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
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
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**

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

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

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

- 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
Quantum Electrodynamics (QED)

- Dirac introduced theory of electron - 1926
- Through the pioneering theoretical work of Feynman, Schwinger, Tomonga, and others, a theory of electrons and photons was worked out with precise predictive power
- Example: magnetic dipole of the electron

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

- 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 = \((115965218.6 \pm 0.4) \times 10^{-11}\)
The New Symmetry Emerges

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
\[ \nabla \text{the photon} \]
and the vector fields responsible for the Weak force
\[ \nabla \text{yet undiscovered } W^+ \text{ and } W^- \]
could be unified if another vector field, mediated by a heavy neutral boson \((Z^0)\), were to exist

This same notion occurred to Salam

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

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

\[
g'/g = \tan \theta_W \quad \sin^2 \theta_W = g'^2/(g'^2 + g^2)
\]
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
**Confirmation of Neutral Currents**

- **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.

- Prescott et al. (SLAC) 1978 confirms theory.
- The first accurate measurement of weak mixing angle.

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

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

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

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

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

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

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

$e^-$

$\nu_e$

$p = uud$

$p_T$

UA1 and UA2 discovered the W and the Z bosons
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

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 $\sin^2\theta_W$

\[ M_Z = 91187.6 \pm 2.1 \text{ MeV} \quad M_W = 80403 \pm 29 \text{ MeV}/c^2 \]
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.
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 $< \sim 800$ GeV/c$^2$ (unitarity arguments)
  - Strength of Higgs coupling increases with mass
    - fermions: $g_{ffh} = m_f / v$  \( v = 246 \) 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 Z\(^0\) measurements
- Electroweak theory and experiments

Electroweak Physics and the International Linear Collider
The Search for the Higgs Boson


![LEP II Image]

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

\[ M_H = 89^{+42}_{-30} \text{ GeV/c}^2 \]

- Standard Model Fit

\[ \Delta \alpha^{(5)}_{\text{had}}(m_Z) = 0.02758 \pm 0.00035 \]
\[ m_Z \text{ [GeV]} = 91.1875 \pm 0.0021 \]
\[ \Gamma_Z \text{ [GeV]} = 2.4952 \pm 0.0023 \]
\[ \sigma^0_{\text{had}} \text{ [nb]} = 41.540 \pm 0.037 \]
\[ R_b = 20.767 \pm 0.025 \]
\[ A^{D,1}_{t,b} = 0.01714 \pm 0.00095 \]
\[ A_t(P_D) = 0.1465 \pm 0.0032 \]
\[ R_c = 0.21629 \pm 0.00066 \]
\[ R_c^{D,b} = 0.1721 \pm 0.0030 \]
\[ A^{D,c}_{t,b} = 0.0992 \pm 0.0016 \]
\[ A^{D,c}_{t,b} = 0.0707 \pm 0.0035 \]
\[ A_b = 0.923 \pm 0.020 \]
\[ A_c = 0.670 \pm 0.027 \]
\[ A_t^{(5)} \text{ (SLD)} = 0.1513 \pm 0.0021 \]
\[ \sin^2 \theta_{W}^{\text{eff}}(Q_{t,b}) = 0.2324 \pm 0.0012 \]
\[ m_W \text{ [GeV]} = 80.404 \pm 0.030 \]
\[ \Gamma_W \text{ [GeV]} = 2.115 \pm 0.058 \]
\[ m_t \text{ [GeV]} = 172.5 \pm 2.3 \]
Light Standard Model-like Higgs

$(\text{SM}) \ M_{\text{higgs}} < 175 \ \text{GeV} \ \text{at 95\% CL.}$

$\text{LEP2 direct limit} \ M_{\text{higgs}} > 114.4 \ \text{GeV}.$

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

$\text{LEP Higgs search - Maximum Likelihood for Higgs signal at}$
$m_{H} = 115.6 \ \text{GeV} \ \text{with overall significance (4 experiments)} \ \sim 2\sigma$
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 later this year/early next year
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
LHC at CERN, colliding protons
first collisions – late this year/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

\[ m_{z'} = 2 \text{TeV}, E_{cm} = 500 \text{ GeV}, L = 1 \text{ab}^{-1} \text{Cr} \]

with and w/o beam polarization

S. Godfrey, P. Kalyniak, A. Tomkins
Colliders (Circular and Linear)

- 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

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

- Therefore
  - Cost (circular) $\sim a R + b\Delta E \sim a R + b (E^4/m^4 R)$
  - Optimization $R \sim E^2 \Rightarrow$ Cost $\sim c E^2$
  - Cost (linear) $\sim a'L$, where $L \sim E$

- At high energy, linear collider is more cost effective

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Jim Brau  | Electroweak Physics and the International Linear Collider  | Purdue, April 18, 2007  | 28
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
  - Suggests Light Higgs Boson
  - established ILC concepts
The International Linear Collider

\[ E_{cm} = 500 \text{ GeV} - 1000 \text{ GeV} \]

Polarized e\(^-\) (~80% and e\(^+\))

Length (500 GeV) ~30 km ~20 miles

Elucidate Electroweak Interaction

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

Construction could begin soon after 2010 (perhaps 2012) and operation in 2018-2020

Intense R&D needed by 2010
ILC Experimental Advantages

Elementary interactions at known $E_{cm}^*$
  eg. $e^+e^- \rightarrow Z H$ \* 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. $R_{beampipe} \sim 1 \text{ cm}$ 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. $H \rightarrow c \bar{c}$
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
Digital Hadron Calorimeter

40 Mcell hadron calorimeter
jet resolution \( \sim 30\% / \sqrt{E} \)
relies on tracker for charged particles

Integrated Detector Designs

SiD

Silicon Tracking
5 Tesla Solenoid

xy view
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
$\sigma_{pt} = 87 \text{ nb} / (E_{cm})^2 \sim 350 \text{ fb} \quad @ \quad 500 \text{ GeV}$
ILC observes Higgs recoiling from a Z, with known CM energy:

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

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

(\(\Downarrow\) - some beamstrahlung)

Invisible decays are included

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

$$g_{ffh} = \frac{m_f}{v} \quad v = 246 \text{ GeV}$$

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.
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 $J^P (e^+ e^- \rightarrow Z H \rightarrow f \bar{f} H)$

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

TESLA TDR, Fig 2.2.6
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

\[ \delta m_{\tilde{\nu}_R} < 0.1 \text{ GeV} \]
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

![Diagram of extra dimensions](image)

![Graph showing linear collider](image)
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**

- **Feb. 2007 – GDE Reference Design Report (w/ cost)**
The GDE Plan and Schedule

2005  2006  2007  2008  2009  2010

Global Design Effort

Baseline configuration
Reference Design

LHC Physics
Technical Design

ILC R&D Program
Expression of Interest to Host

International Mgmt

Global Design Effort
Design to “sample sites” from each region

- Americas – near Fermilab
- Japan – west of Tokyo
- 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.
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.
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 Electroweak Symmetry Breaking, origin of mass, other fundamental physics, and advance understanding of LHC discoveries.

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

- Future discoveries may advance our knowledge of fundamental physics in unanticipated ways.