Beyond the SM 1/3

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CERN & DESY
Four Lessons

1) How could I do anything without knowing everything that had already been done? [...] pick up what I needed to know as I went along. It was sink or swim. [...] But I did learn one big thing: that no one knows everything, and you don’t have to.

2) While you are swimming and not sinking you should aim for rough water. [...] My advice is to go for the messes — that’s where the action is.

Scientist: Four golden lessons
3) Forgive yourself for wasting time. [...] in the real world, it's very hard to know which problems are important, and you never know whether at a given moment in history a problem is solvable [...] get used [...] to being becalmed on the ocean of scientific knowledge.

4) Learn something about the history of science [...] As a scientist, you're probably not going to get rich [...] But you can get great satisfaction by recognizing that your work in science is a part of history.
The SM

Leptons
e, μ, τ
v_e, v_μ, v_τ

Quarks
u, c, t
d, s, b

Photon

W^+W^-

Z^0

Higgs Boson

Gluons

→ M. Schmaltz lecture
The energy frontier

What can we expect to discover?
The SM
The SM

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]

\[ + i F D \bar{\chi} Y + h.c. \]

\[ + X_i y_{i j} X_j \phi + h.c. \]

\[ + m^2 \phi^2 - V(\phi) \]
The SM

determined by gauge symmetry

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]

\[ + i \bar{D} \gamma \nu + h.c. \]

\[ + \bar{\chi} i Y_{ij} X_j \phi + h.c. \]

\[ + |D_w \phi|^2 - V(\phi) \]
The SM

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i F' D \gamma^\mu + h.c. \]

\[ + \bar{\psi} i \gamma_\mu D_\mu \psi + h.c. \]

\[ + \left| D_\mu \phi \right|^2 - V(\phi) \]
The SM

determined by gauge symmetry

fermion masses & mixings

Higgs potential

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]

\[ + i \bar{\psi} D \psi + h.c. \]

\[ + \bar{\chi}_i Y_{ij} \chi_j \phi + h.c. \]

\[ + \frac{1}{2} m_\phi^2 |\phi|^2 - V(\phi) \]
The SM

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]
\[ + i F \bar{D} \gamma \gamma + h.c. \]
\[ + X_i Y_{ij} X_j \phi + h.c. \]
\[ + D_\mu \phi \bar{\phi}^2 - V(\phi) \]
Quark and Lepton mass hierarchy
Masses on a Log-scale

- t
- b
- c
- τ
- s
- μ
- u
- d
- e
SM quark masses: mostly small & hierarchical.

Origin of this structure?

Compare to: $g_s \sim 1$, $g \sim 0.6$, $g' \sim 0.3$, $\lambda_{\text{Higgs}} \sim 1$

\[
Y_D = (m_d, m_s, m_b)/\nu \\
Y_U = V_{\text{CKM}}^\dagger (m_u, m_c, m_t)/\nu
\]

\[
Y_D \approx (10^{-5}, 0.0005, 0.026)
\]

\[
Y_U \approx \begin{pmatrix}
10^{-5} & -0.002 & 0.007 + 0.004i \\
10^{-6} & 0.007 & -0.04 + 0.0008i \\
10^{-8} + 10^{-7}i & 0.0003 & 0.96
\end{pmatrix}
\]
Analog to mysterious spectral lines before QM

Explained by Bohr

Is there an analogue to the Bohr atom, we might discover at the LHC?

\[ \nu = \left( \frac{1}{n^2} - \frac{1}{m^2} \right) R \]

\[ E_n = -\frac{2\pi^2 e^4 m_e}{\hbar^2 n^2} \]
Flavor dynamics @ LHC?

Possible, but ...

1) Lack of scale

\[ \mathcal{L}_{\text{flavor}} = [Y^U]_{ij} \bar{Q}_i H_c u_j + \ldots \]

\[ \text{dim} \quad 0 + 3/2 + 1 + 3/2 = 4 \]

2) Very strong constraints from flavor physics:

Generic flavor dynamics >> 100 TeV

→ D. Straub lecture
The SM

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + iF_\mu \bar{D}_\mu \psi + h.c. + \lambda \bar{\psi} i \gamma_5 \gamma^a \psi \chi_a \phi^a \psi + \kappa \bar{\psi} \gamma^0 \gamma^5 \psi + h.c. + \frac{1}{2} m^2 \phi^2 - V(\phi) \]
What’s the problem?

\[ m_{\text{scalar}}^2 \sim \Lambda^2 \]
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\[ m^2_{\text{scalar}} \sim \Lambda^2 \]

On the Self-Energy and the Electromagnetic Field of the Electron

V. F. Weisskopf
University of Rochester, Rochester, New York
(Received April 12, 1939)

The charge distribution, the electromagnetic field and the self-energy of an electron are investigated. It is found that, as a result of Dirac’s positron theory, the charge and the magnetic dipole of the electron are extended over a finite region; the contributions of the spin and of the fluctuations of the radiation field to the self-energy are analyzed, and the reasons that the self-energy is only logarithmically infinite in positron theory are given. It is proved that the latter result holds to every approximation in an expansion of the self-energy in powers of \( e^4/\hbar c \). The self-energy of charged particles obeying Bose statistics is found to be quadratically divergent. Some evidence is given that the “critical length” of positron theory is as small as \( \hbar/(mc) \cdot \exp(-\hbar c/e^3) \).

Weisskopf, Phys. Rev. 56 (1939) 72
Electro-weak scale unstable

Quantum fluctuations destabilize weak scale

\[ E_n^{(2)} = \sum_{m \neq n} \frac{|\langle \psi_n | H^1 | \psi_m \rangle|^2}{E_n^0 - E_m^0} \]

Sensitive to highest scale \( \Lambda \)

sum over all available states
A light Higgs is unnatural

\[ V(h) = \epsilon \Lambda^2 h^2 + \lambda h^4 \]

\[ \langle h \rangle = 0 \quad \Leftrightarrow \quad \epsilon = \pm \mathcal{O}(1) \]

\[ \Lambda \gg m_W \]

\[ \langle h \rangle = \Lambda \]
A light Higgs is unnatural

\[ V(h) = \epsilon \Lambda^2 h^2 + \lambda h^4 \]

\[ \Lambda \gg m_W \]

\[ \langle h \rangle = 0 \]

No tuning:
\[ \epsilon = \pm \mathcal{O}(1) \]

Needs tuning or new physics close by
\[ \sqrt{\epsilon} \sim m_W / \Lambda \]
\[ \sim M_W / M_{\text{Planck}} \sim 80.4 / 10^{19} \approx 0.000000000000000001 \]
New physics in EW sector

Different to flavor ($M_{\text{flavor}} >> 10^3 \text{ TeV}$), the Higgs constrains only $\sim$ few TeV

\[
\frac{((h^\dagger \sigma^a h) W^a_{\mu\nu} B^{\mu\nu})}{\Lambda^2} \quad \frac{|h^\dagger D_\mu h|^2}{\Lambda^2} \quad \frac{(h^\dagger h)^3}{\Lambda^2}
\]

New dynamics possible and required, promising for LHC!
Overview

1. Motivation for new physics at the TeV scale
2. Supersymmetry
3. Composite/Little Higgs
4. Alternatives (if time allows)
Motivation
Dark matter?
Dark Energy?
Origin of quark mass and mixing hierarchies?
Strong CP?
EW strong coupling/unitarity problem?
Matter-Antimatter asymmetry?
Neutrino masses?
Inflation?
Quantum instability of Higgs mass?
Charge quantization (GUT?)?
Quantum Gravity?
...
✓
Why expect new physics at the LHC?
Dark matter? Weakly interacting massive particle (WIMP) works, but also $m_{DM} = 10^{-15}$ or $10^{12}$ GeV

Dark Energy?

Origin of quark mass and mixing hierarchies?

Strong CP?

**EW strong coupling/unitarity problem**

Matter-Antimatter asymmetry? 100 GeV? $10^{13}$ GeV?

Neutrino masses? $10^{13}$ GeV? 100 GeV?

Inflation?

**Quantum instability of the Higgs mass**

Charge quantization (GUT?)?

Quantum Gravity? TeV or $M_{Planck}$ ...

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SM without the Higgs

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}(h^0, A_\mu, W^\pm_\mu, Z_\mu, G_\mu, q, \ell) \] (unitary gauge)

\[ \sim E^4 + E^2 + \cdots \]

\[ \Lambda \approx 4\pi v \approx 3 \text{ TeV} \]

New physics has to show up below this scale
SM without the Higgs

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}(h^0, A_\mu, W^\pm_\mu, Z_\mu, G_\mu, q, \ell) \]  

(energy scale)

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Adding SM-like Higgs

SM works up to $\Lambda \gg LHC$
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SM works up to $\Lambda \gg \text{LHC}$

$$A \approx \frac{1}{v^2} \left[ s - \frac{s^2}{s - m_h^2} + \ldots \right] \rightarrow \sqrt{s} \gg v$$
Adding SM-like Higgs

SM works up to $\Lambda \gg LHC$

$$s \sim E^2 w^-$$

$$A \simeq \frac{1}{v^2} \left[ m_h^2 + \frac{m_h^4}{s} + \ldots \right] \quad \sqrt{s \gg v}$$
Adding SM-like Higgs

What if the coupling is not exactly like in the SM?

\[ \Lambda \approx 4\pi v \rightarrow \frac{4\pi v}{\sqrt{1 - a^2}} \]
Even if we measure $a < 1$, no guarantee for new physics in reach of LHC.

Example: composite pseudo-Goldstone Higgs:

$$a = \sqrt{1 - (v/f)^2} \approx 0.8 \ldots 0.9$$

$$\Lambda > 6 \ldots 8 \text{ TeV}$$
Stability and meta-stability

Tree-level

\[ V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4 \]

Cabibbo, Maiani, Parisi, Petronzio, '79; Hung '79; Lindner 86; Sher '89; …
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What happens at \( |\phi| \gg v \)? Can ignore \( \mu^2 \ll |\phi|^2 \)

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\[ V \simeq \lambda( |\phi| ) |\phi|^4 \]

decreasing at large Energies

\( \Rightarrow \)
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\[ \sim e^{-\frac{8\pi}{3/\lambda}} \]

tunneling
Stability and meta-stability

SM vacuum is **unstable but sufficiently long-lived**, compared to the age of the Universe (depends on $m_{\text{top}}$, $m_{\text{higgs}}$)

Unlikely the full story, assumes nothing but SM up to the Planck scale …

$m_h = 125.6$ GeV
$m_t = 173.2 \pm 0.9$ GeV

Planck scale

Elias-Miro et al.'12
Degrassi et al.'12
Buttazzo et al.'12
So what should be our guiding principle?
Effective Field Theory

An approximate field theory which works up to a certain energy scale ($\Lambda$), using only degrees of freedom with $m \ll \Lambda$.

Example: QED ($e, \gamma$), for $E \ll M_W$

Is the SM an EFT?

Yes! Breaks down latest at the gravity scale (details unknown).
Principle: UV insensitivity

Naturalness: absence of special conspiracies between phenomena occurring at very different length scales.

Planets do not care about QED.

QED at $E \sim m_e$ does not care about the Higgs.
Hierarchy problem

• Higgs mass sensitive to thresholds (GUT, gravity)

• Enormous quantum corrections $\mathcal{O}(\text{highest scale})$ exceed Higgs mass physical value, need to fine-tune parameters

- - - $\mathbf{x}$ - - +

bare
Hierarchy problem

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$$m_h^2(\text{physical}) = m_h^2(\text{bare}) + \sum_i a_i \Lambda^2$$
• Does the photon quantum correction matter?

• How about the other quarks (u,d,c,s,b)? Why did I only consider the top?
\[ \Lambda = 1 \text{ TeV} \]
$\Lambda = 10 \text{ TeV}$

- Physical
- Bare
- Top
- W/Z
- Higgs
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\[ H \rightarrow X \rightarrow H \quad \Rightarrow \quad \Delta m_H^2 \sim \frac{g_{\text{GUT}}^2}{16\pi^2} M_X^2 \sim (10^{15} \text{ GeV})^2 \]
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e.g. GUT

• The hierarchy problem needs a ‘hierarchy of scales’. The SM alone (no gravity, nothing else): no hierarchy, no problem!
This is not an inconsistency of physics (can always cancel bare vs. quantum) rather it helps us understand where new physics might set in.
Electron Mass

Example 1: Divergent energy of electric field

Classically:

\[ \int_{r=\Lambda^{-1}} d^3r \vec{E}^2 \simeq \alpha \Lambda \]

New physics expected at

\[ \Lambda \sim m_e / \alpha \]

vs.

\[ m_e \]
Electron Mass

Ex1: divergent energy of electric field

Classically:

\[ \int_{r=\Lambda^{-1}} d^3 r \vec{E}^2 \simeq \alpha \Lambda \]

Extend space-time symmetry, relativity + QM: predict positron

\[ \delta m_e \simeq \frac{\alpha}{\pi} m_e \log \left( \frac{\Lambda}{m_e} \right) \]

→ natural electron mass.
Another example: Pion mass

Ex2 Neutral-charged pion mass difference

\[ \delta m^2_{\pi^+} \sim \frac{3\alpha}{4\pi} \Lambda^2 < (m^2_{\pi^+} - m^2_{\pi^0})_{\text{exp}} \approx (4 \text{ MeV})^2 \]

Expect \[ \rightarrow \Lambda < 850 \text{ MeV} \]

Das et al ‘67
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\[ m_{\pi^\pm}^2 - m_{\pi_0}^2 \approx \frac{3 \alpha_{em}}{4\pi} \frac{m_\rho^2 m_{a_1}^2}{m_{a_1}^2 - m_\rho^2} \log \left( \frac{m_{a_1}^2}{m_\rho^2} \right) (m_{\pi^\pm} - m_{\pi_0}) \bigg|_{\text{TH}} \approx 5.8 \text{ MeV} \]
Naturalness disaster

• We don’t understand the cosmological constant

\[ CC = \Lambda_0 \approx (10^{-3} \text{ eV})^4 \]

\[ S = \frac{1}{16\pi G} \int d^4 x \sqrt{-g} (R - \Lambda_0) \]

\[ \delta \Lambda_0 \approx \Lambda^4 \quad \rightarrow \text{new physics at } 10^{-3} \text{ eV or } \sim \text{few mm }!?! \]
Next

Supersymmetry
(new space-time symmetry)

Composite Higgs