Exploring the Energy Frontier; Understanding LHC Discoveries

Jim Brau
University of Oregon
History of the Universe

Big Bang

Superstrings ?

Unified Forces

Inflationary Expansion

Forces Separate

Nucleons Created

Atoms Form

Stars Are Born

Today

Time

$10^{-43}$ s

$10^{-35}$ s

$10^{-10}$ s

$10^{-5}$ s

300 000 Years

$10^9$ Years

$15 \cdot 10^9$ Years

Energy

$10^{17}$ TeV

$10^{13}$ TeV

1 TeV

150 MeV

1 eV

4 MeV

0.7 MeV

accessible with precision meas.

LHC

ILC
Exploring the Energy Frontier

○ Terascale Physics Era begins soon

○ A Linear Collider is the essential complement to the LHC

○ ILC will be ready to go when LHC sets the energy scale

○ Political ups and downs and ups

○ Experiments are challenging, demanding aggressive, focused detector R&D
As astronomers examine the universe with different wavelengths (visible, radio, X-ray, IR, etc.), particle physicists use different initial states. Complementarity is a powerful tool across all sciences.
### Particle Physics Needs Both

<table>
<thead>
<tr>
<th>SM particle</th>
<th>discovery</th>
<th>detailed study</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td></td>
<td>SLAC</td>
<td>HERA</td>
</tr>
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<td></td>
<td>PETRA</td>
<td>Fermilab/ SLC/LEP</td>
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<tr>
<td></td>
<td>BNL + SPEAR</td>
<td>SPEAR</td>
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<td>SPEAR</td>
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<tr>
<td></td>
<td>Fermilab</td>
<td>Cornell/DESY/SLAC/KEK</td>
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<tr>
<td></td>
<td>SPPS/CERN</td>
<td>LEP and SLC</td>
</tr>
<tr>
<td></td>
<td>Fermilab</td>
<td>LHC +? (LC meas. Yukawa cp.)</td>
</tr>
</tbody>
</table>

- Electron experiments have frequently provided most precision as well as discovery.
Virtues of the ILC

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

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

Inclusive Trigger-free data
  total cross-section

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

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

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

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

MODEL INDEPENDENT MEASUREMENTS
Terascale Physics

- Electroweak Symmetry Breaking at Terascale

- Many theories aim to explain Hierarchy Problem
  - SUSY, XDimensions, New Strong Dynamics,
  - Unparticles, Little Higgs, $Z'$, …

- ILC explores all of these
  - Precision mass couplings (including the Higgs)
  - Direct production of new states
  - High energy behavior of cross sections
    (including asymmetries, CP violation, etc.)
ILC Physics

- Light Higgs $h^0$ Br
- Top-Yukawa
- SUSY physics study
- $\gamma\gamma$ Heavy Higgs search
- $e^+e^-$ Heavy Higgs study
- CP-violation
- $\tilde{\chi}^0$  $\tilde{\ell}$  $\tilde{t}$  $\tilde{q}$
- $h^0$ basic property
Confirmation of the completeness of the Standard Model
\[ e^+e^- \rightarrow W^+W^- \] (LEP2)

Demonstration of unification of EW forces
\[ e^-p \rightarrow e^-X \rightarrow \nu_e X \] (HERA)

Electroweak Symmetry Breaking

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

\[ e^-p \rightarrow e^-X \rightarrow \nu_e X \] (HERA)
**Electroweak Symmetry Breaking**

\[ L = g J_{\mu} \cdot W_{\mu} + g' J_{\mu}^\gamma B_{\mu} \]

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

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

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

**WHY?**

- Standard Model 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.
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>$\Delta \alpha_{\text{had}}^{(5)}(m_Z)$</th>
<th>$m_Z$ [GeV]</th>
<th>$\Gamma_Z$ [GeV]</th>
<th>$\sigma_\text{had}$ [nb]</th>
<th>$R_l$</th>
<th>$A_{\text{fb}}^{0,l}$</th>
<th>$A_l(P_t)$</th>
<th>$R_b$</th>
<th>$R_c$</th>
<th>$A_{\text{fb}}^{0,b}$</th>
<th>$A_{\text{fb}}^{0,c}$</th>
<th>$A_b$</th>
<th>$A_c$</th>
<th>$A_l(SLD)$</th>
<th>$\sin^2 \theta_{\text{eff}}(Q_{\text{fb}})$</th>
<th>$m_W$ [GeV]</th>
<th>$\Gamma_W$ [GeV]</th>
<th>$m_t$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Model Fit</td>
<td></td>
<td>$0.02758 \pm 0.00035$</td>
<td>$91.1875 \pm 0.0021$</td>
<td>$2.4952 \pm 0.0023$</td>
<td>$41.540 \pm 0.037$</td>
<td>$20.767 \pm 0.025$</td>
<td>$0.01714 \pm 0.00095$</td>
<td>$0.1465 \pm 0.0032$</td>
<td>$0.21629 \pm 0.00066$</td>
<td>$0.1721 \pm 0.0030$</td>
<td>$0.0992 \pm 0.0016$</td>
<td>$0.0707 \pm 0.0035$</td>
<td>$0.923 \pm 0.020$</td>
<td>$0.670 \pm 0.027$</td>
<td>$0.1513 \pm 0.0021$</td>
<td>$0.2324 \pm 0.0012$</td>
<td>$80.399 \pm 0.025$</td>
<td>$2.098 \pm 0.048$</td>
<td>$173.1 \pm 1.3$</td>
</tr>
</tbody>
</table>

MARCH 2009

Theory uncertainty

$\Delta \alpha_{\text{had}}^{(5)}$

- $0.02758 \pm 0.00035$
- $0.02749 \pm 0.00012$
- Incl. low $Q^2$ data

Excluded

Preliminary
Light Standard Model-like Higgs

MARCH 2009

(SM) $M_{\text{higgs}} < 163 \text{ GeV}$ at 95% CL.

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

W mass ($\pm 25 \text{ MeV}$) and top mass ($\pm 1.3 \text{ GeV}$) consistent with precision measures and indicate low SM Higgs mass.
Even more strict Indirect limits on the light Higgs mass in the CMSSM/ EWPO + FPO + dark matter abundance

\[ m_{h}^{\text{CMSSM}} = 110+8-10(\text{exp.})+-3(\text{theo.}) \text{ GeV}/c^{2} \]

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
- Fermi theory; Weinberg-Salam electroweak theory
- Neutral currents; “ “
- Mass predicted by precision $Z^0$ measurements

**Electroweak theory and experiments**
ILC Higgs Studies
- the Power of Simple Interactions

ILC observes Higgs recoiling from a Z, with known CM energy↓
• powerful channel for unbiassed tagging of Higgs events
• measurement of even invisible decays

(↓ - some beamstrahlung)

1. KNOWN INITIAL STATE
2. MEASURE $Z \rightarrow t^+t^-$
3. CALCULATE RECOIL

Invisible decays are included

500 fb$^{-1}$ @ 500 GeV, TESLA TDR, Fig 2.1.4

Jim Brau Exploring the Energy Frontier APS, Denver, May 3, 2009
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.
Is This the Standard Model Higgs? Precision tells us!

Coupling Precision

<table>
<thead>
<tr>
<th>Deviation from SM value</th>
<th>( \Gamma_n )</th>
<th>( \tau )</th>
<th>( b )</th>
<th>( t )</th>
<th>( W )</th>
<th>( Z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>+30%</td>
<td></td>
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<tr>
<td>+20%</td>
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<tr>
<td>+10%</td>
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<tr>
<td>0% (SM)</td>
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<tr>
<td>-10%</td>
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<tr>
<td>-20%</td>
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<tr>
<td>-30%</td>
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</tbody>
</table>

Model assumption

Limit on \( \rho \) and \( \phi \):

\[ \rho < 1 + 0\%

SUSY or 2HDM

| Deviation from SM value | \( \Gamma_n \) | \( c \) | \( \tau \) | \( b \) | \( t \) | \( W \) | \( Z \) | \( H \) |
|------------------------|---------------|----------------|---------------|----------------|---------------|---------------|
| +30%                    |               |               |               |               |               |               |
| +20%                    |               |               |               |               |               |               |
| +10%                    |               |               |               |               |               |               |
| 0% (SM)                 |               |               |               |               |               |               |
| -10%                    |               |               |               |               |               |               |
| -20%                    |               |               |               |               |               |               |
| -30%                    |               |               |               |               |               |               |

Model Independent Analyses

Extra-dimension (radion-Higgs mixing)

| Deviation from SM value | \( \Gamma_n \) | \( c \) | \( \tau \) | \( b \) | \( t \) | \( W \) | \( Z \) | \( H \) |
|------------------------|---------------|----------------|---------------|----------------|---------------|---------------|
| +30%                    |               |               |               |               |               |               |
| +20%                    |               |               |               |               |               |               |
| +10%                    |               |               |               |               |               |               |
| 0% (SM)                 |               |               |               |               |               |               |
| -10%                    |               |               |               |               |               |               |
| -20%                    |               |               |               |               |               |               |
| -30%                    |               |               |               |               |               |               |

Model Independent Analyses
Strongly Interacting Light Higgs

- Origin of EW scale from new strong interaction
- Technicolor simple example,
  - But inconsistent with EW precision measurements
- Add light pseudo-Goldstone Higgs
  - arxiv/hep-ph/0703164
    - Giudice, Grojean, Pomaral, Rattazzi
  - Fares better on EWP test
- Detectable through deviations in BRs (new interaction)
  - LHC sensitivity $\sim0.2$
  - ILC sensitivity $\sim0.01 \Rightarrow 30$ TeV
Higgs Spin Parity and Charge Conjugation (JPC)

H → γγ or γγ → H
rules out J=1 and indicates C=+1

Production angle (θ) and Z decay angle in Higgs-strahlung reveals J^P (e^+ e^- → Z H → ffH)

LC Physics Resource Book,
Fig 3.23(a)

TESLA TDR, Fig 2.2.8
The Higgs Self Coupling is given by:

$$\Phi(H) = \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

In the Standard Model (SM), $$g_{HHH} = 6\lambda v$$, fixed by $$M_H$$.

The Higgs strahlung process in the SM is shown with a graph, and the result is:

$$\Delta \lambda / \lambda \sim 20\%$$

for 1 ab$$^{-1}$$.
New Physics other than the Higgs

- Motivated by “Hierarchy Problem”
  - Gigantic Mismatched between Electroweak Scale (100 GeV) and the Planck Scale of gravity ($10^{19}$ GeV)
  - Expect More New Physics

- Supersymmetry?
  - new space-time symmetry with new particles

- New Strong Interactions?

- Hidden Dimensions?
Supersymmetry

- Super-partners -> cancellation of divergences
  - Solves “hierarchy problem”
- Dark matter candidate
  - and inspired by string theory
- Many new particles
  - Mass spectrum is model dependent
  - ILC could detail properties

Squarks are well measured at LHC

Light Sleptons & Neutralinos pinned down w/ LC precision
Mass measurements

- \( \Delta m \sim 100 \text{ MeV} \)

Heavy sneutrinos

- \( e^+e^- \rightarrow \tilde{\mu}_R \tilde{\mu}_L \rightarrow \mu^+ \chi_1^0 \mu^+ \chi_1^- \)

- \( \Delta m \sim 50 \text{ MeV} \)

\( m(\text{snu}) \sim 2000 \pm 100 \text{ GeV} \)
Supersymmetry (CMSSM)

CMSSM/
EWPO + FPO + dark matter abundance

(arXiv:0707.3447,
O. Buchmueller, R. Cavanaugh, A. De Roeck,
S. Heinemeyer, G. Isidor, P. Paradisi, F.J. Ronga,
A.M. Weber, and G. Weiglein)

Figure 2. Mass spectrum of super-symmetric particles at the globally preferred \( \chi^2 \) minimum. Particles with mass difference smaller than 5 GeV/\( c^2 \) have been grouped together.
Understanding Dark Matter

Identification of dark matter
SUSY mass and coupling measurements

![Graph showing dark matter mass from supersymmetry measurements](image)
Complementarity with LHC

**Z’ discovered at LHC**

- $m_{Z'} = 2$ TeV, $E_{cm} = 500$ GeV, $L = 1$ ab$^{-1}$
- With and w/o beam polarization

**Couplings determined at ILC**

- $m_{Z'} = 1, 2, 3$ TeV, $E_{cm} = 500$ GeV, $L = 1$ ab$^{-1}$
- S. Godfrey, P. Kalyniak, A. Tomkins

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Jim Brau  
Exploring the Energy Frontier  
APS, Denver, May 3, 2009
Ultimate Unification

- Do Gaugino masses unify?
  - Working together, the ILC and LHC will test this
    - LHC → gluino
    - ILC → wino, zino, photino

- Do quark and lepton couplings unify, as well?
Extra Dimensions

- Extra Dimensions
  - string theory inspired
  - solves hierarchy problem
    - if extra dimensions are large
  - observable at ILC

Graviton emission

G. Wilson

Graviton emission

G. Wilson

Graviton emission

G. Wilson

Graviton emission

G. Wilson

Graviton emission

G. Wilson

Graviton emission

G. Wilson

Graviton emission

G. Wilson
The International Linear Collider

- **500 GeV $E_{cm}$**
  - Two 11 km SuperRF linacs at 31.5 MV/m
  - Centralized injector (polarized electrons)
  - Circular damping rings
  - Undulator based positron source (polarized)
  - Single IR for two detectors (push-pull) w/ 14 mr crossing angle
  - Dual tunnel

- **Upgradable to 1 TeV**

- **Options**
  - Hi luminosity at $M_\tau$ / W pair threshold
  - $\gamma\gamma$, $e\gamma$, $e^-e^-$
2004 Technology Decision allowed concentration of effort on major issues & realistic design

- CesrTA (electron cloud)

- ATF-2 (final focus)
  Demonstrate Fast Kicker perf. and Final Focus Design
  2010
  - Demonstrate ~ 50 nm beam
  2012
  - Stabilize final focus

- SCRF cryomodule gradient
  31.5 MV/m av. req.
  29 in DESY test stand
  27 in DESY FLASH

- Power Distribution
  RF Cluster Concept

- Cost Reduction Studies - rebaseline in 2010
Political Winds Create Unsteady Journey

- 2004 - Technology Choice
- 2006 - EPP2010
- 2007 - Reaction to RDR Cost
  - Omnibus December
- 2008 - New P5: modest support
  - US ILC funding restored
  - Japanese INTEREST
- 2009 - New Presidential Science R&D Emphasis
High Level Interest in Japan

February 26 Symposium in Tokyo
Departing from Japan to Universe – Toward the realization of International Linear Collider
### ILC Detector Performance Requirements

<table>
<thead>
<tr>
<th><strong>Physics Process</strong></th>
<th><strong>Measured Quantity</strong></th>
<th><strong>Critical System</strong></th>
<th><strong>Critical Detector Characteristic</strong></th>
<th><strong>Required Performance</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow b\bar{b}, c\bar{c}, gg$</td>
<td>Higgs branching fractions b quark charge asymmetry</td>
<td>Vertex Detector</td>
<td>Impact parameter $\Rightarrow$ Flavor tag</td>
<td>$\delta_b \sim 5\mu m \oplus 10\mu m/(p \sin^{3/2} \theta)$</td>
</tr>
<tr>
<td>$ZH \rightarrow \ell^+\ell^-X$</td>
<td>Higgs Recoil Mass Lumin Weighted $E_{cm}$ BR ($H \rightarrow \mu\mu$)</td>
<td>Tracker</td>
<td>Charge particle momentum resolution, $\phi(p_t)/p_t^2$ $\Rightarrow$ Recoil mass</td>
<td>$\sigma(p_t)/p_t^2 \sim few \times 10^{-5}$GeV</td>
</tr>
<tr>
<td>$ZH \rightarrow q\bar{q}b\bar{b}$</td>
<td>Triple Higgs Coupling Higgs Mass BR ($H \rightarrow WW^*$) $\sigma(e^+e^- \rightarrow \nu\bar{\nu} W^+W^-)$</td>
<td>Tracker &amp; Calorimeter</td>
<td>Jet Energy Resolution, $\sigma_E/E$ $\Rightarrow$ Di-jet Mass Res.</td>
<td>$\sim 3%$ for $E_{jet} &gt; 100$ GeV $30% / \sqrt{E_{jet}}$ for $E_{jet} &lt; 100$ GeV</td>
</tr>
<tr>
<td>SUSY, eg. $\tilde{\mu}$ decay</td>
<td>$\tilde{\mu}$ mass</td>
<td>Tracker, Calorimeter</td>
<td>Momentum resolution, Hermiticity $\Rightarrow$ Event Reconstruction</td>
<td>Maximal solid angle coverage</td>
</tr>
</tbody>
</table>

Excellent performance needed to fulfill physics potential
The Concepts

ILD

SiD

ILD

4th

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Detector R&D Challenges

- **Vertex Sensors**
  - Fast, 20 µm pixels,
  - thin: 0.1% $X_0$/layer

- **Calorimetry**
  - Finely segmented EM
  - Si-W

- **Tracking**
  - Measure Higgs recoil
  - Resolution $\sim 1/6 \times$ LEP
  - Silicon or TPC

- **Jet energy measurements**
  - Separate W & Z
  - Particle Flow Analysis
  - Dual-readout

Important - broader, generic impact
Options Roadmap for Lepton Colliders

• LHC will help guide energy choice.
  • If a low mass higgs or low mass new states, ILC is well motivated.
  • It’s the only feasible early option.

• There are multiple technologies.
  • ILC is most advanced, but not adequate for high energies >1 TeV.

• Several other technologies are aimed at Multi-Tev regime, but need to mature technology
  • Two-beam acceleration (CLIC)
  • Plasma Wake Field Acceleration (PWFA)
  • Laser Acceleration
  • Muon Collider
Conclusion

- Terascale Physics Frontier will open soon at the LHC
- Precision measurements required to understand LHC discoveries
- ILC will be ready when LHC discoveries justify the next step