The International Linear Collider: The Physics and its Challenges

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Outline

Introduction: personal

Particle Physics: status & future
- History, Matter & Interactions:
- US program and worldwide program
- Open questions

Future Program and Open Questions

ILC Physics
- The ILC: the machine challenges
- The ILC: the detector challenges
Intro: personal

Hadron collider physics with Dzero experiment (MSU, Fermilab)
Since inception, >20 years

Needed something new before retirement......

“Decided” ILC needs senior involvement

Spent sabbatical 2004-2005 at Fermilab.

Learnt a lot, machine & detectors, a lot of progress on ILC that year

Well into ILC, also changed positions,
By Sept 2005: strengthen & define ILC program at Argonne
(Management & ILC)

Technology decision; GDE formed, started on detector concept study, Snowmass 2005

Time scales a concern in HEP

Young people busy & not good for them

Work on ILC only.
State of HEP/Particle Physics
Immense progress over last 40 years

Theory
Dynamics based on (non)-abelian, local gauge invariance, led to unification of forces: EM and weak, strong

Standard Model, with detailed predictions, but also open questions

Experiments
Fixed target
Beams: e, µ, p, π, ν

Higher energy: colliding beams
ee, pp, ep

Strong, competing & complementary accelerator based experimental programs around world:

CERN, DESY, Fermilab, KEK, SLAC
1. Fixed Target

beams → target → detector

protons, muons, neutrinos, etc

2. Colliding beams

Increasing energy probes smaller and smaller distances

Gargamelle in neutrino beam

Dzero event at Tevatron

Increasing energy probes smaller and smaller distances
All matter made up of fermions (quarks & leptons)

Interactions/forces between them mediated by bosons

Understood at such a level that ALL interactions/cross sections can be well calculated and simulated

Very good predictive power (verified by experiment)

at energies reachable today
Fermions make up all known matter

Electromagnetic =
Strong (QCD) =
Weak = \{ \gamma, g, Z, W \}

Leptons
\[ \nu_e, \nu_\mu, \nu_\tau \]

Quarks
\[ u, c, t, d, s, b \]

= All of “day to day” matter

Nuclear reactors

= neutrino industry; Flavor Oscillations
The Standard Model predicts/requires at least one more field \( \Rightarrow \text{Higgs} \)

Part of symmetry breaking, resulting in SM

So far not observed \( \Rightarrow \) problem

To keep Higgs mass finite, avoid divergences in scattering (WW) need additional symmetries i.e. fields i.e. particles

Possible solutions: Supersymmetry (SUSY), extra dimensions, plus ++

Particles are being searched for \( \Rightarrow \) out of energy range accessible now
(experiment: \( m > \sim 250 \text{ Gev/c} \))

Unexplained:

- Mass hierarchy
- Neutrino oscillations
- Matter-antimatter asymmetry in universe

Missing parts
Problems (2)

Astro physical observations

- Cosmic microwave background, rotation curves of galaxies point to need for **Dark Matter**
- Accelerated expansion of universe point to need for **Dark Energy**
- Additional “missing” fields/particles
Observations from universe (large scale)

Questions about universe:

Where is antimatter?
Most mass in universe not in SM particles

So ONLY 4% of universe consist of particles we know.
A lot left to identify.....
State of knowledge of universe...

The “Iceberg” picture of our understanding of universe.

Next step is to address this at accelerators and find the corresponding particles and understand what dark matter and energy are.

Connect cosmic scale to particle scale
Particle Physics accelerators

Interplay needed:
LEP<> Tevatron
HERA<> Tevatron
HERA<> LHC
Tevatron <> Babar

Run I (1.8TeV) 1990-2000
Run II (2TeV) 2005-2010

LEP
196-200 pb⁻¹
10+10 pb⁻¹
5 pb⁻¹
175 pb⁻¹
161.3 pb⁻¹
172 pb⁻¹
183 pb⁻¹
189 pb⁻¹
175 pb⁻¹

SLC
110 pb⁻¹
10 pb⁻¹

e⁺p
47 pb⁻¹

Tevatron
Run II
2->4->? fb⁻¹

HERA
47 pb⁻¹

RHIC pp

CESR

B factories

ILC
empty
world
now

B factories

BaBar, Belle, HERA-B

LHC (14TeV)

LHCb

few
world

US

H Wijers
The future I; will happen

The first BIG step in understanding Higgs and “Iceberg” will the Large Hadron Collider (LHC) at CERN.

Ready for 1st beam end 2007.

Proton-proton collisions at 14 TeV; expect lots of new physics & discoveries.

LHC is discovery machine

Find new/unexplained phenomena & particles

Will be very difficult( impossible....) to distinguish different physics models/theories

(ILC)
The Large Hadron Collider (LHC), will open window to “remainder” of and physics “beyond” the Standard Model.

Completing the Standard Model and the symmetries underlying it plus their required breaking leads us to expect a plethora of new physics. This is the energy/mass regime from ~0.5 TeV to a few TeV.

LHC will discover them or give clear indications that they exist.

We will need a tool to measure precisely and unambiguously their properties and couplings i.e. identify physics.

This is an e⁺e⁻ machine with a centre of mass energy starting at 0.5 TeV up to several TeV. Starting next decade.
Difference in “energy frontier” experiments (ee)

Two main kind of machines:

1) electron - positron ( e^+e^- annihilation) colliders
2) proton-(anti)proton collider ( Tevatron, future LHC)

**e^+e^- annihilation:**

Total energy of e^+ and e^- available as E_{cms} or \sqrt{s}

Scan over resonances

Maximum achieved for E_{cms} =192 GeV

![Graph showing energy range covered by e^+e^- colliders](image)

Very clean environment; precision physics
ILC: Physics Event Rates

- s-channel processes through spin-1 exchange: $\sigma \sim 1/s$
- Cross sections relatively democratic:
  - $\sigma(e^+e^- \rightarrow ZH) \sim 0.5 \cdot \sigma(e^+e^- \rightarrow ZZ)$
- Cross sections are small; for $L = 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$
  - $e^+e^- \rightarrow qq, WW, tt, HX \sim 0.1$ event/train
  - $e^+e^- \rightarrow e^+e^-\gamma \gamma \rightarrow e^+e^-X \sim 200$ /train
- Beyond the Z, no resonances
- W and Z bosons in all decay modes become main objects to reconstruct
- Need to reconstruct final states
- Forward region critical
- Highly polarized e$^-$ beam: $\sim 80\%$
ILC Physics Characteristics

- Cross sections above Z-resonance are very small
- s-channel processes through spin-1 exchange
- Highly polarized e− beam: ~ 80%

\[
\frac{d\sigma_{\bar{f}f}}{d\cos\theta} = \frac{3}{8} \sigma_{\bar{f}f}^{tot} \left[ (1 - P_e A_e)(1 + \cos^2 \theta) + 2(A_e - P_e)A_f \cos \theta \right]
\]

\[
A_f = \frac{2g_{\bar{f}f}g_{Af}}{g_{\bar{f}f}^2 + g_{Af}^2}
\]  
\[A_b = 0.94 \quad A_c = 0.67 \quad A_l = 0.15\]

- Hermetic detectors with uniform strengths
  - Importance of forward regions
  - b/c tagging and quark identification
  - Measurements of spin, charge, mass, ...

- Analyzing power of
  - Scan in center of mass energy
  - Various unique Asymmetries
    - Forward-backward asymmetry
    - Left-Right Asymmetry
      - Largest effects for b-quarks

Identify all final state objects
What should ILC detector be able to do?

Identify ALL of the constituents that we know & can be produced in ILC collisions & precisely measure their properties.

- \(u, d, s\) jets; no ID
- \(c, b\) jets with ID
- \(t\) final states; jets + W's
- \(\nu's\): missing energy; no ID
- \(e, \mu\): yes
- \(\tau\) through decays
- \(\gamma\) ID & measure
- Gluon jets, no ID
- \(W, Z\) leptonic & hadronic

Use this to measure/identify the NEW physics
Examples of accelerators

Linear accelerator (LINACs)

Circular accelerator (synchrotron)
Enormously challenging with many different components, but …

- Polarized electron and positron source & damping rings
- Main accelerator structure
- Beam Delivery system
- ...

At end of accelerator need detector system to extract the physics from the collisions. Needs to be a precision tool able to live within IP environment.
Baseline Machine:

- $E_{CM}$ of operation 200 – 500 GeV
- Luminosity and reliability for 500 fb$^{-1}$ in 4 years
- Energy scan capability with <10% downtime
- Beam energy precision and stability below 0.1%
- Electron polarization of >80%
- Two interaction regions with detectors
- $E_{CM}$ down to 90 GeV for calibration

Upgrades:

- $E_{CM}$ about 1 TeV
- Capability of running at any $E_{CM} < 1$ TeV
- $\mathcal{L}$ and reliability for 1 ab$^{-1}$ in 3 – 4 years

Options:

- Extend to 1 ab$^{-1}$ at 500 GeV in ~2 years
- $e^+e^-, \gamma\gamma, e^-\gamma$ operation
- $e^+$ polarization ~ 50%
- Giga-Z with $\mathcal{L} = \text{several } 10^{33}$ cm$^{-2}$s$^{-1}$
- WW – threshold scan with $\mathcal{L} = 10^{33}$ cm$^{-2}$s$^{-1}$

As defined in

International Scope Document

See www.fnal.gov/directorate/icfa/LC_parameters.pdf
What is the ILC?

Given accel: ~35MV/m  this implies large footprint
Scope of the ILC 500GeV

Main linacs length ~ 21 km, 16,000 RF cavities (total)
RF power ~ 640 10-MW klystrons and modulators (total)
Cryoplants ~ 11 plants, cooling power 24 kW (@4K) each
Beam delivery length ~ 5 km, ~ 500 magnets (per IR)
Damping ring circumference ~ 6.6 km, ~400 magnets each
Beam power ~ 22 MW total
Site power ~ 200 MW total
Site footprint length ~ 47 km (for future upgrade > 1 TeV)
Bunch profile at IP ~ 500 x 6 nm, 300 microns long

Challenging to say the least
ILC time line

2005       2006       2007       2008       2009       2010

Global Design Effort

Baseline configuration
Reference Design
Technical Design
ILC R&D Program
Expression of Interest to Host
International Mgmt

Pursued by a design team that is global: from all regions of world
Pictures/drawings....

RF cavities

Two tunnel layout
Cost Breakdown by Subsystem

- Civil: 31%
- Structures: 18%
- RF: 12%
- Magnets: 6%
- Systems_eng: 8%
- Installation&test: 7%
- Vacuum: 4%
- Controls: 4%
- Cryo: 4%
- Operations: 4%
- Instrumentation: 2%

SCRF Linac
TESLA SCRF cavity

~1m

9-cell 1.3GHz Niobium Cavity

Reference design: has not been modified in 10 years

Cavities have been produced in industry in EU & tested at DESY.

Challenge: produce in other parts of world in industry & develop critical processing procedures.
Major worldwide goal: make cleaning and resulting gradient consistent.
Niobium sheets are formed into half cavities.

Cleanliness of surfaces is critical during the process.

Form into cavities with electron beam welding (need experience).

Currently many step process.
Gradient

Results from KEK-DESY collaboration

After Standard etch Average
28.9 +/- 1.1 MV/m

After EP Average
35.6 +/- 2.3 MV/m

must reduce spread (need more statistics)

good
**SMTF long term goals**

**Goal for 2006:**... produce 1 full working cryo module

**Cavity and Cryomodule Fabrication Plans**

- **9 cell cavity**: Expect first 4 cavities from industry next year
- **Cryo module with 8 cavities**

**Initial cavities will come from DESY, KEK**

**Goal:** By 2009 have built 6-7 cryomodules; finalized design; ready to built all components in industry.

**Shows the need and long time scale for R&D and industrialization of process**
Cryomodule with only 4 cavities.
A cryomodule with 8 nine cell cavities has not been produced yet.
Site selection: Civil site studies

- Design to “sample sites” from each region
  - Americas - near Fermilab
  - Japan
  - Europe - CERN & DESY

- Americas Site - in Illinois - location may vary from the Fermilab site west to near DeKalb

- Design efforts ongoing at Fermilab and SLAC
ILC in Illinois

A magnitude of difference

The International Linear Collider would be in an underground tunnel more than 18 miles long.

Source: Daily Herald
Why ILC detector R&D?

From a naïve perspective looks like simple problem

Extrapolating from LHC

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch Crossing</td>
<td>25 ns (40 MHz); DC 0.5% duty cycle</td>
<td>337 ns 0.5% duty cycle</td>
</tr>
<tr>
<td>Triggering:</td>
<td>40 MHz → 1 kHz → 100 Hz</td>
<td>No hardware trigger ~ 100 Hz Software</td>
</tr>
<tr>
<td>L1, L2, and L3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation</td>
<td>1-100 MRad/yr</td>
<td>≤ 10 kRad/yr</td>
</tr>
<tr>
<td>Physics Occupancy</td>
<td>23 min. bias; 100 tracks</td>
<td>0.3 $\gamma\gamma \rightarrow$ hadrons; 2 tracks</td>
</tr>
<tr>
<td>Per bunch</td>
<td></td>
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</tbody>
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But there are other factors which require better performance.....
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Use this to measure/identify the NEW physics
Backgrounds

“At the ILC the initial state is well defined, compared to LHC, but....”

Backgrounds from the IP
- Disrupted beams
- Extraction line losses
- Beamstrahlung photons
- e⁺e⁻ - pairs

<table>
<thead>
<tr>
<th>√s (GeV)</th>
<th>Beam</th>
<th># e⁺e⁻ per BX</th>
<th>Total Energy (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>Nominal</td>
<td>98 K</td>
<td>197</td>
</tr>
<tr>
<td>1000</td>
<td>Nominal</td>
<td>174 K</td>
<td>1042</td>
</tr>
</tbody>
</table>

Backgrounds from the machine
- Muon production at collimators
- Synchrotron radiation
- Neutrons from dumps, extraction lines

√s (GeV) ~ 12 m

~ 20 cm

H. Weerts

R&D

UTA, Sept 20, 2006
Benchmark measurement is the measurement of the Higgs recoil mass in the channel $e^+e^- \rightarrow ZH$

- Higgs recoil mass resolution improves until $\Delta p/p^2 \sim 5 \times 10^{-5}$
- Sensitivity to invisible Higgs decays, and purity of recoil-tagged Higgs sample, improve accordingly.

Example:

- $\sqrt{s} = 300$ GeV
- $500$ fb$^{-1}$
- beam energy spread of 0.1%

Goal:

- $\delta M_{ll} < 0.1 \times \Gamma_Z$

Illustrates need for superb momentum resolution in tracker
Jet energy resolution

- Many processes have W and Z bosons in the final state; events need to discriminate.
- Need for precision calorimetry:
  - $e^+e^- \rightarrow WW\nu\nu$, $WZ\nu$ and $ZZ\nu\nu$ events
  - Can be indicative of strong EWSB

Goal for now is: $30%/\sqrt{E_{jet}}$

Both UTA and Argonne groups heavily involved in this R&D

Equivalent to needing 40-200% more luminosity