Vacuum energy with mass generation and Higgs bosons

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work with Janina Krzysiak

- Scale hierarchies in particle physics
  - Higgs mass $\ll$ Planck scale
  - Cosmological constant, scale $\ll$ Higgs and Planck masses

- Hints for new particles or something deeper?
- Subtleties with Poincare and RG invariance and mass generation

- Gauge symmetries determine our interactions: Where do they come from?
  - Connecting the cosmological constant and neutrino masses

Krakow Epiphany, January 7th 2020

Hierarchy Puzzles

- Higgs mass squared

$$m_{h\ \mathrm{bare}}^2 = m_{h\ \mathrm{ren}}^2 + \delta m_h^2$$

$$\delta m_h^2 = \frac{K^2}{16\pi^2}\frac{6}{v^2}\left(m_h^2 + m_Z^2 + 2m_W^2 - 4m_t^2\right)$$

- If *K* is taken as a physical scale, why is the Higgs mass so much smaller ?
- Counterterm vanishes if

$$2m_W^2 + m_Z^2 + m_h^2 = 4m_t^2 .$$

Veltman condition for Higgs self energy (Acta Phys Pol B 1981)

Infrared – Ultraviolet Connection

Collective cancelation between bosons and fermions

- Needs Higgs mass about 314 GeV if we take PDG top, W and Z masses

Hierarchy Puzzles - Zero Point Energies

- Zero point energies (important through Cosmological Constant)

$$\rho_{\mathrm{zpe}} = \frac{1}{2}\sum\{\hbar\omega\} = \frac{1}{2}\hbar \sum_{\mathrm{particles}} g_i \int_0^{k_{\mathrm{max}}} \frac{d^3k}{(2\pi)^3}\sqrt{k^2+m^2}.$$

- Symmetries – Covariance - and the correct vacuum Equation of State

$$\rho_{\mathrm{zpe}} = -p_{\mathrm{zpe}} = -\hbar\, g_i\, \frac{m^4}{64\pi^2}\left[\frac{2}{\epsilon} + \frac{3}{2} - \gamma - \ln\left(\frac{m^2}{4\pi\mu^2}\right)\right] + \ldots$$

- For Standard Model particles, ρ_{zpe} comes from coupling to the Higgs
  - Proportional to particle masses, m^4

- (Using a brute force cut-off gives radiation EoS, $\rho = p/3$, for leading term)

Pauli and Veltman constraints

- Pauli constraints and ZPEs

$$\sum_i g_i m_i^4 = 0$$

$$\sum_i g_i m_i^4 \ln m_i^2 = 0$$

- Needs Higgs mass of 319 and 311 GeV to cancel with PDG top, W, Z masses

- Close to the 314 GeV to cancel Veltman condition

$$2m_W^2 + m_Z^2 + m_h^2 = 4m_t^2 .$$

- Pauli and Veltman involve cancellations between bosons and fermions
  (terms have different RG scale dependence)

- Need extra strength in the bosons
  » Consider SM extended to extra scalars and 2 HDMs

Pauli constraints and 2 HDMs

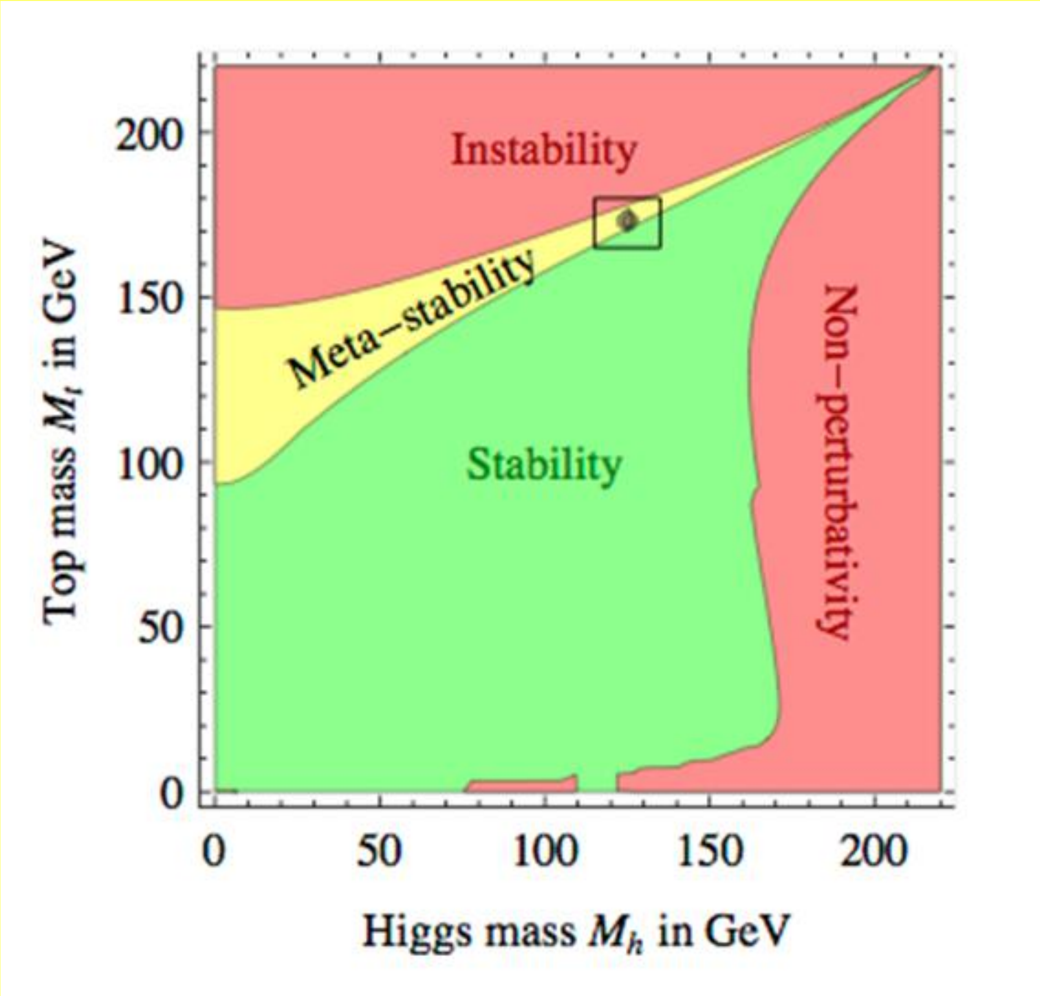
- 2HDMs - Simple extension of SM
  - Extra Higgs doublet with different choices of fermion couplings
  - 5 Higgs bosons, neutral H and h scalars, charged Higgs $H^{\pm}$ and pseudoscalar A
  - SM success → h is very Standard Model like with mass ~ 125 GeV
  - Extra Higgses looked for via direct searches and constraints from EW fits and rare B-decays
  - Type II most constrained (one doublet couples to up-type quarks, one to down-type quarks and leptons)
  - Type II mass constraints $H^{\pm}$ > 600 GeV, A > 530 GeV, H > 400 GeV
  - Would need extra fermions in energy range of the LHC ← not seen (?)

EP extra Higgs searches – see Janina´s talk on Thursday

  - M. Krawczyk: Veltman condition for Type II with H and A masses at 650 GeV, charged mass at 830 GeV

Results from LHC: Critical physics in UV ?

- LHC: So far just Standard Model Higgs and no new particles
- Running masses in loops
- Remarkable: the Higgs and top mass sit in window of possible parameter space where the Standard Model is a consistent theory up to the Planck mass close to the border of a stable and meta-stable vacuum.



$$V(\phi) = \mu^2 \phi\phi^* + \lambda(\phi\phi^*)^2$$

Running masses and SM couplings

- SM works as consistent theory up to Planck mass
- Vacuum stability at 1.3 sigma (maybe less depending on relation between the pole and Monte-Carlo top-quark masses) ← we living close to the edge. Higgs mass ~ 125 GeV important.
- Delicate interplay of UV and IR particle masses/coupling parameters
- Possible connection between particle masses and Planck scale physics
- Veltman conidition works with stable vacuum at about 10^{16} GeV.
- With metastable vacuum need Higgs mass slightly larger to get Veltman crossing below Planck scale, e.g., needs Higgs pole mass about 150 GeV
- Possible new critical phenomena in the UV
  - Where do gauge symmetries and interactions come from ?

Fundamental Symmetries

- Are (gauge) symmetries always present ?

(Gauge symmetries determine our particle interactions)

Making symmetry as well as breaking it

- Emergence: Symmetries dissolving in the UV instead of extra unification

- Standard Model as long range tail of critical system which sits close to Planck scale [Jegerlehner, Bjorken, Nielsen ...]

[SDB, arXiv:2001.01705]

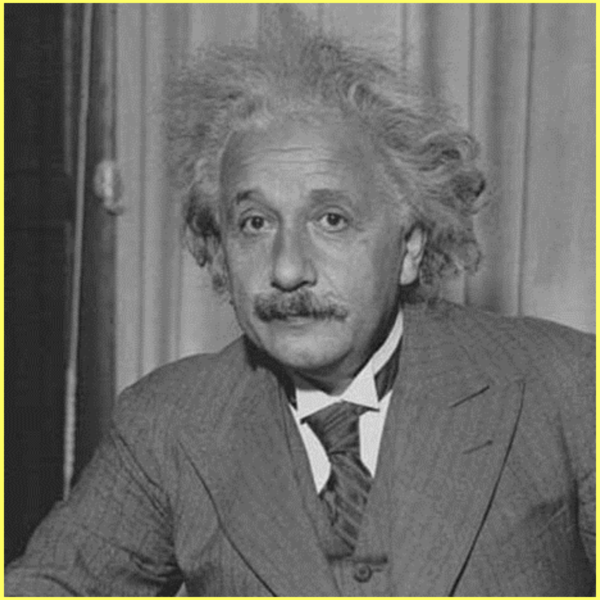
Emergent Symmetries

- Standard Model as an effective theory with infinite tower of higher dimensional operators, suppressed by powers of the (large) emergence scale M
- Global symmetries tightly constrained by gauge invariance and renormalisability when restricted to dimension 4 operators
- Can be broken in higher dimensional operators, suppressed by powers of M
- E.g. Lepton number violation ← Majorana neutrino masses at mass dimension 5 (Weinberg)

$$m_\nu \sim \Lambda_{\rm ew}^2 / M$$

- Symmetry violating terms can become active close to M
  - Possible extra CP violation, baryon number violation in early Universe
- Lorentz/Poincare invariance emerges in quantum systems ← X.-G. Wen, Volovik

The Cosmological Constant



- Vacuum energy is measured just through the Cosmological Constant in General Relativity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \, R = -\frac{8\pi G}{c^2} T_{\mu\nu} + \Lambda g_{\mu\nu} .$$

- Energy density $\rho_{\text{vac}} = \Lambda/(8\pi G)$

receives contributions from ZPEs, vacuum potentials (EWSB, QCD) plus gravitational term

$$\rho_{\text{vac}} = \rho_{\text{zpe}} + \rho_{\text{potential}} + \rho_{\Lambda} ,$$

- The Cosmological Constant determines accelerating expansion of the Universe ← it is an observable and therefore RG scale invariant
  - Numerically, astrophysics (Planck) tells us $\rho_{vac} \sim (0.002\ \text{eV})^4$

Cosmological Constant

- Is an observable and therefore RG scale invariant

$$\frac{d}{d\mu^2}\rho_{\rm vac} = 0.$$

- Scale dependence (explicit μ, in masses and couplings) cancels:
  What is left over?

- Curious: With finite Cosmological Constant there is no solution of Einstein's equations of GR with constant Minkowski metric (Weinberg, RMP)
  - No longer global space-time translational invariant
  - Metric is dynamical with accelerating expansion of the Universe
  - Cf. Success of special relativity and usual particle physics in Lab

Cosmological Constant Scale

- Zero cosmological constant makes sense at dimension 4
  - E.g. Global Minkowski metric works in laboratory experiments

- Cosmological constant scale then suppressed by power of M
  - » 4 dimensions of space-time, so to power of 4 in CC

- Then, scale of Cosmological Constant ~ scale of neutrino mass ~ 0.002 eV

$$\mu_{\rm vac} \sim m_\nu \sim \Lambda_{\rm ew}^2/M$$

  - Einstein's second guess and Feynman lectures ← works at dimension 4

Summary

- LHC results do not *require* anything else at mass dimension 4
- Fine balance of Standard Model parameters and EW vacuum stability
    - Higgs mass correlated with Planck scale physics
- Subtle interplay of Poincare invariance and mass generation
  - Vacuum EoS with ZPE coming from Higgs couplings for SM particles
  - With emergence,
    - Cosmological Constant zero at mass dimension 4
    - Einstein´s second guess, also Feynman gravitation lectures
    - Scale suppressed by power of emergence, just as neutrino masses

[SDB+JK: arXiv:2001.01706]

$$\mu_{\rm vac} \sim m_\nu \sim \Lambda_{\rm ew}^2/M$$