Towards the ILC: Physics and Detectors

Part I: Exploring „The Boson“
Part II: Experimental challenges
Part III: Realizing the ILC

Event reconstruction I
1.) Remove all PFOs with:
   • \( p_T < 500 \text{ MeV} \)
   • \( \Theta < 20^\circ \)
   • \( \Theta > 160^\circ \)
2.) Remove identified isolated leptons from PFO list

8jet signal event
Landmark discovery of Boson H(125) marks the start of long-awaited new research line in the field of particle physics.

- a good candidate for the first fundamental scalar!
- is it the long-sought Higgs boson of the (minimal) Standard Model?
- is it responsible for EWSB? (i.e. is it the excitation of a scalar field with $v \neq 0$ ?
- does it cure the divergence of SM amplitudes at high $E$ ($W_L W_L \rightarrow W_L W_L ...$)?
- Is it embedded into a larger non-SM Higgs sector?
- Is it elementary or composite?
- Does it provide a window to BSM physics?

→ Study the particle with all possible experimental means to the greatest precision
The Tools

Proton proton collisions

\[ p + p \rightarrow H \]

Electron positron collisions

\[ e^+ + e^- \rightarrow H \]
The Tools

Proton proton collisions

\[
p + p \rightarrow H + X
\]

Electron positron collisions

\[
e^+ + e^- \rightarrow H + X
\]

LHC

Running!

Today: ~30 fb\(^{-1}\) @ 7/8 TeV
~2021 300 fb\(^{-1}\) @ 14 TeV
~2030 3000 fb\(^{-1}\) @ 14 TeV HL-LHC

Linear colliders:

ILC

250...500...1000 GeV

TDR

Circular colliders:

CDR

250...1400...3000 GeV

LEP3 90..240GeV (27 km)
TLEP 90..240..350GeV (80 km)

(other: \(\gamma\gamma \rightarrow H\), \(ep \rightarrow H+X\), \(\mu\mu \rightarrow H\))
TDR completed – „(technically) ready to be built“
Two detector concepts (ILD, SiD) delivering DBDs

Optimized for 500 GeV (500 fb\(^{-1}\) in 4 years)
Extendable to ~ 1 TeV

Strong interest from Japan to host the ILC as a global project
Proposal: start at 250 GeV – then 500 GeV – site ok for ~1 TeV
e^+e^- colliders

- clean final states
- full kinematic reconstruction
- low backgrounds
- triggerless operation
- polarized beams

→ a precision tool for discovery

e^+e^- \rightarrow HZ \rightarrow (\tau\tau)(\mu\mu) \rightarrow (\tau\nu)(\tau\nu) (\mu\mu)
The Profile of the Higgs Boson

\[ \mathcal{L}_{EW}^{SM} = -\frac{1}{4} W_a^{\mu \nu} W_a^{\mu \nu} - \frac{1}{4} B_\mu B^{\mu \nu} \]

\[ + \bar{L} \gamma^\mu \left( i \partial_\mu - \frac{1}{2} g \tau_a W_\mu^a - \frac{1}{2} g' Y B_\mu \right) L \]

\[ + \bar{R} \gamma^\mu \left( i \partial_\mu - \frac{1}{2} g' Y B_\mu \right) R \]

\[ - \left| \left( i \partial_\mu - \frac{1}{2} g \tau_a W_\mu^a - \frac{1}{2} g' Y B_\mu \right) \Phi \right|^2 \]

\[ + \mu^2 |\Phi|^2 - \lambda |\Phi|^4 \]

\[ - (\sqrt{2} \lambda_d \bar{L} \Phi R + \sqrt{2} \lambda_u \bar{L} \Phi_c R + h.c.) \]

L may contain more terms – can we discover them?

Bottom-up reconstruction of the Higgs Lagrangian

- Higgs gauge couplings
- Higgs fermion couplings (largest # of SM par´s)
- Higgs mass (\(\mu\))
- Higgs self coupling (\(\lambda\))
- Coupling structure (CP)

Are we ready to call it „a Higgs boson“ ? „the Higgs boson“ ?

scientific goal: understand EWSB (!) through studying the new particle
The quest for precision – why?

Only one example (theory provides many...):

Fit LHC and Tevatron „signal strength“ parameters to the MSSM taking into account limits, B-physics constraints etc.

→ both h and H provide a reasonable fit

- tiny differences between best fit and SM
- tiny differences between h and H hypotheses
- $\Delta \mu / \mu \lesssim 5\%-20\%$

• Many processes at different $\sqrt{s}$ needed & accessible
Higgs analyses at ILC

- spin/parity → CP violation?
- total decay width
- decays (non-standard modes?)
- "model-independent" couplings
- self coupling

- search for additional Higgs-like particles (e.g. low-mass, ...)

Complemented by precise measurements of SM processes related to EWSB

- top quark
- triple gauge couplings
- quartic gauge couplings
- Z/W (e-w. mixing angle, ...)

→ this is discovery physics

No time to discuss everything today...
Towards Higgs couplings

Comparison: compare apples with apples

Collider experiments measure rates / visible cross sections for certain final states

\[ \sigma_{vis} = \sigma_{prod} \times BR(H \rightarrow f) \]

LHC:

- Accessible production modes:
  - gg fusion
  - vector boson fusion
  - WH/ZH associated production
  - ttH production

LC:

- Accessible production modes:
  - vector boson fusion (WW/ZZ)
  - HZ (Higgs-strahlung)
  - ttH

Signal strength \[\mu = \frac{\sigma_{vis}}{\sigma_{vis} (SM)}\]
Table 2.6.4: Expected accuracies for cross section times branching ratio measurements for the 125 GeV $h$ boson.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\sqrt{s}$ and $\mathcal{L}$ ($P_{e^-}, P_{e^+}$)</th>
<th>$\Delta(\sigma \cdot BR)/\sigma \cdot BR$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$250 \text{ fb}^{-1}$ at 250 GeV $\ (-0.8,+0.3)$</td>
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<tr>
<td></td>
<td></td>
<td>$250 \text{ fb}^{-1}$ at 250 GeV $\ (-0.8,+0.3)$</td>
</tr>
<tr>
<td>$h \to b\bar{b}$</td>
<td>$1.1%$</td>
<td>$1.8%$</td>
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<tr>
<td>$h \to c\bar{c}$</td>
<td>$7.4%$</td>
<td>$12%$</td>
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<tr>
<td>$h \to g\bar{g}$</td>
<td>$9.1%$</td>
<td>$14%$</td>
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<tr>
<td>$h \to WW^*$</td>
<td>$6.4%$</td>
<td>$9.2%$</td>
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<tr>
<td>$h \to \tau^+\tau^-$</td>
<td>$4.2%$</td>
<td>$5.4%$</td>
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<tr>
<td>$h \to ZZ^*$</td>
<td>$19%$</td>
<td>$25%$</td>
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<tr>
<td>$h \to \gamma\gamma$</td>
<td>$29-38%$</td>
<td>$29-38%$</td>
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<tr>
<td>$h \to \mu^+\mu^-$</td>
<td>$100%$</td>
<td>$-%$</td>
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</table>

significant recent analysis effort towards ILC TDR (DBD)
all based on very detailed full detector simulation (ILD/SiD)
all are statistics limited (check $bb$) $\Rightarrow$ push for luminosity!
LHC vs LC: „signal strength“

**compare apples with apples**

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC250</th>
<th>+ILC500</th>
<th>ILC1000</th>
<th>CLIC3000</th>
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<td>zz</td>
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<td>gg</td>
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**Precision on signal strength**

\[ \mu = \frac{\sigma}{\sigma_{\text{BR}}}/\left(\frac{\sigma}{\sigma_{\text{BR}}}_{\text{SM}}\right) \]

**LHC** – mostly syst. limited
**LC** – mostly stat. limited

**ILC1000/CLIC1400 further improves precision**

**KD attempt to compile available experimental studies.**
(best estimates)

**HANDLE WITH CARE**

**fineprint:**

ATLAS/CMS from Krakow notes (= preliminary!)

LHC = (ATLAS+CMS)/2 (300 fb⁻¹)
HL-LHC = ATLAS (3000 fb⁻¹)
ILC250 = 250 fb⁻¹ at 250 GeV
+ILC500 = 500 fb⁻¹ at 500 GeV + 250 fb⁻¹ at 250 GeV
ILC1000 + CLIC3000 are only examples

1) prec. on \(\sigma_{HZ}\) (total)
2) prec. on \(\sigma_{WW\text{-Fusion}}\) (total)
LHC: no known (to me) method to extract absolute Higgs BRs

LC: Recoil mass technique in $e^+e^-\rightarrow HZ$ allows us to measure $\sigma_{HZ}$ indep. of H-decay

Once $\sigma_{HZ}$ is known, any signal strength measurement can be turned into absolute BR's measurement: $BR_X = (\sigma \times BR_X)_{\text{meas}} / \sigma(\text{tot})_{\text{meas}}$

unique to lepton colliders (needs $(E,p)$ constraint from initial state)
Invisible Higgs

The recoil mass technique also allows for unbiased observation of any non-SM decay, e.g. $H \rightarrow \text{invisible}$:

\[ 5\sigma \text{ observation for BR}(H \rightarrow \text{inv.}) = 2\% \text{ (at } \sqrt{s} = 350 \text{ GeV/500 fb}^{-1}) \]

New study at 250 GeV: $\text{BR}(H \rightarrow \text{inv}) < 0.7\%$ at 95\%CL

also applies to „LHC-invisible“ decays, e.g. $H \rightarrow gg$, $H \rightarrow qq$ etc.
Towards couplings: total width

no apples at the LHC

LHC: no absolute couplings without assumptions on „invisible“ couplings

ILC: need to measure $\Gamma_{\text{tot}}$ in addition to absolute BR’s to extract couplings in a model-independent way

$$\sigma_{\text{vis}} = \sigma_{\text{prod}} \times BR(H \rightarrow f)$$

$$\sigma_{\text{prod}} \sim g_{Hi}^2 \quad \text{and} \quad BR(H \rightarrow f) = \frac{\Gamma_f}{\Gamma_{\text{tot}}} \sim \frac{g_{Hf}^2}{\Gamma_{\text{tot}}}$$

$$\sigma_{\text{vis}} \sim \frac{g_{Hi}^2 g_{Hf}^2}{\Gamma_{\text{tot}} (g_{Hj}; j = 1 \ldots n)}$$

$$\Gamma_{\text{tot}} := \Gamma(g_{Hj}; j = 1 \ldots n_{\text{vis}})$$

In general, $\sigma_{\text{vis}}$ is a complicated function of all (including „invisible“) couplings.
The total width

\[ \Gamma_{\text{tot}} (\text{SM}) \sim \text{few MeV} \rightarrow \text{no way to measure lineshape except maybe at a } \mu \text{C} \]

\[ \rightarrow \text{In } e^+e^- \text{ access total width through:} \]

\[ \Gamma_{\text{tot}} \sim \frac{BR(H \rightarrow X)}{g_{HX}^2} \]

\[ \rightarrow \text{a) measurement of } BR(H \rightarrow ZZ) (+ g_{HZ} \text{ from recoil mass}) \quad \text{or} \]

\[ \rightarrow \text{b) measurement of } g_{HW} \text{ in } WW\text{-fusion} (+ BR(H \rightarrow WW) \]

Precision on \( \Gamma_{\text{tot}} \) directly enters into precision on (model-independent) couplings and may even dominate!

a) \( BR(H \rightarrow ZZ; 125 \text{ GeV}) = 0.024 \) -- rather low statistics

b) the method of choice!
The total width

Need to measure WW-fusion cross section (e.g. $e^+e^- \rightarrow H\nu\nu \rightarrow bb\nu\nu$)

- need to separate from $HZ\rightarrow bb\nu\nu$ (+ handle interference)
- WW-fusion small at $HZ$ threshold! \( \Rightarrow \) need higher \( \sqrt{s} \)

precision on $\sigma_{WW\text{-fusion}}$:

\[
\begin{align*}
250 \text{ GeV} & : 11.0 \% \\
350 \text{ GeV} & : 3.6 \% \\
500 \text{ GeV} & : 3.2 \%
\end{align*}
\]

\( \Rightarrow \) dominated by error on BR($H\rightarrow bb$)
Higgs couplings at LC

model-independent relative errors on Higgs couplings:

fineprint:
numbers mainly from LC Krakow report
ILC250: KD square-added 5% from $\Delta \Gamma_{\text{tot}}$ (omitted in Krakow report)
analysis are ongoing – KD expects further improvements
+ILC500 means ILC250 + ILC500

further improvements from ILC1000/CLIC1400/CLIC3000 (e.g. $\Delta g_t \approx 4\%$ at ILC1000)
**Events at the ILC:**

- multi jet final states
- leptons, often in jets
- forward region important
- excellent flavour tagging b/c/udsg

Jet energy reconstruction plays a central role at the ILC

---

**ttH → 8 jets event**

[Image credit: P.Roloff, J.Strube, LCWS12]
Detectors for the ILC

What’s different compared to LHC detectors?

Can one use ATLAS/CMS for e^+e^-?
(maybe – see M.Klute et al, arXiv:1208.1662 but not really...)

ILC: different scope, different challenges (and ~20 years of technology advance)

physics:
- low-E jets $\rightarrow$ high efficiency for multi-jet final states
- better momentum resolution $\rightarrow$ Higgs recoil mass
- forward coverage $\rightarrow$ high efficiency, $\gamma\gamma$ background
- charm tagging

operation:
- triggerless readout
- bunch structure – power pulsing (ms beam, 200 ms break)
- radiation damage not a big issue
Technology advances

New detector technologies were invented since design of ATLAS/CMS, e.g.

- highly-granular ultra-thin pixel devices (DEPFET, CMOS, ...)
- MPGDs (GEMs, Micromegas, InGrids) for gaseous detector r/o
- Silicon Photomultipliers (SiPM)

→ „spin-off“ of LC detector R&D to other experiments and v.v.

DEPFET (Belle II)  InGrid (CAST)  SiPM (LHCb)
(Somewhat) complementary approaches
- gaseous vs. Si tracking
- „large“/moderate B vs. „compact“/huge B
- both share approach for vertexing and particle flow reconstruction
What is particle flow?

No strict definition of particle flow

- move away from pure calorimetry to measure jet energies
- move towards full event reconstruction
- use tracking and calorimeters wherever they perform best

Different depths of implementation

A use tracks to correct jet energies ("energy flow", e.g. ALEPH, OPAL, ...)

B aim to reconstruct particles not energy deposits (CMS, ATLAS?)

C high granularity particle flow (ILD, SiD)

   optimize calorimeter (and tracker) for particle flow

How does it work?
How does it work?

Resolution tracker - Calorimeter

$\sigma(E)/E$

$E(\text{GeV})$

[120 GeV]

[370 GeV]

ECAL

HCAL

tracker

[T. Behnke]
Traditional Calorimetry

★ In a typical jet:
  ◦ 60% of jet energy in charged hadrons
  ◦ 30% in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  ◦ 10% in neutral hadrons (mainly $n$ and $K_L$)

★ Traditional calorimetric approach:
  ◦ Measure all components of jet energy in ECAL/HCAL!
  ◦ ~70% of energy measured in HCAL: $\sigma_E/E \approx 60\%/\sqrt{E(\text{GeV})}$
  ◦ Intrinsically “poor” HCAL resolution limits jet energy resolution

High quality tracking information not used

$E_{\text{JET}} = E_{\text{ECAL}} + E_{\text{HCAL}}$

[M. Thomson]
Particle Flow Paradigm

★ Particle flow approach:
  - Try and measure energies of individual particles
  - Reduce dependence on intrinsically “poor” HCAL resolution

★ Idealised Particle Flow Calorimetry paradigm:
  - charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL
  - Neutral hadrons (and ONLY neutral hadrons) in HCAL
  - Only 10% of jet energy from HCAL → improved jet energy resolution

\[
E_{\text{JET}} = E_{\text{ECAL}} + E_{\text{HCAL}}
\]

\[
E_{\text{JET}} = E_{\text{TRACK}} + E_\gamma + E_n
\]

[M. Thomson]
Particle Flow Requirements

**Hardware:** need to be able to resolve energy deposits from different particles
- Requires highly granular detectors (as studied by CALICE)

**Software:** need to be able to identify energy deposits from each individual particle
- Requires sophisticated reconstruction software

Particle Flow Calorimetry = HARDWARE + SOFTWARE

[M. Thomson]
Reconstruction of a Particle Flow Calorimeter:
★ Avoid double counting of energy from same particle
★ Separate energy deposits from different particles

\[ E_{\text{JET}} = E_{\text{TRACK}} + E_\gamma + E_n \]

Level of mistakes, “confusion”, determines jet energy resolution

Three types of confusion:

i) Photons
   Failure to resolve photon

ii) Neutral Hadrons
   Failure to resolve neutral hadron

iii) Fragments
   Reconstruct fragment as separate neutral hadron

[M. Thomson]
Pflow Performance

★ Recall: motivation for high granularity PFlow Calorimetry

Jet energy resolution: \( \frac{\sigma_E}{E} < 3.5\% \)

★ Benchmark performance using jet energy resolution in Z decays to light quarks

★ Use total energy to avoid complication of jet finding (mass resolutions later)

★ Current performance (PandoraPFA + ILD)
  - uds jets (full GEANT 4 simulations)

<table>
<thead>
<tr>
<th>( E_{JET} ) (GeV)</th>
<th>( \frac{\sigma_E}{E_j} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>3.7 %</td>
</tr>
<tr>
<td>100</td>
<td>2.8 %</td>
</tr>
<tr>
<td>180</td>
<td>2.9 %</td>
</tr>
<tr>
<td>250</td>
<td>2.9 %</td>
</tr>
</tbody>
</table>

\( \text{rms}_{90} \)

GOAL MET!

★ Factor 2-3 better than traditional calorimetry!

[M. Thomson]
How is it done?

sampling calorimetry with „ultimate“ transverse & longitudinal segmentation

ECAL (one option):

Tungsten absorber
Silicon sensors as active material
30 layers / 24X₀
Si sensor: 5x5mm² pixel size

HCAL (one option „AHCAL“):

Steel absorber
Scintillating tiles (3x3 cm²) as active mat
readout with Silicon Photomultipliers
48 layers / 6 λ
1 m$^3$ prototype in testbeam (CERN, Fermilab)

Need to validate/improve fine details of complicated hadronic showers (→ GEANT4)
Tracking: material is the challenge!

- ~ factor 4(3) less material in barrel/endcap
- remember material budget for ATLAS/CMS increased time...

TPC ideal for barrel (but keep a eye on endplate)
TPC

• Time Projection Chamber: The central tracker of ILC
• Tracks can be measured with many (~200/track) 3-dimensional $r$-$\phi$-$z$ space points
• $s_{r\phi}<100\mu m$ is expected
• $dE/dx$ information for particle identification
• Two main options for gas amplification: GEM or Micromegas
• Readout pad size $\sim 1x6mm^2 \rightarrow 10^6$ pads/side
• Pixel readout R&D as a future alternative
• Material budget: 5%$X_0$ in barrel region and <25%$X_0$ in endplate region
• Cooling by 2-phase CO$_2$
real data from „Large Prototype“ at DESY
The Pixel-TPC

**GridPix**

Micromegas on a pixelchip
- Insulating pillars between grid and pixelchip
- One hole above each pixel
- Amplification directly above the pixelchip

**Advantages**
- Very high single point resolution
- Perfect alignment
  - Each primary $e^-$ is detected on one pixel
  - Nearly 100% single $e^-$ efficiency
- Low occupancy
First real events from „Bonn“ 8-chip module in LP testbeam
The Pixel-TPC

Next Step: Large Area Module with $O(100)$ Chips

First ideas:
- LP Module with $4 \times 3$ octoboards $= 96$ chips
- Staggered placement
- Active area $\approx 50$

Preparations
- 4 octoboards per FEC
- HDMI for VHDCI cabling
- FPGA code extensions
- Cooling

[M. Lupberger, ...]
ILC: Technical Design Report (Accelerator and Detector) is ready and being handed over today in three global events (Tokyo, CERN, Fermilab)

New organisation led by Lyn Evans is set up.

Goal: realize of the ILC a.s.a.p.
Japanese HEP community proposed to build ILC as a staged global project in JP
Significant political backing (members of parliament, science minister, big industry)
High-level political talks starting

Japanese Prime Minister Abe

Site selection expected this summer
Update of European Strategy

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

c) LHC → HL-LHC (until around 2030)

d) propose post-LHC machine at CERN by next update (~5y) → do R&D

e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation.

f) neutrinos: pave the way for substantial European role in long-baseline expts

formalized on May 30 in Brussels
Conclusions

- Discovery of H(125) turns the physics case for ILC from „hypothetical“ to real!

- Bottom-up reconstruction of the Higgs profile requires high luminosity, precision detectors and a staged running up to at least 500+ GeV

- ILC provides many unique H measurements and is factor of 5-10 more precise where LHC can also contribute, synergy of LHC and ILC

- Strong additional physics case (top, EW gauge boson self couplings, BSM discovery potential for weak signals (not discussed today)

- This potential relies on (challenging) precision detectors → R&D mandatory

Realizing the ILC never was as timely as today!

and finally...
Is it really serious?

yes, it is!