Physics and detectors
International Linear Collider
The Standard Model of Particle Physics

quarks

leptons

gauge bosons

Higgs boson

The Standard Model of Cosmology

- Dark Energy: 75%
- Dark Matter: 21%
- Normal Matter: 4%
These Standard Models leave important unanswered questions.

- Nature of dark matter and energy
- Why is the universe matter-dominated?
- CP violation mechanism in the early universe
- How are they insulated from each other?
- What lies between E-W (~100 GeV) and Plank (10^{19} GeV) scales?

Image shows a pie chart with 4% normal matter, 21% dark matter, and 75% dark energy.
Higgs boson
most recently discovered particle of SM,
(probably)
least well measured
Higgs is unique, in class of its own
not a matter fermion
not a gauge boson
In the SM, the Higgs boson's properties
depend on only its mass
(decay width, branching ratios, ...)

The Higgs sector is (arguably) the most promising place to find
new physics beyond the Standard Model

is CP violated in Higgs interactions?
does Higgs also give mass to dark matter?
is there really only a single type of Higgs boson?
is Higgs really elementary?

is Higgs really elementary?

what lies beyond the SM?

Higgs is unique, in class of its own
not a gauge boson
not a matter fermion
Higgs is unique, in class of its own
(probably) least well measured
most recently discovered particle of SM,
In SM, Higgs couples to particles purely according to their masses. In many models of physics beyond the SM, this relation is altered. By measuring such deviations, we can hope to reveal the nature of underlying physics, and its energy scale.

An example:
Measurement of the Higgs boson properties presents unique opportunity to probe for physics beyond the Standard Model at ~TeV scale.

For physics at ~TeV scale, expect few %-level variations in Higgs boson properties.
Large Hadron Collider

Running at design energy
surpassed design luminosity

→ Higgs boson couplings
ultimiate precision of ~few % on many
increasingly detailed picture of Higgs

3000 fb⁻¹ →

same collision energy, higher luminosity:
High-luminosity LHC [2026 – mid 2030s]:

300 fb⁻¹ →
first "sketch" of its properties
Higgs boson discovery

[last week: end "run 2", "run 3" from 2021-2023
surpassed design luminosity
Running at design energy

Large Hadron Collider
To move beyond LHC precision on Higgs boson properties, require new approach.

b quark discovered in proton fixed target collisions measured in detail at KEKB, PEP-II, SuperKEKB

e.g. W, Z bosons discovered in hadron collider (SppS) measured in detail at lepton colliders LEP, SLC

b quark discovered in proton fixed target collisions measured in detail at KEKB, PEP-II, SuperKEKB

Long history in particle physics of such synergy between hadron and lepton colliders.

Electron – positron collisions require new approach.
Composite particles: collisions between quarks, gluons
dominated by QCD interactions;
wide spectrum of energies
proton momentum → fraction of proton remnants
each carries fraction of

Little debris → clean events
different interactions
democratic occurrence of

Known, fixed energy

Elementary particles
Cross-section [fb]
Contrasting experimental environments
Higgs boson production in electron-positron collisions

Higgs-strahlung

WW-fusion

ZZ-fusion

radiate H from Z

Higgs-fusion

$\sim 0.6 \text{ M Higgs events}$

Total: 2000 fb$^{-1}$ @ 250 GeV:

$\sim 30,000$ events/yr

peak cross-section $\sim 300$ fb

L $\sim 10^{34}$ cm$^{-2}$s$^{-1}$ $\sim 100$ fb$^{-1}$ yr$^{-1}$

initial ILC luminosity

Higgs boson production in electron-positron collisions
The Higgs-strahlung process is particularly powerful because the Higgs can be selected by looking only at Z decay products. We know the initial e^+e^- 4-momentum (lepton collider), we can trivially extract 4-momentum of "H" indirectly from 4-momentum of Z. We can select events with no decay mode bias (e.g., invisible Higgs) and can calculate the Higgs mass. The Higgs can be selected by looking only at Z decay products.
count total number of produced Higgs events, and extract Higgs mass without looking at Higgs decay products. "model independent" not affected by e.g. invisible / unexpectedly weird Higgs decays.
In addition to Higgs physics, ILC will search for direct production of new particles helped by clean experimental environment to cover "blind-spots" of LHC experiments, including invisible signatures of low energy (e.g., \( E > 1 \text{ GeV} \)) signals, or observation of stringent constraints on wider energy range, polarised beams orders of magnitude more luminous than LEP2, or observation of new physics at high scales (\( \sim 10 \text{ TeV} \))

Wide range of electroweak measurements → trigger-less operation → analyse all collisions → models total event rate invisible signatures

Wide range of energy, polarised beams → search for direct production of new particles, or observation of new physics at high scales (\( \sim 10 \text{ TeV} \)).
International Linear Collider project initiated in 2005 under auspices of the International Committee for Future Accelerators (ICFA) → amalgamation of several regional, linear collider studies using different technologies superconducting RF technology selected → lead by B. Barish


Nicomium 1.3 GHz superconducting accelerating structures

average gradient 31.5 MV/m, operated at 2 K

~1m Niobium 1.3 GHz superconducting accelerating structures

Global Design Effort

~7m
e+ e- collisions: C.M.E ~ 250 → 500 GeV, L ~ 10^{32} cm^{-2}s^{-1} with longitudinally polarised beams: e- 80%, e+ 30%

500 GeV machine:
- total length: 31 km
- value estimate: 7.8 billion 2012-USD

Upgradable to 1 TeV
- nm-sized interaction region
- undulator-based e- source; final focus
- e- source; damping rings; main linacs

stable, well-controlled, mature project

Changes to design only via formal change review process

Accelerating technology is mature

Production of niobium cavities in industry;

being used / developed in several other contexts:

e.g. light sources at DESY (E-XFEL), SLAC (LCLS-II), Shanghai;

E-XFEL has been successfully built, commissioned, now running smoothly

17.5 GeV in 2 km

@ ~24 MV/m

10–20% of one ILC arm
Since 2016, proposing initial ILC250 stage, maximum collision energy 250 GeV "Higgs factory" – precision measurement of Higgs

Significantly reduced cost compared to ILC500

ILC will be upgradable to higher energies, if and when the scientific case is sufficiently strong

← improved accelerating technology ← extended tunnel

Maximum collision energy 250 GeV

Since 2016, proposing initial ILC250 stage,
ILC detector design
ILC detector design

General purpose: address wide range of physics analyses

- Charged lepton
- Photon
- Hadron measurement and identification

Highly hermetic collider: relatively low event rates, clean environment

Trigger-less readout: collect all detector signals

Optimal combination of sub-detector information

Precise jet energy measurement by PFA

Analysis of dominant hadronic decays of W, Z, H

Displaced tracks from b, c, t

Momentum resolution

High precision, low material trackers

Designed for particle flow (PFA) reconstruction

Calorimeters with highly granular readout

High precision jet energy measurement by PFA

Precise jet energy measurement by PFA
SiD
- pixel vertex detector
- silicon-only tracking system
- high granularity calorimeters
- 5 T field
- somewhat smaller than ILD
- detectors placed on platforms: move in/out of interaction region

ILD
- pixel vertex detector
- large TPC + silicon strips
- high granularity calorimeters
- 3.5 T field
vertex detector
silicon pixels

ECAL
TPC
HCAL

1.6 → 1.85 m

silicon strips

FCAL

HLA

vertex detector
silicon pixels

ECAL
TPC
HCAL

1.6 → 1.85 m

silicon strips

FCAL

HLA
Typical detector performance (from detailed simulations and prototyping)

**Charged Track Momentum Resolution**

\[
\frac{d_0}{\langle p \rangle} \sim 3 \times 10^{-5} \langle p \rangle
\]

→ important for "recoil" H mass measurement

**Hadronic Jet Energy Resolution**

\[
\frac{\sigma_{\text{E}}}{\text{E}} \sim 3 \% \text{ over wide energy range}
\]

→ optimal combination of tracking and calorimeter

**Charged Track Impact Parameter Resolution**

\[
\sigma_{d_0} \sim 5 \mu m \left( 10 \mu m / p [\text{GeV}] \sin^{3/2} \theta \right)
\]

→ important for identification of b, c, and \( \tau \) decays

**Covers almost 4\( \pi \) solid angle**

→ important for "missing momentum" searches
Expected physics performance
Several key measurements impossible at LHC
Significant improvements with respect to HL-LHC prospects
Strong synergies with HL-LHC in some cases
Model-dependent or better in most cases
% level measurements in most cases

**HL-LHC**
Initial 8 years of ILC
Full 20 year program

arXiv:1506.05992

- Several key measurements impossible at LHC
- Significant improvements compared to HL-LHC prospects
- Strong synergies with HL-LHC in some cases
- % level measurements or better in most cases

**Higgs couplings precisions at ILC**

Model-dependent compared to CMS HL-LHC

Model-dependent at LHC

Higgs couplings precisions at ILC
not in reach of HL-LHC

new particles associated with these models
Another example:

Our matter-dominated universe requires a source of CP violation in early universe.

CP violation in Higgs sector?

Electro-weak baryogenesis at the Electro-Weak breaking scale?

Cannot be accounted for by current known sources of CP violation?
Is the 125 GeV Higgs a CP eigenstate?

$$h_{125} = \cos \psi_{CP} h_{CP}^{even} + \sin \psi_{CP} A_{CP}^{odd}$$

[e.g. extra Higgs doublets]

- pure CP even: $\psi_{CP} = 0$
- standard Model
- $h_{125} = \cos \psi_{CP} h_{CP}^{even}$
- odd: $\psi_{CP} = \pi/2$
- excluded at LHC
- $h_{125}$ = $\cos \psi_{CP} h_{CP}^{even} + \sin \psi_{CP} A_{CP}^{odd}$
- [Standard Model]
- maximally violating $\psi_{CP} = \pi/2$
- or partially violating $\psi_{CP} = \pi/2$
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Correlation between fermion spins carry CP information

Decay of spin-0 particle into 2 fermions:

- Charge +
- Parity
- Spin

General state: \( \left| \uparrow \downarrow \right> - \left| \downarrow \uparrow \right> \) → CP odd
- CP even

CP eigenstates of CP:
- \( \left| \uparrow \downarrow \right> + \left| \downarrow \uparrow \right> \) → CP even
- \( \left| \uparrow \downarrow \right> - \left| \downarrow \uparrow \right> \) → CP odd

Charge = \( \psi \) + e^{2i\phi}
A spin 0 state:

\[ |\uparrow\downarrow\rangle = |\uparrow\downarrow\rangle + e^{2i\psi}|\downarrow\uparrow\rangle \]

\[ \psi = 0 \quad \text{CP even,} \]
\[ \psi = \pi/2 \quad \text{CP odd} \]

[ CP mixing angle $\phi$ ]

Distribution of $4\phi$ is sensitive to CP mixing angle $\phi$.

\[ \phi - \phi = \phi \]

MC level

arbitrary normalisation

MC level

Taus have short lifetime.

Higgs often decays to taus.

Higgs often decays to tau leptons [fermions]

\[ \text{At ILC, we can probe CP of Higgs bosons} \]

[ tau+ polarimeter ]

[ tau- polarimeter ]

[ polarimeter vector ]

most probable spin direction

reconstruct decay kinematics

in its decays to tau leptons [fermions]
Clean ILC environment and high precision detector allow excellent reconstruction of tau lepton decays, including their spin direction.

Full detector simulation and realistic reconstruction will measure CP-sensitive angle $\psi^{CP}$ to precision of $75 \text{ mrad} \approx 4 \text{ deg.}$

Phase of signal distribution $\sim g \left( \cos \psi^{CP} + i \gamma^{5} \sin \psi^{CP} \right) f H$

At ILC250, will measure $\psi^{CP}$ to precision of $\sim 75 \text{ mrad} \approx 4 \text{ deg.}$


Jeans, NIM A810 (2016) 51
ILC: precision exploration of Higgs sector

Many other tests of Standard Model

Higgs sector

New Particle Searches

Electro-Weak sector

high luminosity, polarised beams

clean environment

trigger-less operation

CCD
Potential future ILC energy upgrades
make beautiful measurements of the top quark mass

experimentally precise, theoretically well-understood

Higgs self-coupling — H t t-bar production → top Yukawa coupling

Top quark electro-weak couplings

~ 1 TeV

~ 500 – 600 GeV

~ 350 GeV

Higgs self-coupling ← clearer view of Higgs potential shape

Top quark mass measurement

Threshold scan of $e^+e^-$ → $t\bar{t}$ make beautifully measurable of the top quark

Top quark electro-weak couplings

Higgs self-coupling ← indirect probe of new physics

Top quark electro-weak couplings

~ 1 TeV

~ 500 – 600 GeV

~ 350 GeV
Conclusion

The ILC will make wonderfully precise measurements of the Higgs and top sectors, and will search for new physics, both directly and indirectly. These measurements will help us along the correct BSM path. The ILC will make wonderfully precise measurements of the Higgs and top sectors, and will search for new physics, both directly and indirectly. These measurements will help us along the correct BSM path.

The political process for this large, international project is now in a critical period. Can imagine a series of well-motivated upgrades to ILC's luminosity and energy over a period of 20-30 years. We are ready to build the ILC and its detectors.

First "Higgs factory" stage at 250 GeV before March 7 statement of interest.