Electroweak Physics and
the International Linear Collider

Jim Brau

May 1, 2006
Electroweak Physics and
The International Linear Collider

- Electroweak Physics
  - Development of theory
    - unification of E&M with beta decay (weak interaction)
  - Predictions
    - eg. $M_W$, $M_Z$, asymmetries,....
  - Missing components
    - origin of symmetry breaking (Higgs Mechanism)

- The Hunt for the Higgs Boson
  - Limits, indirect constraints and on-going search
    at TeVatron and LHC

- The International Linear Collider

- ILC physics program
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
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

\[
\nabla \times E = -\frac{\partial B}{\partial t} \\
\nabla \times B = \mu_0 J + \frac{1}{c^2} \frac{\partial E}{\partial t} \\
\n\nabla \cdot E = \rho / \varepsilon_0 \\
\n\n\n\n\n\hspace{1cm}
\text{This new interaction (the weak force) is related to E&M}
\]
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)
  \[ n \rightarrow p + e^- + \nu_e \]

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

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

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

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

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

\[
\mu = g \frac{e \hbar}{2mc} S
\]

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

Theory: \(0.5 \left(\frac{\alpha}{\pi}\right) - 0.32848 \left(\frac{\alpha}{\pi}\right)^2 + 1.19 \left(\frac{\alpha}{\pi}\right)^3 +..\)

\[\approx (115965230 \pm 10) \times 10^{-11}\]

Experiment: \(115965218.7 \pm 0.4 \times 10^{-11}\)
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
\( \gamma \)
the photon
and the vector fields responsible for the Weak force
\( \gamma \)
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

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

\[
W^{(3)}_\mu = \frac{g Z_\mu + g' A_\mu}{\sqrt{g^2 + g'^2}}
\]

\[
B_\mu = \frac{-g' Z_\mu + g A_\mu}{\sqrt{g^2 + g'^2}}
\]

\[
\tan \theta_W = \frac{g'}{g}
\]

\[
\sin^2 \theta_W = \frac{g^2}{g^2 + g'^2}
\]

\[
e J_\mu^{(em)} A_\mu
\]

\[
e = g \sin \theta_W = g' \cos \theta_W
\]

Jim Brau, Univ. Illinois, May 1, 2006
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
Neutral Currents Discovered!

- 1973 - giant bubble chamber Gargamelle at CERN
  - 12 cubic meters of heavy liquid

- Muon neutrino beam
- Electron recoil
- Nothing else

- Neutral Current Discovered
  that is, the effect of the $Z^0$
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

\[ \sin^2 \theta_W = 0.22 \pm 0.02 \]

Prescott et al. (SLAC) 1978 confirms theory

First accurate measurement of weak mixing angle
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.
Discovery of the W and Z

- 1981 - antiprotons were stored in the CERN SPS ring and brought into collision with protons
Discovery of the W and Z

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 $Z^0$ Factories
    - LEP and SLC
  - precision W measurements at colliders
    - LEP2 and TeVatron

\begin{align*}
M_Z &= 91187.5 \pm 2.1 \text{ MeV} \\
M_W &= 80404 \pm 30 \text{ MeV/c}^2
\end{align*}

- 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 $\sin^2 \theta_W$
Confirmation of the completeness of the Standard Model

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

Why is the underlying SU(2)xU(1) symmetry broken?

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.

\[ L = \frac{g}{\sqrt{2}} \sum_i \bar{\psi}_i \gamma^\mu (1 - \gamma^5)(T^+ W^\mu_+ + T^- W^\mu_-) \psi_i - e \sum_i \bar{q}_i \gamma^\mu \psi_i A_\mu - \frac{g}{2 \cos \theta_W} \sum_i \bar{\psi}_i \gamma^\mu (g^V_i g^5 - g^A_i) \psi_i Z_\mu \]
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 < \(~ 800 \text{ GeV/c}^2\) (unitarity arguments)
  - Strength of Higgs coupling increases with mass
    - fermions: \( g_{fhh} = m_f / v \quad v = 246 \text{ GeV} \)
    - gauge boson: \( g_{wwh} = 2 m_Z^2 / v \)
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 Z0 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

$M_H = 89^{+42}_{-30}$ GeV/c$^2$

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha_{\text{had}}^{(5)}(m_Z)$</td>
<td>$0.02758 \pm 0.00035$</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>$91.1875 \pm 0.0021$</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$2.4952 \pm 0.0023$</td>
</tr>
<tr>
<td>$\sigma_0^{\text{had}}$ [nb]</td>
<td>$41.540 \pm 0.037$</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$20.767 \pm 0.025$</td>
</tr>
<tr>
<td>$A_{\text{tb}}^{0,I}$</td>
<td>$0.01714 \pm 0.00095$</td>
</tr>
<tr>
<td>$A_\tau(P_{\tau})$</td>
<td>$0.1465 \pm 0.0032$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>$0.21629 \pm 0.00066$</td>
</tr>
<tr>
<td>$R_{c'}$</td>
<td>$0.1721 \pm 0.0030$</td>
</tr>
<tr>
<td>$A_{\text{tb}}^{0,b}$</td>
<td>$0.0992 \pm 0.0016$</td>
</tr>
<tr>
<td>$A_{\text{tb}}^{0,c}$</td>
<td>$0.0707 \pm 0.0035$</td>
</tr>
<tr>
<td>$A_b$</td>
<td>$0.923 \pm 0.020$</td>
</tr>
<tr>
<td>$A_c$</td>
<td>$0.670 \pm 0.027$</td>
</tr>
<tr>
<td>$A_\mu(SLD)$</td>
<td>$0.1513 \pm 0.0021$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}}^{\text{lep}}(Q_{tb})$</td>
<td>$0.2324 \pm 0.0012$</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>$80.404 \pm 0.030$</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>$2.115 \pm 0.058$</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>$172.5 \pm 2.3$</td>
</tr>
</tbody>
</table>
Light Standard Model-like Higgs

(SM) $M_{higgs} < 175$ GeV at 95% CL. LEP2 direct limit $M_{higgs} > 114.4$ GeV.

W mass ($\pm 30$ MeV) and top mass ($\pm 3$ GeV) consistent with precision measures and indicate low SM Higgs mass

LEP Higgs search - Maximum Likelihood for Higgs signal at $m_H = 115.6$ 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
  - Now through 2009

- **LHC at CERN**
  - Proton/proton collisions at $E_{cm} = 14,000$ GeV
  - First collisions ~2007
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 on all of these possibilities**
Establishing Standard Model Higgs

*precision* studies of the Higgs boson will be required to understand Electroweak Symmetry Breaking; just finding the Higgs is of limited value.

We expect the Higgs to be discovered at LHC (or Tevatron) and the measurement of its properties will begin at the LHC.

We need to measure the full nature of the Higgs to understand EWSB.

*500 GeV International Linear Collider* is the tool needed for these *precision* studies.
Complementarity of Electron Colliders
The Large Hadron Collider and the ILC

- LHC at CERN, colliding protons first collisions - 2007
- 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>Z⁰</td>
<td>SPPS</td>
<td>LEP and SLC</td>
</tr>
</tbody>
</table>

- Electron experiments have frequently provided most precision
Adding Value to LHC measurements

The International Linear Collider will enhance the LHC measurements (“enabling technology”)

How this happens depends on the Physics:

• Add precision to the discoveries of LHC  
  • eg. light higgs measurements
• Measure superpartner masses and properties
• Susy parameters may fall in the tan β /M_A wedge.
• Directly observed strong WW/ZZ resonances at LHC  
  are understood from asymmetries at Linear Collider
• Analyze extra neutral gauge bosons
• Giga-Z constraints
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}

S. Godfrey, P. Kalyniak, A. Tomkins
Storage rings have been the optimal facilities for colliding beam experiments for several decades

- Developed in 1960’s to achieve highest possible center of mass collision energy
- Particle beams stored for many hours
- Efficient transfer of beam energy to interactions

Electron storage rings have a limited useful energy

- LEP ~ 100 GeV beam energy
Linear Colliders

- Acceleration of electrons in a circular accelerator is plagued by Nature’s resistance to acceleration
  - Synchrotron radiation
  - \[ \Delta E = \frac{4\pi}{3} \left( e^2 \beta^3 \gamma^4 / R \right) \] per turn (recall \( \gamma = E/m \), so \( \Delta E \sim E^4/m^4 \))
  - eg. LEP2 \( \Delta E = 4 \) GeV \( \text{Power} \sim 20 \) MW

- For this reason, at very high energy it is preferable to accelerate electrons in a linear accelerator, rather than a circular accelerator
Linear Colliders

- **Synchrotron radiation**
  - $\Delta E \sim (E^4/m^4 R)$

- **Therefore**
  - Cost (circular) $\sim aR + b\Delta E \sim aR + b(E^4/m^4 R)$

  - Optimization $R \sim E^2 \Rightarrow$ Cost $\sim cE^2$

  - Cost (linear) $\sim a'L$, where $L \sim E$

- At high energy, linear collider is more cost effective
The First Linear Collider

- This concept was demonstrated at SLAC in a linear collider prototype operating at ~91 GeV (the SLC)

- SLC was built in the 80’s within the existing SLAC linear accelerator

- Operated 1989-98
  - precision $Z^0$ measurements
  - established ILC concepts
$E_{cm} = 500 \text{ GeV} \quad \text{to} \quad 1000 \text{ GeV}$

Polarized $e^-$

($\sim80\%$ and $e^+$)

Length $(500 \text{ GeV})$

$\sim25 \text{ km}$

$\sim15 \text{ miles}$

**Elucidate Electroweak Interaction**

- precision meas. symmetry breaking
  - Higgs bosons
  - supersymmetric particles
  - extra dimensions

Construction could begin soon after 2010 and operation soon after 2016

- Intense R&D until 2010
ILC Accelerator Physics Challenges

- **Develop High Gradient Superconducting RF systems**
  - Requires efficient RF systems, capable of accelerating high power beams (~MW) with small beam spots (~nm).

- **Achieving nm scale beam spots**
  - High intensity beams of electrons and positrons
  - Damped beams to ultra-low emittance in damping rings
  - Transport beams to collision point without significant emittance growth or uncontrolled beam jitter
  - Cleanly dumped used beams.

- **Reaching Luminosity Requirements**
  - Designs satisfy the luminosity goals in simulations
  - A number of challenging problems in accelerator physics and technology must be solved, however.
ILC Experimental Advantages

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

Democrat 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. $R_{beampipe} \sim 1$ cm and $\sigma_{hit} \sim 3 \mu$m

Calorimetry with Particle Flow Precision
  $\sigma_E/E \sim 30-40\%/\sqrt{E}$

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

Detector performance translates directly into effective luminosity
The Linear Collider provides very special experimental conditions (e.g., superb vertexing and jet calorimetry)

- **Giga-pixel Vertex Detector**
- **Silicon-Tungsten EM Calorimetry**
  - SLD Lum (1990)
  - Aleph Lum (1993)
  - Opal Lum (1993)
  - 90 Mcell Si/W EM calorimeter central element in particle flow measurement
Jim Brau, Univ. Illinois, May 1, 2006

Linear Collider Detectors

Digital Hadron Calorimeter

- 40 Mcell hadron calorimeter
  - jet resolution ≈30% / $\sqrt{E}$
  - relies on tracker for charged particles

Integrated Detector Designs

- SiD
- 5 Tesla Solenoid

Also, GLD, LDC, 4th
Electroweak precision measurements suggest there should be a relatively light Higgs boson:

*When it’s discovered, we will want to study its nature. The ILC is essential to this program.*

Mass Measurement
Total width
Particle couplings
  vector bosons
  fermions (including top)
Spin-parity-charge conjugation
Self-coupling

*The ILC makes precise measurements*
Recall, \( \sigma_{pt} = 87 \text{ nb} / (E_{cm})^2 \sim 350 \text{ fb} \) @ 500 GeV
ILC observes Higgs recoiling from a Z, with known CM energy

- powerful channel for unbiassed tagging of Higgs events
- measurement of even invisible decays

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

Invisible decays are included

500 fb\(^{-1}\) @ 500 GeV, TESLA TDR, Fig 2.1.4
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.
Higgs Spin Parity and Charge Conjugation ($J^P_C$)

$H \rightarrow \gamma \gamma$ 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
Is This the Standard Model Higgs?

Arrows at:
- $M_A = 200-400$
- $M_A = 400-600$
- $M_A = 600-800$
- $M_A = 800-1000$

HFITTER output

Conclusion:
- For $M_A < 600$, good sensitivity
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
- dark matter?
- many new particles
  - ILC could detail properties

\[ \delta m_{\tilde{\nu}} < 0.1 \text{ GeV} \]
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
Some Steps Toward the ILC

- **2002- DOE/NSF High Energy Physics Advisory Panel**
  - A high-energy, high-luminosity electron-positron linear collider should be the highest priority of the US HEP community, preferably one sited in the US
  - Similar statements in other regions ⇒ global consensus on next collider

- **2003- DOE Office of Science Future Facilities Plan**
  - Linear Collider is ranked first among mid-term projects

- **2004 – Technology choice by ICFA (Superconducting RF)**

- **2005 – Global Design Effort formed**
  - Baseline Configuration Document

- **Apr. 26, 2006 – NRC Report on the Future of Particle Physics**

- **end of 2006 – GDE Reference Design Report (w/ cost)**
Given the excitement of the scientific opportunities in particle physics, and in keeping with the nation’s broader commitment to research in the physical sciences, the committee believes that the United States should continue to support a competitive program in this key scientific field.

Action Item 1: The highest priority for the U.S. national effort in elementary particle physics should be to continue to be an active partner in realizing the physics potential of the LHC experimental program.

Action Item 2: The United States should launch a major program of R&D, design, industrialization, and management and financing studies of the ILC accelerator and detectors.

Action Item 3: The United States should announce its strong intent to become the host country for the ILC and should undertake the necessary work to provide a viable site and mount a compelling bid.
Design to “sample sites” from each region

- Americas – near Fermilab
- Japan
- Europe – CERN & DESY

**Illinois Site**

- depth 135m
- Glacially derived deposits overlaying Bedrock.
- The concerned rock layers are from top to bottom
  - the Silurian dolomite,
  - Maquoketa dolomitic shale,
  - the Galena-Platteville dolomites.
Conclusion

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

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

- This physics follows a century of unraveling the mystery of the electroweak interaction.

- We can imagine future discoveries may further our knowledge of fundamental physics in unanticipated ways.