New Higgs Physics from the Lattice

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Outline

- Outlook for the Higgs Particle
  - Relevance to LHC physics?
  - The Particle Data Group figure
  - Early work on triviality and the Renormalization Group
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► **Standard Model Renormalization Group**
  - The running gauge couplings
  - The running top quark yukawa coupling
  - The running Higgs coupling and Higgs mass lower bound
  - The running Higgs coupling and Higgs mass upper bound
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- **The Standard Model and its UV Completions**
  - Cutoff dependent Higgs mass bounds
  - Standard Model, effective theories, and UV completions
  - Higher derivative (Lee-Wick) Higgs sector as UV completion
  - Gauged higher derivative (Lee-Wick) extension
  - UV $\beta$-function and the Renormalization Group
  - S-matrix, unitarity, and causality
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- **Conclusions and Outlook**
  - Higgs mass bounds will depend on TeV threshold of UV completion
  - Need for nonperturbative lattice work
My collaborators:

Earlier work on vacuum instability:
Kieran Holland talk University of the Pacific
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Earlier work on higher derivative (Lee-Wick) extension:
Chuan Liu Beijing University
Karl Jansen DESY, Zeuthen
My collaborators:

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New work of our lattice Higgs collaboration:

<table>
<thead>
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<th>University</th>
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<tr>
<td>Zoltan Fodor</td>
<td>University of Wuppertal</td>
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<td>Kieran Holland</td>
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<td>Daniel Nogradi</td>
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<td>Chris Schroeder</td>
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A Giant Takes On Physics’ Biggest Questions

“The physicists, wearing hardhats, kneepads and safety harnesses, are scrambling like Spiderman over this assembly, appropriately named Atlas, ducking under waterfalls of cables and tubes and crawling into hidden room-size cavities stuffed with electronics. They are getting ready to see the universe born again.”
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“To add to the confusion, according to the Standard Model, the Higgs can have only a limited range of masses without severe damage to the universe. If it is too light, the universe will decay. If it is too heavy, the universe would have blown up already. According to Dr. Ellis, there is a magic value between 160 billion and 180 billion electron volts that would ensure a stable universe and require no new physics at all.”
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What if UV completion in TeV range?
Outlook for the Higgs Particle

What the Particle Data Book tells us

- Standard Model is expected to be UV-incomplete on TeV scale
  - low cut-off is favored by the hierarchy problem
  - war of choice for theorists
- Higgs particle $\rightarrow$ how Electroweak symmetry is broken in nature
- Higgs discovery potential $\leftrightarrow$ Energy scale of new physics

Lower bound on the Higgs mass from direct searches is 114.4 GeV

From Electroweak precision measurements:

$M_H = 76^{+33}_{-24}$ GeV with $2\sigma$ error

Ignores intrinsic cutoff! Tension in data analysis!

Landau Pole and Vacuum Instability

(mis)representations of triviality?

Lattice and modern view on effective field theories should be reconciled

Should this PDG figure be reworked nonperturbatively?

Effects of new Higgs physics from UV completion?
Outlook for the Higgs Particle

Early Work on Triviality and Renormalization Group Fixed Points

Running of $\lambda, g_t, g_3$

- **Top-Higgs sector (1-loop)**

  $R = \frac{\lambda}{g_t^2} = \frac{m_H^2}{4m_t^2}$

  \[ \frac{dg_t^2}{dt} = -\frac{9}{16\pi^2} g_t^4 \]

  \[ g_t^2 \frac{dR}{dg_t^2} = \frac{1}{3} (8R^2 + R - 2) \]

  IR fixed line at $\bar{R} = \frac{1}{16} (\sqrt{65} - 1) = 0.44$

  **trivial fixed point only!**

  The Landau pole is the upper bound

  Is $\lambda(\Lambda) = 0$ the lower bound?

- **Top-Higgs-QCD sector (1-loop)**

  Pendleton-Ross fixed point:

  $m_t = \sqrt{\frac{2}{9}} g_3 (\mu = m_t) v / \sqrt{2} \approx 95 \text{ GeV}$

  $m_H = \sqrt{\left(\frac{\sqrt{689} - 25}{72}\right) g_3 \sqrt{2} v} \approx 53 \text{ GeV}$

Weak gauge couplings and 2-loop destabilize the Pendleton-Ross fixed point

"Landau pole" only in $\alpha_1$ at $\mu = 10^{41} \text{ GeV}$ with all couplings running
Standard Model Renormalization Group

2-loop RG with 1-loop matching

\[ \mu = M_Z \] initial conditions:
\[ \alpha_1(M_Z) = 0.0102 \]
\[ \alpha_2(M_Z) = 0.0338 \]
\[ \alpha_3(M_Z) = 0.123 \]

Higgs and Yukawa couplings:
\[ m_f = y_f v \]
\[ m_H = \lambda^{1/2} v \]
\[ v = 246.22 \text{ GeV} \]

\( \alpha_1 \) is \( U(1)_Y \) coupling

“Landau pole” in \( \alpha_1 \)

\[ \approx 10^{41} \text{ GeV} \text{ for } m_H = 80 \text{ GeV} \]

inherited from QED

\[ \text{shifted to } \approx 10^{48} \text{ GeV} \text{ for } m_H = 500 \text{ GeV} \]

(i) Gauge sector (2-loop):
\[
(4\pi)^4 g_1^{-3} \beta^{(2)}_{g_1} = \frac{199}{50} g_1^2 + \frac{27}{10} g_2^2 + \frac{44}{5} g_3^2 - \sum_g (\frac{17}{5} y_{u_g}^2 + y_{d_g}^2 + 3 y_{e_g}^2),
\]
\[
(4\pi)^4 g_2^{-3} \beta^{(2)}_{g_2} = \frac{9}{10} g_1^2 + \frac{35}{6} g_2^2 + 12 g_3^2 - \sum_g (3 y_{u_g}^2 + 3 y_{d_g}^2 + y_{e_g}^2),
\]
\[
(4\pi)^4 g_3^{-3} \beta^{(2)}_{g_3} = \frac{11}{10} g_1^2 + \frac{9}{2} g_2^2 - 26 g_3^2 - 4 \sum_g (y_{u_g}^2 + y_{d_g}^2).
\]
Top yukawa coupling $y_t$

For $m_H < 160 GeV$ monotone decrease in $y_t$

Lower Higgs mass bound (and vacuum instability?) might remain perturbative with running $\lambda$ for $m_H < 160 GeV$

$y_t \approx 5$ pseudo-fixed point

At $m_H = 500 GeV$ strong yukawa coupling below the Planck scale

$m_H = 500 GeV$ Higgs mass range is becoming strongly interacting

*Upper bound with heavy Higgs in modified SM is strong coupling problem*

(ii) Yukawa sector (1-loop):

$$(4\pi)^2 y_{\tau}^{-1} \beta_{y_{\tau}}^{(1)} = 3y_{\tau}^2 + 2 \sum_g (3y_{u_g}^2 + 3y_{d_g}^2 + y_{e_g}^2) - \frac{9}{4} g_1^2 - \frac{9}{4} g_2^2,$$

$$(4\pi)^2 y_{t}^{-1} \beta_{y_{t}}^{(1)} = 3y_{t}^2 - 3y_{b}^2 + 2 \sum_g (3y_{u_g}^2 + 3y_{d_g}^2 + y_{e_g}^2) - \frac{17}{20} g_1^2 - \frac{9}{4} g_2^2 - 8g_3^2,$$

$$(4\pi)^2 y_{b}^{-1} \beta_{y_{b}}^{(1)} = 3y_{b}^2 - 3y_{t}^2 + 2 \sum_g (3y_{u_g}^2 + 3y_{d_g}^2 + y_{e_g}^2) - \frac{1}{4} g_1^2 - \frac{9}{4} g_2^2 - 8g_3^2.$$
Standard Model Renormalization Group

At low Higgs masses negative $\lambda$ would suggest vacuum instability

Large changes in $U_{eff}(\phi)$ from 1-loop to 2-loop would call for nonperturbative calculations

Running gauge couplings are important!

Problem is on borderline of perturbation theory, at best

Talks by Holland and Nogradi

(iii) Higgs sector (1-loop):

$$(4\pi)^2 \beta^{(1)}_{\lambda} = 12\lambda^2 + 8\lambda \sum_g (3y_{u_g}^2 + 3y_{d_g}^2 + y_{e_g}^2) - 9\lambda(\frac{1}{5}g_1^2 + g_2^2) - 16 \sum_g (3y_{u_g}^4 + 3y_{d_g}^4 + y_{e_g}^4) + \frac{9}{4}(\frac{3}{25}g_1^4 + g_2^4 + \frac{2}{5}g_1^2g_2^2),$$
Upper bound and running coupling $\lambda$

At large Higgs masses growing $\lambda$ requires strong coupling

Call for nonperturbative calculations

Running gauge couplings are important!

Is large $m_H$ consistent with EW data?

What is the Standard Model beyond PT?

Talks by Holland and Nogradi
The Standard Model and UV Completions

Cutoff dependent Higgs mass bounds

Cutoff dependent bounds
Holland, Kuti

Different answers with different cutoff functions under $\lambda(\Lambda_{\text{cutoff}}) = 0$ condition

Role of higher dimensional operators on the cutoff scale?

What is the robust physical interpretation?
The scale $M$ of new physics and the lattice scale $\Lambda$
The Standard Model and UV Completions

Standard Model, Effective Field Theories, and UV Completions

The scale $M$ of new physics and the lattice scale $\Lambda$

Continuum Wilsonian RG

UV Completion

unknown new physics
The Standard Model and UV Completions

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Continuum Wilsonian RG

UV Completion

Unkon new physics

Below new scale $M$ integrated UV completion is represented by non-local $\mathcal{L}_{\text{eff}}$ which has all higher dimensional operators in derivative expansion,

\[ \frac{1}{M^2} \phi \Box^2 \phi, \quad \frac{1}{M^4} \phi \Box^3 \phi, \quad \frac{\lambda_6}{M^2} \phi^6, \quad \text{etc} \ldots \]

Propagator $\frac{K(p^2/M^2)}{p^2 + M^2}$ with analytic $K$ thins out

UV completion with exponential damping
The Standard Model and UV Completions

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UV completion with exponential damping

At the symmetry breaking scale $v = 250 \text{ GeV}$ only relevant and marginal operators survive

Only $-1/2m_H^2$ and $\lambda \phi^4$ terms in $V_{\text{Higgs}}(\phi)$, in addition to $(\nabla \phi)^2$ operator

Narrow definition of Standard Model: only relevant and marginal operators are kept at scale $M$
The Standard Model and UV Completions

Standard Model, Effective Field Theories, and UV Completions

The scale $M$ of new physics and the lattice scale $\Lambda$

**Continuum Wilsonian RG**

**Lattice Wilsonian RG**

Regulate with lattice at scale $\Lambda = \pi / a$

$L_{\text{lattice}}$ has all higher dimensional operators like $a^2 \phi \Box^2 \phi$, $a^4 \phi \Box^4 \phi$, $a^2 \lambda_6 \phi^6$ etc...

UV Completion

Unknown new physics

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Choice of $L_{\text{lattice}}$ is irrelevant unless crossover phenomenon is required to insert intermediate $M$ scale
The Standard Model and UV Completions

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UV Completion

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Lattice Wilsonian RG

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$\mathcal{L}_{\text{lattice}}$ has all higher dimensional operators like $a^2 \phi \Box^2 \phi, a^4 \phi \Box^4 \phi, a^2 \lambda \phi^6$ etc ...

Scale $M$ missing

At the symmetry breaking scale $v = 250 \, \text{GeV}$ only relevant and marginal operators survive

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The scale $M$ of new physics and the lattice scale $\Lambda$

### Continuum Wilsonian RG

**UV Completion**

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$\mathcal{L}_{\text{lattice}}$ has all higher dimensional operators like $a^2 \phi \Box^2 \phi, a^4 \phi \Box^4 \phi, a^2 \lambda_6 \phi^6$ etc ...

Possible to insert intermediate continuum scale $M$ with $\mathcal{L}_{\text{eff}}$ to include

$$\frac{1}{M^2} \phi \Box^2 \phi, \frac{1}{M^4} \phi \Box^3 \phi, \frac{\lambda_6}{M^2} \phi^6, \text{etc} ...$$

or, Lee-Wick and other UV completions

which exist above scale $M$ (not effective theories!)

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Choice of $\mathcal{L}_{\text{lattice}}$ is irrelevant unless crossover phenomenon is required to insert intermediate $M$ scale
The Standard Model and its UV Completions

Higher derivative (Lee-Wick) Higgs sector as UV completion

- Represent the Higgs doublet with four real components \( \phi^a \) which transform in the vector representation of \( O(4) \) and include new higher derivative terms in the kinetic part of the \( O(4) \) Higgs Lagrangian,

\[
\mathcal{L}_H = \frac{1}{2} \partial_\mu \phi^a \partial^\mu \phi^a - \frac{\cos(2\Theta)}{M^2} \Box \phi^a \Box \phi^a + \frac{1}{2M^4} \Box \partial_\mu \phi^a \Box \partial^\mu \phi^a - V(\phi^a \phi^a)
\]

- The Higgs potential is \( V(\phi^a \phi^a) = -\frac{1}{2} \mu^2 \phi^a \phi^a + \lambda (\phi^a \phi^a)^2 \).
- The higher derivative terms of the Lagrangian lead to complex conjugate ghost pairs in the spectrum of the Hamilton operator.
- Complex conjugate pairs of energy eigenvalues and the related complex pole pairs in the propagator are parametrized by \( \mathcal{M} = Me^{\pm i\Theta} \). Choice \( \Theta = \pi/4 \) simplifies.
- The absolute value \( M \) of the complex ghost mass \( \mathcal{M} \) will be set on the TeV scale.
- Unitary S-matrix, macroscopic causality, Lorentz invariance
  (old controversies about unitarity and Lorentz invariance were cited again by Grinstein, O’Connell, Wise)

\( \lambda > 0 \) asymptotically!
Vacuum instability?
The Standard Model and its UV Completions

Gauged higher derivative (Lee-Wick) extension

- Higher derivative Yang-Mills gauge Lagrangian for the $SU(2)_L \times U(1)$ weak gauge fields $W_\mu, B_\mu$ follows similar construction with covariant derivative $D_{\mu}^{ab} = \delta^{ab} \partial_\mu + gf^{abc} W^c_\mu$,

$$\mathcal{L}_W = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} - \frac{1}{4M^4} D^2 G^a_{\mu\nu} D^2 G^{a\mu\nu},$$

- $\mathcal{L}_W$ is superrenormalizable but not finite.
- Full gauged Higgs sector is described by the Lagrangian $\mathcal{L} = \mathcal{L}_W + \mathcal{L}_B + \mathcal{L}_{Higgs}$,

$$\mathcal{L}_{Higgs} = (D_{\mu} \Phi)^\dagger D^\mu \Phi + \frac{1}{2M^4} (D_{\mu} D^\dagger D \Phi)^\dagger (D_{\mu} D^\dagger D \Phi) - V(\Phi^\dagger \Phi)$$

- Gauge-covariant derivative is $D_{\mu} \Phi = \left( \partial_\mu + i \frac{g}{2} \sigma \cdot W_\mu + i \frac{g'}{2} B_\mu \right) \Phi$.
- Similar fermion construction: $\mathcal{L}_{\text{fermion}} = i \overline{\Psi} D \Psi + \frac{i}{2M^4} \overline{\Psi} \not{p}^2 \not{p} \not{p}^2 \Psi$.

SM particle content is doubled
Logarithmic divergences only
Liu’s Thesis (1994)

UV $\beta$-function and the Renormalization Group

- Higher derivative Higgs sector is finite field theory
- Mass dependent $\beta(t)$-function vanishes asymptotically
- Grows logarithmically in gauged Higgs sector
- Running Higgs coupling $\lambda(t)$ freezes asymptotically
- The fixed line of allowed Higgs couplings must be positive!
- Vacuum instability? Higgs mass lower bound from $\lambda(\infty) > 0$?
The Standard Model and its UV Completions

S-matrix, Unitarity, and Causality

Liu, Jansen, Kuti

Cross section phase shift

Equivalence theorem, Goldstone scattering

Higgs mass upper bound relaxed

\( m_H = 1 \text{ TeV}, \text{ or higher,} \)

but \( \rho \)-parameter and other Electroweak precision?

Phase shift reveals ghost, microscopic time advancement, only \( \pi/2 \) jump in phase shift

\( m_H = 1 \text{ TeV}, \ M = 3.6 \text{ TeV} \)

\( v/M = 0.07, \ m_H/M = 0.28 \)
The Standard Model and its UV Completions

The rho-parameter

\[ \rho - 1 \big|_{\text{Higgs}} = \frac{\Pi^H_W}{M^2_{W,\text{tree}}} - \frac{\Pi^H_Z}{M^2_{Z,\text{tree}}} \]

\[ = -\frac{3}{4} g'^2 \int \limits_{k^2 < \Lambda^2} \frac{d^4 k}{(2\pi)^4} \frac{\Sigma_H(k^2)}{(k^2 + M^2_{W,\text{tree}})(k^2 + M^2_{Z,\text{tree}})(k^2 + \Sigma^2_H(k^2))} \]
Conclusions and Outlook

Higgs vacuum instability and the Higgs mass range in Standard Model has strong dependence on UV completion and new physics on the TeV scale.

- Life does not have to be boring in 4D without supersymmetry, or technicolor
- Example: Lee-Wick paradigm as minimal extension
- Each new effective theory will have its own predictions for Higgs mass range
- Is the strongly interacting Higgs sector ruled out?
- Golden opportunity for new Higgs physics from the lattice