancel particle loop divergences

• If no Higgs below $\sim \text{ TeV}$, New Strong Interactions among $WZ$ bosons needed to restore unitarity.
Cosmic connections

- Existence of Dark Matter (DM) is well established.

~ 1 TeV Weakly Interacting Massive particles (WIMP) could account for the observed DM density.

Can WIMP be the lowest mass SuperSymmetric particle?

- How to Unify gravity with other forces?

Motivates String theory & Extra Dimensions
Part of the solution for other problems
TeV physics with the LHC & with the ILC

- CM parton-parton collisions
- Unknown $E_{CM}$ & quantum numbers
- Can discover TeV physics directly

- Clean point like collisions
- $E_{CM}$ & quantum numbers tunable
- Use polarization to suppress backgrounds
- A powerful tool to probe New Physics
Cross sections for physics at ILC
ILC sensitivity to New Physics

The LHC has higher mass reach, but precision makes ILC the ultimate probe of new physics

• ILC physics menu:
  • The nature of electromagnetic symmetry breaking & detailed study of the Higgs
  • Supersymmetry, its mass spectrum & parameters
  • New gauge interactions
  • Extra dimensions
  • Precision measurements
    • $\Delta M_{\text{Top}} \approx 100 \text{ MeV}$, $\Delta \Gamma_{\text{Top}} \approx 2\%$
    • $\Delta M_Z$ & $\Delta M_W \approx 5 \text{ MeV}$ (from 30 MeV)
    • $\Delta (\sin^2 \vartheta) \approx 10^{-5}$ (from $2 \cdot 10^{-4}$)

• LHC & ILC Complementary
• Essential to understanding the New Physics
Higgs physics at the ILC

- Detailed precision measurements
- Establish spin, parity (SM Higgs $0^+$)
- Measure decay modes to discriminate between SM and SuperSymmetric Higgs
- Higgs couplings to gauge bosons & to itself to confirm its role in EW symmetry breaking
Higgs production at the ILC

\[ \sigma(e^+e^- \rightarrow HX) \text{ [fb]} \]

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

\[ M_H \text{ [GeV]} \]

ILC RDR, arXiv:0709.1893

\( ttH \) kinematically limited at 500 GeV ILC
Higgsstrahlung - the Golden channel for Higgs studies

\[ e^+ e^- \rightarrow ZH \]
\[ Z \rightarrow \mu^+ \mu^- ; \quad e^+ e^- \]
Evidence of new physics if the Higgs production rate is not as expected

I. Higgs mass & production rates measured independent of decay modes - includes even invisible Higgs decays
II. Enables detailed studies with tagged Higgs
III. Fully establish Higgs mechanism!
IV. Higgs factory
Some examples....

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Measurements of Higgs production couplings, decay branching ratios (from ILC RDR)

<table>
<thead>
<tr>
<th>Decay</th>
<th>Rel. precision (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b b</td>
<td>1.0–2.4</td>
</tr>
<tr>
<td>c c</td>
<td>8.1–12.3</td>
</tr>
<tr>
<td>τ τ</td>
<td>4.6–7.1</td>
</tr>
<tr>
<td>g g</td>
<td>4.8–10</td>
</tr>
<tr>
<td>W W</td>
<td>3.6–5.3</td>
</tr>
<tr>
<td>γ γ</td>
<td>23 - 35</td>
</tr>
</tbody>
</table>

Makes possible model independent extraction of Higgs couplings, constraints non SM Higgs - only possible at ILC
Coupling Precision

- LHC: 300 fb^{-1} x 2
- ILC

- Model assumption: Limit on \( \rho \) and \( \rho' \):
  \[ \frac{\rho}{\rho_{SM}} \cdot \frac{\rho'}{\rho'_{SM}} < 1 + 5\%

SUSY or 2HDM

- ILC

- Model Independent Analyses

Yamashita
LHC-ILC interplay on Higgs couplings

LHC + mild model assumptions

LHC + ILC model independent

Precision mostly dominated by ILC. ttH coupling better than LHC alone due to ILC input to LHC fit.

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Detector requirements for ILC physics

• Excellent vertex resolution
  Impact parameter $5 \mu m \oplus \frac{10 \mu m \ \text{GeV}/c}{p \sin^{3/2} (\theta)}$ ($\sim 1/3$ of SLD)
  Improve tracking momentum resolution,
  Identify heavy flavors decays for Higgs studies
  Efficient Z, W & t reconstruction

• Calorimeter: Highest, granularity & resolution
  Particle flow to measure separately charged particle, photons and neutral energy to improve resolution
  Resolution $\sim 30\% / \sqrt{E}$ (2 time better than LEP)
  High purity W & Z reconstruction
  Higgs reconstruction in multijet events
Purity "d" for $e^+ e^- \rightarrow \nu \bar{\nu} WW/e^+e^- ZZ$ events versus invariant mass cut for two values of calorimeter resolution [from ILC RDR]
Measure Higgs with precision limited only by the knowledge of beam energy

Unprecedented demands on the tracker momentum resolution

\[ \Delta(1/p_T) \sim 2 \times 10^{-5} \text{ (GeV/c)}^{-1} \] more than 10 times better than at LEP!

\[ \frac{\delta p_T}{p_T^2} = 2 \times 10^{-5} \quad \frac{\delta p_T}{p_T^2} = 8 \times 10^{-5} \]

\[ \mu^+ \mu^- \] recoil mass at \( \sqrt{s} = 500 \text{ GeV} \). \( M_H = 120 \text{ GeV} \), for two values of the tracker resolution.
A TPC tracker for the ILC

TPC an ideal central tracker for ILC

• Low mass, minimal photon conversion
• High efficiency, high granularity continuous tracking,
• Excellent pattern recognition,
• Particle ID
  • \( \Delta (1/p_T) \sim 1 \times 10^{-4} \text{ (GeV-1) (TPC alone)} \)
  • \( \sim 3 \times 10^{-5} \text{ (GeV-1) (vertex + Si inner tracker + TPC)} \)

TPC parameters:

• 200 track points
• \( \sigma (r, \varphi) \leq 100 \mu m \) includes stiff 90° tracks \( \sim 2 \text{ m drift} \)
• \( \sigma (z) \sim 1 \text{ mm} \)
• \( \sigma_{2\text{ track}} (r, \varphi) \sim 2 \text{ mm} \)
• \( \sigma_{2\text{ track}} (z) \sim 5 \text{ mm} \)
• \( dE/dx \sim 5\% \)
## ILC detector development in Canada

<table>
<thead>
<tr>
<th>TPC</th>
<th>Carleton, Montreal &amp; Victoria</th>
<th>NSERC supported since 2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorimetry</td>
<td>McGill &amp; Regina</td>
<td>Proposed new initiative</td>
</tr>
</tbody>
</table>

Significant progress in ILC TPC R&D with Canada among the leading world groups
3 ILC Detector Concepts - 2 with TPCs

• LOI (Letters of Intent) by 31 March 2009
• LsOI evaluated by IDAG for a Technical Design Proposal
• The collaborations to produce Engineering Design Reports (EDRs) by 2012
Limits on achievable TPC resolution

- The physics limit of TPC resolution comes from transverse diffusion: 
  \[ \sigma_x^2 \approx \frac{D_{Tr}^2 \cdot z}{N_{eff}} \]
  \[ N_{eff} = \text{effective electron statistics.} \]
- For best resolution, choose a gas with smallest diffusion in a high B field.

Pad width limits the MPGD TPC resolution

ExB systematics limits wire/pad TPC resolution

Micro Pattern Gas Detector

Anode pads width \( w \)

Cathode pads width \( w \)

Direct signal on MPGD anode pads

Induced cathode signal determined by geometry

For small diffusion, less precise centroid for wide pads

Accurate centroid determination possible with wide pads

\[ \sigma_x^2 \approx \sigma_0^2 + \frac{1}{N_{eff}} \left[ D_{Tr}^2 \cdot z + w^2 / 12 \right] \]

\[ \sigma_x^2 \approx \sigma_0^2 + \frac{D_{Tr}^2 \cdot z}{N_{eff}} \]
**Micro-Pattern Gas Detector**

**development for the ILC TPC**

ILC tracker goal: $\sigma_{r\phi} \leq 100 \mu m$ including stiff 90° 2 m drift tracks

Anode wire/cathode pad TPC resolution limited by ExB effects
Negligible ExB effects for Micro Pattern Gas Detectors (MPGD)

TESLA TPC TDR: 2 mm $\times$ 6 mm pads (1,500,000 channels) with GEMs or Micromegas
LC TPC R&D: 2 mm pads too wide with conventional readout
For the GEM $\sim$ 1 mm wide pads ($\sim$3,000,000 channels)
Even narrower pads would be needed for the Micromegas

The new MPGD readout concept of charge dispersion to achieve good resolution with $\sim$ 2 mm $\times$ 6 mm pads.
ILC challenge: $\sigma_{Tr} \sim 100 \mu m$ (all tracks 2 m drift)

Classical anode wire/cathode pad TPC limited by ExB effects

Micro Pattern Gas Detectors (MPGD) not limited by ExB effect

Worldwide R&D to develop MPGD readout for the ILC TPC
TPC R&D for the ILC - a world wide effort

LCTPC/LP Groups (19Sept06)

**Americas**
- Carleton
- Montreal
- Victoria
- Cornell
- Indiana
- LBNL
  - Purdue (observer)

**Asia**
- Tsinghua
- CDC:
- Hiroshima
- KEK
- Kinki U
- Saga
- Kagakuin

**Europe**
- LAL Orsay
- IPN Orsay
- CEA Saclay
- Aachen
- Bonn
- DESY
- U Hamburg

**Other groups**
- Tokyo UA&T
- U Tokyo
- U Tsukuba
- Minadano SU-IIT
- TU Munich (observer)
- Freiburg
- MPI-Munich
- Rostock
- Siegen
- NIKHEF
- Novosibirsk
- Lund
- CERN

**MPI-Munich**

Ron Settles
Tsinghua Nov 2006 -- LCTPC Design
Issues: R&D Planning
Finding the avalanche position on a proportional wire

Telegraph equation (1-D):
\[ \frac{L}{R} \frac{\partial^2 Q}{\partial t^2} + \frac{1}{RC} \frac{\partial Q}{\partial t} = \frac{1}{RC} \frac{\partial^2 Q}{\partial x^2} \]

Deposit point charge at t=0

Solution for charge density (L ~ 0)
\[ Q(x,t) = \sqrt{\frac{RC}{4\pi t}} e^{-\frac{x^2RC}{4t}} \]

Generalize charge division to charge dispersion in 2D

Finding the avalanche location on a MPGD resistive anode surface

Telegraph equation 2-D generalization
\[ \frac{\partial Q}{\partial t} = \frac{1}{RC} \left[ \frac{\partial^2 Q}{\partial r^2} + \frac{1}{r} \frac{\partial Q}{\partial r} \right] \]

Solution for charge density in 2-D
\[ Q(r,t) = \frac{RC}{2t} e^{-\frac{r^2RC}{4t}} \]
Charge dispersion in a MPGD with a resistive anode

- Modified GEM anode with a high resistivity film bonded to a readout plane with an insulating spacer.
- 2-dimensional continuous RC network defined by material properties & geometry.
- Point charge at \( r = 0 \) & \( t = 0 \) disperses with time.
- Time dependent anode charge density sampled by readout pads.

Equation for surface charge density function on the 2-dim. continuous RC network:

\[
\frac{\partial \rho}{\partial t} = \frac{1}{RC} \left[ \frac{\partial^2 \rho}{\partial r^2} + \frac{1}{r} \frac{\partial \rho}{\partial r} \right]
\]

\[\Rightarrow \rho(r,t) = \frac{RC}{2t} e^{-\frac{r^2RC}{4t}}\]

Simulating the charge dispersion phenomenon


• The charge dispersion equation describe the time evolution of a point like charge deposited on the MPGD resistive anode at $t = 0$.
• For improved understanding & to compare to experiment, one must include the effects of:
  • Longitudinal & transverse diffusion in the gas.
  • Intrinsic rise time $T_{\text{rise}}$ of the detector charge pulse.
  • The effect of preamplifier rise and fall times $t_r$ & $t_f$.
  • And for particle tracks, the effects of primary ionization clustering.
Charge dispersion prototype tests

- 15 cm drift length
- GEMs/Micromegas
- Detailed simulation
- Cosmic tests B = 0
- Beam tests
- High field cosmic tests
GEM TPC charge dispersion simulation (B=0)

Cosmic ray track, Z = 67 mm Ar+10%CO$_2$

Centre pulse used for normalization - no other free parameters.

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**Transverse resolution (B=0) - Cosmic Rays**

**Ar+10%CO₂**


K. Boudjemline et al., NIM. A574, 22 (2007).

A. Bellerive et al., LCWS 2005, Stanford

\[
\sqrt{\sigma_0^2 + \frac{C_D^2}{N_e} z}
\]

*Compared to conventional readout, charge dispersion gives better resolution for the GEM and the Micromegas.*
KEK beam test at 1 Tesla Canadian/French & Japan/German TPCs

- 4 GeV/c hadrons (mostly $\pi$s)
- 0.5 & 1 GeV/c electrons
- Super conducting 1.2 T magnet without return yoke
- Inner diameter: 850 mm
- Effective length: 1 m

Canadian TPC in the beam outside the magnet

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Transverse spatial resolution $\text{Ar+5\%iC4H10}$

$E=70\text{V/cm}$ $D_{Tr} = 125 \mu\text{m}/\sqrt{\text{cm}}$ (Magboltz) @ $B=1\text{T}$

Micromegas TPC $2 \times 6 \text{ mm}^2$ pads - Charge dispersion readout

$\sigma_x = \sqrt{\sigma_0^2 + \frac{C_d^2 \cdot z}{N_{\text{eff}}}}$

$4 \text{ GeV/c } \pi^+ \text{ beam}$

$\theta \sim 0^\circ$, $\phi \sim 0^\circ$

$\text{Extrapolate to } B = 4\text{T}$

Use $D_{Tr} = 25 \mu\text{m}/\sqrt{\text{cm}}$

Aleph TPC gas

$\sim 20 \mu\text{m}/\sqrt{\text{cm}}$ (Ar/CF4 97/3)

Examples:

$D_{Tr} = 25 \mu\text{m}/\sqrt{\text{cm}}$ (Ar/CH4 91/9)

$\sigma_{Tr} \approx 100 \mu\text{m}$ (2.5 m drift)

$\sigma_0 = (52\pm1) \text{ mm}$

$N_{\text{eff}} = 22\pm0$ (stat.)
Extrapolation confirmed 5 T cosmic tests at DESY COSMo (Carleton, Orsay, Saclay, Montreal) Micromegas TPC

\[ D_{\text{Tr}} = 19 \mu m/\sqrt{\text{cm}}, \; 2 \times 6 \text{ mm}^2 \text{ pads} \]

~ 50 \mu m av. resolution over 15 cm (diffusion negligible)
100 \mu m over 2 meters looks within reach!

M. Dixit et. al, NIM A 581, 254 (2007)
GEM-TPC cosmic tests at DESY done by Victoria Group

Transverse resolution vs. B field

Resolution gets better with B

1.2 mm x 7 mm pads TDR gas
Transverse 2-track resolution measured with a laser

(Victoria group)

Good resolution achieved for tracks separated by > 1.5 x pad width
Preparing the TPC for ILC

• A formal Linear Collider TPC (LC-TPC) collaboration recently formed
• Goal - construct a 1 meter prototype & comprehensive beam tests in a 4 T magnet in a beam with ILC like time structure with realistic electronics by 2010(12)
• Two possible readout options being developed
  • 1) GEM with 1 mm pads
  • 2) Micromegas with ~ 2 mm pads with charge dispersion readout
1 m Large Prototype TPC for tests at DESY (2007-2010)
7 panels GEMs with 1 mm pads & Micromegas with 2 mm wide pads
Up to 10,000 instrumented channels

TPC endplate: 7 modules with Micromegas with charge dispersion readout.
To be built by Canada and France

Large prototype in the 1 T magnet PCMAG. The 6 GeV electron beam will enter through the magnet coil transverse to the drift direction. The magnet has no iron.
GDE Timeline

- **TDP I : 2010**
  - Technical risk reduction
  - Cost risk reduction
  - Global design

- **TDP II : 2012**
  - RD unit test (KEK)
  - Complete necessary technical designs (exceptions)
  - Project plan by consensus

- Detailed engineering will follow before construction
Detector Timeline

- Detector Design Phase I  : 2010
  - Focus on critical R&Ds
  - LOI validation by IDAG
    (March 31 09 LOI deadline)
  - Update physics performance
  - MDI

- Detector Design Phase II  : 2012
  - React to LHC results
  - Confirm physics performance
  - Complete necessary R&Ds
  - Complete technical designs
  - Cost (reliable)
Summary

• The physics case for the ILC is compelling
• Expect to gain momentum after LHC results

At 5 T, an unprecedented flat ~ 50 μm resolution has been demonstrated with 2 x 6 mm² readout pads for drift distances up to 15 cm. The ILC-TPC resolution goal ~100 μm for all tracks up to 2 m drift appears feasible (Carleton & UVIC).

• The innovative Canadian MPGD readout concept of charge dispersion a serious candidate for the ILC TPC readout.

• New calorimetry initiative in Canada (Regina & McGill)

• Canadian responsibilities for large 1 m prototype tests to 2010
  • Construct seven large Micromegas panels with charge dispersion shared with France (Carleton & Montreal)
  • Calibration (Victoria)
  • Electronics development (Carleton & Montreal)