The Higgs Boson: A Tale of Two Universes

Markus Luty
UC Davis/QMAP

Outline

- Present understanding of Standard Model of particle physics

- Prospects for future advances in understanding
  the principles of fundamental physics

The Higgs boson plays a truly central role!

Physics Really Works!

. . . but it might take 50 years.

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

Effective Theories

Theories are *tools* to understand the laws of nature

- Effective (phenomenological) theories

  Include only observed particles/interactions

  Driven by experimental data

- "Aspirational" theories

  Include unobserved degrees of freedom/interactions

  Motivated by theoretical principles

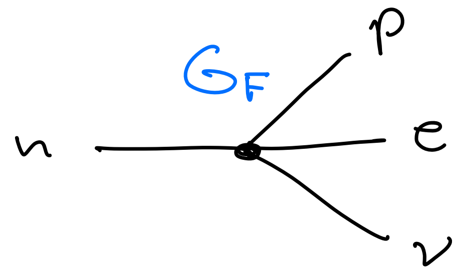
  Compatible with experimental data

  Make predictions beyond current observations

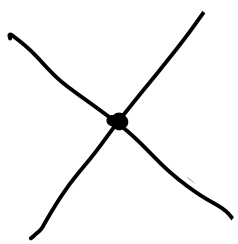
Weak Interactions

- Fermi theory (1932)

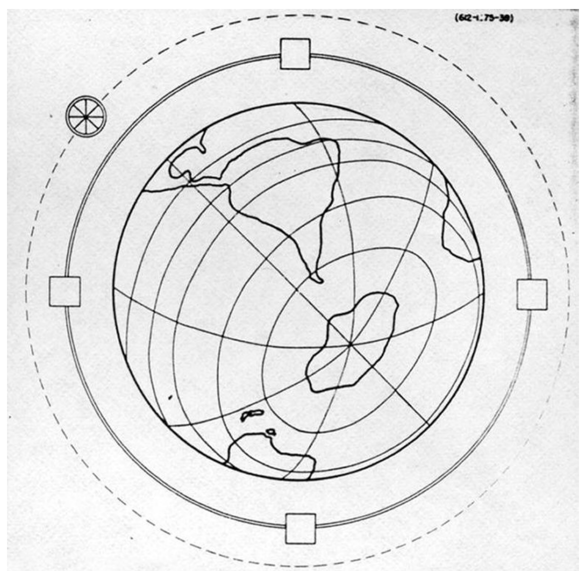
  $n \to pe\nu$ described by



  Breaks down at high energy:



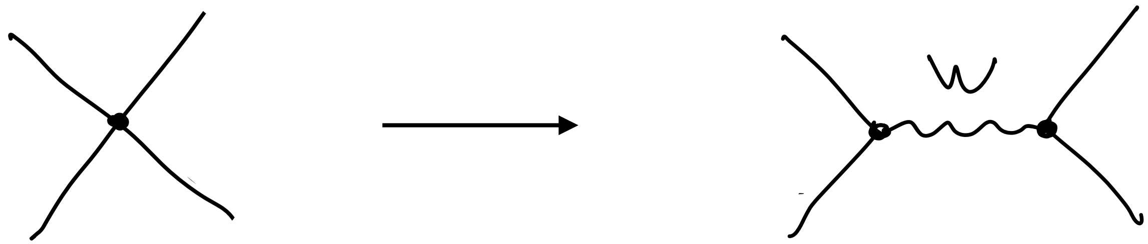
$\sim G_F E^2 \qquad \Rightarrow \quad E \lesssim \text{TeV}$



Fermi's "Globatron" $E_{\text{cm}} \sim$ TeV (1954)

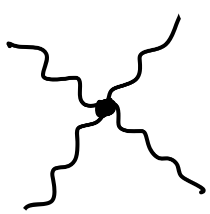
Weak Interactions

- Intermediate vector bosons (1960's)

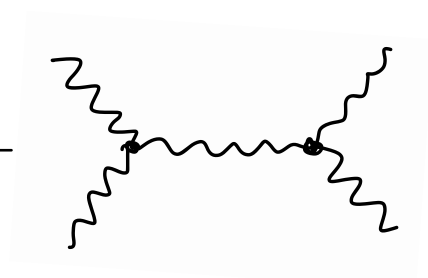


Reduces to Fermi theory for $E \ll m_W$

Also breaks down at high energies:



$+$



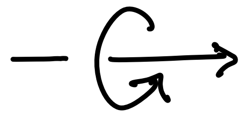
$$\sim \frac{E^2}{m_W^2} \qquad \Rightarrow \quad E \lesssim \text{TeV}$$

Good high energy behavior requires new degrees of freedom

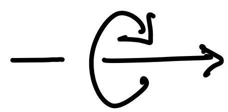
"Higgs sector"

Why Higgs Sector?

- Massless spin 1 particle (photon):

$\gamma_+ =$  helicity: $h = \hat{p} \cdot \vec{S} = +1$

$v = c$

CPT $\Rightarrow$ $\gamma_- =$  $h = -1$

2 spin states $\Leftrightarrow$ 2 polarizations of electromagnetic wave

- Massive spin 1 particle:

$W = \bullet$

$v = 0$

$$S_z = \begin{pmatrix} 1 & & \\ & 0 & \\ & & -1 \end{pmatrix}$$

3 spin states

Why Higgs Sector?

Large boost in the z direction:

$$p^\mu = \begin{pmatrix} m_W \\ 0 \\ 0 \\ 0 \end{pmatrix} \longrightarrow \begin{pmatrix} \sqrt{p^2 + m_W^2} \\ 0 \\ 0 \\ p \end{pmatrix} \simeq \begin{pmatrix} p \\ 0 \\ 0 \\ p \end{pmatrix}$$

$$h = 0 \text{ polarization:} \quad \epsilon^\mu = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \longrightarrow \frac{1}{m_W} \begin{pmatrix} p \\ 0 \\ 0 \\ \sqrt{p^2 - m_W^2} \end{pmatrix} \simeq \frac{p^\mu}{m_W}$$

$\Rightarrow$ growing amplitudes at high energies

$\Rightarrow$ new degrees of freedom required with $m \lesssim$ TeV

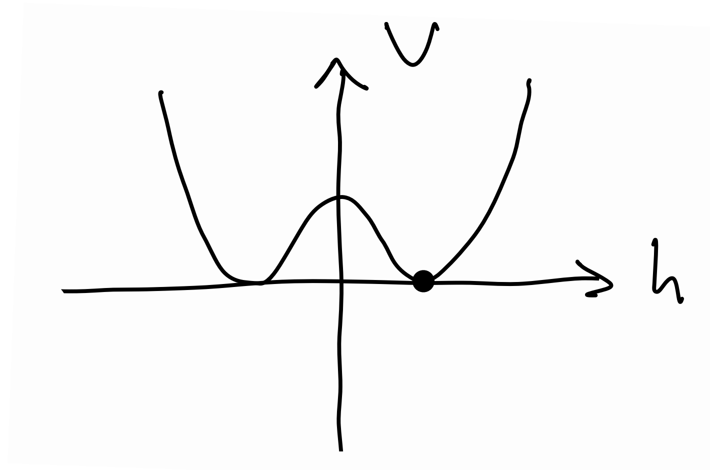
"No-lose theorem" at LHC

Minimal Higgs Sector

All growing amplitudes can be canceled by incorporating a single spin-0 particle (the Higgs boson).

This defines the Standard Model of particle physics.

- Higgs field costs energy to turn *off*
- Particle masses arise from interactions with the Higgs field
- Higgs particle is a quantum excitation of the Higgs field



Beyond the Standard Model?

The Standard Model can be consistently extrapolated to the Planck scale $M_{\text{Planck}} \sim 10^{19}$ GeV

...but it cannot possibly be the final theory:

- Does not explain cosmology

  Dark matter, inflation, baryogenesis

- Open conceptual questions

  Unification, quantum gravity, hierarchy problem,...

Hierarchy Problem

The Higgs boson is a spin-0 elementary particle

Massive and massless version have same degrees of freedom:

$$h = \bullet \qquad\qquad S = 0$$

$v = 0$

Interaction with heavy particles $\Rightarrow$ quantum fluctuations give *additive* contributions to Higgs mass:

$$\Delta m_h^2 \propto m_X^2$$

This does not happen for particles with $S \neq 0$.

E.g quantum fluctuations cannot turn a massless spin-1 particle (2 spin states) into a massive one (3 spin states).

Requires new physics at $E \lesssim$ TeV?

Fine Tuning

Contribution from heavy particles can cancel:

E.g. $m_X \sim 10^{19}$ GeV

$$m_h^2 = 2{,}357{,}128{,}067{,}460{,}539{,}571{,}746{,}259{,}\underline{968{,}067}\ \text{GeV}^2$$
$$- 2{,}357{,}128{,}067{,}460{,}539{,}571{,}746{,}259{,}\underline{952{,}442}\ \text{GeV}^2$$
$$= (125\ \text{GeV})^2$$

It seems crazy, but fine-tuned theory is perfectly consistent.

Are there "natural" theories with no fine-tuning?

Supersymmetry

Spacetime symmetry that relates bosons and fermions

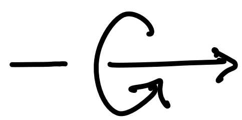
h (spin 0) $\longleftrightarrow$ $\tilde{h}$ (spin $\frac{1}{2}$ "Higgsino")

Exact supersymmetry $\Rightarrow m_h = m_{\tilde{h}}$

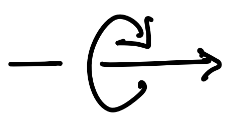
Fermion mass protected from quantum fluctuations

$\Rightarrow$ no fine tuning for Higgs mass.

Massless fermion:

$\psi_+ =$  $h = +\frac{1}{2}$

$v = c$

$\psi_- =$  $h = -\frac{1}{2}$

$m_\psi = 0 \Rightarrow h = \pm\frac{1}{2}$ states decoupled $\Rightarrow$ chiral symmetry

Quantum fluctuations preserve chiral symmetry

Supersymmetry

Requires "superpartners" for all particles:

$$t \ (\text{spin } \tfrac{1}{2}) \quad \longleftrightarrow \quad \tilde{t} \ (\text{spin } 0 \ \text{"stop"})$$

$$\vdots$$

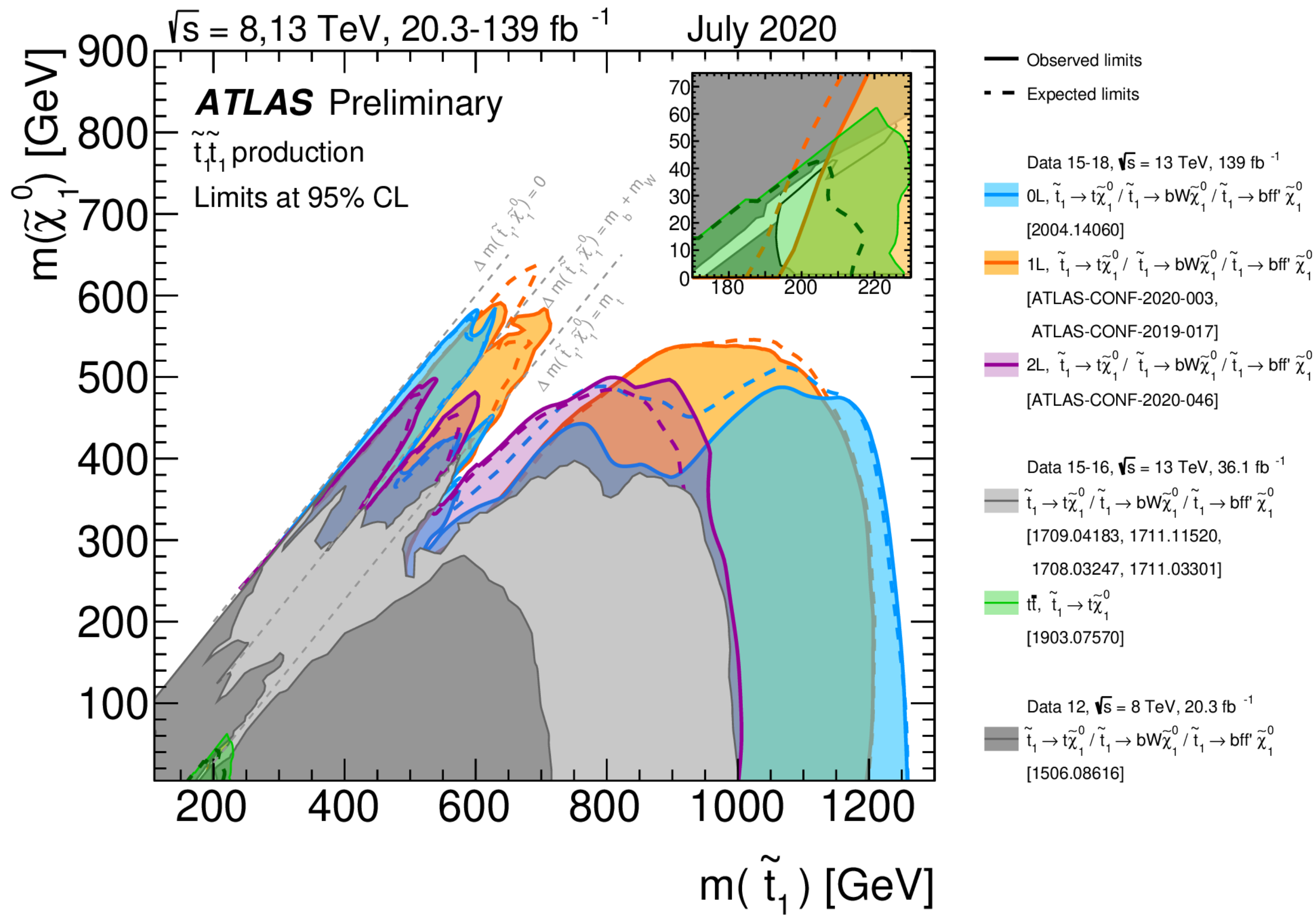
Broken supersymmetry: $m_{\tilde{h}} \neq m_h$, $m_{\tilde{t}} \neq m_t, \ldots$

$$\Rightarrow \quad \Delta m_h^2 \sim \frac{y_t^2}{16\pi^2}\left(m_{\tilde{t}}^2 - m_t^2\right)$$

Naturalness $\Rightarrow m_{\tilde{t}} \lesssim$ TeV

What does the LHC tell us?

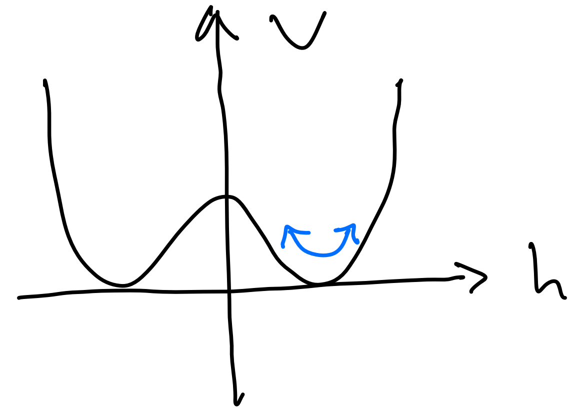
...It's Complicated



Bounds depend on decay chains (full superpartner spectrum)

$m_{\tilde{t}} \lesssim$ TeV allowed, but $\lesssim 1\%$ tuning seems unavoidable

PNGB Higgs



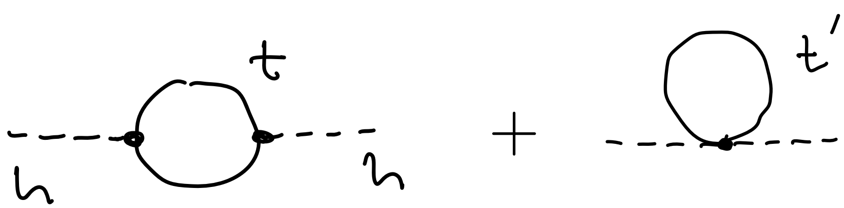
Higgs mass $\leftrightarrow$ curvature of Higgs potential

Field shift symmetry:

$$h \mapsto h + \lambda \quad \Rightarrow V(h) \equiv 0$$

Standard model interactions break shift symmetry

Requires additional "partner" particles to restore (approximate) shift symmetry.



$$\Rightarrow \quad \Delta m_h^2 \sim \frac{y_t^2}{16\pi^2}(m_{t'}^2 - m_t^2)$$

LHC exclusion: $m_{t'} \gtrsim$ TeV

$\sim 10\%$ to $\sim 1\%$ tuning hard to avoid

Is Nature Fine-Tuned?

Are there mechanisms that can explain fine-tuning?

- Cosmological adjustment mechanisms

- Anthropics

  ⋮

Anthropics

The Standard Model has *two* tuned couplings:

$m_h^2, \;\; \Lambda =$ cosmological constant

The existence of complex structure in the universe is very sensitive to changes in these parameters.

$$\delta m_h^2 \sim 10 m_h^2 \Rightarrow \text{no stable nuclei} \qquad \delta\Lambda \sim 10\Lambda \Rightarrow \text{no galaxies}$$

If the universe has many causally disconnected regions with different values of these parameters, only those regions with values close to what we observe will have complex structure.

Radical implications, but does not require radical theoretical inputs.

The most conservative explanation the tiny observed value of the cosmological constant?

A Tale of Two Universes

- New physics near the TeV scale with novel symmetries explain why the Higgs mass is insensitive to UV physics.

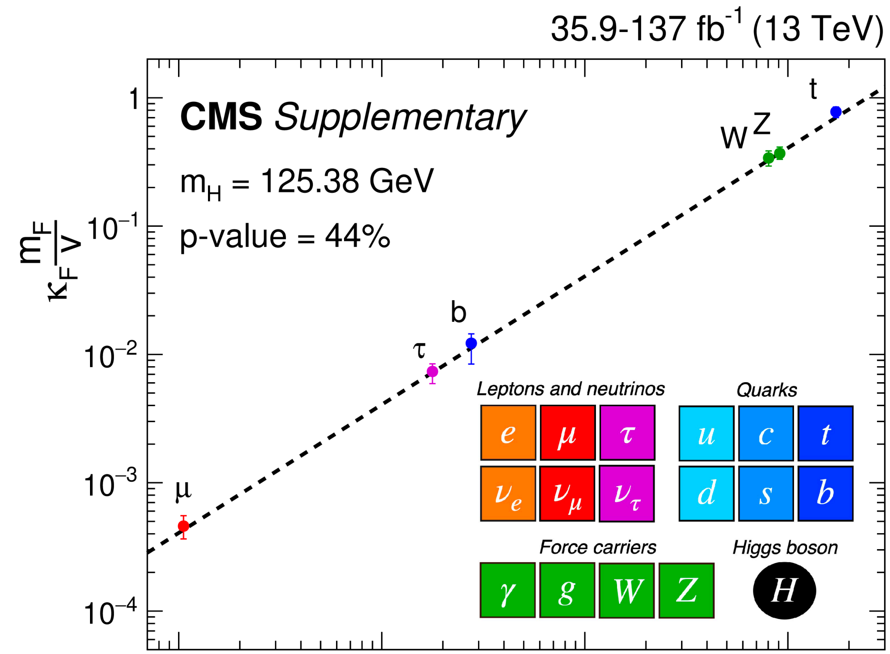
- The Higgs mass is sensitive to UV physics, but its value is explained by our location in space and time.

- Other possibilities?

SM as an Effective Theory

Is the 125 GeV particle discovered 10 years ago *the Higgs*?

Measure couplings are compatible with Standard Model predictions over several orders of magnitude.



Higgs couplings are predicted to high accuracy in Standard Model
$\Rightarrow$ measuring them is a search for new physics.

SM as an Effective Theory

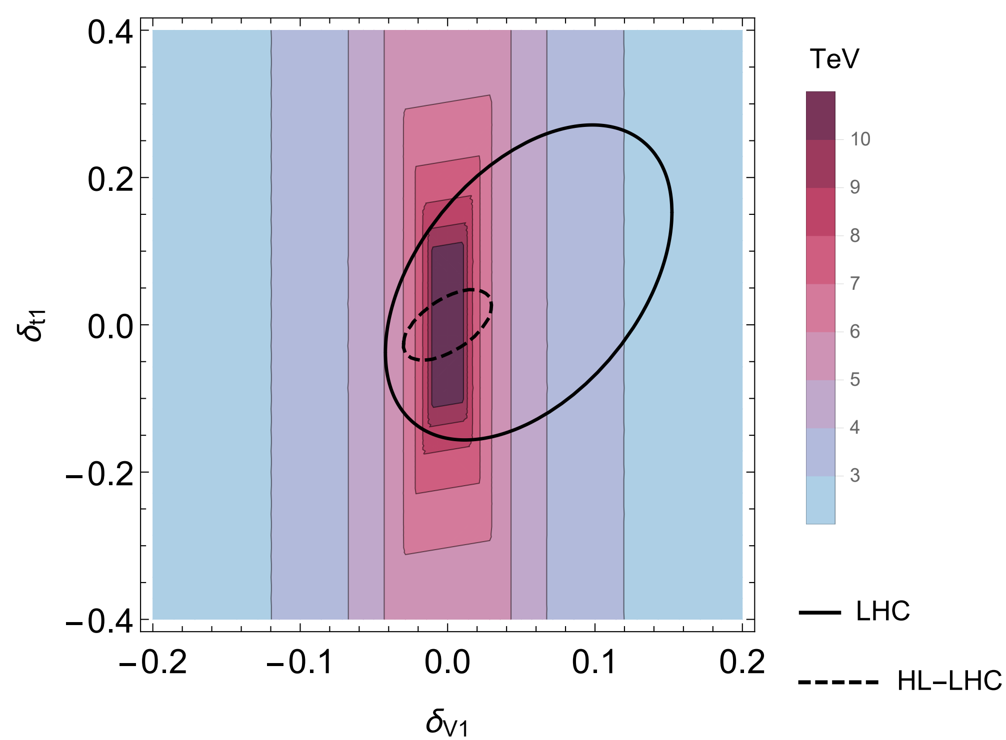
Any deviation from predictions of the Standard Model requires new physics at $E \lesssim \#$ GeV.

Reason: the Standard Model is the most general theory of observed particles with good high energy behavior.

Model-independent estimate of scale of new physics from unitarity:
(Abu-Ajamieh, Chang, Chen, ML 2020)

$$\delta_{V1} = \frac{g_{hVV} - g_{hVV}^{(\mathrm{SM})}}{g_{hVV}^{(\mathrm{SM})}}$$

$$\delta_{t1} = \frac{g_{htt} - g_{htt}^{(\mathrm{SM})}}{g_{htt}^{(\mathrm{SM})}}$$



Conclusions

- The Higgs boson is at the heart of some of the most important questions in fundamental physics.

- Further experimental study of the Higgs and going further into the high-energy frontier are both essential to answer these questions.

- Theory needs bold speculation and rigorous phenomenological analysis.

Strong reasons to be optimistic about the next 10 years of Higgs physics!

Thanks!