

Where are we heading?

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Purpose of this talk

A brief, broad brush status report of particle physics

- Where we are
- How we got here (some historical perspective)
- Problems and challenges
- Where we might be heading

What you will not hear in this talk

- New experimental information
- New theoretical computations
- New models
- New concepts

Higgs particle

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*



The Standard Model with a single weakly coupled Higgs works extremely well.

And recent data continues to confirm it with increasing accuracy.

The SM description of Nature is at least approximately true.

More data soon

- The LHC will resume operation in 2015
- Higher energy and higher luminosity
- More detailed information with higher energy reach



Data from other experiments

Will not discuss here

- Precision measurements (not accelerators)
- Dark matter searches. Could be related to electroweak breaking
- Cosmology (Planck, BICEP2, KEK Array ...)



What will the LHC find?



- Of course, we do not know.
- But we can anticipate...

Options for the near future

- Nothing beyond the Standard Model with its single Higgs
- Going beyond the Standard Model
 - Discrepancies in the Higgs production rate and/or the various decay modes branching ratios
 - Small discrepancies in other processes
 - Additional particles

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 (e.g. spin $3/2$)

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

But let us start from the beginning...

The Standard Model is extremely successful

- Many experimental tests of the model
- No known discrepancy between theory and experiment
- Unprecedented accuracy

Open problems with the SM

- 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 SM

- 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 (or most of) 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 (beyond the SM)
- Cosmology
 - dark matter
 - dark energy
 - inflation

Theoretical progress during the past 35 years

- Cosmology (early Universe, inflation)
- 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 between them and other branches of physics 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

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

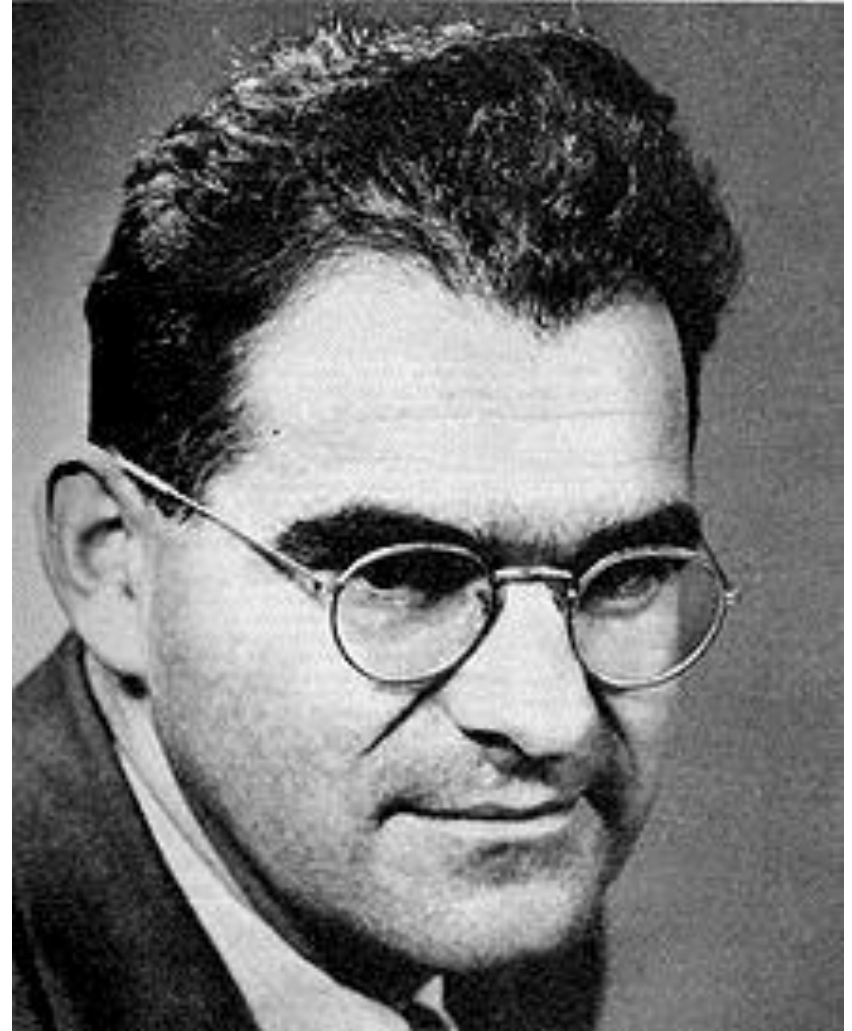
Its newer version involves the electroweak scale

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

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

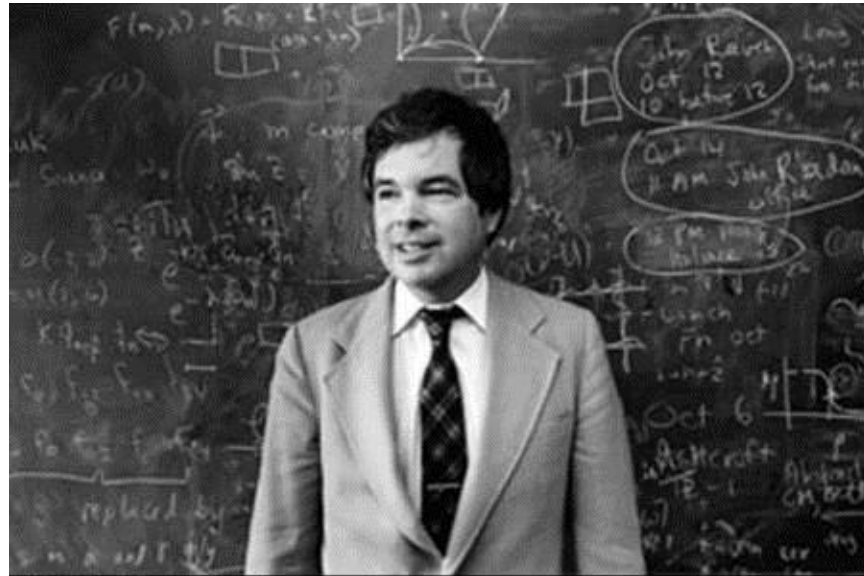
Hierarchy problem/Naturalness

We should avoid
quantum field theories
with quadratic
divergences.
Logarithmic divergences
are OK.
(Weisskopf)



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



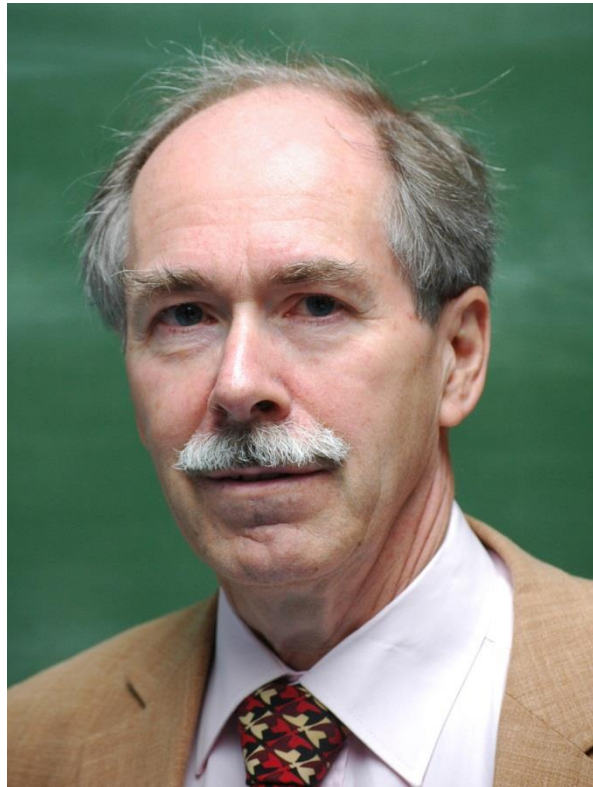
Hierarchy problem/Naturalness

- 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 dimensionless parameter is naturally small only if the theory is more symmetric when it is exactly zero ('t Hooft) – technical naturalness.



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 $\theta_{\text{QCD}} = 0$
 - Only logarithmic divergence (with small coefficient)
 - The explanation must involve low energy physics.
Axions? $m_{up} = 0$? 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 contrived.

Natural solutions to the Higgs hierarchy problem: Supersymmetry

It is hard to make SUSY fully natural.

In the Minimal SUSY Standard Model the Higgs self-coupling is related to the gauge coupling:

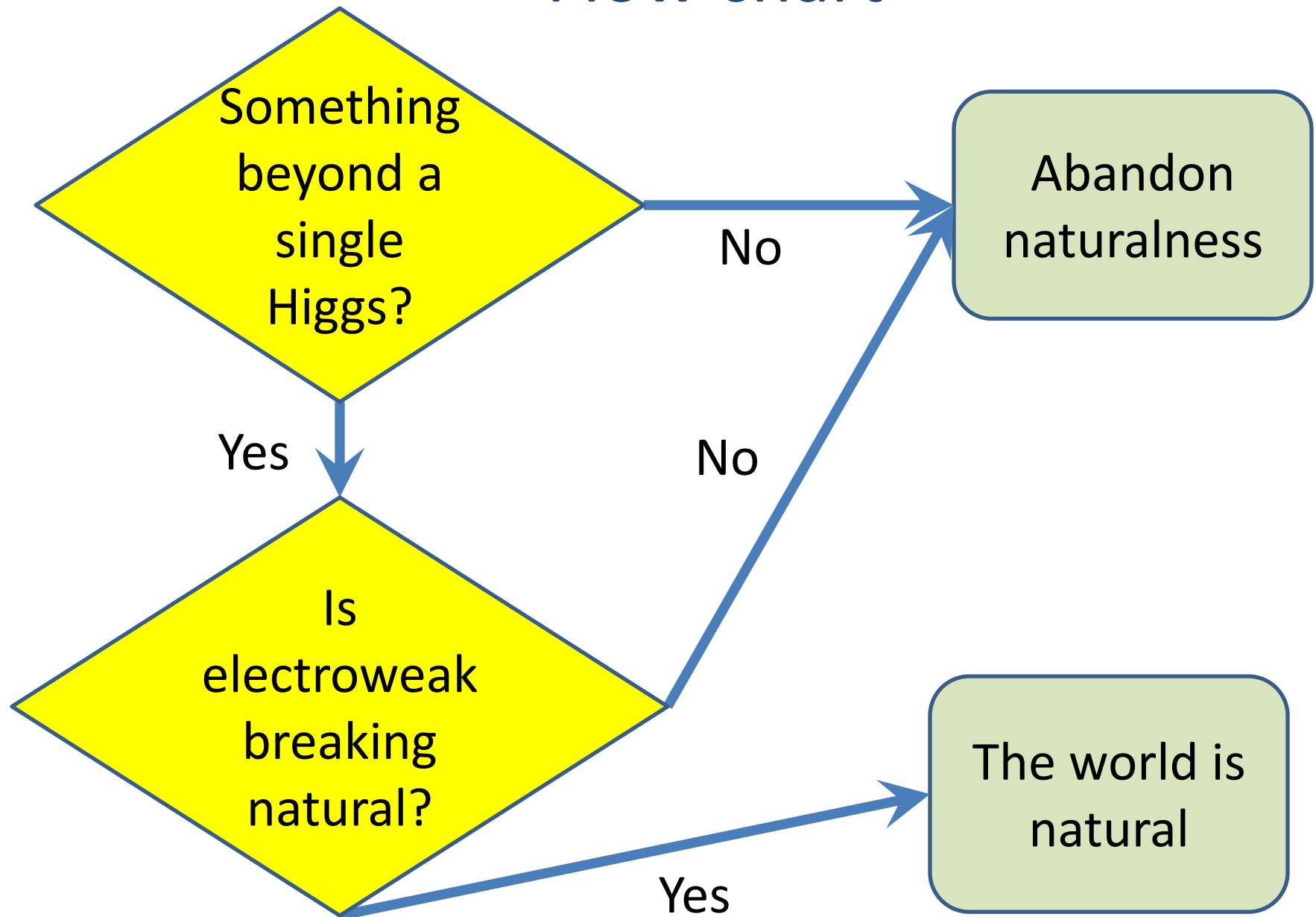
- Classically $m_{Higgs} \leq m_Z$
- Quantum corrections can lift the Higgs mass, but for reaching 125GeV we need
 - heavy stop
 - large A-terms
 - going beyond the minimal model
- Everyone of these is possible, but problematic.

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



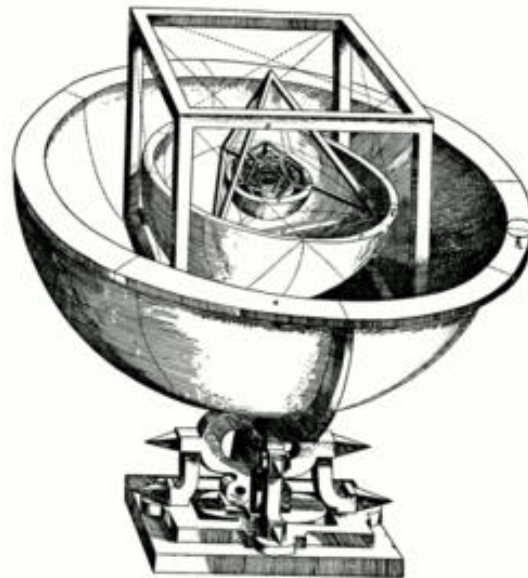
If TeV Physics is unnatural

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 of the planets 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.
 - Perhaps we can gain one (or even two) more order of magnitude in energy, but it is hard to imagine much more than that.
 - Hopefully, this statement wrong.
- Now

Conclusions

The LHC can find:

- No discrepancy with the minimal Standard Model
- New physics beyond the minimal Standard Model that 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!**