Criterios para jerarquías naturales

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References

Talk based on:

- A. de Gouvea, D. Hernandez and T. M. P. Tait, "Criteria for Natural Hierarchies", arXiv:1402.2658 [hep-ph].

Outline

I. Introduction
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I. Introduction

- Discovery of a SM-like Higgs boson at the LHC renews the question of whether EW symmetry breaking is *natural*.
- Fundamental scalar fields are regarded as unnatural.
- What naturalness really offers as guideline to new energy scales in physics?
- Proposal of a very concrete and unambiguous definition of fine tuning.

We speak of a hierarchy problem (HP) when two largely different energy scales are present in the theory, but there is no symmetry that stabilizes the light scale from corrections coming from the large scale.

II. The hierarchy problem

SM implements spontaneous symmetry breaking of $SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{EM}}$ through the existence of a $SU(2)_L$-doublet Higgs scalar with $Y = +1/2$, whose potential is

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4 \,. \tag{1}$$

Together both μ and λ set

- Higgs vacuum expectation value $v = \sqrt{\mu^2/\lambda} = 246$ GeV (which controls masses of W, Z and SM fermions).
- Mass of the physical Higgs boson, $M_h^2 = \lambda v^2$.

LHC measurement of M_h allows us to reconstruct completely the Higgs potential at the EW scale.

II. The hierarchy problem

Hierarchy (fine tuning or naturalness) problem refers to quantum corrections to μ^2 or, equivalently, v^2.

Naïve description

- Corrections to scalar mass-squared are quadratically divergent and SM-particle loops induce quantum corrections proportional to the unknown cutoff scale.

$$\delta\mu^2 = -\frac{3\lambda_t^2}{8\pi^2} \times \Lambda\,, \tag{2}$$

  where $\lambda_t = \sqrt{2}m_t/v$ and Λ is the cutoff scale.
- $\delta\mu^2 \gg \mu^2$ (or $\Lambda \gg$ TeV) implies unnatural fine tuning of the counter term.
- This argument invests the regulator with physical meaning.

II. The hierarchy problem

- SM incomplete: gravitation, dark matter, neutrino masses, inflation, Landau poles.
- Gravity often considered as the ultimate source of HP: new states with Planck scale masses (M_{Pl}) contributing to $\delta\mu^2$.
- No generic reason to believe that $\delta\mu^2$ is related to λ_t: top quark no more special than any SM particle.
- Fine tuning of the EW scale associated with thresholds from heavy particles, calculable and dependent on the nature of the UV completion of the SM.
- **Naturalness constraint**: $\delta\mu^2 \lesssim 100^2$ GeV^2.

If there is new physics (NP) beyond SM "talking" to the Higgs sector, NP introduces large finite corrections to μ^2. If NP couplings are $\mathcal{O}(1)$, $\Lambda_{\mathrm{NP}} <$ TeV to avoid unnatural fine tuning.

III. Heavy fermion

We extend the SM degrees of freedom by at least one new heavy fermion Ψ (Majorana or Dirac). Under what circumstances are SM + Ψ models natural?

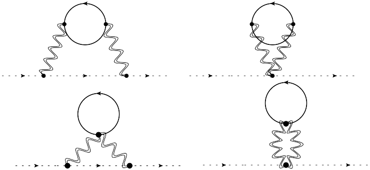
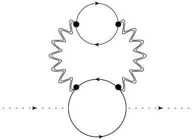
A. Uncoupled Ψ

B. SM-Charged Ψ

C. Yukawa-Coupled Ψ

III.A. Uncoupled Ψ

- If $\mathcal{L}_{\mathrm{SM}+\Psi} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\Psi} \implies$ no loop corrections to μ^2.
- If $\mathcal{L}_{\mathrm{SM}+\Psi}$ does not split:

Gravity loops	Mixed gravity-SM loops
	
$\delta\mu^2 \sim \frac{1}{(16\pi^2)^2}\frac{M_\Psi^4}{M_{\mathrm{Pl}}^4} \times \mu^2$	$\delta\mu^2 \sim \frac{\lambda_t^2}{(16\pi^2)^3}\frac{M_\Psi^4}{M_{\mathrm{Pl}}^4} \times M_\Psi^2$
No fine tuning	$M_\Psi \lesssim 10^{14}$ GeV

III.B. SM-Charged Ψ

Ψ charged under $SU(2)_L \times U(1)_Y$ contribute to $\delta\mu^2$ at 2-loop level:

$$\delta\mu^2 = \left(\frac{g^2}{16\pi^2}\right)^2 \times F\left(\frac{M_{W,Z}^2}{M_\psi^2}\right) \times M_\Psi^2 \,. \tag{3}$$

(F dimensionless factor of order one).

- For $(g^2/16\pi^2) \lesssim \mathcal{O}(10^{-2})$, no fine tuning implies $M_\Psi \lesssim 10$ TeV.
- New EW-coupled fermions viable WIMP candidates for dark matter (exp. constraints implies $M_\Psi \sim 5$ TeV). "Minimal Dark Matter" models are natural.

III.C. Yukawa-Charged Ψ

Ψ couples to Higgs field through Yukawa interaction involving a SM fermion ψ: $\mathcal{L}_{\mathrm{SM}+\Psi} \supset y_{\mathrm{new}}(\psi H)\Psi$. Quantum corrections to μ^2 at 1-loop level:

$$\delta\mu^2 \sim C\,\frac{y_{\mathrm{new}}^2}{16\pi^2} \times M_\Psi^2\,, \tag{4}$$

where C is the color factor appropriate for Ψ and ψ.

Naturalness imposes $y_{\mathrm{new}} M_\Psi \lesssim 1$ TeV:
either M_Ψ is at the TeV scale, or
Ψ is weakly coupled to the Higgs boson.

An example

Type-I seesaw mechanism

$$\mathcal{L}_{\rm SM} + \bar{N}_i \bar{\sigma}^\mu \partial_\mu N^i - \frac{M_R^{ij}}{2} N_i N_j - y_{ij} L^i N^j H + h.c. \,, \qquad (5)$$

where i, j are family indices, M_R is the right-handed neutrino mass matrix and y is the neutrino Yukawa coupling matrix ($\psi = L_i$ and $\Psi = N_i$). At 1-loop we obtain

$$\delta\mu^2 = -\frac{1}{4\pi^2} \sum_{ij} |y_{ij}|^2 \times M_j^2 \,. \qquad (6)$$

Assuming degenerate heavy neutrinos with mass M,

$$M \lesssim 8 - 14 \times 10^3 \text{ TeV} \,. \qquad (7)$$

IV. Heavy boson

Theories containing one or more heavy bosons in addition to the SM degrees of freedom: heavy scalar (real or complex) Φ of mass M_Φ or massive gauge bosons consequence of spontaneous symmetry breaking. Under what circumstances are SM + Φ models natural?

A. $|H|^2|\Phi|^2$ Coupling

B. $|H|^2\Phi$ Coupling

IV.A. $|H|^2|\Phi|^2$ Coupling

Independently of Φ quantum numbers:

$$\mathcal{L}_{\mathrm{SM}+\Phi} \supset \lambda_{\mathrm{new}} |H|^2 |\Phi|^2 \,. \tag{8}$$

At 1-loop level, M_Φ contributes to Higgs boson mass squared,

$$\delta\mu^2 \sim \frac{\lambda_{\mathrm{new}}}{16\pi^2} \times M_\Phi^2 \,. \tag{9}$$

Naturalness dictates that either
interaction strength is very small or $M_\Phi \lesssim 1$ TeV.

Two examples

"Higgs portal" dark matter

SM is augmented to include one gauge-singlet scalar that couples to the SM via Eq.(8). Requirement that Φ is a thermal relic making up all of dark matter places bounds on combinations of λ_{new} and $M_\Phi \implies M_\Phi < 1$ TeV (natural!).

Grand unified gauge theory (GUT)

SM is the low-energy remnant of a GUT, spontaneously broken at $M_{\text{GUT}} \gg v$. Higgs doublet make up part of a GUT multiplet and μ^2 receives corrections from loops of the GUT bosons

$$\delta\mu^2 = \frac{C}{16\pi^2} \times M_{\text{GUT}}^2 \,. \tag{10}$$

C coefficient of $\mathcal{O}(g, g', g_S)$. Proton decay limits require $M_{\text{GUT}} \gtrsim 10^{16}$ GeV (GUT very fine tuned!).

Some comments on supersymmetry (SUSY)

- If the theory is supersymmetric at high energy scales (e.g. the GUT scale), there are additional contributions to μ^2 from the superpartners, whose couplings are guaranteed by SUSY to lead to $\delta\mu^2 = 0$.
- SUSY cannot be an exact symmetry of Nature, must be broken. If softly broken, it shields μ^2 from quadratic corrections.
- The existence of soft SUSY-breaking parameters induces finite quantum corrections to μ^2

$$\delta\mu^2 \sim \frac{\lambda^2}{16\pi^2} \times \tilde{m}^2 \,. \tag{11}$$

- If Nature was softly-broken suypersymmetric, $\tilde{m}^2$ must be around 1 TeV in order to avoid its own hierarchy problem.

IV.B. $|H|^2\Phi$ Coupling

A gauge-singlet scalar can also couple to a pair of Higgs via

$$\mathcal{L}_{\mathrm{SM}+\Phi} \supset \kappa_{\mathrm{new}} |H|^2 \Phi \,. \tag{12}$$

where κ_{new} is a coupling constant with mass dimensions. This new coupling induces for $M_\Phi \gg M_h$ a correction

$$\delta\mu^2 \sim -\frac{\kappa_{\mathrm{new}}^2}{16\pi^2} \times \log\left(\frac{M_\Phi^2}{M_h^2}\right) \,, \tag{13}$$

Theory will be finely tuned unless $\kappa_{\mathrm{new}} \lesssim \mathcal{O}(\mathrm{TeV})$.

The interaction effectively shields the Higgs mass from the heavy mass scale M_Φ, despite allowing for relatively large coupling between Higgs and Φ sectors.

V. Summary and conclusions

- Arguments based on top quarks assign physical meaning to the cutoff. If such assumptions are abandoned, top partner fields as harbingers of naturalness lose much of its motivation.
- Unambiguous and concrete measure of fine tuning based on the finite corrections induced by integrating out heavy particles.
- Main message: naturalness depends on the class of new particles and how they “talk” to the Higgs field.
- SM without new heavy particles is natural. Nature reveals that there is BSM physics: dark matter, nonzero neutrino masses, possible unification of gauge couplings, baryogenesis, strong CP problem, flavor puzzle, gravitation...

V. Summary and conclusions

- GUTs by themselves are extremely fine tuned.
- Gravity induces perturbative corrections proportional to μ^2, even if the new particle masses are relatively close to Planck scale.
- Type-I seesaw becomes unnatural unless $M_R \lesssim 1000$ TeV.
- Thermal dark matter is natural as long as dark matter mass is below tens of TeV.

Naturalness is a powerful motivating force behind the search of new TeV-scale degrees of freedom.

Additional bibliography

- F. Vissani, "Do experiments suggest a hierarchy problem?", Phys. Rev. D **57** (1998) 7027 [hep-ph/9709409].
- J. A. Casas, J. R. Espinosa and I. Hidalgo, "Implications for new physics from fine-tuning arguments. 1. Application to SUSY and seesaw cases", JHEP **0411** (2004) 057 [hep-ph/0410298].
- J. A. Casas, J. R. Espinosa and I. Hidalgo, "Expectations for LHC from naturalness: modified versus SM Higgs sector", Nucl. Phys. B **777** (2007) 226 [hep-ph/0607279].
- S. P. Martin, "A Supersymmetry primer", in *Kane, G.L. (ed.): Perspectives on supersymmetry II* 1-153 [hep-ph/9709356].