Where are we heading?

Nathan Seiberg

IAS

2016

Kavli Institute for the Physics and Mathematics of the Universe

東京大学 国際高等研究所 カブリ数物連携宇宙研究機構

KAVLI IPMU

Two half-talks

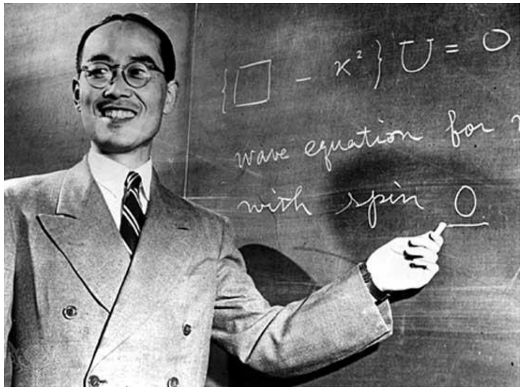
- A brief, broad brush status report of particle physics and what the future could be like
- The role of symmetries in physics and how it is changing

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 (more below)
  - Hierarchy of quark and lepton masses (they span 5 orders of magnitudes)
  - Pattern of CKM angles (why are they small?)
  - Strong CP problem ($\theta_{QCD} < 10^{-11}$)
  - Electroweak scale and Higgs mass
- Dark matter
- Neutrino masses and mixing angles (not small). Beyond the SM, but reflects physics at much higher energies. Will not discuss today.

More data soon

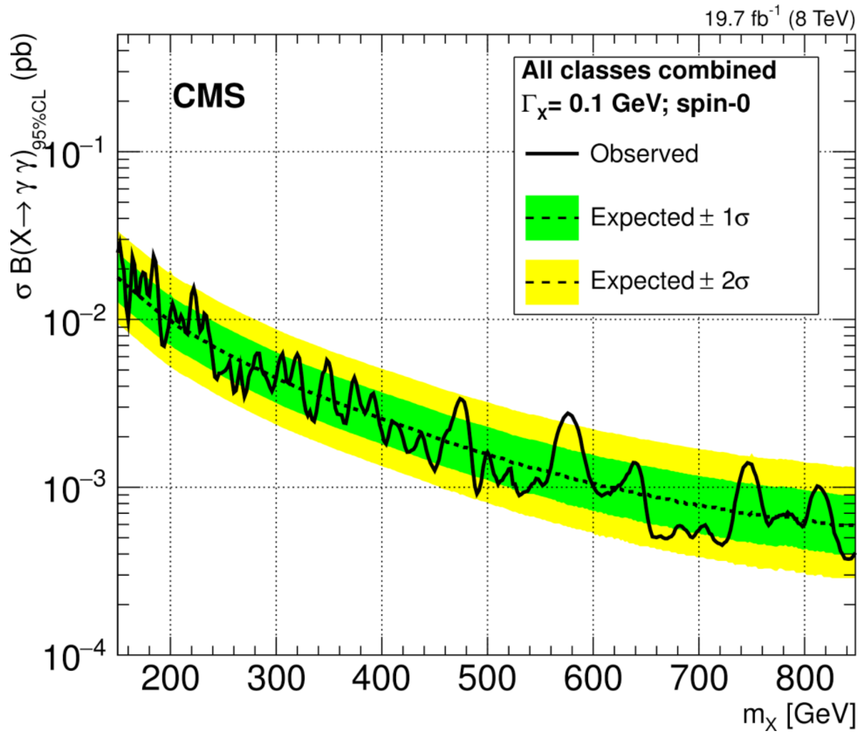
- The LHC is operating at higher energy – 6.5 TeV per beam and higher luminosity
- Data from other experiments (precision measurements, dark matter searches, cosmology, astrophysics)

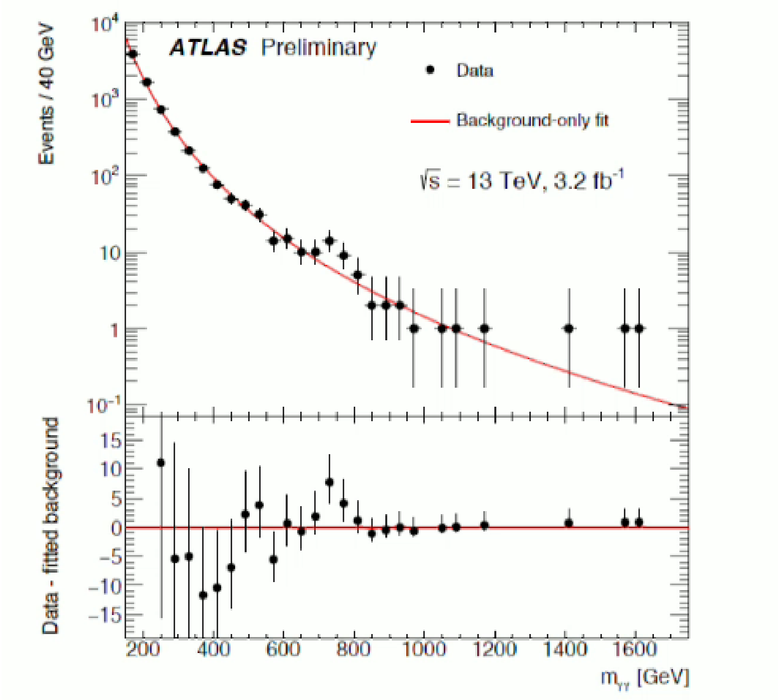
Options for the near future

- 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

First sign of physics beyond the SM?

Di-photon resonance at 750GeV (reassurance in Moriond)?





Possible conceptual extensions of the SM

- 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)

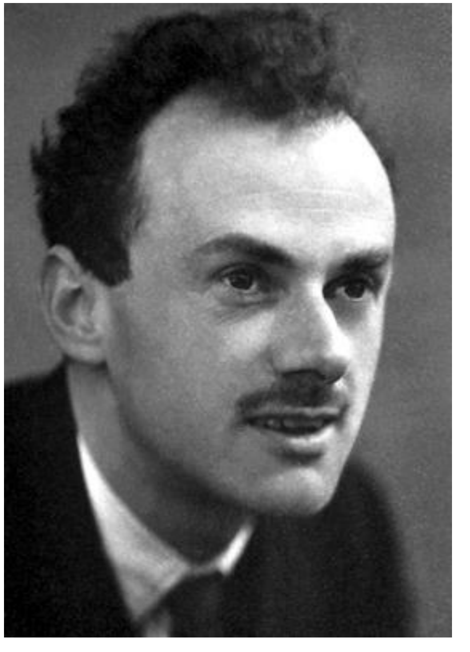
The measured Higgs mass ~125GeV is uncomfortably high for (minimal) supersymmetry and uncomfortably low for strong dynamics.

More details below

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

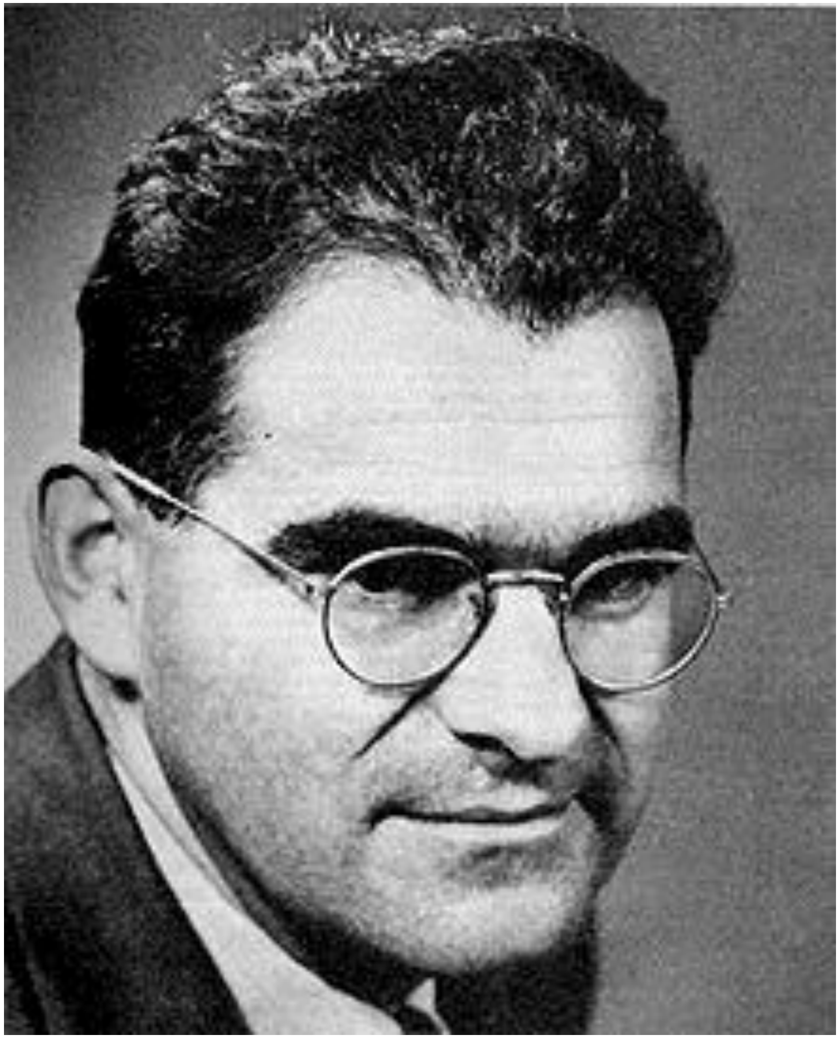
$$M_W,\ M_Z,\ M_H \ll M_{Planck}$$

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

Hierarchy problem/Naturalness

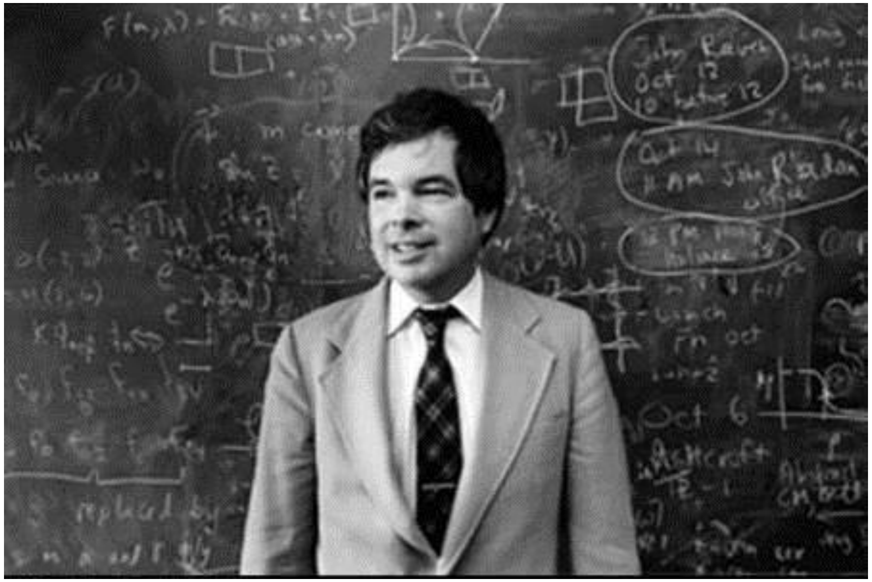
We should avoid quantum field theories with quadratic divergences. Logarithmic divergences are OK.

(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

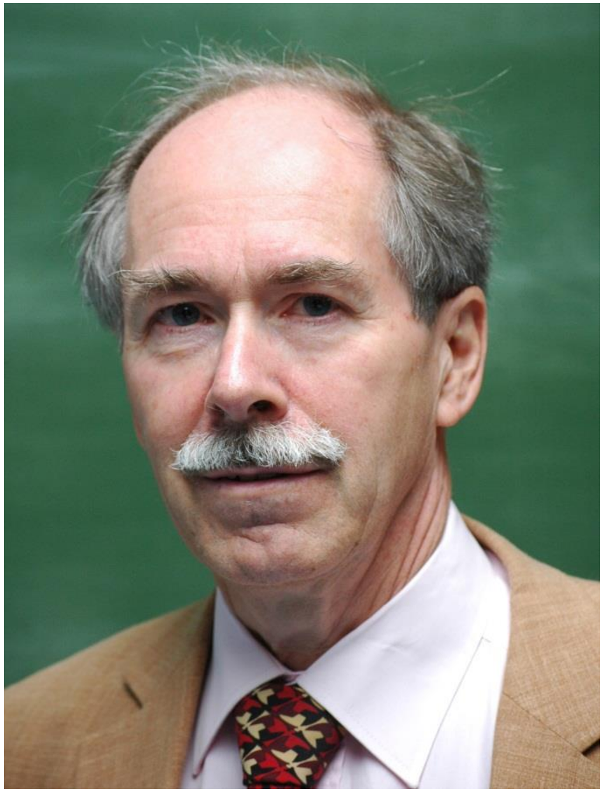


Hierarchy problem/Naturalness

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

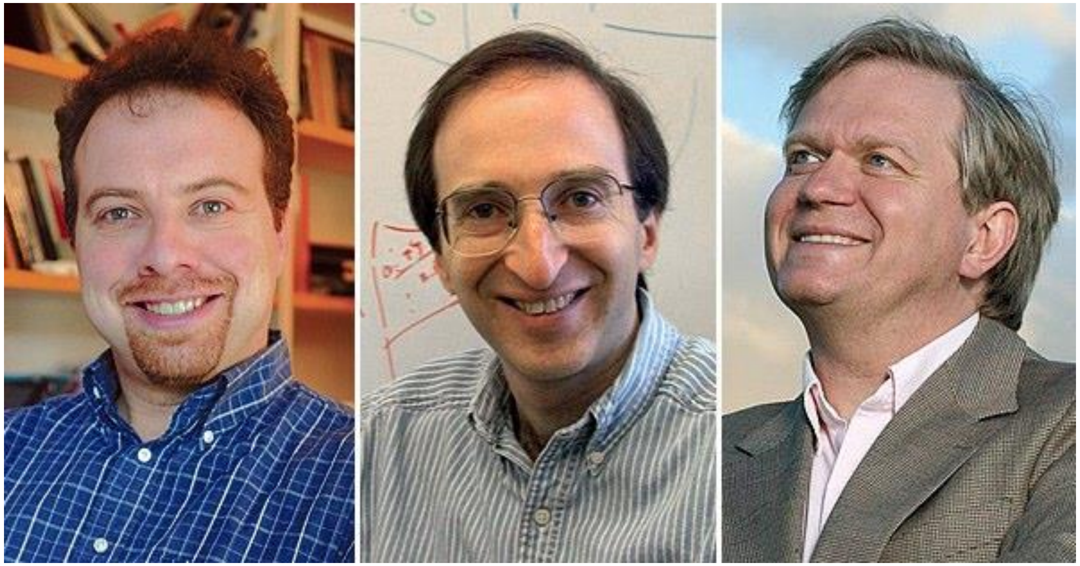
Hierarchy problem/Naturalness

- Higgs mass and the electroweak scale
  - Quadratic divergences – sensitivity to high energy physics
  - No symmetry is restored when they vanish. (The *SU(2) X 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.
- We used to think that it vanishes. We did not have a mechanism explaining why it is zero, but we hoped that one day we would find a principle setting it to zero.
- Now that we know that 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.

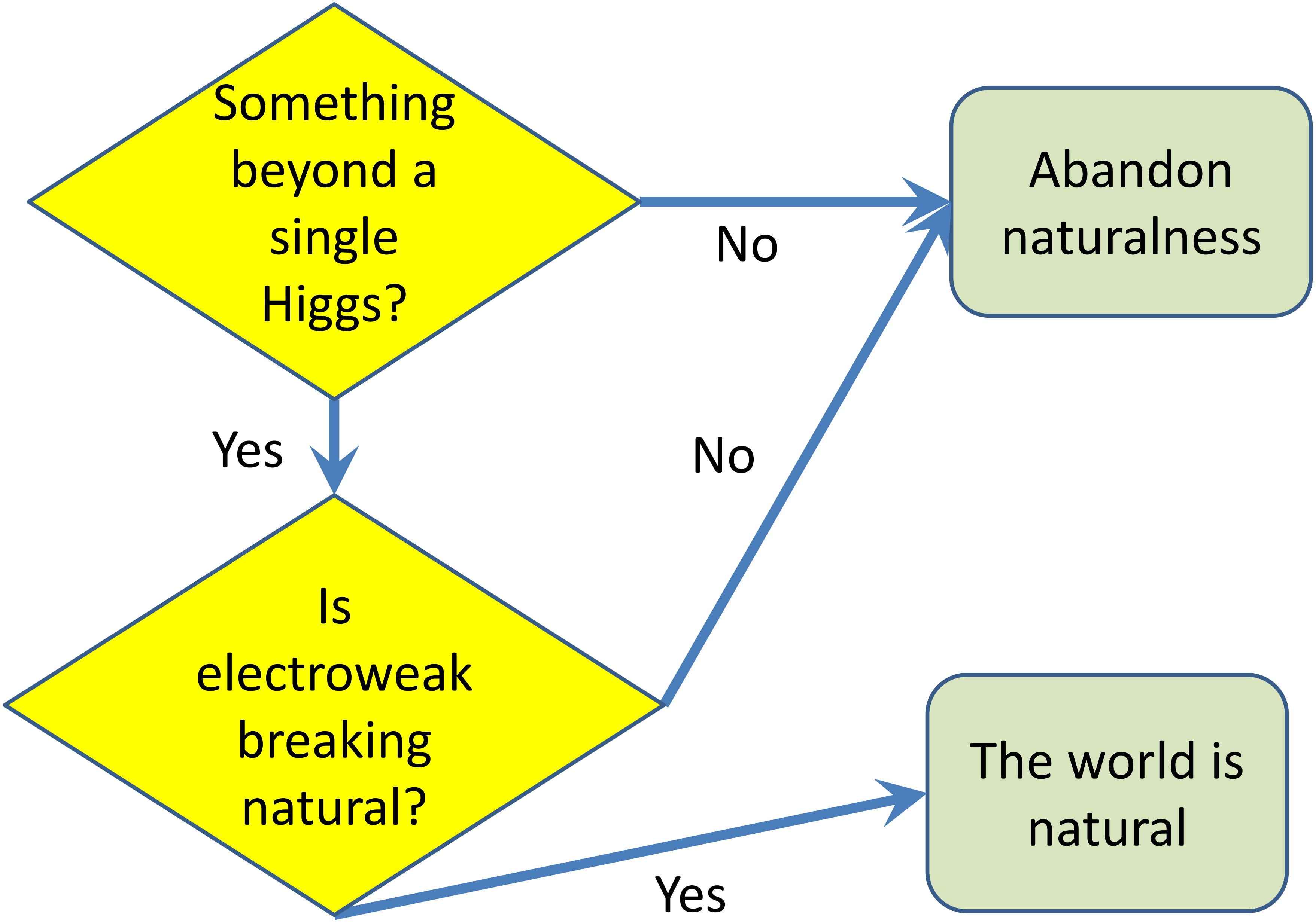
Natural solutions to the Higgs hierarchy problem: Supersymmetry

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 for the near future



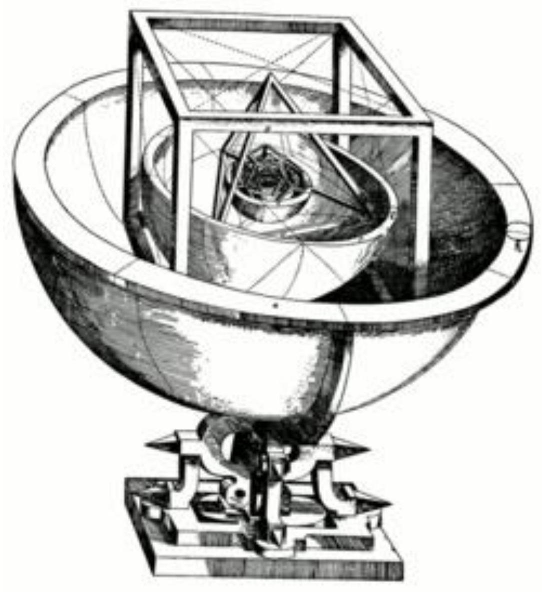
If TeV Physics is unnatural

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?

Conclusions

The LHC can find:

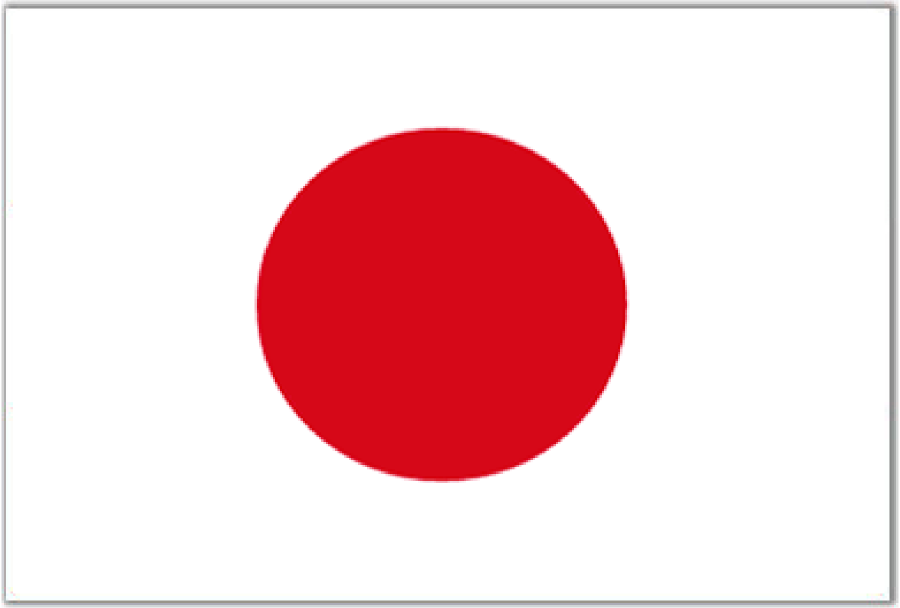
- No discrepancy with the minimal Standard Model
- New physics beyond the minimal Standard Model that does not address the stability of the weak scale
- A natural explanation of the weak scale
  - Supersymmetry
  - Strong dynamics
  - Something we have not yet thought about

Conclusions

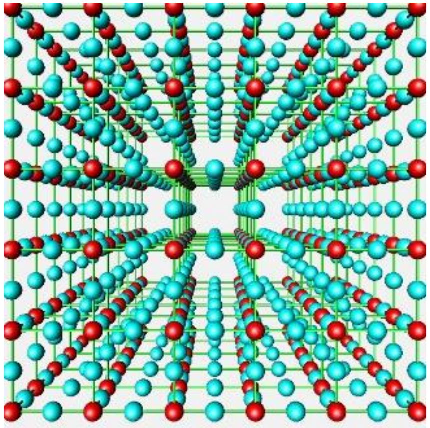
All these options are interesting

- 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.

Symmetries



Physicists love symmetries



- Crystallography
- Lorentz
- Flavor $SU(2)$, $SU(3)$
  - Consequence of light quarks. Quarks are deep.
- Color
  - Gauge symmetry is deep

Gauge symmetry is deep

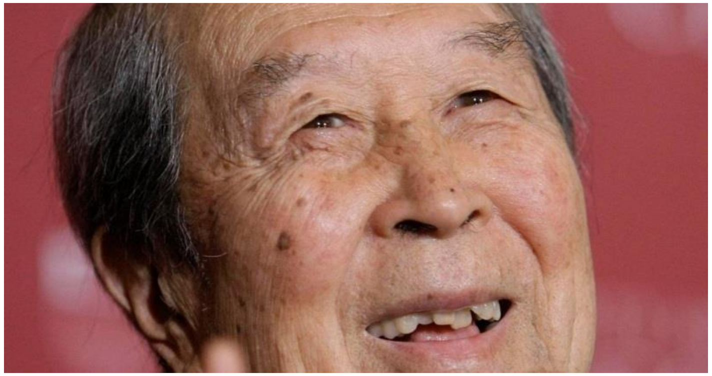
- Largest symmetry (a group for each point in spacetime)
- Useful in making the theory manifestly Lorentz invariant, unitary and local (and hence causal)
- Appears in
  - Maxwell theory, the Standard Model
  - General Relativity
  - Many condensed matter systems
  - Deep mathematics (fiber bundles)

But

- Because of Gauss law the Hilbert space is gauge invariant. (More precisely, it is invariant under small gauge transformation; large gauge transformations are central.)
- Hence: gauge symmetry is not a symmetry.
  - It does not act on anything.
- A better phrase is gauge redundancy.

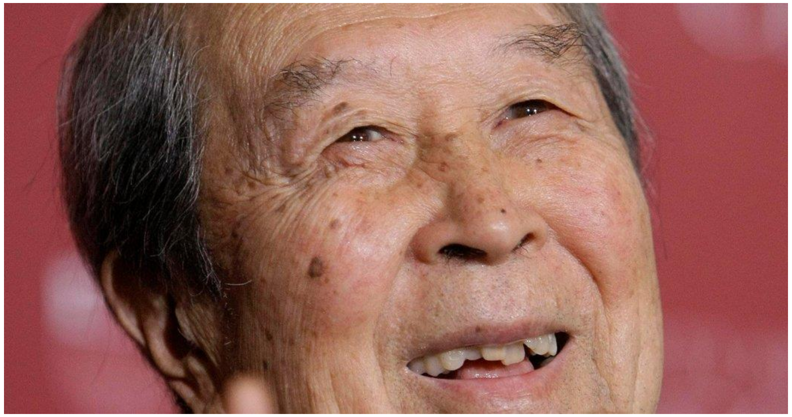
Gauge symmetries cannot break

- Not a symmetry and hence cannot break
- For spontaneous symmetry breaking we need an infinite number of degrees of freedom transforming under the symmetry. Not here.



- This is the deep reason there is no massless Nambu-Goldstone boson when gauge symmetries are "broken."

Gauge symmetries cannot break



For weakly coupled systems (e.g. Landau-Ginsburg theory of superconductivity, or the weak interactions) the language of spontaneous gauge symmetry breaking is appropriate and extremely useful [Stueckelberg, Anderson, Brout, Englert, Higgs].

Global symmetries can emerge as accidental symmetries at long distance.

Then they are approximate.

Exact gauge symmetries can be emergent.

Examples of emergent gauge symmetry

- Simple dualities in free theories
  - In *3d* a compact scalar is dual to Maxwell theory, whose gauge symmetry is emergent.
  - In *4d* Maxwell theory is dual to a magnetic Maxwell theory. Its gauge symmetry is emergent.
- Common in condensed matter physics
  - Fractional Hall effect
  - Particle-vortex duality in 2+1 dimensions
  - …

Duality in interacting field theories $\boldsymbol{N}=4$ supersymmetry

- This is a scale invariant theory characterized by a gauge group G and a complex coupling constant $\tau=\frac{\theta}{2\pi}+\frac{4\pi}{g^2}i$ for each factor in G.
- For simply laced G the theory with τ is the same as with $\tau+1$ (shift θ by 2π) and the same as with $-1/\tau$ (generating $SL(2,\boldsymbol{Z})$). The latter maps strong to week coupling.
- The duality is an exact equivalence of theories.
  - Same spectrum of states
  - Same spectrum of operators
  - Same correlation functions

Duality in interacting field theories
$\mathcal{N} = 4$ supersymmetry

- The gauge symmetry of the dual description is emergent!
- Which of the two gauge symmetries is fundamental?
- Which set of gluons is elementary?
- Perhaps neither gauge symmetry is fundamental.
- Notion of "elementary particle" is ill-defined.

Interacting gauge theories

Start at short distance with a gauge group G. Depending on the details we end up at long distance with:

- IR freedom – a free theory based on G (same theory)
- A nontrivial fixed point. Interacting conformal field theory – no notion of particles.
- An approximately free (IR free) theory of bound states
- An empty theory – gap (possibly topological order)

All these options are realized in QCD for various numbers of flavors. (The approximately free theory is a theory of pions.)

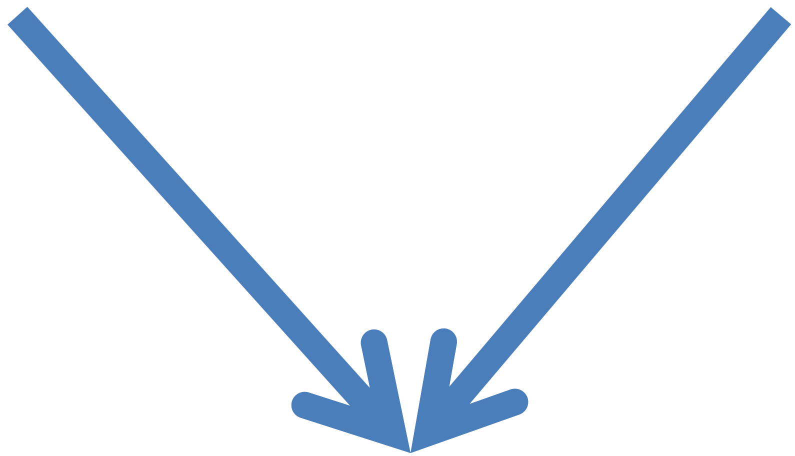
Duality in interacting field theories
$\boldsymbol{N} = 1$ supersymmetry

Electric theory

G

Magnetic theory

$\tilde{G}$



Non-trivial IR fixed point

Duality in interacting field theories
$N = 1$ supersymmetry

Another option:

Electric theory

Based on G

$\downarrow$

Approximately free theory (IR free)

Based on $\tilde{G}$

Duality in interacting field theories
$\boldsymbol{N} = 1$ supersymmetry

In the UV an asymptotically free theory based on G

In the IR an IR free theory based on $\tilde{G}$

At low energies QCD has pions. This theory has a non-Abelian gauge theory.

- The gauge fields of $\tilde{G}$ are composite.
- Their gauge symmetry is emergent.
- There is no ambiguity in the IR gauge symmetry – approximately free massless gauge fields.

Many more examples. Duality and emergent gauge symmetries are ubiquitous.

Emergent general covariance and emergent spacetime

- So far we discussed duality between two field theories
- String-string duality
  - T-duality
  - S-duality
  - U-duality
- String-fields duality
  - Matrix models for low dimensional string theories
  - BFSS M(atrix) model
  - AdS/CFT
  - More generally gauge-gravity duality

Conclusions

- Gauge symmetries can come and go.
- They can emerge.
- It is often convenient to use them to make the description manifestly Lorentz invariant, unitary and local.
  - But there can be different such descriptions.
- Gauge symmetry is not fundamental.
- Look for a formulation of field theory that makes the duality manifest.
  - We should not be surprised by duality!