Many contributions to this talk from colleagues, especially
J. Barkeloo, L. Braun, M. Breidenbach,
C. Gallagher, C. Potter, A. Steinhebel
The physics opportunities of the ILC include:
- precision measurement of Higgs boson couplings
- search for exotic modes of Higgs boson decay
- search for dark matter particles and other invisible states
- search for heavy resonances through 2-fermion processes
- precision measurement of the top quark mass
- precision measurement of top quark electroweak couplings
- measurement of the triple Higgs boson coupling
- and more (eg. WW threshold and gigaZ)
Advantage of Higgs Studies at e+e−

Effects of new physics on the Higgs boson are expected to be small, of about a few-percent at most.

Typical LHC Higgs boson samples have large backgrounds. Furthermore, not all Higgs decay modes are observed.

At LHC, Higgs couplings are determined in a model-dependent way and precision is limited.

On the other hand, the very low backgrounds and simple reactions in e+e− make higher precision, model-independent measurements feasible, if detectors are capable.

All major decay modes are observed in e+e−.
Center-of-mass energies:
- 200 GeV up to 1 TeV.
- Special running at the Z-pole and WW threshold.
- Higgs Factory, Giga-Z, Top Yukawa couplings, di-boson production, SUSY, other new physics motivated by alternative models.
- Each physics topic creates a particular set of requirements.

Detector designs developed for the full energy range.
ILC Experimental Advantages

❖ Radiation damage is mostly not an issue (except very forward)
   ❖ collisions dominated by electroweak processes
❖ Trigger-less operation - record every interaction (< 6 Gb/sec)
❖ Bunch train structure allows pulse power w/ gas cooling

❖ Relatively low event rates
❖ Elementary interactions at known $E_{cm}$ (e.g. $e^+e^- \rightarrow ZH$)
❖ Democratic Cross sections (e.g. [e$^+e^- \rightarrow ZH] \sim 1/2 [e^+e^- \rightarrow \bar{d}d]$)
❖ Highly Polarized Electron Beam (~ 80% - & positron pol. 30%)
❖ Tunable center-of-mass energy

❖ Compared to LHC - trigger-less, ~no pileup, low occupancy, no rad.

❖ THESE FEATURES ENHANCE PRECISION MEASUREMENTS
❖ OPPORTUNITY FOR DETECTOR OPTIMIZATION
ILC Design Evolution

- ILC first designed for initial running at 500 GeV.
- Now, ILC250 proposed as first-stage with primary motivation to study Higgs-strahlung.
- Many studies at 500 GeV - conditions milder at 250 GeV, but expect to eventually operate at 500 GeV, even higher.

arXiv:1306.6327 - Volume 1: Executive Summary
  R&D in the Technical Design Phase
arXiv:1306.6328 - Volume 3.II: Accelerator
  Baseline Design
ILC Beam Structure

- Beam structure important consideration in detector optimization.
- Bunch trains at 5 Hz.
- 1312 bunches/train in first-stage (ILC250)

- Duty cycle < 1%
- Average low power achieved by power pulsing during readout (also requires quiescent currents). Minimizes passive material and space.
Physics Drives Detector Requirements

Clean events with low backgrounds motivate unprecedented detector performance

### Physics Process

<table>
<thead>
<tr>
<th>Measured Quantity</th>
<th>Critical System</th>
<th>Critical Detector Characteristic</th>
<th>Required Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow b\bar{b}, c\bar{c}, g\gamma, \tau\tau )</td>
<td>Higgs branching fraction</td>
<td>b quark charge asymmetry</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</td>
<td>Higgs Lumin Weight</td>
<td>( \sigma(p_t) / p_t^2 \sim \text{few} \times 10^{-5} \text{GeV}^{-1} )</td>
</tr>
<tr>
<td>( \mu^+\mu^- \gamma )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ZH + H\nu\nu \rightarrow \mu^+\mu^- X )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ZHH )</td>
<td>Triple Higgs Coupling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ZH</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table><p>ightarrow q\bar{q}b\bar{b} ) | Higgs Mass | BR (H \rightarrow \mu\mu) | ~3% for ( E_{\text{jet}} &gt; 100 \text{ GeV} ) |
| ( ZH \rightarrow ZWW^* ) | | BR (H \rightarrow WW^*) | 30% / ( \sqrt{E_{\text{jet}}} ) for ( E_{\text{jet}} &lt; 100 \text{ GeV} ) |
| ( \nu\bar{\nu}W^+W^- ) | | | |
| SUSY, eg. ( \tilde{\mu} ) decay | ( \tilde{\mu} ) mass | Tracker, Calorimeter | Maximal solid angle coverage |</p>

**MOTIVATION FOR:**

High granularity, dense integration, super light materials, low power, air cooling, power pulsing

**High Granularity Calorimetry for the ILC**

J. Brau - 9 September 2020
Main 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. Provides input to Particle Flow Calorimetry.
- 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.
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High Granularity Calorimetry for the ILC

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- 1312 bunches/train in first-stage (ILC250)

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1312 bunches (0.73 ms) ~200 ms

Buffer Data Readout and Low Power
ILC Detector Requirements

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- **Excellent flavor tagging efficiency and purity** (for both b- and c-quarks, and hopefully also for s-quarks).
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- **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 events.**

Separate W&Z di-jet events.

For 100 GeV jet - 3% resolution needed.

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

Brient & Videau, arXiv:0202004
Requirements Achieved in ILC Designs

- Clean events with low backgrounds enable unprecedented detector performance motivated by physics goals.
  - High granularity
  - Dense integration
  - Super light materials
  - Low/pulse power
  - Air cooling

Documented and refined:
arXiv:0712.2356
Letter of Intent to IDAG - 2009
arXiv:0911.0006
Technical Design Report - 2013
arXiv:1306.6329
Recent updates:
arXiv:1903.01629, 1912.04601
ILC Detectors

- Two Validated detector concepts.
- Complementary: tracking technology, magnetic field, calorimetry, etc.

<table>
<thead>
<tr>
<th>SiD</th>
<th>ILD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>Tracking</td>
</tr>
<tr>
<td>6.0 m</td>
<td>Outer Radius</td>
</tr>
<tr>
<td>5 Tesla</td>
<td>B Field</td>
</tr>
</tbody>
</table>

- Design: High efficiency
- Goals: High resolution, Low fake rate, Control of systematics

Both employ particle flow calorimetry
Concepts use large $BR^2/\sigma$ to achieve required very good momentum resolution:

$$\sigma\left(\frac{1}{p_t}\right) \leq 5 \times 10^{-5} \, (GeV^{-1})$$

- Silicon Tracking (SiD) - strips
  - 5 barrel layers, 4 forward disks
  - 1.2 m outer radius
  - Pixels being considered
  - $B = 5T$

- TPC with silicon (ILD)
  - up to 228 hits per track
  - 1.8 m outer radius
  - $B = 3.5 \, T$
Silicon tracking w/ gas cooling → Low material

- Linkage between readout/mechanics/powering/cooling studies.
- Maintain low mass construction.
- Tracking material from SiD design:

![sid02 Tracker Material Scan](image)

SiC foam, J. Goldstein
Tracking Performance starts PFA

arXiv:1306.6329
Typical Jet Fractions

<table>
<thead>
<tr>
<th>Type</th>
<th>$E/E_{\text{tot}}$</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM</td>
<td>26.55</td>
<td>19.33</td>
</tr>
<tr>
<td>CH</td>
<td>69.59</td>
<td>19.49</td>
</tr>
<tr>
<td>NH</td>
<td>3.299</td>
<td>6.632</td>
</tr>
</tbody>
</table>

Neutral Hadrons

Charged Hadrons

EM
ILC Calorimetry

- Typical hadronic jet energy
  - charged hadrons ~65%
  - photons ~25%
  - neutral hadrons ~10%

- Special conditions of ILC motivates particle flow approach for improved jet resolution (~3%) over traditional calorimetry. (inside coil).

- **Particle Flow (both validated detectors, ILD and SiD)**
  - use tracker momentum measurement
  - highly granular particle calorimeters to add neutral energy (EM + Had)

- Forward calorimeters (specialized) also needed
  - Measure luminosity via small angle Bhabha scattering
  - Provide fast feedback to machine via beamstrahlung remnants
  - in a higher radiation environment
Jet Energy Measurement via Particle Flow

Particle Flow:
- Jet resolution goal is 3-4\% above 100 GeV
- In jet measurements, use the excellent resolution of tracker, which measures bulk of the energy in a jet
- Requires high granularity in calorimeter ⇒ \(~10^8\) cells

<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>(~65-70%)</td>
<td>Tracker</td>
<td>(&lt; 0.005% p_T) negligible</td>
</tr>
<tr>
<td>Photons</td>
<td>(~25-30%)</td>
<td>ECAL</td>
<td>(~ 15% / \sqrt{E})</td>
</tr>
<tr>
<td>Neutral Hadrons</td>
<td>(~5-10%)</td>
<td>ECAL + HCAL</td>
<td>(~ 60% / \sqrt{E})</td>
</tr>
</tbody>
</table>

Headroom for confusion

\(< 2\% \text{ @ 100 GeV}\)
Testing PFA Concept w/ Pandora

- Pattern recognition for particle flow calorimetry implementation for the ILC.
- Exploiting the fine granularity detectors.
- Reconstructs paths of individual visible particles.
- Identification of trajectories allows particle four-momenta from subdetector with best measurements.
- Unprecedented jet energy resolution.

Jet energy resolution (in %) for Z' events as a function of jet energy in a realistic detector PandoraPFA.

Also shown are effects of confusion and result assuming perfect PFA.

High Granularity Calorimetry for the ILC
Calorimetry- Optimized for Particle Flow
Cost constrained!

- SiD Silicon-Tungsten ECAL
  - Tungsten absorber
  - 20 “thin”+10 “thick” layers
  - 20 x 0.64 $X_0$ + 10 x 1.3 $X_0$
    ~26 $X_0$

- Baseline Readout
  - 13 mm$^2$ silicon pads
  - KPiX 1024 channel system bump bonded directly to large Si Sensors

- SiD HCAL
  - 40 layers steel absorber (4.5 $\lambda$)

- Proposed Readout
  - 3x3 cm scintillator w/ SiPM’s

Particle flow significantly improves jets resolution by reducing contribution of hadron calorimeter resolution.
SiD ECal

- Measure energy of photons (~25% of jet energy)
- Identify charged tracks depositions in calorimeter by matching tracks with calorimeter depositions
- Measure initial depositions of neutral hadron interactions

- Each of these requirements done independently rely on high granularity to separate processes
  - Transverse spreading of showers (scaling with Moliere radius) compromises granularity
HCal: \( \frac{\Delta E}{E} = 0.094 \oplus \frac{0.56}{\sqrt{E}} \)

ECal: \( \frac{\Delta E}{E} = 0.01 \oplus \frac{0.17}{\sqrt{E}} \)
Transverse EM Shower Development Important

- Separation of “particles” in ECal depends on transverse shower profile
- Recent LumiCal beam test
  - 4 layers
  - 2 x 3.5 mm W
  - W/Si every 13.5 mm
  - Only instrumented four layers
- Measured $R_M = 24$ mm
  - Note: $R_M(W) = 9.3$ mm

Transverse EM Shower Development

- Transverse shower development, and multiple “track” confusion, contained by maintaining small Moliere radius.

<table>
<thead>
<tr>
<th>LumiCal</th>
<th>Wide gap</th>
<th>Narrow gap</th>
<th>No gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>W(mm)</td>
<td>7</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>gap(mm)</td>
<td>6.5</td>
<td>2.5</td>
<td>1.0</td>
</tr>
<tr>
<td>R_M(cm)</td>
<td>2.4</td>
<td>1.86 †</td>
<td>1.30 †</td>
</tr>
</tbody>
</table>

† Assumes pure W. Detail depends on alloy.

Silicon sensors and KPiX ASIC

- 6 inch wafers, 1024 13 mm² pixels
- One 1024 channel KPiX ASIC on each wafer
- KPiX readout is bump-bonded directly to sensor

~1 mm gap: minimize Moliere radius, keep calorimeter compact

Tungsten plates thermal bridge to cooling on edge
Silicon-tungsten ECal - very high granularity

SiD ECal Design

- 6 inch wafers
- 1024 13 mm² pixels
- KPiX readout and cable are bump-bonded directly to sensor
- 1 mm readout gaps -> 13 mm effective Moliere radius
- Tungsten plates thermal bridge to edge cooling
- Feeds Particle Flow (~3% jet resolution at 100 GeV)
- EM resolution: 17%/sqrt(E)
KPiX – a readout system on a chip

- A 1024 channel system to be bump bonded directly to large Si Sensors – enabling the Si Tracker and EMCal.
- Optimized for the ILC, with multi-hit recording during the train, and digitization and readout during the inter-train gap (199 ms).
- Front-end power down during inter-train gap. Mean power/channel <20 µW.
- Large dynamic range (for calorimetry) by dynamically switching the charge amp feedback cap.
- Pixel level trigger; trigger bunch number recorded.

J. Brau et al., 2012 IEEE NSS and MIC Record N35-3, SLAC-PUB-15285.
Initial test beam module for T-511 only
9 Si + 8 W layers (~ 6 $X_0$)
Test beam ECAL prototype design – with SiD longitudinal profile

• First system test EMCal sensors in SLAC End Station A beam.

• 12.1 GeV electrons

• Utilized successfully bump bonded KPiX to sensor and sensor to cable.

• Uncovered issues related to many pixels triggered simultaneously. One part of solution may be on sensor:
single-electron showers

Event display
– Kyle Travis and Dylan Mead
another one-electron event
Test Beam Results

- Upstream layer
- Two overlaid runs

Beam size profile in depth

Upstream layer - MIPs
Simulation of Test Beam

- Geant4 - generated electron showers through 9 simulated Si layers (6 $X_0$ tungsten)
- Poisson distribution of events with 1, 2, 3, 4, or 5 simultaneous electrons
  - $\langle n \rangle = 0.8725$
- Random exclusion of “dead pixels”
- Normal distribution of events shifted from center

Work done at the University of Oregon: A. Steinhebel, J. Barkeloo, D. Mead
Simulation vs. Test Beam Data ($6X_0$)

Total Measured Charge per Cleaned or Simulated Electron Events ($6X_0$)

- 37.3% simulated events had $>1$ electron

Steinhebel and J. Brau, arXiv:1703.08605
Test Beam - Counting Electrons in $6X_0$
Test Beam Results – Counting Electrons in 6 $X_0$

Simulated 2-Electron Event Counting Efficiency

Correctly count 2-electrons with 98.5% average efficiency when separated by >1 cm

Steinhebel and J. Brau, arXiv:1703.08605
Calorimeter Geometry

**HCal**
Scintillator sampling calorimeter
Steel/polystyrene

**ECal**
Solid state sampling calorimeter
Tungsten alloy/silicon

Simulation Studies

Steinhebel and J. Brau,
arXiv:1703.08605
Geometry Effects

Leakage into HCal

Steinhebel and J. Brau, arXiv:1703.08605
Can performance be maintained with fewer layers?

16+8
16 x 0.64 $X_0$, 8 x 1.3 $X_0$

20+10
20 x 0.64 $X_0$, 10 x 1.3 $X_0$

BASELINE DESIGN
Reducing ECAL depth from $26 \times X_0$ to $21 \times X_0$ increases leakage.

Can resolution be recovered?
Resolution and Leakage for Different Average Electron Energy

$\theta = 0^\circ$ to $45^\circ$, $\phi = 17^\circ$ to $23^\circ$

- Average Leakage (16+8 Layers)
- Resolution (16+8 Layers)
- Resolution (20+10 Layers)
- Resolution (60 Thin Layers)

L. Braun et al., arXiv:2002.05871
Neural Net Corrections for Energy

Hi longitudinal and transverse segmentation allows detailed analysis, event-by-event.

L. Braun et al., arXiv:2002.05871
SiD SiW ECAL is Cost Constrained!

From the ILC TDR:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beamline Systems</td>
<td>3.7</td>
<td>1.4</td>
<td>4.0</td>
<td>10.0</td>
<td></td>
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<tr>
<td>VXD</td>
<td>2.8</td>
<td>2.0</td>
<td>8.0</td>
<td>13.2</td>
<td></td>
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<td>Tracker</td>
<td>18.5</td>
<td>7.0</td>
<td>24.0</td>
<td>53.2</td>
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</tr>
<tr>
<td>ECAL</td>
<td>104.8</td>
<td>47.1</td>
<td>13.0</td>
<td>288.0</td>
<td></td>
</tr>
<tr>
<td>HCAL</td>
<td>51.2</td>
<td>23.6</td>
<td>13.0</td>
<td>28.1</td>
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<td>Muon System</td>
<td>8.3</td>
<td>3.0</td>
<td>5.0</td>
<td>22.1</td>
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<tr>
<td>Electronics</td>
<td>4.9</td>
<td>1.6</td>
<td>44.1</td>
<td>41.7</td>
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<tr>
<td>Magnet</td>
<td>115.7</td>
<td>39.7</td>
<td>28.3</td>
<td>11.8</td>
<td></td>
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<tr>
<td>Installation</td>
<td>4.1</td>
<td>1.1</td>
<td>4.5</td>
<td>46.0</td>
<td></td>
</tr>
<tr>
<td>Management</td>
<td>0.9</td>
<td>0.2</td>
<td>42.0</td>
<td>18.0</td>
<td>30.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>314.9</strong></td>
<td><strong>126.7</strong></td>
<td><strong>186.0</strong></td>
<td><strong>532.1</strong></td>
<td><strong>30.0</strong></td>
</tr>
</tbody>
</table>

M&S Cost (incl. contingency) = ~33M$ + ~2.4M$ (no. of layers)
The Future for SiW ECal is MAPS

- M. Breidenbach at SLAC is investigating this approach.
- Monolithic technologies have the potential to provide higher granularity, thinner, intelligent detectors at lower overall cost.
  - Significantly lower material budget
    - Eliminate the need for bump bonding or other challenging interconnect methods.
    - Can be thinned to less than 100 μm.
  - Smaller pixel size.
    - Not limited by bump bonding.
  - Lower costs
    - Can be implemented in standard commericial CMOS technologies (ATLAS estimated a savings in cost of about $35M switching to MAPS for the ITK upgrade.)
Particle Flow Technologies

- **High granularity**
  - HCal ~ O(1 cm³) - ECal ~ O(0.001 cm³)
- **Scintillator**
  - strips or cells, read out by SiPMs
- **Gas**
  - glass RPC, either Digital or Semi-digital
  - MPGD (GEM, MicroMegas, …)
    - built-in suppression of sparks
    - tuning of resistivity allows variation of high rate capability
- **Semi-conductor diodes**
  - silicon for ECal
  - GaAs considered for radiation hardness requirements

**CALICE COLLABORATION HAS DEVELOPED MANY TECHNOLOGIES**
CALICE Technologies

Validation

- A rich test beam program, with a variety of different prototypes

Electromagnetic - Tungsten absorbers
analog: Silicon and Scintillator/SiPM
digital: Silicon (MAPS)

39 Mpixels in 160 cm²

Hadronic - Steel and Tungsten absorbers
analog: Scintillator/SiPM (Fe and W)

(Semi)digital: RPCs (Fe, W digital only)

+ few-layer SD prototype with Micromegas
AHCAL testbeam prototype

- 38 active layers of 72*72 cm²
- 4 HBUs per module
  - 16 SPIROC 2E readout ASICs, 576 channels of 3*3 cm² tiles
  - in total: 608 ASICs, ~22000 channels
- all modules with surface-mount MPPCs
  - S13360-1325PE
  - 2668 pixels
  - operated at 5V overvoltage
  - nominal operation voltage within 200mV in a module -> use same voltage
- all modules are interchangeable, so positioning in stack according to quality (worst modules in the back)
- steel absorber stack corresponding to ~1% of ILD barrel
Event displays and online monitoring

Test Beam - H2 at SPS
Online Monitoring: Energy Sums

Electron Beam

- 10 GeV
- 20 GeV
- 30 GeV
- 40 GeV
- 50 GeV

Pion Beam

- 10 GeV
- 40 GeV
- 60 GeV
- 100 GeV

Energy Sum [MIP]

Energy [MIP]
Selected CALICE Publications


Conclusion

- Highly granular calorimeters working with efficient tracking detectors offer excellent performance based on Particle Flow technique.
- The ILC detectors (SiD and ILD) have been conceived to achieve excellent performance based on this technique.
- Simulation and test beam studies of prototype calorimeters have achieve promising performance.
- Integration of chosen subsystems (tracking, calorimeters, solenoid) to realize overall performance with realistic engineering constraints has begun, but much needs to be completed.
- There’s much still to be done to finalize detailed choices and performance optimization. SiD seeks colleagues to challenge assumptions and improve choices.