Gedanken Worlds without Higgs

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Electroweak theory successes

$\rightsquigarrow$ search for agent of EWSB

What the LHC *is not really* for . . .

- Find the Higgs boson,
  the Holy Grail of particle physics,
  the source of all mass in the Universe.
- Celebrate.
- Then particle physics will be over.

We are not ticking off items on a shopping list . . .

We are exploring a vast new terrain
. . . and reaching the Fermi scale

SM shortcomings

- No explanation of Higgs potential
- No prediction for M_H
- Doesn't predict fermion masses & mixings
- M_H unstable to quantum corrections
- No explanation of charge quantization
- Doesn't account for three generations
- Beyond scope: dark matter, matter asymmetry, etc.

$\rightsquigarrow$ imagine more complete, predictive extensions

Challenge: Understanding the Everyday World

What would the world be like, without a (Higgs) mechanism to hide electroweak symmetry and give masses to the quarks and leptons?

(No EWSB agent at $v \approx 246$ GeV)

Consider effects of all SM interactions!
$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

Modified Standard Model: No Higgs Sector: $\overline{\mathrm{SM}}_1$

$\mathbf{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ with massless u, d, e, ν

(treat $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ as perturbation)

Nucleon mass little changed:

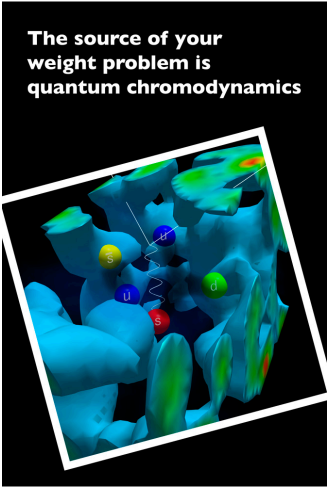
$$M_p = C \cdot \Lambda_{\mathrm{QCD}} + \dots$$

$$3\,\frac{m_u + m_d}{2} = (7.5 \text{ to } 15)\ \mathrm{MeV}$$

Small contribution from virtual strange quarks

M_N decreases by $< 10\%$ in chiral limit: $939 \rightsquigarrow 870$ MeV

QCD accounts for (most) visible mass in Universe



(*not* the Higgs boson)

Modified Standard Model: No Higgs Sector: $\overline{\text{SM}}_1$

QCD has exact $\text{SU}(2)_\text{L} \otimes \text{SU}(2)_\text{R}$ chiral symmetry.

At an energy scale $\sim \Lambda_{\text{QCD}}$, strong interactions become strong, fermion condensates $\langle \bar{q}q \rangle$ appear, and

$$\text{SU}(2)_\text{L} \otimes \text{SU}(2)_\text{R} \to \text{SU}(2)_\text{V}$$

$\leadsto$ 3 Goldstone bosons, one for each broken generator:
3 massless pions (Nambu)

Fermion condensate . . .

links left-handed, right-handed fermions

$$\langle \bar{q}q \rangle = \langle \bar{q}_{\mathrm{R}} q_{\mathrm{L}} + \bar{q}_{\mathrm{L}} q_{\mathrm{R}} \rangle$$

$$1 = \tfrac{1}{2}(1 + \gamma_5) + \tfrac{1}{2}(1 - \gamma_5)$$

$$\mathsf{Q}^a_{\mathrm{L}} = \begin{pmatrix} u^a \\ d^a \end{pmatrix}_{\mathrm{L}} \qquad u^a_{\mathrm{R}} \quad d^a_{\mathrm{R}}$$

$$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_{\mathrm{L}})_Y: \; (\mathbf{3}, \mathbf{2})_{1/3} \qquad (\mathbf{3}, \mathbf{1})_{4/3} \quad (\mathbf{3}, \mathbf{1})_{-2/3}$$

transforms as $\mathrm{SU}(2)_{\mathrm{L}}$ doublet with $|Y| = 1$

Induced breaking of $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$

Broken generators: 3 axial currents; couplings to π: $\bar{f}_\pi$

Turn on $SU(2)_L \otimes U(1)_Y$*:*

Weak bosons couple to axial currents, acquire mass $\sim g\bar{f}_\pi$

$$g \approx 0.65,\; g' \approx 0.34,\; f_\pi = 92.4 \text{ MeV} \rightsquigarrow \bar{f}_\pi \approx 87 \text{ MeV}$$

$$\mathcal{M}^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} \frac{\bar{f}_\pi^2}{4} \qquad (w_1, w_2, w_3, \mathcal{A})$$

same structure as standard EW theory

Induced breaking of $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$

Diagonalize:

$$\begin{aligned} \overline{M}_W^2 &= g^2 \bar{f}_\pi^2/4 \\ \overline{M}_Z^2 &= (g^2 + g'^2)\bar{f}_\pi^2/4 \\ \overline{M}_A^2 &= 0 \end{aligned}$$

$$\overline{M}_Z^2/\overline{M}_W^2 = (g^2 + g'^2)/g^2 = 1/\cos^2\theta_W$$

NGBs become longitudinal components of weak bosons.

$$\overline{M}_W \approx 28 \text{ MeV} \qquad \overline{M}_Z \approx 32 \text{ MeV}$$

$$(M_W \approx 80 \text{ GeV} \qquad M_Z \approx 91 \text{ GeV})$$

No fermion masses . . .

(Possible division of labor)

Inspiration for Technicolor $\rightsquigarrow$ *Extended Technicolor . . .*

Higher scales? $uu \to X^{4/3} \to e^+ d^c$ mixes p, e^+

$$\varepsilon \equiv \mathcal{M}(p \leftrightarrow e^+) \approx \frac{4\pi\alpha_{\mathrm{U}}}{M_X^2}\Lambda_{\mathrm{QCD}}^3 \approx 10^{-36}\ \mathrm{GeV}$$

(e^+, p) mass matrix

$$\mathrm{M} = \begin{pmatrix} 0 & \varepsilon \\ \varepsilon^* & M_p \end{pmatrix}$$

$$\rightsquigarrow m_e = |\varepsilon|^2 / M_p \approx 10^{-72}\ \mathrm{GeV}$$

Electroweak scale

EW theory: *choose* $v = (G_F\sqrt{2})^{-1/2} \approx 246$ GeV

$\overline{\text{SM}}$: *predict*

$$\overline{G}_F = 1/(\bar{f}_\pi^2\sqrt{2}) \approx 93.25\ \text{GeV}^{-2} \approx 8 \times 10^6\ G_F$$

Cross sections, decay rates $\times(\overline{G}_F/G_F)^2 \approx 6.4 \times 10^{13}$

Real world: $\sigma(\nu_e n \to e^- p) \approx 10^{-38}\ \text{cm}^{-2}$

$\rightsquigarrow \overline{\text{SM}}$: $\bar{\sigma}(\nu_e n \to e^- p) \approx$ few mb

Weak interaction strength $\sim$ residual strong interactions

$\overline{\mathrm{SM}}_1$: Hadron Spectrum

Pions absent (became longitudinal $W^{\pm}$, Z^0)

ρ, ω, a_1 "as usual," but

$$\rho^0 \to W^+W^-$$
$$\rho^+ \to W^+Z$$
$$\omega \to W^+W^-Z$$

$M_\Delta > M_N; \quad \Delta \to N(W^{\pm}, Z, \gamma)$

Nucleon mass little changed: look in detail

Nucleon masses . . .

"Obvious" that proton should outweigh neutron

. . . but false in real world: $M_n - M_p \approx 1.293$ MeV

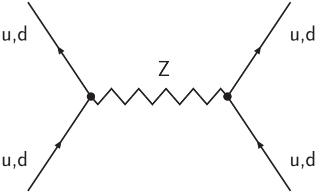
Real-world contributions,

$$\begin{aligned} M_n - M_p &= \cancel{(m_d - m_u)} - \tfrac{1}{3}(\delta m_q + \delta M_{\mathrm{C}} + \delta M_{\mathrm{M}}) \\ &\rightsquigarrow -1.7 \text{ MeV} \end{aligned}$$

. . . but weak contributions enter.

Weak contributions are not negligible

$$\overline{M}_n - \overline{M}_p\Big|_{\text{weak}} \propto dd - uu$$



$$\begin{aligned}\overline{M}_n - \overline{M}_p\Big|_{\text{weak}} &= \frac{\overline{G}_{\text{F}}\Lambda_{\text{h}}^3\sqrt{2}}{3}x_{\text{W}}(1-2x_{\text{W}}) \approx \frac{\overline{G}_{\text{F}}\Lambda_{\text{h}}^3\sqrt{2}}{24} \\ &= \frac{\Lambda_{\text{h}}^3}{3\bar{f}_\pi^2}x_{\text{W}}(1-2x_{\text{W}}) \approx \frac{\Lambda_{\text{h}}^3}{24\bar{f}_\pi^2} > 0\end{aligned}$$

$x_{\text{W}} = sin^2\theta_{\text{W}} \approx \frac{1}{4}$

perhaps a few MeV?

Bending the rules . . .

$$\left.\overline{M}_n - \overline{M}_p\right|_{\text{weak}} \text{ doesn't depend on } g$$

(in point-coupling limit)

$$\left.\overline{M}_n - \overline{M}_p\right|_{\text{em}} \propto \alpha \propto g^2 x_{\text{W}}$$

Amusing that (for fixed x_{W})
increasing or decreasing g
increases or decreases em with respect to weak

Consequences for β decay

Scale decay rate $\Gamma \sim \overline{G}_{\mathrm{F}}^2 |\overline{\Delta M}|^5 / 192\pi^3$ (rapid!)

$$\bar{\tau}_\mu \longrightarrow 10^{-19}\ \mathrm{s}$$

$n \longrightarrow p e^- \bar{\nu}_e$ or $p \longrightarrow n e^+ \nu_e$

Example: $\left|\overline{M}_n - \overline{M}_p\right| = M_n - M_p \rightsquigarrow \bar{\tau}_N \approx 14\ \mathrm{ps}$

No Hydrogen Atom?

Neutron could be lightest nucleus

Strong coupling in $\overline{\text{SM}}$

In SM, Higgs boson regulates high-energy behavior

Gedanken experiment: scattering of

$$W_L^+ W_L^- \quad \frac{Z_L^0 Z_L^0}{\sqrt{2}} \quad \frac{HH}{\sqrt{2}} \quad H Z_L^0$$

In high-energy limit, s-wave amplitudes

$$\lim_{s \gg M_H^2} (a_0) \rightarrow \frac{-G_F M_H^2}{4\pi\sqrt{2}} \cdot \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} & 0 \\ 1/\sqrt{8} & 3/4 & 1/4 & 0 \\ 1/\sqrt{8} & 1/4 & 3/4 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix} .$$

Strong coupling in $\overline{\text{SM}}$

In *standard model*, $|a_0| \le 1$ yields

$$M_H \le \left(\frac{8\pi\sqrt{2}}{3G_\text{F}}\right)^{1/2} = 4v\sqrt{\pi/3} = 1\ \text{TeV}$$

In $\overline{\text{SM}}_1$ *Gedanken* world,

$$\overline{M}_H \le \left(\frac{8\pi\sqrt{2}}{3\overline{G}_\text{F}}\right)^{1/2} = 4\bar{f}_\pi\sqrt{\pi/3} \approx 350\ \text{MeV}$$

violated because no Higgs boson $\rightsquigarrow$ strong scattering

Strong coupling in $\overline{\text{SM}}$

SM with (very) heavy Higgs boson:

s-wave W^+W^-, Z^0Z^0 scattering as $s \gg M_W^2, M_Z^2$:

$$a_0 = \frac{s}{32\pi v^2}\begin{bmatrix} 1 & \sqrt{2} \\ \sqrt{2} & 0 \end{bmatrix}$$

Largest eigenvalue: $a_0^{\text{max}} = s/16\pi v^2$

$$|a_0| \le 1 \Rightarrow \sqrt{s^\star} = 4\sqrt{\pi}v \approx 1.74 \text{ TeV}$$

$$\boxed{\overline{\text{SM}}\text{: } \sqrt{s^\star} = 4\sqrt{\pi}\bar{f}_\pi \approx 620 \text{ MeV}}$$

$\overline{\text{SM}}$ becomes strongly coupled on the hadronic scale

Strong coupling in $\overline{\text{SM}}$

As in standard model . . .

$I = 0,\ J = 0$ and $I = 1,\ J = 1$: attractive

$I = 2,\ J = 0$: repulsive

As partial-wave amplitudes approach bounds,
WW, WZ, ZZ resonances form,
multiple production of W and Z

in emulation of $\pi\pi$ scattering approaching 1 GeV

Detailed projections depend on unitarization protocol

What about atoms?

Suppose some light elements produced in BBN survive

Massless $e \Longrightarrow \infty$ Bohr radius

No meaningful atoms

No valence bonding

No integrity of matter, no stable structures

Strong-interaction symmetries

- ▷ Strong CP problem: $\mathcal{L}_\theta = \frac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu}$
  can be tuned away if at least one $m_q = 0$

- ▷ Real world: strong interactions respect P & C
  Gedanken world: long-range "strong" interactions from W, Z exchange (no pions) so P & C are violated

Look more closely at NN interaction in $\overline{\text{SM}}_1$

Nuclear force in the *Gedanken* world

▷ Size of hadrons:
$1/m_\pi \approx 1.4$ fm in real world
$1/\overline{M}_W \approx 7$ fm in $\overline{\mathrm{SM}}_1$

▷ π-exchange in real world

$$A(N_1 N_2 \to N_3 N_4) \sim \frac{g^2_{\pi NN}}{m^2_\pi} \qquad g_{\pi NN} \approx 14$$

W-exchange in *Gedanken* world

$$\overline{A}(N_1 N_2 \to N_3 N_4) \sim \frac{g^2}{8\overline{M}^2_W} \sim \frac{1}{2\overline{f}^2_\pi}$$

▸ $\overline{\mathrm{SM}}m$

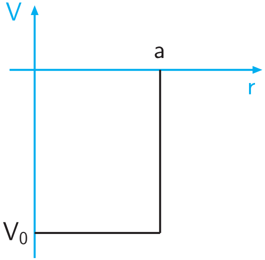
Nuclear force in the *Gedanken* world

- *NN* scattering amplitude smaller in $\overline{\text{SM}}_1$:

$$\bar{A}/A = \frac{m_\pi^2}{2\bar{f}_\pi^2 g_{\pi NN}^2} = 0.0065$$

but (as we saw) 5× longer range

- Bound states as $\xi = 2\mu V_0 a^2/\hbar^2\pi^2 \sim O(1)$



(μ: reduced mass)

$$\frac{\bar{\xi}}{\xi} = \frac{m_\pi^2}{2\bar{f}_\pi^2 g_{\pi NN}^2} \cdot \frac{m_\pi^2}{\overline{M}_W^2} \approx \frac{1}{6}$$

Not $\ll 1$

EWSB with $n_g > 1$ fermion generations: $\overline{\text{SM}}_{n_g}$

Spontaneously broken $\text{SU}(n_g)_\text{L} \otimes \text{SU}(n_g)_\text{R} \to \text{SU}(n_g)_\text{V}$

$$
\begin{aligned}
|\Pi^+\rangle &= \frac{1}{\sqrt{n_g}} \sum_{i=1}^{n_g} |u_i \bar{d}_i\rangle \\
|\Pi^0\rangle &= \frac{1}{\sqrt{2n_g}} \sum_{i=1}^{n_g} |(u_i \bar{u}_i - d_i \bar{d}_i)\rangle \\
|\Pi^-\rangle &= \frac{1}{\sqrt{n_g}} \sum_{i=1}^{n_g} |d_i \bar{u}_i\rangle .
\end{aligned}
$$

3 of $(4n_g^2 - 1)$ NGBs

$$\overline{M}_W^2 = n_g\, g^2 \bar{f}_\pi^2/4 \quad \overline{M}_Z^2 = n_g (g^2 + g'^2) \bar{f}_\pi^2/4 \quad \overline{G}_\text{F} \propto 1/n_g$$

so $\sqrt{s^\star} = 4\sqrt{\pi n_g}\bar{f}_\pi \approx 620\sqrt{n_g}$ MeV

Meson spectrum in $\overline{\mathrm{SM}}_{n_g}$

n_g^2 NGBs each with charge ± 1

$\sim$ real-world $\pi^{\pm}$ $(n_g = 1)$; & $K^{\pm}$, $D^{\pm}$, $D_s^{\pm}$ $(n_g = 2)$

$2n_g(n_g - 1)$ charge-zero NGBs with flavor

$\sim K^0, \bar{K}^0$, and $D^0, \bar{D}^0$ $(n_g = 2)$

$2n_g - 1$ self-conjugate flavor-nonsinglet NGBs

$\sim \pi^0$ $(n_g = 1)$; & η and η_c $(n_g = 2)$

After EWSB, $4n_g^2 - 4$ NGBs

$\rightsquigarrow$ very large hadrons, very long range nuclear forces

Goldberger–Treiman: $|g_A|\, M_N = f_\pi g_{\pi NN}$

Baryon spectrum in $\overline{\text{SM}}_{n_g}$

Similar to real-world spectrum . . . (weak decays)

$$\mathbf{n_q} \otimes \mathbf{n_q} \otimes \mathbf{n_q} = S_3 \oplus M_1 \oplus M_2 \oplus A_3$$

$$\begin{aligned} \dim(S_3) &= \frac{n_q(n_q+1)(n_q+2)}{3!} \\ \dim(M) &= \frac{n_q(n_q^2-1)}{3} \\ \dim(A_3) &= \binom{n_q}{3} \end{aligned}$$

$SU(2n_g)_{\text{flavor}}$ symmetry exact

equal masses within multiplets

Massless fermion pathologies . . .

Vacuum readily breaks down to e^+e^- plasma

. . . persists with GUT-induced tiny masses

"hard" fermion masses: explicit $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ breaking

NGBs $\longrightarrow$ pNGBs

$$\mathrm{SM}m\text{:}\ a_J(f\bar{f} \to W_L^+ W_L^-) \propto G_\mathrm{F} m_f E_\mathrm{cm}$$

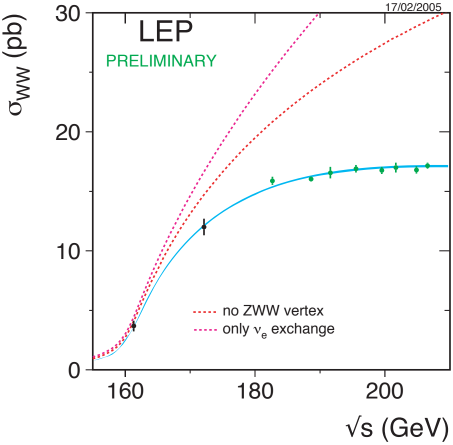
saturate p.w. unitarity at

$$\sqrt{s_f} \simeq \frac{4\pi\sqrt{2}}{\sqrt{3\eta_f}\, G_\mathrm{F} m_f} = \frac{8\pi v^2}{\sqrt{3\eta_f}\, m_f}$$

$\eta_f = 1(N_\mathrm{c})$ for leptons (quarks)

Hard electron mass: $\sqrt{s_e} \approx 1.7 \times 10^9$ GeV . . .

Gauge cancellation need not imply renormalizable theory



Hard top mass: $\sqrt{s_t} \approx 3$ TeV

Add explicit fermion masses to $\overline{\mathsf{SM}}$: $\rightsquigarrow$ $\overline{\mathsf{SM}}m$

$a_J(f\bar{f} \to W_L^+ W_L^-)$ unitarity respected up to

$$\sqrt{s^\star} = 4\sqrt{\pi n_g}\bar{f}_\pi \approx 620\sqrt{n_g}\ \text{MeV}$$

(condition from WW scattering)

$$\rightsquigarrow m_f \lesssim \frac{2\sqrt{\pi n_g}\bar{f}_\pi}{\sqrt{3\eta_f}} \approx \begin{cases} 126\sqrt{n_g}\ \text{MeV (leptons)} \\ 73\sqrt{n_g}\ \text{MeV (quarks)} \end{cases}$$

would accommodate real-world e, u, d masses

Extension to $N_c > 3$

EWSB scale is related to QCD confinement scale in $\overline{\text{SM}}$

Examine N_c scaling laws, $N_c \to \infty$ limit

QCD: hold $g_3^2 N_c =$ constant as $N_c \to \infty$

Anomaly freedom fixes quark charges:

$$Q_u = Q_d + 1 = \tfrac{1}{2}\left[1 - (2Q_e + 1)/N_c\right]$$

$SU(2)_L \otimes U(1)_Y$: $g^2 N_c,\ g'^2 N_c,\ e^2 N_c \to$ fixed as $N_c \to \infty$

…compensates $f_\pi \propto \sqrt{N_c}$

$\overline{M}_W$ independent of N_c, so $\overline{G}_F \propto 1/\sqrt{N_c}$

SM as low-energy limit of ...

LR-symmetric $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}$

$$Q = I_{3L} + I_{3R} + \tfrac{1}{2}(B - L)$$

Real world (?), $\mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L} \to \mathrm{U}(1)_Y$

Gedanken world:

QCD breaks $\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}$
$\to \mathrm{SU}(2)_V \otimes \mathrm{U}(1)_{B-L}$

At $\Lambda_V \approx 10^{-24}\Lambda_{QCD}$, $\mathrm{SU}(2)_V$ confines leptons,
leaves $\mathrm{U}(1)_{B-L}$ long-range force (not em)

SM as low-energy limit of . . .

Pati-Salam $\mathrm{SU}(4)_{\mathrm{PS}} \otimes \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{SU}(2)_{\mathrm{R}}$

lepton number as fourth color; charge quantization

Real world (?), broken to $\mathrm{SU}(3)_{\mathrm{c}} \otimes \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{U}(1)_{Y}$

Gedanken world:

SU(4)$_{\mathbf{PS}}$ breaks $\mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{SU}(2)_{\mathrm{R}} \to \mathrm{SU}(2)_{\mathrm{V}}$

At $\Lambda_{\mathrm{V}} \approx 10^{-21}\Lambda_{\mathrm{PS}}$, $\mathrm{SU}(2)_{\mathrm{V}}$ produces V-glueballs;

no residual long-range force!

"EWSB" doesn't lead to low-energy electromagnetism

In summary . . .

- $\overline{\text{SM}}$: QCD-induced $\text{SU}(2)_\text{L} \otimes \text{U}(1)_Y \to \text{U}(1)_\text{em}$
- No fermion masses; division of labor?
- No physical pions in $\overline{\text{SM}}_1$
- No quark masses: might proton outweigh neutron?
- Infinitesimal m_e: integrity of matter compromised
- $\overline{\text{SM}}$ exhibits strong W, Z dynamics below 1 GeV
- $\overline{M}_W \approx 30$ MeV in *Gedanken* world
- $\overline{G}_\text{F} \sim 10^7\, G_\text{F}$: accelerates β decay
- Weak, hadronic int. comparable; nuclear forces
- Infinitesimal m_ℓ: vacuum breakdown, e^+e^- plasma
- $\overline{\text{SM}}m$: effective theory through hadronic scale

Outlook

How different a world, without a Higgs mechanism:
preparation for interpreting LHC insights

$\overline{\text{SM}}$, $\overline{\text{SM}}m$: explicit theoretical laboratories
complement to studies that retain Higgs, vary v
(very intricate alternative realities)

Fresh look at the way we have understood the real world
(possibly > 1 source of SSB, hard fermion masses)

How might EWSB deviate from the Higgs mechanism?