Prospects for the measurement of the Higgs Potential @ FCC

Seung J. Lee

Based on collaboration with Benjamin Fuks, Jeong Han Kim (arXiv:1510.07697)
Higgs Chapter of the report on Physics at 100 TeV (R. Contino et al.)
And also with B. Bellazzini, C. Csaki, J. Hubisz, J. Serra, J. Terning (arXiv:1511.08218)
How well do we understand the EWSB, i.e. Higgs Potential?

\[ V(H) = -\frac{\mu^2}{4} H^2 + \lambda (H^\dagger H)^2 \]
How well do we understand the EWSB, i.e. Higgs Potential?

\[ V(H) = \mu^2 H + \lambda (H^+ H)^2 \]
How well do we understand the EWSB, i.e. Higgs Potential?

\[ V(\tilde{h}) = \tilde{v}^{2\Delta} \tilde{m}^{4 - 2\Delta} \sum_{n=0}^{\infty} \frac{c_n}{n!} \left( \frac{\tilde{h}}{\tilde{v}^{\Delta}} \right)^n \]
Higgs Potential is unknown: e.g. a toy model

\[ V_{SM}^\mu(H) = -\mu^2 H^+ H + \lambda(H^+ H)^2 \]
Let's consider the following potential

\[ \tilde{V}(H) = -\lambda |H|^4 + c_6 |H|^6 \]

\( c_6 \sim \Lambda^{-2} \)
Higgs Potential is unknown: e.g. a toy model

Let's consider the following potential

\[ \tilde{V}(H) = -\lambda |H|^4 + c_6 |H|^6 \]

With this potential the VEV and mass of the Higgs are given by,

\[ v^2 = \frac{4 \lambda}{3 c_6}, \quad \frac{m_h^2}{v^2} = 2\lambda \]

experimentally \[ \lambda \approx 0.13 \]

\[ V_\text{SM}(H) = -\mu^2 H^+ H + \lambda (H^+ H)^2 \]
Let's consider the following potential

\[ \tilde{V}(H) = -\lambda |H|^4 + c_6 |H|^6 \]

\[ c_6 \sim \Lambda^{-2} \]

With this potential the VEV and mass of the Higgs are given by,

\[ v^2 = \frac{4 \lambda}{3 c_6}, \quad \frac{m_h^2}{v^2} = 2\lambda \]

\[ \lambda \approx 0.13 \]

defining \( c_6 = 1/ f^2 \), we find \( f \sim 600 \text{ GeV} \), so new physics effects from such scale might have escaped detection with \( \Lambda \sim 4\pi f \)

\[ V_{\text{SM}}(H) = -\mu^2 H^+ H + \lambda (H^+ H)^2 \]
Let’s consider the following potential

$$\tilde{V}(H) = -\lambda |H|^4 + c_6 |H|^6$$

With this potential the VEV and mass of the Higgs are given by,

$$v^2 = \frac{4 \lambda}{3 c_6}, \quad \frac{m_h^2}{v^2} = 2\lambda$$

defining $c_6 = 1/f^2$, we find $f \sim 600 \text{ GeV}$, so new physics effects from such scale might have escaped detection with $\Lambda \sim 4\pi f$

$$V_{\text{SM}}(H) = -\mu^2 H^+H + \lambda (H^+H)^2$$
However, FCC can potentially distinguish between the two possibilities just presented.

In particular, via double Higgs production, the triple Higgs coupling can be probed: i.e.

\[
\lambda_{hhh} = 3 \frac{m_h^2}{v} \quad \leftrightarrow \quad \tilde{\lambda}_{hhh} = 7 \frac{m_h^2}{v}
\]
However, FCC can potentially distinguish between the two possibilities just presented.

In particular, the triple Higgs coupling $\lambda_{hhh}$ can be probed.
we need future colliders to understand the underlying dynamics of the EWSB
we need future colliders to understand the underlying dynamics of the EWSB
Probing the EWSB mechanism

- Establishing the SM nature of the electroweak symmetry breaking mechanism
  - Finding a Higgs is the first step ✓
  - Deriving the form of the scalar potential is necessary ×

- Establishing the SM nature of the Higgs boson ?
  - Measurements of the Yukawa interaction strengths (i.e., the fermion masses)

The scalar potential

\[ V_h = \frac{m_h^2}{2} h^2 + (1 + \kappa_3) \lambda_{hhh}^\text{SM} v h^3 + \frac{1}{4} (1 + \kappa_4) \lambda_{hhhh}^\text{SM} h^4 \]

with

\[ \lambda_{hhh}^\text{SM} = \lambda_{hhhh}^\text{SM} = \frac{m_h^2}{2v^2} \]

is \( \kappa_3 = 0? \)

Di-Higgs production at the LHC can help

is \( \kappa_4 = 0? \)

No way for the LHC (hhh cross section of \( \sim 0.01 \text{ fb} \))

Idea: probing triple-Higgs production at the FCC

Sensitivity to both \( \kappa \) parameters
Triple Higgs production at the FCC

- **Triple Higgs production total rate**
  - Small in the Standard Model (~ 3-4 fb)
  - Could be much larger with new physics

- **Dependence on the $\kappa$ parameters**
  - $\kappa_3$: very strong
    - Can reach 20 fb for large and negative values
  - $\kappa_4$: milder (but not negligible)

Could it be constrained?

\[
(1 + \kappa_3) \lambda_{hh}^{SM} v h^3 + \frac{1}{4} (1 + \kappa_4) \lambda_{hhhh}^{SM} h^4
\]
Triple Higgs production at the FCC

Production cross section for $pp \rightarrow hh\ h$

$\sqrt{s} = 100\ TeV$

Could it be constrained?

$E_{T}^{h} \ g_{SM} + \frac{1}{4}(1+\kappa)\ g_{SM} h^{4}$

Graphical representations of Feynman diagrams involving Higgs and top quark interactions.
Considered triple Higgs signals

🔹 Decay modes with the larger branching ratios
  - 4 b-jets and a 2 W’s (22%): boosted techniques?
    ➢ see the di-Higgs case at the LHC
  - 6 b-jets (19.5%): boosted techniques or angular information?
    ➢ see the di-Higgs case at the LHC

Necessitates FCC detector details — Study of other channels

🔹 Decay in the 4b + 2γ channel
  - Clean, low background (cf. the diphoton)
  - Small branching fraction (0.232%)
  - Only studied channel so far [Papaeftathiou & Sakurai] [Chen, Yan, Zhao, Zhong & Zhao]

🔹 Decay in the 4b + 2τ channel
  - Large branching fraction (6.46%)
  - Not studied yet, but the 2b+2τ channel is interesting in the di-Higgs case at the LHC

Why not at the FCC?
The 4b + 2γ channel: generalities

Simulation details

- Parton-level study + smearing of the four-momenta (à la ATLAS)
- **b-tagging performance**: two LHC-inspired working points
  - Very efficient (70%) with larger fake rates (18%, for c-jets, 1% for lighter jets)
  - Less efficient (60%) with smaller fake rates (1.8%, for c-jets, 0.1% for lighter jets)

How good should the b-tagging be to observe a triple-Higgs signal

Selection strategy for 20 ab⁻¹

- Four jets (with an invariant mass smaller than 600 GeV), 2 photons
- Two dijet systems compatible with a Higgs ($m_{jj} \in [105, 140]$ GeV)
- The diphoton system compatible with a Higgs ($m_{\gamma\gamma} \in [125-M, 125+M]$ GeV)

What is the best M-value?

- At least $N_b^{\text{min}}$ b-tagged jets

What is the best choice?
A low fake rate is primordial for a good sensitivity (1.8%/0.1% for a 60% efficiency)

- Requiring at least 4 b-jets gives slightly better results
  (the background efficiency drops faster than the signal one)
- Poorer results for a fake rate of 18%/1% for a 70% efficiency
  - Better signal acceptance
  - Much worse background contamination due to the fakes
Phots with a $p_T$ greater than 20 GeV are very well reconstructed ($\sigma/E \sim 0.1/\sqrt{E}$)

- A loss of signal efficiency implies to maintain $M$ not too small
- A too large $M$ implies a more important background contamination
  - However, mild effects on the sensitivity

$M = 2$ GeV gives the best results
The $4b + 2\gamma$ channel: luminosity goals for $3\sigma$

- At least 4 b-tags
- $M = 2$ GeV
- b-tagging: 60% / 1.8% / 0.1%

- Large and negative $\kappa_3$ $\iff$ huge cross section $\iff$ BSM hints reachable with low luminosity
- Other $\kappa_3$ values $\iff$ more luminosity is required
- The scanned region of the parameter space cannot be entirely covered
The 4b + 2τ channel: generalities

Simulation details
- Parton-level study + smearing of the four-momenta (à la ATLAS)
- **b-tagging performance:** two LHC-inspired working points
  - Very efficient (70%) with larger fake rates (18%, for c-jets, 1% for lighter jets)
  - Less efficient (60%) with smaller fake rates (1.8%, for c-jets, 0.1% for lighter jets)
- **tau-tagging performance:** two LHC-inspired working points
  - Very efficient (80%) with a small fake rate (0.1%)
  - More conservative (50%) with a larger fake rates (1%)

How good should the b- and tau-tagging be to observe a triple-Higgs signal

Selection strategy for 20 ab$^{-1}$
- Four jets, 2 taus
- Two dijet systems compatible with a Higgs ($m_{jj} \in [105, 140]$ GeV)
- The ditau system compatible with a Higgs ($m_{\tau\tau} \in [115, 135]$ GeV)
- At least $N_b^{\text{min}}$ b-tagged jets

What is the best choice?
The $4b + 2\tau$ channel: b- and tau-tagging

- A good b-tagging efficiency is essential (70% for an 18% / 1% fake rate)
  - Requiring at least 3 b-jets gives slightly better results (better signal efficiency)
  - Smaller fake rate and efficiency: the signal efficiency drops faster than the background one

- A very efficient tau-tagger is essential (80% for a 0.1% fake rate)
  - All sensitivity is lost for a more conservative choice of (50% / 1%)
Summary

—we considered triple Higgs production at the FCC
  — Decay in the 4b + 2γ and 4b + 2τ channels
  — Effects of the b-tagging and tau-tagging performances on the sensitivity
  — Effect of the diphoton mass resolution

—we considered the diphoton channel yields the best sensitivity
  — Controlling the b-tagging fake rate is mandatory
  — The diphoton mass requirement cannot be too tight
  — A good fraction of the parameter space can be covered (but not the SM case)
    ★ A small part even with a few ab⁻¹
—we considered the ditau channel could be complementary
  — An excellent tau-tagger is required
Condensed matter systems can produce a light scalar by tuning the parameters close to a critical value where a continuous phase transition occurs.
Condensed matter systems can produce a light scalar by tuning the parameters close to a critical value where a continuous phase transition occurs. Phase transitions happening at zero temperature are usually referred to as quantum phase transitions (QPT).
Condensed matter systems can produce a light scalar by tuning the parameters close to a critical value where a continuous phase transition occurs.

Phase transitions happening at zero temperature are usually referred to as quantum phase transitions (QPT).

At the second order QPT, at the critical point, all masses vanish & the theory is scale invariant, characterized by the scaling dimensions of the field.
Post Higgs question: The Quantum Critical Higgs


- Condensed matter systems can produce a light scalar by tuning the parameters close to a critical value where a continuous phase transition occurs.

- Phase transitions happening at zero temperature are usually referred to as quantum phase transitions (QPT).

- At the second order QPT, at the critical point, all masses vanish & the theory is scale invariant, characterized by the scaling dimensions of the field.

- And at low energies we will see the universal behavior of some fixed point that constitutes the low-energy EFT.
Post Higgs question: The Quantum Critical Higgs

Condensed matter systems can produce a light scalar by tuning the parameters close to a critical value where a continuous phase transition occurs.

- Phase transitions happening at zero temperature are usually referred to as quantum phase transitions (QPT).
- At the second order QPT, at the critical point, all masses vanish & the theory is scale invariant, characterized by the scaling dimensions of the field.
- And at low energies we will see the universal behavior of some fixed point that constitutes the low-energy EFT.

It is important to know whether the underlying theory has a QPT.

Condensed matter systems can produce a light scalar by tuning the parameters close to a critical value where a continuous phase transition occurs.

Phase transitions happening at zero temperature are usually referred to as quantum phase transitions (QPT).

At the second order QPT, at the critical point, all masses vanish & the theory is scale invariant, characterized by the scaling dimensions of the field.

And at low energies we will see the universal behavior of some fixed point that constitutes the low-energy EFT.

It is important to know whether the underlying theory has a QPT.

And if so, whether it is more interesting than mean-field theory like the Standard Model of particle physics.
Ising Model

\[ H = -J \sum s(x)s(x + n) \]

\( s(x) = \pm 1 \)

\[ \langle s(0)s(x) \rangle = e^{-|x|/\xi} \]

at \( T = T_c \) \( \xi \rightarrow \infty \)
Critical Ising Model is Scale Invariant

\[ \langle s(0)s(x) \rangle \propto \frac{1}{|x|^{2\Delta-1}} \]
Critical Ising Model is Scale Invariant

\[ \langle s(0)s(x) \rangle \propto \frac{1}{|x|^{2\Delta - 1}} = \int d^3p \frac{e^{ip \cdot x}}{|p|^{4-2\Delta}} \]

at \( T = T_c \)


critical exponent
Quantum Phase Transition

We are here
At a QPT the approximate scale invariant theory is characterized by the scaling dimension $\Delta$ of the gauge invariant operators, where $1 < \Delta < 2$. In general, the two point function of a scalar with scaling dimension $\Delta$ in a CFT is

$$G_{\text{CFT}}(p) = -\frac{i}{(-p^2 + i\epsilon)^{2-\Delta}}$$

SM: $\Delta = 1 + \mathcal{O}(\alpha/4\pi)$.

We propose to present a general class of theories describing a Higgs field near a non-mean-field QPT.

In such theories, in addition to the pole (Higgs), there can also be a Higgs continuum, representing additional states associated with the dynamics underlying the QPT

$$G_h(p^2) = \frac{i}{p^2 - m_h^2} + \int_{\mu^2}^\infty dM^2 \frac{\rho(M^2)}{p^2 - M^2}$$

One result of the presence of the continuum will be the appearance of form factors in couplings of the Higgs to the SM particles.
What would be a general low-energy EFT consistent with a QPT and no new massless particles?
What would be a general low-energy EFT consistent with a QPT and no new massless particles?

We consider a QPT Higgs scenario where Higgs is (partially) imbedded into a strongly coupled sector (approximately conformal at scale well above the EW scale)
What would be a general low-energy EFT consistent with a QPT and no new massless particles?

We consider a QPT Higgs scenario where Higgs is (partially) imbedded into a strongly coupled sector (approximately conformal at scale well above the EW scale)

=> Higgs pick up a significant anomalous dimension, and there is a large mixing with the continuum
What would be a general low-energy EFT consistent with a QPT and no new massless particles?

We consider a QPT Higgs scenario where Higgs is (partially) imbedded into a strongly coupled sector (approximately conformal at scale well above the EW scale)

=> Higgs pick up a significant anomalous dimension, and there is a large mixing with the continuum

The effects of Higgs emerging from the quantum critical point can be parametrized in terms of form factors in a model independent way.
We consider a QPT Higgs scenario where Higgs is (partially) imbedded into a strongly coupled sector (approximately conformal at scale well above the EW scale)

=> Higgs pick up a significant anomalous dimension, and there is a large mixing with the continuum

The effects of Higgs emerging from the quantum critical point can be parametrized in terms of form factors in a model independent way.

**On-shell behavior:**
constant form factors
We consider a QPT Higgs scenario where Higgs is (partially) imbedded into a strongly coupled sector (approximately conformal at scale well above the EW scale)

⇒ Higgs pick up a significant anomalous dimension, and there is a large mixing with the continuum.

The effects of Higgs emerging from the quantum critical point can be parametrized in terms of form factors in a model independent way.

What would be a general low-energy EFT consistent with a QPT and no new massless particles?

On-shell behavior: constant form factors

Off-shell behavior: nontrivial momentum dependent form factors
What would be a general low-energy EFT consistent with a QPT and no new massless particles?

We consider a QPT Higgs scenario where Higgs is (partially) imbedded into a strongly coupled sector (approximately conformal at scale well above the EW scale)

=> Higgs pick up a significant anomalous dimension, and there is a large mixing with the continuum

The effects of Higgs emerging from the quantum critical point can be parametrized in terms of form factors in a model independent way.

On-shell behavior: constant form factors

Off-shell behavior: nontrivial momentum dependent form factors
In **NDA**, loop corrections $\sim$ original n-point function. e.g. $n = 6$:

\[
\mathcal{L} = \frac{\alpha_n}{\Lambda^{n-4}} \phi^n
\]

Loop contribution with two insertions of this operator (that contributes to the same n-point) would be one in which each vertex has $n/2$ external lines, and $n/2$ propagators exchanged in $n/2 - 1$ loops.

**Quantum corrections:**

\[
\alpha_n \rightarrow \alpha_n \left(1 + \frac{\alpha_n}{(16\pi^2)^{n/2-1}}\right)
\]

\[
\alpha_n \sim (16\pi^2)^{n/2-1}
\]
In **NDA**, loop corrections ~ original n-point function. e.g. n = 6:

\[ \mathcal{L} = \frac{\alpha_n}{\Lambda^{n-4}} \phi^n \]

Loop contribution with two insertions of this operator (that contributes to the same n-point) would be one in which each vertex has \( n/2 \) external lines, and \( n/2 \) propagators exchanged in \( n/2 - 1 \) loops.

Quantum corrections e.g. with this, we can see that the n-point contribution to the gluon fusion process is suppressed by insertions of the perturbative coupling of the top-quark to the strongly coupled sector, along with a loop factor that is only partially cancelled by the large coefficient

\[ \alpha_n \sim (16\pi^2)^{n/2-1} \]
If the shaded region corresponds to the n-point function, there are $n - 1$ insertions of the top Yukawa, and $n - 2$ loops. There are $n - 1$ scalar propagators and $n - 2$ fermionic propagators running in these loops.

Estimate for the contribution of the n-point correlator to the $h\bar{t}t$ coupling:

$$g_n^{tth} \sim 4\pi \left( \frac{\lambda_t}{4\pi} \right)^{n-1}$$
If the shaded region corresponds to the n-point function, there are $n - 1$ insertions of the top Yukawa, and $n - 2$ loops. There are $n - 1$ scalar propagators and $n - 2$ fermionic propagators running in these loops.

estimate for the contribution of the $n$-point correlator to the $h\bar{t}t$ coupling:

$$g_{n}^{tth} \sim 4\pi \left( \frac{\lambda_t}{4\pi} \right)^{n-1}$$

e.g. double Higgs production through gluon fusion would be dominated by
If the shaded region corresponds to the n-point function, there are \(n - 1\) insertions of the top Yukawa, and \(n - 2\) loops. There are \(n - 1\) scalar propagators and \(n - 2\) fermionic propagators running in these loops.

The dominant contribution comes from the tree diagram:

e.g. double Higgs production through gluon fusion would be dominated by
Form factors for trilinear Higgs self coupling

SO(4) global symmetry is gauged in the 5D bulk

\[ \lambda_5 (H^\dagger H)^2 \]

\[ F_{hhh} = \frac{\lambda_5}{L^2} \mathcal{V} \int_R^\infty dz \frac{1}{a} \left( \frac{z}{R} \right)^2 \frac{K_{2-\Delta}(\mu z)}{K_{2-\Delta}(\mu R)} \prod_{i=1}^3 \frac{K_{2-\Delta}(\sqrt{\mu^2 - p_i^2} z)}{K_{2-\Delta}(\sqrt{\mu^2 - p_i^2} R)} \]

Higgs momentum: 200 GeV (Red), 400 GeV (Blue), and 600 GeV (Green)

\[ \Delta = 1.2 \text{ (Red)}, 1.4 \text{ (Blue), and 1.6 (Green)} \]

\[ \mu = 400 \]

\[ \Delta = 1.5 \]
Direct Signal (e.g. Holographic Generalized Free Fields)

- Form factors for trilinear Higgs self coupling
- SO(4) global symmetry is gauged in the 5D bulk

\[ \lambda_5 (H^*H)^2 \]

\[ F_{hhh} = \frac{\lambda_5}{L^2} \mathcal{V} \int_R^\infty dz \frac{1}{a} \left( \frac{z}{R} \right)^2 \frac{K_{2-\Delta}(\mu z)}{K_{2-\Delta}(\mu R)} \prod_{i=1}^{3} \frac{K_{2-\Delta}(\sqrt{\mu^2 - p_i^2} z)}{K_{2-\Delta}(\sqrt{\mu^2 - p_i^2} R)} \]

Higgs momentum: 200 GeV (Red), 400 GeV (Blue), and 600 GeV (Green)

Delta = 1.2 (Red), 1.4 (Blue), and 1.6 (Green)
Double Higgs production

Dashed lines correspond to the case where only the Higgs two-point function has non-trivial behavior inherited from a sector with strong dynamics.

Direct Signal (e.g. Holographic Generalized Free Fields)
Summary: Higgs Potential

\[ V(\tilde{h}) = \tilde{v}^{2\Delta} \tilde{m}^{4-2\Delta} \sum_{n=0}^{\infty} \frac{c_n}{n!} \left( \frac{\tilde{h}}{\tilde{v}\Delta} \right)^n \]
We need FCC to really understand the EWSB!