Physics and Detectors of the International Linear Collider

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Lecture presented at the Second International Accelerator School for Linear Colliders, Erice, Italy October 9, 2007
LHC will open exploration of Terascale physics
  - Deep significance to fundamental physics
  - What is nature of ElectroWeak Symmetry Breaking?
  - Are there new symmetries of space and time?
  - Are there hidden extra dimensions?
  - Dark matter particles might explain astrophysical observations

ILC is needed to explore and elucidate nature of Terascale
  - Deeper look into Terascale questions
  - Precision exploration of new physics

Sophisticated, precise detectors are required to exploit the scientific opportunity of the ILC

ENORMOUS EFFORTS ON MANY ASPECTS
THIS TALK IS NECESSARILY SELECTIVE DUE TO BREADTH OF SUBJECT
ILC Physics
A central focus of particle physics research today is the origin of Electroweak Symmetry Breaking.

- The weak nuclear force and the electromagnetic force have been unified into a single description \( SU(2) \times U(1)_Y \).

- Why is this symmetry hidden?

- The answer to this appears to promise deep understanding of fundamental physics:
  - the origin of mass
  - supersymmetry and possibly the elements of dark matter
  - additional unification (strong force, gravity)
  - and possibly hidden space-time dimensions
Electromagnetism and Radioactivity

- Maxwell unified Electricity and Magnetism with his famous equations (1873)
- Matter spontaneously emits penetrating radiation
  - Becquerel uranium emissions in 1896
  - The Curies find radium emissions by 1898

\[
\begin{align*}
\nabla \times E &= -\frac{\partial B}{\partial t} \\
\nabla \times B &= \mu_0 J + \frac{1}{\varepsilon_0} \frac{\partial E}{\partial t} \\
\nabla \cdot E &= \rho / \varepsilon_0 \\
\nabla \cdot B &= 0
\end{align*}
\]

This new interaction (the weak force) is related to E&M
Advancing understanding of Beta Decay

- Pauli realizes there must be a neutral invisible particle accompanying the beta particle:
  - the neutrino

- Fermi develops a theory of beta decay (1934)
  - $n \rightarrow p + e^- + \bar{\nu}_e$

- 1956 - Neutrino discovered
  - Reines and Cowan
  - Savannah River Reactor, SC
EM and Weak Theory in 1960

Weak Interaction Theory

- Fermi’s 1934 pointlike, four-fermion interaction theory

\[ M = G J_{\text{baryon}}^{\text{weak}} J_{\text{lepton}}^{\text{weak}} = G (\bar{\psi}_p O \psi_n) (\bar{\psi}_e O \psi_\nu) \]

V-A

- Theory **fails at higher energy**, since rate increases with energy, and therefore will violate the “unitarity limit”

\[ W = \frac{2\pi}{\hbar} G^2 |M|^2 \frac{dN}{dE_0} \]

- Speculation on **heavy mediating bosons** but no theoretical guidance on what to expect
Through the pioneering theoretical work of Feynman, Schwinger, Tomonga, and others, a theory of electrons and photons was worked out with precise predictive power. An example is the magnetic dipole of the electron:

\[
\left(\frac{g-2}{2}\right) = \mu = g \left(\frac{e\hbar}{2mc}\right) S
\]

Current values of electron \((g-2)/2\):

- **Theory**: \(0.5 \left(\frac{\alpha}{\pi}\right) - 0.32848 \left(\frac{\alpha}{\pi}\right)^2 + 1.19 \left(\frac{\alpha}{\pi}\right)^3 +..\)
  
  \[= (115965230 \pm 10) \times 10^{-11}\]

- **Experiment**: \(115965218.6 \pm 0.4 \times 10^{-11}\)
A MODEL OF LEPTONS*

Steven Weinberg†

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences.
Weinberg realized that the vector field responsible for the EM force
the photon
and the vector fields responsible for the Weak force
yet undiscovered $W^+$ and $W^-$
could be unified if another vector field,
mediated by a heavy neutral boson ($Z^0$), were to exist
This same notion occurred to Salam
Electroweak Unification

- There remained a phenomenological problem:
  - where were the effects of the $Z^0$

- These do not appear so clearly in Nature
  - they are small effects in the atomic electron energy level

- One has to look for them in high energy experiments
Weinberg-Salam Model predicts there should be some parity violation in polarized electron scattering

- The dominant exchange is the photon (L/R symmetric)
- A small addition of the weak neutral current exchange leads to an expected asymmetry of $\sim 10^{-4}$ between the scattering of left and right-handed electrons

$\sin^2 \theta_W = 0.22 \pm 0.02$
W and Z Masses

- Knowing $\sin^2\theta_W$ allows one to predict the W and Z boson masses in the Weinberg-Salam Model

\[
M_{W^\pm} = \left( \frac{e^2 \sqrt{2}}{8G \sin^2 \theta_W} \right)^{1/2} = \frac{37.4}{\sin \theta_W} \text{ GeV} \sim 80 \text{ GeV/c}^2
\]

\[
M_{Z^0} = \frac{M_{W^\pm}}{\cos \theta_W} = \frac{75}{\sin 2\theta_W} \text{ GeV} \sim 90 \text{ GeV/c}^2
\]

- Motivated by these predictions, experiments at CERN were mounted to find the W and Z
Antiprotons stored at CERN in 1981

$W^- \rightarrow e^- \bar{\nu}_e$

$\bar{p} = \bar{u}\bar{d} \rightarrow uud$

$W^-$

$p = uud$

$p_T$

$\bar{\nu}_e$

$e^-$

Missing $p_T$

UA1 and UA2 discovered the W and the Z bosons
Discovery of the W and Z

- That was over 20 years ago
- Since then:
  - precision studies at Z⁰ Factories
    - LEP and SLC
  - precision W measurements at colliders
    - LEP2 and TeVatron

\[
M_Z = 91187.5 \pm 2.1 \text{ MeV} \quad M_W = 80398 \pm 25 \text{ MeV}/c^2
\]

- These precise measurements (along with other precision measurements) test the Standard Model with keen sensitivity
  - eg. are all observables consistent with the same value of \( \sin^2 \theta_W \)
Electroweak Symmetry Breaking

Confirmation of the completeness of the Standard Model

\[ e^+e^- \rightarrow W^+W^- \] (LEP2)
The Higgs Boson

- Why is the underlying $SU(2) \times U(1)$ symmetry broken?

\[ L = g J_\mu \cdot W_\mu + g' J_\mu^Y B_\mu \]

\[ \text{broken} = -\frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i \gamma^\mu (1 - \gamma^5)(T^+ W^+_\mu + T^- W^-_\mu) \psi_i \]

\[ -e \sum_i q_i \bar{\psi}_i \gamma^\mu \psi_i A_\mu \]

\[ -\frac{g}{2\cos \theta_W} \sum_i \bar{\psi}_i \gamma^\mu (g^V_i - g^A_i \gamma^5) \psi_i Z_\mu . \]

- Theoretical conjecture is the Higgs Mechanism: a non-zero vacuum expectation value of a scalar field, gives mass to W and Z and leaves photon massless.
The Higgs Boson

- This scalar field, like any field, has quanta, the Higgs Boson or Bosons
  - Minimal model - one complex doublet  $\Rightarrow$ 4 fields
    - 3 “eaten” by $W^+$, $W^-$, $Z$ to give mass
    - 1 left as physical Higgs

- This spontaneously broken local gauge theory is renormalizable - t’Hooft (1971)

- The Higgs boson properties
  - Mass  $< \sim 800 \text{ GeV}/c^2$ (unitarity arguments)
    - but hierarchy problem
  - Strength of Higgs coupling increases with mass
    - fermions: $g_{fh} = m_f / v$, $v = 246 \text{ GeV}$
    - gauge boson: $g_{wh} = 2 m_Z^2 / v$
Anticipated Particles

Positron
Neutrino
Pi meson
Quark
Charmed quark
Bottom quark
W boson
Z boson
Top quark
Higgs boson

Dirac theory of the electron
missing energy in beta decay
Yukawa’s theory of strong interaction
patterns of observed particles
absence of flavor changing neutral currents
Kobayashi-Maskawa theory of CP violation
Weinberg-Salam electroweak theory
Mass predicted by precision Z' measurements
Electroweak theory and experiments
The Search for the Higgs Boson

- LEP II (1996-2000)

\[ M_H > 114 \text{ GeV/c}^2 \text{ (95\% conf.)} \]
**Standard Model Fit**

**M_H = 76 ±33 -24 GeV/c^2**

### Measurement vs. Fit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement</th>
<th>Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \alpha_{\text{had}}^{(5)} )</td>
<td>0.02758 ± 0.00035</td>
<td>0.02768</td>
</tr>
<tr>
<td>( m_Z ) [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>91.1875</td>
</tr>
<tr>
<td>( \Gamma_Z ) [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>2.4957</td>
</tr>
<tr>
<td>( \sigma_{\text{had}}^0 ) [nb]</td>
<td>41.540 ± 0.037</td>
<td>41.477</td>
</tr>
<tr>
<td>( R_b )</td>
<td>20.767 ± 0.025</td>
<td>20.744</td>
</tr>
<tr>
<td>( A_{\text{FB}}^0 )</td>
<td>0.01714 ± 0.00095</td>
<td>0.01645</td>
</tr>
<tr>
<td>( A_{\text{FB}} )</td>
<td>0.1465 ± 0.0032</td>
<td>0.1481</td>
</tr>
<tr>
<td>( R_b )</td>
<td>0.21629 ± 0.00066</td>
<td>0.21586</td>
</tr>
<tr>
<td>( \alpha_s )</td>
<td>0.1721 ± 0.0030</td>
<td>0.1722</td>
</tr>
<tr>
<td>( A_{\text{FB}}^0 )</td>
<td>0.0992 ± 0.0016</td>
<td>0.1038</td>
</tr>
<tr>
<td>( A_{\text{FB}}^0 )</td>
<td>0.0707 ± 0.0035</td>
<td>0.0742</td>
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<tr>
<td>( A_{\text{FB}}^0 )</td>
<td>0.923 ± 0.020</td>
<td>0.935</td>
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<tr>
<td>( A_{\text{FB}}^0 )</td>
<td>0.670 ± 0.027</td>
<td>0.668</td>
</tr>
<tr>
<td>( A_{\text{FB}}^0 )</td>
<td>0.1513 ± 0.0021</td>
<td>0.1481</td>
</tr>
<tr>
<td>( \sin^2 \theta_{\text{eff}} )</td>
<td>0.2324 ± 0.0012</td>
<td>0.2314</td>
</tr>
<tr>
<td>( m_W ) [GeV]</td>
<td>80.398 ± 0.025</td>
<td>80.374</td>
</tr>
<tr>
<td>( \Gamma_W ) [GeV]</td>
<td>2.140 ± 0.060</td>
<td>2.091</td>
</tr>
<tr>
<td>( m_t ) [GeV]</td>
<td>170.9 ± 1.8</td>
<td>171.3</td>
</tr>
</tbody>
</table>
(SM) $M_{higgs} < 144 \text{ GeV}$ at 95% CL.
LEP2 direct limit $M_{higgs} > 114.4 \text{ GeV}$.

W mass ($\pm 25 \text{ MeV}$) and top mass ($\pm 2 \text{ GeV}$) consistent with precision measures and indicate low SM Higgs mass

**LEP Higgs search - Maximum Likelihood for Higgs signal at** $m_{H} = 115.6 \text{ GeV}$ with overall significance (4 experiments) $\sim 2\sigma$
The Search for the Higgs Boson

- **Tevatron at Fermilab**
  - Proton/anti-proton collisions at $E_{cm} = 2000$ GeV
  - through 2009 (perhaps 2010)

- **LHC at CERN**
  - Proton/proton collisions at $E_{cm} = 14,000$ GeV
  - First collisions in 2008
Models of Electroweak Symmetry Breaking

**Standard Model Higgs**
- excellent agreement with EW precision measurements
- implies $M_H < 175$ GeV (but theoretically ugly - h’archy prob.- $M_h$ unstable)

**MSSM Higgs**
- expect $M_h < \sim 135$ GeV
- light Higgs boson (h) may be very “SM Higgs-like”
  (de-coupling limit)

**Non-exotic extended Higgs sector**
- eg. 2HDM

**Strong Coupling Models**
- New strong interaction

**The ILC will provide critical data to assess these possibilities**
Complementarity of Electron Colliders
The Large Hadron Collider and the ILC

- LHC at CERN, colliding protons first collisions – next year
- History demonstrates the complementarity of hadron and electron experiments

<table>
<thead>
<tr>
<th>discovery</th>
<th>facility of discovery</th>
<th>facility of detailed study</th>
</tr>
</thead>
<tbody>
<tr>
<td>charm</td>
<td>BNL + SPEAR</td>
<td>SPEAR at SLAC</td>
</tr>
<tr>
<td>tau</td>
<td>SPEAR</td>
<td>SPEAR at SLAC</td>
</tr>
<tr>
<td>bottom</td>
<td>Fermilab</td>
<td>Cornell/DESY ⇒ B Factories</td>
</tr>
<tr>
<td>$Z^0$</td>
<td>SPPS/CERN</td>
<td>LEP and SLC</td>
</tr>
</tbody>
</table>

- Electron experiments have frequently provided most precision
Complementarity with LHC

SUSY mass and coupling measurements
=> Identification of dark matter

Z’ discovered at LHC
Couplings determined at ILC

$m_{Z'} = 2\text{TeV}, E_{cm} = 500 \text{ GeV}, L = 1 \text{ab}^{-1}$
with and w/o beam polarization
S. Godfrey, P. Kalyniak, A. Tomkins
- Higgs Mechanism
- Supersymmetry
- Strong Electroweak Symmetry Breaking
- Precision Measurements at lower energies
Electroweak precision measurements suggest there should be a relatively light Higgs boson:

- When it’s discovered, its nature must be studied.
- The ILC is essential to this program.

Mass Measurement (~50 MeV at 120 GeV)
Total width
Particle couplings
  - Vector bosons
  - Fermions (including top)
Spin-parity-charge conjugation
Self-coupling

The ILC makes precise measurements
Higgs Production Cross-section

ILC program ~ 500 events / fb

\[ \sigma_{e^+e^- \rightarrow \text{Higgs}} = 87 \text{ nb} / (E_{\text{cm}})^2 \sim 350 \text{ fb} \quad @ 500 \text{ GeV} \]
ILC observes Higgs recoiling from a Z, with known CM energy:

• powerful channel for unbiased tagging of Higgs events
• measurement of even invisible decays

\[ \text{Tag } Z \rightarrow l^+ l^- \]
\[ \text{Select } M_{\text{recoil}} = M_{\text{Higgs}} \]

\( (\downarrow \text{ - some beamstrahlung}) \)

Invisible decays are included

500 fb\(^{-1}\) @ 500 GeV, TESLA TDR, Fig 2.1.4
Higgs Couplings
the Branching Ratios

\[ g_{fh} = \frac{m_f}{v} \quad v = 246 \text{ GeV} \]

Measurement of BR’s is powerful indicator of new physics
e.g. in MSSM, these differ from the SM in a characteristic way.
Higgs BR must agree with MSSM parameters from many other measurements.
Is This the Standard Model Higgs?

**b vs. W**

TESLA TDR, Fig 2.2.6

Arrows at:

- $M_A = 200-400$
- $M_A = 400-600$
- $M_A = 600-800$
- $M_A = 800-1000$

HFITTER output

**Conclusion:**

For $M_A < 600$, likely to distinguish $b$ vs $W$
Is This the Standard Model Higgs? 
Precision tells us!

**Coupling Precision**

- **LHC** 300 fb$^{-1} \times 2$

**Model assumption**

$\frac{g_1^h}{g_2^h} < 1 + 5\%$

**SUSY or 2HDM**

- **ILC**
Higgs Self Coupling

\[ \Phi(H) = \lambda v^2 H^2 + \lambda v H^3 + 1/4 \lambda H^4 \]

SM: \( g_{HHH} = 6 \lambda v \), fixed by \( M_H \)

\( \Delta \lambda/\lambda \sim 10\text{-}20\% \) for 1 ab\(^{-1}\)

SM Double Higgs-strahlung: \( e^+ e^- \rightarrow ZHH \)

\( \sigma \) [fb]
Higgs Spin Parity and Charge Conjugation ($J^{PC}$)

$H \rightarrow \gamma\gamma$ or $\gamma\gamma \rightarrow H$

rules out $J=1$ and indicates $C=+1$

Production angle ($\theta$) and $Z$ decay angle in Higgs-strahlung reveals $J^P (e^+ e^- \rightarrow Z H \rightarrow ffH)$

LC Physics Resource Book, Fig 3.23(a)

TESLA TDR, Fig 2.2.8
New Physics Beyond the Higgs

- Motivated by Hierarchy Problem
  - Gigantic Mismatched between electroweak scale (100 GeV) and the Planck Scale ($10^{19}$ GeV)

- Supersymmetry
  - new space-time symmetry with new particles

- New Strong Interactions

- Hidden Dimensions
Supersymmetry

- **Supersymmetry**
  - particles matched by super-partners
    - super-partners of fermions are bosons
    - super-partners of bosons are fermions
  - inspired by string theory
  - cancellation of divergences
    - Solves “hierarchy problem”
  - dark matter?
  - many new particles
    - ILC could detail properties

\[
\delta m_{\tilde{\nu}_R} < 0.1 \text{GeV}
\]
Why Supersymmetry #1

It solves the hierarchy problem

\[ H^0 = - H^0 \]

The Higgs mass naturally diverges in Standard Model.

SUSY cancels diverges exactly for unbroken SUSY.

Weak breaking (that is \( \sim 1 \) TeV) solves this problem.
Why Supersymmetry #2

Gauge coupling constants unify

This is achieved for $\sin^2 \theta^\text{SUSY}_W = 0.2335(17)$

Experiment: $\sin^2 \theta^\text{exp}_W = 0.2314(2)$
Why Supersymmetry #3, #4, #5

#3: Provides cold dark matter candidate
If lightest SUSY particle is stable, it is an excellent dark matter candidate.

#4: Link to gravity
SUSY offers the theoretical link to incorporate gravity. Most string models are supersymmetric.

#5: Predicts light Higgs boson
SUSY predicts a light (< 135 GeV) Higgs boson as favored by EW precision data.
Supersymmetry

Mass spectrum is model dependent

Squarks are well measured at LHC

Sleptons/Neutralinos may benefit from precise spectroscopy at the Linear Collider
Sparticle Mass Models

Next to lightest
Visible Sparticle
vs.
Lightest
Visible Sparticle

Ellis, Olive, Santoso, & Spanos
LSP Usually Light

\[ e^+ e^- \rightarrow \chi_1 \chi_2 \]

Lightest visible sparticle (GeV) →

Lightest invisible sparticle (GeV) →

Kalinowski
Is Dark Matter SUSY?

Precise measurement of couplings by the ILC critical to this understanding
Extra Dimensions

- Extra Dimensions
  - string theory inspired
  - solves hierarchy problem ($M_{\text{planck}} \gg M_{\text{EW}}$)
    - if extra dimensions are large
  - large extra dimensions observable at ILC
Cosmic connections

- Early universe
- GUT motivated inflation
- Dark matter
- Accelerating universe
- Dark energy
- What happened to the anti-matter?
History of the Universe

extrapolation via precision measurement

LHC, ILC
RHIC, HERA
Detector Requirements are defined by
ILC machine parameters
physics goals

ILC creates new challenges and opportunities,
different in many respects from the challenges and
opportunities of the LHC detectors

Physics motivates
Triggerless event collection (software event selection)
Extremely precise vertexing
Synergistic design of detectors components:
vertex detector, tracker, calorimeters integrated for optimal jet
reconstruction
Advanced technologies based on recent detector innovations

Detector R&D to optimize ILC opportunity is critically needed
ILC Experimental Advantages

Elementary interactions at known $E_{cm}^*$
  eg. $e^+e^- \rightarrow ZH \quad *$ beamstrahlung manageable

Democratic Cross sections
  eg. $\sigma (e^+e^- \rightarrow ZH) \sim 1/2 \sigma (e^+e^- \rightarrow d\bar{d})$

Inclusive Trigger
  total cross-section

Highly Polarized Electron Beam
  $\sim 80\%$ (positron polarization? – R&D)

Exquisite vertex detection
  eg. $R_{\text{beampipe}} \sim 1 \text{ cm}$ and $\sigma_{\text{hit}} \sim 3 \mu\text{m}$

Calorimetry with Particle Flow Precision
  $\sigma_E/E_{\text{jet}} \sim 3\%$ for $E_{\text{jet}} > 100 \text{ GeV}$

Advantage over hadron collider on precision meas.
  eg. $H \rightarrow c\bar{c}$

Detector performance translates directly into effective luminosity
Power of Constrained Initial State + Simple Reactions

- Well defined initial state
- Democratic interactions

Higgs recoiling from a Z, with known CM energy, provides a powerful channel for unbiased tagging of Higgs events, allowing measurement of even invisible decays (\(\Downarrow\) - some beamstrahlung)

Demands Precise Tracking

500 fb\(^{-1}\) @ 500 GeV, TESLA TDR, Fig 2.1.4
Effect of Tracking Resolution

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

\[ \sqrt{s} = 350 \text{ GeV} \]
\[ L = 500 \text{ fb}^{-1} \]

\[ \frac{\delta p_t}{p_t^2} = a \oplus \frac{b}{p_t \sin \theta} \]

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

\[ a = 1.0 \times 10^{-5} \]
\[ b = 1.0 \times 10^{-3} \]
\[ \Delta M_h = 85 \text{ MeV} \]

\[ a = 4.0 \times 10^{-5} \]
\[ b = 1.0 \times 10^{-3} \]
\[ \Delta M_h = 153 \text{ MeV} \]

\[ a = 8.0 \times 10^{-5} \]
\[ b = 1.0 \times 10^{-3} \]
\[ \Delta M_h = 273 \text{ MeV} \]
The Electroweak Precision Measurements
Anticipate a Light Higgs – Then What?

- Measurement of BR’s is powerful indicator of new physics
e.g. in MSSM, these differ from the SM in a characteristic way.
- Higgs BR must agree with MSSM parameters from many other measurements.
Detector R&D Required

- Performance requirements for ILC Detector exceed state-of-the-art
  - Calorimeters with ~100 million cells being developed for PFA
    - Jet resolution goal ~ 3-4% for E_{jet} > 100 GeV
  - Pixel Vertex Detector with \sim 10^9 \leq 20 \mu m pixels
    - Impact parameter resolution 5 \mu m \oplus 10 \mu m/(p \sin^{3/2} \theta)
    - Sensitivity to full 1 msec bunchtrain
  - Tracking resolution \sigma(1/p) \leq 5 \times 10^{-5} /GeV
    - TPC with silicon
    - Silicon microstrips
  - High Field Solenoid up to 5 Tesla
  - High quality forward tracking systems
  - Triggerless readout

- R&D Essential

  DISCOVERY OPPORTUNITY IS GREAT
  - limited by detector performance
  - small cross sections/significant backgrounds
  - advances different from LHC required
### Collider Parameters

<table>
<thead>
<tr>
<th>Machine parameter</th>
<th>Value (approx.)</th>
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<tr>
<td>#bunches/train</td>
<td>2820</td>
</tr>
<tr>
<td>#trains/sec</td>
<td>5</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>308 nsec</td>
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<tr>
<td>bunches/sec</td>
<td>14100</td>
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<tr>
<td>length of train</td>
<td>868 µsec</td>
</tr>
<tr>
<td>train spacing</td>
<td>199 msec</td>
</tr>
<tr>
<td>crossing angle</td>
<td>14 mrad</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
</tbody>
</table>

**Graphical Representation:**
- **20 mrad** incoming beam
- **14 mrad** disrupted beam
- **push-pull** configuration
- **868 µs** and **199 ms** time intervals
Background Sources

IP Backgrounds
- Beam-beam Interactions
  - Disrupted primary beam
    - Extraction line losses
  - Beamstrahlung photons
  - $e^+e^-$ pairs
- Radiative Bhabhas
- $\gamma \gamma \rightarrow \text{hadrons/} \mu^+\mu^-$

Machine backgrounds
- Muon production at collimators
- Collimator edge scattering
- Beam-gas
- Synchrotron radiations
- Neutrons from dumps/extr. line

Somewhat manageable -
- Scale with luminosity
- Transport them away from IP
- Shield sensitive detectors
- Exploit detector timing
- Reliable simulations.

Harder to handle -
- Don’t make them
- Keep them from IP if you do
- Dominated by beam halo
- Dependent on assumptions
VXD background hits

- Pair background hit rate on the 1st layer of the Vertex Detector (R=24mm)
- Simulation using CAIN and JUPITER
- Hit rate of the Low Q option is ~1/3 of the nominal option, as expected

<table>
<thead>
<tr>
<th>B (tesla)</th>
<th>Nominal</th>
<th>Low Q</th>
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<tbody>
<tr>
<td>3</td>
<td>0.488</td>
<td>0.149</td>
</tr>
<tr>
<td>4</td>
<td>0.48</td>
<td>0.113</td>
</tr>
<tr>
<td>5</td>
<td>0.183</td>
<td>0.069</td>
</tr>
</tbody>
</table>

GLD study
Event Rates and Backgrounds

- **Event rates (Luminosity = 2 x 10^{34})**
  - \( e^+e^- \rightarrow qq, WW, tt, HX \)
    - ~ 0.1 event / train
  - \( e^+e^- \rightarrow e^+e^- \gamma\gamma \rightarrow e^+e^- X \)
    - ~ 200 /train

- **Background**
  - 6 x 10^{10} \gamma / BX (from synchrotron radiation, scatters into central detector)
  - 40,000-250,000 \( e^+e^- / BX \) (90-1000 TeV) @ 500 GeV
  - Muons: < 1 Hz/cm^2 (w/ beamline spoilers)
  - Neutrons: \sim 3 \times 10^8 /cm^2/ yr @ 500 GeV

Ref: Maruyama, Snowmass 2005
The Concepts

Teams working on LDC and GLD are in the process of merging → ILD
ILC Detector Requirements

- **Two-jet mass resolution** comparable to the natural widths of W and Z for an unambiguous identification of the final states.
- Excellent **flavor-tagging** efficiency and purity (for both b- and c-quarks, and hopefully also for s-quarks).
- Momentum resolution capable of reconstructing the **recoil mass** to di-muons in Higgs-strahlung with resolution better than beam-energy spread.
- Hermeticity (both crack-less and coverage to very forward angles) to precisely determine the **missing momentum**.
- **Timing** resolution capable of separating bunch-crossings to suppress overlapping of events.
## The Concepts

<table>
<thead>
<tr>
<th>ILD</th>
<th>Tracking</th>
<th>ECal Inner Radius</th>
<th>Solenoid</th>
<th>EM Cal</th>
<th>Hadron Cal</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiD</td>
<td>silicon</td>
<td>1.27 m</td>
<td>5 Tesla</td>
<td>Si/W</td>
<td>Digital (RPC..)</td>
<td>Had cal inside coil</td>
</tr>
<tr>
<td>LCD</td>
<td>TPC gaseous</td>
<td>1.58 m</td>
<td>4 Tesla</td>
<td>Si/W</td>
<td>Digital or Analog</td>
<td>Had cal inside coil</td>
</tr>
<tr>
<td>GLD</td>
<td>TPC gaseous</td>
<td>2.1 m</td>
<td>3 Tesla</td>
<td>W/ Scin.</td>
<td>Pb/ Scin.</td>
<td>Had cal inside coil</td>
</tr>
<tr>
<td>4th</td>
<td>TPC gaseous</td>
<td>1.5 m</td>
<td>3.5 Tesla</td>
<td>crystal</td>
<td>Dual readout fiber</td>
<td>Double Solenoid (open mu)</td>
</tr>
</tbody>
</table>
Simple events (relative to Hadron collider) make particle level reconstruction feasible

Heavy boson mass resolution requirement sets jet energy resolution goal

\[ e^+ e^- \rightarrow WW\nu\bar{\nu}, \quad e^+ e^- \rightarrow ZZ\nu\bar{\nu} \]

This event shows single bunch crossing in tracker, 150 bunches in the vertex detector
CALORIMETRY IS THE STARTING POINT IN THE SiD DESIGN

- **assumptions**
  - Particle Flow Calorimetry will result in the best possible performance
  - Silicon/tungsten is the best approach for the EM calorimeter
  - Silicon tracking delivers excellent resolution in smaller volume
  - Large B field (5 Tesla) desirable to contain electron-positron pairs in beamline
  - Cost is constrained
Current paradigm: Particle Flow

- Jet resolution goal is $30\% / \sqrt{E}$
- In jet measurements, use the excellent resolution of tracker, which measures bulk of the energy in a jet

<table>
<thead>
<tr>
<th>Particles in Jet</th>
<th>Fraction of Visible Energy</th>
<th>Detector</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged</td>
<td>~65%</td>
<td>Tracker</td>
<td>&lt;$0.005% p_T$ negligible</td>
</tr>
<tr>
<td>Photons</td>
<td>~25%</td>
<td>ECAL</td>
<td>~15% / $\sqrt{E}$</td>
</tr>
<tr>
<td>Neutral Hadrons</td>
<td>~10%</td>
<td>ECAL + HCAL</td>
<td>~60% / $\sqrt{E}$</td>
</tr>
</tbody>
</table>

Headroom for confusion

$< 20\% / \sqrt{E}$
EM Calorimetry

- Physics with isolated electron and gamma energy measurements require ~10-15% / $\sqrt{E} \pm 1\%$
- Particle Flow Calorimetry requires fine grained EM calorimeter to separate neutral EM clusters from charged tracks entering the calorimeter
  - Small Moliere radius
    - Tungsten
  - Small sampling gaps – so not to spoil $R_M$
  - Separation of charged tracks from jet core helps
    - Maximize $BR^2$

- One technology choice – Si/W calorimeter
  - Good success using Si/W for Luminosity monitors at SLD, DELPHI, OPAL, ALEPH
  - Oregon/SLAC/BNL/Davis/Annecy
  - CALICE Si/W
- Another choice - Scintillator sampling

<table>
<thead>
<tr>
<th>material</th>
<th>$R_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>18.4 mm</td>
</tr>
<tr>
<td>Lead</td>
<td>16.5 mm</td>
</tr>
<tr>
<td>Tungsten</td>
<td>9.5 mm</td>
</tr>
<tr>
<td>Uranium</td>
<td>10.2 mm</td>
</tr>
</tbody>
</table>
Silicon/Tungsten EM Calorimeter

Transverse Segmentation \( \sim 3.5 \text{ mm} \)
30 Longitudinal Samples
Energy Resolution \( \sim 15\% / E^{1/2} \)

SLAC/Oregon/BNL/Davis/Annecy

Si/W also being developed by CALICE Collaboration
Silicon/Tungsten EM Calorimetry for ILC

SLAC/Oregon/BNL/Davis/Annecy
Dense, fine grained silicon tungsten calorimeter (builds on SLC/LEP experience)
- Pads: 12 mm$^2$ to match Moliere radius ($\sim R_m/4$)
- Each six inch wafer read out by one chip
- < 1% crosstalk

Electronics design
- Noise < 2000 electrons
- Single MIP tagging (S/N $\sim$ 7)
- Dynamically switchable feedback capacitor scheme achieves required dynamic range: 0.1-2500 MIPs – 4 deep storage/bunch train

Passive cooling – conduction in W to edge
Scintillator/Tungsten ECAL

- Cheaper and larger granularity (3x3 - 5x5cm²)
- Scintillator strips may be cost-effective way for granularity
  - (1cm x Ycm)
- Read out by fibre + PMT or SiPM/MPPC

Colorado
- staggered cells
  - 5 cm x 5 cm

SiPMs
(invented in Russia)

Particle Beam

Absorber

Z-Layer

Absorber

X-Layer

Absorber

Tile-Layer

Japan/Korea/Russia

SiPM

SiPM

SiPM

Resistor

R_n≈400 kΩ

Depletion Region

2 μm

substrate

42μm

2μm

pixels

Al

hv

U_{bias} ~50V
Hadron Calorimeter

Again Highly Segmented – for Particle Flow

- Longitudinal: ~40 samples
- 4 – 5 \lambda (limited by cost - coil radius)
- Would like fine (1 cm^2?) lateral segmentation
- For 10000 m^2 of 1 cm^2 HCAL = 10^8 channels – cost!

**Two Main Options:**

★ Tile HCAL (Analogue readout)
  Steel/Scintillator sandwich
  Lower lateral segmentation
  ~ 3x3 cm^2 (motivated by cost)

★ Digital HCAL
  High lateral segmentation
  ~ 1x1 cm^2
digital readout (granularity)
RPCs, wire chambers, GEMS...

\[ \text{OPEN QUESTION} \]

The Digital HCAL Paradigm

- Sampling Calorimeter:
  Only sample small fraction of the total energy deposition

- Energy depositions in active region follow highly asymmetric Landau distribution
## Hadron Calorimetry (~4\(\lambda\))

### Options for Digital HCal: SS or Tungsten / 3 readout technologies

<table>
<thead>
<tr>
<th></th>
<th>Scintillator</th>
<th>GEMs</th>
<th>RPCs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology</strong></td>
<td>Proven (SiPM?)</td>
<td>Relatively new</td>
<td>Relatively old</td>
</tr>
<tr>
<td><strong>Electronic readout</strong></td>
<td>Analog (multi-bit) or</td>
<td>Digital (single-bit)</td>
<td>Digital (single-bit)</td>
</tr>
<tr>
<td></td>
<td>Semi-digital (few-bit)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Thickness (total)</strong></td>
<td>~ 8mm</td>
<td>~8 mm</td>
<td>~ 8 mm</td>
</tr>
<tr>
<td><strong>Segmentation</strong></td>
<td>3 x 3 cm(^2)</td>
<td>1 x 1 cm(^2)</td>
<td>1 x 1 cm(^2)</td>
</tr>
<tr>
<td><strong>Pad multiplicity for MIPs</strong></td>
<td>Small cross talk</td>
<td>Measured at 1.27</td>
<td>Measured at 1.6</td>
</tr>
<tr>
<td><strong>Sensitivity to neutrons (low energy)</strong></td>
<td>Yes</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td><strong>Recharging time</strong></td>
<td>Fast</td>
<td>Fast?</td>
<td>Slow (20 ms/cm(^2))</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>Proven</td>
<td>Sensitive</td>
<td>Proven (glass)</td>
</tr>
<tr>
<td><strong>Calibration</strong></td>
<td>Challenge</td>
<td>Depends on efficiency</td>
<td>Not a concern (high efficiency)</td>
</tr>
<tr>
<td><strong>Assembly</strong></td>
<td>Labor intensive</td>
<td>Relatively straight forward</td>
<td>Simple</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Not cheap (SiPM?)</td>
<td>Expensive foils</td>
<td>Cheap</td>
</tr>
</tbody>
</table>

---

J. Repond
Calorimeter Reconstruction

- High granularity calorimeters – very different to previous detectors (except LEP lumi. calorimeters)
- “Tracking calorimeter” – requires a new approach to ECAL/HCAL reconstruction

ILC calorimetric performance = HARDWARE + SOFTWARE

Performance will depend on the software algorithm

Nightmare from point of view of detector optimisation

a priori not clear what aspects of hadronic showers are important (i.e. need to be well simulated)

M. Thomson
LDC00Sc

\[ Z \rightarrow uds \ (|\cos \theta| < 0.7) \]

**100 GeV jets**

- 100 GeV Jets, B = 4T
- 100 GeV Jets, B = 3T
- 100 GeV Jets, B = 5T

\[ \alpha = 0.315 \left( \frac{B}{4} \right)^{-0.19} \left( \frac{R}{1.68} \right)^{-0.49} \left( 1 + 6.3e^{-\frac{N}{8.0}} \right) \]

**180 GeV jets**

- 180 GeV Jets, B = 4T
- 180 GeV Jets, B = 3T
- 180 GeV Jets, B = 5T

\[ \alpha = 0.42 \left( \frac{B}{4} \right)^{-0.31} \left( \frac{R}{1.78} \right)^{-0.61} \left( 1 + 21.6e^{-\frac{N}{7.1}} \right) \]

**LDC Jet energy performance found to depend mainly on:**
- HCAL thickness
- TPC Radius
- B-field

**Empirical Parametrizations**

M. Thomson
Tracking for any modern experiment should be conceived as an integrated system, combined optimization of:

- the inner tracking (vertex detection)
- the central tracking
- the forward tracking
- the integration of the high granularity EM Calorimeter

Pixelated vertex detectors are capable of track reconstruction on their own, as was demonstrated by the 307 Mpixel CCD vertex detector of SLD, and is being planned for the ILC.

Track reconstruction in the vertex detector impacts the role of the central and forward tracking system.
Inner Tracking/Vertex Detection for the ILC

Detector Requirements
- Excellent spacepoint precision (\(< 4 \text{ microns}\))
- Superb impact parameter resolution (\(5\mu m \oplus 10\mu m/(p \sin^{3/2}\theta)\))
- Transparency (\(\sim 0.1\% \ X_0 \ \text{per layer}\))
- Track reconstruction (find tracks in VXD alone)
- Sensitive to acceptable number of bunch crossings (\(<150 = 45 \ \mu\text{sec}\))
- EMI immunity
- Power Constraint (\(< 100 \ \text{Watts}\))

Concepts under Development for International Linear Collider
- Charge-Coupled Devices (CCDs)
  - demonstrated in large system (307Mpx) at SLD, but slow \(\Rightarrow\) Column Parallel CCDs, FPCCD
- Monolithic Active Pixels – CMOS
  - MAPs, FAPs, Chronopixels, 3D-Fermilab
- DEpleted P-channel Field Effect Transistor (DEPFET)
- Silicon on Insulator (Sol)
- Image Sensor with In-Situ Storage (ISIS)
- HAPS (Hybrid Pixel Sensors)
SiD Vertex Layout

5 barrel layers
4 end disks

Design drivers:
Smallest radius possible
Clear pair background

Role:
Seed tracks & vertexing
Improve forward region

Z = 6.25 cm

SLD Vertex Detector designed to read out
800 kpixels/channel at 10 MHz, operated at
5 MHz => readout time = 200 msec/ch
ILC requires faster readout for 300 nsec bunch spacing
<< 1 msec
Possible Solution: Column Parallel Readout
LCFI (Bristol,Glasgow,Lancaster,Liverpool,Nijmegen,Oxford,RAL)

**CPC1 produced by E2V**
- Two phase operation
- Metal strapping for clock
- 2 different gate shapes
- 3 different types of output
- 2 different implant levels

➢ *Clock with highest frequency at lowest voltage*

(Whereas SLD used one readout channel for each 400 columns)
Image Sensor with In-situ Storage (ISIS)

- EMI concern (SLC experience) motivates delayed operation during beam
- Robust storage of charge in buried channel during beam passage
  - Pioneered by W F Kosonocky et al IEEE SSCC 1996, Digest of Technical Papers, 182
  - T Goji Etoh et al, IEEE ED 50 (2003) 144; runs up to 1 Mfps.
- ISIS Sensor details:
  - CCD-like charge storage cells in CMOS or CCD technology
  - Processed on sensitive epi layer
  - p+ shielding implant forms reflective barrier (deep implant)
  - Overlapping poly gates not likely to be available, may not be needed
  - Test device built by e2v for LCFI Collaboration

Diagram of Image Sensor with In-situ Storage (ISIS)
FPCCD (KEK)

- Fine-pixel CCD
  - (5µm)^2 pixel
  - Fully-depleted to suppress diffusion
  - Immune to EMI
  - CCD is an established technology
  - Baseline for GLD

- Fully-depleted CCD exists (Hamamatsu: astrophys.)
- Background hits can be further reduced by hit pattern (~1/20)
- No known problems now
- Prototyping
Monolithic CMOS for Pixel Detector

Concept

- Standard VLSI chip, with thin, un-doped silicon sensitive layer, operated undepleted

Advantages

- Decoupled charge sensing and signal transfer (improved radiation tolerance, random access, etc.)
- Small pitch (high tracking precision)
- Thin, fast readout, moderate price

R&D

- Strasbourg IReS has been working on development of monolithic active pixels since 1989; others (RAL, Yale/Or., etc.)
- IReS prototype arrays of few thousands pixels demonstrated viability.
- Large prototypes now fabricated/tested.
- Attention on readout strategies adapted to specific experimental conditions, and transfer to AMS 0.35 OPTO from TSMC 0.25
  - \( \sim < 12 \text{ um epi vs. } < 7 \text{ um} \)
- Application to STAR

Parallel R&D:

- FAPS (RAL): 10-20 storage caps/pixel
**Chronopixel (CMOS)**

**Yale/Oregon/Sarnoff**

- **Completed Macropixel design last year**
  - Key feature – stored hit times (4 deep)
  - 645 transistors
  - Spice simulation verified design
  - TSMC 0.18 μm ⇒ ~50 μm pixel
    - Epi-layer only 7 μm
    - Talking to JAZZ (15 μm epi-layer)
  - 90 nm ⇒ 20-25 μm pixel

- **January, 2007**
  - Completed design - Chronopixel
  - Deliverable – tape for foundry

- **Near Future (dependent on funding)**
  - Fab 50 μm Chronopixel array
    - Demonstrate performance
  - Then, 10-15 μm pixel
3D/SOI

- Designs based on newly available technologies, separate circuit, detector layers
  - SOI - thin circuit layer on oxide on fully depleted substrate (OKI, ASI(Cypress))
    - 12 bit 26 micron x-ray counting chip OKI/KEK (due soon)
    - ILC pixel readout chip (designed)
  - 3D - multi-layered circuit assembly based on thinned, bonded silicon
    - Full time stamp/double correlated sample in 20 micron pixel, low power
    - Due back in August
  - Thinned sensors - MIT-LL
    - 50, 100 microns thick, 4-side abuttalbe
  - S/N ~100:1 in SOI/3D
  - Demonstrated laser annealing of backside
  - Demonstrated FPIX chip thinning to 15 microns
Inner Tracking/Vertex Detection (DEPFET)

Concept
- Field effect transistor on top of fully depleted bulk
- All charge generated in fully depleted bulk; assembles underneath the transistor channel; steers the transistor current
- Clearing by positive pulse on clear electrode
- Combined function of sensor and amplifier

Properties
- Low capacitance ➤ low noise
- Signal charge remains undisturbed by readout ➤ repeated readout
- Complete clearing of signal charge ➤ no reset noise
- Full sensitivity over whole bulk ➤ large signal for m.i.p.; X-ray sens.
- Thin radiation entrance window on backside ➤ X-ray sensitivity
- Charge collection also in turned off mode ➤ low power consumption
- Measurement at place of generation ➤ no charge transfer (loss)
- Operation over very large temperature range ➤ no cooling needed

MPI Munich, MPI Halle, U. Bonn, U. Mannheim
Central Tracking

- Two general approaches being developed for the ILC
  - **TPC** (GLD, LDC, 4th)
    - Builds on successful experience of PEP-4, ALEPH, ALICE, DELPHI, STAR, ...
    - Large number of space points, making reconstruction straightforward
    - \( \frac{dE}{dx} \Rightarrow \) particle ID, bonus
    - Minimal material, valuable for calorimetry
    - Tracking up to large radii

- **Silicon** (SiD)
  - Superb spacepoint precision allows tracking measurement goals to be achieved in a compact tracking volume
  - Robust to spurious, intermittent backgrounds
    - ILC is not a storage ring
Central Tracking with TPC

**Issues for an ILC TPC**

- Optimize novel gas amplification systems
  - Conventional TPC readout based on MWPC and pads
    - limited by positive ion feedback and MWPC response
  - Improvement by replacing MWPC readout with micropattern gas chambers (eg. GEMs, Micromegas, Medipix)
    - Small structures (no E×B effects)
    - 2-D structures
    - Only fast electron signal
    - Intrinsic ion feedback suppression
- Neutron and gamma backgrounds (~130 bunch crossings)
- Optimize single point and double track resolution
- Performance in high magnetic fields
- Demonstrate large system performance with control of systematics
- Minimize impact of endplate
Central Tracking with Silicon

Expecting the machine backgrounds (esp. beam loss occurrences) of the ILC to be erratic (based on SLC experience), robustness of silicon is very attractive.

single bunch timing

The SiD barrel tracking is baselined as 5 layers of pixellated vertex detector and 5 layers of Si strip detectors (in ~10 cm segments) going out to 1.25 meters

With superb position resolution, compact tracker which achieves the linear collider tracking resolution goals is possible

Compact tracker makes the calorimeter smaller and therefore cheaper, permitting more aggressive technical choices (assuming cost constraint)

Silicon tracking layer thickness determines low momentum performance
• Closed CF/Rohacell cylinders
• Nested support via annular rings
• Power/readout motherboard mounted on support rings

• Cylinders tiled with 10x10cm sensors with readout chip
• Single sided ($\phi$) in barrel
• $R, \phi$ in disks
• Modules mainly silicon with minimal support (0.8% $X_0$)

Overlap in $\phi$ and $z$
Material Budget of Silicon Tracker

~ 0.8 %/layer at normal incidence
Robust Pattern Recognition with Silicon

- $t\bar{t}$ event in VXD

  w/ backgrounds from 150 bunch crossings
  - BUT 1 billion pixels!

  clean detection with time stamping
Excellent momentum resolution with Silicon

WITH 2\mu M BEAM CONSTRAINT

- SDAUG05: 5T, R=125cm
- SD PETITE: 5T, R=100cm
- LOW FIELD: 4T, R=125cm

\[ \frac{\delta p_t}{p_t} \]

At 90°

\[ \text{At 90°} \]

\[ \text{0.5\%} \]
DID (Detector-Integrated Dipole)

- **Xing angle (w/o correction)**
  - beam sees $B_{\text{transverse}}$ of solenoid → spiral

- Still head-on (mod xing angle) ?
  - Yes for e+e-.
  - No for e-e-.

Problems still for e+e-:
  - SR emittance growth (significant in some cases)
  - Polarization vector rotation (minor problem?)
DID and anti-DID

Align B with **incoming** e+/e- beams (on av.) - **DID**

- Solves SR emittance growth
- $\times 2Bt$ for outgoing beams
  - $\rightarrow$ worse pair background

Align B with **outgoing** e+/e- beams (on av.) - **anti DID**

- Pair background $\sim 0$ mrad xing angle
- $\times 2Bt$ for incoming beams
  - $\rightarrow$ worse for SR emittance growth
  - $\sim$OK for 14 mrad

**DID or antiDID, not both simultaneously**
Single IR with Push-Pull Detectors

- Large cost saving compared with 2 IR
  - ~200 M$ compared with 2 IR with crossing angles 14/14 mrad
- Push-pull detectors
  - Task force of WWS and GDE studied issues
  - Initial conclusion:
    - No show-stopper
    - But need careful design and R&D
      - For example, need quick switch-over
    - 2 IR should be kept as an ‘Alternative’
Concept of IR hall with two detectors

The concept is evolving and details being worked out.

Platform for electronic and services (~10*8*8m). Shielded (~0.5m of concrete) from five sides. Moves with detector. Also provide vibration isolation.

A. Seryi, Feb 4, 2007, Beijing
Energy Measurement

■ Goal:
  ● 100ppm (10^{-4}) absolute energy measurement

■ Baseline:
  ● 1 upstream + 1 downstream spectrometers / beam
  ● Upstream spectrometer
    ◆ 4-magnet chicane + RF BPMs
    ◆ 1mm offset + σ=100nm:10^{-4}
  ● Downstream spectrometer
    ◆ 3-magnet chicane w/wigglers
      + SR photon detectors
Polarization Measurement

- **Goal**:
  - 0.25% accuracy (particularly on Z)

- **Baseline**:
  - 1 upstream + 1 downstream polarimeters / beam
  - Compton polarimeter
    - Shoot circularly-polarized photon at the electron beam at a focus.
    - Measure the Compton-scattered electron.
    - Polarization vector at IP = that at the polarimeter
      → beam direction at IP parallel to that at the polarimeter
    - 4-magnet chicane
Luminosity Measurement

- Accuracy goal: $10^{-3}$ or better absolute
- Detector: LUMCAL (LUMMON/FCAL)
  - ~30-90 mrad
  - ~10 Bhabhas / bunch train
  - Default: Si-W calorimeter
- R&D required
  - The precision achievable for different xing angles?
    Careful systematics studies.
  - $10^{-4}$ desirable for Giga-Z, larger polar angles?
  - Backgrounds from pairs etc.?

- ‘Physics’ events (central detector):
  - Acollinear Bhabha $\rightarrow$ Luminosity spectrum, etc.
Organization

- **World Wide Study (WWS)** - [http://physics.uoregon.edu/~lc/wwstudy](http://physics.uoregon.edu/~lc/wwstudy)
  - Formed in 1998 (Vancouver ICHEP)
  - 18 member organizing committee - 6/region
  - Co-chairs
    - S. Komamiya ➔ H. Yamamoto
    - D. Miller ➔ F. Richard
    - C. Baltay ➔ J. Brau
  - Tasks
    - Recognize and coordinate detector concept studies
    - Register and coordinate detector R&Ds
    - Interface with GDE
    - Organize LCWS (International Linear Collider Workshop, 1 per year now)

- **Research Director**
  - S. Yamada appointed by ILCSC - fall 2007
  - WWS co-chairs advising
  - Forming International Detector Advisory Group
  - Coordinating with GDE Directorate
The GDE Plan and Schedule

Global Design Effort

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
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</tr>
</tbody>
</table>

Project

Baseline configuration

Reference Design

Detector Concept Report (issued w/RDR)

Detector Outline Document

LHC Physics

ILC R&D Program

Engineering Design

Bids to Host; Site Selection;

International Mgmt

International Mgmt

Jim Brau

Physics and Detectors of the International Linear Collider

Erice, October 9, 2007
Detector Roadmap

(not yet fully implemented)

• 2007 – Writing of Physics and Detector volumes (2 vol. of RDR) ✓
  Call for Letters of Intent from Detector groups
  ILCSC, Research Director

• 2008 – Letters of Intent received by ILCSC, RD
  International Detector Advisory Group reviews LOIs
  Guides community to the definition of two detectors for
  EDR preparation
  Collaborations formed to develop EDRs

• 2009-2011 – Development of two engineered designs,
  produce first engineering design reports (EDRs) for the two overall detectors,

NOTE - THESE EFFORTS NEED NOT REPRESENT THE FINAL SELECTION OF DETECTORS
FOR THE ILC EXPERIMENTAL PROGRAM
Conclusion

- Current status of Electroweak Precision measurements indicates the physics at the LHC and ILC will be rich.

- The International Linear Collider will be a powerful tool for investigating Electroweak Symmetry Breaking, the origin of mass, and other fundamental physics, advancing our understanding of LHC discoveries.

- DISCOVERY OPPORTUNITIES at the ILC will be limited by detector performance, requiring advances different from those at LHC. The program of ILC Detector R&D is developing these capabilities.