Conformal and Electro-Weak Symmetry Breaking

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Topical Workshop: Rethinking Naturalness

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...wait for the upgrade ...

THIS WASN'T PREDICTED IN OUR MODEL — WHAT SHOULD WE DO?

DON'T SAY ANYTHING. MAYBE NO ONE WILL NOTICE.

...this may already point into new directions
Look again carefully at the SM as QFT

- The SM itself (without embedding) is a QFT like QED
  - infinities, renormalization ➔ only differences are calculable
  - SM itself is perfectly OK ➔ many things unexplained…

- Has (like QED) a triviality problem (Landau poles ↔ infinite \( \lambda \))
  - running \( U(1)_Y \) coupling (pole well beyond Planck scale… - like in QED)
  - running Higgs / top coupling ➔ upper bounds on \( m_H \) and \( m_t \)
    ➔ requires some scale \( \Lambda \) where the SM is embedded
    ➔ the physics of this scale is unknown ➔ explicit scale or effective

- Another potential problem is vacuum instability (↔ negative \( \lambda \))
  - does occur in SM for large top mass > 79 GeV ➔ lower bounds on \( m_H \)

SM as QFT (without an embedding):
- a hard cutoff \( \Lambda \) and the sensitivity towards \( \Lambda \) has no meaning
- renormalizable, calculable … - just like QED
SM: Triviality and Vacuum Stability Bounds

\[ \Lambda (\text{GeV}) \]

\[ m_H (\text{GeV}) \]

126 GeV < \( m_H < 174 \) GeV

SM does not exist w/o embedding
- U(1) coupling
- Higgs self-coupling

\[ \lambda (M_{\text{pl}}) \simeq 0 \]
- EW-SB radiative
- just SM?

Holthausen, ML, Lim (2011)

126 GeV is here!

RGE arguments seem to work
- we need some embedding
\[ \longleftrightarrow \] no BSM physics observed!
- just a SM Higgs

ML ‘86

\[ \Lambda \]

\[ \ln (\mu) \]

Landau pole

OLC 2016
A special Value of $\lambda$ at $M_{\text{Planck}}$?

Holthausen, ML Lim (2011)

Different conceivable special conditions:

- Vacuum stability
  \[ \lambda(M_{\text{pl}}) = 0 \ [7-12] \]

- vanishing of the beta function of $\lambda$
  \[ \beta_\lambda(M_{\text{pl}}) = 0 \ [9, 10] \]

- the Veltman condition \[13-15\]  \[ \text{Str} M^2 = 0, \]
  \[ \delta m^2 = \frac{\Lambda^2}{32\pi^2 v^2} \text{Str} M^2 \]
  \[ = \frac{1}{32\pi^2} \left( \frac{9}{4} g_2^2 + \frac{3}{4} g_1^2 + 6\lambda - 6\lambda_t^2 \right) \Lambda^2 \]

- downward flow of RG trajectories
  \[ \rightarrow \text{IR QFP} \rightarrow \text{random } \lambda \text{ flows to } m_H > 150 \text{ GeV} \]
  \[ \rightarrow m_H \sim 126 \text{ GeV flows to tiny values at } M_{\text{Planck}} \ldots \]
• Why do all these boundary conditions work?
  - suppression factors compared to random choice = $O(1)$
  - $\lambda = F(\lambda, g_i^2, \ldots) \Rightarrow$ loop factors $1/16\pi^2$
  - top loops $\Rightarrow$ fermion loops $\Rightarrow$ factors of $(-1)$

$\Rightarrow$ scenarios ‘predicting’ sufficiently suppressed (small/tiny) $\lambda$ at $M_{\text{Planck}}$ are OK
$\Rightarrow$ more precision $\Rightarrow$ selects options ; e.g. $\gamma_m = 0$ now ruled out
$\Rightarrow$ Planck scale boundary conditions seem to fit to experiment…!!!
Is the Higgs Potential at $M_{\text{Planck}}$ flat?

Holthausen, ML, Lim

Notes:
- remarkable relation between weak scale, $m_t$, couplings and $M_{\text{Planck}}$ ↔ precision
- strong cancellations between Higgs and top loops
  → very sensitive to exact value and error of $m_H$, $m_t$, $\alpha_s = 0.1184(7)$ → currently 1.8σ in $m_t$
- other physics: DM, $m_\nu$ … axions, …Planck scale thresholds… SM+ ↔ $\lambda = 0$
  → top mass errors: data ↔ LO-MC → translation of $m_{\text{pole}}$ → MS bar
  → be cautious about metastability
  → IS THERE A MESSAGE IN : $\lambda(M_{\text{planck}}) \sim 0$ ? ; and what if also $m^2 = 0$?
Re-thinking Naturalness…

think about / discuss / understand old or new modified basic concepts …
… before you write down specific models
… before you complicate things (confuse yourself…) by technical steps (like a lattice, \( \Lambda \), …) which are unphysical
… and/or before you start to discuss non-perturbative stuff

⇒ new concepts ⇒ new symmetries ⇒ ???
Interpretating special Conditions: E.g. $\lambda(M_{\text{Planck}}) = 0$

$\lambda \phi^4 \Rightarrow 0$ at the Planck scale $\Rightarrow$ no Higgs self-interaction ($V$ is flat)
$\Rightarrow m_H$ at low $E$ radiatively generated - value related to $m_t$ and $g_i$
$\Rightarrow$ SM emdeded directly / related to gravity …!? 

- What about the hierarchy problem?
  $\Rightarrow$ GR is different: Non-renormalizable!
  $\Rightarrow$ requires new concepts beyond QFT/gauge theories: … ?
  $\Rightarrow$ BAD: We have no facts which concepts are realized by nature
  $\Rightarrow$ Two GOOD aspects:

1) QFTs cannot explain absolute masses and couplings
   - QFT embedings = shifting the problem only to the next level
   $\Rightarrow$ new concepts beyond QFT might explain absolute values
2) Asymmetry SM$\leftrightarrow$Planck scale may allow new solutions of the HP

→ new non-QFT Planck-scale concepts could have mechanism which explain hierarchies

→ lost in effective theory = SM

Anaology: Type II superconductor

Ginzburg-Landau effective QFT $\leftrightarrow$ BCS theory

\[ E \approx \alpha |\phi|^2 + \beta |\phi|^4 + \ldots \]

$\leftrightarrow$ $\alpha, \beta$, dynamical details lost

→ The hierarchy problem may be an artefact of the bottom-up QFT perspective. New concepts beyond QFT at the Planck-scale could explain things top-down.
Within known Concepts: Symmetry...
The Hierarchy Problem: Not $\Lambda \rightarrow$ two explicit scalar Scales

- Renormalizable QFTs with two scalars $\varphi$, $\Phi$ with masses $m$, $M$ and a mass hierarchy $m \ll M$
- These scalars must interact since $\varphi^+\varphi$ and $\Phi^+\Phi$ are singlets
  $\Rightarrow \lambda_{\text{mix}}(\varphi^+\varphi)(\Phi^+\Phi)$ must exist in addition to $\varphi^4$ and $\Phi^4$
- Quantum corrections $\sim M^2$ drive both masses to the (heavy) scale
  $\Rightarrow$ two vastly different scalar scales are generically unstable

Therefore: If (=since) the SM Higgs field exists

$\Rightarrow$ problem: embedding with a 2nd scalar with much larger mass

$\Rightarrow$ usual solutions:

- a) new scale @TeV
- b) protective symmetry @TeV

}$\Rightarrow$ LHC !

b) is usually SUSY, but SUSY & gauge unification = SUSY GUT

$\Rightarrow$ doublet-triplet splitting problem $\Rightarrow$ hierarchy problem back

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Conformal Symmetry as Protective Symmetry

- Exact (unbroken) CS
  ➔ absence of $\Lambda^2$ and $\ln(\Lambda)$ divergences
  ➔ no preferred scale and therefore no scale problems

- Conformal Anomaly (CA): Quantum effects explicitly break CS
  existence of CA ➔ CS preserving regularization does not exist
  - dimensional regularization is close to CS and gives only $\ln(\Lambda)$
  - cutoff reg. ➔ $\Lambda^2$ terms; violates CS badly ➔ Ward Identity

  **Bardeen:** maybe CS still forbids $\Lambda^2$ divergences
  ➔ CS breaking ↔ $\beta$-functions ↔ $\ln(\Lambda)$ divergences
  ➔ anomaly induced spontaneous EWSB

**NOTE:** asymmetric logic! The fact the dimensional regularization kills a $\Lambda^2$ dependence is well known. Argument goes the other way!
Looking at it in different Ways…

• Basics of QFT: Renormalization ↔ commutator
  - $[\Phi(x),\Pi(y)] \sim \delta^3(x-y)$ ➔ delta function ➔ distribution
  - freedom to define $\delta^*\delta$ ➔ renormalization ↔ counterterms
  - along come technicalities: lattice, $\Lambda$, Pauli-Villars, MS-bar, …

• Reminder: Technicalities do not establish physical existence!

• Nice examples ➔ BPHZ-renormalization

• Symmetries are essential!

**Question:** Is gauge symmetry spoiled by discovering massive gauge bosons? ➔ NO ↔ Higgs mechanism

➔ non-linear realization of the underlying symmetry
➔ important consequence: naïve power counting is wrong

Gauge invariance ➔ only log sensitivity
Versions of QCD…

- **QCD with massless (chrial) fermions**
  - gauge + conformal symmetry
  - dimensional transmutation $\Lambda_{\text{QCD}}$
  - reference scale; everything else is scale ratios
  - no $\Lambda^2$ sensitivity – there is no other physical scale!
  - no hierarchy problem

**Question:** Do fundamental theories require absolute scales? Why not everything in relative terms? Don’t blame a theory on scale problems which you invented (a lattice, a cutoff, …)

**Important:** The conformal anomaly
- dimensional transmutation $\leftrightarrow$ $\beta$-fcts. $\leftrightarrow$ logs
Now massless scalar QCD…

- Massless scalar instead of chiral fermions
- Gauge and conformal symmetry
- Technically there seems to be a $\Lambda^2$ divergence
  ➔ but this has no meaning since (if) there is no other explicit physical scale
- Dimensional transmutation ; ➔ $\Lambda_{\text{QCD}}$
  ➔ reference scale ; everything else is scale ratios
  ➔ conformal anomaly ➔ $\beta$-fcts. ➔ only logs

Relict of conformal symmetry
 ➔ only log sensitivity
Implications

Gauge invariance $\Rightarrow$ only log sensitivity

If conformal symmetry is realized in a non-linear way $\Rightarrow$ protective relic of conformal symmetry $\Rightarrow$ only log sensitivity

- No hierarchy problem, even though there is the conformal anomaly
- Dimensional transmutation due to log running like in QCD
  $\Rightarrow$ scalars can condense and set scales like fermions
  $\Rightarrow$ use this in Coleman Weinberg effective potential calculations
  $\leftrightarrow$ most attractive channels (MAC) $\leftrightarrow$ $\beta$-functions
Implementing the Ideas at different Levels

-> at all levels: non-linear realization of conformal symmetry
Further general Comments

• New (hidden) sector \[\leftrightarrow\]\ DM, neutrino masses, …

• Question: Isn’t the Planck-Scale spoiling things?  
  \[\Rightarrow\] non-linear realization… \[\Rightarrow\] conformal gravity…  
  ideas: see e.g. 1403.4226 by A. Salvio and A. Strumia  
  K. Hamada, 1109.6109, 0811.1647, 0907.3969, …

• Question: What about inflation?  
  see e.g. 1405.3987 by K. Kannike, A. Racioppi, M. Raidal  
  or 1308.6338 by V. Khoze

• What about unification …

• UV stability: ultimate solution should be asymptotically safe (have UV-FPs) … \[\Rightarrow\] U(1) from non-abelian group

• Justifying classical scale invariance \[\Rightarrow\] …
Open points… but let’s play with the idea
Why the minimalistic SM does not work

Minimalistic:
SM + choose $\mu = 0 \iff$ CS

Coleman Weinberg: effective potential
$\Rightarrow$ CS breaking (dimensional transmutation)
$\Rightarrow$ induces for $m_t < 79$ GeV
- a Higgs mass $m_H = 8.9$ GeV

This would conceptually realize the idea, but:
Higgs too light and the idea does not work for $m_t > 79$ GeV

Reason for $m_H \ll v$: $V_{\text{eff}}$ flat around minimum
$\iff m_H \sim \text{loop factor} \sim 1/16\pi^2$

AND: We need neutrino masses, dark matter, …
Realizing the Idea via Higgs Portals

- SM scalar \( \Phi \) plus some new scalar \( \varphi \) (or more scalars)
- CS \( \rightarrow \) no scalar mass terms
- the scalars interact \( \Rightarrow \) \( \lambda_{\text{mix}}(\varphi^+\varphi)(\Phi^+\Phi) \) must exist
  
  \( \Rightarrow \) a condensate of \( <\varphi^+\varphi> \) produces \( \lambda_{\text{mix}}<\varphi^+\varphi>(\Phi^+\Phi) = \mu^2(\Phi^+\Phi) \)
  
  \( \Rightarrow \) effective mass term for \( \Phi \)

- CS anomalous … \( \rightarrow \) breaking \( \rightarrow \) only \( \ln(\Lambda) \)
  
  \( \Rightarrow \) implies a TeV-ish condensate for \( \varphi \) to obtain \( <\Phi> = 246 \) GeV

- Model building possibilities / phenomenological aspects:
  - \( \varphi \) could be an effective field of some hidden sector DSB
  - further particles could exist in hidden sector; e.g. confining…
  - extra hidden U(1) potentially problematic \( \leftrightarrow \) U(1) mixing
  - avoid Yukawas which couple visible and hidden sector
  
  \( \Rightarrow \) phenomenology safe due to Higgs portal, but there is TeV-ish new physics!
Radiative SB in conformal LR-extension of SM

(\text{use isomorphism SU(2) } \times \text{ SU(2)} \cong \text{ Spin(4) } \rightarrow \text{ representations})

\begin{align*}
\text{particle} & \quad \text{parity } \mathcal{P} & \quad \mathbb{Z}_4 & \quad \text{Spin}(1, 3) \times (\text{SU}(2)_L \times \text{SU}(2)_R) \times (\text{SU}(3)_C \times \text{U}(1)_{B-L}) \\
L_{1,2,3} = \left\{ \begin{array}{c} L_L \\ -iL_R \end{array} \right\} & \quad P^{PL}(t, -x) & \quad L_R \rightarrow iL_R & \quad \left[ \left( \frac{1}{2}, 0 \right) \left( 2, 1 \right) + \left( 0, \frac{1}{2} \right) \left( 1, 2 \right) \right] (1, -1) \\
Q_{1,2,3} = \left\{ \begin{array}{c} Q_L \\ -iQ_R \end{array} \right\} & \quad P^{PQ}(t, -x) & \quad Q_R \rightarrow -iQ_R & \quad \left[ \left( \frac{1}{2}, 0 \right) \left( 2, 1 \right) + \left( 0, \frac{1}{2} \right) \left( 1, 2 \right) \right] (3, \frac{1}{3}) \\
\Phi = \begin{pmatrix} 0 & \Phi \\ -\Phi^* & 0 \end{pmatrix} & \quad P\Phi^*P(t, -x) & \quad \Phi \rightarrow i\Phi & \quad (0, 0) \left( 2, 2 \right) (1, 0) \\
\Psi = \begin{pmatrix} \chi_L \\ -i\chi_R \end{pmatrix} & \quad P\Psi(t, -x) & \quad \chi_R \rightarrow -i\chi_R & \quad (0, 0) \left[ \left( 2, 1 \right) + \left( 1, 2 \right) \right] (1, -1)
\end{align*}

\rightarrow \text{ the usual fermions, one bi-doublet, two doublets} \\
\rightarrow \text{ a } \mathbb{Z}_4 \text{ symmetry} \\
\rightarrow \text{ no scalar mass terms } \leftrightarrow \text{ CS}
Most general gauge and scale invariant potential respecting $Z_4$

\[ V(\phi, \psi) = \frac{\kappa_1}{2} (\overline{\psi} \psi)^2 + \frac{\kappa_2}{2} (\overline{\psi} \Gamma \psi)^2 + \lambda_1 (\text{tr} \phi^\dagger \phi)^2 + \lambda_2 (\text{tr} \phi \phi + \text{tr} \phi^\dagger \phi^\dagger)^2 + \lambda_3 (\text{tr} \phi \phi - \text{tr} \phi^\dagger \phi^\dagger)^2 + \beta_1 \overline{\psi} \text{tr} \phi^\dagger \phi + f_1 \overline{\psi} \Gamma [\phi^\dagger, \phi] \psi, \]

calculate $V_{\text{eff}}$

Gildner-Weinberg formalism (RG improvement of flat directions)
- anomaly breaks CS
- spontaneous breaking of parity, $Z_4$, LR and EW symmetry
- $m_H << v$; typically suppressed by 1-2 orders of magnitude
  Reason: $V_{\text{eff}}$ flat around minimum
  $\leftrightarrow m_H \sim$ loop factor $\sim 1/16\pi^2$
  $\rightarrow$ generic feature $\rightarrow$ predictions
- everything works nicely...

requires moderate parameter adjustment for the separation of the LR and EW scale... PGB...?
New scalar representation $S \rightarrow$ QCD gap equation:

$$C_2(S)\alpha(\Lambda) \gtrsim X.$$ 

$C_2(\Lambda)$ increases with larger representations $\leftrightarrow$ condensation for smaller values of running $\alpha$

$$\mathcal{L} = \mathcal{L}_{\text{SM, } m^2 \to 0} + (D_{\mu;i,j}S_j)^\dagger(D_{\mu;k}S_k) + \lambda_{HS}H^\dagger H S - \lambda_{1_z} [\bar{S} \times S \times \bar{S} \times S]_{1_z}$$

$$\lambda_{HS} \langle S^\dagger S \rangle H^\dagger H \rightarrow \lambda_{HS} \Lambda^2 H^\dagger H$$

$$m_{h}^2 = 2\lambda_{HS} \Lambda^2$$

$$\frac{\lambda_h}{\lambda_{HS}} = \frac{\Lambda^2}{v^2}$$
Figure 3. The $S$ pair production cross section from gluon fusion channel is calculated for different values of $m_S$. The 95% confidence level exclusion limit on $\sigma \times \text{BR}$ for $\sqrt{s} = 7$ TeV by ATLAS is plotted. We assume 100% BR of $\langle S^+ S \rangle$ into two jets.
Realizing the Idea: Examples for other Directions

**SM + extra singlet: \( \Phi, \varphi \)**
Nicolai, Meissner, Farzinnia, He, Ren, Foot, Kobakhidze, Volkas

**SM + extra SU(N) with new N-plet in a hidden sector**
Ko, Carone, Ramos, Holthausen, Kubo, Lim, ML

**SM embedded into larger symmetry (CW-type LR)**
Holthausen, ML, M. Schmidt

**SM + colored scalar which condenses at TeV scale**
Kubo, Lim, ML

Since the SM-only version does not work \( \Rightarrow \) observable effects:
- Higgs coupling to other scalars (singlet, hidden sector, …)
- dark matter candidates \( \leftrightarrow \) hidden sectors & Higgs portals
- consequences for neutrino masses
Neutrino Masses = New Physics...

Simplest possibility: add 3 right handed neutrino fields

\[ \nu_L \ g_N \ \nu_R \]

\[ \nu_R \times \nu_R \]

\[ <\phi> = v \]

\[ \mathcal{L} \]

Majorana

\[ \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} \]

like quarks and charged leptons \( \Rightarrow \) Dirac mass terms (including NMS mixing)

New ingredients: 1) Majorana mass (explicit) 2) lepton number violation

6x6 block mass matrix block diagonalization \( M_R \) heavy \( \Rightarrow \) 3 light \( \nu \)'s

NEW ingredients, 9 parameters \( \Rightarrow \) SM+
Are right-handed neutrinos established?

New scalar tripelts $(3_L)$ or fermionic $1_L \rightarrow 3_L$

 gauche left-handed Majorana mass term:

$$\Rightarrow M_L \overline{LL}^c$$

Both $\nu_R$ and new singlets / triplets:

$\Rightarrow$ see-saw type II, III

$$m_\nu = M_L - m_D M_R^{-1} m_D^T$$

Higher dimensional operators: $d=5, \ldots$

$$\Rightarrow \mathcal{L}_{mass} = \kappa \cdot \overline{\nu}_L \nu_L \Phi^T \Phi$$

$$\Rightarrow M_L \overline{LL}^c$$
Radiative neutrino mass generation

SUSY, extra dimensions, …

→ inspiring options, many questions, connections to LFV, LHC, ...
→ SM+ → can/may solve two of the SM problems:
  - Leptogenesis as explanation of BAU
  - keV sterile neutrinos as excellent warm dark matter candidate
→ progress:
  - new experimental results  ...waiting...
  - theoretical guidance  ...guessing...
Guidance by the larger Picture: GUTs

Gauge unification suggests GUTs

Ingredients:
- unified gauge group
- unified particle multiplets $\leftrightarrow \nu_R$
  $\Rightarrow$ Q, L Yukawa couplings connected
  ....
  $\Rightarrow$ proton decay, ...
- generations are just copies

**Diagram:**

- $SU(5) \times U(1)$
  - $SU(3)_C \times SU(3)_L \times SU(3)_R$
- $SO(10)$
- $SU(4)_{PS} \times SU(2)_L \times SU(2)_R$
- $SU(5)$
- $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- $SU(3)_C \times SU(2)_L \times U(1)_Y$
Flavour Unification

- so far no understanding of flavour, 3 generations
- apparent regularities in quark and lepton parameters
  ➞ flavour symmetries (finite number for limited rank)
  ➞ symmetry not texture zeros

Examples:
- $U(1)$
- $SU(2)$
- $SU(3)$
- $SO(3)$
- $S(3)_L \times S(3)_R$
- $O(3)_L \times O(3)_R$
- $A_4; Z_3 \triangleleft Z_2$
- $S(3)$
- Nothing
**GUT & Flavour Unification**

- **GUT group x flavour group**
  - example: $SO(10) \times SU(3)_F$
  - SSB of $SU(3)_F$ between $\Lambda_{GUT}$ and $\Lambda_{Planck}$
  - all flavour Goldstone Bosons eaten
  - discrete sub-groups survive \(\leftrightarrow\) SSB
    - e.g. $Z_2$, $S_3$, $D_5$, $A_4$, ...
  - structures in flavour space
  - compare with data

- **aim:** distinguish models by future precision and learn about the origin of flavour
- **reality so far:** many models get killed by data (see e.g. $\theta_{13}$...)

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Hints / Arguments / … for Sterile Neutrinos

**Particle Physics:** LSND, Gallium, MiniBooNE, reactor anomaly, …

**CMB:** $N_\nu = 3.3 \pm 0.27 \rightarrow$ extra eV-ish $\nu$’s possible PLANCK 2013

**BBN:** $N_\nu = 3-4 \rightarrow$ possible e.g. Coc

**Astrophysics:** keV-ish sterile neutrinos could explain pulsar kicks
Kusenko, Segre, Mocioiu, Pascoli, Fuller et al., Biermann & Kusenko, Stasielak et al., Loewenstein et al., Dodelson, Widrow, Dolgov, …

**Dark matter:** keV sterile neutrinos are excellent WDM
Asaka, Blanchet, Shaposhnikov, … ML, Bezrukov, Hettmanperger

**Sterile $\nu$’s and improved EW fits:** TeV-ish $\nu$’s improve $\chi^2$
Akhmedov, Kartavtsev, ML, Michaels and J. Smirnov

Most likely not all true, but one is enough:

**VERY IMPORTANT IMPLICATIONS** $\rightarrow$ new direct experiments
Options for Neutrino Mass Spectra

\[ \begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} M_L & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} \]

\(M_L, \ m_D, \ M_R\) may have almost any form / values:
- zeros (symmetries)
- 0 + tiny corrections
- scales: \(M_W, M_{GUT}, \ldots\)

\(\Rightarrow\) diagonalization: 3+N EV
\(\Rightarrow\) 3x3 active almost unitary

<table>
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<tr>
<th>(M_L=0, \ m_D = M_W, \ M_R=\text{high}: \text{see-saw})</th>
<th>(M_R) singular singular-SS</th>
<th>(M_L = M_R = 0)</th>
<th>(M_L = M_R = \varepsilon) pseudo Dirac</th>
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Conformal Symmetry & Neutrino Masses


• No explicit scale ➞ no explicit (Dirac or Majorana) mass term ➞ only Yukawa couplings ⊗ generic scales

• Enlarge the Standard Model field spectrum like in 0706.1829 - R. Foot, A. Kobakhidze, K.L. McDonald, R. Volkas

• Consider direct product groups: SM ⊗ HS

• Two scales: CS breaking scale at O(TeV) + EW scale

➤ spectrum of Yukawa couplings ⊗ TeV or EW scale ➤ many possibilities
Examples

\[ \mathcal{M} = \begin{pmatrix} 0 & y_D \langle H \rangle \\ y_D^{T} \langle H \rangle & y_M \langle \phi \rangle \end{pmatrix} \]

- generically expect a TeV seesaw
- BUT: \( y_M \) might be tiny
- wide range of sterile masses \( \Rightarrow \) includes pseudo-Dirac case

Radiative masses

\( \mathcal{M} = m_L \)

or

\[ \mathcal{M} = \begin{pmatrix} \mu_1 & y_D \langle H \rangle \\ y_D^{T} \langle H \rangle & \mu_2 \end{pmatrix} \]

\( \Rightarrow \) pseudo-Dirac case

Yukawa seesaw:
SM + \( \nu_R \) + singlet
\( \langle \phi \rangle \approx \) TeV
\( \langle H \rangle \approx 1/4 \) TeV
More Examples: Inverse Seesaw

Seesaw & LNV

\[ \nu_R : (1_{SU(2)}, 0_Y, 0_{HS}) \]
\[ \nu_x : (1_{SU(2)}, 0_Y, n_{HS}) \]

\[ \epsilon = \frac{1}{2} y_D^\dagger (y_{Rx}^{-1})^* (y_{Rx}^{-1})^T y_D \cdot \frac{\langle H \rangle^2}{\langle \phi \rangle^2} \]

\[ \langle \phi \rangle > \langle H \rangle \text{ and } m_\nu \approx \mu \epsilon \]

\mu \text{ is suppressed (LNV) natural scale keV}

The punch line:
- all usual neutrino mass terms can be generated
- No explicit masses \(\Rightarrow\) all via Yukawa couplings \(\Rightarrow\) different numerical expectations

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More Flexible Neutrino Mass Spectrum

...see-saw spectrum may be rather different than usual. E.g. ...

- Leptogenesis from the decay of two remaining heavy sterile neutrinos works perfectly!  
  Bezrukov, Kartavtsev, ML

- One light sterile neutrino $\sim$ keV = DM

- Light active neutrinos < eV

$m_\nu$

Leptogenesis
Summary

- SM (+m_\nu+DM) works perfectly; no signs of new physics

- The standard hierarchy problem suggests TeV scale physics ... which did (so far...) not show up

- Revisit how the hierarchy problem may be solved
  - \( \lambda(M_{\text{Planck}}) = 0 \)? ↔ precise value for \( m_t \)
  - Embeddings into QFTs with classical conformal symmetry
    - SM: Coleman Weinberg effective potential – excluded
    - extended versions → work!
    → implications for Higgs couplings, dark matter, …
    → implications for neutrino masses
    → testable consequences @ LHC, DM search, neutrinos