Detector & physics studies for a linear $e^+e^-$ collider

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Acknowledgements and disclaimer

This talk is a personal view and does not necessarily reflect the position of projects I’m involved in (LCC, ILC, ILD, CLIC)

Most of the material is based on studies in the framework of ILD or CLICdp, and would not have been possible without a large effort of many people to design detectors, develop MC tools, etc.
Present and future projects

Particle physics' current energy-frontier installation

HL-LHC collects $3 \text{ ab}^{-1}$ by 2037

Long-term future may include a 27 TeV “energy doubler” at CERN or a brand-new hadron collider with a center-of-mass energy up to 100 TeV
A brief history of collider physics

1972: a 5M$ collider starts operation on a SLAC parking lot
1974: Two colliders in one country discover the same particle

1984: First LHC workshop

1994: SSC canceled, LHC approved

2005: envisaged start of the LHC
2010: start of the LHC

2020: decide next energy-frontier facility?

2035: start of operation of collider XXX

Particle physics was so easy back then!

HEP needs a plan!
Linear $e^+e^-$ colliders

**Accelerating cavities**

SLC was built with 17 MV/m cavities (1989-1998)

Intense R&D and industrialization program to improve acceleration gradient

→ 35 MV/m super-conducting cavities
   (mature & industrialized, XFEL/ILC)

→ 100 MV/m “warm” cavities
   (concept proven in large-scale tests, CLIC)

→ Plasma wakefield (when?)

See Daniel Schulte’s talk, this morning

Or these excellent reviews of the future of **cold** and **warm** RF technologies
Lepton collider projects

**e^+e^- collider projects:**
- ILC (TDR, negotiations):
  250, 500, 1000 GeV
- CLIC (CDR):
  380, 1500, 3000 GeV
- CEPC (pre-CDR, TDR ~2020):
  250 GeV, tt production?
- FCC-ee (CDR 2018):
  90, 160, 240, 350, 370 GeV

*Detailed design reports for ILC/CLIC CEPC/FCC-ee CDR expected soon*

**Clear complementarity:**
Circular is superior at low energy, linear is the only option at high energy
ILC operating scenario

Scenario H-20 accumulates:
- 2 \text{ ab}^{-1} at 250 \text{ GeV}
- 4 \text{ ab}^{-1} at 500 \text{ GeV}
- 200 \text{ fb}^{-1} at top threshold in several stages over 20 years

ILC envisages 80% electron and 30% positron polarization
See: arXiv:1801.02840
ILC operating scenario

To reduce the cost of the initial project, the focus of the project is 250 GeV operation

Physics case of standalone 250 GeV with 2 ab$^{-1}$ run worked out in arXiv:1710.07621

Committee on Future Projects in High Energy Physics (JAHEP, Japan)

With the discovery of the 125 GeV Higgs boson at the LHC, construction of the International Linear Collider (ILC) with a collision energy of 250 GeV should start in Japan immediately without delay so as to guide the pursuit of particle physics beyond the Standard Model through detailed research of the Higgs particle. In parallel, continuing studies of new physics should be pursued using the LHC and its upgrades.

ICFA Statement on the ILC Operating at 250 GeV as a Higgs Boson Factory (Ottawa, November 2017)

The discovery of a Higgs boson in 2012 at the Large Hadron Collider (LHC) at CERN is one of the most significant recent breakthroughs in science and marks a major step forward in fundamental physics. Precision studies of the Higgs boson will further deepen our understanding of the most fundamental laws of matter and its interactions. The International Linear Collider (ILC) operating at 250 GeV center-of-mass energy will provide excellent science from precision studies of the Higgs boson. Therefore, ICFA considers the ILC a key science project complementary to the LHC and its upgrade. ICFA welcomes the efforts by the Linear Collider Collaboration on cost reductions for the ILC, which indicate that up to 40% cost reduction relative to the 2013 Technical Design Report (500 GeV ILC) is possible for a 250 GeV collider. ICFA emphasizes the extendibility of the ILC to higher energies and notes that there is large discovery potential with important additional measurements accessible at energies beyond 250 GeV. ICFA thus supports the conclusions of the Linear Collider Board (LCB) in their report presented at this meeting and very strongly encourages Japan to realize the ILC in a timely fashion as a Higgs boson factory with a center-of-mass energy of 250 GeV as an international project, led by Japanese initiative.
CLIC technology has the unique capability to reach a center-of-mass energy of 1.5-3 TeV.

The staging scheme envisages:

- 500 fb\(^{-1}\) at 380 GeV (initial stage)
- 100 fb\(^{-1}\) at 350 GeV (threshold scan)
- 1.5 ab\(^{-1}\) at 1.5 TeV
- 3 ab\(^{-1}\) at 3 TeV
LC detector R&D
Next-generation pixel detectors

Vertex detector R&D for linear collider has yielded several new technologies that are mature enough to make their way into experiments:

- **CMOS** (STAR, Mu3e, ALICE, ATLAS)
- **DEPFET** (Belle II, X-ray imaging)
- **FPCCD**, **SOIPIX** have prototypes that meet most LC (and CEPC?) requirements

**If high read-out speed is required:**
- ultra-thin hybrid detectors
- depleted CMOS
- 3D integrated devices

**BEAST2 commissioning detector at Belle II:**
**DEPFET + CMOS + hybrid pixels**
4D tracking

The advent of ultra-fast position-sensitive silicon detectors...

LGAD =
Low-Gain Avalanche Detectors

iLGAD = inverted LGAD
(uniform gain, higher cost)

Technology CNM/RD50
G. Pellegrini et al., NIM A 765 (2014)

Ultra-Fast Silicon Detectors
Santa Cruz, Florence 2012 (60-100 ps)

Characterization
Turin/CNM/UCSC, arXiv:1312.1080 (20 ps)

The hype spreads
several groups (10 ps)

Opportunity for PID
Combining dE/dx from the CEPC TPC (3% resolution) with a 50 ps TOF measurement from the silicon yields a very good separation up to 10 GeV

Manqi Ruan, LCWS17
Highly granular calorimetry: research

Si+W ECAL

Fe-AHCAL

Realistic prototypes: EM and hadronic resolution

Monte Carlo + Pandora: particle-flow performance of the complete system

3% jet energy resolution

superb substructure measurements

Validated with TB
Highly granular calorimeter: development

Industrial-style integration

CALICE development is well beyond the performance & proof-of-principle stage

CMS HGCAL to demonstrate a complete highly granular calorimeter can be built and operated successfully
LC detector design & performance
Detector design

**Detailed design of the experiment**
informed by 20 years of R&D
optimized for benchmark performance
extensively documented for TDR

ILD: large detector, silicon
+ gaseous tracking

SiD: compact, 5 T B-field,
all-silicon tracking

CLIC: deep CALO, modified
forward region, larger VXD

ILC detector designs successfully
ported to CLIC environment and
then developed further. Ready for
CEPC to adopt, adapt and improve!
Detector performance

Detector performance and physics benchmarks studies are made possible by a large effort on simulation and reconstruction software

**Core software packages:**
- Persistency: LCIO
- Geometry: DD4HEP
- Reco framework: Marlin
- Grid submission toolkit: iLCDirac

**High-level reconstruction algorithms**
- LCFI vertex + flavour tagging
- PandoraPFA (+Arbor)
- FastJet + VLC jets

\[ \sqrt{s} = 250 \text{ GeV}, \, e^+e^- \rightarrow Zh \rightarrow \mu^+\mu^-h \]
Detector optimization

Complex multi-parameter problem

Benchmark studies $\rightarrow$ requirements

Detector R&D $\rightarrow$ feasibility

Costing studies $\rightarrow$ feasibility

MC studies $\rightarrow$ optimal detector parameters

Example: HCAL granularity

ILC and CLIC detector concepts have extensively documented the impact of calorimeter granularity, tracker parameters, and vertex detector performance
LC physics potential
Precision physics at $e^+e^-$ colliders

For precision there is nothing like $e^+e^-$

Machine: per mille level control over luminosity, polarization and beam energy calibration

Selection: democratic cross sections allow for truly inclusive measurements (no trigger!)

Detector: very little pile-up or radiation damage

Theory: no PDFs, small QCD corrections

Predictions at few per-mille level already today!

Example: top quark pair production
LHC13: $\sim$5% (NNLO scale + PDF)
LC500: $\sim$0.5% (N$^3$LO scale + EW)


Challenge: excellent detectors must make sure the experiment matches few per mille theory precision
Effective field theory

Extend SM Lagrangian with D6 operators. Effect suppressed by new physics scale $\Lambda$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O} (\Lambda^{-4})$$

(59 Wilson coefficients represents general high-scale NP compatible with gauge invariance)

Economy: EFT limits can be mapped on many NP scenarios

Connection: EFT relates measurements in different sectors (EW, Higgs, top)

Standard: LHC increasingly use EFT to interpret measurements (i.e. LHCtopWG)

LC pioneers Higgs couplings + EWPO + WW fit in EFT framework arXiv:1708.08912

Michael Peskin: SMEFT + ILC = GOLD (source: Facebook)

LC Higgs physics potential
Higgs couplings: LHC

LHC run 1 Legacy paper:
arXiv:1606.02266

\[ \mu = 1.09 \pm 0.11. \]

VBF production: 5.4 \( \sigma \)

H \( \to \tau\tau \) decay 5.5 \( \sigma \)

“The data are consistent with the SM predictions for all parameterisations considered.”

LHC + HL-LHC reaches 5-10%
Higgs coupling measurements

Higgs recoil-mass analysis is a goldmine

The 250 GeV ILC is expected to be sensitive to invisible Higgs decays with branching ratios as small as 0.3% [20], a factor of 20 below the expected HL-LHC sensitivity, arXiv:1710.07621
Higgs couplings: CLIC

Initial run is already very good
0.38 TeV + 1.5 TeV + 3 TeV better still!

Higgs paper: arXiv:1608.07538
Higgs self-coupling

**Crucial test of the Higgs mechanism**

Small rates, complex final states, challenging jet clustering and combinatorics

Very hard at any collider... Sophisticated full simulation study of (Z)bbbb and (Z)WWWW

**ILC with 4 ab$^{-1}$ at $\sqrt{s} = 500$ GeV:** measure the self-coupling $\lambda$ with **26%** precision. (**10%** when combined with 1 TeV).

**CLIC at 1.4 TeV and 3 TeV:** measure $\lambda$ to **10%**.
Top Yukawa coupling

At the LHC the top quark Yukawa coupling is inferred from the observed $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ rates.
Run I result: $k_t = 1.43 \pm 0.23$

The top Yukawa coupling can be measured directly in associated $ttH$ production.
Run I result: $\mu_{ttH} = 2.3 \pm 0.7$
CMS observation:

Prospects for full LHC programme:
$K_u \rightarrow 14-15\% \ (300/\text{fb})$
$K_u \rightarrow 7-10\% \ (3/\text{ab})$

Snowmass Higgs report
Top quark Yukawa coupling

Complex multi-jet events: $t\bar{t}H, H \rightarrow b\bar{b}$
Exclusive jet reconstruction
0 leptons $→$ 8 jets
1 lepton $→$ 6 jets

**Challenges:**
Small signal sample
Large background rejection
Jet reconstruction and pairing

**ILC**  : 3% with 4 ab$^{-1}$ at 550 GeV  
**ILC**  : 4% with 1 ab$^{-1}$ at 1 TeV

**CLIC**  : 3.8% with 1.5 ab$^{-1}$ at 1.4 TeV

**FCChh target:** 1% precision
EFT – Higgs self coupling

D6 operators in di-Higgs production

$ZHH^* = \text{(trilinear) self-coupling, } ZZH^* \text{ and (cuartic) coupling } ZZHH^* + \text{host of other operators}$

$$g_{ZZH} \quad g_{ZZHH} \quad \text{(and other, BSM, couplings) in } \sigma(e^+e^- \rightarrow HHZ)$$

Understand the constraint on trilinear Higgs coupling (operator coefficient $c_6$) in a global fit to the Higgs sector + EWPO + TGC

Compare with “indirect model-dependent constraint” from ZH production rate

(McCullough, arXiv:1312.3322)

2D fit in $c_H - c_6$ plane: complementary constraints from LHC-LC-CEPC

Input LHC: 50% Input ILC: 26%
LC VBS physics potential
Vector boson scattering

The process that demanded a Higgs boson...

EWK process isolated during run I at the LHC using same-sign WW and WZ production

Forward “tag” jets, high-mass VV’ system
ATLAS arXiv:1611.02428
CMS arXiv:1410.6315

Test Higgs-suppression of longitudinal VBS, constrain anomalous couplings (aTGC and aQGC), measure Higgs properties, Campbell, Ellis arXiv:1502.02990

Towards a global fit of a complete vector boson EFT, including all relevant aTGC and aQGCs, and Higgs operators
Limits on anomalous quartic couplings: LHC vs. CLIC

ATLAS run-I, from Green, Meade, Pleier, arXiv:1610.07572

CLICdp prospects for 3 TeV
LC top physics potential
The machine parameters can be tuned (at a cost in instantaneous luminosity) to minimize the impact of the luminosity spectrum on the threshold shape. Higher precision - per unit luminosity – in the mass extraction + potential gain in the width measurement. The details of the scan can be further optimized.
Threshold scan: potential

A multi-parameter fit can extract the PS mass with excellent precision

<table>
<thead>
<tr>
<th>Uncertainty Type</th>
<th>Uncertainty</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainty</td>
<td>~20 MeV</td>
<td>100 fb⁻¹</td>
</tr>
<tr>
<td>Scale uncertainty</td>
<td>~40 MeV</td>
<td>$N^3$LO QCD, arXiv:1506.06864</td>
</tr>
<tr>
<td>Parametric uncertainty</td>
<td>~30 MeV</td>
<td>$\alpha_s$ world average, arXiv:1604.08122</td>
</tr>
<tr>
<td>Experimental systematics</td>
<td>25-50 MeV</td>
<td>including LS, arXiv:1309.0372</td>
</tr>
</tbody>
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This threshold mass can be converted to the $\overline{\text{MS}}$ scheme with ~10 MeV precision

Marquard et al., PRL114, arXiv:1502.01030

A very competitive top quark mass measurement:

$$\Delta m_t \sim 50 \text{ MeV} \quad ( = 3 \times 10^{-4}, \text{cf.} \, \Delta m_b \sim 1\% )$$

This is a real prospect, not a target! Build the machine and we perform the measurement.
Top quark mass: alternatives

There are (at least) two further ways to determine the top quark mass with \(~100\) MeV statistical precision using the 380 GeV data.

Potential of the high-energy run remains to be explored (see hep-ph/0703207).
Top anomalous couplings

\[
\Gamma_{\mu}^{t\bar{t}X} (k^2, q, \bar{q}) = ie \left\{ \gamma_\mu \left( F_{1V}^X (k^2) + \gamma_5 F_{1A}^X (k^2) \right) - \frac{\sigma_{\mu\nu}}{2m_t} (q + \bar{q})^\nu \left( iF_{2V}^X (k^2) + \gamma_5 F_{2A}^X (k^2) \right) \right\}
\]

CLIC staging, CERN-2016-004

Based on arXiv:1505.06020

arXiv:1710.06737

Measurements in pair production in early stage have excellent BSM sensitivity
Top physics at high energy

Top reconstruction at $\sqrt{s} > 1$ TeV challenges
jet reconstruction: arXiv:1607.05039

Top tagging studied in detail in CLIC top paper

Impact of 4-fermion operators $\mu \ E^2$ → best constrained at high energy
Impact of 2-fermion operators $\sim c$ → best constrained at low energy

$\frac{1}{\sigma} \frac{\partial \sigma}{\partial \tilde{C}_i} \bigg|_{\tilde{C}_i=0, \forall i} \equiv S_i^\sigma$

$e^+ e^- \rightarrow t \bar{t}, \text{LO}$
$(P_{e^+}, P_{e^-}) = (0\%, -80\%)$

$\sqrt{s} \text{ [GeV]}$

Durieux, Perelló, Vos, Zhang
Global EFT fit

Global 7-parameter fit – top-philic scenario

380 GeV + 1.4 TeV + 3 TeV
(indiv. + global limits)

380 GeV + 1.4 TeV
(indiv. + global limits)

380 GeV
(individual limits only)

CLIC top physics program provides tight constraints on all 7 coefficients
cf. current Tevatron+LHC limits from TopFitter collaboration are O(10)
all operator limits significantly exceed HL-LHC prospects
limits on 4-fermion and dipole moment operators are excellent!
From EFT to concrete scenario

Re-express EFT constraints as limits on the canonical composite Higgs scenario, characterized by a coupling strength $g_*$ and NP scale $m_*$ (Giudice 2007)

The top quark is naturally composite in this framework (Pomarol 2008), the only viable option to generate the top Yukawa coupling (Ratazzi 2008)

Benchmarks: partial ($t_L$ and $t_R$ composite) & total ($t_R$ maximally composite)

Pessimistic $5\sigma$ discovery contours reach 7-15 TeV, in favourable cases > 20 TeV
Summary

The European strategy update must decide on the global future of HEP.

LC community has made significant progress towards a complete proposal

- comprehensive detector R&D program → technologies already on the market
- particle-flow detector concept → optimal global performance

The LC physics program complements the LHC + HL-LHC in important ways.

- Higgs couplings: sub-%
- Top Yukawa coupling: 3-4%
- Higgs self-coupling: ~10%
- vector-boson scattering: order of magnitude
- top mass measurement: $\Delta m_t \sim 50$ MeV
- top quark EW couplings: order of magnitude

A real chance for HEP to explore the energy regime 1-10 TeV

LC-CEPC synergy to be exploited more fully

And much more that I haven’t discussed

Topical cross-project studies and workshops