New approaches to Naturalness

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Naturalness at a crisis point

All traditional solutions are “fine tuned” at this point

SUSY, Little Higgs, Composite Higgs, Twin Higgs …

Null experiments when expecting a discovery are the most “interesting”

Must rethink Naturalness

Naturalness

Unless the theory is fine tuned, there must be new physics (particles) at the scale

$$m_H^2 \sim g^2 \Lambda_{NP}^2$$

$$m_H^2 \sim y_t^2 \Lambda_{NP}^2$$

$$m_H^2 \sim \lambda \Lambda_{NP}^2$$

Naturalness

Much of what is said about Naturalness is wrong

$$m_H^2 \sim y_t^2 \Lambda_{NP}^2$$

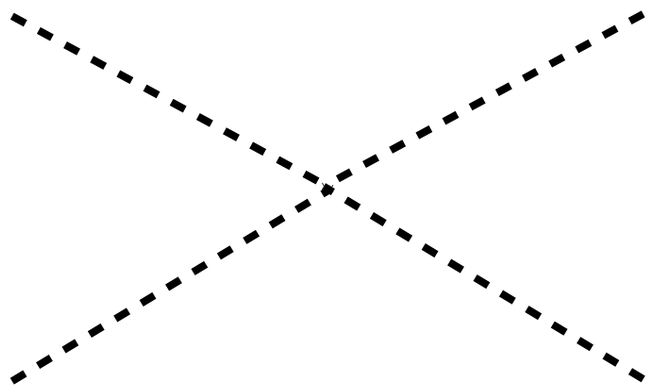
$$m_H^2 \sim \lambda \Lambda_{NP}^2$$

Parable of the confused physicist

$$V = \frac{1}{2} m^2 \phi^2$$

One day, a physicist happens across a good ol' fashioned scalar field theory

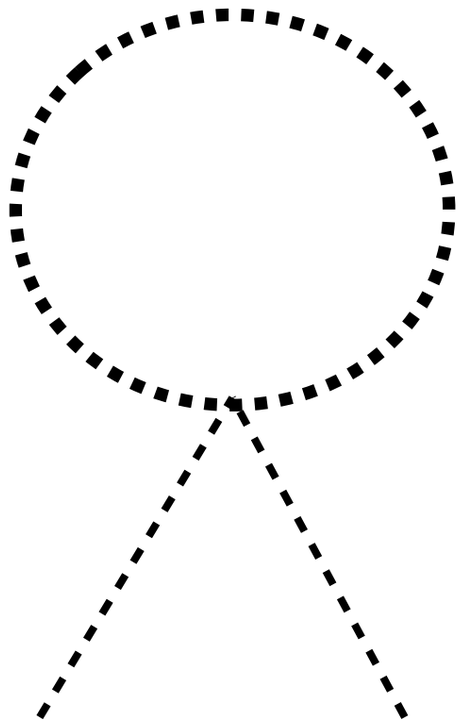
Parable of the confused physicist



$$\sigma(\phi\phi \to \phi\phi) \to \lambda^2$$

Upon finding the scalar, this physicist proceeds to smash them together

Parable of the confused physicist



$$m^2 \gtrsim \frac{\lambda \Lambda_{NP}^2}{16\pi^2}$$

After discovering the quartic interaction, they proceed to decide that there is a Hierarchy problem

Parable of the confused physicist

$$E \gtrsim 100\Lambda_{NP}$$

Motivated by this, they go to higher energies and look for new particles

Upon going to higher energies, they find nothing!

They conclude that the universe is fine-tuned as any SUSY/Little phi/Composite phi UV completion is fined tuned

Parable of the confused physicist

$$V = \frac{\phi^6}{\Lambda^2} \qquad \Lambda \gg \Lambda_{NP}$$

A little disappointed, the physicists decides to do precision phi physics

Hard work is rewarded with the discovery of a dimension six operator

Parable of the confused physicist

$$V = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4!}\phi^4 + \frac{1}{6!}\frac{\lambda^2\phi^6}{m^2} + \cdots \approx \epsilon^4 \cos\left(\frac{\phi}{F}\right)$$

Being a bit of a numerologist, the physicist finds a pattern

Scalar looks like it is periodic!

Parable of the confused physicist

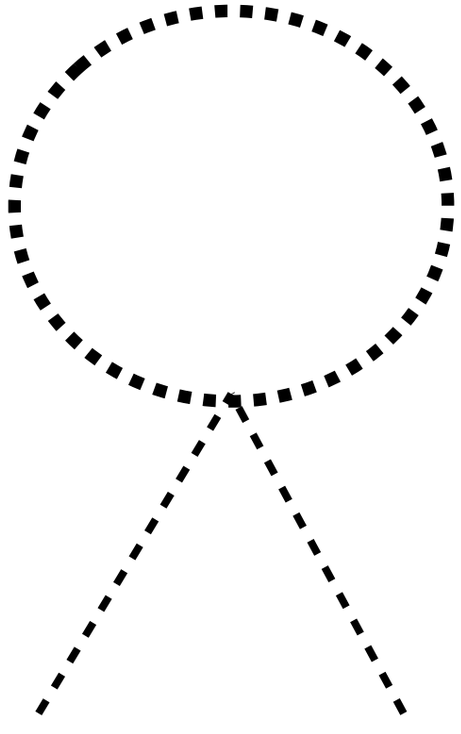
$$V = \epsilon^4 \cos\left(\frac{\phi}{F}\right)$$

Mass term is technically natural

As epsilon goes to zero, there is an enhanced symmetry

Parable of the confused physicist

There is no Hierarchy Problem!



Changes the mass term while leaving the quartic alone : Breaks the shift symmetry

Symmetry determines the mass entirely once the quartic is measured

Parable of the confused physicist

$$V = \epsilon^4 \cos\left(\frac{\phi}{F}\right) \qquad \Lambda_{NP} \sim F \gg \epsilon$$

Discovery of higher dimensional operator solved all questions modulo two

Are there new particles at epsilon?

Are there new particles at F?

Parable of the confused physicist

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Discovery of higher dimensional operator solved all questions modulo two

Are there new particles at epsilon?

Are there new particles at F?

No! An example from axion literature proves it

Parable of the confused physicist

$$\mathcal{L} = f^2|\Phi|^2 - |\Phi|^4 + \frac{\Phi^n}{M_{pl}^{n-4}}$$

n > 15 for quality reasons (Z_n symmetry)

Radial mode can be integrated out at a scale f

Pseudo-Goldstone boson matches onto our previous theory

Parable of the confused physicist

$$V = \frac{f^n}{M_{pl}^{n-4}} \cos\frac{n\phi}{f} = \epsilon^4 \cos\frac{\phi}{F}$$

$$\Lambda_{NP} \sim F = \frac{f}{n}$$

No new particles at epsilon!

No new particles at F!

Parametric separation of scales possible at large n

Parable of the confused physicist

$$V = \frac{f^n}{M_{pl}^{n-4}} \cos \frac{n\phi}{f} = \epsilon^4 \cos \frac{\phi}{F}$$

There is a UV completion that does not have new particles at the scale required by Naturalness!

UV completion is not fine-tuned

Parable of the confused physicist

$$V = \epsilon^4 \cos\left(\frac{\phi}{F}\right)$$

The confused physicist is confused no longer

There is no Hierarchy problem because the mass term is connected to the quartic coupling by an exact discrete shift symmetry

In order to sniff this symmetry out, they needed to do precision physics to find a higher dimensional operator

Moral

Symmetries that solve the Naturalness problem cannot always be seen at the renormalizable level

The way forward may not be the search for new particles but instead the search for new interactions

Naturalness as current phrased is incorrect when applied to self quartics

Naturalness?

Naturalness as current phrased is incorrect when applied to self quartics

Is Naturalness when applied to Yukawa couplings correct?

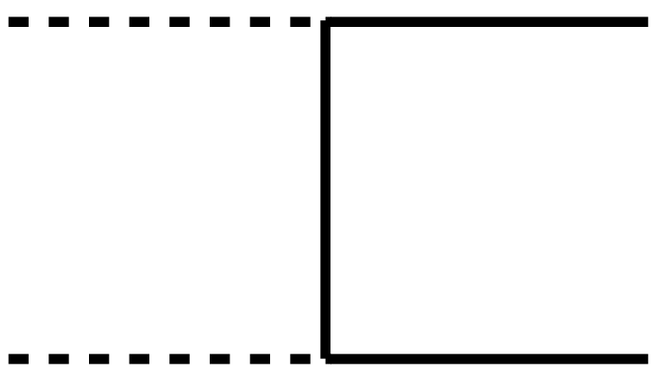
Is Naturalness when applied to gauge couplings correct?

Parable of the confused physicist (II)

$$V = \frac{1}{2} m^2 \phi^2$$

Consider another timeline for the confused physicist

Parable of the confused physicist (II)



$$\mathcal{L} \supset -\frac{1}{2}m^2\phi^2 + y\phi\psi\psi^c + M\psi\psi^c$$

Upon colliding the phi, they discover a fermion
Yukawa coupled to the scalar!

Fermion is barely detectable at the collider

Parable of the confused physicist (II)

$$\mathcal{L} \supset -\frac{1}{2}m^2\phi^2 + y\phi\psi\psi^c + M\psi\psi^c$$

As before, the confused physicist applies Naturalness

$$m^2 \gtrsim \frac{y^2}{16\pi^2}\Lambda_{NP}^2$$

Parable of the confused physicist (II)

$$\mathcal{L} \supset -\frac{1}{2}m^2\phi^2 + y\phi\psi\psi^c + M\psi\psi^c$$

Take some parameters to guide the eye

$$M \sim 10^6 m \qquad\qquad y \sim \frac{1}{2}$$

Parable of the confused physicist (II)

$$\mathcal{L} \supset -\frac{1}{2}m^2\phi^2 + y\phi\psi\psi^c + M\psi\psi^c$$

The physicist is immediately confused

$$M \gg \Lambda_{NP} \sim \frac{m}{y} \gg m$$

Naturalness predicts that new particles should already have been seen!

Parable of the confused physicist (II)

Even the finite contribution leaves the physicist confused

$$\Delta m^2 \sim y^2 M^2$$

Cancelation of the finite piece requires

$$\Delta m^2 \sim y^2 M^2 + y'^2 M'^2 \ll m^2$$

Parable of the confused physicist (II)

After some algebra

$$M' \lesssim M + \frac{m^2}{M}$$

With confidence the collider people say
that there is no particle that close in mass
to the newly discovered fermion

SUSY partner is not there

Parable of the confused physicist (II)

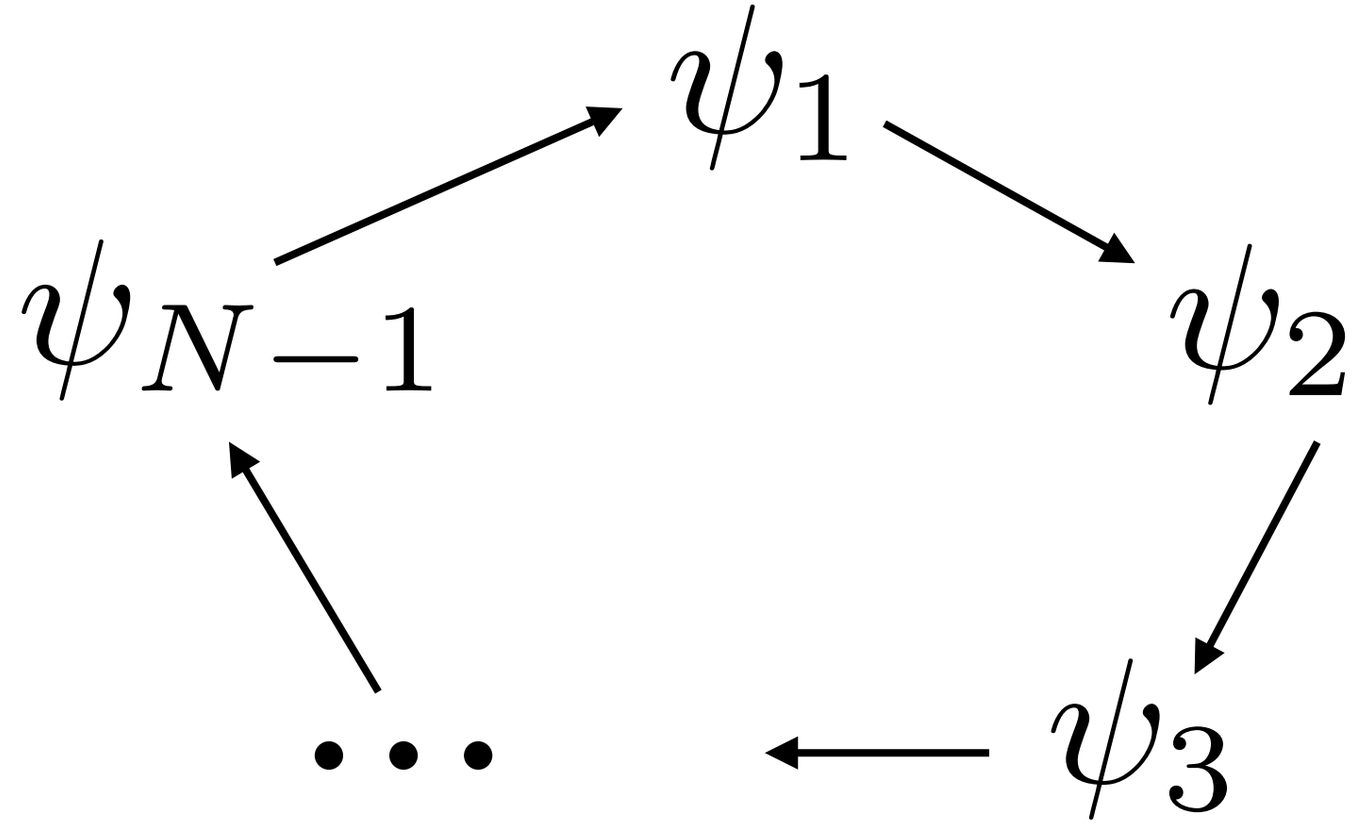
You know how this goes, lets just jump to the UV completion

Discovers N~10 fermions all with large O(1) Yukawa couplings with phi

UV completion

Z_N symmetry where N ~ 15

$$\Phi \to e^{i2\pi/N}\Phi$$



UV completion

$$\mathcal{L} = \sum_j \left(m_\psi + Re(y_r \Phi e^{i2\pi j/N}) + Im(y_i \Phi e^{i2\pi j/N}) \right) \psi_j \psi_j^c$$

Most general Lagrangian consistent with symmetry

Easier to look at after integrating out the radial mode

UV completion

$$\mathcal{L} = \sum_j \left(m_\psi + \epsilon \sin\left(\frac{\phi}{f} + \frac{2\pi j}{N} \right) \right) \psi_j \psi_j^c$$

$$\epsilon \sim \frac{m_\psi}{5}$$

This particular UV completion has a special property that result in the generated mass for phi to be exponentially small

UV completion

Due to Z_N symmetry, potential for phi must be of the form

$$V(\phi) = \sum_k d_k \Phi^{kN} = \sum_k c_k e^{iNk\phi/f}$$

Spurion from which to build the potential is

$$\epsilon\, e^{i\frac{\phi}{f}+\theta}$$

Clearly need N insertions to generate a mass term

UV completion

Can see this explicitly by calculating the 1-loop potential

$$V_{1-\mathrm{loop}} \propto m_\psi^4 (\frac{\epsilon}{m_\psi})^N \cos(\frac{N\phi}{f} + \theta)$$

Exponentially suppressed (10^{-6}) mass

Yukawa couplings are O(0.1) if $f \sim m_\psi$

Moral

A weaker but still explicit counter example to Naturalness applied to Yukawa couplings

A collection of particles particles only 10% similar canceling to a precision of 10^{-12}

A field theoretic conspiracy

Conjecture

Higher dimensional operators play a critical role in evading the current notion of Naturalness

What if the reason why we haven't seen any new particles are the TeV or meV scale is because the symmetry that solves the problem is higher dimensional in nature?

Conjecture

Higher dimensional operators solve Naturalness

We shouldn’t be looking for new particles, we should be looking for new interactions

Higgs

We should be looking for higher dimensional operators involving the Higgs and/or the top quark

The scale suppressing these interactions could be much larger than the TeV scale

C.C.

We should be looking for higher dimensional operators involving the the stress energy tensor and Riemann invariants

Amusingly some of the best bounds come from the LHC!

LHC is probing solutions to the cosmological constant problem?

Conclusion

Naturalness as typically stated is incorrect

Two explicit counter examples for Yukawa and quartic interactions

Maybe there exists a higher dimensional operator solution to the two major Hierarchy problems?