Vacuum Stability
on the ultimate fate of the Standard Model

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Physics at the LHC and beyond
Quy-Nhon, Vietnam
Outline

• Introduction
  • the scary resilience of the SM

• Vacuum Stability
  • is the universe (meta-) stable?
  • theoretical and experimental uncertainties

• What could it mean?
  • Planck scale embedding and conformal symmetry
  • Cosmology
References

an old question

N. V. Krasnikov, Yad. Fiz. 28 (1978) 549.
J. A. Casas, J. R. Espinosa and M. Quiros,
References

revitalized by the BEH scalar discovery

MH, K. S. Lim and M. Lindner,

J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori, A. Riotto and A. Strumia,

F. Bezrukov, M. Y. Kalmykov, B. A. Kniehl and M. Shaposhnikov,

S. Alekhin, A. Djouadi and S. Moch,

G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori and A. Strumia,

D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio, and A. Strumia,

Shaposhnikov, [arXiv:1311.4979].

Figure 1. Measured Higgs boson rates at ATLAS, CMS, CDF, D0 and their average (horizontal gray band at $\pm 1\sigma$). Here 0 (red line) corresponds to no Higgs boson, 1 (green line) to the SM Higgs boson (including the latest data point, which describes the invisible Higgs rate).

The $\chi^2$ is approximated as

$$\chi^2 = \sum_{I} \left( \frac{R_{\text{exp}} - 1}{R_{\text{err} I}} \right)^2,$$

where the sum runs over all measured Higgs boson rates $I$.

The theoretical uncertainties on the Higgs production cross sections $\sigma_j$ start to be non-negligible and affect the observed rates in a correlated way. We take into account such correlations in the following way. We subtract from the total uncertainty $R_{\text{err} I}$ the theoretical component due to the uncertainty in the production cross sections, obtaining the purely experimental uncertainty, $R_{\text{err} I} - \text{exp}$. The theoretical error is reinserted by defining a $\chi^2$ which depends on the production cross sections $\sigma_j$,

$$\chi^2 = \sum_{I} \left( \frac{R_{\text{exp}} - R_{\text{th} I}(\sigma_j)}{R_{\text{err} - \text{exp} I}} \right)^2 + \sum_{j} \left( \frac{\sigma_j - \sigma_{\text{th} j}}{\sigma_{\text{err} j}} \right)^2.$$

\[ \text{(2.1)} \]

\[ \text{(2.2)} \]

A similar procedure was described by Azatov et al. in \[7\].

Note that the size of the theory uncertainty depends on the applied cuts, and that the scaling of the production cross section to yield the best-fit value relative to the theoretical central value may be different for very different sets of selection cuts (due to the QCD and PDF uncertainties).

$\sigma_{pp \to h} = (19.4 \pm 2.8)$ pb,

$\sigma_{pp \to jjh} = (1.55 \pm 0.04)$ pb,

$\sigma_{pp \to Wh} = (0.68 \pm 0.03)$ pb,

$\sigma_{pp \to Zh} = (0.39 \pm 0.02)$ pb,

$\sigma_{pp \to t\bar{t}} = (0.128 \pm 0.018)$ pb.

\[ \text{(2.3)} \]

\[ \text{(2.4)} \]

\[ \text{(2.5)} \]
no Supersymmetry
LHC Results Run I

ATLAS Exotics Searches - 95% CL Exclusion

Status: ICHEP 2014

$\int L dt = (1.0 - 20.3) fb^{-1}$

$\sqrt{s} = 7, 8$ TeV

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**Extra Dimensions**

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ATLAS Preliminary

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*Only a selection of the available mass limits on new states or phenomena is shown.*

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7
SM may be valid up to Planck Scale

- Higgs mass determines self-coupling
  \[ \lambda(m_t) = \frac{m_h^2}{2v^2} (1 + \delta_h(m_t)) \]
- SM stays perturbative up to the Planck scale
- first SM coupling to become non-perturbative is gravitational coupling
- non-trivial interplay between top and BEH boson contributions

### Figure 1: Renormalisation of the SM gauge couplings

- SM couplings: \( g_1, g_2, g_3 \)
- Yukawa couplings: \( y_t, y_b, y_\tau \)
- Higgs quartic coupling and Higgs mass parameter \( m \).

All parameters are defined in the \( m_s \) scheme. We include two-loop thresholds at the weak scale and three-loop RG equations. The thickness indicates the ±1 uncertainties in \( M_t, M_h, \tau_3 \).

Planck mass, we find the following values of the SM parameters:

- \( g_1(M_{Pl}) = 0.6168 \) (56a)
- \( g_2(M_{Pl}) = 0.5057 \) (56b)
- \( g_3(M_{Pl}) = 0.4873 + 0.0002 \) (56c)
- \( y_t(M_{Pl}) = 0.3823 + 0.0051 \) (56d)
- \( M_t \) (in GeV) = 173.35 ± 0.0021
- \( M_h \) (in GeV) = 125.66 ± 0.0029

All Yukawa couplings, other than the one of the top quark, are very small. This is the well-known flavour problem of the SM, which will not be investigated in this paper.

The three gauge couplings and the top Yukawa coupling remain perturbative and are fairly weak at high energy, becoming roughly equal in the vicinity of the Planck mass. The near equality of the gauge couplings may be viewed as an indicator of an underlying grand unification even within the simple SM, once we allow for threshold corrections of the order of 10% around \( 10^{16} \) GeV (of course, in the spirit of this paper, we are disregarding the acute naturalness problem). It is amusing to note that the ordering of the coupling constants at low energy is completely overturned at high energy. The (properly normalised) hypercharge \( \lambda \) is given by:

\[ \lambda(m_t) = \frac{m_h^2}{2v^2} (1 + \delta_h(m_t)) \]
SM Extrapolation

Scylla and Charybdis

\[ \mu \frac{d}{d\mu} \lambda \approx \frac{1}{16\pi^2} \left( 24\lambda^2 - 6y_t^4 \right) \]

large scalar mass:
- self-coupling dominates
- self-coupling grows
- Higgs eventually becomes strongly coupled
- no Landau pole before the Planck scale if \( m_h < 174 \) GeV

small scalar mass:
- top Yukawa coupling dominates
- self-coupling decreases
- potential becomes unstable for negative self-coupling
- vacuum unstable for \( m_h < 126 \) GeV

\[ \left[ \text{MH, Lim, Lindner 1111.2415} \right] \]
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\[ \mu \frac{d}{d\mu} \lambda \approx \frac{1}{16\pi^2} \left( 24\lambda^2 - 6y_t^4 \right) \]

measured BEH boson mass implies nearly vanishing self coupling at Planck scale!
accuracy crucial
Vacuum Decay?

Universe can decay through potential barrier!
Quantum (not thermal) fluctuations!
Lifetime of the universe should be larger than age of the universe!
Is there an 'occasion for anxiety'?

hot when the false vacuum decays, even on the scale of high-energy physics, and the zero-temperature computation of $\Gamma/V$ is inapplicable. If this time is on the order of years, the decay of the false vacuum will lead to a sort of secondary big bang with interesting cosmological consequences. If this time is on the order of $10^9$ yr, we have occasion for anxiety.

Fate of the false vacuum: Semiclassical theory*

Sidney Coleman

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 24 January 1977)
Vacuum Decay

- Situation analogous to superheated liquid
- diff. decay rate
  \[ d\Phi = dt \, dV \, \Lambda_B^4 e^{-S(\Lambda_B)} \]
- classical bounce action
  \[ S(\Lambda_B) = \frac{8\pi^2}{3|\lambda(\Lambda_B)|} \]
- scale R of bounce determined by maximal scale breaking effect
  - qm running of couplings
  - maximize
    \[ \Lambda_B^4 e^{-S(\Lambda_B)} \]
  - gravitational contributions irrelevant as long as \( \Lambda_B \ll M_{Pl} \)
  
  [Isidori et al. 2008]

- to get decay rate, one has to integrate over history of the universe
- integration over past dominated by recent past -> robust
- integration over future depends on dark energy
Vacuum Decay

- Situation analogous to superheated liquid
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[Isidori et al. 2008]

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Vacuum decay

- Situation analogous to a superheated liquid
- Diff. decay rate:
  \[ d\phi = dt \, dV \, \Lambda_B^4 \]
- Classical bounce action:
  \[ S(\Lambda_B) = \frac{3|\chi(\Lambda_B)|}{\Lambda_B^4} \]
- Scale \( R \) of bounce:
  - Maximal scale,
  - QM running,
  - Maximize:
    \[ \Lambda_B^4 \]
- Gravitational contributions:
  - Irrelevant as long as \( \Lambda_B \ll M_{Pl} \)

- No reason to worry about vacuum decay from a practical point of view
- Interesting question: is the SM stable, metastable or what?

Integration over past dominated by recent past -> robust

Dark energy
**Calculation of Critical Mass**

**Input:** Pole masses $m_h$ and $m_t$ and SM parameters at $M_Z$

- **Convert to MS-bar parameters**
  
  $y_t(\mu) = 2^{3/4} \sqrt{G_F} M_t \left(1 + \delta y_t \left(M_t, \alpha_s, \alpha, s_W^2, M_Z, \mu\right)\right)$
  
  $\lambda(\mu) = 2^{1/2} G_F M_h^2 \left(1 + \delta \lambda \left(M_t, \alpha_s, \alpha, s_W^2, M_Z, \mu\right)\right)$

- **Evolve up to Planck scale**
  
  $\mu \frac{d}{d\mu} \lambda = \beta_\lambda(\lambda, y_t, g_i)$, \quad $\mu \frac{d}{d\mu} y_t = \beta_{y_t}(\lambda, y_t, g_i)$

- **Minimize bounce action**
  
  $\min \Lambda_B^4 e^{-S_B} \Rightarrow \max S_B \Rightarrow \min |\lambda(\mu = \Lambda_B)| \Rightarrow \lambda(\mu = \Lambda_B) = \beta_\lambda(\mu = \Lambda_B) = 0$
NNLO Vacuum Stability

**2-loop matching conditions**
translate MS-bar parameters in physical observables
- Bezrukov, Kalmykov, Kniehl, Shaposhnikov
  - $\delta y_t$ to $O(\alpha_s^0)$, $\delta \lambda$ to $O(\alpha_s)$ [1205.2893]
- Degrassi, Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia
  - $\delta y_t$ to $O(\alpha_s^0)$, $\delta \lambda$ to $O(y_t^4)$ [1205.6497]
- Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia
  - full NNLO [1307.3536]
- Spencer-Smith [1405.1975]
  - mass dependent ren. scheme

**3-loop RGEs**
evolve MS-bar parameters with energy
- Mihila, Salomon, Steinhauser
  - $\beta g$ three loops [1201.5868]
- Chetyrkin, Zoller
  - $\beta y_t$, $\beta \lambda$ three loops [1205.2892] & [1303.2890]
- Bednyakov, Pikelner, Velizhanin
  - $\beta y_t$, $\beta \lambda$ three loops [1212.6829] & [1303.4364]

**Reduced theoretical error from**
2.5 GeV to 0.3 GeV

$$M_h > 129.6 \text{ GeV} + 2.0(M_t - 173.35 \text{ GeV}) - 0.5 \text{ GeV} \frac{\alpha_3(M_Z) - 0.1184}{0.0007} \pm 0.3 \text{ GeV}.$$  

[Shaposhnikov, 1311.4979]
State of the art

Spencer-Smith, 2014

mass depend ren.

SM is probably meta-stable

claim 3.5 sigma

optimistic theoretical errors

• most important factor: determination of MS bar top Yukawa
Biggest Caveat

you have to trust the error bars on the top mass

- usually the MC top mass measured at the tevatron is used
- theoretically problematic
- cleaner t tbar cross-section gives larger error  
  (see talks by Tenchini, Yokoya)

ALSO:

- gravitational corrections?  
  (Lalak, Lewicki, Olszewski’14, Branchina, Messina’13)

- keep in mind the somewhat arbitrary definition of theoretical errors (twiggle the RG scale) 
  (see talk by Passarino)

\[ \Delta \alpha_s = 0.0004 \] is quoted in Ref. [49]. This can be done either in \( e^+ e^- \rightarrow q \bar{q} \) events on the Z-resonance (the so-called GigaZ option) or at high energies [43] or in a combined fit with the top quark mass and total width in a scan around the \( t \bar{t} \) threshold [48].

Assuming for instance that accuracies of about \( \Delta m_t \approx 200 \text{ MeV} \) and \( \Delta \alpha_s \approx 0.0004 \) can be achieved at the ILC, a (quadratically) combined uncertainty of less than \( \Delta M_H \approx 0.5 \text{ GeV} \) on the Higgs mass bound eq. (1) could be reached. This would be of the same order as the experimental uncertainty, \( \Delta M_H < \sim 100 \text{ MeV} \), that is expected on the Higgs mass.

At this stage we will be then mostly limited by the theoretical uncertainty in the determination of the stability bound eq. (1) which is about \( \pm 1 \text{ GeV} \). The major part of this uncertainty originates from the the QCD threshold correction to the coupling \( \lambda \) which are known at the two-loop accuracy [6, 7]. It is conceivable that, by the time the ILC will be operating, the theoretical uncertainty will decrease provided more refined calculations of these threshold corrections beyond NNLO are performed.

The situation is illustrated in Fig. 1 where the areas for absolute stability, metastability and instability of the electroweak vacuum are displayed in the \( [M_H, m_{\text{pole}t}] \) plane at the 95\% confidence level. The boundaries are taken from Ref. [6] but we do not include additional lines to account for the theoretical uncertainty of \( \Delta M_H = \pm 1 \text{ GeV} \) (which could be reduced in the future) and ignore for simplicity the additional error from the \( \alpha_s \) coupling.

As can be seen, the 2\( \sigma \) blue–dashed ellipse for the present situation with the current Higgs and top quark masses of \( M_H = 126 \pm 2 \text{ GeV} \) and \( m_{\text{pole}t} = 173.3 \pm 2.8 \text{ GeV} \), and in

This situation occurs when the true minimum of the scalar potential is deeper than the standard electroweak minimum but the latter has a lifetime that is larger than the age of the universe [5]. The boundary for this region is also taken from Ref. [6].

\[ [M_H, \text{Lim}, \text{Lindner}, 1112.2415], \]  
\[ [\text{Alekhin, Djouadi, Moch}, 1207.0980] \]
Smaller Caveat
Smaller Caveat
My Conclusion:

At present, we do not know whether our vacuum is stable or metastable.

Shaposhnikov, 1311.4979

Now mostly a experimental question....
What could it mean?

Caveat: speculation
Option 1: BSM to the rescue?

- the SM does not unequivocally require new physics below $M_P$ to be stable
- BSM needed for neutrino masses, dark matter,…
- to minimally extend the SM
  - new contributions to beta functions or thresholds
- additional scalars generally good, new fermions with large couplings to Higgs disfavored
  - potential problem for type I see-saw models for $M_R > 10^{13}$ GeV

\[ 0.1 \text{eV} \sim m_\nu \sim \frac{y^2 v^2}{M_R} \]
Option 2: Planck Scale Boundary Conditions

Excluded Region by
LHC @ 95% CL

assumption: SM valid up to Planck scale
EW symmetry breaking induced by Planck scale effects
scatterplot of random values for self-couplings at Planck scale
during 2011: Higgs bounds from LHC and Tevatron ruled out
generic values at Planck scale

[MH, Lim, Lindner 1111.2415]
Option 2: Planck Scale Boundary Conditions

- Assumption: SM valid up to Planck scale
- EW symmetry breaking induced by Planck scale effects
- Think of boundary conditions as possible imprints from Planck scale physics
- Viable boundary conditions loopy; give small $\lambda$ at $M_P$

\[ \lambda(M_P) = 0, \text{Str}(M^2)(M_P) = 0, \beta_\lambda(M_P) = 0 \]

most interesting

[1111.2415]
Planck Scale Boundary Conditions

**3σ bands in**
- \( M_t = 173.4 \pm 0.7 \text{ GeV} \) (gray)
- \( \alpha_3(M_Z) = 0.1184 \pm 0.0007 \) (red)
- \( M_h = 125.7 \pm 0.3 \text{ GeV} \) (blue)

- \( M_t = 171.4 \text{ GeV} \)
- \( \alpha_3(M_Z) = 0.1205 \) (green)
- \( \alpha_3(M_Z) = 0.1463 \) (red)
- \( M_t = 175.3 \text{ GeV} \)

**Beta function of the Higgs quartic \( \beta_\lambda \)**

\[ \lambda(M_P) = 0 \text{ and } \beta_\lambda(M_P) = 0 \]

first proposed by Frogatt, Nielsen as multiple point principle \([\text{hep-ph/9917135}]\)

independently predicted by Shaposhnikov and Wetterich from asymptotic safety of gravity \([0912.0208]\) (idea that gravity has non-perturbative fix-point \([\text{Weinberg 79}]\))
Planck Scale Boundary Conditions

\[
\delta m_H^2 = \frac{\Lambda^2}{16\pi^2} C_V
\]

\[
C_{V1}(\mu) = 6\lambda(\mu) + \frac{9}{4} g^2(\mu) + \frac{3}{4} g'^2(\mu) - 6y_t^2(\mu)
\]

Veltman's Condition: \( \text{Str}(M^2) = 0 \)

\textit{perturbative quantum corrections to BEH mass should vanish}

- if evaluated at EW scale, Higgs mass would be 314 GeV
- if evaluated at Planck scale, it works

\[ \text{[Masina, Quiros, 1308.1242]} \]
Planck Scale Boundary Conditions

Why do all these boundary conditions work?
- suppression factors compared to random choice = O(1)
  - \( \lambda = F(\lambda, g_i^2, \ldots) \) loop factors 1/16\(\pi^2\)
- top loops-> fermion loops factors of (-1)
  scenarios ‘predicting’ sufficiently suppressed (small/tiny) \( \lambda \) at \( M_{\text{planck}} \) are OK
  more precision -> selects options ; e.g. \( \gamma_m = 0 \) now ruled out

- if evaluated at EW scale, Higgs mass would be 314 GeV
- if evaluated at Planck scale, it works
SM Planck Scale Embedding

Hierarchy Problem (why $m \ll M_P$?)

the other peculiarity of the SM scalar potential

Gravity is different, finite quantum gravity corrections cannot be calculated

very unnatural, SM cannot be standard EFT

One approach (Nicolai, Meissner): classical scale invariance of particle physics action as quantum gravity boundary condition

[in Planck scale units, at the Planck scale, the BEH scalar potential nearly vanishes]

$$V(\phi) = m^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$
SM Planck Scale Embedding

Solve the hierarchy problem at the Planck scale (Nicolai, Meissner hep-th/0612165)

- quantum gravity action may lead to **classical scale invariance** of the particle physics action (Nicolai, Meissner 0710.2840)

- Wilsonian argument might not apply to the Planck scale
  - no intermediate (e.g. GUT) scale possible!

- on the classical level, the only SM parameter that breaks conformal symmetry is the BEH boson mass

\[ \delta m_H^2 \sim M_P^2 + M_{GUT}^2 \]

"gravity is special" dangerous, cannot be there

\[ \frac{d m_H^2}{d \ln \mu} = \frac{3m_H^2}{8\pi^2} \left( 2\lambda + y_t^2 - \frac{3g_2^2}{4} - \frac{3g_1^2}{20} \right) \]
Classical Scale Invariance

• there is **no internal symmetry** that could forbid Higgs mass term
  • extend space-time symmetry-\(\Rightarrow\)SUSY or conformal symmetry
• beta functions break scale symmetry \(-\)\(\Rightarrow\) SM cannot be conformally invariant on QM level
• **Coleman-Weinberg**: if one sets the Higgs mass to zero on tree-level, Higgs acquires a VEV and breaks symmetry
  • **does not work in SM**, top too heavy, Higgs to light
  • SM therefore has to extended to make this idea work
• origin of scale separation: logarithmic running of dimensionless parameters
BSM models based on classical scale invariance

many models

R. Hempfling, PLB379, 153 (1996)
Foot, Kobakhidze, Volkas, PLB655, 156 (2007); PRD82, 035005 (2010); PRD84, 075101 (2011)
Foot, Kobakhidze, McDonald, Volkas, PRD76, 075014 (2007); PRD77, 035006 (2008)
S. Iso, N. Okada and Y. Orikasa, PLB676, 81 (2009)
M. Holthausen, M. Lindner and M.A. Schmidt, PRD82, 055002 (2010)
J.S. Lee and A. Pilaftsis, PRD86, 035004 (2012)
C. Englert, J. Jaeckel, V. Khoze and M. Spannowsky, JHEP 1304, 060 (2013)
V. Khoze, JHEP 1311, 215 (2013)
M. Holthausen, J. Kubo, K.S. Lim and M. Lindner, JHEP 1312, 076 (2013)

taken from talk by
RV=Ray Volkas at
SUSY 2014
Classical Scale Invariance

- minimal scale invariant SM does not work
- simplest extension: singlet scalar with Higgs portal coupling
- may be used to explain other things in the SM: dark matter, inflation, baryogenesis, dark energy...

\[ \lambda_{HS} S^\dagger S H^\dagger H \]

Theoretical Possibilities

\[ \langle H \rangle \gg \langle S \rangle \]

- Coleman-Weinberg breaking for Higgs
- stable \( V_{\text{eff}} \) requires new particle(s) with **sizable** couplings to the Higgs
- survivability up to Planck scale a challenge
- interesting collider phenomenology

\[ \langle H \rangle \ll \langle S \rangle \]

- SM-like electroweak symmetry breaking
- effective Higgs mass term generated by S-VEV
- coupling to Higgs can be arbitrarily small (fine-tuning)
- easy to hide and to do
- testable more via dark matter etc.

e.g. Hill, 1401.4185

e.g. Volkas et al., 1310.0223
Cosmology: Interplay with Inflation

- recently BICEP-2 reported a large value for the tensor-to-scalar ratio $r=0.16$
- this would imply an GUT scale energy density during inflation
- stochastic fluctuations will push Higgs expectation value to $H_{\text{inf}}=10^{13}$ GeV
- if SM develops instability around $10^{11}$ GeV, the universe would never had survived
- if the BICEP2 results holds up, the distinction between meta-stable and stable is crucial

\[ p \sim \exp \left( -\frac{H_{\text{inf}} N_e}{32 \Lambda_I} \right) \]
An example. Today, Tuesday, June 24, the web site Russia Today reported that Higgs particle theorists assert that the universe should not exist.

Recognized British cosmologists stated, "After the Big Bang, the universe should have collapsed in a matter of microseconds.

"... Robert Hogan, of King's College in London stated that during the time of the early universe, they expected cosmic inflation. That was a rapid enlargement of the universe just after the Big Bang. This growth created a large shake-up which could make the entire universe collapse.

"... With this data, Hogan and physicist Malcolm Fairbairn, also from King's College in London, attempted to recreate the conditions of this cosmic inflation after the Big Bang."

I use just a few of the lines relating to the topic, but I take the liberty of asking: Why do those who inform the people not publish one line about what the world's most important scientific centers know about what occurred, or could occur, in the universe?

Attached below is the message I sent to Diego Armando Maradona.

I beg your pardon for the time I have taken with these lines.

Fidel Castro Ruz

http://www.granma.cu/idiomas/ingles/cuba-i/25jun-Note%20from%20Fidel.html
Conclusions

• what we have learned from the LHC so far:
  • SM is consistent field theory down to very small scales
  • no signal for BSM physics

• EW vacuum might be stable or meta-stable
  • precision top Yukawa determination will tell

• BEH scalar potential nearly vanishes near Planck scale
  • this allows one to speculate that the EW scale might be more closely liked to Planck scale physics

• Classical Scale Invariance might alleviate the hierarchy problem and motivate such scenarios
  • non fine-tuned models predict new particles with sizable couplings to the Higgs