

The Fate of the False Higgs Vacuum

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Outline

► Standard Model Higgs Mass Bounds from RG

- Relevance to LHC physics?
- The Particle Data Group figure
- Triviality and the Renormalization Group
- Unstable effective potential

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- Lattice effective potential and large N
- RG with intrinsic cutoff
- Regulator dependent Higgs mass lower bound
- Standard Model, effective theories, UV completions

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▶ Higher Derivative (Lee-Wick) UV Completion

- Lee-Wick Higgs sector without false vacuum
- Gauged Lee-Wick extension
- β -function
- S-matrix and unitarity

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▶ Conclusions and Outlook

- The fate of the false Higgs vacuum depends on UV completion
- Need for nonperturbative lattice work?

My collaborators:

Earlier work on vacuum instability:

Kieran Holland

University of the Pacific

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Earlier work on higher derivative (Lee-Wick) extension:

Chuan Liu Beijing University

Karl Jansen DESY, Zeuthen

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New work of our lattice Higgs collaboration:

Zoltan Fodor University of Wuppertal

Kieran Holland University of the Pacific

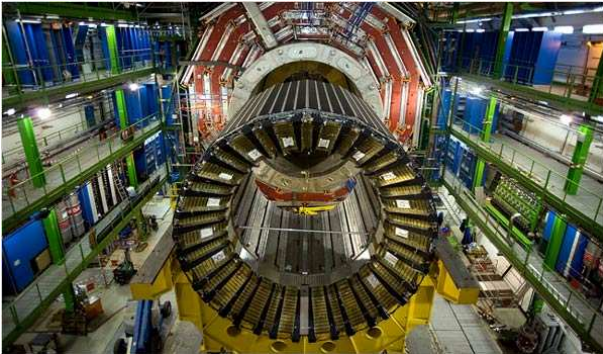
Daniel Negradi University of Wuppertal

Chris Schroeder University of California, San Diego

The New York Times

Tuesday, May 15, 2007

A Giant Takes On Physics' Biggest Questions

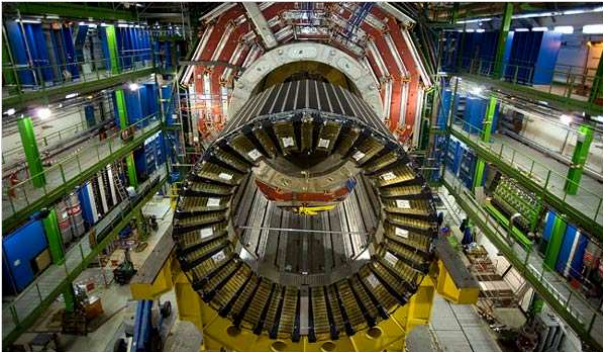


“The physicists, wearing hardhats, kneepads and safety harnesses, are scrambling like Spiderman over this assembly, appropriately named Atlas, ducking under waterfalls of cables and tubes and crawling into hidden room-size cavities stuffed with electronics. They are getting ready to see the universe born again.”

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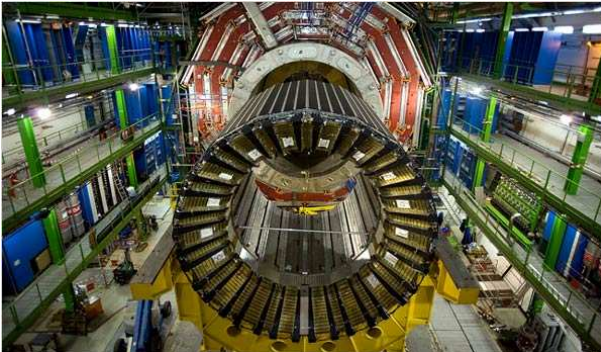


“To add to the confusion, according to the Standard Model, the Higgs can have only a limited range of masses without severe damage to the universe. If it is too light, the universe will decay. If it is too heavy, the universe would have blown up already. According to Dr. Ellis, there is a magic value 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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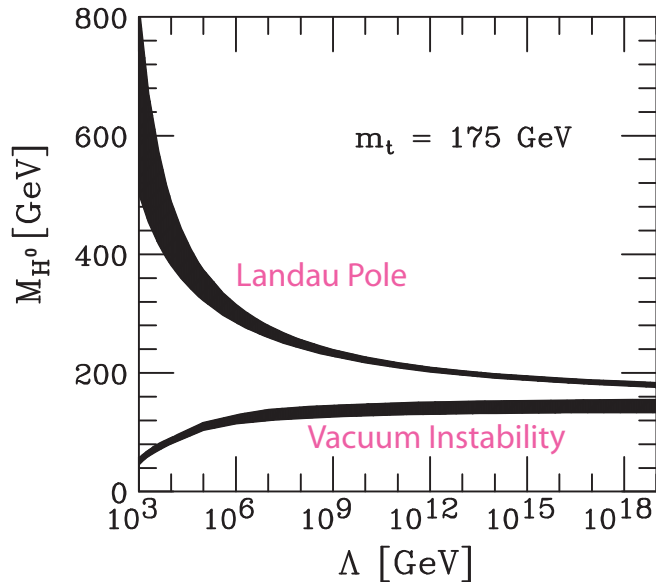
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Interview without UV completion?

Standard Model Higgs Mass Bounds from RG

What the Particle Data Book tells us

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



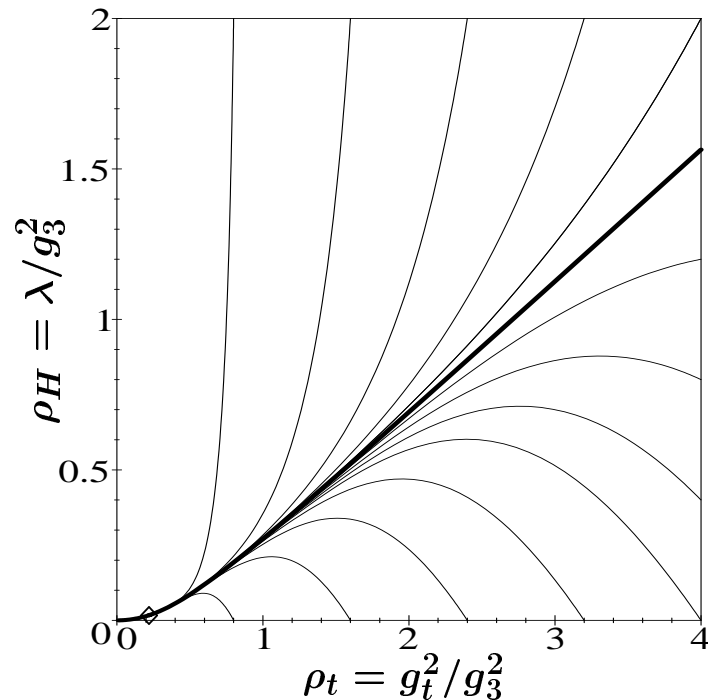
- ▶ Lower bound on the Higgs mass from direct searches is 114.4 GeV
- ▶ From Electroweak precision measurements:
 $M_H = 76^{+33}_{-24}$ GeV with 2σ error
ignores intrinsic cutoff!
- ▶ Landau Pole and Vacuum Instability
misrepresentations of triviality?
- ▶ Lattice and modern view on effective field theories should be reconciled

Should this PDG figure be reworked nonperturbatively?

Standard Model Higgs Mass Bounds from RG

Triviality and Renormalization Group Fixed Points

running of λ, g_t, g_3



► Top-Higgs sector

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

$$\frac{dg_t^2}{dt} = \frac{9}{16\pi^2} g_t^4$$

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

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

Ross-Pendleton fixed point:

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

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

Complete Standard Model is trivial again in perturbation theory!

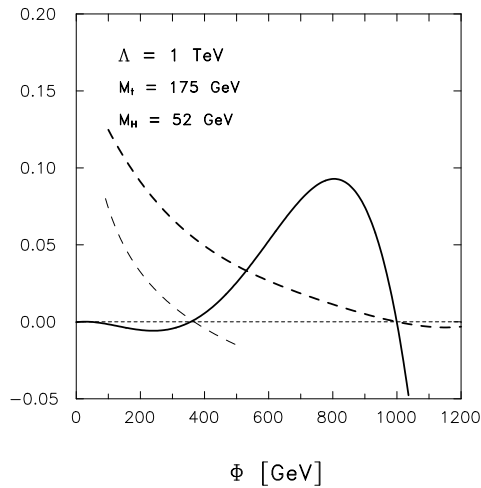
Ross-Pendleton fixed point is destroyed by weak gauge couplings

Standard Model Higgs Mass Bounds from RG

Top loop induced Higgs vacuum instability

Effective Higgs potential

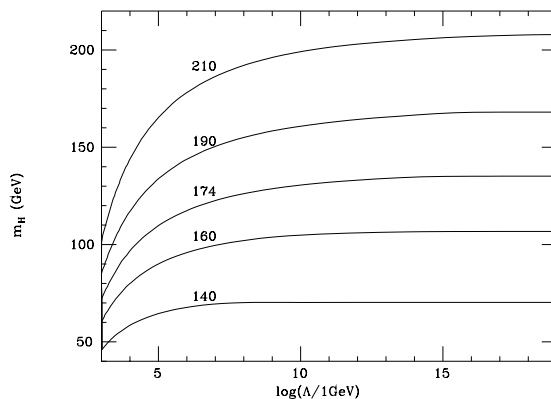
Casas, Espinoza, Quiros



- ▶ Vacuum instability: m_t destabilizes ground state if m_H below some critical value
- ▶ Small running couplings $\lambda(\mu)$, $g_t(\mu)$, $g_3(\mu)$ in RG improved $V_{\text{eff}}(\phi)$
- ▶ Tunneling time $\gg 14$ billion years across barrier is often used to set lower Higgs mass bound (Hall, Ellis, Linde, Sher, ...)
- ▶ **Higgs vacuum instability: misrepresentation of triviality? tunneling universe from false vacuum?**

Higgs mass lower bound:

Altarelli, Isidori



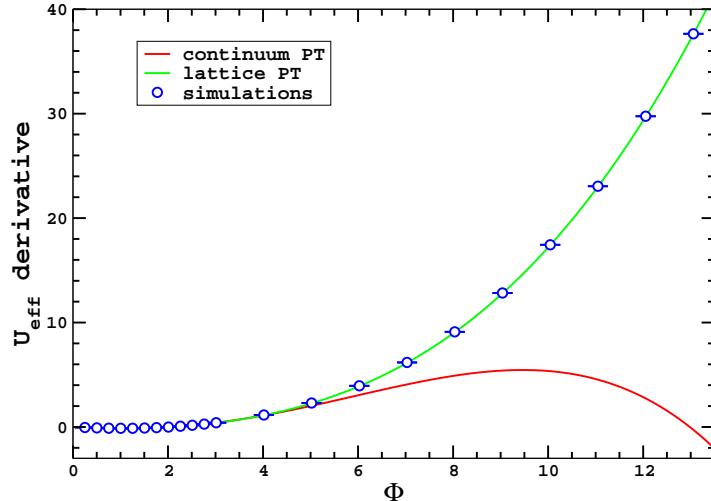
Interpretation of Higgs vacuum instability requires more refined view of what we call the Standard Model

Fate of the False Higgs Vacuum

Lattice effective Higgs potential and large N with generic regulator

Lattice U_{eff}

Holland,Kuti



Staggered fermions are being replaced by chiral fermions in new lattice Higgs collaboration of Fodor,Holland,Kuti,Nogradi,Schroeder:

Exact same results are expected,

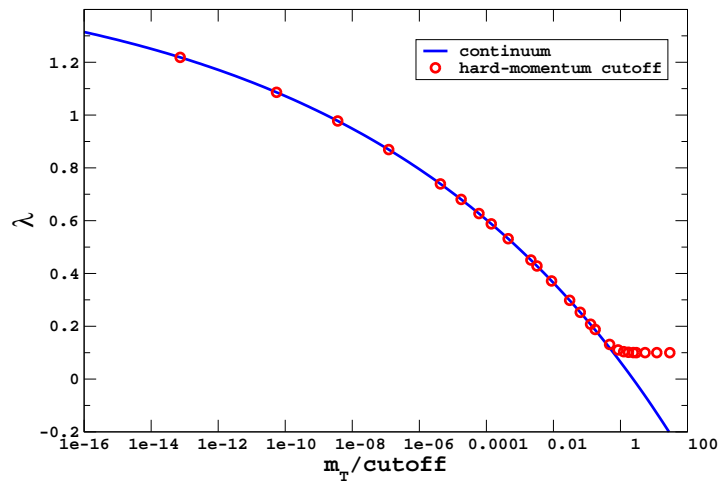
and being obtained!

- ▶ Staggered fermion lattice simulations clearly show the absence of vacuum instability
- ▶ Lattice applications which are relevant for continuum SM will require chiral fermions (demanding extreme lattice computing)
- ▶ Confirmed by large N using other regulators
- ▶ Generic behavior: $\phi \geq \Lambda_{\text{cutoff}}$ for unstable range of $V_{\text{eff}}(\phi)$
- ▶ What happens when ignoring the cutoff in the running RG equations?

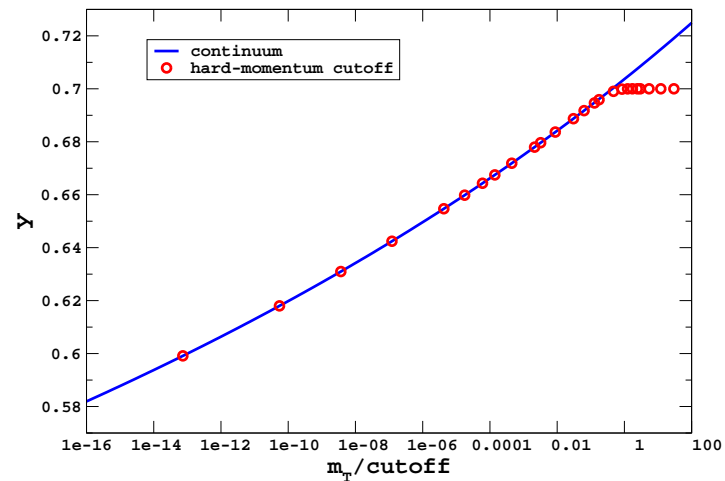
Fate of the False Higgs Vacuum

RG running with intrinsic cutoff

running Higgs coupling λ



running top yukawa coupling



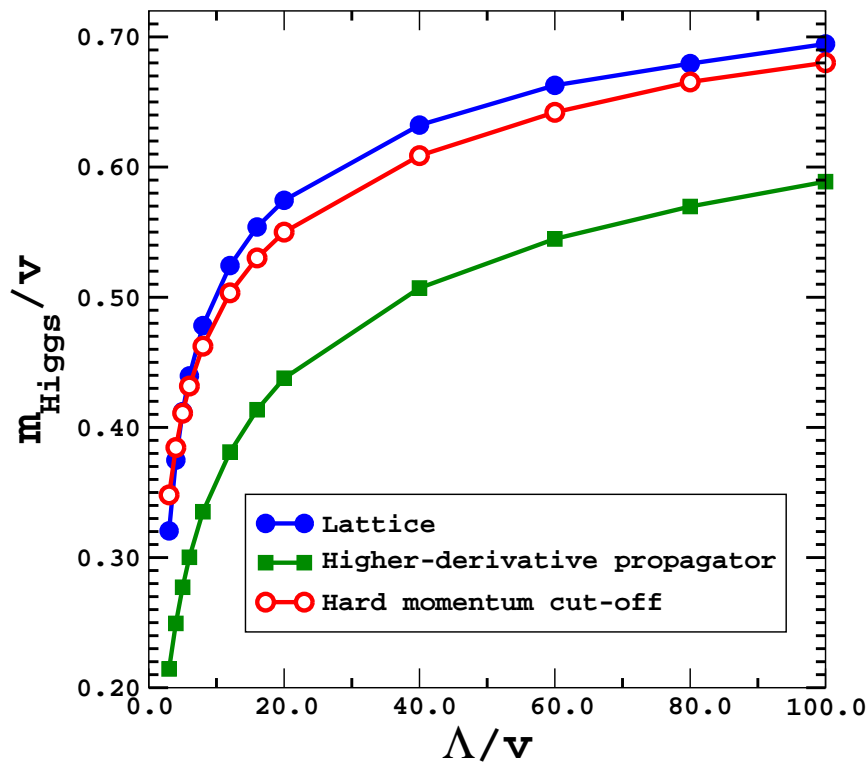
- ▶ Exact RG running with regulator in place breaks away from “continuum” RG running close to Λ_{cutoff}
- ▶ Can the $\lambda(\Lambda_{\text{cutoff}}) = 0$ condition serve as a definition of Higgs lower bound?

Fate of the False Higgs Vacuum

Cutoff dependence of the Higgs mass lower bound

Regulator dependent bounds

Holland, Kuti



- ▶ Different answers with different regulators under $\lambda(\Lambda_{\text{cutoff}}) = 0$ condition
- ▶ Can higher dimensional operators on the cutoff scale lead to false vacuum?
- ▶ What is the robust physical interpretation?

Fate of the False Higgs Vacuum

SM as Effective Field Theory and UV Completions

The scale M of new physics and the lattice scale Λ

Fate of the False Higgs Vacuum

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Continuum Wilsonian RG

UV Completion

unknown new physics

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

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

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

UV completion with exponential damping

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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 $-1/2 m_H^2$ 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

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Lattice Wilsonian RG

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

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

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Scale M missing

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

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

or, Lee-Wick and other UV completions

which exist above scale M (not effective theories!)

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Higher Derivative (Lee-Wick) Extension

Lee-Wick Higgs sector: UV completion without false vacuum

Jansen, Kuti, Liu, Phys. Lett. B309 (1993) p.119 and p.127

- ▶ Represent the Higgs doublet with four real components ϕ^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,

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

- ▶ 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 $\mathcal{M} = M e^{\pm i\Theta}$. 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 re-created by Grinstein, O'Connell, Wise)

$\lambda > 0$ on all scales!

False vacuum cannot develop!

Higher Derivative (Lee-Wick) Extension

Gauged Lee-Wick extension

- ▶ Higher derivative Yang-Mills gauge Lagrangian for the $SU(2)_L \times U(1)$ weak gauge fields W_μ, B_μ follows similar construction with covariant derivative $D_\mu^{ab} = \delta^{ab} \partial_\mu + g f^{abc} W_\mu^c$,

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

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

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

- ▶ 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: $\mathcal{L}_{\text{fermion}} = i \bar{\Psi} \not{D} \Psi + \frac{i}{2M^4} \bar{\Psi} \not{D}^2 \not{D} \not{D}^2 \Psi$.

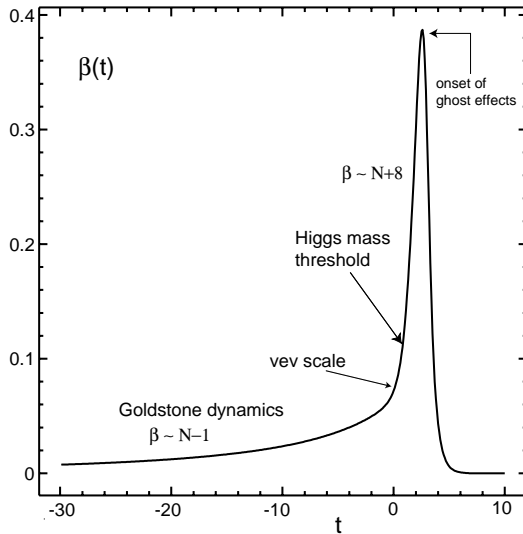
SM particle content is doubled

Logarithmic divergences only

Higher Derivative (Lee-Wick) Extension

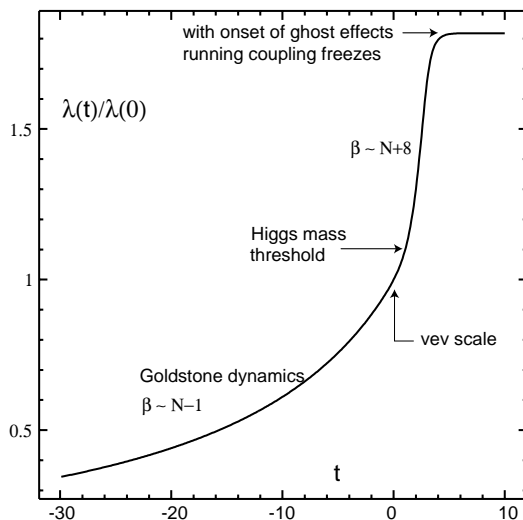
Liu's Thesis (1994)

β function:



- ▶ Higher derivative Higgs sector is finite field theory
- ▶ Mass dependent $\beta(t)$ -function vanishes asymptotically
- ▶ Grows logarithmically in gauged Higgs sector

running Higgs coupling:



- ▶ Running Higgs coupling $\lambda(t)$ freezes asymptotically
- ▶ The fixed line of allowed Higgs couplings must be positive!
- ▶ **No vacuum instability!**
Higgs mass lower bound from $\lambda(\infty) > 0$

Higher Derivative (Lee-Wick) Extension

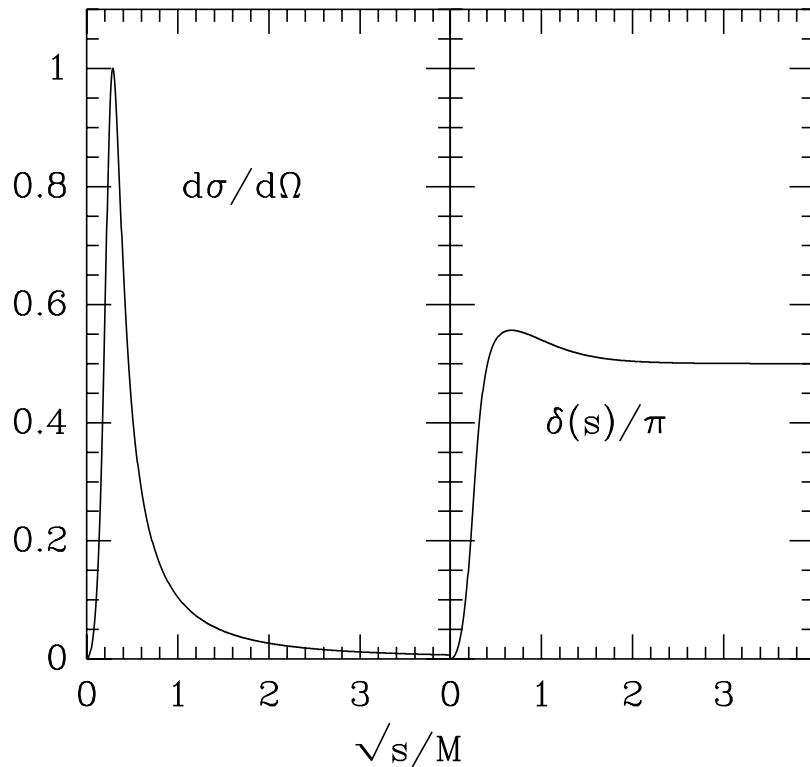
Unitarity and Causality

Liu, Jansen, Kuti

Nucl.Phys. B34 (1994) p.635

cross section

phase shift



- ▶ Equivalence theorem, Goldstone scattering
- ▶ Higgs mass upper bound relaxed
- ▶ $m_H = 1$ TeV, or higher, but ρ -parameter?
- ▶ Phase shift reveals ghost, microscopic time advancement, only $\pi/2$ jump in phase shift

$m_H = 1$ TeV, $M = 3.6$ TeV

$v/M = 0.07$, $m_H/M = 0.28$

Conclusions and Outlook

- ▶ Lee-Wick paradigm is minimal extension and free of vacuum instability!
- ▶ No Higgs vacuum instability in minimal Standard Model without very special nonrenormalizable operators (strong dependence on UV completion and new physics)
- ▶ The existence of the partition function (path integral) itself provides correct strategy for Higgs mass lower bound
- ▶ Life does not have to be boring in 4D without supersymmetry, or technicolor
- ▶ 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?