Apologies: Many recent studies not included …

During the SSC time in the mid 80's

**Supercollider physics**

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Eichten *et al.* summarize the motivation for exploring the 1-TeV (≈10^{12} eV) energy scale in elementary particle interactions and explore the capabilities of proton-(anti)proton colliders with beam energies between 1 and 50 TeV. The authors calculate the production rates and characteristics for a number of conventional processes, and discuss their intrinsic physics interest as well as their role as backgrounds to more exotic phenomena. The authors review the theoretical motivation and expected signatures for several new phenomena which may occur on the 1-TeV scale. Their results provide a reference point for the choice of machine parameters and for experiment design.
Summary of the Very Large Hadron Collider Physics and Detector Workshop

Physics at the high energy frontier beyond the LHC
March 13-15, 1997
Fermi National Accelerator Laboratory, Batavia, Illinois

G. Anderson (Fermilab), U. Baur (SUNY at Buffalo), M. Berger (Indiana University), F. Borcherding (Fermilab), A. Brandt (Fermilab), D. Denisov (Fermilab, Co-Chair and Co-editor), S. Eno (University of Maryland), T. Han (University of California–Davis), S. Keller (Fermilab, Co-Chair and Co-editor), D. Khazins (Duke University), T. LeCompte (Argonne National Laboratory), J. Lykken (Fermilab), F. Olness (Southern Methodist University), F. Paige (Brookhaven National Laboratory), R. Scalise (Southern Methodist University), E. H. Simmons (Boston University), G. Snow (University of Nebraska–Lincoln), C. Taylor (Case Western Reserve University), J. Womersley (Fermilab).

Theory Overview
in the light of future hadron colliders

Tao Han
Univ. of Wisconsin - Madison

VLHC workshop, Fermilab, Oct. 16, 2003

The Standard Model as It Is
The Need For Going Beyond SM
The Role of Future Hadron Colliders
The Higgs boson is discovered & the SM completed!

For the 1\textsuperscript{st} time (ever): a consistent theory valid up to an exponentially high scale, perhaps to $M_{\text{Pl}}$!

“... 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. ”

--- Albert Michelson (1894)

Michelson–Morley experiments (1887): the moving-off point for modern physics!

Will History repeat itself (soon)?
New Era: Under the Higgs lamp post

The LHC “Observation” papers: Now 7,250 cites each!
Question 1: The Nature of EWSB?

\[ v = (\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV} \]
\[ m_H \approx 125 \text{ GeV} \]

All we know:

It is a weakly coupled new force, underwent a 2\textsuperscript{nd} order phase transition.

With new physics near the EW scale:

\[ V(h) \to m_h^2(h\dagger h) + \frac{1}{2}\lambda(h\dagger h)^2 + \frac{1}{3!\Lambda^2}(h\dagger h)^3, \]
\[ \Rightarrow \lambda_{hhh} = (7/3)\lambda_{hhh}^{\text{SM}} \]
\[ \Rightarrow \lambda_{hhh} = (5/3)\lambda_{hhh}^{\text{SM}} \]

leading to EW phase transition strong 1\textsuperscript{st} order!

\[ \Rightarrow \mathcal{O}(1) \text{ deviation on } \lambda_{hhh} \]
Question 2: The “Naturalness”

Higgs mass is “un-natural” in the Wilson/’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.

Cancelation in perspective:

$$m_H^2 = 36,127,890,984,789,307,394,520,932,878,928,933,023$$
$$-36,127,890,984,789,307,394,520,932,878,928,917,398$$
$$= (125 \text{ GeV})^2 \ ?$$

Natural: O(1 TeV) new physics, associated with ttH.
Unknown: Deep UV-IR correlations?
Agnostic: Multiverse/anthropic?
Question 3: The Dark Sector

The un-protected operator may reveal secret Higgs portal: \( k_s H^\dagger H S^* S, \frac{k_X}{\Lambda} H^\dagger H \tilde{\chi}\tilde{\chi}. \)
CERN Reports on “Physics at a 100 TeV Collider”:
CEPC/SppC: China

Qinhuangdao (秦皇岛)

- Easy access
- 50 km from Qinhuangdao
- 70 km from Qinhuangdao
- 300 km from Beijing
- 3 h by car
- 1 h by train

"Chinese Toscana"

S. Su

Yifang Wang

CepC, SppC

E+e-: 240 GeV
pp: 70-100 TeV

CEPC/SppC: China
http://cepc.ihep.ac.cn/preCDR/volume.html

Five-year plans: 2016, 2021…

Y. Wang
Someday … (maybe!)
“Canonical” energy / luminosity: 100 TeV, $3 - 30 \text{ ab}^{-1}$

(Perhaps)

- Technology limitation (high field magnets?)
- Budgetary consideration (> 10 B$?)
- Geological / geographic consideration
Parton luminosities: 1000 x higher! \(\sqrt{S} = 100 \, \text{TeV}\)

Quark/gluon partons:

Vector-boson partons:
Production Rates @ FCC_{hh}/SPPC

![Graph showing production rates vs. energy]

<table>
<thead>
<tr>
<th>Process</th>
<th>(\sigma (100 \text{ TeV})/\sigma (14 \text{ TeV}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pp</td>
<td>1.25</td>
</tr>
<tr>
<td>W</td>
<td>~7</td>
</tr>
<tr>
<td>Z</td>
<td>~7</td>
</tr>
<tr>
<td>WW</td>
<td>~10</td>
</tr>
<tr>
<td>ZZ</td>
<td>~10</td>
</tr>
<tr>
<td>tt</td>
<td>~30</td>
</tr>
<tr>
<td>H</td>
<td>~15 (ttH ~60)</td>
</tr>
<tr>
<td>HH</td>
<td>~40</td>
</tr>
<tr>
<td>stop (m=1 TeV)</td>
<td>~10(^3)</td>
</tr>
</tbody>
</table>

Experiments at 100 TeV probe the SM in a regime where the electroweak symmetry is effectively restored. A couple of new features are worth noting (more details will be given in Section 6.2.2). First of all, in processes at the very high energies \(p^\hat{s}\), EW gauge bosons are copiously produced by radiation. For \(p_T\)'s approaching \~10 TeV, the electroweak Sudakov factor \(\sim 0.1\), and we have "electroweak radiation" in complete analogy with electromagnetic and gluon radiation. For instance, a W or Z gauge boson would be radiated to a light quark with 10 TeV of energy with a probability of 10% and to a gauge boson with a probability of 20%. These production rates are one-to-two orders of magnitude higher than what we typ-
**Higgs Self-couplings:**

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

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

**Triple coupling sensitivity:** Test the shape of the Higgs potential, and the fate of the EW-phase transition!

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**Table 1-24.** Expected per-experiment precision on the triple-Higgs boson coupling. ILC numbers include \(b\bar{b}b\bar{b}\) and \(b\bar{b}W^+W^-\) final states and assume \((e,e^+)\) polarizations of \((0.8,0.3)\) at 500 GeV and \((0.8,0.2)\) at 1000 GeV. ILC500-up is the luminosity upgrade at 500 GeV, not including any 1000 GeV running. ILC1000-up is the luminosity upgrade with a total of 1600 fb\(^{-1}\) at 500 GeV and 2500 fb\(^{-1}\) at 1000 GeV. CLIC numbers include only the \(b\bar{b}b\bar{b}\) final state and assume 80% electron beam polarization. HE-LHC and VLHC numbers are from fast simulation [102] and include only the \(b\bar{b}\) final state.

<table>
<thead>
<tr>
<th>(\sqrt{s}) (GeV)</th>
<th>HL-LHC</th>
<th>ILC500</th>
<th>ILC500-up</th>
<th>ILC1000</th>
<th>ILC1000-up</th>
<th>CLIC1400</th>
<th>CLIC3000</th>
<th>HE-LHC</th>
<th>VLHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\int Ldt) (fb(^{-1}))</td>
<td>14000</td>
<td>500</td>
<td>500</td>
<td>500/1000</td>
<td>500/1000</td>
<td>1400</td>
<td>3000</td>
<td>33,000</td>
<td>100,000</td>
</tr>
<tr>
<td>3000/expt</td>
<td>500</td>
<td>1600†</td>
<td>500+1000</td>
<td>1600+2500†</td>
<td>1500</td>
<td>+2000</td>
<td>3000</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>(\lambda)</td>
<td>50%</td>
<td>83%</td>
<td>46%</td>
<td>21%</td>
<td>13%</td>
<td>21%</td>
<td>10%</td>
<td>20%</td>
<td>8%</td>
</tr>
</tbody>
</table>

~10%@1TeV
(Fujii’s talk)

Snowmass 1310.8361
Mass reach at 100 TeV: ~7x over LHC
Pushing the “Naturalness” limit

Top quark partners searches:
The Higgs mass fine-tune: $\frac{8m_H}{m_H} \sim 1\% \ (1 \text{ TeV}/\Lambda)^2$
Thus, $m_{\text{stop}} > 8 \text{ TeV} \Rightarrow 10^{-4} \text{ fine-tune!}$
WIMP DM Searches

GeV low mass: DD difficult; Collider complementary

\[ \sigma_{SI} \begin{cases} \approx 10^{-47} \text{ cm}^2 & \text{for winos,} \\ \leq 10^{-48} \text{ cm}^2 & \text{for higgsinos.} \end{cases} \]

100 GeV or higher mass: DD + ID + HE Collider Too hard for O(1) TeV
WIMP DM: \( M_{DM} < 1.8 \text{ TeV} \left( \frac{g_{eff}}{0.3} \right) \)
New Particle Searches

Electroweak Resonances: $Z', W'$

Colored Resonances:

$\sim 6x$ over LHC
Bread & Butter Physics

At energies $Q^2 >> v^2$, $m_t^2$, $m_w^2 \rightarrow$ EW symm restored.

ISR: enhanced initial-state radiations
- $W^+, W^-, Z^0, t$ “partons” in the protons
  the top quark will be as “massless” at SppC
  as the b-quark at the Tevatron:

  $m_b/E_{\text{TeV}} \sim 3.5/1\times10^3 \sim 3.5\times10^{-3}$
  $m_t/E_{\text{SPPC}} \sim 160/50\times10^3 \sim 3.2\times10^{-3}$

FSR: Lots salient features!
- $W^+, W^0, B$ showers like $SU(2)_L \times U(1)_Y$ gluons
- Showers merge to QED below $v$ (unlike $\Lambda_{\text{QCD}}$)
- $h, W_L, Z_L$ radiation off tops

Conclusions

• Higgs boson is a new class!
• Search for new physics BSM: “under the Higgs lamppost”
• It calls for new colliders at the energy frontier: $FCC_{hh}/SPPC$
  $\lambda_{hhh} < 10\% \Rightarrow$ Conclusive for EWPT
  6x LHC reach: 10 – 30 TeV $\Rightarrow$ fine-tune $< 10^{-4}$
  WIPM DM mass $\sim 1 – 5$ TeV

Rich Bread & Butter physics!

A 100-TeV pp Collider holds high promise!
Site selections (a few main candidates)

1) Qinhuangdao
2) Shaanxi Province
3) Near Shenzhen and Hong Kong