

Now What?

Aspen 2013 - Higgs Quo Vadis

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IAS

What you will not hear in this talk

- New experimental information
- New theoretical computations
- New models

Instead, a brief theorist perspective on where we are, how we got here, and where we might be heading.

First, all of us, theorists and experimentalists, must congratulate the LHC people and the ATLAS and CMS teams for their spectacular heroic achievement.

The experiment works better than expected and the analysis uncovered a very difficult to find signal.

Is it a Higgs?

Now it is official:

CERN press office

**New results indicate that particle discovered at
CERN is a Higgs boson**

Geneva, 14 March 2013. the new particle is
looking more and more like a Higgs boson...

Is it the Higgs?

The SM with a single weakly coupled Higgs seems to work extremely well.

It is at least approximately true.

Options for the near future

- Nothing beyond the SM with its single Higgs
- Going beyond the SM
 - Discrepancies in the Higgs production rate and/or the various decay modes branching ratios
 - Small discrepancies in other processes
 - Additional particles
- There could be progress in the study of dark matter. It could even be connected with electroweak breaking (will not discuss here).

Extending the Standard Model

- Additional scalars (e.g. 2HD models)
- Additional fermions (e.g. massive vector-like particles)
- Additional gauge fields (e.g. Z')
- Higher spins?

Some of these can point to more conceptual extensions of the Standard Model...

More conceptual extensions

- Supersymmetry – it is weakly coupled
- Strong coupling dynamics for electroweak breaking – Technicolor, warped extra dimensions (i.e. strongly coupled field theory that is dual to a weakly coupled gravitational theory)
- Something else we have not yet thought about

One line status report (with many caveats)

The measured Higgs mass $\sim 125\text{GeV}$ is uncomfortably high for (minimal) supersymmetry and uncomfortably low for strong dynamics.

More details below

Open problems with the Standard Model

- Where did the spectrum of particles come from?
 - Gauge group
 - Quarks and leptons quantum numbers
 - Generations
- What determines the electroweak scale (Higgs, W, Z masses)?
- Where did the Yukawa couplings come from?
 - Lead to fermion masses
 - Quarks mixing angles
 - CP violation
 - ...

Open problems with the Standard Model

- Hierarchies
 - Hierarchy of quark and lepton masses (they span 5 orders of magnitudes)
 - Pattern of CKM angles (why are they small?)
 - Strong CP problem ($\theta_{\text{QCD}} < 10^{-11}$)
 - Electroweak scale and Higgs mass
- Dark matter
- Neutrino masses and mixing angles (not small)

Historical perspective

- All these problems were known in the late 70's.
- Despite a lot of progress, it is fair to say that we still do not have a clue about any of them.
- Our best chance for making progress here – continue the fantastic work at the LHC (and other experiments) and hope to find physics beyond the Standard Model.
- But it is not true that we have not made any progress during these past 35 years...

Experimental progress during the past 35 years

- All the parameters of the SM have been measured
 - masses of W and Z
 - masses of all quarks
 - all quarks mixing angles
 - most recently the Higgs mass
- Neutrino masses and mixing angles were measured (beyond the SM)
- More information about dark matter
- Most surprising, dark energy (and other facts about cosmology)

Theoretical progress during the past 35 years

Mostly, not directly related to experiment

- Better understanding of quantum field theory, its dynamics and its possible phases
- Better understanding of quantum gravity (through string theory) and its surprising properties
- Many powerful connections between these ideas and modern mathematics

Hierarchy problem/Naturalness

- Dimensional analysis usually works – observables are given typically by the scale of the problem times a number of order one.
- Dirac's large numbers problem: Why is the proton so much lighter than the Planck scale?

$$M_p \ll M_{Planck}$$



Hierarchy problem/Naturalness

This particular problem is now understood as following from asymptotic freedom

$$\frac{M_p}{M_{Planck}} \sim e^{-\frac{a}{g^2}} \ll 1$$

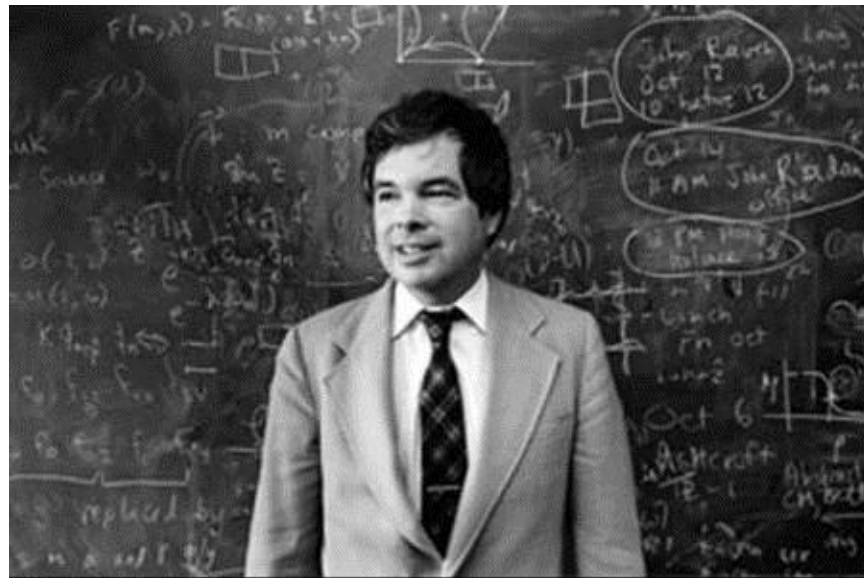
Its newer version involves the electroweak scale

$$M_W, M_Z, M_H \ll M_{Planck}$$

More generally, the intuitive hierarchy problem: where did very small dimensionless numbers come from?

Hierarchy problem/Naturalness

- Small scalar masses are unnatural (Wilson)
 - It is like being very close to a phase transition
 - Scalar mass terms suffer from large quadratic divergences



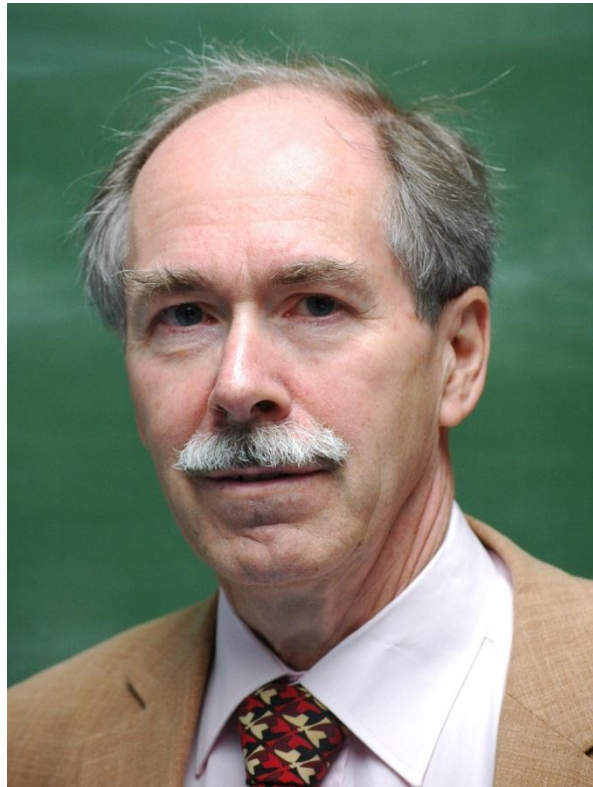
Hierarchy problem/Naturalness

- Alternatively, they are extremely sensitive to small changes of the parameters of the theory at high energy – delicate unnatural cancellations between high energy parameters (Weinberg)



Hierarchy problem/Naturalness

- A parameter is small only if the theory becomes more symmetric when it is exactly zero ('t Hooft)



Hierarchy problem/Naturalness

- The intuitive problem
 - Where did small numbers come from?
 - Why doesn't dimensional analysis work? All dimensionless numbers should be of order one.
 - Can postpone the solution to higher energies
- The technical problem
 - Even if in some approximation we find a hierarchy, higher order corrections can destabilize it.
 - Quantum fluctuations tend to restore dimensional analysis.
 - Must solve at the same scale

Hierarchy problem/Naturalness

- Hierarchy in fermion masses and mixing angles
 - Only the intuitive problem – enhanced symmetry when they vanish.
 - The origin (explanation) can arise from extremely high energy physics .
- Strong CP problem
 - Both the intuitive and the technical issue – no enhanced symmetry when $\theta_{\text{QCD}} = 0$
 - The explanation must involve low energy physics. Axions? $m_{\text{up}} = 0$? Something else?

Hierarchy problem/Naturalness

- Higgs mass and the electroweak scale
 - Quadratic divergences – sensitivity to high energy physics
 - No symmetry is restored when they vanish. (The $SU(2) \times U(1)$ symmetry is always present but might be spontaneously broken.)
 - Both the intuitive and the technical problems
 - Hence, expect to solve it at low energies

The biggest hierarchy problem



The biggest hierarchy problem

- The cosmological constant is quartically divergent – it is fine tuned to 120 decimal points.
- 35 years ago we thought that the cosmological constant is zero. We did not have a mechanism explaining why it is zero, but we could imagine that one day we would find a principle setting it to zero.
- Now that we know it is nonzero, our Naturalness prejudice is being shaken.

Natural solutions to the Higgs hierarchy problem: Technicolor

- Technicolor is basically dead
 - Precision measurements (the S and T parameters) and the measured m_H disfavor it
 - More intuitively, the measured mass of the Higgs tells us that it is weakly coupled. Strong coupling solutions like Technicolor tend to lead to a strongly coupled Higgs.
 - More sophisticated composite Higgs models could work, but they are somewhat complicated and artificial.

Natural solutions to the Higgs hierarchy problem: SUSY

It is hard to make SUSY fully natural.

In the MSSM the Higgs self-coupling is related to the gauge coupling. Hence:

- At tree level $m_{Higgs} \leq m_Z$
- Radiative corrections can lift the Higgs mass, but for reaching 125GeV we need
 - Heavy stop
 - Large A-terms
 - Going beyond the minimal model

The Higgs in SUSY

The three options of lifting m_{Higgs} are possible but

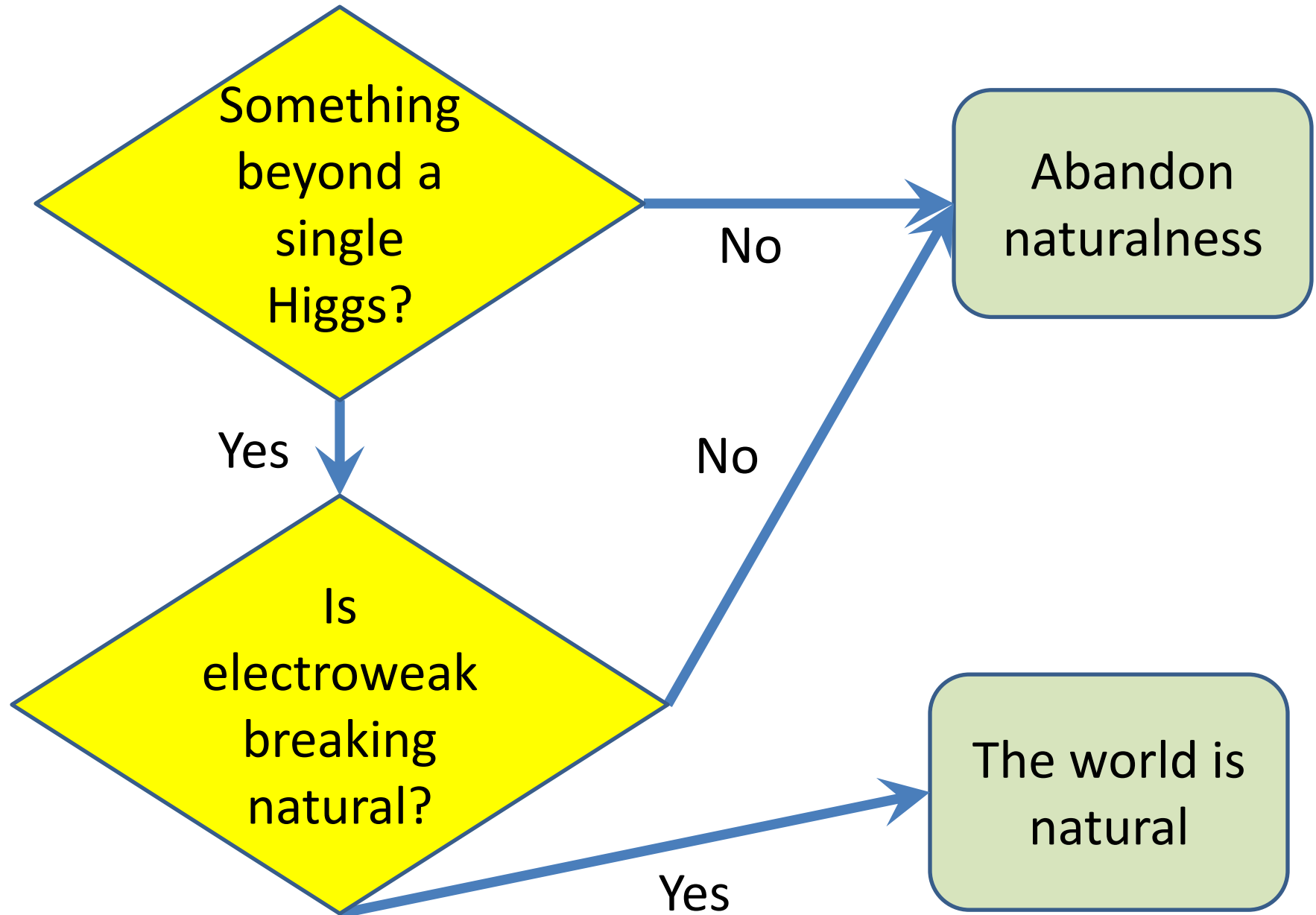
- Heavy stop needs fine tuning
- Large A -terms are hard to generate, while preserving small flavor changing neutral currents.
- Going beyond the minimal model is possible, but has its own problems.

Options about naturalness

- Naturalness is correct
 - Natural SUSY
 - Some other natural solution of the hierarchy problem could be discovered.
 - Hopefully, this will happen soon
- Physics at the TeV range is unnatural
 - A single Higgs and nothing else
 - Unnatural (split) supersymmetry
 - Some other new particles will be found, not addressing the hierarchy problem.

If it is unnatural, then we'll have to reexamine our Naturalness ideas.

Flow chart



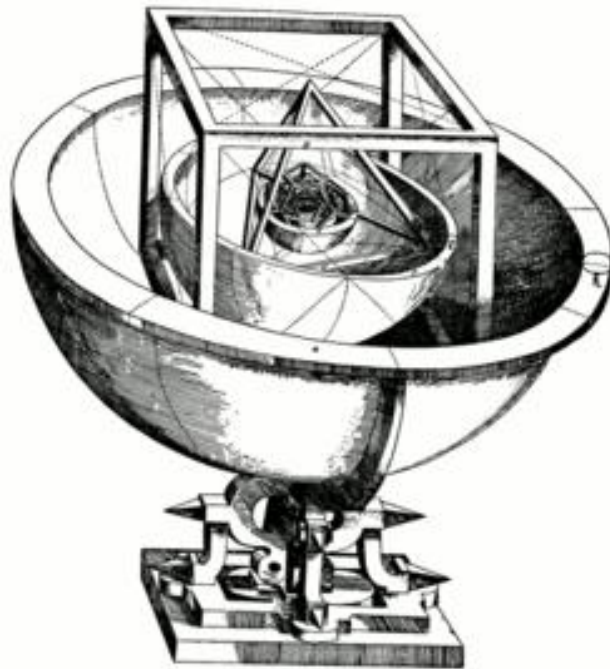
If TeV Physics is unnatural

Leading option: landscape of vacua (and perhaps the A-word)

- The world is much bigger than we think (a multiverse)
- The laws of physics are different in different places – the laws of physics are environmental
- Predicting or explaining the parameters of the SM (e.g. the electron mass) is like predicting the sizes of the orbits of the planets.

A historical reminder

Kepler had a beautiful mathematical explanation of the sizes of the orbits in terms of the 5 Platonic solids. This turned out to be the wrong question.



If TeV Physics is unnatural

- Should we attempt to solve other naturalness questions (strong CP, ratios of fermion masses and mixing angles)?
- What will be the right questions to ask and to explore?
- Some might say that we should stop looking for deeper truth at shorter distances. Instead, some or all the parameters are environmental and should not be explained.
- End of reductionism?

But if so, a strange coincidence

- We are approaching a boundary of theoretical understanding (end of reductionism?)
- We are approaching a boundary in our technological ability to explore shorter distances.
- Now

Conclusions

The LHC can find:

- No discrepancy with the minimal Standard Model
- New physics beyond the minimal Standard Model which does not address the stability of the weak scale
- A natural explanation of the weak scale
 - Supersymmetry
 - Strong dynamics
 - Something we have not yet thought about

Conclusions

All these options are interesting

- They give us correct reliable information about Nature
- They point to a deep physical principle with far reaching philosophical consequences about the Universe. Is our world natural? Is it special? End of reductionism?
- We are in a win-win situation. Every outcome is interesting.

**The future will be very
exciting!**