Naturalness Successes

and the connection to the Higgs Sector

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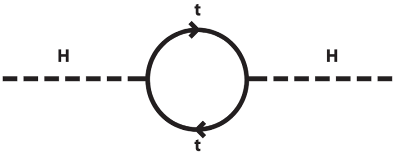
Naturalness as a guiding principle for model building

The Higgs sector in the Standard Model

$$m_H^2 = m_0^2 + \delta m_H^2 \qquad \delta m_H^2 \propto \Lambda^2$$

Higgs physical mass (CMS & ATLAS, 2015)

$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \ \text{GeV}$$



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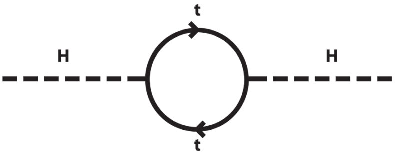
Operational definition of naturalness

No fine-tuning between m_0 and δm_H^2 $\rightarrow$ **New physics $\sim$1 TeV**



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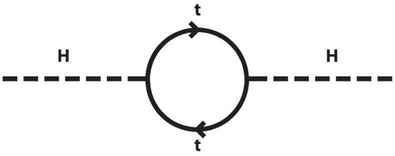

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Naturalness in literature

Recent literature on naturalness

- Naturalness after LHC8 (Giudice, 2013)
- Naturalness Under Stress (Dine, 2015)
- Which fine-tuning arguments are fine? (Grinbaum, 2012)
- Narratives of “Naturalness” in Today’s Particle Physics Community (Borrelli, 2015)
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But. . .

- How is the use of naturalness *justified* in physics literature?
- Are there any differences in the situations in which the naturalness principle is applied?

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“It should be clear that the naturalness has been voted in on the basis of a record of solid achievements” (Nelson, 1985).

Naturalness achievements

Reconstructions

- Positron.
- Charged Pion mass difference.

Successes

- Charm quark proposal.
- Charm quark mass prediction.

Outline

Historical sketch: the 1970s

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- The quark model had been playing around for almost a decade, though the quarks were mainly treated as mathematical entities.

"It is fun to speculate about the way quarks would behave if they were physical particles of finite mass (instead of purely mathematical entities. . .)" (Gell-Mann,1964)

Historical sketch: the 1970s

- The quark model had been playing around for almost a decade, though the quarks were mainly treated as mathematical entities.
- The best model of weak interactions was a non-renormalizable model, the V-A theory.

$$\mathcal{L}_I = gW_\lambda J^\lambda + h.c.$$

$$J^\lambda = \bar{l}\gamma^\lambda(1-\gamma_5)\mathcal{C}_L l + \bar{q}\gamma^\lambda(1-\gamma_5)\mathcal{C}_H q$$

Historical sketch: the 1970s

- The quark model had been playing around for almost a decade, though the quarks were mainly treated as mathematical entities.
- The best model of weak interactions was a non-renormalizable model, the V-A theory.
- Naturalness was not properly defined until the late 1970s/early 1980s.

Dynamics of Spontaneous Symmetry Breaking in the Weinberg- Salam Theory (Susskind, 1979)

Naturalness, Chiral Symmetry, and Spontaneous Chiral Symmetry Breaking ('t Hooft, 1980)

The Infrared Ultraviolet Connection (Veltman, 1981)

Problems with the V-A model

- Flavour Changing Neutral Currents (FCNC)

$$\boxed{K^+ \rightarrow \pi^+ + \bar{l} + l}$$

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$$\boxed{K_L - K_S \text{ mass difference}}$$

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V-A cutoff

- It was expected that strong contributions would soften the allowed processes.
- This was shown to be not possible (Ioffe & Shabalin, 1968).
  $\boxed{\Lambda \sim 2 \text{ GeV}}$

The naturalness rationale

Take the neutral Kaon mass difference computed in the V-A model (1-loop)(Giudice 2008, Pierce 2008, Baumann and MacAllister 2014, Craig 2017):

$$\frac{m_{K_L^0} - m_{K_S^0}}{m_{K_L^0}} = \frac{G_F^2 f_K^2}{6\pi^2} \sin\theta_c \Lambda^2$$

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We do not know up to what energy the V-A model is valid. There are two options:

- The theory is valid up to energies higher than $\Lambda > 2$ GeV, thus another contributions must produce **delicate cancellations** into the kaon mass difference.
- **New physics appear** before fine-tuning is necessary. Charm quark mass ~ 1.5 GeV.

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Main questions

- Was this argument used for the charm quark proposal and its mass computation?
- Does this example have any conceptual difference with respect to the Higgs naturalness problem?

The GIM mechanism

Weak Interactions with Lepton-Hadron Symmetry, 1970

Aim *Solve* the selection rules violation that the V-A theory predicts.

"Serious difficulties occur only when [the V-A model] is considered as a quantum field theory, and is examined in other than lowest-order perturbation theory [...]. **Our principal concern is the fact that these properties [selection rules] are not necessarily maintained by higher-order weak interactions**".

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Aim: *Solve* the selection rules violation that the V-A theory predicts.

Proposal: *Introduction* of a fourth quark c: each process with an internal u line diagram adds another one with an internal c diagram that cancels in the limit $m_c = m_u$.

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Consequences: Explains why the FCNC and $|\Delta S| = 2$ are suppressed. Smooths the path towards a renormalizable theory.

Charm quark mass, 1970-1974

1972 Weinberg Renormalizable electroweak model including semileptonic processes with u and d quarks.

July 1973 Vainshtein and Khriplovich *"[t]he need for introducing supercharged hadrons is connected with the requirement that there be no weak neutral currents with $|\Delta S| = 1$".*

June 1974 Ma Similar considerations.

August 1974 Gaillard and Lee *"Empirically, the strength of second-order processes involving a change of strangeness is characterized by $G_F\Lambda^2$ [...], where Λ is typically of the order of several GeV, as for the $K_L - K_S$ mass difference and the decay $K_L \to \mu\bar{\mu}$. A mechanism is thus required to suppress the contribution of order $[G_F\Lambda^2]$".*

Charm quark mass determination, 1970-1974

November 1967	Renormalizable electroweak model for leptons.	
April 1968	Ioffe and Shabalin computation.	$\Lambda_W \sim 5$ GeV
May 1968	Mohapatra *et al.* computation.	$\Lambda_W \sim 3-4$ GeV
October 1970	Glashow-Iliopoulous-Maiani paper — charm quark proposal.	
March 1972	Renormalizable electroweak model including semileptonic processes with *up* and *down* quarks.	
July 1973	Vainshtein and Khriplovich computation.	$m_c \leq 9$ GeV
June 1974	Ma computation.	$m_c \sim 5$ GeV
August 1974	Gaillard and Lee computation.	$m_c \sim 1.5$ GeV
November 1974	November Revolution — discovery of the charmed mesons.	
February 1983	Discovery of $W^{\pm}$ bosons.	

The Higgs naturalness problem

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- The expressions are conceptually different.
- The role of Λ: differences between renormalizable and non-renormalizable theories.

Conclusions

Naturalness role in the 1970s

- The naturalness principle was not used to propose a fourth quark.
- The naturalness principle did not have a *relevant role* at the time of determining the charm quark mass.
- There is not a *crucial* difference between the charm quark example and other reconstructions (electron mass, pion mass difference. . .) as claimed in the last two decades physics literature.

The Higgs naturalness problem

- The Higgs naturalness problem has conceptual differences with respect to the charm quark and the other reconstructions.
- *Historical highlight* The naturalness principle *started* to be used in the literature with respect to the question of a possible fundamental scalar particle.