Field Manual of Fine-Tuning

Chapter Notes: Particle Physics

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Physics Covered
Particle Physics

Previous Chapter:
Unknown, possibly fine-structure constants

Following Chapter:
Unknown, likely nucleosynthesis

Types of Fine-Tuning:

X small, for fundamental constants X such that process still happens. Fine-tuning of coefficients to account for renormalisability.
A/B (dimensionless) too large/small, where A and B are ratio of quantities such as masses.

Directly explored Fine-Tuned Parameters:

- v_H: vacuum expectation value of the Higgs field
- m_H: mass of the Higgs boson
- m_q: mass of quarks
- m_l: mass of charged leptons
- m_ν: mass of neutrinos

Indirectly explored Fine-Tuned Parameters:

- $m_{Z^0,W^\pm}$: mass of electroweak gauge bosons
- m_g: mass of the gluon
- θ_W: Weinberg angle
- $\Delta m_{\nu,ij}$: mass hierarchy in neutrino sector
- g_w: electroweak coupling constant
- g_s: strong coupling constant
- α_e: electroweak fine structure constant
- α_s: strong fine structure constant
- $\Delta m_{p,n}$: mass difference between protons and neutrons
- $\Delta m_{u,d}$: mass difference between up and down quarks.

Assumed Background:

- quantum field theory

Outline of Chapter:

Introduction: The Standard Model

- There is no way to properly quantify fine-tunings in particle physics.
- Fine-tuning in particle physics is not related to initial conditions, but rather to values of parameters.
- "First principle" explanation for masses and couplings: why is there such a big scale gap between different particle masses.

Naturalness

- What is naturalness, why is it important and why we expect it?
- Isn't naturalness simply an "aesthetic" argument?
- Why do we adopt naturalness as a valid scientific driver? Historical examples.
- "If parameters do not seems natural, there is usually a reason", e.g. symmetry, new physics.
- Degeneracy of $c\Lambda^2$ $\rightarrow$ why expect $c \sim 1$ rather than a smaller Λ?
- Why expect naturalness of parameters instead of naturalness of a function of these parameters.

Hierarchy problem

- Higgs mass seems closer to electroweak than to Planck scale without an apparent reason.
- Consequences of $m_H - m_{Pl} \ll m_H - m_{EW}$?
- "Little hierarchy problem" and consequences for supersymmetry.

Strong-CP problem

- What is the strong-CP problem and what are possible solutions?
- Usually two approaches are adopted: either we introduce a new particle (in this case the axion), or we change our theory. People have been opting for the former for decades. At what stage does something become so unnatural/unusual that it is worth introducing some new particle to preserve your symmetry?
- Are there possible fine-tunings in the θ_{CP} angle? If θ_{CP} were much larger or much smaller it would affect matter-genesis (?).

Flavours

- Why is $m_t \sim E_{EW}$? Is it just a coincidence?
- Why are the masses of particles in different generations so different? Why don't these masses scale equally? $\rightarrow$ SM is an effective theory
- Why is our universe made of 1st generation particles?

Higgs

- Higgs vev (v_H) is ≈ 246 GeV. This is fixed by the potential. Why the potential has this shape?
- Is v_H more of a fixed parameter coming from the theory, or is it an initial condition "dialed" from a distribution like the cosmological constant in some models?

Standard Model - Problems

- The standard Standard Model does not predict neutrino masses.
- The SM is more of an effective theory than a fundamental one.
- There are 28 free parameters in the SM. How many of these are actual free parameters, and how many may be possibly related to others? (e.g.: m_t and m_c can be written in terms of m_u, and so there are two fewer free parameters).
- We would still have ~ 10 free parameters, unless we have unification.
- Terms of $\mathcal{O}(4)$ should be set to zero to guarantee renormalisability. Higher order terms would converge if coefficients are of order 1. No real physical motivation to expect coefficients to be $\mathcal{O}(1)$.

- If the SM is not just an effective theory, but part of a more fundamental physical theory, it should work for the case of curved space-times. But QFT doesn't work with curvature.

Others

- Do extra dimension models solve fine-tuning?
- Alleviating fine-tuning with extra dimension models: e.g.: technicolor, brane world, Randall-Sundrum

Fine-Tuning Issues

- Mass of top m_t may be totally different than what it is without affecting anything in the universe, provided that $m_t \gg m_u$ and $m_t \ll$ energy scale of symmetry breakings.
- Anthropic consequences for the mass of neutrinos and neutrino mass hierarchy: if, for the sake of argument, we had a universe made of 3rd generation particles instead of 1st, then an inverted mass hierarchy would imply that processes involving neutrino production would carry a smaller fraction of energy (rest mass) than the processes we have now. This might have consequences, for example, for supernovae (huge amounts of energy are emitted as νs).
- Consequences of changing the Higgs vev to another value.
- Even if we had $m_u = m_d$, it is not clear that $m_p = m_n$.
- Stability of atoms for $m_e \gg m_n - m_p$ and $m_e \ll m_n - m_p$.
- π^0 as p-n mediator: is there any fine-tuning?
- Possible relation between neutrino mass and supernovae.