Higgs and New Physics

LianTao Wang
Univ. of Chicago

Outline

- Why is Higgs important? (brief)

- What can the (HL)-LHC contribute?

  Highlight some promising directions.
Why focusing on the Higgs
Why focusing on Higgs?

Higgs is simple.

A simple “Mexican hat” potential.

⇒ Electroweak symmetry breaking
⇒ gives masses of SM particles
Why focusing on Higgs?

Yet, Higgs is confusing.

Sure, the math is simple.
It does not give us clues for a deeper understanding.

Different from other SM particles:
gauge boson (gauge symmetry), fermion (chiral symmetry)
Why focusing on Higgs?

Yet, Higgs is confusing.

Sure, the math is simple.
It does not give us clues for a deeper understanding.

Different from other SM particles:
gauge boson (gauge symmetry), fermion (chiral symmetry)

Maybe not as simple as it seems?

Is it elementary (like electron) or composite (like proton or pion)?
Is the Higgs the only spin-0 particle, or there are similar ones?
Where does the electroweak scale come from?
Higgs and everything else

Weak interaction vs gravitation
$10^2$ vs $10^{18}$

Matter > anti-matter
Electroweak phase

The dark world

Inflation, age of universe, …

Flavor puzzle
Higgs and everything else

Weak interaction vs gravitation
$10^2$ vs $10^{18}$

Matter > anti-matter
Electroweak phase

The dark world

Inflation, age of universe, ...

Flavor puzzle

Higgs is likely to play a role in many of these, but how?
What do we know?

Higgs coupling other SM particles:

Higgs couplings. Presently, known to about 10%

Other electroweak couplings known to much better precision $\mathcal{O}(10^{-3})$. 
What do we know?

Higgs potential?

\[ V(\phi) \]

Higgs field value in our universe

an alternative potential

Standard Model potential

\[ 0 \quad 1 \quad \phi \]
mediated by the exchange of Higgs bosons. The fact that such a force is stronger for heavier particles makes it qualitatively different from all other interactions in the Standard Model, whose interaction strengths come in multiples of some basic unit of charge, like the electron charge for fermions. Why is the Higgs field non-zero in the first place? According to the Standard Model there is no symmetry that enforces the Higgs field to be non-zero. Remarkably, interactions with the Higgs field also provided a consistent theoretical mechanism that did the job. Within the Standard Model the interaction is known as a “Yukawa” interaction [14]. Thus any particle’s interaction with the Higgs field has to be directly related to that particle’s mass. The stronger the interaction, the larger the resulting mass for the particle. For producing fermion masses: each fermion interacts with the Higgs field with a different strength, e.g. the stronger the interaction, the larger the resulting mass for the particle.

What do we know?

Higgs potential?

Figure 2:

- Higgs field value in our universe
- Standard Model potential
- An alternative potential
- Current experimental knowledge

The red curve shows the potential within the Standard Model. The blue curve represents our current experimental knowledge of the potential. Alternative potentials differ substantially from the Standard Model away from that minimum. The blue curve is the energetic minimum of the potential, as indicated by Fig. 2.
A simple “Mexican hat” potential.

⇒ Electroweak symmetry breaking
⇒ gives masses of SM particles
A simple “Mexican hat” potential?

- Electroweak symmetry breaking
- Gives masses of SM particles

We need to know better!
What can (HL)-LHC do?
What can (HL)-LHC do?

Precision

Are we really sure the SM is as simple as it appears to be?

This is the “bread and butter”.
Higgs coupling

Higgs coupling other SM particles:

Eventually at the LHC

Higgs couplings. Presently, known to about 10% 1- a few %
Figure 2: Higgs potential. Potential energy density $V(\phi)$ associated with the Higgs field, as a function of the value of $\phi$. The red curve shows the potential within the Standard Model. The Higgs field has a value corresponding to a minimum of the potential and the region highlighted in black represents our current experimental knowledge of the potential. Alternative potentials that differ substantially from the Standard Model away from that minimum (e.g. the blue curve) would be equally consistent with current data.

Remarkably, interactions with the Higgs field also provided a consistent theoretical mechanism for producing fermion masses: each fermion interacts with the Higgs field with a different strength (or “coupling”), and the stronger the interaction, the larger the resulting mass for the particle. Within the Standard Model the interaction is known as a “Yukawa” interaction [14]. Thus any question about the origin of the masses of fermions reduces to a question about the origin of the fermions’ interactions with the Higgs field.

Why is the Higgs field non-zero in the first place? According to the Standard Model there is a potential energy density associated with the value of the Higgs field and the lowest potential energy corresponds to a non-zero value of the Higgs field. The Standard Model potential has a form dictated by internal consistency conditions. With some simplifications, labeling the magnitude of the Higgs field as $h$, the potential has the form

$$V(h) = \frac{h^4}{2} + \frac{1}{2}h^2.$$  \hspace{1cm} (1)

This is illustrated by the red line in Fig. 2. The minimum of the potential, i.e. the energetically most favourable choice for $h$, lies at a value of $h$ that is non-zero, $h = 1$. An important implication of the Higgs field’s non-zero constant value is the impossibility to carry angular momentum, or more technically having “spin 0”. A non-zero value for the spin would break at least one of the well-tested space-time symmetries. Hence, the excitation of the Higgs field, the Higgs boson, must be a spin-0 particle and is in fact the only known fundamental particle with this property.

One of the reasons for the central importance of the discovery of the Higgs boson was that it finally made it possible to start testing the remarkable theoretical picture outlined above. It is not possible to probe the interactions of a given particle with the Higgs field. However, one can instead measure a particle’s interaction with the excitations of the Higgs field, i.e. with a Higgs boson. If the Standard Model provides the correct picture for the generation of mass, the strength of any particle’s interaction with the Higgs boson has to be directly related to that particle’s mass. Aside from providing a powerful way of testing the Higgs mechanism, the interaction of the Higgs boson with other particles is intriguing because it implies the existence of a “fifth force”, mediated by the exchange of Higgs bosons. The fact that such a force is stronger for heavier particles makes it qualitatively different from all other interactions in the Standard Model, whose interaction strengths come in multiples of some basic unit of charge, like the electron charge for $3\times 10^{-10}$.
Figure 2: Higgs potential. Potential energy density $V(\phi)$ associated with the Higgs field, as a function of the value of $\phi$. The red curve shows the potential within the Standard Model. The Higgs field has a value corresponding to a minimum of the potential and the region highlighted in black represents our current experimental knowledge of the potential. Alternative potentials that differ substantially from the Standard Model away from that minimum (e.g. the blue curve) would be equally consistent with current data.

Remarkably, interactions with the Higgs field also provided a consistent theoretical mechanism for producing fermion masses: each fermion interacts with the Higgs field with a different strength (or "coupling"), and the stronger the interaction, the larger the resulting mass for the particle. Within the Standard Model the interaction is known as a "Yukawa" interaction [14]. Thus any question about the origin of the masses of fermions reduces to a question about the origin of the fermions' interactions with the Higgs field.

Why is the Higgs field non-zero in the first place? According to the Standard Model there is a potential energy density associated with the value of the Higgs field and the lowest potential energy corresponds to a non-zero value of the Higgs field. The Standard Model potential has a form dictated by internal consistency conditions. With some simplifications, labeling the magnitude of the Higgs field as $H$, the potential has the form $V(\phi)/2 + \frac{1}{4}H^2$.

This is illustrated by the red line in Fig. 2. The minimum of the potential, i.e. the energetically most favourable choice for $\phi$, lies at a value of $\phi$ that is non-zero, $H = 1$. An important implication of the Higgs field's non-zero constant value is the impossibility to carry angular momentum, or more technically having "spin 0". A non-zero value for the spin would break at least one of the well-tested space-time symmetries. Hence, the excitation of the Higgs field, the Higgs boson, must be a spin-0 particle and is in fact the only known fundamental particle with this property.

One of the reasons for the central importance of the discovery of the Higgs boson was that it finally made it possible to start testing the remarkable theoretical picture outlined above. It is not possible to probe the interactions of a given particle with the Higgs field. However, one can instead measure a particle's interaction with the excitations of the Higgs field, i.e. with a Higgs boson. If the Standard Model provides the correct picture for the generation of mass, the strength of any particle's interaction with the Higgs boson has to be directly related to that particle's mass.

Aside from providing a powerful way of testing the Higgs mechanism, the interaction of the Higgs boson with other particles is intriguing because it implies the existence of a "fifth force", mediated by the exchange of Higgs bosons. The fact that such a force is stronger for heavier particles makes it qualitatively different from all other interactions in the Standard Model, whose interaction strengths come in multiples of some basic unit of charge, like the electron charge for $3\times$.
Figure 2: Higgs potential. Potential energy density $V(\phi)$ associated with the Higgs field, as a function of the value of $\phi$. The red curve shows the potential within the Standard Model. The Higgs field has a value corresponding to a minimum of the potential and the region highlighted in black represents our current experimental knowledge of the potential. Alternative potentials that differ substantially from the Standard Model away from that minimum (e.g. the blue curve) would be equally consistent with current data.

Remarkably, interactions with the Higgs field also provided a consistent theoretical mechanism for producing fermion masses: each fermion interacts with the Higgs field with a different strength (or "coupling"), and the stronger the interaction, the larger the resulting mass for the particle. Within the Standard Model the interaction is known as a "Yukawa" interaction [14]. Thus any question about the origin of the masses of fermions reduces to a question about the origin of the fermions' interactions with the Higgs field.

Why is the Higgs field non-zero in the first place? According to the Standard Model there is a potential energy density associated with the value of the Higgs field and the lowest potential energy corresponds to a non-zero value of the Higgs field. The Standard Model potential has a form dictated by internal consistency conditions. With some simplifications, labeling the magnitude of the Higgs field as $\phi$, the potential has the form $V(\phi)/2 + 1/4$.

This is illustrated by the red line in Fig. 2. The minimum of the potential, i.e. the energetically most favourable choice for $\phi$, lies at a value of $\phi$ that is non-zero, $\phi = 1$. An important implication of the Higgs field's non-zero constant value is the impossibility to carry angular momentum, or more technically having "spin 0". A non-zero value for the spin would break at least one of the well-tested space-time symmetries. Hence, the excitation of the Higgs field, the Higgs boson, must be a spin-0 particle and is in fact the only known fundamental particle with this property.

One of the reasons for the central importance of the discovery of the Higgs boson was that it finally made it possible to start testing the remarkable theoretical picture outlined above. It is not possible to probe the interactions of a given particle with the Higgs field. However, one can instead measure a particle's interaction with the excitations of the Higgs field, i.e. with a Higgs boson. If the Standard Model provides the correct picture for the generation of mass, the strength of any particle's interaction with the Higgs boson has to be directly related to that particle's mass.

Aside from providing a powerful way of testing the Higgs mechanism, the interaction of the Higgs boson with other particles is intriguing because it implies the existence of a "fifth force", mediated by the exchange of Higgs bosons. The fact that such a force is stronger for heavier particles makes it qualitatively different from all other interactions in the Standard Model, whose interaction strengths come in multiples of some basic unit of charge, like the electron charge.
hZZ vs Higgs self-coupling

\[ \frac{1}{\Lambda^2} (H^\dagger \partial H)^2 \]

\[ \frac{1}{\Lambda^2} (H^\dagger H)^3 \]

Modify H-Z coupling \( \Rightarrow \delta_{Zh} \)

Modify Higgs self-coupling \( \Rightarrow \delta_{\lambda_3} \)
hZZ vs Higgs self-coupling

\[ \frac{1}{\Lambda^2} (H^\dagger \partial H)^2 \quad \text{Modify H-Z coupling } \rightarrow \delta_{Zh} \]

\[ \frac{1}{\Lambda^2} (H^\dagger H)^3 \quad \text{Modify Higgs self-coupling } \rightarrow \delta_{\lambda_3} \]

No special symmetry, both will generally be there.
All dim-6 operator \( \Rightarrow \) similar size of modification

H-Z coupling much better measured, should be the place to first discover such a modification.
hZZ vs Higgs self-coupling

\[
\frac{1}{\Lambda^2} (H^\dagger \partial H)^2 \quad \text{Modify H-Z coupling} \Rightarrow \delta_{Zh}
\]

\[
\frac{1}{\Lambda^2} (H^\dagger H)^3 \quad \text{Modify Higgs self-coupling} \Rightarrow \delta_{\lambda_3}
\]

However, \( \delta_{Zh} \propto g_z \), while \( \delta_{\lambda_3} \) is not related to \( \lambda_{3,\text{SM}} \).

With some tuning, one can find models in which \( \delta_{\lambda_3} > \delta_{Zh} \).
Simplest example: Higgs + singlet

\[ \mathcal{L} \supset V(H) + V(S) + \lambda H^\dagger HS^2 \]

For \( m_s > m_h \), integrating out singlet

\[ \Rightarrow \quad \frac{1}{\Lambda^2} (H^\dagger \partial H)^2 \quad \text{and} \quad \frac{1}{\Lambda^2} (H^\dagger H)^3 \]
Statement #1: Parameter space with first order electroweak phase transition has large deviation in $h_{ZZ}$, which can be probed by CEPC.

Models with 1st order EWSB, need large self-interaction.
Statement #1: Parameter space with first order electroweak phase transition has large deviation in $h_{ZZ}$, which can be probed by CEPC.

$F_{cc-ee/ILC250/CEPC}$

Interesting progress.

Models with 1st order EWSB, need large self-interaction.
Self-coupling: bottom line

- Unique coupling, never seen before, good to see it.
- Generically, H-Z coupling (better measured) more sensitive to new physics.
- If we are lucky (e.g. 1st order EWPT), may see large deviation in self-coupling.
What can (HL)-LHC do?

Rare processes

Unlikely, but seeing one can teach us a lot.

Large luminosity leads to big improvements.
HL-LHC as particle factories

Promising for rare decay with distinct final state!

- $>10^{11}$ W and Zs
- $>10^9$ tops
- $>10^8$ Higgses
Windows into dark sector: portals

- Any known (SM) particle can in principle have small couplings to dark sector.
Windows into dark sector: portals

- Any known (SM) particle can in principle have small couplings to dark sector.

![Diagram](image-url)
Higgs to dark sector

Standard Model  \( h \)  Dark Sector

“Higgs portal”

Decay back to SM
Higgs portal

$$\lambda H^\dagger H \mathcal{O}_{\text{dark}}$$

$$\mathcal{O}_{\text{dark}} = \text{SM singlet}$$
Higgs portal

$$\lambda H^\dagger H \mathcal{O}_{\text{dark}}$$

$$\mathcal{O}_{\text{dark}} = \text{SM singlet}$$

Example 1: $$\lambda H^\dagger HS^2$$ to avoid fine-tuning, $$\lambda \sim \frac{m_S^2}{v^2}$$

$$\text{BR}(h \to SS) \sim \frac{m_S^4}{(m_h m_b)^2} \sim \text{a few \%} \quad \text{if} \ m_S \sim 10 \text{ GeV}$$
Higgs portal

\[ \lambda H^\dagger H \mathcal{O}_{\text{dark}} \]

\[ \mathcal{O}_{\text{dark}} = \text{SM singlet} \]

Example 1: \( \lambda H^\dagger HS^2 \) to avoid fine-tuning, \( \lambda \sim m_S^2 / v^2 \)

\[ \text{BR}(h \rightarrow SS) \sim m_S^4 / (m_h^2 m_b^2) \sim \text{a few \%} \quad \text{if } m_S \sim 10 \text{ GeV} \]

Example 2: \( \frac{H^2}{\Lambda^2} F_{\mu\nu} D_{\mu\nu} \)

\[ \text{BR}(h \rightarrow \gamma_D \gamma_D) \sim (v/\Lambda)^4 (m_h^2 / m_b^2) \sim \text{a few \%} \quad \text{if } \Lambda \sim \text{TeV} \]
Higgs portal

\[ \lambda H^\dagger H \mathcal{O}_{\text{dark}} \quad \mathcal{O}_{\text{dark}} = \text{SM singlet} \]

Example 1: \( \lambda H^\dagger H S^2 \) to avoid fine-tuning, \( \lambda \sim \frac{m_S^2}{v^2} \)

\[ \text{BR}(h \to SS) \sim \frac{m_S^4}{(m_h m_b^2)} \sim \text{a few \%} \quad \text{if } m_S \sim 10 \text{ GeV} \]

Example 2: \( \frac{H^2}{\Lambda^2} F_D^{\mu\nu} F_D^{\mu\nu} \)

\[ \text{BR}(h \to \gamma_D\gamma_D) \sim \frac{(v/\Lambda)^4 (m_h^2/m_b^2)}{\sim \text{a few \%} \quad \text{if } \Lambda \sim \text{TeV}s} \]

Reasonable to have a small but still sizable BR
Higgs to dark sector

Standard Model \leftrightarrow \text{Dark Sector} \quad \text{"Higgs portal"}

Decay back to SM

\[ h \rightarrow 2 \rightarrow 3 \quad h \rightarrow 2 \rightarrow 3 \rightarrow 4 \quad h \rightarrow 2 \rightarrow (1 + 3) \]

Long lived particles
Higgs exotic decays

<table>
<thead>
<tr>
<th>Decay Topologies</th>
<th>Decay mode $F_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \to 2$</td>
<td>$h \to E_T$</td>
</tr>
<tr>
<td>$h \to 2 \to 3$</td>
<td>$h \to \gamma + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (b\bar{b}) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^-) + E_T$</td>
</tr>
<tr>
<td>$h \to 2 \to 3 \to 4$</td>
<td>$h \to (b\bar{b}) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^-) + E_T$</td>
</tr>
<tr>
<td>$h \to 2 \to (1+3)$</td>
<td>$h \to b\bar{b} + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to \gamma \gamma + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to \ell^+\ell^- + E_T$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay Topologies</th>
<th>Decay mode $F_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \to 2 \to 4$</td>
<td>$h \to (b\bar{b})(b\bar{b})$</td>
</tr>
<tr>
<td></td>
<td>$h \to (b\bar{b})(\tau^+\tau^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^-)(\mu^+\mu^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^-)(\mu^+\mu^-)$</td>
</tr>
<tr>
<td>$h \to 2 \to 4 \to 6$</td>
<td>$h \to (\ell^+\ell^-)(\ell^+\ell^-) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^-) + E_T + X$</td>
</tr>
<tr>
<td>$h \to 2 \to 6$</td>
<td>$h \to \ell^+\ell^- + E_T + X$</td>
</tr>
<tr>
<td></td>
<td>$h \to \ell^+\ell^- + E_T + X$</td>
</tr>
</tbody>
</table>
Higgs exotic decays

Simple, Great sensitivity from the LHC
# Higgs exotic decays

<table>
<thead>
<tr>
<th>Decay Topologies</th>
<th>Decay mode $F_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \to 2$</td>
<td>$h \to E_T$</td>
</tr>
<tr>
<td>$h \to 2 \to 3$</td>
<td>$h \to \gamma + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (bb) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (jj) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\tau^+\tau^-) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\gamma\gamma) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^-) + E_T$</td>
</tr>
<tr>
<td>$h \to 2 \to 3 \to 4$</td>
<td>$h \to (bb) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (jj) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\tau^+\tau^-) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\gamma\gamma) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^-) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\mu^+\mu^-) + E_T$</td>
</tr>
<tr>
<td>$h \to 2 \to (1+3)$</td>
<td>$h \to bb + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to jj + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to \tau^+\tau^- + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to \gamma\gamma + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to \ell^+\ell^- + E_T$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay Topologies</th>
<th>Decay mode $F_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \to 2 \to 4$</td>
<td>$h \to (bb)(bb)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (bb)(\tau^+\tau^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (bb)(\mu^+\mu^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\tau^+\tau^-)(\tau^+\tau^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\tau^+\tau^-)(\mu^+\mu^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (jj)(jj)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (jj)(\gamma\gamma)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (jj)(\mu^+\mu^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^-)(\ell^+\ell^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^-)(\mu^+\mu^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\mu^+\mu^-)(\mu^+\mu^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\gamma\gamma)(\gamma\gamma)$</td>
</tr>
<tr>
<td>$h \to 2 \to 4 \to 6$</td>
<td>$h \to (\ell^+\ell^-)(\ell^+\ell^-) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^-) + E_T + X$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^- + E_T + X$</td>
</tr>
<tr>
<td>$h \to 2 \to 6$</td>
<td>$h \to \ell^+\ell^- + E_T + X$</td>
</tr>
</tbody>
</table>

Simple, Great sensitivity from the LHC

With MET, less lepton
Higgs exotic decays

<table>
<thead>
<tr>
<th>Decay Topologies</th>
<th>Decay mode $F_i$</th>
<th>Decay Topologies</th>
<th>Decay mode $F_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \to 2$</td>
<td>$h \to E_T$</td>
<td>$h \to 2 \to 4$</td>
<td>$h \to (bb)(bb)$</td>
</tr>
<tr>
<td></td>
<td>$h \to \gamma + E_T$</td>
<td></td>
<td>$h \to (bb)(\tau^+\tau^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (bb) + E_T$</td>
<td></td>
<td>$h \to (bb)(\mu^+\mu^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (jj) + E_T$</td>
<td></td>
<td>$h \to (\tau^+\tau^-)(\tau^+\tau^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\gamma\gamma) + E_T$</td>
<td></td>
<td>$h \to (\tau^+\tau^-)(\mu^+\mu^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^-) + E_T$</td>
<td></td>
<td>$h \to (jj)(\gamma\gamma)$</td>
</tr>
<tr>
<td>$h \to 2 \to 3$</td>
<td></td>
<td>$h \to 2 \to 3 \to 4$</td>
<td>$h \to (jj)(\gamma\gamma)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (bb) + E_T$</td>
<td></td>
<td>$h \to (jj)(\mu^+\mu^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (jj) + E_T$</td>
<td></td>
<td>$h \to (\ell^+\ell^-)(\ell^+\ell^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\tau^+\tau^-) + E_T$</td>
<td></td>
<td>$h \to (\ell^+\ell^-)(\mu^+\mu^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\gamma\gamma) + E_T$</td>
<td></td>
<td>$h \to (\mu^+\mu^-)(\mu^+\mu^-)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\ell^+\ell^-) + E_T$</td>
<td></td>
<td>$h \to (\gamma\gamma)(\gamma\gamma)$</td>
</tr>
<tr>
<td></td>
<td>$h \to (\mu^+\mu^-) + E_T$</td>
<td></td>
<td>$h \to \gamma\gamma + E_T$</td>
</tr>
<tr>
<td>$h \to 2 \to (1+3)$</td>
<td></td>
<td>$h \to 2 \to 4 \to 6$</td>
<td>$h \to \ell^+\ell^- + E_T + X$</td>
</tr>
<tr>
<td></td>
<td>$h \to bb + E_T$</td>
<td></td>
<td>$h \to (\ell^+\ell^-)(\ell^+\ell^-) + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to jj + E_T$</td>
<td></td>
<td>$h \to (\ell^+\ell^-)(\ell^+\ell^-) + X$</td>
</tr>
<tr>
<td></td>
<td>$h \to \tau^+\tau^- + E_T$</td>
<td></td>
<td>$h \to \ell^+\ell^- + E_T + X$</td>
</tr>
<tr>
<td></td>
<td>$h \to \gamma\gamma + E_T$</td>
<td></td>
<td>$h \to \ell^+\ell^- + E_T$</td>
</tr>
<tr>
<td></td>
<td>$h \to \ell^+\ell^- + E_T$</td>
<td></td>
<td>$h \to \ell^+\ell^- + X$</td>
</tr>
</tbody>
</table>

Simple, Great sensitivity from the LHC

With MET, less lepton

More hadronic
# Higgs exotic decays

## Decay Topologies | Decay mode $F_i$
--- | ---
$h \to 2$ | $h \to E_T$
$h \to 2 \to 3$ | $h \to \gamma + E_T$
 | $h \to (bb) + E_T$
 | $h \to (jj) + E_T$
 | $h \to (\tau^+\tau^-) + E_T$
 | $h \to (\gamma\gamma) + E_T$
 | $h \to (\ell^+\ell^-) + E_T$
$h \to 2 \to 3 \to 4$ | $h \to (bb) + E_T$
 | $h \to (jj) + E_T$
 | $h \to (\tau^+\tau^-) + E_T$
 | $h \to (\gamma\gamma) + E_T$
 | $h \to (\ell^+\ell^-) + E_T$
 | $h \to (\mu^+\mu^-) + E_T$
$h \to 2 \to (1 + 3)$ | $h \to bb + E_T$
 | $h \to jj + E_T$
 | $h \to \tau^+\tau^- + E_T$
 | $h \to \gamma\gamma + E_T$
 | $h \to \ell^+\ell^- + E_T$

## Decay Topologies | Decay mode $F_i$
--- | ---
$h \to 2 \to 4$ | $h \to (bb)(bb)$
 | $h \to (bb)(\tau^+\tau^-)$
 | $h \to (bb)(\mu^+\mu^-)$
 | $h \to (\tau^+\tau^-)(\tau^+\tau^-)$
 | $h \to (\tau^+\tau^-)(\mu^+\mu^-)$
 | $h \to (jj)(jj)$
 | $h \to (jj)(\gamma\gamma)$
 | $h \to (jj)(\mu^+\mu^-)$
$h \to 2 \to 4 \to 6$ | $h \to (\ell^+\ell^-)(\ell^+\ell^-) + E_T$
 | $h \to (\ell^+\ell^-)(\mu^+\mu^-)$
 | $h \to (\mu^+\mu^-)(\mu^+\mu^-)$
 | $h \to (\gamma\gamma)(\gamma\gamma)$
 | $h \to (\gamma\gamma) + E_T$
$h \to 2 \to 6$ | $h \to \ell^+\ell^- + E_T + X$
 | $h \to \ell^+\ell^- + E_T$
Simplest example: Higgs + singlet

\[ \mathcal{L} \supset V(H) + V(S) + \lambda H^\dagger HS^2 \]

For \( m_s < 0.5 \times m_h \)

After EWSB, \( \Gamma(h \rightarrow ss) \propto (\lambda v)^2 \).

Can be significant since \( \Gamma_{h}^{\text{SM,tot}} \) is very narrow.

If \( \langle S \rangle = 0 \), missing energy

If \( \langle S \rangle \neq 0 \), singlet mixes with Higgs, prefers to decay to heavy fermion
The current reach of all the searches in Table 1 is limited by statistics, so updated analyses using all available data will improve the sensitivity. More sophisticated analyses, including new reconstruction and identification techniques, can help complete the coverage of the full mass range. Additional searches in uncovered channels may also bring additional sensitivity and are interesting cross checks in case an excess is observed.

4.1.2 SM+s

Searches for decays to a new light scalar, s, often focus on the heaviest particles that are kinematically allowed in the scalar decay. Decays to muons are considered for $m_{\mu\mu}\pi^0$. Between $m_{\mu\mu}$ and the $\tau\tau$ thresholds, the sensitivity steadily decreases to about 3–6 TeV. The strongest constraints appear at the lowest masses from the $\mu\mu\mu\mu$ mode, setting branching ratio limits down to $10^{-5}$. Between the $J/\psi$ and the $\tau\tau$ thresholds, the sensitivity steadily decreases to about $10^{-6}$.
Simplest example: Higgs + singlet

\[ h \rightarrow ss \rightarrow \bar{f}f\bar{f}f \]

A lot of room to improve!

M. Cepeda, S. Gori, V. Outschoorn, J. Shelton, 2111.12751
Interesting target: 1st order EW phase transition

Extra scalar wants to be light, with sizable coupling to the Higgs

Carena, Liu, Wang, 1911.10206
Kozaczuk, Ramsey-Musolf, Shelton, 1911.10210
Interesting target: 1st order EW phase transition

M. Carena, J. Kozaczuk, Z. Liu, T. Ou, M. Ramsey-Musolf, J. Shelton, Y. Wang, K. Xie 2203.08206
Interesting target: 1st order EW phase transition

- The strongly first-order EWPT parameter space for the spontaneous breaking model and the projections at the HL-LHC, respectively. The brown and light blue shadows are the strong first-order EWPT regions from Refs. [6, 7], see text for details.
- Projections of the reach of future lepton colliders are shown in dashed lines.
- The strongly first-order EWPT parameter space for the spontaneous breaking model and the projections at the HL-LHC, respectively. The brown and light blue shadows are the strong first-order EWPT regions from Refs. [6, 7], see text for details.

M. Carena, J. Kozaczuk, Z. Liu, T. Ou, M. Ramsey-Musolf, J. Shelton, Y. Wang, K. Xie 2203.08206
Interesting alternative

Toy model of a landscape, $N$ scalars $S_i$.

If each scalar has two vacua $\Rightarrow 2^N$ vacua

Can be a large landscape for $N \gg 1$ (e.g. $N \sim 10^2$)
Interesting alternative

Toy model of a landscape, $N$ scalars $S_i$.

If each scalar has two vacua $\Rightarrow 2^N$ vacua

Can be a large landscape for $N \gg 1$ (e.g. $N \sim 10^2$)

Connection to the Higgs mass, Higgs couples to the scalars

$$\mathcal{L} \supset H^\dagger H \sum_{i,j}^N \lambda_{ij} S_i S_j + \ldots, \quad N \gg 1$$
Interesting alternative

If $m_S$ not too far away from weak scale, some of them with have $m_{S_i} < 0.5 \times m_h$

Rate into a particular final decay chain $\propto \lambda^2 \sim 1/N^2$, tiny.
However, many possible channels, total $h \rightarrow$ scalars can be sizable!
Interesting alternative

If $m_S$ not too far away from weak scale, some of them with have $m_{S_i} < 0.5 \times m_h$

Rate into a particular final decay chain $\propto \lambda^2 \sim 1/N^2$, tiny.
However, many possible channels, total $h \rightarrow$ scalars can be sizable!

$\Rightarrow b/c/\tau$ rich states, but not reconstructing particular resonances.
Are we ready for this?

New ideas to trigger and tag on this kind of final states?
Long lived particle (LLP)

Decay back to SM
Can be long lived.
\( c \tau \) can be 1 km or more
Higgs portal long lived particles

\( h \rightarrow XX \)

\( X: \text{LLP} \)

Potential to do better, \( \text{BR}(h \rightarrow XX) < 10^{-5} \)
HL-LHC as particle factories

> $10^{11}$ W and Zs

> $10^9$ tops

> $10^8$ Higgses

Promising for rare decay with distinct final state!
Similarly: top rare decay

H. Bahl, S. Koren, LTW 2307.11154
Similarly: top rare decay

H. Bahl, S. Koren, LTW 2307.11154

Range of lifetimes for $S$, $N$, and $Z'$

Can have LLPs

Can use the other top as trigger
HL-LHC as particle factories

HL-LHC

More studies needed!

> $10^{11}$ W and Zs

> $10^9$ tops

> $10^8$ Higgses

Promising for rare decay with distinct final state!
Aside: comment on Higgs final state

Useful, however:
Aside: comment on Higgs final state

Useful, however:

From Goldstone equivalence theorem, for heavy $X$, we expect to have channels with $h \leftrightarrow Z_L$, may also have channels with $W_L$

Need to be careful whether the Higgs final state is the most sensitive channel.
Summary

- Higgs boson is *there*. It is *important*, and yet *mysterious*.
- Need a better picture to understand it!
- Higgs boson is also an *obvious* place to look for new physics.

*In particular, exotic decays can benefit a lot from higher statistics.*
A lot to look forward to...
Extra
Higgs self-coupling

\[ \frac{\delta k_3}{k_3} (\%) \]

Legend:
- HL-LHC
- ILC500
- CLIC3000
- FCC-ee
- FCC-hh
- $\mu$10TeV
Higgs+singlet
Higgs portal dark matter

\[ \mathcal{O} = H \dagger H X_{dm} X_{dm} \quad \supseteq \quad h \rightarrow X_{dm} X_{dm} \]

Figure 1.24: Overview of the Physics Case for CEPC-SPPC
Windows into dark sector: portals

- Any known (SM) particle can in principle have small couplings to dark matter/dark sector.

Diagram:
- Higgs
- Neutrino
- Z, W
- Top