

A model of flavor with exponentially spread Yukawa couplings

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After the discovery [1] of the Higgs boson [2] at the LHC, the only unexplained sector in the standard model (SM) is the flavour sector.

SM Yukawa couplings seem not to be connected to any known local or global symmetry. Instead, they resemble arbitrary dimensionless numbers spanning over 6 orders of magnitude for charged fermions and at least 12 orders of magnitude if the SM neutrinos are Dirac particles.

Two main approaches so far

- **Froggat-Nielsen Mechanism**
- **Fermions in different branes of Extradimensions**

Froggat-Nielsen Mechanism, that introduces $U(1)_F$ flavour symmetric non-renormalizable operators involving a large number of scalar flavon fields that are suppressed by a large cut-off scale Λ . When the flavon ϕ obtains a vacuum expectation value (VEV) $\langle\phi\rangle$, effective Yukawa couplings Y are induced as powers of the expansion parameter $\lambda \sim \langle\phi\rangle/\Lambda$ as $Y \sim \lambda^n$.

Extra-dimensions

fermions in different branes that are located in different places in extra dimensions [7]. The Yukawa couplings are induced due to overlaps of the fermion wave-functions with the Higgs wave-function in extra dimensions. This scenario allows for exponential parameterisation of the measured Yukawa couplings,

- Main idea is to shift the origin of fermion masses, with **chiral (ChSB)** and **flavor symmetry breaking**, in a **dark sector**
- Then communicate this “flavor” and ChSB by some Higgs portal type of **scalar messenger fields** to the SM sector
- Yukawa coupling (set to zero at tree level by a Z_2 symmetry) are induced at 1-loop by exchange of messengers + SSB of Z_2
- There exists a mechanism to generate fermion masses that are exponential spread → we apply it to the Dark Sector
- **BUT mechanism of ChSB this requires :**
 - dark fermions (**N = number of SM fermions, but SM singlet**)
 - charged under an exact **$U(1)_F$ gauge symmetry**
 - dark fermions have different $U(1)_F$ charges
 - $U(1)_F$ gauge sector has a **Lee-Wick term** (higher derivative)

U(1) Lee-Wick model

In the seminal papers [11, 12] Lee and Wick proposed a new approach to quantum field theories that prompted the construction of more general theories in which the S-matrix is fully unitary, although the Lagrangian is not Hermitian.

This required the introduction of negative norm states which are associated with massive unstable particles. However, despite the presence of an indefinite metric, unitarity can be recovered, provided the negative norm states are massive and have a finite decay width

[11] T. D. Lee and G. C. Wick, Nucl. Phys. B **9**, 209 (1969).

[12] T. D. Lee and G. C. Wick, Phys. Rev. D **2**, 1033 (1970).

- The regulator of Pauli-Villars plays a role of a physical DOF
- Higher derivative term contains two poles: one is a negative norm state (ghost)
- If it has decay width, time dependence grows exponentially
- Lee-Wick shown that if the ghost pole has an imaginary part there is a way to make the theory consistent, avoiding that time-dependence grows exponentially, with unitary S matrix.
- This requires a modification of usual integration contour in Feynman diagrams
- Advantages: UV behaviour of the theory is improved
- We show that a vectorial $U(1)$ gauge theory with Lee-Wick term when coupled to fermions can induce spontaneous ChSB

Chiral symmetry breaking induced by a $U(1)$ Lee-Wick term

a massless Dirac field ψ , minimally coupled to a $U(1)_F$ gauge theory, a higher derivative term in the pure gauge sector of the $U(1)_F$ Lagrangian $\mathcal{L}$ as

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\gamma^\mu D_\mu\psi + \frac{1}{\Lambda^2} \partial^\alpha F_{\alpha\mu} \partial^\beta F_\beta{}^\mu \quad (2)$$

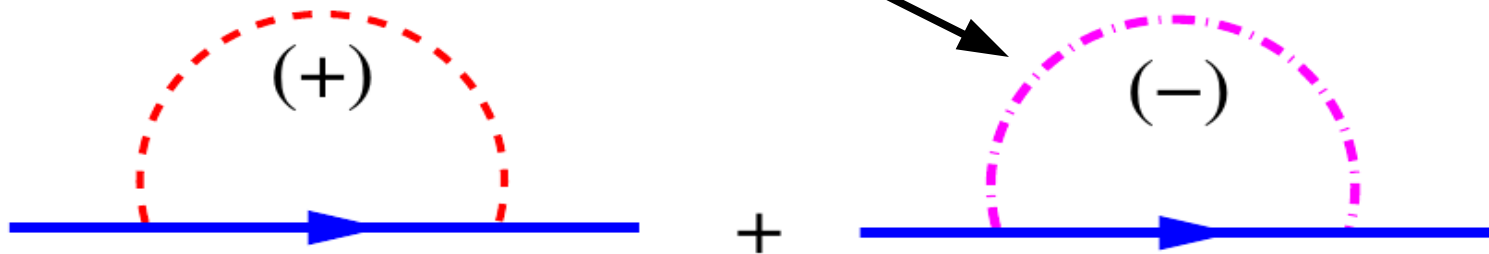
Let consider the Nambu – Jona-Lasinio mechanism

fermion mass term arises as a non-trivial solution of the self-consistent mass gap equation, namely

$$m = \Sigma(\hat{p}, m)|_{\hat{p}=m} , \quad (3)$$

Now, due to the presence of the indefinite metric and $U(1)_F$ gauge symmetry for the Lagrangian in Eq.(2), the self-energy Σ turns out to be finite at one loop and gauge invariant

Massive ghost photon of mass $\sim \Lambda$



$$m = \Sigma(\hat{p}, m)|_{\hat{p}=m}$$

In the weak coupling regime, the solution exists only for $m \ll \Lambda$

$$m = -\frac{\alpha m}{2\pi} \int_0^1 dx (2-x) \log \left(\frac{m^2}{\Lambda^2} \frac{(1-x)^2}{x} \right) + \mathcal{O}\left(\frac{m^2}{\Lambda^2}\right)$$

the sign in front of integral is crucial for the existence of the solution $\rightarrow$ depends on the spin nature of interaction (scalars have $+$ $\rightarrow$ no solution in weak coupling regime)

Solution

$$m = \Lambda \exp \left\{ -\frac{2\pi}{3\alpha} + \frac{1}{4} \right\} \quad \alpha = g^2/4\pi$$

Resummation of large $\alpha^n \log^n(\Lambda/m)$

 $m = \Lambda \exp \left\{ -\frac{2\pi}{3\alpha(\Lambda)} + \frac{1}{4} \right\}$

or equivalently, by requiring m to be RGE invariant

$$m = \Lambda \exp \left\{ -\frac{2\pi}{3\alpha(\mu)} + \frac{1}{4} \right\} \left(\frac{\Lambda}{\mu} \right)^{\frac{4}{9}}$$

Notice the non-perturbative structure of the solution as function of α

Case of N-fermions

Case of universal charges $\longrightarrow$ mass degeneracy

Relation between α evaluated at Λ and m scales

$$\alpha(\Lambda) = \alpha(m) \left(1 + \frac{4}{9} N_f \right)$$

Case of non-universal charges

$$m_f = \Lambda \exp \left\{ -\frac{2\pi}{3\alpha(\Lambda)q_f^2} + \frac{1}{4} \right\}$$

Mass degeneracy is removed $\rightarrow$ mass splitting is exponentially spread

This suggests that SM flavor might have origin from this mechanism

Now, it is tempting to speculate whether this ChSB pattern for the fermion masses could be consistent with the observed mass spectrum of quarks and leptons.

Apply to the SM fermions (No Higgs mechanism)

$$\alpha^{-1} = \frac{3}{2\pi} \frac{q_e^2 q_\mu^2 \log \left(\frac{m_e}{m_\mu} \right)}{q_e^2 - q_\mu^2},$$

$$\Lambda = m_e \left(\frac{m_\mu}{m_e} \right)^{\frac{q_\mu^2}{q_\mu^2 - q_e^2}}.$$

If we assign, for example, the charges in the lepton sector as a sequence of integer numbers as $q_e = 4$, $q_\mu = 5$, $q_\tau = 6$, we get

$$\alpha^{-1}(\Lambda) \simeq 113, \quad \text{and} \quad \Lambda \simeq 1.4 \text{ TeV}. \quad (13)$$

prediction for the tau mass $\Rightarrow m_\tau \simeq 1.9 \text{ GeV}$.

prediction for the heaviest neutrino $\Rightarrow m_{\nu_\tau} \simeq 5 \text{ eV}$

Model phenomenologically ruled out

- No Yukawa couplings
- when embedded in SM there is perturbative unitary breaking
- $U(1)$ interaction coupled to quarks and lepton is too strong !

How to embed this idea in the SM ?

How to transmit the ChSB to the Yukawa couplings ?

main idea is to assume that this mechanism is acting on fundamental fermions which belong to a dark sector. These fermions must be singlet under the SM gauge group. Then, the flavor and ChSB of the dark sector is transferred to the SM Yukawa couplings by Higgs portal type messenger fields.

Scalar messengers fields has same quantum numbers as quarks and Leptons (resemble squarks and slepton of SUSY models)

Yukawa couplings induced at 1-loop, turn out to be finite and proportional to the ChSB terms (fermion masses) of Dark Sector

We introduce a Z_2 symmetry $H \rightarrow -H$ to forbid Yukawa couplings at tree-level $\rightarrow$ spontaneously broken.

Lagrangian of the Dark Sector

$$\begin{aligned}\mathcal{L}_{DS} = & i \sum_i (\bar{Q}^{U_i} \mathcal{D}_\mu \gamma^\mu Q^{U_i} + \bar{Q}^{D_i} \mathcal{D}_\mu \gamma^\mu Q^{D_i}) \\ & + \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{\Lambda^2} \partial^\mu F_{\mu\alpha} \partial_\nu F^{\nu\alpha},\end{aligned}$$

In addition to the Higgs field we need to introduce a singlet scalar field **S**, that is odd under parity symmetry as Higgs and gets a vev $\langle \mathbf{S} \rangle = \mu$

In the case in which the scalar messenger masses are much larger than the dark fermion masses, by using dimensional analysis, the generated Yukawa couplings are expected to be of the form

$$Y_i \sim \frac{M_{Q_i} \mu L}{\bar{m}^2}, \quad (17)$$

 **mass of Dark fermions**

Messenger sector

- $2N_f$ complex scalar $SU(2)_L$ doublets: $\hat{S}_L^{U_i}$ and $\hat{S}_L^{D_i}$,
- $2N_f$ complex scalar $SU(2)_L$ singlets: $S_R^{U_i}$ and $S_R^{D_i}$,
- one real $SU(2)_L \times U(1)_Y$ singlet scalar: S_0 ,

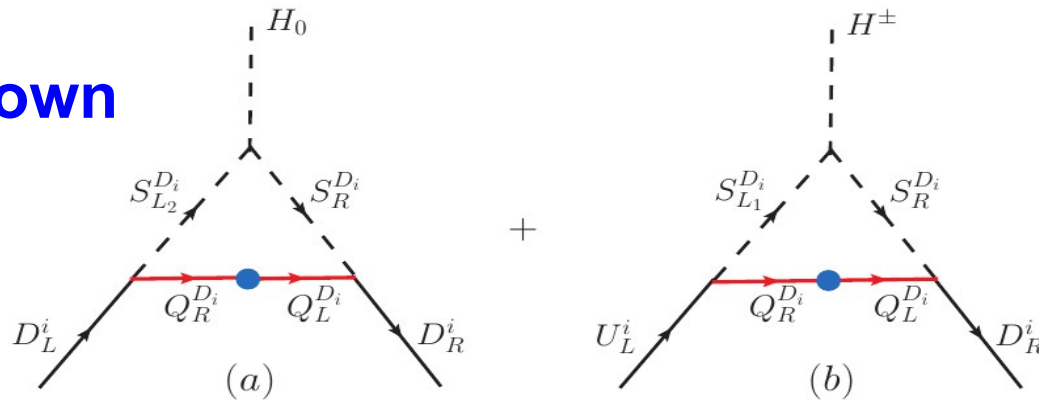
Lagrangian of messenger sector

$$\begin{aligned}\mathcal{L}_{MS}^I = & g_L \left(\sum_{i=1}^{N_f} [\bar{q}_L^i Q_R^{U_i}] \hat{S}_L^{U_i} + \sum_{i=1}^{N_f} [\bar{q}_L^i Q_R^{D_i}] \hat{S}_L^{D_i} \right) + \\ & + g_R \left(\sum_{i=1}^{N_f} [\bar{U}_R^i Q_L^{U_i}] S_R^{U_i} + \sum_{i=1}^{N_f} [\bar{D}_R^i Q_L^{D_i}] S_R^{D_i} \right) + \\ & + \lambda_S S_0 \left(\tilde{H}^\dagger S_L^{U_i} S_R^{U_i} + H^\dagger S_L^{D_i} S_R^{D_i} \right) + h.c., \quad (20)\end{aligned}$$

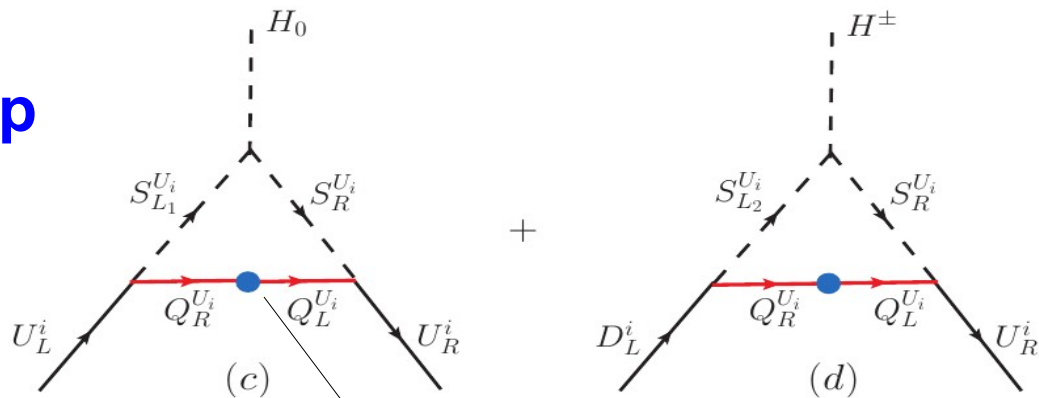
g_L, g_R universal (flavor) couplings (origin of flavor is only in the charge sector of $U(1)$)

Dynamical generation of Yukawa couplings at 1-loop

Yukawa Down



Yukawa Up



Dark fermion mass insertion

Finite result by power counting → predictivity

one-loop result for the Yukawa coupling in the UP sector

$$Y^{U_i} = \frac{\lambda_S g_L g_R \mu M_{Q^{U_i}}}{16\pi^2 \bar{m}^2} C_0(x_i) ;$$

$$M_{Q^{U_i}} = \Lambda \exp \left(-\frac{2\pi}{3\alpha q_{U_i}^2} \right) \quad x_i = M_{Q^{U_i}}^2 / \bar{m}^2$$

After EWSB

- **C0(x)** loop function
- **m(bar)** → average messenger mass

$$m_i = \Lambda_{\text{eff}} \exp \left(-\frac{2\pi}{3\alpha q_i^2} \right)$$

$$\Lambda_{\text{eff}} \sim \left(\frac{v\mu\Lambda}{\bar{m}^2} \right) \frac{\lambda_S g_L g_R C(x_i)}{16\pi^2}$$



Is now proportional to Λ and is a ratio of different scales

Yukawas sum rules

$$Y^{U_j} = Y^{U_i} \exp \left\{ \frac{2\pi \left(q_{U_j}^2 - q_{U_i}^2 \right)}{3\alpha q_{U_i}^2 q_{U_j}^2} \right\} \frac{C_0(x_j)}{C_0(x_i)}$$

to avoid stable heavy charged particles in the spectrum, messenger masses should be always heavier than the corresponding dark fermion ones. In the case of a large mass gap between the messenger and dark fermion sector, the last term multiplying the exponential in Eq.(25) can be well approximated by $C_0(x_j)/C_0(x_i) \sim 1$.

CKM can arise in this framework as a mismatch between the Dark sector masses and SM masses

Phenomenological consequences in the Dark sector

- In the case of degenerate charges there are N^2 NG bosons (scalars) in the Dark sector, as composite fields, since the symmetry is $U(N)_L \times U(N)_R \rightarrow U(N)_V$
- In the case of non-degenerate charges there remains 1 massless NG boson and N^2-1 pseudo-NG scalars in the Dark sector, as composite fields, since the symmetry is $SU(N)_L \times SU(N)_R$
- Mass term of PNG scalars will be proportional to the splitting of $U(1)$ charges in the Dark sector

Naturalness and Vacuum Stability bounds

large values of μ , required to generate the top-quark Yukawa coupling, can in principle spoil naturalness in the Higgs sector. This is due to the fact that the trilinear coupling of the Higgs and messenger sector can induce one loop contributions to the Higgs mass square δm_H^2 , which is of order

$$\delta m_H^2 \sim \frac{\lambda_S^2 \mu^2}{16\pi^2}.$$

Eliminate μ from the top Yukawa couplings ~ 1

$$\delta m_H^2 \sim \frac{16\pi^2 \bar{m}^2}{(g_L g_R)^2 x_t C_0^2(x_t)} \quad x_t = M_{Q_t}^2 / \bar{m}^2$$

To avoid fine-tuning large values of g_L and g_R are required

Assume $g_L = g_R \sim 1$ and Dark fermion masses = messenger masses

$$\delta m_H^2 \sim 4 \times 10^4 \left(\frac{\bar{m}}{\text{TeV}} \right)^2 m_H^2$$

For a messenger mass of order 1 TeV a fine-tuning of order 10^{-4} is required !

Potential solutions $\rightarrow$ SUSY extensions or Lee-Wick extension to the scalar sector as well

In order to avoid tachions in messenger sector

this implies

$$M_{Q_i} > \frac{m_i}{LC_0(x_i)}$$

$$\lambda_S \mu v < \bar{m}^2$$

$$\xrightarrow{\text{xt}=1} M_{Q_t} \gtrsim \left(\frac{55}{g_L g_R} \right) \text{TeV}$$

On the other hand, for the lightest quarks, assuming their mass to be of order 10 MeV, we get

$$M_{Q_u} \gtrsim \left(\frac{1.6}{g_L g_R} \right) \text{ GeV} .$$

So Dark fermions partners for the light generations could be relatively light !

The messengers in the leptonic sector could be also light: since the heaviest dark fermion associated to Lepton flavor could be also light

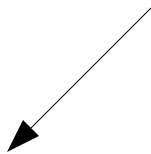
Phenomenological tests

For example, the coloured messengers can be pair produced at the LHC by the gluon fusion mechanism

$$g g \rightarrow S S^\dagger ,$$

or by the quark fusion mechanism

$$q \bar{q} \rightarrow S S^\dagger ,$$



Can be enhanced by large g_L and g_R couplings !

Heavy messenger masses of order of $> O(10 \text{ TeV})$ cannot be detected at LHC $\rightarrow$ but for 100 TeV collider could be fine

Motivation for hadron collider @ 100 TeV !

Impact on Higgs decays

$$A(H \rightarrow \gamma\gamma) = \frac{\lambda_S \mu \alpha}{\bar{m}^2 4\pi} L_F \hat{F}_{\mu\nu} \hat{F}^{\mu\nu},$$

If we eliminate μ from top Yukawa coupling

$$A(H \rightarrow \gamma\gamma) \sim \frac{4\pi\alpha}{g_L g_R M_{Q_t} C_0(x_t)} L_F \hat{F}_{\mu\nu} \hat{F}^{\mu\nu}.$$

Much smaller than SM contribution , since $M_{Q_t} \sim 50$ TeV

$$A(H \rightarrow \gamma\gamma)_{SM} \sim \frac{\alpha g}{4\pi m_W} L_F^{SM} \hat{F}_{\mu\nu} \hat{F}^{\mu\nu}$$

Conclusions

- We proposed a new paradigm for the dynamical generation of exponentially spread Yukawa couplings
- The new idea is that exponentially spread fermion masses are generated non-perturbatively in the dark sector
- Chiral and flavor symmetry breaking is transferred to the SM via some messenger fields coupled to the Higgs field
- Important ingredient is the existence in the Dark sector of a $U(1)$ exact gauge symmetry containing a Lee-Wick term
- Dark fermions, as well as messengers, carry different $U(1)$ charges
- Many potential phenomenological implications at colliders