# New symmetries and electro-weak symmetry breaking


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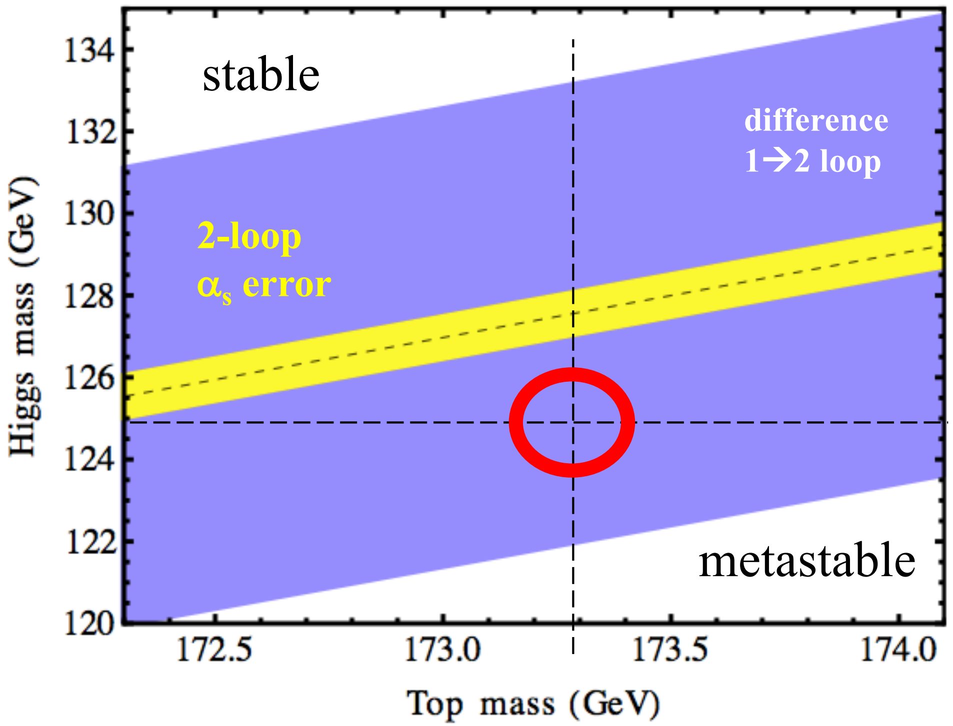
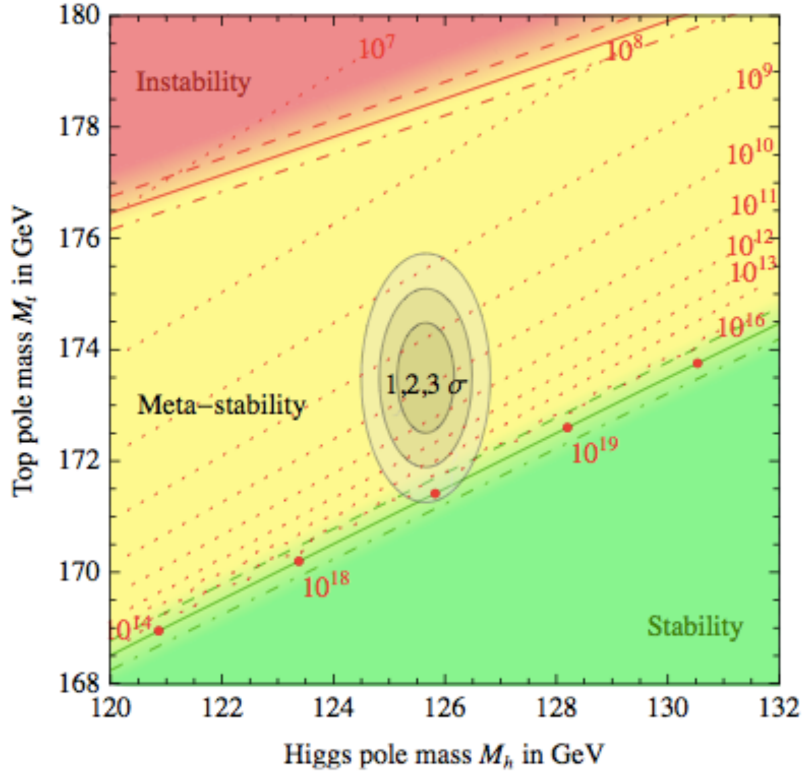
# Is the Higgs Potential at $M_{Planck}$ flat?

**Holthausen, ML, Lim (2011)** **Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia**




**Experimental values point to metastability. Is it fully established?**

➔ we need to include DM, neutrino masses, …? are all errors (EX+TH) fully included?

➔ be cautious about claiming that metastability is established

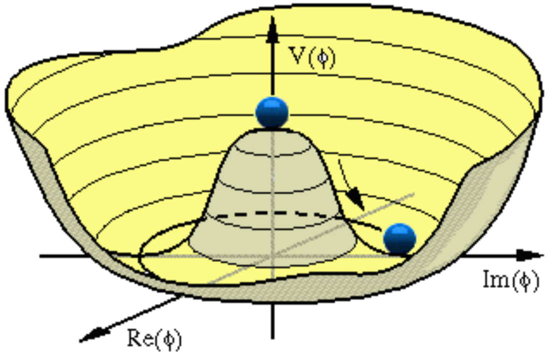
➔ An important aspect:

- a remarkable relation between weak scale, $m_t$, couplings and $M_{Planck}$ ←→ precision
- remarkable interplay between gauge, Higgs and top loops (log divergences – not $\Lambda^2$)

# Is there a Message?

- $\lambda(M_{Planck}) \simeq 0$? ➔ remarkable log cancellations
  $M_{planck}$, $M_{weak}$, gauge, Higgs & Yukawa couplings are unrelated

- remember: $\mu$ is the only single scale of the SM ➔ special role
  ➔ if in addition $\mu^2 = 0$ ➔ $V(M_{Planck}) \simeq 0$
  ➔ flat Mexican hat (<1%) at the Planck scale!




➔ conformal (or shift) symmetry as solution to the HP

➔ combined conformal & EW symmetry breaking
- conceptual issues
- realizations

# Generic Questions

- **Isn't the Planck-scale spoiling things (explicit scale, cut-off, …)?**
  ➔ renormalizable QFTs (SM) don't have cut-offs
  - explicit scales in embeddings act like a cut-off
  - important: no cutoff if the emebedding has no explicit scale

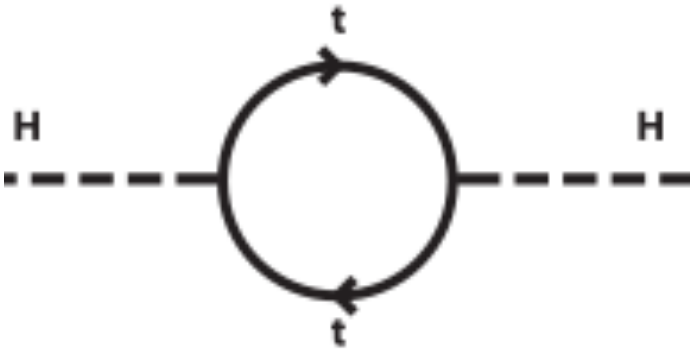
  ➔ non-linear realization of conformal symmetry… ➔ ~conformal gravity…
  ➔ protected by conformal symmetry up to conformal anomaly
  ➔ some mechanism that generates $M_{Planck}$ by dimensional transmutation
  ➔ working assumption: $M_{Planck}$ somehow generated in a conformal setting

- **Are $M_{planck}$ and $M_{weak}$ connected?**
  ➔ maybe …
  ➔ here assumed to be an independently generated scales

- **UV: ultimate solution should be asymptotically safe ➔ UV-FPs…**

- **Conceptual change for scale setting:**
  So far a rollover of scale generation: SM → BSM → GUT → gravity ($M_{Planck}$)
  here: only relative scales – absolute scale is meaningless

# Non-linear Realization of Conformal Symmetry




If conformal symmetry is realized in a non-linear way:

➔ protection by conformal symmetry

➔ only log sensitivity

←→ conformal anomaly

←→ β-functions

- **Avoids hierarchy problem, even though there is the the conformal anomaly - only logs ←→ β-functions**
- **Dimensional transmutation by log running like in QCD**
  ➔ scalar QCD: scalars can condense and set scales like fermions
  ➔ also for massless scalar QCD: **scale generation; no hierarchy**

# Why the minimalistic SM does not work

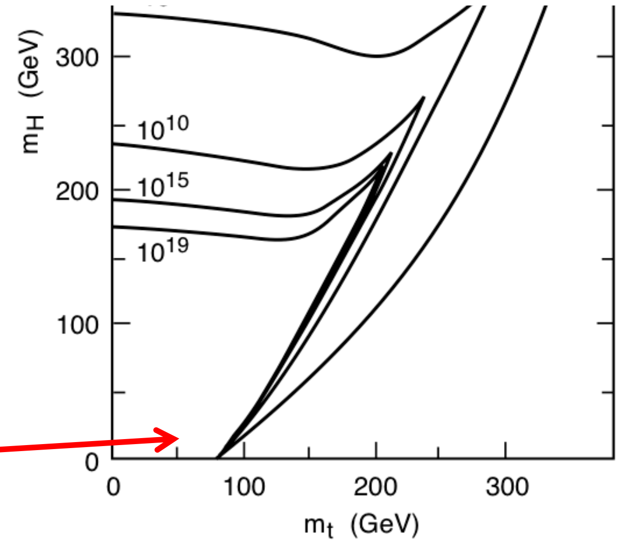
**Minimalistic version: → "SM-"**

SM + with $\mu = 0$ ←→ CS

Coleman Weinberg: effective potential

→ CS breaking (dimensional transmutation)

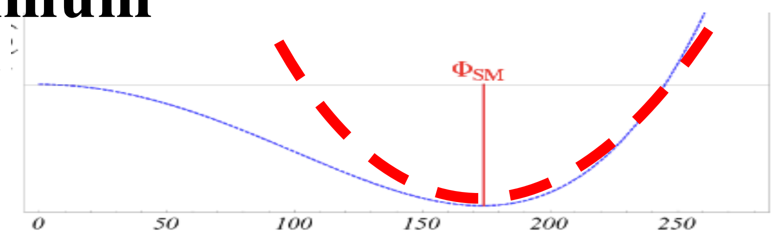
→ induces for $m_t < 79$ GeV
a Higgs mass $m_H = 8.9$ GeV




This would conceptually realize the idea, but:

Higgs too light and the idea does not work for $m_t > 79$ GeV

**Reason for $m_H \ll v$: $V_{eff}$ flat around minimum**
**←→ $m_H \sim$ radiative 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 → no scalar mass terms
- the scalar portal $\lambda_{mix}(\varphi^+\varphi)(\Phi^+\Phi)$ must exist

→ a condensate of $\langle\varphi^+\varphi\rangle$ produces $\lambda_{mix}\langle\varphi^+\varphi\rangle(\Phi^+\Phi) = \mu^2(\Phi^+\Phi)$
→ effective mass term for $\Phi$

- CS anomalous … → breaking → only $\ln(\Lambda)$

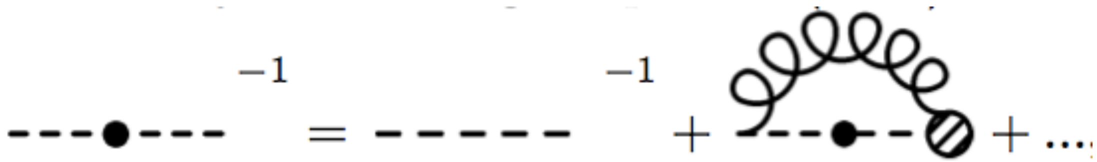
→ implies a TeV-ish condensate for $\varphi$ to obtain $\langle\Phi\rangle = 246$ GeV

- 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 ←→ U(1) mixing
  - avoid Yukawas which couple visible and hidden sector

  → phenomenology safe due to Higgs portal, but there is TeV-ish new physics!

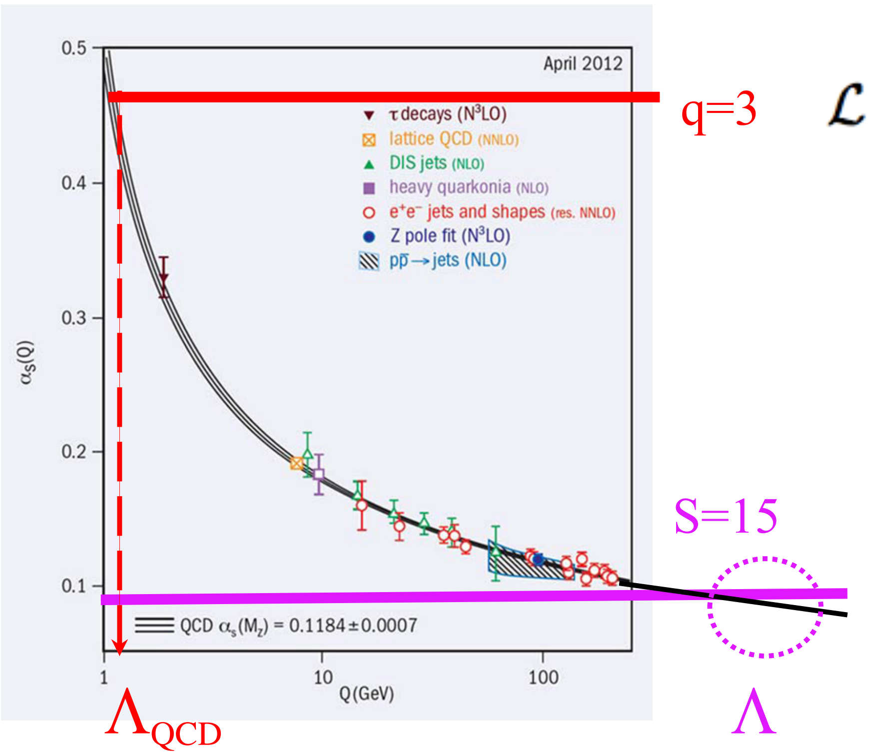
# Rather minimalistic: SM + QCD Scalar S

**J. Kubo, K.S. Lim, ML** New scalar representation S → QCD gap equation:



→ $C_2(S)\alpha(\Lambda) \gtrsim X$

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

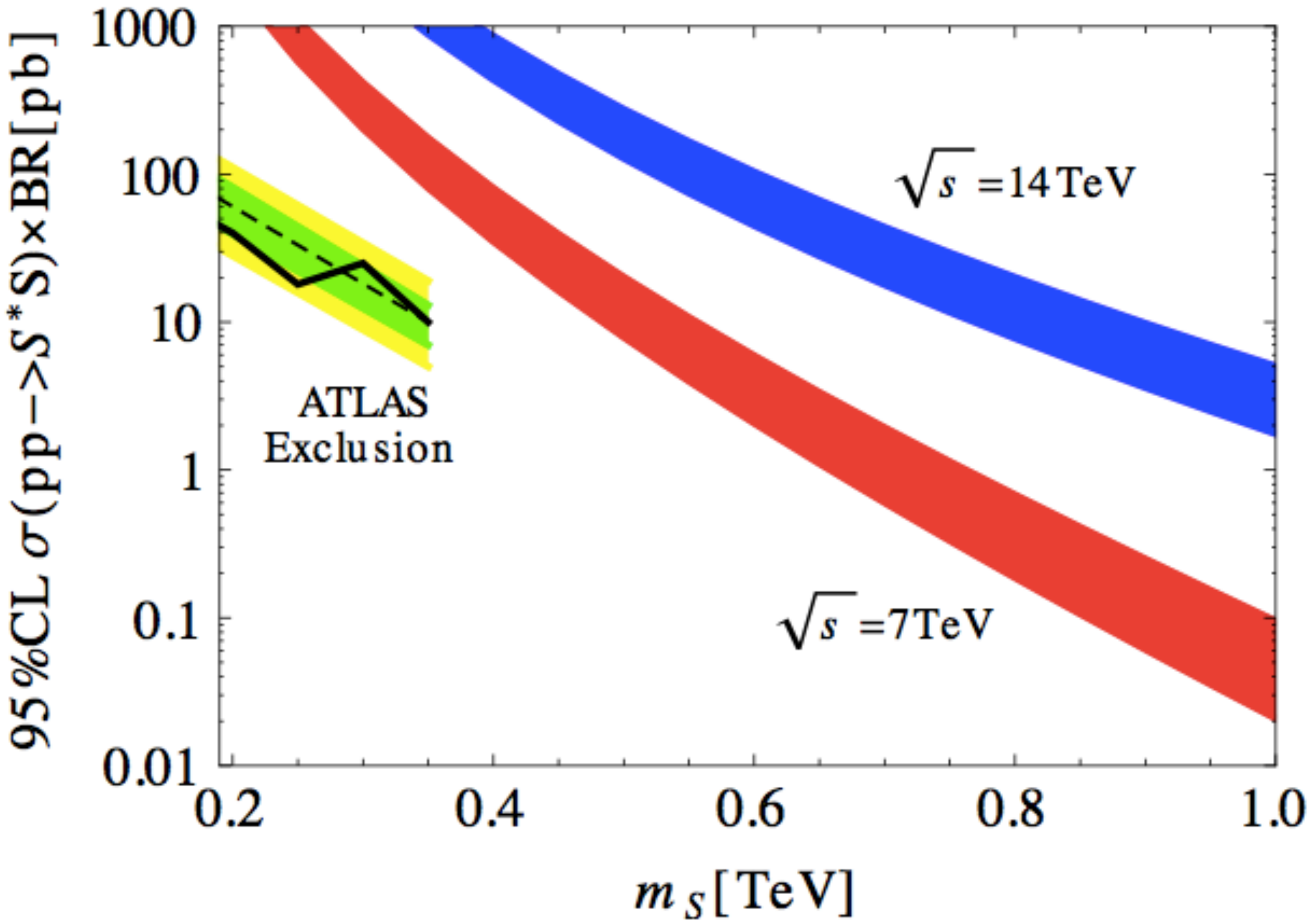



$$\mathcal{L} = \mathcal{L}_{\mathrm{SM},m^2\to 0} + (D_{\mu,ij}S_j)^\dagger (D^\mu_{ik}S_k) + \lambda_{HS}H^\dagger H S^\dagger S - \lambda_{1_i}\left[\bar{\boldsymbol{S}}\times\boldsymbol{S}\times\bar{\boldsymbol{S}}\times\boldsymbol{S}\right]_{\mathbf{1}_i}$$

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

$$m_h^2 = 2\lambda_{HS}\Lambda^2 \qquad \frac{\lambda_h}{\lambda_{HS}} = \frac{\Lambda^2}{v^2}$$

# Phenomenology




S pair production cross section from gluon fusion (assumed: 100% BR into two jets)

# Realizing this Idea: Left-Right Extension

**M. Holthausen, ML, M. Schmidt**

## Radiative SB in conformal LR-extension of SM

(use isomorphism SU(2) × SU(2) $\simeq$ Spin(4) → representations)

| particle | parity $\mathcal{P}$ | $\mathbb{Z}_4$ | $\mathrm{Spin}(1,3) \times (\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R) \times (\mathrm{SU}(3)_C \times \mathrm{U}(1)_{B-L})$ |
|---|---|---|---|
| $\mathbb{L}_{1,2,3} = \begin{pmatrix} L_L \\ -\mathrm{i}L_R \end{pmatrix}$ | $P\mathbb{PL}(t,-x)$ | $L_R \to \mathrm{i}L_R$ | $\left[\left(\underline{\mathbf{\tfrac{1}{2}}},\underline{\mathbf{0}}\right)(\underline{\mathbf{2}},\underline{\mathbf{1}}) + \left(\underline{\mathbf{0}},\underline{\mathbf{\tfrac{1}{2}}}\right)(\underline{\mathbf{1}},\underline{\mathbf{2}})\right](\underline{\mathbf{1}},-1)$ |
| $\mathbb{Q}_{1,2,3} = \begin{pmatrix} Q_L \\ -\mathrm{i}Q_R \end{pmatrix}$ | $P\mathbb{PQ}(t,-x)$ | $Q_R \to -\mathrm{i}Q_R$ | $\left[\left(\underline{\mathbf{\tfrac{1}{2}}},\underline{\mathbf{0}}\right)(\underline{\mathbf{2}},\underline{\mathbf{1}}) + \left(\underline{\mathbf{0}},\underline{\mathbf{\tfrac{1}{2}}}\right)(\underline{\mathbf{1}},\underline{\mathbf{2}})\right](\underline{\mathbf{3}},\tfrac{1}{3})$ |
| $\Phi = \begin{pmatrix} 0 & \Phi \\ -\tilde{\Phi}^\dagger & 0 \end{pmatrix}$ | $\mathbb{P}\Phi^\dagger\mathbb{P}(t,-x)$ | $\Phi \to \mathrm{i}\Phi$ | $(\underline{\mathbf{0}},\underline{\mathbf{0}})(\underline{\mathbf{2}},\underline{\mathbf{2}})(\underline{\mathbf{1}},0)$ |
| $\Psi = \begin{pmatrix} \chi_L \\ -\mathrm{i}\chi_R \end{pmatrix}$ | $\mathbb{P}\Psi(t,-x)$ | $\chi_R \to -\mathrm{i}\chi_R$ | $(\underline{\mathbf{0}},\underline{\mathbf{0}})[(\underline{\mathbf{2}},\underline{\mathbf{1}}) + (\underline{\mathbf{1}},\underline{\mathbf{2}})](\underline{\mathbf{1}},-1)$ |

**→ the usual fermions, one bi-doublet, two doublets**

**→ a $Z_4$ symmetry**

**→ no scalar mass terms ←→ CS**

## ➔ Most general gauge and scale invariant potential respecting Z4

$$\mathcal{V}(\Phi,\Psi) = \frac{\kappa_1}{2}\left(\overline{\Psi}\Psi\right)^2 + \frac{\kappa_2}{2}\left(\overline{\Psi}\Gamma\Psi\right)^2 + \lambda_1\left(\mathrm{tr}\Phi^\dagger\Phi\right)^2 + \lambda_2\left(\mathrm{tr}\Phi\Phi + \mathrm{tr}\Phi^\dagger\Phi^\dagger\right)^2 + \lambda_3\left(\mathrm{tr}\Phi\Phi - \mathrm{tr}\Phi^\dagger\Phi^\dagger\right)^2$$
$$+ \beta_1\,\overline{\Psi}\Psi\mathrm{tr}\Phi^\dagger\Phi + f_1\,\overline{\Psi}\Gamma[\Phi^\dagger,\Phi]\Psi\,,$$

➔ calculate $V_{eff}$

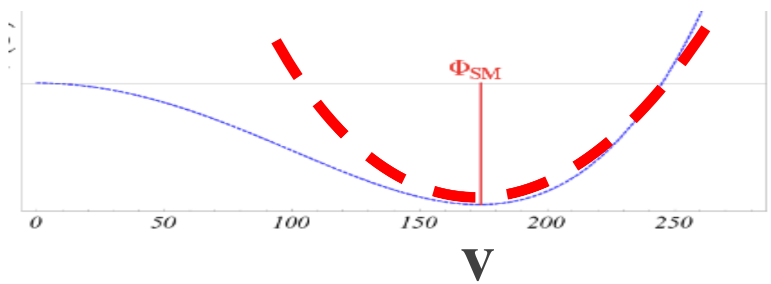
➔ Gildner-Weinberg formalism (RG improvement of flat directions)

- 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: $V_{eff}$ flat around minimum

  ←➔ $m_H \sim$ loop factor $\sim 1/16\pi^2$

  ➔ generic feature ➔ predictions
- everything works nicely…




➔ requires moderate parameter adjustment for the separation of the LR and EW scale… PGB…?

# SM ⊗ hidden $SU(3)_H$ Gauge Sector

Holthausen, Kubo, Lim, ML

- **hidden $SU(3)_H$:**

$$\mathcal{L}_{\rm H} = -\frac{1}{2}{\rm Tr}\ F^2 + {\rm Tr}\ \bar{\psi}(i\gamma^\mu D_\mu - yS)\psi$$

gauge fields ; $\psi = 3_H$ with $SU(3)_F$ ; **S = real singlet scalar**

- **SM coupled by S via a Higgs portal:**

$$V_{{\rm SM}+S} = \lambda_H (H^\dagger H)^2 + \frac{1}{4}\lambda_S S^4 - \frac{1}{2}\lambda_{HS} S^2 (H^\dagger H)$$

- **no scalar mass terms**
- **use similarity to QCD, use NJL approximation, …**
- **χ–ral symmetry breaking in hidden sector:** $SU(3)_L x SU(3)_R$ → $SU(3)_V$ ➔ **generation of TeV scale**

➔ **transferred into the SM sector through the singlet S**

➔ **dark pions are PGBs: naturally stable ➔ DM**

# Realizing the Idea: Specific Realizations

## SM + extra singlet: Φ, φ

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, (Hambye, Strumia) , …

## SM embedded into larger symmetry (CW-type LR)

Holthausen, ML, M. Schmidt

## SM + QCD colored scalar which condenses at TeV scale

Kubo, Lim, ML

**Since the SM-only version does not work → observable effects:**

- Higgs coupling to other scalars (singlet, hidden sector, …)
- dark matter candidates ↔ hidden sectors & Higgs portals
- consequences for neutrino masses

# Conformal Symmetry & Neutrino Masses

ML, S. Schmidt and J.Smirnov

- **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) + induced EW scale**

**Important consequence for fermion mass terms:**
→ spectrum of Yukawa couplings ⊗ TeV or EW scale
→ interesting consequences ←→ Majorana mass terms are no longer expected at the generic L-breaking scale → anywhere

# Examples

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

**Yukawa seesaw:**

SM + $\nu_R$ + singlet

$\langle\phi\rangle \approx$ TeV

$\langle H\rangle \approx 1/4$ TeV

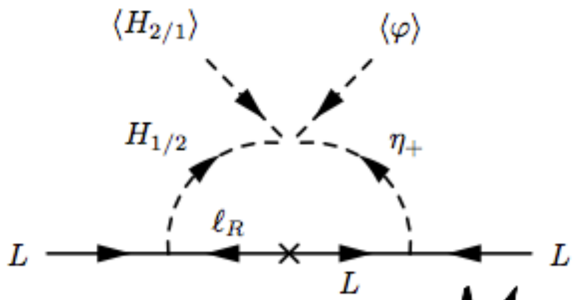
➔ generically expect a TeV seesaw

BUT: $y_M$ can be tiny

➔ wide range of sterile masses ➔ including pseudo-Dirac case

➔ suppressed $0\nu\beta\beta$

**Radiative masses**




$\mathcal{M} = m_L$ or

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

➔pseudo-Dirac case

The punch line:
all usual neutrino mass terms can be generated

→ suitable scalars
→ no explicit masses
all via Yukawa couplings
→ different numerical expectations

# Another Example: Inverse Seesaw

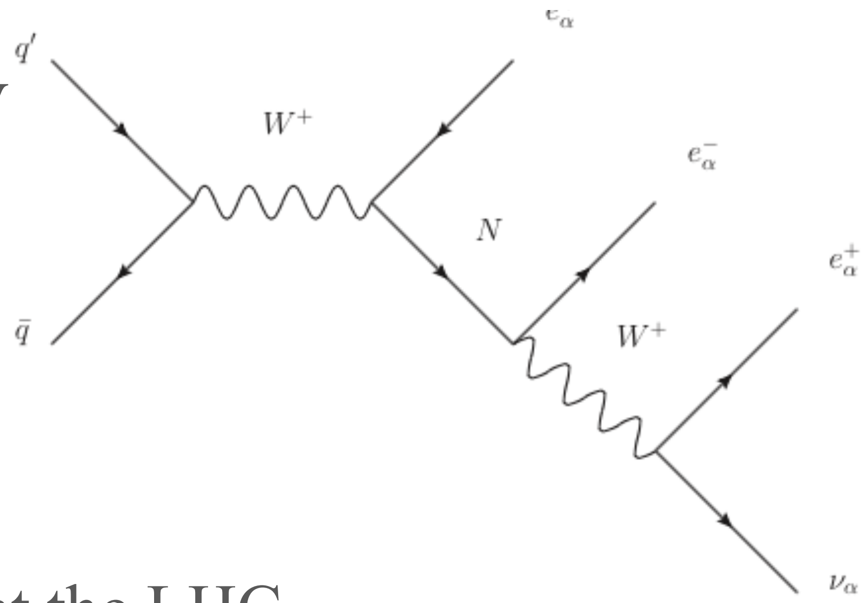
$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

Humbert, ML, J. Smirnov

| | $H$ | $\phi_1$ | $\phi_2$ | $L$ | $\nu_R$ | $N_R$ | $N_L$ |
|---|---|---|---|---|---|---|---|
| $U(1)_X$ | 0 | 1 | 2 | 0 | 0 | 1 | 1 |
| Lepton Number | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| $U(1)_Y$ | 1 | 0 | 0 | -1 | 0 | 0 | 0 |
| $SU(2)_L$ | 2 | 1 | 1 | 2 | 1 | 1 | 1 |

$$\mathcal{M} = \begin{pmatrix} 0 & y_D\langle H\rangle & 0 & 0 \\ y_D\langle H\rangle & 0 & y_1\langle\phi_1\rangle & \tilde{y}_1\langle\phi_1\rangle \\ 0 & y_1\langle\phi_1\rangle & y_2\langle\phi_2\rangle & 0 \\ 0 & \tilde{y}_1\langle\phi_1\rangle & 0 & \tilde{y}_2\langle\phi_2\rangle \end{pmatrix}$$

- ➔ light eV "active" neutrino(s)
- ➔ two pseudo-Dirac neutrinos; m≃TeV
- ➔ sterile state with μ ≈ keV




- ➔tiny non-unitarty of PMNS matrix
- ➔tiny lepton universality violation
- ➔suppressed 0νββ decay ←!
- ➔lepton flavour violation
- ➔tri-lepton production could show up at the LHC
- ➔keV neutrinos as warm dark matter →

# Implications for Neutrino Mass Spectra

3x3 matrix

3 0 … N 3xN NxN

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

<u>Usually:</u>

$M_L$ tiny or 0, $M_R$ heavy

→ see-saw & variants

light sterile: F-symmetries…

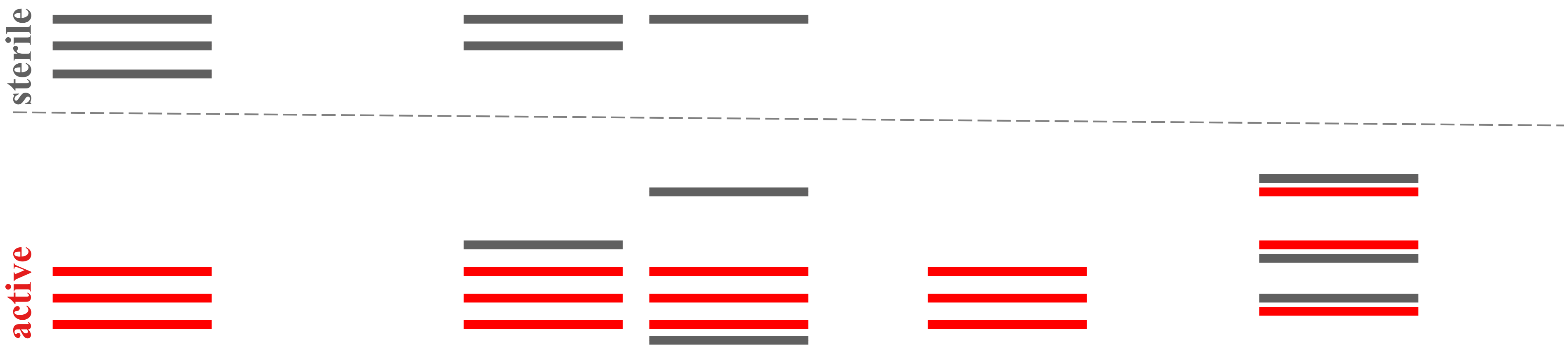
<u>Now:</u>

<u>$M_L$, $M_R$ may have any value:</u>

➔ diagonalization: 3+N EV

➔ 3x3 active almost unitary

| $M_L=0$, $m_D = M_W$, $M_R$=high: see-saw | $M_R$ singular singular-SS | $M_L = M_R = 0$ Dirac | $M_L = M_R = \varepsilon$ pseudo Dirac |
|---|---|---|---|



# Conformal Symmetry & Dark Matter

**Different natural and viable options:**

1) A keV sterile neutrino is in all cases easily possible

2) New particles which are fundamental or composite DM candidates:
   - hidden sector pseudo-Goldstone-bosons
   - stable color neutral bound states from new QCD representations

➔ some look like WIMPs
➔ others are extremely weakly coupled (via Higgs portal)
➔ or even coupled to QCD (threshold suppressed…)

# Emerging Internal Symmetries from Effective Spacetimes

**1703.10188: ML, S. Ohmer**

**Can global internal and spacetime symmetries be connected without supersymmetry?**

Re-visit ingredients of the Coleman-Mandula theorem: …

➔ G locally isomorphic to

**Poincare group $P(1,3) \otimes$ "internal symmetries"**

Important ingredient: **fundamental 4d space-time**

➔ **new directions if 4d Minkowski spacetime is effective:**

- external symmetries which induce internal symmetries in effective 4-d theories
- internal degrees of freedom and spacetime symmetries can mix in agreement with the Coleman-Mandula theorem

# A simple Example

Consider: D = 4 + d, i.e. d extra dimensions and ***$M_4 \times \Sigma_d$* spacetime**
with 4d Minkowski spacetime $M_4$ and d-dim. space $\Sigma_d$ with internal symmetry $G_d$
➔ spacetime symmetry factorizes ***$G \rightarrow P(1,3) \otimes G_d$***

If the space described by ***$G_d$*** is translational invariant
➔(4+d) momentum $P^A = \int d^3x\, d^dy\, T^{0A}$ and energy-momentum tensor $T^{AB}$ conserved

Assume $m^2 = P^{\dagger}_A{}^* P^A$ commutes with all group generators
➔ particle momenta in the extra dim. contribute to the energy-momentum relation

$$E^2 = m^2 + |\vec{p}|^2 + \left(p_4^2 + \cdots + p_{D-1}^2\right)$$

although the generators $P^a$ commute with all generators of P

**The new conserved charges do not discretize 4d scattering processes:**
➔ from a 4d perspective: scattering respects additional internal symmetries

**CM:** Factorization of the general symmetry group of the S-matrix G can also include additional spacetime symmetries **$G \rightarrow P(1,3) \otimes G_d \otimes$ "internal symmetries"**
**Examples:** KK theories with UEDs for dark matter ...

# Rotational Symmetries

4d spacetime is also rotational invariant
➔ natural to consider rotational symmetries in extra dimensions

simplest case: d=2, i.e. two extra space-like dimensions

extra spacetime $\Sigma_2 \cong \mathbb{R}^2$ with spacetime symmetry $G_2 \cong \mathbb{R}^2 \rtimes SO(2)$

full spacetime $\mathcal{M}_4 \times \mathbb{R}^2$ with symmetry $\mathcal{P}(1,3) \otimes \left(\mathbb{R}^2 \rtimes SO(2)\right)$

**Again, we find two additional conserved momenta:**
➔ "hidden" spin in the extra plane which, for d=2 can take values $s_h \in \mathbb{R}$

**From a 4d perspective, this corresponds to a global U(1) symmetry**
In other words: The 4d U(1) charge can be identified with the "hidden" spin $s_h$.

# Mixed Symmetries

**Cases where global internal and spacetime symmetries**

- **mix in agreement with the Coleman-Mandula theorem**
- **can be combined in a single global symmetry**

assume that spacetime arises effectively
elementary particles are irreducible representations of global spacetime symmetry

$$\boldsymbol{P(1,3) \otimes G_3} \text{ with } G_3 \cong \mathbb{R}^3 \rtimes SU(3)$$

of spacetime $\mathbf{M_4 \otimes \Sigma_3}$

The **global SU(3)** symmetry mixes an internal **global U(1)$_\mathbf{I}$** symmetry and the rotational spacetime symmetry described by the **compact group SU(2)**

The fact that the SU(3) symmetry mixes global internal and spacetime symmetries becomes evident upon compactification of one extra dimension onto a circle ➔ spacetime breaks to

$$\mathcal{M}_4 \times \mathbb{R}^3 \to \mathcal{M}_4 \times \mathbb{R}^2 \times S^1 \quad ➔ \quad SU(3) \to U(1)_I \otimes U(1)_S$$

discrete "hidden" spin ➔ **copies with different mass ➔ "generations"**

# Summary

- **SM works perfectly; (so far) no signs of new physics**

- **The old hierarchy problem…? No new physics observed**
  $\lambda(M_{Planck}) = 0$ ? ←→ **precise value for $m_t$ → is there a message?**

**→ Embedings into QFTs with conformal symmetry**

→ implications for BSM phenomenology

→ implications for Higgs couplings, dark matter, …

→ implications for neutrino masses

**→ testable consequences: @LHC, dark matter, neutrinos**

- **Emerging internal symmetries from effective spacetimes**

→ interesting possibilities & phenomenology