The Utility of Naturalness

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HISTORICAL SLIDE – 2 YEARS OLD

Should we believe in the Higgs boson?

The Higgs boson is a speculative particle explanation for elementary particle masses.

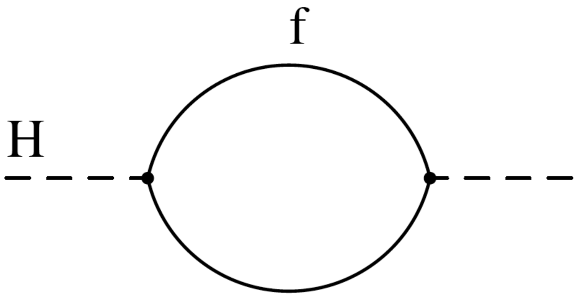
Cons:

1. One particle carries all burdens of mass generation?
2. Fundamental scalar not known in nature.
3. Hasn't been found yet.
4. Too simplistic -- dynamics for vev not built in.
5. Idea not stable to quantum corrections.

Pros: Still consistent with experimental facts!

Higgs boson unstable to QM

A quantum loop is quadratically divergent. Higgs mass, connected to Higgs vev, is unstable to the highest mass scales in the theory.



$$m_H^2 \sim \frac{\alpha_f}{4\pi}\Lambda^2 \quad \Rightarrow \quad \Lambda^2 \sim M_{Pl}^2\ ?$$

Confusing: M_{Pl} is 10^{18} times more massive than Higgs boson.

Cures of the Naturalness Problem, and the Resulting Higgs boson Entourage

1. Disallow all scalars in the theory (Technicolor).
2. Symmetry cancels quadratic divergences (supersymmetry)
3. Disallow higher mass scales (extra dimensions).

Implication: "New Physics" needs to be found at LHC.

Statics and Dynamics of Higgs Mass

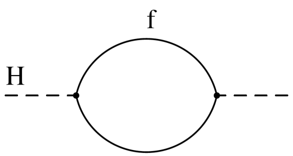
Principle: SUSY, Xdim,
Little Higgs, Compositeness, etc.

$$H^\dagger(m_{EW}^2 + \text{stabilizers} + \cdots)H + \Delta\mathcal{L}[\text{stabilizer dynamics}] + \cdots$$

Top squarks, radion,
T-odd top partners, etc.

Gluinos, KK Gravitons, etc.

SUSY:



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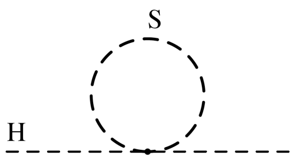


$$m_H^2 \sim \frac{\alpha_f}{4\pi}\Lambda^2 - \frac{\alpha_f}{4\pi}\Lambda^2 \sim 0 + \cdots$$

OLD SLIDE – 2 YEARS OLD

New Physics Ideas and Higgs boson viability

Trying to fix and understand Higgs physics leads to new ideas that have states that look very similar to the Standard Model Higgs boson.

Precision Electroweak Data almost demands this to be true.

What does the future hold for the Higgs boson?

DISCOVERY!!

Physicists Find Elusive Particle Seen as Key to Universe

Pool photo by Denis Balibouse

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

By DENNIS OVERBYE

Published: July 4, 2012 | 122 Comments

mass = 126 GeV

New York Times

What does "almost 'The' Standard Model Higgs boson" mean?

The boson has the same, measured mass of 126 GeV.

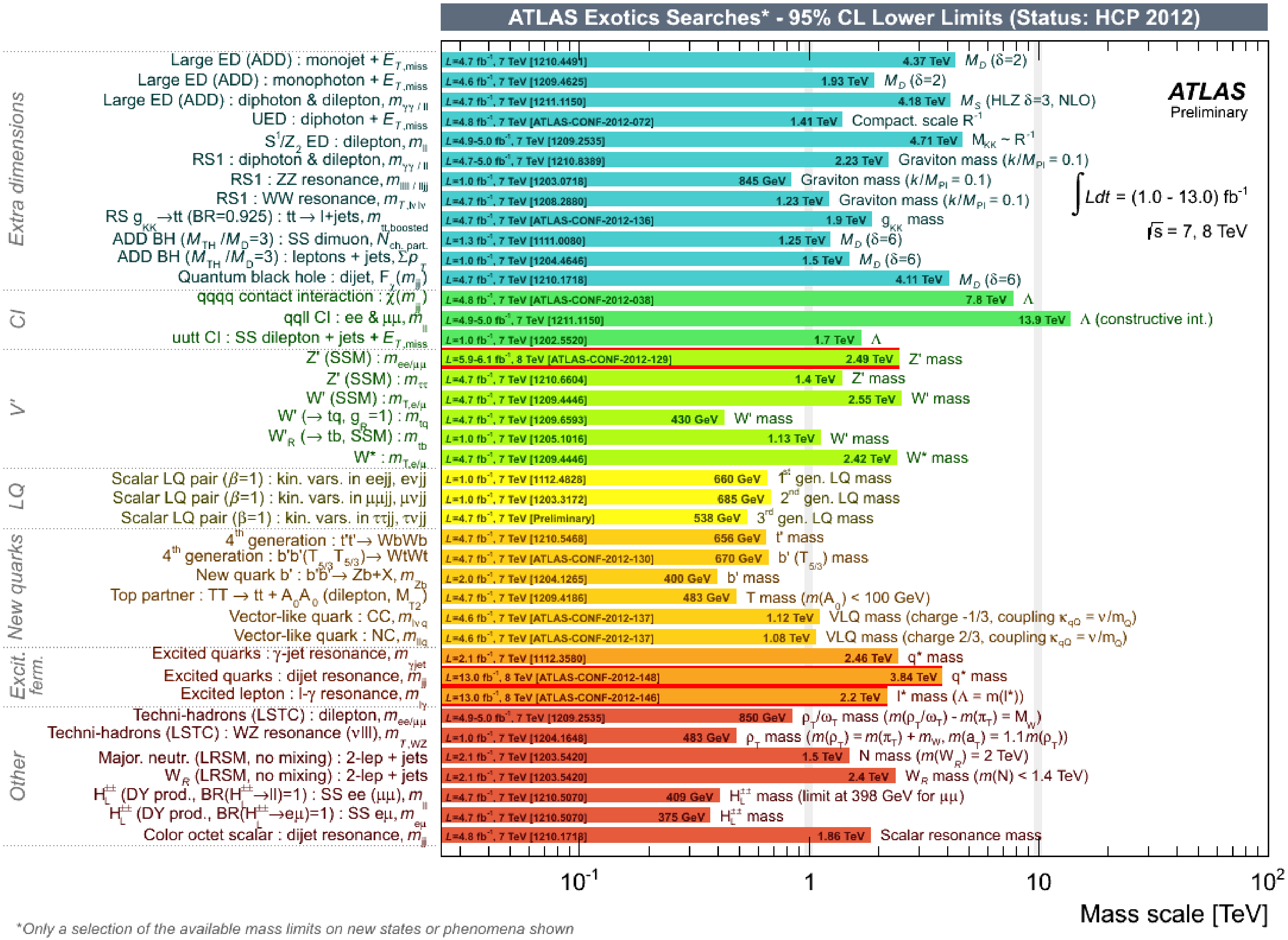
However, its production rates are slightly different, and its probabilities of decaying into various other particles are slightly different.

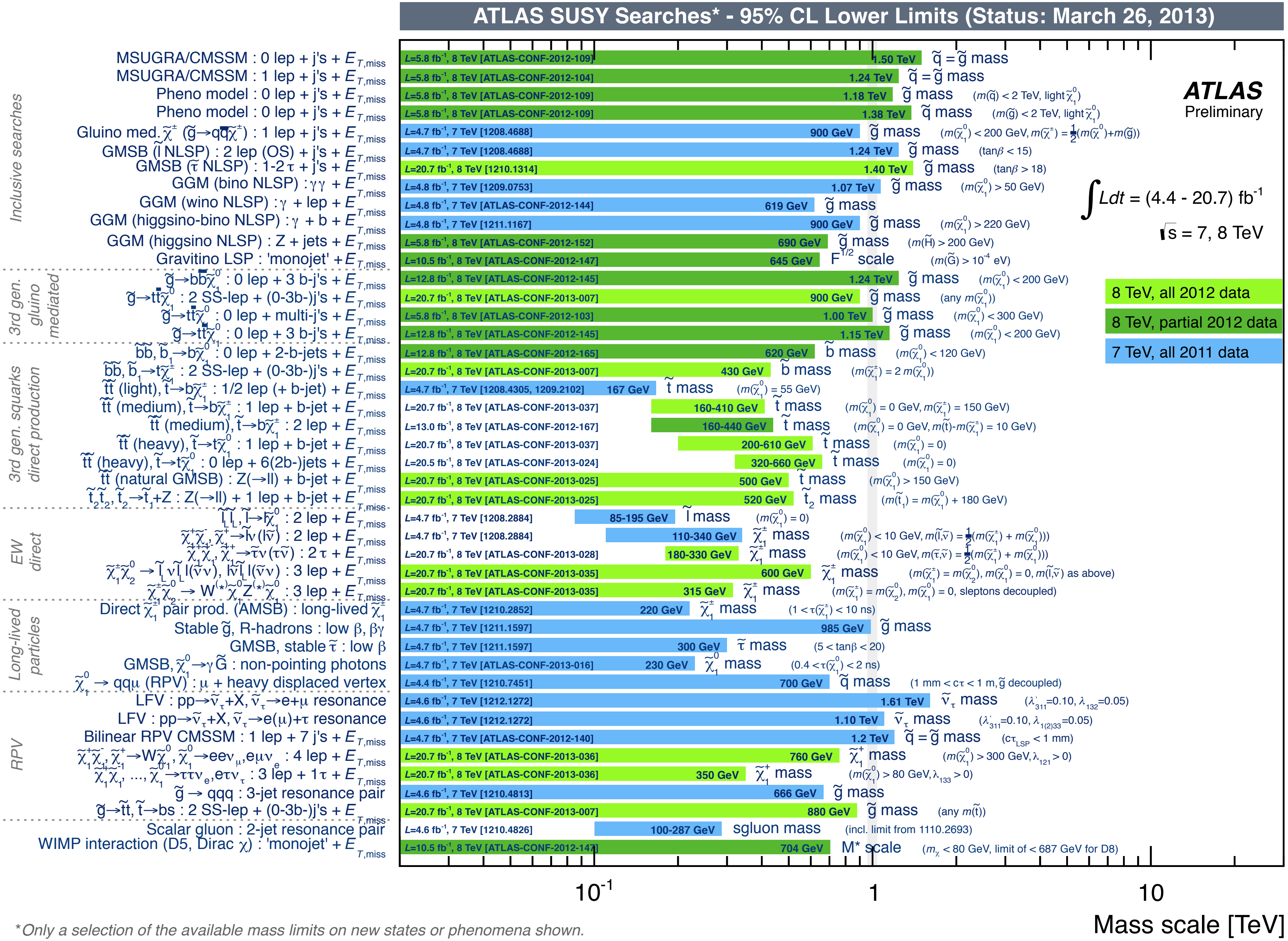
$$\begin{aligned} Br(H \to bb)_{SM} &= 60\% \\ Br(H \to WW)_{SM} &= 20\% \\ Br(H \to \tau\tau)_{SM} &= 6\% \\ Br(H \to \gamma\gamma)_{SM} &= 0.2\% \\ &\vdots \end{aligned}$$

$$\begin{aligned} Br(H \to bb) &= Br(H \to bb)_{SM}\,(1+\epsilon_b) \\ Br(H \to WW) &= Br(H \to WW)_{SM}\,(1+\epsilon_W) \\ Br(H \to \tau\tau) &= Br(H \to \tau\tau)_{SM}\,(1+\epsilon_\tau) \\ Br(H \to \gamma\gamma) &= Br(H \to \gamma\gamma)_{SM}\,(1+\epsilon_\gamma) \end{aligned}$$

The deviations from these Br's may be only a few percent or less. Will take many years to be sensitive to that, and perhaps even requires another collider (e+e-).

But nothing else has been found….





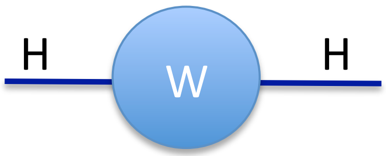
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Losing the Naturalness Religion

Starting to hear many more comments like:

"Quadratic divergence Naturalness problem is just philosophical – not really a data-driven concern."

"Dimensional regularization has no quadratic divergence Naturalness problem, so maybe it doesn't exist"

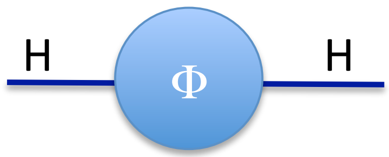


$$\rightarrow \quad m_W^2 \left(\frac{1}{4-n} - \gamma_E + \ln 4\pi + 1 - \ln \frac{m_W^2}{\mu^2} \right) + \cdots$$

(Note, there is no Λ^2 cutoff funny business – only 1/(4-n))

Sensitivity to higher physical scales persists

However, all it takes is for any massive particle to interact with the Higgs and there is a real physical quantum correction to contend with.



$$\Delta m_H^2 \propto \lambda_\Phi \, m_\Phi^2 \ln m_\Phi$$

It is inconceivable to me that there is nothing else between "here" (10^2 GeV) and the Planck scale (10^{18} GeV). And if there is another scalar (even if exotically charged!) there is no simple symmetry to forbid it from coupling to the Higgs boson.

Nevertheless, the discovery of the Higgs without yet discovering supporting entourage (susy, Xdim, composite states, etc.) is disheartening to many.

Anguished query from the youngsters:
Should I still take this "philosophical concept" of Naturalness seriously as a guiding principle?

Connection to "technical naturalness"

Or sometimes called 't Hooft Naturalness:

A parameter can be small in a theory if an enhanced symmetry arises by setting it to zero.

We sometimes do not worry too much about Naturalness (or Absolute Naturalness, one might call it) if a quantity is technically natural.

Example, given our current understanding, there is no serious sleep loss or urgent predictions for LHC just because the electron mass is 10^6 times smaller than the top mass. Chiral symmetry protects it.

People try to make Higgs Naturalness problem into a technical naturalness problem by noting that if mass goes to zero then a conformal symmetry may be relevant.

However, the conformal symmetry must be broken, and new physics generally needs to be nearby to solve the problem.

General point: small parameters explained by technical naturalness still need explanation (e.g., for electron Froggatt-Nielsen, flavon fields, etc.).

Hypothesis: A large hierarchy in QFT calls out to be explained by further dynamics or an additional principle.
Either way: "new physics".

Showing that Naturalness Principle is Effective

It is very recent that Naturalness in QFT has gained its apotheosis. *Absolute Naturalness* one might call it.

It was explicitly articulated in the context of the central question of electroweak symmetry breaking and the Higgs boson. Naturalness has been the oxygen of "Beyond the Standard Model Physics".

We can show the concept's effectiveness (if it is) by waiting for new dynamics to arise at LHC that stabilizes the Higgs boson to these Naturalness-voiding quadratic divergences.

QED Application

JDW, arXiv:1305.3434

In the meantime, we can test the principle of Naturalness as a guide by applying it to the past.

Example: The early days of Quantum Electrodynamics.

Specifically, why is the electron so light??

(I wonder: Why didn't "they" ask that question more earnestly?)

Quantum Electrodynamics

$$\mathcal{L} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^{\mu}(\partial_{\mu} - ieA_{\mu})\psi + m_e\bar{\psi}\psi$$

A,F contain the photon and ψ is the electron (m_e=5x10^{-4} GeV).

Extraordinary theory:

1. Relativistic invariant
2. Dirac equation built in
3. Massless photon – electromagnetic radiation
4. Electromagnetic gauge invariance
5. Renormalizable! (infinities easily handled)
6. Fits the low-energy data very well

Subsequent theories had to live up to QED (e.g., renormalizability of the massive weak interactions, etc.)

The electron mass

Hard to imagine QED being criticized from the perspective of the 1940s. But what if they took naturalness seriously?

Naturalist: Why is the electron mass so small?

Skeptic: Small compared to what?

Naturalist: Newton's gravity scale $(G_N)^{-1/2}=10^{18}$ GeV

Skeptic: What's gravity got to do with a little particle's mass?

Naturalist: G_N is a dimensionful scale parameter in the action of natural law just like the electron mass is. How can we have such a large hierarchy between dimensionful numbers?

Skeptic: Nobody understands gravity. It’s not renormalizable. It’s too remote. We don’t understand it.

Naturalist: Precisely! We don’t understand it, so let’s try.

Skeptic: Maybe Dirac was right with his Large Number Hypothesis. The universe spots us one very large number and we just have to live with it. I’m willing to live with that, especially if it involves mysterious and remote gravity!

Naturalist: Ok. I'll give you that for now. Who am I to argue with Dirac. But what about the electron to proton mass ratio m_p/m_e = 10^3.

Skeptic: 10^3 is no big deal. That can just be an accident. People do get struck by lightening you know, and that's much less rare.

Naturalist: Ok, then what about Fermi's new theory of β decay. His constant is orders of magnitude larger yet than the proton!

Skeptic: Hmm. (Stalling) Remind me about Fermi's Theory….

E. Fermi, Zeitschrift für Physik, 88 (1934) 161.

Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

Sehen wir zunächst von den Relativitätskorrektionen und der Spinwirkung ab, so ist wohl die einfachste mögliche Wahl von (9) die folgende:

$$H = g\left\{Q\,\psi(x)\,\varphi(x) + Q^*\,\psi^*(x)\,\varphi^*(x)\right\}, \tag{10}$$

wo g eine Konstante mit den Dimensionen $L^5 M T^{-2}$ darstellt; x reprä-

Theory innovation

Aus den Daten der Tabelle 2 kann man eine, wenn auch sehr grobe, Abschätzung der Konstante g gewinnen. Nimmt man etwa an, daß in den Fällen wo (50) gleich Eins wird, man $\tau F(\eta_0) = 1$ hat (d. h., in Sekunden, $= 3600$), so bekommt man aus (45):

$$g = 4 \cdot 10^{-50}\,\mathrm{cm}^3 \cdot \mathrm{erg}.$$

Dieser Wert gibt natürlich nur die Größenordnung von g.

Experimental savvy

Fermi's Constant in the day…

$g = 4 \times 10^{-50}$ cm^3 erg = 3.25×10^{-6} GeV^{-2}

This translates into scale $M_F = g^{-1/2}$ = 555 GeV.

$M_F/m_e = 10^6$ Now that's starting to be concerning!

Today, we quote Fermi's constant as

$G_F = 1.166 \times 10^{-5}$ GeV^{-2} where the normalization is set by

$$\frac{G_F}{\sqrt{2}}\left[\bar{u}\gamma^{\mu}\frac{(1-\gamma_5)}{2}d\right]\left[\bar{e}\gamma_{\mu}\frac{(1-\gamma_5)}{2}\nu\right]$$

Agreed: small m_e not Natural

Now what do we do?

We cogitate… We wait… We ponder…

And then a Realistic Intellectual Leap (RIL) happens.

RIL #1: m_e is closer zero than it is to M_F.

Skeptic: What does that do for us?

Answer: Let's try to start with a theory that forbids electron mass and see if we have an idea to let in a little bit of mass later.

Forbidding the electron mass

It's obvious that the problem is that ψψ is gauge invariant.
How can we make it non-gauge invariant.

We cogitate… We wait… We ponder…

RIL #2: The representation structure of the Lorentz group allows us to write QED in two component spinors:

$$\mathcal{L} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\psi_L^\dagger\gamma^\mu(\partial_\mu - ieA_\mu)\psi_L + \psi_R^\dagger\gamma^\mu(\partial_\mu - ieA_\mu)\psi_R + m_e(\psi_L^\dagger\psi_R + \psi_R^\dagger\psi_L)$$

Laporte & Uhlenbeck (1931):

$$\begin{aligned} mc\chi_\ell - \left(\frac{h}{i}\partial^{\dot\sigma}{}_\ell + \phi^{\dot\sigma}{}_\ell\right)\psi_{\dot\sigma} &= 0 \\ mc\psi_{\dot m} + \left(\frac{h}{i}\partial_{\dot m}{}^{\lambda} + \phi_{\dot m}{}^{\lambda}\right)\chi_\lambda &= 0 \end{aligned}$$

Staring at this we see a qualitative difference between the mass term and the photon interaction term. Mass requires both right and left components, whereas photon int. does not.

→ **RIL #3**: *The electron mass can be forbidden by assigning* ψ_L *different properties than* ψ_R*, thereby disallowing* $\psi_L^\dagger\psi_R + \psi_R^\dagger\psi_L$ *as an invariant of the theory.*

This is the introduction of chirality into the theory.

$$\mathcal{L} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\psi_L^\dagger\gamma^\mu(\partial_\mu - ieA_\mu)\psi_L$$
$$+\psi_R^\dagger\gamma^\mu(\partial_\mu - ieA_\mu)\psi_R + m_e(\psi_L^\dagger\psi_R + \psi_R^\dagger\psi_L)$$

ψ_L differently than ψ_R. The electric charge for both we must keep at -1, but we must assign different charges for each under the new symmetry G. A simple concrete start to this would be to let G be some new abelian group $U(1)'$ and assign ψ_R double the charge of ψ_L. In other words, our spectrum is

$$\text{Under } U(1)_{EM} \times U(1)' :$$
$$\psi_L = (-1,-1), \quad \psi_R = (-1,-2)$$

With these charge assignments the $\bar{\psi}\psi$ term is no longer allowed.

The next step is to regain the electron mass through some other means.

After time I think it is inevitable that people would think of

RIL #4: *The electron mass can be reintroduced by adding a condensing scalar field* Φ *with charges* $(0,1)$ *under* $U(1)_{EM} \times U(1)'$ *that allows the interaction* $y_e \psi_L^\dagger \Phi \psi_R + h.c.$, *which leads to the electron mass* $m_e = y_e \langle \Phi \rangle$.

This is basically the start of the Higgs discussion, but certainly by 1950 with Ginzburg-Landau theory it was in the air to have a complex scalar function order parameter interact with QED!

RIL #4 might look to be the least plausible RIL to some, but I think it is might be the most plausible.

Building on Landau's theory of phase transitions (1937), Ginzburg-Landau theory of superconductivity (1950) looks like the Higgs boson.

power series functional expansion of Ψ was presented that looks very similar to the Higgs potential of today, and its minimization enables $|\Psi|^2$ to obtain a non-zero value (vacuum expectation value) below a critical temperature. Furthermore, Ψ was recognized to have a phase symmetry, equivalent to transformations under $U(1)_{EM}$, and the energy density of the system contained the term

$$\frac{1}{2m}\left|-i\hbar\,\mathrm{grad}\,\Psi - \frac{e}{c}\mathbf{A}\Psi\right|^2 \tag{10}$$

where it was noted that gauge invariance required replacing $i\hbar\,\mathrm{grad}$ to $i\hbar\,\mathrm{grad} - (e/c)\mathbf{A}$, which is what we today call the covariant derivative.

At this point it's all chug and crank. RIL#5 below would be obvious, and hardly an "intellectual leap" given RIL#1-#4:

RIL #5: *To avoid massless states in conflict with experiment, the new symmetry $U(1)'$ should be a local gauge symmetry analogous to $U(1)_{EM}$. When $U(1)'$ is broken by $\langle\Phi\rangle$ the new photon gets a mass, $m_{A'}^2 = \frac{1}{2}g'^2\langle\Phi\rangle^2$ and there remains a physical propagating scalar boson with mass $m_\varphi^2 = 2\lambda\langle\Phi\rangle^2$.*

This is the most obvious RIL, and easiest to achieve, but its consequences are huge. We started with a non-empirical philosophical criterion (Naturalness) and are led to our first "real" physics prediction.

RIL #6: Researchers trying to renormalize this theory would discover that U(1)' has chiral anomalies, and would be forced to add cancelling exotics.

Now, as it stands our theory is sick, because there are anomalies. The $U(1)'$-graviton-graviton and $U(1)'^3$ anomaly cancelation conditions are not met among the fermions. This necessitates additional fermions in the spectrum that are charged under $U(1)'$. There are many possibilities that could be written down. In an exhaustive table among these possibilities would be the following exotic fermions:

$$\text{Exotics}: \; 6Q'_{1/3} + 3Q'_{4/3} + 3Q'_{-2/3} + 1Q'_{-1}$$

where nQ'_q means n copies of fermions with charge q. These add to our original fermions $1Q'_{-1} + 1Q'_{-2}$. These

$$\text{Exotics}: \ 6Q'_{1/3} + 3Q'_{4/3} + 3Q'_{-2/3} + 1Q'_{-1}$$

where nQ'_q means n copies of fermions with charge q. They add to our original fermions $1Q'_{-1} + 1Q'_{-2}$. These charge assignments and multiplicities are exactly those of the Standard Model fermions under twice hypercharge

Field	$SU(3)$	$SU(2)_L$	T^3	$\frac{Y}{2}$	$Q = T^3 + \frac{Y}{2}$
g^a_μ (gluons)	**8**	**1**	0	0	0
$(W^\pm_\mu, W^0_\mu)$	**1**	**3**	$(\pm1, 0)$	0	$(\pm1, 0)$
B^0_μ	**1**	**1**	0	0	0
$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	**3**	**2**	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$\frac{1}{6}$	$\begin{pmatrix} \frac{2}{3} \\ -\frac{1}{3} \end{pmatrix}$
u_R	**3**	**1**	0	$\frac{2}{3}$	$\frac{2}{3}$
d_R	**3**	**1**	0	$-\frac{1}{3}$	$-\frac{1}{3}$
$E_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	**1**	**2**	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$-\frac{1}{2}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
e_R	**1**	**1**	0	-1	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	**1**	**2**	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$\frac{1}{2}$	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$
$\Phi^c = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix}$	**1**	**2**	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$-\frac{1}{2}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$

But Naturalness is not yet solved!

A more worrisome objection is that we have replaced one problem with Absolute Naturalness (the electron mass) for another Naturalness problem, and so have not achieved our objective. If the Φ mass is $-\mu^2 \sim m_F^2$ (natural) then $y_e \sim 10^{-6}$ (unnatural), or phrased differently, if $-\mu^2 \sim m_e^2$ (natural) then $-\mu^2/M_F^2 \sim 10^{-6}$ (unnatural). Either way there is a problem with respect to Absolute Naturalness. Thus, all we have done is recast the Naturalness problem rather than solved it.

Responses:
(1) Working to solve Naturalness (not necessarily solving it) fruitful.
(2) Theory space of where to go next is infinite. Naturalness provides discrete path(s) and gateway(s) through which to investigate.
(3) We are not done in our Naturalness quest: this is the next door.

Conclusion 1/2

Thus, it is plausible that if Naturalness were religiously held to by researchers in the 1940's/50's, we would have been led to

1. Exotic gauge symmetry and exotic massive gauge boson
2. Higgs boson and Higgs mechanism
3. Exotic charged fermion scenarios, including identifying full SM content as one viable prediction

These are correct and extraordinarily fruitful results from merely taking Naturalness seriously.

But it would nevertheless take many decades to experimentally find all these implications.

(Depressed unimaginative skeptics would gloat during that time.)

Conclusion 2/2

Same situation today? Naturalness for Higgs leads to many exotic implications.

Analogies: Supersymmetry & Extra Dimensions & Etc

1. Solves Naturalness problem
2. Exotics are required for self-consistency
3. Criticism that exchanges one problem (quadratic instability) for another problem (SUSY: μ term problem; Xdim: size of compact dimensions)
4. No theorem for how long it will take to discover it (could be decades, and decades more)

Historical considerations suggest taking Naturalness seriously has value. Present circumstances may not warrant its abandonment.