Physics at Future Lepton Colliders

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Matthew McCullough
CERN
The European Particle Physics Strategy Update (EPPSU) process takes a bottom-up approach, whereby the community is first invited to submit proposals (also called inputs) for projects that it would like to see realised in the near-term, mid-term and longer-term future. National inputs as well as inputs from National Laboratories are also an important element of the process. All these inputs are then reviewed by the Physics Preparatory Group (PPG), whose role is to organize a Symposium around the submitted ideas and to prepare a community discussion on the importance and merits of the various proposals. The results of these discussions are then concisely summarised in this Briefing Book, prepared by the Conveners, assisted by Scientific Secretaries, and with further contributions provided by the Contributors listed on the title page. This constitutes the basis for the considerations of the European Strategy Group (ESG), consisting of scientific delegates from CERN Member States, Associate Member States, directors of major European laboratories, representatives of various European organizations as well as invitees from outside the European Community. The ESG has the mission to formulate the European Strategy Update for the consideration and approval of the CERN Council.
Next Steps:

An $e^+e^-$ Higgs factory is the blindingly obvious next step!

Put the Higgs boson under a magnifying glass!
• The Higgs boson has a size/wavelength. What’s inside?

\[ \lambda_h \approx 10^{-17} \text{ m} \]

\[ \lambda_{10 \text{ TeV}} \approx 10^{-19} \text{ m} \]

Precision measurements are different ways of probing the “compositeness of the Higgs”.
Higgs Factories

- Unprecedented examination of the Higgs boson:

\[ \lambda_h \approx 10^{-17} \text{ m} \]

\[ \lambda_{10 \text{ TeV}} \approx 10^{-19} \text{ m} \]
Theorists have been exploring many connections between the origin of the Higgs mass and the cosmology. One example: “Crunching Dilaton”.

Future Z-factories are by far the most comprehensive probes of this scenario!
The origin of mass.
Higgs Couplings

By measuring how a massive fundamental particle interacts with the Higgs boson, we measure how that particle got mass.
What sort of precision should we aim for?

- 95% confidence it exists: Around 50% accuracy
- 5σ discovery it exists: Around 20% accuracy.
- Quantum structure: Around 5% accuracy.
Higgs factories offer enormous precision, digging deep into quantum structure of the Higgs boson!

Figure 2. Expected relative precision (%) of the $\kappa$ parameters in the kappa-3 scenario described in Section 2. For details, see Tables 4 and 5. For HE-LHC, the S2’ scenario is displayed. For LHeC, HL-LHC and HE-LHC a constrained $\kappa_\gamma \leq 1$ is applied.
The birth of our Universe.
The Electroweak Phase Transition

With a superconductor we can tune the temperature up and down and study the details of the phase transition.
The Electroweak Phase Transition

The EW phase transition only happened once, a long long time ago. How can we tell what happened, and study the details of the phase transition?
The Electroweak Phase Transition

Difficult to make model-independent statements, however scenarios with modified EWPT produce correlated deviations in precision Higgs. Example:

Very simple: Add a singlet scalar.
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A powerful probe of the one of the most important historical events in fundamental physics.

Very simple: Add a singlet scalar.
The Shape of the Potential

Measuring the Higgs self-coupling is the only way to probe the structure of the Higgs potential.

\[ V(H) = \frac{1}{2} m_h^2 h^2 + \frac{1}{6} \lambda h^3 + \ldots \]

Discovering the Higgs was difficult enough, now we want to know how it interacts with itself...
However, \[ O_6 = \frac{c_6}{M^2} |H|^6 \]
is also very very special, since:
\[ [c_6] = C^4 \quad , \quad [\bar{h}] = C^{-2} \]

At one-loop we have:
\[ [\bar{h}c_6] = C^2 \]

Thus, if any other coupling enters the game, coupling dimension is too large to match any other dim-6 operator!
A Unique Operator

Observation:

This operator is a mountain-top in RG-space.

Insert into any one-loop diagram and no dim-6 counterterms will be required, result always finite!
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Can see where it lies in the space of Dim-6 operator RG space in papers by Jenkins, Manohar, Trott and collaborators...
At high energies we can use Higgs pair production, at low energies quantum effects:

This is the future of the Higgs self coupling (Higgs potential)...
Evidence for dark matter is now overwhelming

- Rotation curves
- CMB
- Large scale structure
- Velocity dispersions
- Gravitational lensing (Bullet Cluster)
- ....

Yet we have no clue what it is at the particle level!
Only 18% of all matter in Universe is visible.

Within that 18% we observe extraordinary complexity.

Similarly, the dark sector, and dark matter, may be much more complex than just a single state.
Theorists are constantly developing new models to understand the origin of dark matter. Forbidden dark matter is one example where a Tera-Z program offers a unique probe!
Comment: On Energy

It is tempting to associate the weakly coupled frontier with the low mass range. Why?

Case study: The Higgs boson is the most mysterious particle in nature. If it has rare decays then the only shot at discovering them is through Higgs boson decays.
The Higgs is totally different from other particles and could be our new window to the dark sector:

**Higgs**

**Standard Model**

**Standard Model**

1612.09284
The Higgs is totally different from other particles and could be our new window to the dark sector:

The only way to search for such scenarios is with a Higgs boson. At lower energies, suppressed by tiny additional factors:

$$\text{Rate} \propto \frac{\Gamma_h^2 E_{\text{CM}}^2}{m_h^4} \times \text{other factors}$$

Trivial calculation: Low energy probes can not do the job of high energy.
Conclusions

After the discovery of the Higgs Boson fundamental physics is now poised to ask the big, structural, questions.

The only way we can hope to understand the origin of this weird superconducting Universe we live in is to measure every facet of the Higgs.