Physics Motivation For Future Colliders

Hep 2018, UTFSM, Jan. 12, 2018

Tao Han, University of Pittsburgh

TLEP Report 1308.6176; CEPS pre-CDR; Snowmass Reports;
High Energy Physics IS at an extremely interesting time:

The completion of the SM:
First time ever, we have a consistent relativistic/quantum mechanical theory: weakly coupled, unitary, renormalizable, vacuum-(quasi?)stable.

Valid up to an exponentially high scale, perhaps to the Planck scale $M_{Pl}$!
“... most of the grand underlying principles have been firmly established. (An eminent physicist remarked that) the future truths of physical science are to be looked for in the sixth place of decimals. ”
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--- Albert Michelson (1894)

Michelson–Morley experiments (1887): “the moving-off point for the theoretical aspects of the second scientific revolution”

Will History repeat itself (soon)?
New Era:
Under the Higgs lamp post
Question 1: The Nature of EWSB?

In the SM, \( m_H^2 = 2\mu^2 = 2\lambda v^2 \Rightarrow \mu \approx 89 \text{ GeV}, \lambda \approx \frac{1}{8}. \)

underwent a 2\textsuperscript{nd} order phase transition (\(?\))

---

All we know:
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underwent a 2\(^{\text{nd}}\) order phase transition (?)

All we know: 

With new physics near the EW scale:

\[
V(h) \rightarrow m_h^2 (h^\dagger h) + \frac{1}{2} \lambda (h^\dagger h)^2 + \frac{1}{3!\Lambda^2} (h^\dagger h)^3, \Rightarrow \lambda_{hhh} = (7/3)\lambda_{hhh}^{\text{SM}}
\]

\[
\Rightarrow \lambda_{hhh} = (5/3)\lambda_{hhh}^{\text{SM}}
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\rightarrow \lambda_{hhh} = \left(\frac{5}{3}\right)\lambda_{hhh}^{\text{SM}}
\]

EW phase transition strong 1\textsuperscript{st} order!
\[ \rightarrow O(1) \] deviation on \( \lambda_{hhh} \)

X.M.Zhang (1993); C. Grojean et al. (2005)
Question 2: The “Naturalness”

“… scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry.”

Ken Wilson, 1970
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“unnatural” in the ‘t Hooft sense:

\[ m_H^2 = m_{H0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 \]

If \( \Lambda^2 \gg m_H^2 \), then unnaturally large cancellations must occur.
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If \( \Lambda^2 \gg m_H^2 \), then unnaturally large cancellations must occur.

- Natural: \( O(1 \text{ TeV}) \) new physics, associated with \( ttH \).
- Unknown: Deep UV-IR correlations: gravity at UV?
- Agnostic: Multiverse/anthropic?
A “natural” EW theory?

• “Natural SUSY”:

Relevant to the Higgs and the “Most Wanted”:

\( \tilde{H}^0, \tilde{\tau}, \tilde{b}, (\tilde{g}); S, \tilde{S} \ldots \)

LHC Run 2 bounds:

\[
m_{\tilde{t}} > 800 - 1100 \text{ GeV} \\
m_{\tilde{\chi}^\pm} > 600 - 1100 \text{ GeV}
\]
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  \(m_{\tilde{\chi}^\pm} > 600 - 1100 \text{ GeV}\)

• New strong dynamics, “Compositeness”:
  The top-quark partner \(T’\),
  Current ATLAS/CMS limit:
  \(M_{T'} > 1400 \text{ GeV, for } M_A < 100 \text{ GeV}\).
Question 3: The Dark Sector
The un-protected operator may reveal secret Higgs portal:

\[ k_s H^\dagger H S^* S, \quad \frac{k\chi}{\Lambda} H^\dagger H \bar{\chi}\chi. \]
Question 4: The “Flavor Puzzle”

- Particle mass hierarchy
- Patterns of quark, neutrino mixings
- New CP-violation sources?

Higgs Yukawa couplings as the pivot!
LHC Leads the Way (2015-2030)

e+e- & Z, 240-350 GeV

CERN’s Large Hadron Collider
Circumference: 27 km
Energy: 14 TeV

US/European super proton collider
100 km; 100 TeV

International Linear Collider
Length: 31 km
≤1 TeV

China’s electron–positron collider
52 km; 240 GeV
China’s super proton collider
52 km; ≤70 TeV

China-hosted international electron–positron collider
80 km; 240 GeV
China-hosted international super proton collider
80 km; ≤100 TeV

Existing — Proposed
TeV, teraelectronvolt; GeV, gigaelectronvolt
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CEPC/SppC?

FCC?
LHC Leads the Way (2015-2030)

ILC as Higgs Factory & beyond

CEPC/SppC?

FCC?
LHC Leads the Way (2015-2030)

ILC as Higgs Factory & beyond

<table>
<thead>
<tr>
<th>Facility</th>
<th>HL-LHC</th>
<th>ILC</th>
<th>ILC(LumiUp)</th>
<th>CLIC</th>
<th>TLEP (4 IPs)</th>
<th>HE-LHC</th>
<th>VLHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{s}$ (GeV)</td>
<td>14,000</td>
<td>250/500</td>
<td>250/500/1000</td>
<td>350/1400/3000</td>
<td>240/350</td>
<td>33,000</td>
<td>100,000</td>
</tr>
<tr>
<td>$\mathcal{L}dt$ (fb$^{-1}$)</td>
<td>3000/expt</td>
<td>250+500+1000</td>
<td>1150+1600+2500</td>
<td>500+1500+2000</td>
<td>10,000+2600</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>$dt$ ($10^7$s)</td>
<td>6</td>
<td>3+3+3</td>
<td>(ILC 3+3+3) + 3+3+3</td>
<td>3.1+4+3.3</td>
<td>5+5</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>
International Linear Collider as a Higgs Factory & beyond

$E_{cm} \ (GeV) = 250, 350, 500, 1000 \ GeV$

Under serious consideration in Japan:
The detailed plan and accelerator design for the 250 GeV stage of the ILC is described in this paper. The purpose of this stage at 250 GeV makes sense from the point of view of physics. The purpose of modes and a new, more powerful theoretical approach, to be described in Section 3, is to present this argument in detail.

There were three main physics reasons for starting at 500 GeV: first, the ability to use the couplings of the top quark, including the direct measurement of the top-Yukawa coupling from the couplings of the Higgs boson, be measured absolutely without reference to the Higgs boson decay mode, and the background from at a fixed lab-frame energy (110 GeV for the electron beam and ).

The evolution of the data-taking envisioned in was defined for the ILC . This operating scenario assumed the construction of a 500-GeV machine, which within a 20-year period would accumulate integrated luminosities of 4 ab . The ILC Technical Design Report . Following the publication of the ILC Technical Design Report , a canon- case study working group, K. Fujii et al. : Stage studies: 1710.07261; 1801.02841

Under serious consideration in Japan:

Integrated Luminosities [fb]

ILC, Scenario H-20

- ECM = 250 GeV
- ECM = 350 GeV
- ECM = 500 GeV

Integrated Luminosities [fb]
international FCC collaboration (CERN as host lab) to design:

- \( pp \)-collider (FCC-hh)  
  main emphasis, defining infrastructure requirements

\( \sim 16 \, \text{T} \Rightarrow 100 \, \text{TeV} \, pp \) in 100 km

- 80-100 km tunnel infrastructure in Geneva area, site specific

- \( e^+ e^- \) collider (FCC-ee), as a possible first step

- \( p-e \) (FCC-he) option, one IP, FCC-hh & ERL

- HE-LHC w FCC-hh technology
CERN Yellow Reports on “a 100 TeV pp Collider”:
Vol. 1. SM; 2. Higgs; 3. BSM; 4. Accelerator
Fastest Possible Technical Schedules

- Technical schedule defined by magnets program and by CE
- earliest possible physics starting dates:
  - FCC-hh: 2043
  - FCC-ee: 2039
  - HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)

M. Benedikt
CEPC (circular e⁻e⁺)/SppC: China

Qinhuangdao (秦皇岛)

CepC, SppC

e⁺e⁻: 240 GeV
pp: 70-100 TeV

50 km

70 km

easy access
300 km from Beijing
3 h by car
1 h by train

“Chinese Toscana”
CEPC/SppC Preliminary Conceptual Design Reports:
Vol. 1: Physics & Detector;  Vol. 2: Accelerator
http://cepc.ihep.ac.cn/preCDR/volume.html
$e^+e^-$ colliders: Energy/Lumi projection

<table>
<thead>
<tr>
<th>$E_{cm}$</th>
<th>running time</th>
<th>statistics (FCC-ee)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 GeV</td>
<td>1-2 yrs</td>
<td>$10^{12}$ $Z$ (Tera Z)</td>
</tr>
<tr>
<td>160 GeV</td>
<td>1-2 yrs</td>
<td>$10^8$-$10^9$ WW(Oku W)</td>
</tr>
<tr>
<td>240 GeV</td>
<td>4-5 yrs</td>
<td>$2 \times 10^6$ ZH (Mega H)</td>
</tr>
<tr>
<td>350 GeV</td>
<td>4-5 yrs</td>
<td>$10^6$ $t\bar{t}$ (Mega top)</td>
</tr>
</tbody>
</table>
Z-FACTORY: TERA (10^{12}) Z PHYSICS

- Clean environment, $\Delta E_{\text{cm}} < 1 \text{ MeV}$, $10^5 \times \text{LEP-I}$
- possible longitudinal polarization
- $Z$-pole: $\Delta M_Z, \Delta \Gamma_Z < 0.1 \text{ MeV}, \Delta \sin^2 \theta_w < 10^{-6}$
- Thr. scan: $\Delta M_W \sim O(1 \text{ MeV}), \Delta m_t \sim O(10 \text{ MeV}), \Delta m_H \sim O(10 \text{ MeV})$. 

TLEP Report: 1308.6176
Figure 7. The Higgs boson production cross section as a function of the centre-of-mass energy in unpolarized $e^+e^-$ collisions, as predicted by the HZHA program [39]. The thick red curve shows the cross section expected from the Higgs-strahlung process $e^+e^- \rightarrow HZ$, and the thin red curve shows the fraction corresponding to the $Z \rightarrow \nu\bar{\nu}$ decays. The blue and pink curves stand for the WW and ZZ fusion processes (hence leading to the $H\nu\bar{\nu}$ and $He^-e^+$ final states), including their interference with the Higgs-strahlung process. The green curve displays the total production cross section. The dashed vertical lines indicate the centre-of-mass energies at which TLEP is expected to run for five years each, $\sqrt{s} = 240$ GeV and $\sqrt{s} \sim 2m_{top}$.

The number of Higgs bosons expected to be produced, hence the integrated luminosity delivered by the collider, are therefore key elements in the choice of the right Higgs factory for the future of high-energy physics: a per-mil accuracy cannot be reached with less than a million Higgs bosons. The Higgs production cross section (obtained with the HZHA generator [39]), through the Higgs-strahlung process $e^+e^- \rightarrow HZ$ and the WW or ZZ fusion processes, is displayed in figure 7. A possible operational centre-of-mass energy is around 255 GeV, where the total production cross section is maximal and amounts to 210 fb. The luminosity profile of TLEP as a function of the centre-of-mass energy (figure 3) leads to choose a slightly smaller value, around 240 GeV, where the total number of Higgs bosons produced is maximal, as displayed in figure 8. The number of WW fusion events has a broad maximum for centre-of-mass energies between 280 and 360 GeV. It is therefore convenient to couple the analysis of the WW fusion with the scan of the $t\bar{t}$ threshold, at $\sqrt{s}$ around 350 GeV, where the background from the Higgs-strahlung process is smallest and most separated from the WW fusion signal.
Figure 7. The Higgs boson production cross section as a function of the centre-of-mass energy in unpolarized $e^+e^-$ collisions, as predicted by the HZHA program \[^{[39]}\]. The thick red curve shows the cross section expected from the Higgs-strahlung process $e^+e^- \rightarrow HZ$, and the thin red curve shows the fraction corresponding to the $Z \rightarrow \nu\bar{\nu}$ decays. The blue and pink curves stand for the $WW$ and $ZZ$ fusion processes (hence leading to the $H\nu\bar{\nu}$ final states), including their interference with the Higgs-strahlung process. The green curve displays the total production cross section. The dashed vertical lines indicate the centre-of-mass energies at which TLEP is expected to run for five years each, $\sqrt{s} = 240$ GeV and $\sqrt{s} \sim 2m_{\text{top}}$. Rapidly decreasing with the new physics scale $\Lambda$, typically like $1/\Lambda^2$. For $\Lambda = 1$ TeV, departures up to 5\% are expected \[^{[7,8]}\]. To discover new physics through its effects on the Higgs boson couplings with a significance of 5\$\sigma$, it is therefore necessary to measure these couplings to fermions and gauge bosons with a precision of at least 1\%, and at the per-mil level to reach sensitivity to $\Lambda$ larger than 1 TeV, as suggested by the negative results of the searches at the LHC.

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"Recoil mass" $m^2_h = (p_{e^-} + p_{e^+} - q_{\mu^-} - q_{\mu^+})^2$
**Higgs-Factory:**

- **ILC:** $E_{cm} = 250 \ (500) \ \text{GeV}, \ 250 \ (500) \ \text{fb}^{-1} \ (0.5 \times 10^5 \ \text{Higgs})$

  Model-independent measurement:
  \[ \Gamma_H \sim 6\%, \ \Delta m_H \sim 30 \ \text{MeV} \]

  (HL-LHC: assume SM, $\Gamma_H \sim 5-8\%, \ \Delta m_H \sim 50 \ \text{MeV}$)

- **FCCee/CEPC** $10^6 \ \text{Higgs}: \ \Gamma_H \sim 1\%, \ \Delta m_H \sim 5 \ \text{MeV}$
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- **FCC/CEPC**: $10^6$ Higgs: $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

  Couplings to sub-percent:

  ![Graph showing precision of Higgs boson couplings](image)

  - LHC 3000 fb$^{-1}$ (ATLAS: ATL-PHYS-PUB-2014-016 (2014), Model Dependent x fit)
  - LHC 3000 fb$^{-1}$ $\otimes$ ILC 250 GeV, 2000 fb$^{-1}$ (Model Independent EFT fit)
  - LHC 3000 fb$^{-1}$ $\otimes$ ILC 250 GeV, 2000 fb$^{-1}$ $\otimes$ ILC 500 GeV, 4000 fb$^{-1}$ $\otimes$ 350 GeV, 200 fb$^{-1}$ (Model Independent EFT fit)

  ILC Report: 1308.6176
The Next Energy Frontier: 100 TeV Hadron Collider

\[ \tau^{1/2} = (s/S)^{1/2} \]

\[ \hat{s}^{1/2} [\text{TeV}] \]

\[ \frac{dL_{100}}{dT} = 10^{10} \]

\[ \frac{dL_{140}}{dT} = 10^4 \]

\[ \frac{dL_{100}}{dL_{14}} = 10^4 \]

\[ \frac{dL_{100}}{dL_{14}} = 10^2 \]

\[ \sqrt{s} (\text{TeV}) \]
Higgs Production @ FCC$_{hh}$/SPPC

Snowmass QCD Working Group: 1310.5189
Higgs Self-couplings:

\[ \mathcal{L} = -\frac{1}{2} m_H^2 H^2 - \frac{g_{hhh} H^3}{3!} - \frac{g_{hhhh} H^4}{4!} \]

\[ g_{hhh} = 6 \quad v = \frac{3 m_H^2}{v}, \quad g_{hhhh} = 6 = \frac{3 m_H^2}{v^2}. \]

Triple Higgs boson coupling \( \lambda_{hhh} \):
Test the shape of the Higgs potential, and the fate of the EW-phase transition (EWPT):
O(100\%) deviation needed for 1\textsuperscript{st} order EWPT;
O(10\%) accuracy needed for a conclusive test.
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HL-LHC \sim 50\%; \quad ILC(1\ TeV),\ CLIC(3\ TeV) \sim 10\%;

FCC\(_{hh}@3\text{ ab}^{-1}\): \sim 8\%
Mass reach at 100 TeV: 
\(~ 7\times \) over LHC

1000 evt @ 3 ab⁻¹
Pushing the “Naturalness” limit

The Higgs mass fine-tune: $\frac{\delta m_H}{m_H} \sim 1\% \ (1 \text{ TeV}/\Lambda)^2$

Thus, $m_{\text{stop}} > 8 \text{ TeV} \Rightarrow 10^{-4}$ fine-tune!
DM Searches

LUX collaboration, 2013

GeV low mass:
DD difficult;
Collider complementary

100 GeV or higher mass:
DD + ID + HE Collider
WIMP DM: $M_{DM} < 1.8\,\text{TeV} \left(\frac{g_{\text{eff}}^2}{0.3}\right)$
New Particle Searches

Electroweak Resonances: $Z', W'$

Colored Resonances:

Excited Quark
- Black 100 TeV
- Red 14 TeV

- $ug \rightarrow u^*$
- $dg \rightarrow d^*$

$M \sim 40 - 50$ TeV!

~ 6x over LHC
Conclusions

• Higgs boson is a new class.

NP BSM $\rightarrow$ “under the Higgs lamppost”

LHC will lead the way: $g \sim 10\%$; $\lambda_{HHH} \sim 50\%$; $Br_{\text{inv.}} \sim 20\%$

but it also calls for new colliders:

Precision: FCC$_{ee}$/CEPC

Tera Z: $\Delta M_Z, \Delta \Gamma_Z < 0.1$ MeV, $\Delta \sin^2 \theta_w < 10^{-6}$.

At thresholds: $\Delta M_W \sim 1$ MeV, $\Delta m_t \sim 10$ MeV

Mega Higgs: $\kappa_v \sim 0.2\%$, $\Gamma_H \sim 1\%$, $Br_{\text{inv.}} \sim 1\%$, $\Delta m_H \sim 5$ MeV.
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  **Energy frontier:** FCC$_{hh}$/SPPC
  
  $g \sim 10\%$; $\lambda_{hhh} < 10\%$ → Conclusive for EWPT
  
  **6x LHC reach:** $10 - 30 \text{ TeV} \rightarrow$ fine-tune $< 10^{-4}$
  
  **WIPM DM mass:** $\sim 1 - 5 \text{ TeV}$
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WIMP DM mass $\sim 1 - 5$ TeV

An exciting journey ahead!
Site selections (a few main candidates)

1) Qinhuangdao

2) Shaanxi Province

3) Near Shenzhen and Hongkong
“Canonical” energy / luminosity: 100 TeV, $3 - 30 \text{ ab}^{-1}$

(Perhaps)

- Technology limitation (high field magnets?)
- Budgetary consideration (> 10 B$?)
- Geological / geographic consideration
Atomic physics: Rydberg const. $E_0 \sim \alpha^2 m_e \rightarrow O(25 \text{ eV}), \text{ very natural!}$

Nuclear physics?

- Binding energy $\sim 2 \text{ MeV}$
- $\delta \theta / \theta \sim 10^{-2}$ rather unnatural!

Solar eclipses:

Earth  Moon  Sun