Snowmass EF1/EF2
“Higgs Report” Theory

Patrick Meade
C.N. Yang Institute for Theoretical Physics
Stony Brook University

EF1 conveners: Sally Dawson, Caterina Vernieri
EF2 conveners: PM, Isobel Ojalvo
I. Executive Summary

II. Why the Higgs is the Most Important Particle

III. Higgs Status
   A. Experimental Status of SM Higgs
   B. Current status of theoretical Precision
   C. Multi Higgs production and Self Interactions

IV. The future...
   A. Production Mechanisms at Future Colliders
   B. Future mass and width measurements
   C. Couplings to Standard Model Particles
      1. Top Yukawa
      2. Charm Yukawa
      3. Strange Yukawa
      4. Electron Yukawa
   D. Beyond the $\kappa$ framework
   E. CP violating Higgs coupling measurements
   F. Prospects for observing Double Higgs production and measuring Higgs self-couplings

V. Learning about BSM Physics through Higgs measurements
   A. Additional Higgs Singlets
   B. Two Higgs Doublet Models
      1. Higgs and Flavor
   C. BSM in Higgs loops
   D. Higgs Exotic Decays

VI. Detector/accelerator requirements to observe new physics

VII. Conclusion

References
“Theory Side”

- Why we care about the Higgs and studying its properties in more details
- What theory is needed to understand the Higgs
- BSM side
  - What do we expect for Higgs precision
  - What can we say about BSM scenarios involving the Higgs
- Complementarity of direct and indirect searches involving the Higgs

(See also tomorrow’s TF-EF cross frontier session)
Another way of saying this, take the section 2.2 of the EF report and apply it to the Higgs!
Another way of saying this, take the section 2.2 of the EF report and apply it to the Higgs!

**Direct and Indirect Limits**

- **HF Indirect Bounds**
  - BSM@tree-level
  - $\sim 1\%$

- **Indirect Bounds**
  - BSM@loop level

- **LHC Limits**

- ** Increased precision **

- **BSM@tree-level**
  - $\lesssim 0.1\%$

- **HE Collider Limits**
Why are you here? Because hopefully we all know the Higgs is the most unique **AND** central player in the Standard Model.
We’ve all probably seen this figure with the Higgs being the last piece of the SM and now we’re done?
Absolutely not! After all you just saw all the myriad of updated projections in Isobel’s talk…
But what do they mean? And when is it enough?
For example we can take a snapshot of all of the many many bar charts - after the first stages of proposed Higgs Factories

<table>
<thead>
<tr>
<th>EF benchmarks</th>
<th>$y_u$</th>
<th>$y_d$</th>
<th>$y_s$</th>
<th>$y_c$</th>
<th>$y_t$</th>
<th>$y_e$</th>
<th>$y_\mu$</th>
<th>$y_\tau$</th>
<th>Gauge Couplings</th>
<th>Higgs Factory</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC/HL-LHC</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>Tree</td>
<td>□</td>
</tr>
<tr>
<td>ILC/C^3 250</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>Loop induced</td>
<td>□</td>
</tr>
<tr>
<td>CLIC 380</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>Higgs Width</td>
<td>□</td>
</tr>
<tr>
<td>FCC-ee 240</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>$\lambda_3$</td>
<td>□</td>
</tr>
<tr>
<td>CEPC 240</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>$\lambda_4$</td>
<td>□</td>
</tr>
</tbody>
</table>

Order of Magnitude for Fractional Uncertainty

- $\lesssim \mathcal{O}(10^{-3})$
- $\mathcal{O}(0.01)$
- $\mathcal{O}(0.1)$
- $\mathcal{O}(1)$
- $\gg \mathcal{O}(1)$

Clearly many parameters greatly improve compared to HL-LHC, but also many don’t even achieve $O(1)$ accuracy
Okay, but that’s just the first stages, what about our most futuristic plans at higher energies that have been studied during Snowmass?
More energy = More Higgses

This is for lepton colliders, but also true for hadron colliders, e.g. we have more gluons at lower x
How Many Higgs??

Take this with many grains of salt...

Different energies access different dominant processes (different physics you can access), have different experimental challenges

This is to understand orders of magnitude and what you could do if you could exploit them all!

$\text{HL-LHC} \sim .35 \times 10^9$

End of LHC $\sim O(100)$ million Higgses!

ILC250/350 $\sim .6 \times 10^6$

Low energy e+e- Higgs factories

$\sim 1$ million Higgs

FCC-ee 240/365 $\sim 1.2 \times 10^6$

CEPC 240 $\sim 1.1 \times 10^6$

Moderate energy e+e- Higgs factories

$\sim$ few million Higgs

CLIC-380 $\sim .2 \times 10^6$

ILC500/1000 $\sim 4.5 \times 10^6$

FCC-hh $\sim 27 \times 10^9$

27 billion Higgses

$\text{CLIC 1500/3000} \sim 3.4 \times 10^6$

$\text{Moderate energy e+e- Higgs factories}$

$\sim 1$ million Higgs

Speculative high energy options (run plans specified here)

Muon (or electron colliders)

$\begin{align*}
6 \text{ TeV} & \sim 3.2 \times 10^6 \\
10 \text{ TeV} & \sim 9.5 \times 10^6 \\
14 \text{ TeV} & \sim 22 \times 10^6 \\
30 \text{ TeV} & \sim .12 \times 10^9 \\
100 \text{ TeV} & \sim .18 \times 10^9
\end{align*}$

Millions to 100s of millions

Collider in the sea

$\begin{align*}
500 \text{ TeV} & \sim 400 \times 10^9
\end{align*}$

Can approach a trillion Higgs
Not surprising from this perspective why we have the same rough starting point with similar detector environs

<table>
<thead>
<tr>
<th>EF benchmarks</th>
<th>$y_u$</th>
<th>$y_d$</th>
<th>$y_s$</th>
<th>$y_c$</th>
<th>$y_b$</th>
<th>$y_t$</th>
<th>$y_e$</th>
<th>$y_\mu$</th>
<th>$y_\tau$</th>
<th>Gauge Couplings</th>
<th>Higgs Width</th>
<th>$\lambda_3$</th>
<th>$\lambda_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC/HL-LHC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tree</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILC/C$^3$ 250</td>
<td></td>
<td></td>
<td>?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Loop induced</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLIC 380</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC-ee 240</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CEPC 240</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Order of Magnitude for Fractional Uncertainty

- $\star \leq O(10^{-3})$
- $O(0.01)$
- $O(0.1)$
- $O(1)$
- $> O(1)$

*No study Beyond HL-LHC
Big improvement with Energy, but also the SM is not even close to “complete” so we must press forwards
One thing to keep in mind always...

Gauge bosons are egalitarian

The Higgs is not.
LEP 17 M Z's

"Major" BF's \( O(\%) \)

Higgs Factory \( O(1) \) M H's

"Major" \( \text{DY} \sim 10^{-3} \) ~ \( 10^3 \) events

\( \text{MM} \sim 10^{-4} \) ~ \( 10^2 \) events

\( \text{SS} \sim 10^{-4} \)

\( \text{WZ} \sim 10^{-8} \) **CRAP!!**
<table>
<thead>
<tr>
<th>EF benchmarks</th>
<th>( y_u )</th>
<th>( y_d )</th>
<th>( y_s )</th>
<th>( y_c )</th>
<th>( y_b )</th>
<th>( y_t )</th>
<th>( y_e )</th>
<th>( y_\mu )</th>
<th>( y_\tau )</th>
<th>Tree</th>
<th>Loop induced</th>
<th>Higgs Width</th>
<th>( \lambda_3 )</th>
<th>( \lambda_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC/HL-LHC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
</tr>
<tr>
<td>ILC/C^3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
</tr>
<tr>
<td>CLIC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
</tr>
<tr>
<td>FCC-ee/CEPC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
</tr>
<tr>
<td>( \mu )-Collider</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
</tr>
<tr>
<td>FCC-hh/SPPC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
<td>( \mathcal{O}(1) )</td>
</tr>
</tbody>
</table>

Order of Magnitude for Fractional Uncertainty:
- \( \mathcal{O}(10^{-3}) \)
- \( \mathcal{O}(0.01) \)
- \( \mathcal{O}(0.1) \)
- \( \mathcal{O}(1) \)
- \( \mathcal{O}(\infty) \)

So what precision is enough?
Zeroth order answer... whenever we find a deviation!

- **Gauge Interactions**
- **Yukawa Interactions**
- **Higgs Interactions**

Where most of parameters in SM are
Remember that *any* deviation implies new physics

Although parameters from Higgs are arbitrary the structure is delicately balanced once set
Therefore *any* deviation points to a scale where there *must* be new physics

FIG. 27: Scale where unitarity is violated as a function of precision of Higgs coupling measurements. The bound is typically only saturated in strongly interacting scenarios and in specific models tends to be significantly lower.[77].

**Similar to Lee-Quigg-Thacker Bounds that said the Higgs had to be there...**
The reverse of this shouldn’t inspire doubt though…

If we don’t see a deviation in the muon Yukawa this doesn’t mean all new physics is above 100 TeV!

Are there targets? Are there expected deviation sizes?
Why is the Higgs so central and important?

II. WHY THE HIGGS IS THE MOST IMPORTANT PARTICLE

Over the past decade, the LHC has fundamentally changed the landscape of high energy particle physics through the discovery of the Higgs boson and the first measurements of many of its properties. As a result of this, and no discovery of new particles or new interactions at the LHC, the questions surrounding the Higgs have only become sharper and more pressing for planning the future of particle physics.

The Standard Model (SM) is an extremely successful description of nature, with a basic structure dictated by symmetry. However, symmetry alone is not sufficient to fully describe the microscopic world we explore: even after specifying the gauge and space-time symmetries, and number of generations, there are 19 parameters undetermined by the SM (not including neutrino masses). Out of these parameters 4 are intrinsic to the gauge theory description, the gauge couplings and the QCD theta angle. The other 15 parameters are intrinsic to the coupling of SM particles to the Higgs sector, illustrating its paramount importance in the SM. In particular, the masses of all fundamental particles, their mixing, CP violation, and the basic vacuum structure are all undetermined and derived from experimental data. Therefore, as simply a test of the validity of the SM, all these couplings must be measured experimentally. However, the centrality of the Higgs boson goes far beyond just dictating the parameters of the SM.

The Higgs boson is connected to some of our most fundamental questions about the Universe. Its most basic role in the SM is to provide a source of Electroweak Symmetry Breaking (EWSB). However, while the Higgs can describe EWSB, it is merely put in by hand in the Higgs potential. Explaining why EWSB occurs is outside the realm of the Higgs boson, and yet at the same time by studying it we may finally understand its origin. There are a variety of connected questions and observables tied to the origin of EWSB for the Higgs boson. For example, is the Higgs mechanism actually due to dynamical symmetry breaking as observed elsewhere in nature? Is the Higgs boson itself a fundamental particle or a composite of some other strongly coupled sector? The answers to these questions have a number of ramifications beyond the origin of EWSB.

If the Higgs boson is a fundamental particle, it represents the first fundamental scalar particle discovered in nature. This has profound consequences both theoretically and experimentally. From our modern understanding of quantum field theory viewed through the lens of Wilsonian renormalization, fundamental scalars should not exist in the low energy spectrum without an ultra-violet (UV) sensitive fine tuning. This is known as the naturalness or hierarchy problem. From studying properties of the Higgs boson, one can hope to learn whether there is some larger symmetry principle at work such as supersymmetry, neutral naturalness, or if the correct theory is a composite Higgs model where the Higgs is a pseudo-Goldstone boson.

Experimentally, there are also a number of intriguing directions that open up if the Higgs boson is a fundamental particle. The most straightforward question is whether the Higgs boson is unique as the only scalar field in our universe or is it just the first of many? From a field theoretic point of view, one can construct the lowest dimension gauge and Lorentz invariant operator in the SM from the Higgs boson alone. This means that generically if there are other “Hidden” sectors beyond the SM, at low energies the couplings of the Hidden sector particles to the Higgs boson are predicted to be the leading portal to the additional sectors. Additionally, with a scalar particle the question remains as to whether the minimal Higgs potential is correct. The form of the potential has repercussions for both our...
How do these ideas correlate to observables?

The understanding of the early universe and its ultimate fate is crucial. The Standard Model (SM) predicts that the electroweak symmetry should be restored at high temperatures. However, the actual form of the potential determines whether there was a phase transition and its strength. Additionally, the shape of the Higgs potential controls our universe's future as its vacuum may be metastable.

The Higgs boson is connected to fundamental questions like flavor, mass, and CP violation. While it gives mass to all elementary fermions, the Yukawa couplings determine the masses, CKM matrix, and CP-violating phase. This makes the Higgs boson a direct connection to the origin of multiple generations, flavor, and CP violation. Studying it more precisely could provide insight into these fundamental puzzles.

The neutrino sector also connects to the SM Higgs boson or a new Higgs-like boson that breaks electroweak symmetry. Understanding the SM Higgs boson's properties is central to high-energy physics (HEP). The connections reviewed so far can be expanded, and new fundamental mysteries like the Higgs portal could connect to Dark Matter or other cosmological mysteries.

The goal of this report is to connect the many fundamental questions related to the Higgs boson to various observables and vice versa. Understanding how to map various observables to the interesting questions is crucial for deciphering collider projects' contributions. In Figure 2, we provide a visual representation of the types of observables and their deeply intertwined web with fundamental ideas.

While Figure 2 is qualitative, it highlights two important lessons: many observables map to fundamentally different questions, and connecting from observables related to Higgs physics to fundamental questions is non-trivial. This has been referred to as the "Higgs Inverse Problem." Additionally, Higgs-related observables don't fit into standard effective field theory (EFT) fits. While Higgs coupling deviations are a gold-standard for future collider projects, deviations don't occur in isolation. Deviations in Higgs couplings or differential measurements must be due to new physics that couples to the Higgs boson, leading to a need for a comprehensive comparison of collider sensitivities to new physics in the Higgs sector with other direct searches and indirect constraints on beyond-the-Standard-Model (BSM) physics.
Future colliders offer new observables

Higgs without Higgs Program
What are the expected size of the effects in the Higgs sector?

\[ \delta \eta_{SM} \sim c_\eta \frac{v^2}{M^2} \]

Also important to recall, SMEFT or HEFT doesn’t always capture interesting physics.

Scale and Precision matter.

We’ll give examples:

- SM Neutral e.g. scalar singlet
  \[ \sim \left( \frac{\lambda_{h^2 s}}{2M^2} \right) \frac{v^2}{M^2} \]
  \( M \lesssim 1.7 \) TeV
  \( M \lesssim 5.5 \) TeV

- SM Charged e.g. 2HDM
  \[ \sim \left( \frac{\lambda_{h^2 s} v^2}{M^2} \right) \frac{v^2}{M^2} \]
  \( M \lesssim 0.8 \) TeV
  \( M \lesssim 1.4 \) TeV

- SM Neutral e.g. scalar singlet
  \[ \sim \left( \frac{\lambda_{h^2 s}^2}{48\pi^2} \right) \frac{v^2}{M^2} \]
  \( M \lesssim 0.1 \) TeV
  \( M \lesssim 0.4 \) TeV

- SM Charged w/ SM loop e.g. stops in SUSY
  \[ \sim \frac{1}{4} \frac{m_t^2}{m_{\tilde{t}}^2} \]
  \( M \lesssim 0.9 \) TeV
  \( M \lesssim 2.8 \) TeV

Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision.
So at this basic level...

- Big questions can connect to observables

- Observables measurable at the 1% to .1% (future colliders on the books) are typically testing up to the few TeV scale
  
  - Direct and Indirect complementarity clearly matters here!

- But what about some specific connections?
Naturalness

- Love it or Hate it - it’s tied to our understanding of QFT and born out in applications of QFT

\[ \epsilon = \frac{m_h^2}{\Delta m_h^2} \]

\[ \frac{\delta \eta_{SM}}{\eta_{SM}} \sim c\epsilon \]

- Hard to go too far without specific models - depending on type of contributions Soft, SuperSoft etc. Direct searches or Indirect Searches can be more powerful tests of naturalness
Thermal History of Universe

FIG. 28: The Higgs boson as the keystone of the Standard Model is connected to numerous fundamental questions that can be investigated by studying it in detail.

FIG. 29: An example from [49] demonstrating different patterns of Higgs deviations from different classes of models, in this case a 2HDM example and scalar singlet model.

The stark difference between models shown in Figure 29, stems from the fact that a SM singlet inherently affects Higgs couplings universally since it carries no distinguishing quantum numbers, while a 2HDM does. Therefore one can potentially distinguish certain classes of models with precision measurements at Higgs factories. However, it should also be noted that the particular points shown in Figure 29 correspond to a 2HDM with a 600 GeV mass scale and a singlet with a 2.8 TeV scalar. Both of these are clearly out of the direct search reach of circular Higgs factories despite having the precision to test them via Higgs couplings. However, only a 10 TeV muon collider or FCC-hh among the proposed future machines would be able to both reach this level of Higgs precision and directly discover the new physics states of the benchmark collider scenarios considered, as even a 3 TeV CLIC would be insufficient [84].

While this represents just one small corner of the Higgs Inverse problem, it does illustrate the complementary nature of Higgs precision and high energy colliders. In the EF04 topical report where EFT fits are considered there is additional discussion about the general inverse problem of relating patterns of EFT coefficients to new physics.

Another possible direction to organize BSM models is purely through the type of signature it manifests. An example of this which is less studied is the production of triple-Higgs or even quad-Higgs final states at HL-LHC and future colliders. This is often thought of as a process that is too rare to observe, in the case of probing the SM quartic coupling, or has no appreciable rates at the LHC regardless of physics case. However, there are now viable models...
Hard to give definite targets, and how to not confuse?

The SM predicts that the electroweak symmetry should be restored at high temperatures. However, depending on the actual form of the potential, the question remains as to whether there even was a phase transition let alone its strength. Additionally, depending on the shape of the Higgs potential, it controls the future of our universe as our vacuum may only be metastable.

Finally, the Higgs boson is connected to some of the most puzzling questions in the universe: flavor, mass and CP violation. While it is often stated that the Higgs boson gives mass to all elementary fermions, this is just the tip of the proverbial iceberg. The Yukawa couplings determine not only the masses, but also the CKM matrix and its CP violating phase. Thus the Higgs boson is the only known direct connection to whatever is responsible for the origin of multiple generations, flavor and known CP violation. By studying it with more precision, we may perhaps gain insight into these fundamental puzzles or at the very least test if this picture is correct. Furthermore, these puzzles also extend to the neutrino sector. Whatever form neutrino masses take, Majorana, Dirac or both, their mass still must connect to the SM Higgs boson or a new Higgs-like boson must exist that also breaks the electroweak symmetry.

The understanding of the early universe and its ultimate fate. For the early universe, the SM predicts that the electroweak symmetry should be restored at high temperatures. However, depending on the actual form of the potential the question remains as to whether there even was a phase transition let alone its strength. Additionally, depending on the shape of the Higgs potential, it controls the future of our universe as our vacuum may only be metastable.
FIG. 28: The Higgs boson as the keystone of the Standard Model is connected to numerous fundamental questions that can be investigated by studying it in detail.

FIG. 29: An example from [49] demonstrating different patterns of Higgs deviations from different classes of models, in this case a 2HDM example and scalar singlet model.

The stark difference between models shown in Figure 29, stems from the fact that a SM singlet inherently affects Higgs couplings universally since it carries no distinguishing quantum numbers, while a 2HDM does. Therefore one can potentially distinguish certain classes of models with precision measurements at Higgs factories. However, it should also be noted that the particular points shown in Figure 29 correspond to a 2HDM with a 600 GeV mass scale and a singlet with a 2.8 TeV scalar. Both of these are clearly out of the direct search reach of circular Higgs factories despite having the precision to test them via Higgs couplings. However, only a 10 TeV muon collider or FCC-hh among the proposed future machines would be able to both reach this level of Higgs precision and directly discover the new physics states of the benchmark collider scenarios considered, as even a 3 TeV CLIC would be insufficient [84].

While this represents just one small corner of the Higgs Inverse problem, it does illustrate the complementary nature of Higgs precision and high energy colliders. In the EF04 topical report where EFT fits are considered there is additional discussion about the general inverse problem of relating patterns of EFT coefficients to new physics.

Another possible direction to organize BSM models is purely through the type of signature it manifests. An example of this which is less studied is the production of triple-Higgs or even quad-Higgs final states at HL-LHC and future colliders. This is often thought of as a process that is too rare to observe, in the case of probing the SM quartic coupling, or has no appreciable rates at the LHC regardless of physics case. However, there are now viable models...
I. Executive Summary

A future Higgs Factory will provide improved precision on measurements of Higgs couplings beyond those obtained by the LHC, and will enable a broad range of investigations across the fields of fundamental physics, including the mechanism of electroweak symmetry breaking, the origin of the masses and mixing of fundamental particles, the predominance of matter over antimatter, and the nature of dark matter. Future colliders will measure Higgs couplings to a few per cent, giving a window to beyond the Standard Model (BSM) physics in the 1-10 TeV range.

Can be more systematic from this perspective
Singlet Extensions of SM Higgs Sector

\[ \mathcal{L} \supset \lambda_{hhS} \phi^2 S + \lambda_{\phi S} \phi^2 S^2 \]

Despite their simplicity there still is a lot of physics involved - but still effectively a mass/mixing or mass/coupling

FIG. 31: This figure is from [78] Figure 8.11, where on the LHS the direct and indirect sensitivity to a singlet which mixes with the SM Higgs, while on the RHS it is the limit of no-mixing but also overlaid with regions of parameter space for a strong first-order phase transition.
Singlet Extensions of SM Higgs Sector

\[ \mathcal{L} \supset \lambda_{hhS} \phi^2 S + \lambda_{\phi S} \phi^2 S^2 \]

FIG. 30: Production of a pair of Higgs bosons in the complex singlet model. \( h_1 \) is the SM Higgs boson, and \( h_2, h_3 \) are new gauge singlet scalars. The maximum rates allowed by current LHC data are shown\(^{[89]}\).

More nontrivial phenomenology investigated by a number of whitepapers
2HDM

Lots of new phenomena can occur because at renormalizable level you can couple to Fermions!

Typically classified by

\[ \tan \beta \quad \cos(\beta - \alpha) \]

\[ \lambda_f^{(1)} = \frac{\sqrt{2}}{v} m_f, \quad \lambda_f^{(2)} = \frac{\eta_f}{\tan \beta} \lambda_f^{(1)}, \]

where \( \eta_f \) dictates the type of 2HDM, given in Table VIII, and \( m_f \) is the mass of fermion type \( f \).

\[
\begin{array}{cccccc}
\eta_u & \text{Type-I} & \text{Type-II} & \text{Type-L} & \text{Type-F} \\
1 & 1 & 1 & 1 & 1 \\
\eta_d & 1 & -\tan^2 \beta & 1 & -\tan^2 \beta \\
\eta_l & 1 & -\tan^2 \beta & -\tan^2 \beta & 1 \\
\end{array}
\]

This comes from Glashow-Weinberg Condition for avoiding FCNCs it is NOT a necessary condition
FIG. 32: Matching the 2HDM type-I and type-II to the SMEFT at dimension-6 and dimension-8[96].

FIG. 33: Limits on the parameters of a 2HDM from precision Higgs couplings combined with HL-LHC results. LHS: Limits from future $e^+e^-$ colliders[99]. RHS: Limits from a 3 TeV muon collider.
FIG. 34: Capability of HL-LHC to probe the scalar sector of the 2HDM. 

Table IX: Summary of the second doublet Yukawa structure for different 2HDMs which are free from tree-level FCNCs at tree-level in all generations. In each column we indicate the relation between the up- and down-type quark Yukawas for the second Higgs doublet and the SM Yukawa matrices. Non-universally flavor aligned stands for Yukawas that are flavor-aligned with the SM Yukawas, without sharing the SM Yukawa hierarchies. Real (complex) proportional stands for proportionality to the corresponding up or down SM Yukawa matrix, with one up- and one down-type real (complex) proportionality coe.
2HDM future colliders

FIG. 33: Limits on the parameters of a 2HDM from precision Higgs couplings combined with HL-LHC results. LHS: Limits from future $e^+e^-$ colliders[99]. RHS: Limits from a 3 TeV muon collider.
2HDM w/ flavor beyond NFC

<table>
<thead>
<tr>
<th>Model</th>
<th>up-type</th>
<th>down-type</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFV [100]</td>
<td>polynomial of SM Yukawas</td>
<td>polynomial of SM Yukawas</td>
</tr>
<tr>
<td>gFC [101, 102]</td>
<td>non-universally flavor aligned</td>
<td>non-universally flavor aligned</td>
</tr>
<tr>
<td>NFC (types I-IV) [92]</td>
<td>real proportional</td>
<td>real proportional</td>
</tr>
<tr>
<td>Aligned 2HDM [103, 104]</td>
<td>complex proportional</td>
<td>complex proportional</td>
</tr>
<tr>
<td>up-type SFV [105, 106]</td>
<td>real proportional</td>
<td>non-universally flavor aligned</td>
</tr>
<tr>
<td>down-type SFV [105, 106]</td>
<td>non-universally flavor aligned</td>
<td>real proportional</td>
</tr>
</tbody>
</table>

An example of the interplay of new observables and precision measurements of Higgs couplings is shown in Figure 35.

FIG. 35: Probes of flavor violation in a 2HDM at future colliders[64].
FIG. 36: The bounds on stop masses in the MSSM for a fixed value of $\tan \beta$, for future $e^+e^-$ colliders and the FCC-hh adapted from [113]. As can be seen even with the most precise Higgs measurements, the LHC has already probed this space albeit with assuming particular decay modes.
Exotic Higgs Decays

FIG. 37: Higgs portal model with $h \rightarrow SS$. The shaded region allows for an electroweak phase transition. From Ref [83].
Conclusions

• We’ve tried to emphasize how important the Higgs is and how connected to so many different SM issues and BSM possibilities

• We’ve tried to give context to what Higgs precision actually means

• We’ve tried to give a number of examples for what future colliders can do, as well as illustrating theory points that are new compared to European Strategy

• There’s still an enormous amount of work to be done on all fronts for the Higgs, but hopefully this gives a basis for where we are and why it’s SO crucial that we develop and construct experiments to study the Higgs to death!

• We welcome your questions, feedback, and any help in tweaking this to make the final version as strong as possible!